

Motorcycle rider model for injury prediction

Public report

Project within Trafiksäkerhet och automatiserade fordon - FFI - December 2020

Authors:

Jolyon Carroll, Linus Lundin, Maria Oikonomou, Philip Singh, Madelen Fahlstedt,
Shiyang Meng and Johan Iraeus

Date:

June 2025



Fordonstrategisk
Forskning och
Innovation

Content

1. Summary	4
2. Sammanfattning på svenska	6
3. Background	8
4. Purpose, research questions and method	11
5. Objectives	14
6. Results and deliverables	15
WP1: Injury Identification and Boundary Conditions	15
WP2: Identification of Knowledge Gaps, Development and Validation of the HBM	16
WP3: Development of Motorcycle Models	19
WP4: Testing.....	21
WP5: Positioning and Morphing of HBMs.....	23
WP6: Evaluation of Countermeasures	26
7. Dissemination and publications	29
7.1 Dissemination.....	29
7.2 Publications.....	30
8. Conclusions and future research	31
Conclusions regarding the objectives.....	31
Conclusions regarding the research and direction for further efforts.....	32
9. Participating parties and contact persons	33
10. References	34

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

Globally, motorcyclists are the most vulnerable road user and the number of people being injured on motorcycles is growing worldwide. In multi-vehicle crashes, where passenger cars are the most frequent collision partner, then one of the most common scenarios is different angled impacts of PTW front to passenger car side. This can often lead to severe thoracic and head injuries for the PTW rider.

Despite clear evidence that motorcycle riders are a vulnerable group of road users only few countermeasures, whether preventative or protective, exist to prevent or mitigate these fatalities. In addition, few tools such as anthropometric test devices exist for the development of protective countermeasures. With regard to the virtual human body models, today there is no human body model developed and validated for motorcycle rider impact evaluation and for development of protection systems. There was a clear need for a versatile biofidelic tool that can be used to develop countermeasures to protect the motorcycle rider in a crash. To address this need, the SAFER HBM was evaluated as a motorcycle rider in this project.

The overall goal of the project was therefore to develop a biofidelic refined SAFER HBM (average male) capable of predicting motorcycle rider crash kinematics and injury risk. The focus was on prediction of kinematics and injury risk for the head and chest in motorcycle to vehicle (motorcycle front-to-vehicle side) crashes for different motorcycle types and rider postures.

Now, through this project activity, the SAFER HBM thorax has been validated for PTW to car loading using available PMHS data. Validation data gaps were identified, and a novel PMHS component test series was initiated. Additionally, the baseline 50th percentile male SAFER HBM was compared to PMHS kinematics in a PTW to the side of a car impact, as an initial validation step. This application required the use of a new rider positioning tool, developed within the project, and models of a motorcycle and helmet, also developed within the project. The comparison of kinematics showed many similarities, but also highlighted some differences, mainly related to differences in anthropometry, and stiffnesses of the HBM pelvis and PTW fuel tank.

Rider posture variability was quantified for average sized males on three PTWs and for average sized females on one PTW. This data will be used in future projects to analyze how rider posture influence injury risk, and how important this variability is compared to other sources of variability, e.g. variability in crash parameters. This data can also be used to evaluate the robustness of countermeasures, like the PTW mounted airbag.

This project has taken the first step towards developing an integrated tool for evaluation of motorcycle rider safety to be used for development of protection systems. It is not the final step. Future developments can include development of a population of motorcycle

riders of different anthropometries and sex. The developments can also include analysis of rider induced pre-crash avoidance manoeuvres and addressing additional injuries sustained by the riders.

The broader overall goal of this research was to create new knowledge and develop assessment tools and methods for motorcycle rider crash analysis, which can be used to improve the protection of the population of motorcycle riders. It has succeeded and we look forward to continuing these efforts in future projects.

2. Sammanfattning på svenska

Trots tydliga bevis för att motorcyklister är en sårbar trafikantgrupp finns det endast få motåtgärder, vare sig förebyggande eller skyddande, för att förebygga eller mildra dessa dödsfall. Dessutom finns det få verktyg, såsom antropometriska testanordningar, för utveckling av skyddande motåtgärder.

När det gäller virtuella människokroppsmodeller finns det idag ingen människokroppsmodell som är utvecklad och validerad för utvärdering av motorcyklisters stötar och för utveckling av skyddssystem. Det fanns ett tydligt behov av ett mångsidigt biofideliskt verktyg som kan användas för att utveckla motåtgärder för att skydda motorcyklisten vid en krock. För att möta detta behov utvärderades SAFER HBM som motorcykelförare i detta projekt.

Inom ramen för tillgängliga fordonmodeller och utan användning av morfning har SAFER HBMs thorax validerats för lastfall mellan motorcykel (MC) och personbil. Behov av ytterligare validering identifierades, och en ny serie komponentprov med PMHS initierades. Kinematiken för den oförändrade humanmodellen (50 percentil man) jämfördes med responsen för PMHS i en MC mot bil kollision. Jämförelsen genomfördes med hjälp av ett nytt verktyg för positionering av MC-förare samt en av tre framtagna MC-modeller, som kalibrerats mot nya krockdata. Möjligheten för skyddssystem att minska skaderisken i detta scenario demonstrerades också av de industriella projektpartnererna.

Projektresultaten har använts i utvecklingen av koncept för skyddssystem samt i forskningsaktiviteter hos projektets industripartners. De nya data och de framtagna modellerna kommer fortsatt att användas för att analysera faktorer som påverkar skaderisk för förare. Förhoppningen är att ytterligare stärka möjligheterna till skadeförebyggande åtgärder, såsom demonstrerats med en MC-monterad krockkudde.

Projektet involverade fyra parter och var uppdelat i sex tekniska arbetspaket. Projektet präglades av god samverkan och främjade ett engagemang inom teamet för de gemensamma intresseområdena. De utsatta målen i projektet uppnåddes, men tog längre tid än ursprungligen planerat. Detta berodde delvis på medvetna justeringar i tidsplanen som möjliggjorde för yngre forskare att fortsatt leda centrala uppgifter trots yttre personliga omständigheter. Förseningarna som uppstod inom relaterad biomekanisk forskning utnyttjades genom anpassning av aktiviteter och för att skapa värdefulla lärandemöjligheter.

Det övergripande målet med denna forskning var att skapa ny kunskap och utveckla bedömningsverktyg och metoder för analys av motorcykelolyckor, vilka kan användas för att förbättra skyddet av motorcykelförarpopulationen. Det har varit framgångsrikt och vi ser fram emot att fortsätta dessa ansträngningar i framtida projekt. Kunskapen och de

framtagna utvärderingsverktygen har även integrerats i utbildningsaktiviteter inom Chalmers. Exempelvis genom analys av skadebegränsande koncept för bäckenet i masterskursen "Skadebiomekanik".

3. Background

Motorcycles are growing as a compact means of transport in congested cities and as a leisure or lifestyle object with a generally positive trend in registration numbers in Europe. Throughout this project there has been a year-on-year increase in motorcycle registrations in Europe, despite the Covid pandemic (ACEM; acem.eu), with more than 1 million new registrations in each of the last two years. Motorcycles could have a high potential as agile, space-saving and clean mobility solution in cities. However, whilst this may be true, the question remains, “Is motorcycling a safe mobility choice?”

Globally, motorcyclists are the most vulnerable road user and the number of people being injured on motorcycles is growing worldwide. Of all fatal vehicle crashes, 30% involve two or three-wheelers; resulting in 375 000 fatally injured motorcycle riders annually.

In Southeast Asia, where powered-two-wheelers (PTWs) are a common means of transportation, 46% of the traffic fatalities are motorcyclists (WHO, 2024). In Europe, the use of PTWs is less common with only 1 PTW per every 10 people, but still there are more than 35 million PTWs on the continent; and PTW riders account for 19% of all traffic fatalities (EC, 2024). As PTWs account for a smaller than average proportion of road-user km-travelled, this means that the fatality risk per km much greater than, for example, a passenger car. About 20 times greater according to the OECD (OECD/ITF, 2015). Findings from Australia indicate that the crash rate of a moped in terms of distance travelled could be up to four times greater compared to the crash rate of a motorcycle. (Blackman & Hayworth, 2013).

