

# **INTEGRATED SAFETY: ESTABLISHING LINKS FOR A COMPREHENSIVE VIRTUAL TOOL CHAIN**

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## **ABSTRACT**

As technologies for injury prevention and crash avoidance both contribute to injury reduction in car crashes, tools predicting the combined effect of all safety features are needed. This study aims at establishing a computer simulation methodology including two important elements for assessing this combined effect. The first element describes the states of the involved vehicles or objects at crash initiation regarding positions, orientations and velocities as parameters used for crash evaluation. The second element focuses on the car occupant, enabling computationally efficient prediction of occupant position transfer during pre-crash maneuvers. An extended aim is to demonstrate how data flows between these elements in an example case study.

Real-world data from the Volvo Cars traffic accident database (VCTAD) was used as the basis for pre-crash simulations involving two cars, with and without a conceptual autonomous emergency braking (AEB) function. For cases in which the crash was not avoided by the AEB function, the crash configuration was identified. A simplified occupant kinematics model (SOCKIMO) was developed and applied to these remaining crashes, supporting the selection of crash situations to be analyzed in detail. The SAFER human body model (HBM) was used for simulation of the occupant response, providing information on pre-crash kinematics as well as the occupant crash response.

As a result, a novel crash configuration definition for estimating the consequences of car crashes based on preceding events was established. The Volvo parametric crash configuration (VPARCC) definition can be used as a link between pre-crash and crash simulation tools as well as for illustrating sets of real-world accident data and how these change based on maneuvers preceding a crash. SOCKIMO results demonstrated occupant kinematics similar to those of volunteers, and the subsequent simulations using the SAFER HBM showed considerable changes in occupant crash response based on pre-crash vehicle kinematics.

The VPARCC definition can also be applied to collision objects such as trucks or vulnerable road users. The developed SOCKIMO can be used to filter out cases from large crash data sets to be further analyzed with detailed models such as finite element active HBMs. By applying the more detailed HBM, the effects of avoidance maneuvers on occupant kinematics relevant for injury prediction can be evaluated. This approach would not be possible using simplified occupant models only (due to the lack of details) or by using detailed models only (due to the large simulation effort).

The presented methodology for estimating combined safety performance can be used for transferring output from pre-crash simulations to input for crash simulations. The feasibility of combining the individual elements of this methodology was demonstrated in an example case where autonomous emergency braking led to a large change in the crash configuration and was predicted to introduce substantial occupant pre-crash excursion. In this example case, it was shown that the present A-HBM tool is able to cover the complete sequence from pre-crash maneuvers to crash in one single simulation.

## INTRODUCTION

Road traffic safety continues to play a major role in the overall health of the world's population. Today, it is the eighth leading cause of death for people of all ages, annually amounting to approximately 1.35 million fatalities worldwide [1]. Continuing to strive for improved safety is therefore in the interest of all stakeholders in road traffic systems. Visions of reducing the number of road fatalities towards zero have been put forward by numerous countries, states and cities [2]. However, recent data suggest that the number of fatalities and injuries on European as well as on U.S. roads has started to level out or even increase [3, 4].

From a vehicle design point of view, a long tradition of improvements has been seen relating to crash safety, i.e. injury prevention in case of a crash occurring. More recently, automated collision avoidance technologies have emerged, raising expectations for a future with autonomous vehicles in which crashes can be avoided. By studying real-world crash data, it can be seen that both systems for injury prevention as well as systems for collision avoidance do have considerable effects on the number of injuries [5]. Developing assessment tools that predictively can quantify how many crashes can be avoided, but also predict the effect on injuries from those remaining, non-avoided, crashes is therefore important for injury prevention in future passenger cars. Today, assessment of the real-world safety performance of a car model is done by analysis of retrospective data, available years after introduction. In addition to this, the effect of safety systems is predicted already before these systems have been put into production. This is done with established methods [6] involving physical crash testing and simulation using computer aided engineering (CAE). For integrated safety, i.e. how safety systems aimed at collision avoidance and injury prevention interact with and complement each other, methods need to be refined in order to make such predictions. The use of virtual tools for integrated safety is therefore a key component in order to predict expected crash outcomes, providing decision-making data for developing the most effective safety systems.