Despite clear evidence that motorcycle riders are a vulnerable group of road users only few countermeasures, whether preventative or protective, exist to prevent or mitigate these fatalities. In addition, few tools such as anthropometric test devices exist for the development of protective countermeasures. Thus, there remains a need for a versatile biofidelic tool that can be used to develop countermeasures to protect the motorcycle rider in a crash. With regard to the virtual human body models, today there is no human body model developed and validated for motorcycle rider impact evaluation and for development of protection systems.

For motorcycles, the most common crash configuration in Europe (Germany, based on GIDAS data) was found to be a motorcycle that drives at 50 km/h into the side of a passenger car traveling at 20 km/h. In China, the most common crash configuration is a car that travels at 55km/h colliding with a motorcycle traveling at 30km/h (based on CIDAS data). These configurations match the common traffic conflicts for fatally and seriously injured PTW riders. According to Morris et al. (2018), the three most common collision scenarios are: a scenario where the opponent vehicle was turning left and the PTW was going straight and was coming from the opposite direction, a crossing scenario where the PTW was perpendicularly coming from the right side of the opponent vehicle, and where the PTW driver lost the control of their vehicle.

To protect the number of motorcyclists involved in fatal road collisions certain policies have already been adopted successfully in Europe. Some countries in Europe introduced mandatory helmet wearing in the 1970s (Hungary before that) and all have such legislation now. The helmet was assessed to be the most important protection for motorcycle users, since it helps to reduce the number of fatal and serious head injuries by 20% - 30% per annum, saving 1000 lives per year (Otte et al. 2013). In 2001, the European Commission published results from the COST Action 327, yielding a report investigating the consequences of head injuries on motorcycle users, to provide data useful to design new helmets with enhanced protection performances. This was followed by COST Action 357 looking at collision occurrence and accident prevention options with motorcycle helmets (PROHELM, Bogerd, et al., 2010).

The helmet standard used at the start of this project (UN Regulation No. 22.05) evaluated the helmet in pure linear impacts where the helmet and head form were dropped onto flat and kerbstone anvils. This standard has been replaced by the new version, UN Regulation 22.06, where tests for angled impacts against a 45 degree rigid and stationary impact surface have been added. In these new tests measurements were also introduced to assess the rotational kinematics of the head. This is an important step forward, but there is still little known about the interaction between a helmet and a car structure.

The concept of protecting the rider with an airbag that deploys from the PTW is not new. Initial research on this topic began early in the 1970s and continues to this day. Some of the early research at the National Highway Traffic Safety Administration (NHTSA, U.S. Department of Transportation) and TRL (The UK's Transport Research Laboratory) identified issues with this technology that are still relevant today. Testing of leg protectors and PTW airbags also fed the need for a standard way to assess PTW safety systems and the writing of the ISO standard, 13232, on 'test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles'; as first released in 1996. The formative research and standard assessment method paved the way for airbag concepts to be developed by Honda (for a touring motorcycle; Kuroe et al., 2005), by Yamaha (for a scooter; Deguchi, 2003), by Piaggio (for another scooter, within the European Framework Project SIM – Safety In Motion) and by MIROS (for a small capacity motorcycle; Ariffin et al., 2013). Although, the Honda airbag is the only example that has made it into a production PTW, so far.

Airbag jackets are another protective system to increase motorcyclists' safety and, in this case, protect the thorax (Grassi et al., 2018). Most of the currently available airbag devices on the market are certified by the European Standard EN 1621-1 and EN 1621-4 for motorcyclist protective clothing against mechanical impacts. These standards, attending to the maximal force transmitted to a rigid anvil in a series of drop-tests, assign three different levels of protection to any airbag tested (UDV, Ufo Kompakt 91, 2019 & Ballester et al., 2019). However, the correspondence of the boundary conditions of this procedure to those occurring in a real accident (UDV, 2019 & Arando-Marco et al., 2020) is questionable and the biomechanical basis to establish those force thresholds

is unknown. This lack of knowledge was acknowledged by the European Union in the recent 5 million Euro Horizon 2020 grant to a consortium of researchers, governments and industry for a project entitled 'Protective Innovations Of New Equipment for Enhanced Rider Safety' (PIONEERS 2018-2020). The aim of the PIONEERS project was to deliver new knowledge about how to prevent injuries to riders of PTWs through the development of novel and enhanced on-board and on-rider technologies.

4. Purpose, research questions and method

The novel thing about this project was the ambition to generate data from crash tests and use data from PMHS tests in an attempt to create a so-called virtual test method where physical crash tests are used as validation of a simulation setup. Simulation can then be used to supplement physical tests with a larger number of impacts where various parameters can be varied. For example, it can be ensured that the crash protection is effective when varying the collision angle, collision speed, geometric properties and deformation properties of the motorcycle as well as of the car involved and many more parameters. This was the intention of the method described in ISO 13232, but now the opportunity arrives to use finite element models instead of multibody and to use a HBM for injury prediction instead a model of the crash test dummy (a model of a model).

However, at the beginning of the project the software tools needed to handle complicated cases involving FE HBMs and assist on their positioning and articulation at an industrial scale were not available. Most work had been carried out at research level, with specialized tools that could not be easily used in production and certainly not for such complex load cases as that of a motorcycle rider.

An ability to consider different motorcycles in different crashes with different riders also lends itself to a virtual testing approach. It is hypothesized, based on similar work on vehicle occupants, that injury risk will depend on the characteristics of the rider, such as anthropometry, sex and age (Hu et al., 2019). Important steps to address this have been taken in several preceding projects, developing methods and tools to morph human body models (HBMs) so as to represent diversity observed in the population. That work was further advanced in this project with the goal of developing methods to position a HBM in various postures representative of riders of PTWs.

Bringing the background and purpose together, the ultimate goal for the project was defined to develop a biofidelic refined SAFER HBM (average male) capable to predict motorcycle rider crash kinematics and injury risk. Focus was on prediction of kinematics and injury risk for the head and chest in motorcycle to vehicle (motorcycle front-to-vehicle side) crash for different motorcycle types and rider postures.

The broader overall goal of this research was to create new knowledge and develop assessment tools and methods for motorcycle rider crash analysis, which can be used to improve the protection of the population of motorcycle riders. This is motivated by the assertion that it is essential to have a holistic view; covering a variety of factors with the ability to influence the complex motorcycle rider to vehicle interactions.

In terms of the narrow scope definition, then the following Research Topics and combinations of them, were proposed:

- A) Identification of injuries sustained by motorcycle riders in crashes. Definition of the prerequisites to represent a range of motorcycle riders identified in epidemiology.
- B) Investigate the interaction between the rider, the motorcycle and the vehicle in crashes to form the basis for a protection system for the rider.
- C) Update a state-of-the-art SAFER HBM for evaluation and development of protection principles for motorcycle riders in different postures.

This project has taken the first step towards developing an integrated tool for evaluation of motorcycle rider safety to be used for development of protection systems. It is not the final step. Future developments can include development of a population of motorcycle riders of different anthropometries and sex. The developments can also include analysis of rider induced pre-crash avoidance manoeuvres and addressing additional injuries sustained by the riders.

Regarding the method, the project was structured into seven work packages, working in parallel, addressing the research questions on the model development. The Work Packages (WP) are:

- WP1 Injury Identification and Boundary Conditions
- WP2 Identification of Knowledge Gaps, Development and Validation of the HBM
- WP3 Development of Motorcycle Models
- WP4 Testing
- WP5 Positioning and Morphing of HBMs
- WP6 Evaluation of Countermeasures/Industrialisation
- WP7 Dissemination

WP1 defined the boundaries for the project. Our priority injuries were selected in this work package based on the collision data and literature. In correspondence with this selection, data were identified that could be used for the development of the human body model.

In WP2, the SAFER HBM model was scrutinized based on its ability to predict motorcycle rider crash kinematics and injuries.

Within WP3, virtual motorcycle models were developed and validated to be used in the subsequent motorcycle rider crash analysis.