In this process, understanding future crash scenarios and transferring this knowledge into specific crash configurations becomes an important factor. Methods on calculating the effect of collision avoidance systems in terms of injury outcome and accidents avoided or mitigated have been developed. Lindman and Tivesten [7] presented such a method based on available traffic accident data with the aim to support the system development process by offering an opportunity to alternate input parameters, such as, braking (acceleration) level in order to determine the effect of these changes. The method was further refined including the actual system algorithm in a relevant car and sensing model by Lindman et al [5]. These methods include estimations of the consequences of a crash using risk functions based on real-world traffic accident data, by assuming a modified injury risk as a result of reduced crash severity. However, these methods as well as established ways for describing crashes such as using the collision deformation classification (CDC) or principal direction of force (PDOF) [8] were found to lack the level of detail needed to describe subtle relative changes in crash configuration to support CAE studies in the form of structural and occupant finite element (FE) simulations. With a refined description of crash configurations, the effects of collision avoidance interventions can be described and evaluated by simulating a range of traffic situations that are likely to occur. By applying probable distributions of the input parameters, the robustness and sensitivity of the system can be evaluated.

Another context for which the interaction between systems for collision avoidance and injury prevention becomes increasingly important relates to occupant re-positioning due to pre-crash accelerations, regardless from human drivers or autonomous intervention systems. These effects are possible to study in volunteer experiments [9] and it has been found that the muscle activation of car occupants has a considerable influence on the kinematic pre-crash response [10], leading to a need for active human body models (A-HBMs) in order to study these effects using CAE tools. Several approaches to A-HBMs have been made [11, 12] and a potential for use in product development has been demonstrated [13]. The most detailed injury prediction response based on tissue level can be provided by FE HBMs, which however are all computationally intensive. This is even more pronounced when pre-crash maneuvers are considered, these often have a duration of seconds whereas crash simulation typically spans 100-200 milliseconds. It is therefore not seen as feasible to deploy FE A-HBMs directly in larger simulation studies with thousands of cases for estimating the effect of collision avoidance systems. In this context, a computationally efficient model indicating occupant pre-crash motion including effects of muscle tensioning is therefore desired. With such a tool, a number of critical or dimensioning cases could be filtered out from a larger sample set for analysis using FE A-HBMs. From volunteer studies of belted passenger car occupant kinematics during pre-crash maneuvers, it has been observed that the pelvis displacement is small compared to that of the head and torso [14], suggesting a model of only the upper body could be useful for studying pre-crash occupant kinematics.

The overall aim of this study is to create a CAE methodology for predicting the combined safety performance from collision avoidance systems (e.g. autonomous emergency braking, AEB) as well as systems for injury prevention (e.g. seatbelts and airbags). Specific aims are to establish two important elements in this simulation methodology. The first element concerns real-world data, and the transfer of real-world pre-crash situations into crash configurations to be used in crash simulations providing insight into occupant protection. The second considers the human occupant, enabling computationally efficient prediction of position transfer between pre-crash situations and crash. An extended aim is to demonstrate how data flows between these elements in an example case study.

## THE VOLVO CAE TOTAL SAFETY PERFORMANCE METHODOLOGY

In order to obtain a useful overall methodology based on simulation models, it is of great importance that the individual components can be shown to deliver valid results. The overall validity of this overall methodology will not be possible to prove until validation data is available, i.e. when real-world data can be collected that reflect the actual safety performance. Since this is a process that involves a sufficiently large number of vehicles being put in production and deployed in real-world situations, it could take several years before these effects can be seen. The approach in this study is therefore to assess the validity of each included element in the overall methodology and ensure that each such element delivers realistic results.

A novel methodology is presented for estimating the total safety performance based on CAE tools, i.e. how the effects of countermeasures aimed at injury prevention before and during a crash can be described using computer models in order to summarize these effects for larger sets of traffic scenarios. This is followed by one specific example case which was chosen to demonstrate and further explain the selection process and transfer of data between CAE tools. Focus is placed on the elements that was recently developed in order to bridge gaps and create links in the overall methodology.

### Overall description of the methodology

The overall methodology contains seven elements, as displayed in Figure 1. It has its basis in real-world data, and provides output of car occupant response during the complete sequence of events covering both pre-crash and crash phases. When applying the methodology, the process starts with identifying real-world traffic situation datasets relevant for the research question at hand, as illustrated by element 1 and ends with the output that is given from occupant pre-crash and crash simulation in element 7. Each of these and intermediate elements are further described below.

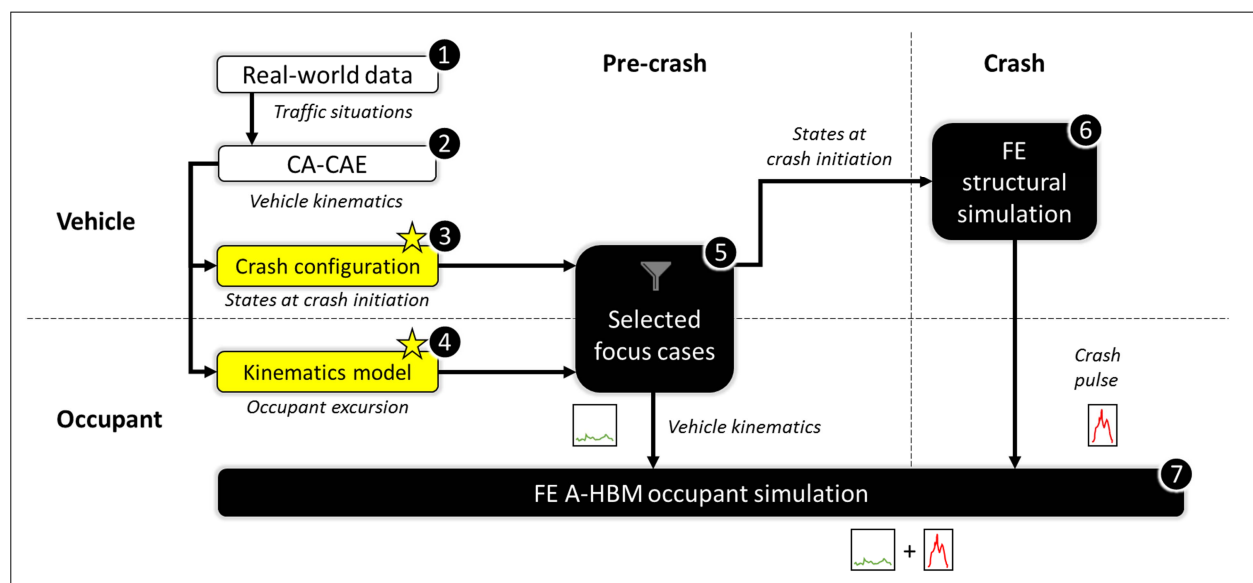


Figure 1. Overview of Volvo CAE total safety performance methodology, with element numbers encircled.

**Element 1: Real-world data.** Representing a range of real-world traffic situations, a set of data is used as the starting point for this methodology. Each case in this database represents a collision relevant for the research question that will be studied. Information needed for the baseline pre-crash simulation are e.g. vehicle paths in relation to vehicle velocities and to the surroundings in a numerical time history data (THd) format.

**Element 2: CA-CAE.** In the next step, a “Baseline” pre-crash simulation is performed to reflect the original real-world data. This is then compared to another dataset called “Treatment” which includes the collision avoidance technology to be studied. This tool for collision avoidance CAE (in the following abbreviated to CA-CAE) should include models where sensor and actuator parameters can be adjusted. The CA-CAE tools may also include driver models to simulate how human drivers interact with the vehicle. In its simplest form, the driver model is a path follower that provides driver input in order to make the vehicle follow the time-dependent states given in the real-world data cases. The validity of the CA-CAE tools should be ensured by comparing subsets of pre-crash simulation data to corresponding data collected from physical tests performed on test tracks or public roads.