WP4 coordinated motorcycle testing so as to provide data to validate the motorcycle models developed in WP3. PMHS tests were commissioned to support the project and motorcycle rider surrogate tool development. Primarily efforts were concentrated around understanding a series of three full-scale, whole body crash tests. After which a subsequent series of simplified pendulum swing tests were commissioned to support further developments in the model and general understanding of injury causation.

In WP5 a tool for handling and biofidelic positioning the SAFER HBM model as a motorcycle rider was developed.

The SAFER HBM model was used in WP6 in an industrial context to evaluate concepts of protection systems such as inflatable vests, inflatable clothing and helmets.

The results from the project have been, and continue to be, disseminated in scientific publications as well as in conference presentations. WP7 accommodates those dissemination activities.

5. Objectives

A summary of the project implementations is as follows:

Increase knowledge in a specific area	The knowledge generated in the project will enhance the knowledge about motorcycle rider kinematics and injury risk in crashes. The HBM tool developed in the project will be used to understand the motorcycle rider injury risk in accidents. The
Be passed on to other advanced technological development projects	The capabilities of the SAFER HBM developed in this project can also be used in the SAFER HBM as an occupant or pedestrian.
Be passed on to product development projects	The SAFER HBM model will be used to develop protection systems for motorcycle riders. The protection system can be both motorcycle mounted system and/or personal protection system such as inflatable jacket etc.
Introduced to the market	The first protection systems for motorcycle rider protection can be expected to be introduced to the market within 5 years.
Used in investigations, regulations, permit matters/political decisions.	Yes, by making the model available for other to use, the intention is to make it a desired tool for a wider context of occupant protection evaluations, such as included in consumer information tests and eventually regulation.

6. Results and deliverables

The list of publications from the project is listed in Section 7, under Dissemination, and the successful satiation of objectives is described in Section 8. Before reaching those sections, the detailed results and deliverables obtained within the project are described here. These are presented work package (WP) by work package, rather than chronologically.

WP1: Injury Identification and Boundary Conditions

All WP1 deliverables were completed. The most critical injuries sustained by PTW riders—ranked by severity using the Abbreviated Injury Scale (AIS)—were identified and documented alongside rider posture, pre-crash behavior, and anthropometry (Deliverable 1.0a).

Findings showed that for injuries up to AIS2, the upper and lower extremities were most affected, while AIS3+ injuries primarily involved the head and thorax. Accident analysis revealed a roughly equal distribution of single- and multi-vehicle crashes, with regional variation. In multi-vehicle cases, the most common scenario involved the front of a PTW striking the side of a passenger car.

Recognizing thoracic injury as a critical issue for PTW riders, an expert workshop and existing literature motivated a dedicated review of thoracic loading in frequent PTW front-to-car side collisions (Deliverable 1.0b, Lundin et al., 2023). The review synthesized data from physical and virtual studies using ATDs, PMHSs, and FE models, identifying four principal loading parameters: direction, location, distribution, and magnitude. These parameters, outlined in Table 1, provide a structured basis for PMHS test selection and validation of FE-HBMs as well as guiding design of novel PMHS tests.

Table 1. Impact parameters describing the thoracic loading experienced by PTW riders in upright impacts to the side of passenger cars. Reprinted from (Lundin et al., 2023)

Loading Parameter	Description
Location	Transverse thoracic plane: Anterior to lateral parts of the thorax Coronal thoracic plane: Entire rib cage region
Distribution	Flat and curved injury sources Small (Ø2-3cm), middle (Ø10-20cm), and large (Ø50cm) object diameter
Direction	Primarily in anterior-posterior to lateral direction with vertical components
Magnitude	Dependent on loading distribution and studied injury severity level

Using the identified parameters, four available PMHS test series were selected from literature. Qualitative validation showed that SAFER HBM v10 responses generally aligned with PMHS corridors, though towards the upper corridor bounds. Quantitative assessment (ISO/TS 18571:2014) found fair correlation in most cases, except for two impact scenarios where rapid, elevated force peaks led to poor ratings. For all but one impact scenario, the model predicted rib fracture risks (Number of fractured ribs 2+ (NFR2+), NFR3+) consistent with PMHS data.

Overall, SAFER HBM v10 demonstrates fair biofidelity in thoracic loading identified for PTW riders and rib fracture prediction, showing promise as a PTW rider surrogate—demonstrating its usefulness as a human representation to broaden simulation-enhanced safety development to include road users outside cars.

However, comprehensive validation of HBMs will require new PMHS tests that capture loading to the anterior-superior thorax and include vertical force components. It is also important to move beyond the 50th percentile male to ensure the model's relevance across diverse rider populations to ensure equal protection for the entire rider population.

WP2: Identification of Knowledge Gaps, Development and Validation of the HBM

The SAFER HBM was originally developed to represent a car occupant under typical loading conditions. However, recent versions have adopted a more versatile “one-model” approach, enabling also applications such as pedestrian simulations (Lindgren et al., 2023). Expanding the model to loading scenarios not originally considered—such as those in PTW crashes—can introduce challenges, including numerical instabilities. During this project, no such limitations were observed in the head or thorax, the two primary regions of focus, that would hinder the model's ability to predict injury risk for PTW riders. Nevertheless, as noted in WP1, available PMHS component tests do not cover loading to the upper thorax or include vertical force components, underscoring the need for new test data to fully evaluate HBM performance in these areas.

High loads were observed in the pubic symphysis (PS) joint when anterior-posterior forces were applied to the pelvis—resulting from contact with the fuel tank. These loads exceeded the range used in the current validation of the PS joint. Because the SAFER HBM does not include element erosion, the material response of the PS joint was stiffened beyond the validated range to prevent negative element volume and simulation failure. Importantly, the published validation of the PS joint (Brynskog et al., 2022) remains valid, while now also supporting higher loads without causing numerical instabilities.

As further detailed in WP4, a repeatable full-scale PMHS PTW crash test procedure was developed to replicate real-world crash conditions (Van Meter et al., 2023). These tests were used to support the validation of the SAFER HBM (50th percentile), which was positioned to closely match the configurations used in tests 2301 and 2302, with an initial focus on rider kinematics.

To illustrate overall kinematic trends, images were extracted from the high-speed camera footage of the third PMHS test (test 2302) and the SAFER HBM simulation. These stills, presented in Figure 1, show gross visual agreement in motorcycle motion—characterized by a leftward twist of the front wheel and handlebar, combined with pitching and yaw—as well as in general rider kinematics. Although the HBM has a more horizontally oriented spine following the fuel tank impact, both the HBM and the PMHS show an upward head trajectory that results in the head passing over the roof rail. In contrast, the PTW Dummy (Carroll & Bolte, 2024) showed no upward head motion, with the head instead striking the roof rail directly, perhaps due to an even stiffer pelvis-fuel tank interaction.

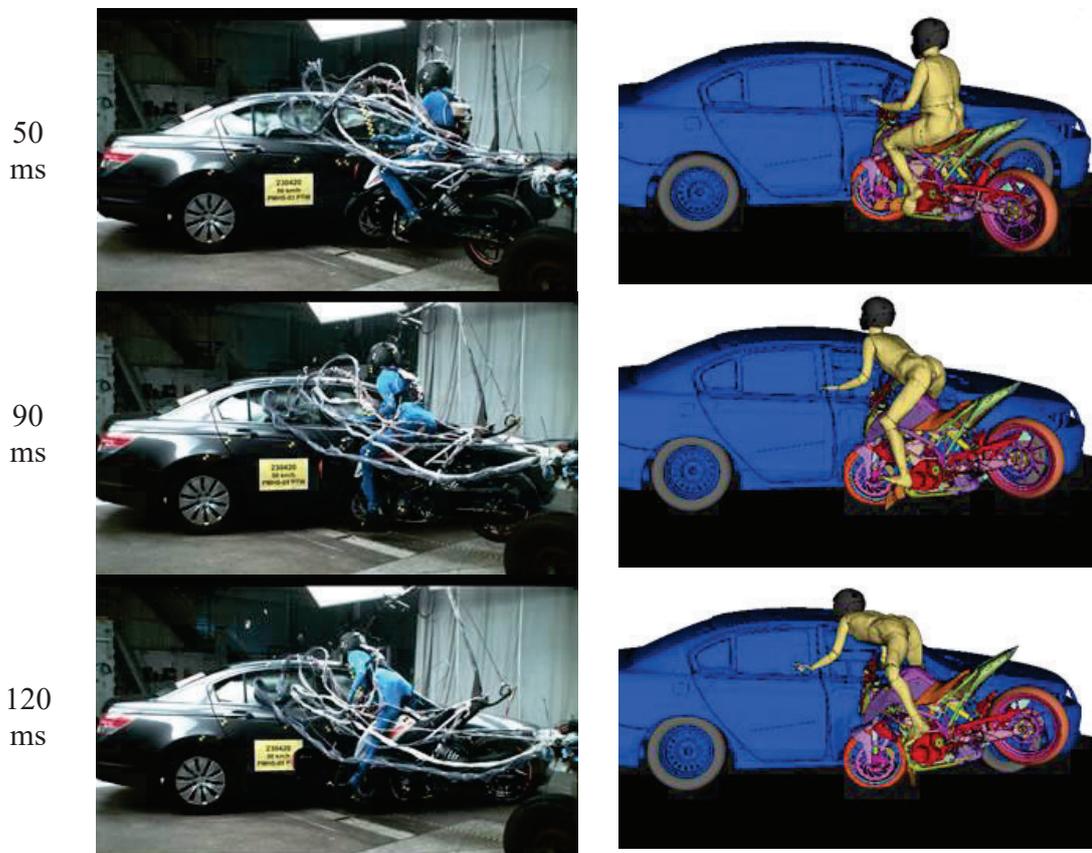


Figure 1. Still images from the video, showing an overview of the kinematics during the third PMHS test (2302, left) and the HBM simulation (right).

Kinematic analysis of the HBM and PMHSs was further supported by tracking fiducial markers placed on the PMHSs, MCs, and car across tests, scaled using each PMHS's femur length. All data were processed according to the SAE J211 coordinate system for impact testing. To visualize test variability, envelopes were created by shading the range between the minimum and maximum X and Z positions of tracked PMHS and MC markers at each time point. This spread is compared with the HBM simulation in Figure 2. The HBM's acromion, humeral lateral epicondyle (HLE), and front axle markers fall within the observed test envelopes. However, deviations were noted for the head (Head Top), greater trochanter (GT), lateral femoral epicondyle (LFE), and mudflap markers.

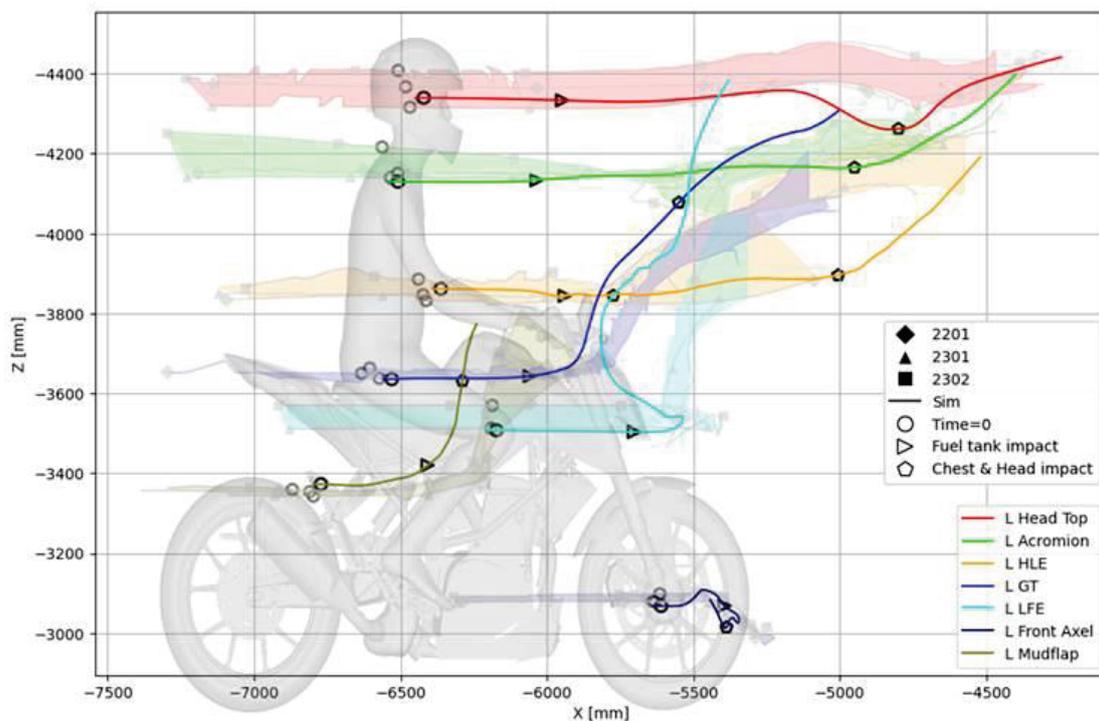


Figure 2. Kinematic tracking (0-200ms) comparison between the three PMHS tests (2201, 2301, and 2302) and the simulation, for the left side head, acromion, humeral lateral epicondyle (HLE), greater trochanter (GT), lateral femoral epicondyle (LFE), front axle, and mudflap markers.

The GT marker, which reflects pelvis-to-fuel tank interaction, shows an earlier upward trajectory in the simulation than in the PMHS tests (also observed at 50ms in Figure Figure 2), suggesting a stiffer HBM pelvic response. This behavior is expected, as all PMHSs experienced multiple pelvic fractures and substantial permanent deformation of the fuel tank, while the HBM lacks fracture modelling and thus maintains pelvic structural integrity. Additionally, the fuel tank in the simulation model exhibited less

deformation compared to the physical tests. The stiffer pelvis response also affects connected markers, such as the LFE (knee), due to the direct linkage via the femur. The HBM's head kinematics may also be influenced by this stiffer behavior, with earlier downward motion potentially caused by the more rigid pelvis affecting the spine and ultimately the head kinematics.

Other factors may also contribute to these differences. For instance, during some PMHS tests—particularly test 2201 and, to a lesser extent, 2302—the overhead head support was released later than intended, which could have artificially delayed head drop. Differences in anthropometry, including stature and seated height between the PMHSs and the baseline HBM, may further influence results.

To enable further comparisons through a closer kinematic match between the simulation and physical tests, it is recommended that the SAFER HBM should be morphed to reflect the anthropometric characteristics of each tested PMHS more closely—specifically stature, seated height, and limb lengths. This adjustment may result in a closer kinematic match, supporting further in-depth validation, including assessments of rib fracture risk and potentially rib strains and accelerations. In parallel, further refinement of motorcycle-to-car interaction, particularly the response of the front wheel assembly with the door and sill, should be undertaken. These refinements are essential to address interaction effects not captured by current rigid wall motorcycle model tests, as further discussed in WP4.

WP3: Development of Motorcycle Models

All WP3 deliverables were met. Three new finite element motorcycle models were developed in this project (Gowda et al., 2025), each representing a unique motorcycle type: naked, scooter, and touring (Figure 3).

All three models are tuned and compared reasonably well with controlled laboratory tests, i.e., rigid wall barrier tests. Multiple measurement metrics are compared against to ensure the fidelity of the motorcycle models, including center of gravity displacement, front suspension compression, rigid wall force, and linear horizontal acceleration measured at motorcycle. Detailed comparisons between the simulations and physical crash tests can be found in Gowda et al. (2025). The fuel tank stiffness was later turned to match the fuel tank deformation depth and area from the PMHS tests provided from WP4.

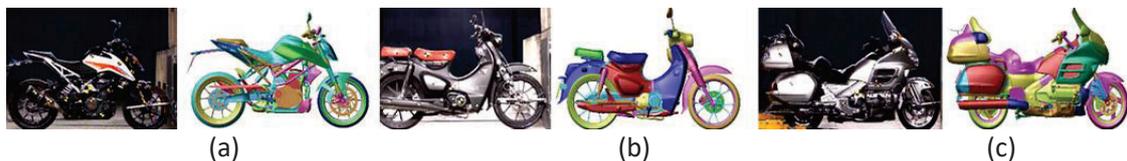


Figure 3. Three new finite element motorcycle models and their physical counterparts in a rigid wall barrier test setup: (a) KTH Duke 390, (b) Honda Super Cub, and (c) Honda Gold Wing.