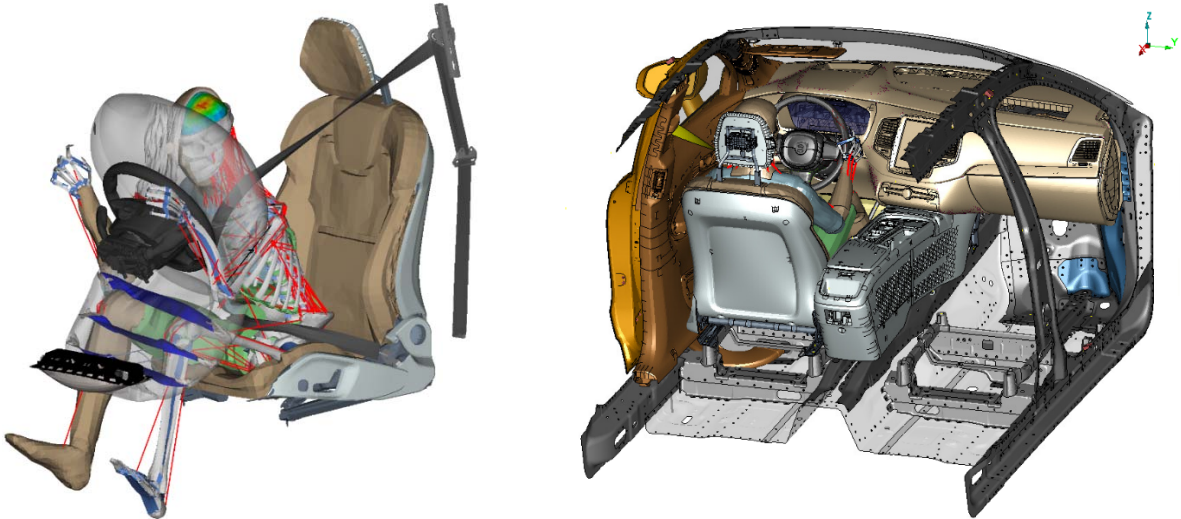
**Elements 3-4: Crash configuration and occupant pre-crash kinematics model.** The output from the CA-CAE tools in element 2 are time histories of variables describing the states of all vehicles or objects involved in a crash. If the CA-CAE tools indicate that the collision is avoided, the process will stop after element 2. However in cases where a crash still occurs, the influence of the pre-crash phase needs to be described and possibly considered in the crash phase. For this purpose, element 3 in Figure 1 regarding crash configuration and element 4, an occupant pre-crash kinematics model, are defined. These elements describe how the pre-crash phase has influenced the crash configuration as well as how the occupant position may have been affected by the pre-crash phase. They are both marked with a star in Figure 1, and proposals for such elements are presented in separate sections below.

**Element 5: Selected focus cases.** In the next phase, the methodology allows the user to select certain cases that may be of special interest by filtering out cases where the crash configuration indicates high crash severity, if particular impact locations are identified or if a pre-crash intervention changes the crash configuration to a large extent. Since the number of cases can be extensive, the occupant pre-crash kinematics model is used to further filter out cases where it can be expected that the occupant would experience considerable pre-crash excursion, i.e. displacement due to vehicle accelerations. By selecting this smaller sample of the collision avoidance simulation cases, the simulation effort using the FE A-HBM (element 7) where the pre-crash vehicle kinematics is combined with the crash pulse from the FE structural crash simulation can be substantially reduced.

**Element 6: FE structural crash simulation.** The purpose of the crash configuration definition is to provide a description of the states of the ego/host vehicle at impact as well as the crash counterpart that can be fed into an FE structural crash simulation of the two objects involved in the collision, or as input to setting up physical crash tests. This simulation could theoretically include also an FE A-HBM, however due to computational efficiency, the structural and occupant crash simulations are normally split into two separate simulations for each case. In this way, output from the FE structural crash simulation can be fed into the complete-sequence (pre-crash and crash) occupant crash simulation using an FE A-HBM, element 7 in Figure 1.

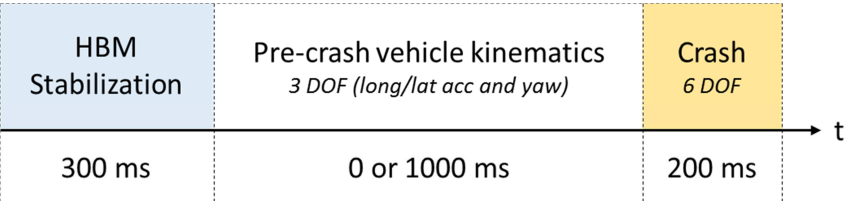
**Element 7: FE A-HBM occupant simulation.** In this element, the effects of the pre-crash phase and the subsequent crash is studied using an occupant and interior model. For the development of the current methodology, the SAFER HBM occupant model was used. This is a 50th percentile male model based on the THUMS v3 model but substantially updated by the partners of the SAFER Vehicle and Traffic Safety Centre at Chalmers in Gothenburg, Sweden. The head and brain model has been replaced with the KTH head model [15]. The rib cage has been updated with a more detailed model with rib curvature and cortical bone thickness representative of the average 50<sup>th</sup> male from relatively large sample studies [16, 17]. The cervical and lumbar spine of the model has been updated with non-linear ligament [18] and intervertebral disc models.