There are uncertainty parameters in the model, mainly associated with coefficient of friction. This means that coefficient of friction needs to be tuned for angled impacts and contact with deformable surfaces which are unseen in the perpendicular and rigid wall barrier tests. Future work may comprehensively characterise the contact phenomenon between the motorcycle tyre and contacting surface at different speeds to define friction parameters without tuning.

Overall, these newly developed virtual tools help development and evaluation of new safety concepts in the current and future projects to enhance the safety of road users outside the vehicle.

In addition, the objective to develop a finite element model of a motorcycle helmet was also met. This has been performed based on CAD-files. The helmet has been validated according to experimental testing from 13 different motorcycle helmets on the market, in order to replicate a general motorcycle helmet. The set-up for the experimental tests is seen in Figure 4. The experimental tests are drop tests against a 45° anvil with an impact velocity of 7.5 m/s. The headform used was the Hybrid III.



Figure 4. Experimental set-up. Left: rotation around the 'X'-axis. Middle: rotation around Y. Right: rotation around Z.

FE-simulations were performed with the same set-up as the experimental testing. The results from the simulations together with the experimental corridor includes resultant linear acceleration, rotational acceleration and rotational velocity of the head. Good correlation was observed for all kinematic metrics. A chinstrap and comfort padding were added to the helmet according to the fit of the head of the SAFER HBM, the main reason for this was to keep the helmet in place on the head prior to the contact between the head and the vehicle.

WP4: Testing

All WP4 deliverables were met within the project. However, there were some variations in approach when compared with the original description of the work package. To describe the discrepancies and ultimate achievements in more detail, the work package is divided into two parts. The first part was to conduct physical testing to support the motorcycle model development in Work Package 3. The second part was to make information and data available from PMHS tests conducted with novel setups relating to motorcycle crashes.

D4.0 was an internal report describing results from crash tests with a touring motorcycle, a step-through scooter style motorbike and a small naked sports motorcycle.

Within the project, four powered two-wheelers (PTWs) were purchased for the purpose of creating replica finite element models for numerical crash simulations. Each of these PTWs was tested physically to provide correlation data for the models. To cover a variety of PTWs, the project proposal suggested that the vehicles should come from the various categories of touring, cruise motorcycles, and both a two-wheel and three-wheel scooter. Autoliv attempted to provide the project with access to the model of a three-wheel scooter and a small sports-touring motorcycle that had been modelled previously. The testing concerns the same small sports touring motorcycle and three other PTWs, a large touring motorcycle, another global market naked sports motorcycle and a small step-through two-wheeler. Unfortunately access to the large three-wheeled scooter could not be secured with the vehicle manufacturer (who owns the model).

The testing fulfilled the project objective of generating useful correlation data for subsequent comparison with simulated counterparts of PTWs. The testing matched the description in the project application, with four PTWs being crashed. In each case the PTW was propelled at 40 km/h into a rigid wall (formed of concrete blocks), as in Figure 5.

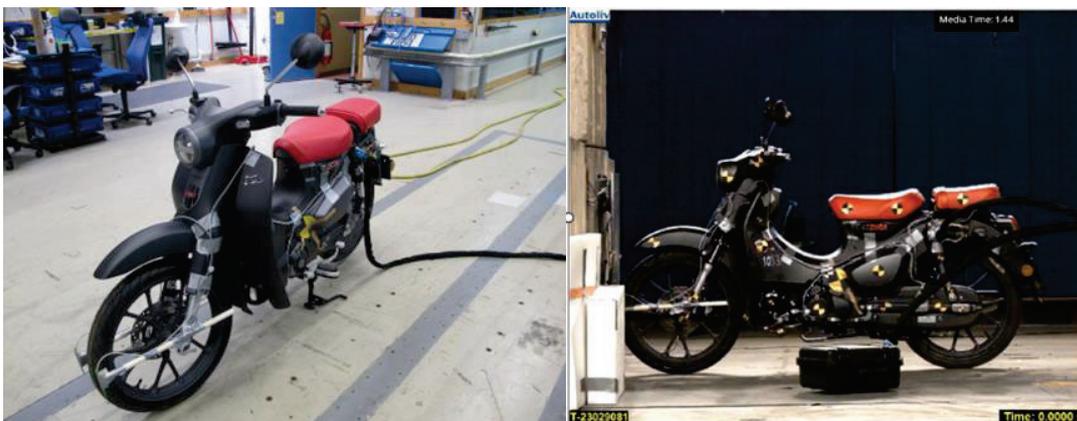


Figure 5. Honda Super Cub prepared for testing and at the moment of impact

A simple test setup crashing the PTWs at 40 km/h into a rigid wall was used to generate the most useful data for correlation with the models. This avoided complications from the rider loading the PTW or from the collision partner yielding or creating a yaw effect on the front of the PTW. It was passed to WP3 and used as a tuning target for the PTW models created within the project. This has created a precedent for future studies too.

As an important limitation from this testing, it should be noted that there could be only one physical test with each PTW due to the destructive nature of the testing. Many channels of instrumentation from a variety of sensors on each PTW were used to try and record the key crash behaviour in each test under this condition. Whilst examples are shown in D4.0, the full data are available for future research. However, and finally, care should be taken if the models are used in different circumstances, moving away from the validation data that were generated here. It might be that further experimentation is needed to check model performance in other conditions too, depending on the potential modelling application.

Deliverables 4.4 and 4.5, which are both internal project reports, concern the PMHS testing. Reflecting the order of the testing and not the description of work in the project application, the contents of Deliverable 4.5 are described first.

According to the planned work, three full-scale tests with a motorcycle crashing into the side of a car with a PMHS rider were commissioned by Autoliv in private work running in parallel with this project (Figure 6). The results from those tests have been made available to the project team and form the basis of the correlation work in WP2. The available data are catalogued in D4.5 for future reference and in this way, the deliverable has satisfied the original project plan for it.



Figure 6. High-speed video still from time of pelvis fracture in PMHS Test 2 out of 3.

Beyond the practical completion of testing, work describing the data generated and preparation for analysis in other tasks, the efforts around the PMHS tests have created a friendly working relationship between members of the project team and those at Ohio State University in the U.S. This relationship has been important as we work together to shape the subsequent component tests. That process is described in Deliverable 4.4.

As described in the internal report D4.4, it should have delivered results from a series of component-level tests with PMHS. However, due to difficulties defining the precise procedure to be used and external factors delaying the tests, it instead documents the decisions being taken in defining the test work. The involvement of the project team in this definition is seen as a positive outcome, particularly given the learning opportunities it presents.

It is still expected that the data from these tests are valuable in the development of rider surrogate test tools. Therefore, D4.4 partially meets the intended objective, describing the test setup and the data to be expected, rather than the data already produced.

To summarise the efforts on the component-level series of test, five PMHS will be impacted against a rigidly-mounted replication of a roof-rail. Tests severities will be tuned to non-injurious, approximately injurious and also extend up to those seen in the full-scale PMHS tests which preceded this. Thereby future research will still be provided with a whole package of novel experimental work, including data from component tests. It is just that WP2 was not provided with this input in time to adjust the SAFER-HBM as was originally planned when the project was proposed.

WP5: Positioning and Morphing of HBMs

All planned deliverables related to rider posture and HBM positioning were successfully completed. These included volunteer tests to define rider postures, the development of a positioning method for PTW riders, and the creation of rider models representing various PTW-specific postures.

Palpated anatomical landmark locations were recorded in a photogrammetric laboratory from 20 male and 10 female volunteers with prior riding experience, all approximately representative of the 50th percentile in stature and body mass. Male volunteers were measured on three stationary PTW types—naked, scooter, and touring—while female participants were assessed on a touring motorcycle. The measurements of the female sample was limited to a single PTW to examine whether differences in average posture and variability compared to males would justify expanding future studies to encompass a broader range of anthropometries.

Following the collection of anatomical landmark locations, a thorough data validation was conducted to identify and remove outliers while preserving the maximum observed variance among volunteers.

Principal Component Analysis (PCA) was applied to the posture data to determine average postures and describe posture variability. To interpret the full-body postures, 3D marker data were translated into skeletal landmarks and joint centers, which were then used to construct kinematic linkage models of body segments and joint angles.

For both male and female datasets, the first few PCs captured the majority of posture variability, highlighting the effectiveness of PCA in dimensionality reduction. Specifically, seven PCs explained 80% of the variance for males, while four PCs captured the same proportion for females. These components described variation in posture features including seat position, spinal curvature, pelvic tilt, extremity flexion, and head orientation.

Among males, average joint angle differences across PTW types were $10 \pm 9^\circ$ (mean \pm SD), while within-group variability reached $26 \pm 11^\circ$ (± 2 SD). Notably, 19 out of 26 measured joint angles showed greater variability between individuals on the same PTW than between average postures across different PTW types. This finding challenges the common practice in PTW safety assessments of using a single rider posture per vehicle type.

For females, PC1 and PC2 alone accounted for 56% of the variance, with head position varying vertically by up to 76 mm and thoracic spine curvature by 22° . A direct comparison of average postures (

Figure 7) revealed that female riders sat 26 mm further forward, had a smaller pelvic tilt angle (14°), and exhibited greater flexion in the hips (13° sagittal, 4° horizontal), knees (10°), and lumbar spine ($6\text{--}9^\circ$) than males. Their head position was also 35 mm lower relative to the motorcycle, which may influence head-to-vehicle interaction dynamics in a crash—potentially increasing the likelihood of head contact with the opposing vehicle rather than clearance over it. Shoulder, elbow, and upper spine angles were largely similar between the two groups. Statistically significant differences ($p < 0.05$) were identified for several key joint angles, particularly in the pelvis, hip, knee, and lumbar spine regions.

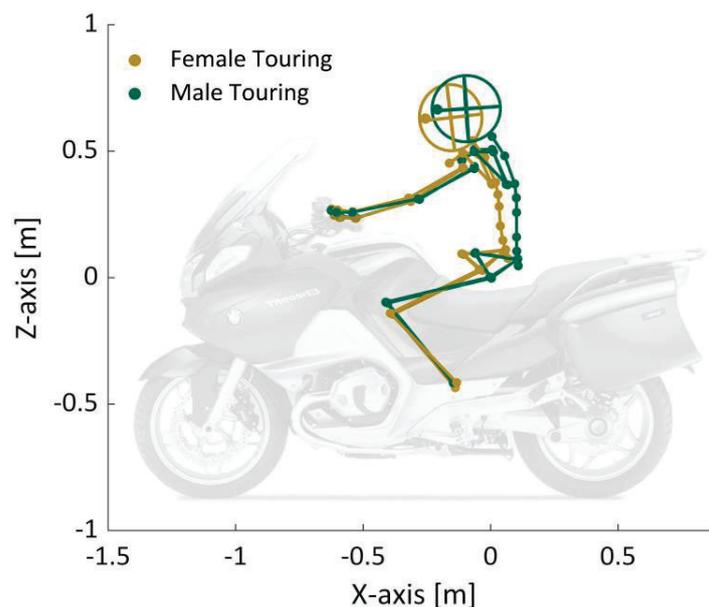


Figure 7. Average male and female rider postures on the touring motorcycle.

The PCA provided representative postures for 50th percentile female and male riders, capturing both average postures and full-body variability. To replicate these postures within Human Body Models (HBMs), a dedicated positioning tool—HBM Landmark Positioning—was developed.

The Landmark Positioning tool was designed to address the challenge of accurately reproducing experimentally derived postures in HBMs. It utilizes ANSA's HBM Articulation tool to instantly and accurately position the HBM based on the location of a given set of skeletal landmarks. By matching the HBM's landmarks to a given input, the tool enables rapid and biofidelic configuration of alternative HBM postures for crash simulation applications.

In this project, the tool was applied using the defined PTW rider postures as input, allowing configuration of biofidelic rider postures for crash simulations in just a few minutes. The tool supports positioning based on up to 52 skeletal landmarks located on the head, spine, pelvis, and upper and lower extremities. A minimum of 22 landmarks is required to achieve full-body positioning to an alternative posture (including 4 on the head, 4 on the pelvis, 2 on the spine, and 3 on each upper and lower limb).

The Landmark Positioning tool can give a single posture or multiple posture configurations in a single run. Desired postures can be provided either directly as target points within ANSA or imported via CSV files through the tool interface. Additionally, the tool generates an automated report on element quality after the positioning process, providing useful feedback for the HBM mesh. The tool can be used with any supported HBM model, enabling the broader use of the rider postures identified through this research into a wide range of HBMs. This allows for direct application of these postures in crash analysis and offers the potential to enhance the robustness of safety system design.

A beta version of the Landmark Positioning tool was shared with project partners for evaluation during the work in WP6 and further refined based on feedback. The final version was released in ANSA v.25.1.0 pre-processor from BETA CAE Systems and made publicly available in January 2025.

In summary, the findings of this work package emphasize the necessity of incorporating anthropometric diversity into rider models. While the female sample size limited statistical power and introduces some constraints on generalizability, the observed differences in both average posture and variability between the male and female samples highlight the need for broader representation in future posture studies. The identified PCs reflect natural interdependencies in human posture and can be applied directly as positioning targets in simulations. Integration with the Landmark Positioning Tool enables these published posture sets to be readily and reproducibly implemented in FE-HBM positioning workflows, supporting more representative crash simulations and

the development of robust safety systems. Overall, these findings provide a solid foundation for enhancing rider models and improving PTW safety assessments in ongoing and future research.

WP6: Evaluation of Countermeasures

A new safety concept to protect the thorax, called a ‘one size fits all’ motorcycle airbag (i.e., a universal motorcycle airbag), was developed and evaluated using the SAFER HBM across three motorcycle types: naked, scooter, and touring (Gowda et al., 2025). Its protection principle was identified – the motorcycle airbag prevents the rider from direct impact with the opposing vehicle and sometimes also the rider’s own vehicle (such as instrument cluster and handlebar), Figure 8.

This universal motorcycle airbag concept was evaluated in a range of collision conditions where the impact angle and speed were varied and the risk of two or more fractured ribs was estimated above 50% without any thorax protection. The results are promising. Even though the airbag was designed to deploy frontally, it remained effective (i.e., 42%-100% reduction in the risk of two or more fractured ribs) for angled impacts up to 50 degrees from the pure lateral (perpendicular) direction. The larger the impact angle, the more glancing the impact. Beyond 60 degrees, the airbag became less effective or ineffective. In a glancing impact with a vehicle, the most severe impact may also shift from the vehicular impact to a subsequent fall or ground impact. This suggests that a holistic approach, combining both wearable protection and in-vehicle protection (or the motorcycle airbag), is necessary to provide total protection for motorcycle riders. Future work could evaluate wearable solutions further, especially in simulations combining the vehicular impact phase and the ground impact phase.

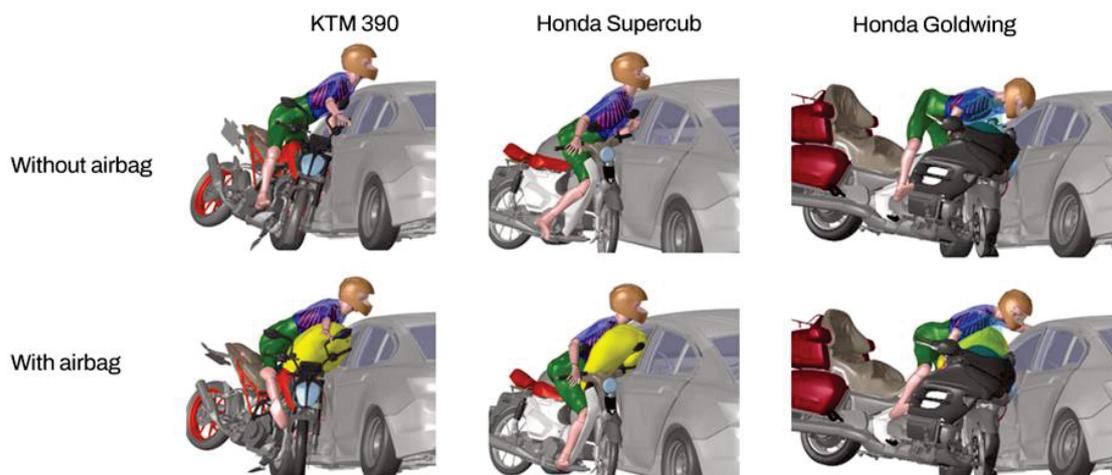


Figure 8. The 'one size fits all' airbag at 120 ms after the first contact between the motorcycle and the car. Note how the airbag prevented the direct contact between the rider's thorax and roof rail.

Helmet designs were also evaluated using the tool developed in this project including the SAFER HBM motorcyclist, positioning tool and motorcycle models. Different configurations were evaluated for different helmet designs with a focus on the interaction between the helmet, head and vehicle where the helmet geometry was kept constant. The different configurations consisted of variation in motorcycle type (naked and scooter), impact velocity and impact angle of the motorcycle.

All configurations resulted in an impact to the frontal part of the helmet, specifically the chin bar region (Figure 9). This impact point on the helmet has also been shown to be one of the most common in vehicle to motorcyclist impacts in several studies (e.g. Wisch et al. 2019, Whyte et al. 2016). All evaluated helmet designs included a chin bar. A previous study has shown the protective effect of the chin bar compared to an open-face helmet (Meng et al. 2023).

The performance of the different helmet designs was dependent on impact configuration and the injury metrics that were evaluated. For some impact configurations the effect on the strain within the brain tissue had a variation up to 26% dependent on the helmet design, where the brain tissue strain is associated with the risk of brain injury.

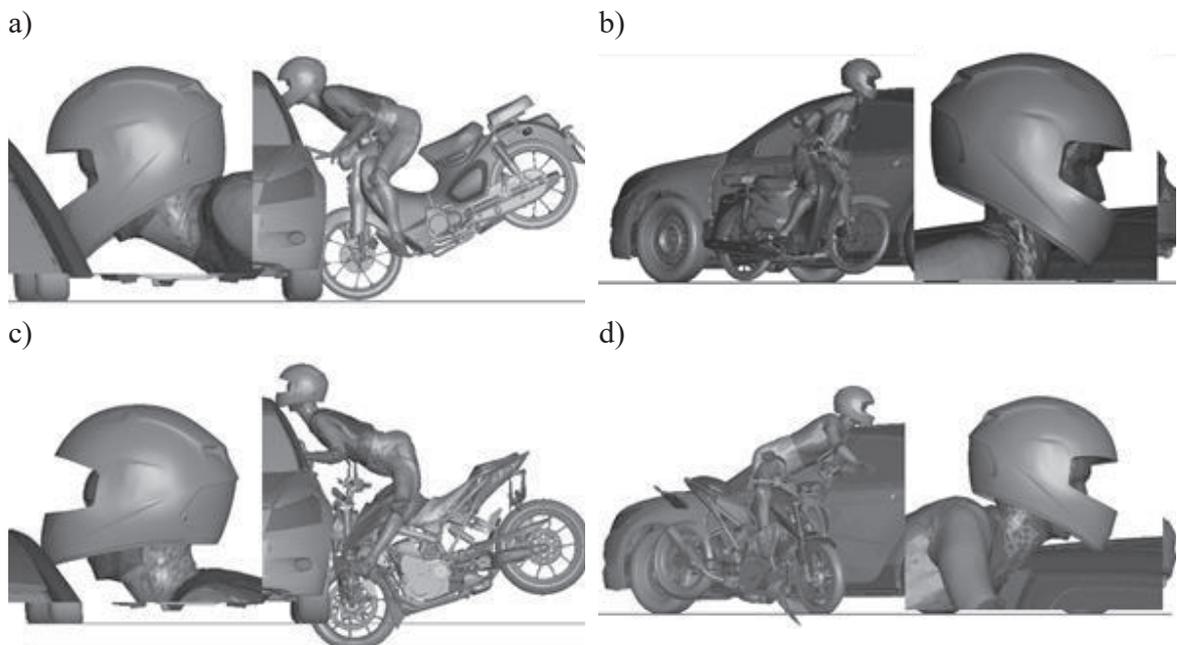


Figure 9. The time at initial contact between the helmet and the vehicle; a) Scooter 0 degrees impact angle relative to the vehicle with a velocity of the scooter of 30 km/h; b) Scooter 45 degrees 50 km/h; c) Naked 0 degrees 50 km/h; d) Naked 45 degrees 50 km/h.

The kinematics before the head impact for the different motorcycle types differed due to the interaction with the motorcycle (Figure 9). However, this difference in kinematics did not significantly affect the risk of brain injury in the configuration evaluated. More configurations should be evaluated to better understand how the helmet performance is affected by different impact configurations.

As mentioned above, all impacts were initially on the chin bar region in this evaluation. Today, the European certification of motorcycle helmets (UN Regulation No. 22.06), includes an evaluation of the chin bar area. The test is performed by dropping the helmet mounted on a headform against a flat surface at 6 m/s and measuring the peak linear acceleration, that should not exceed 250 g. The question raised by this research is whether this test is a representative way to evaluate the performance of the chin bar region in vehicle-to-motorcyclist interactions. The results in this project did not show any correlation between linear acceleration and brain tissue strain, however, it is only based on a limited number of configurations, as presented in Figure 9.

Future work with this developed tool can be an important factor in developing improved motorcycle helmets for vehicle to motorcyclist interaction as well as developing certification test methods that drive the market towards safer helmets. With this tool the robustness of the countermeasures and test methods can be evaluated further with, for example, impact velocities, impact angles, seating postures and different types of motorcyclists.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Comment
Increase knowledge in the field	The deliverables included publications and dissemination activities contributing to the global knowledge enhancement in the area of PTW safety, as well as partner internal skills creations having a direct impact on development of motorcycle rider crash protection
Be passed on to other advanced technological development projects	There are (confidential) testing and technology development projects going on within Mips and Autoliv and these benefit from the possibility to use the SAFER HBM as a rider model in CAE. These projects support our understanding of the protection that can be offered by countermeasures on the rider or built into the PTW.
Be passed on to product development projects	By extension the understanding of potential, and how to assess the potential, trickles down to application products with a specific product in mind. Yes, the SAFER HBM is being used in product development on both wearable and on-bike countermeasures.
Introduced on the market	The HBM positioning tool is available in the latest ANSA release from BETA CAE (Cadence). Therefore, the tool is on the market. The SAFER HBM has not been released for commercial exploitation yet. Mips and Autoliv continue to supply components to manufacturers of helmets and inflatable jackets. A new PTW airbag on-bike has not reached the market yet, but is imminent.
Used in investigations / regulatory / licensing / political decisions	Swedish-led research into PTW protection was evident at the fourth ministerial conference on road safety in Marrakech. There was a great focus on motorcycle helmets – with suggestions for a multitude of actions, policy proposals, and initiatives to enhance legal action.

7.2 Publications

The formal publications resulting from the project are, as follows:

Meng, S., Gowda, S., Lubbe, N. (2022). The Face Airbag: A Novel Concept for Facial Impact Protection. IRCOBI Conference, 2022, Porto, Portugal. URL: <http://www.ircobi.org/wordpress/downloads/irc22/pdf-files/2259.pdf>

Meringolo, D., Van Meter, M., Tesney, A., et al. (2023). Development of a Test Methodology for PMHS-Occupied Powered Two-Wheeler and Motor Vehicle Crash Scenario. Injury Biomechanics Symposium 2023, Poster presentation.

Lundin, L., Iraeus, J., Pipkorn, B. (2023). Powered Two-Wheeler Rider Thoracic Impact Loading in Crashes with the Side of Passenger Cars: Literature Review and Human Body model Validation. IRCOBI Conference, 2023, Cambridge, UK. URL: <http://www.ircobi.org/wordpress/downloads/irc23/pdf-files/2351.pdf>

Van Meter, M., Carroll, J., Meng, S., et al. (2023). Development of Powered Two-Wheeler PMHS Crash Test Methodology. IRCOBI Conference 2023, Cambridge, UK. URL: <http://www.ircobi.org/wordpress/downloads/irc23/pdf-files/2356.pdf>

Oikonomou, M., Lioras, A., Rorris, L., et al. (2023). Positioning Human Body Models in cyclists' postures based on experimental data. 11th International Cycling Safety Conference, 2023. The Hague, Netherlands. URL: https://swov.nl/sites/default/files/bestanden/downloads/ICSC2023_Book_of_abstracts.pdf#page=254

Lundin, L., Oikonomou, M., Lioras, A., et al. (2024). Quantifying Rider Posture Variability in Powered Two- and Three-Wheelers for Safety Assessment. *Traffic Inj. Prev.*, 25(7), pp.956–967. DOI: 10.1080/15389588.2024.2351607

Lundin, L. (2024). Towards Safer Powered Two- and Three-Wheeler Riders: Enhancing Human Body Models for Thoracic Injury Assessment. Licentiate Thesis, Chalmers University of Technology: Gothenburg, Sweden. URL: <https://research.chalmers.se/en/publication/543771>

Gowda, S., Pipkorn, B., Shiyang, M. (2025). Evaluation of a “One Size Fits All” Motorcycle Airbag Concept using Finite Element Human Body Models. IRCOBI Asia Conference 2025, Chennai, India. URL: <https://www.ircobi.org/wordpress/downloads/irc25-asia/pdf-files/A2521.pdf>

Lundin, L., Oikonomou, M., Rorris, L., et al. (2025). Female Rider Posture Variability on a Touring Motorcycle. IRCOBI Conference 2025. Vilnius, Lithuania. URL: In press

Lundin, L., Oikonomou, M., Svensson, M.Y., et al. (2025). Variations in Posture Among Average Sized Female Riders on a Touring Motorcycle. Report. URL: <https://research.chalmers.se/en/publication/545698>

8. Conclusions and future research

Conclusions regarding the objectives

A PhD student was hired for the project and hosted at Chalmers University. Also, contributions were received from a second student based at the industrial partner BETA CAE. The expected contributions from the students were several peer-review publications and a Licentiate report. These have been satisfied. Having two students working on the project exceeded our expectations going into the project.

To further support model refinement, a comprehensive Master's thesis project has been initiated involving two students. The focus is on developing a morphometric model to improve fracture prediction of the first rib, which has been shown to play a key role in the identified upper thoracic loading conditions for PTW riders.

The senior researchers of the project were also expected to produce publications and conference presentations to further support the creditability and international acceptance of the SAFER HBM model. This can be demonstrated through, for example, the countermeasure evaluation (Gowda et al., 2025).

The project results have been used in protection system concept development and research activities by the industrial partners of the project. The HBM model is used in the evaluation of motorcycle rider kinematics for various impact configurations, as our only reference point for comparison with dummy models.

The model is being used for development and evaluation of robust protection system for the motorcycle rider such as motorcycle mounted airbags, inflatable clothing, and helmets.

The knowledge and assessment tools developed in the project have been integrated into educational activities within Chalmers Master's programs. For instance, in the "Impact Biomechanics" course, where students were given the task of designing a novel restraint system aimed at reducing pelvic loading. Their concepts were evaluated through simulation using the ANSA articulation to position the validated SAFER HBM in representative 50th percentile rider postures on one of the PTW FE models developed in the project.

This project has built on the results from previous SAFER HBM development projects. It is complimentary to and has been performed in collaboration with other current research projects aimed at developing the SAFER HBM for advanced car passenger protection evaluation. As such, we remain confident that the results from this project will also contribute to the development of the SAFER HBM for passenger protection. The positioning tool developed in this project can also be used to position the SAFER HBM

as a vehicle occupant. In addition, the tool will in the future be refined to take additional steps towards quality assured virtual evaluations with the SAFER HBM model.

Conclusions regarding the research and direction for further efforts

Within the project the SAFER HBM thorax has been validated for PTW to car loading using available PMHS data. Validation data gaps were identified, and a novel PMHS component test series was initiated. Additionally, the baseline 50th percentile male SAFER HBM was compared to PMHS kinematics in a PTW to the side of a car impact, as an initial validation step. The comparison showed many similarities, but also highlighted some differences, mainly related to differences in anthropometry, and stiffnesses of the HBM pelvis and PTW fuel tank. This calls for further refinement of the deformable parts of the PTW and possibly updates to the HBM pelvis. Additionally, the HBM should be morphed to each of the PMHS anthropometries, to account for variability in anthropometry.

Rider posture variability has been quantified for average sized males on three PTWs and for average sized females on one PTW. This data will be used in future projects to analyze how rider posture influences injury risk, and how important this variability is compared with other sources of variability, e.g. variability in crash parameters. This data can also be used to evaluate the robustness of countermeasures, like the PTW-mounted airbag. As the female posture varied significantly from the male, it is recommended to continue to quantify the female rider postures on more PTW types. Additionally, the rider postures should be quantified over a larger part of the population (outside the average female and male), to enable positioning of morphed HBMs, and analysis of how the injury risk varies over the population.

While the project has provided valuable insights on PTW rider kinematics in a common crash configuration (and will also extend this to analysis of rider injury risk outside this project), it is recommended to extend the scope, in a first step to include more PTW types and more collision partners (vehicle sizes), to be able to better represent the real-life variability. In a second step, more crash configurations can be added to the analysis.

The focus on head and thorax in this project makes perfect sense as these are the most commonly, seriously-injured body parts. However, injuries to the lower extremities, and in particular to the pelvis, are also very frequent, can often lead to long-term impairments, and might require other countermeasures than the ones suggested in this project. To enable this development, the HBM (pelvis) needs a validated injury criteria with an associated injury risk function, something that is lacking today.

9. Participating parties and contact persons

There were four parties involved in this project and all contributed to its success. The project-related contact persons within these organisations are:

Jolyon Carroll, Autoliv: jolyon.carroll@autoliv.com



Stylios Seitanos, BETA CAE: sseita@beta-cae.com



Mats Svensson, Chalmers: mats.svensson@chalmers.se



Madelen Fahlstedt, Mips: madelen.fahlstedt@mipsprotection.com



10. References

Brynskog, E., Iraeus, J., Pipkorn, B., et al. (2022). Population Variance in Pelvic Response to Lateral Impacts—A Global Sensitivity Analysis. IRCOBI Conference, 2022, Porto, Portugal. URL: <https://www.ircobi.org/wordpress/downloads/irc22/pdf-files/2234.pdf>

Carroll, J., Bolte IV, J. (2024). The Powered Two-Wheeler Crash Test Dummy Behaviour Compared with PMHS Reference Responses in One Full-Scale Motorcycle-to-Car Collision. IRCOBI Conference 2023, Stockholm, Sweden. URL: <https://www.ircobi.org/wordpress/downloads/irc24/pdf-files/2480.pdf>

Lindgren, N., Yuan, Q., Pipkorn, B., et al. (2023). Development and Whole-Body Validation of Personalizable Female and Male Pedestrian SAFER Human Body Models. arXiv preprint arXiv:2305.13918.

Meng, S., Ivarsson, P., & Lubbe, N. (2023). Evaluation of full-face, open-face, and airbag-equipped helmets for facial impact protection. *Accident Analysis and Prevention*, 191. URL: <https://doi.org/10.1016/j.aap.2023.107181>

Whyte, T., Gibson, T., Anderson, R., et al. (2016). Mechanisms of Head and Neck Injuries Sustained by Helmeted Motorcyclists in Fatal Real-World Crashes: Analysis of 47 In-Depth Cases. *Journal of Neurotrauma*, 33(19), 1802–1807. URL: <https://doi.org/10.1089/neu.2015.4208>

Wisch, M., Breunig, S., Piantini, S., et al. (2019). *D1.1 Powered Two-Wheelers-Road Traffic Accident Scenarios and Common Injuries*. URL: <https://pioneers-project.eu/wp-content/uploads/2020/12/Deliverable-D1.1.pdf>