The SAFER HBM, Figure 2, has active musculature implemented using Hill-type beam muscle elements controlled by feedback controllers [19]. The most recent update of the active muscle control includes an omnidirectional lumbar and cervical spine controller [20], which enables modelling of both car driver and passenger reflexive and postural responses in pre-crash scenarios.



**Figure 2:** *The SAFER HBM in a crash simulation with soft tissues blanked out to show the musculoskeletal structure (left) and overview of the FE vehicle interior model (right).*

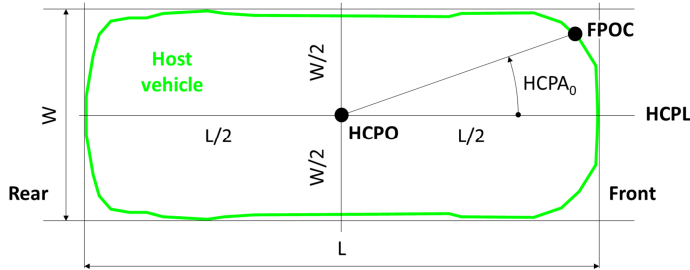
The vehicle interior used in this study consists of a rigid sled model representing a passenger car body structure where deformable models of the interior components such as seat, steering wheel, instrument panel, airbags and seat belts are included, Figure 2. To simulate the complete sequence of events, three phases are included in the same occupant simulation model as illustrated in Figure 3. The first phase is for HBM stabilization needed for the model to find equilibrium under gravity loading and with active muscles. During this phase which lasts for 300 ms, the rigid sled is stationary. In the following phase of pre-crash vehicle kinematics (PCVK), the maneuver from the CA-CAE pre-crash simulation is given as prescribed motion to the sled. In this study, the PCVK includes three degrees of freedom (DOF): longitudinal and lateral acceleration of the vehicle as well as yaw velocity. The PCVK phase has a duration of 1000 ms when included. In the last phase of the sequence, a crash pulse lasting 200 ms recorded from the FE structural crash simulation, see element 6 in Figure 1, is applied to the rigid sled model using a complete 6 DOF description, i.e. accelerations in all three local directions as well as rotational velocities around the same axes. The SAFER HBM model was used to estimate driver kinematics during the PCVK and the crash.



**Figure 3.** *Overview of simulation sequence for pre-crash and crash.*

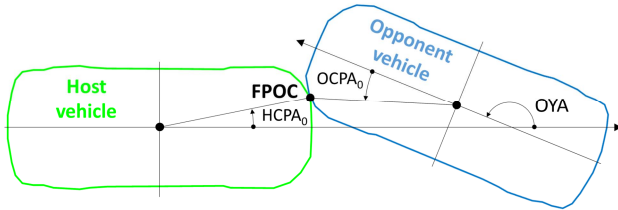
### Volvo Parametric Crash Configuration – VPARCC (element 3)

In order to describe and store the states at crash initiation regarding positions, orientations and velocities, the Volvo parametric crash configuration (abbreviated VPARCC) is proposed. In this approach, the first point of contact (FPOC) between two colliding objects is used (for visualization, two identical passenger cars are used here). This part of the crash configuration is to be interpreted as a birds-eye view of the physical appearance of the two objects when first contact occurs. In this definition, the host vehicle serves as the reference system according to SAE [21], where the FPOC is described. Furthermore, the heading direction is defined to coincide with the longitudinal axis of each vehicle, even though in the generalized case the velocity vector at the time of collision may differ from the heading direction in the crash configuration. By utilizing the host center point (HCPO), a counter-clockwise angle around HCPO between the host center plane (HCPL) and the FPOC can be defined as the original host collision point angle (called  $HCPA_0$ ) as illustrated in Figure 4.



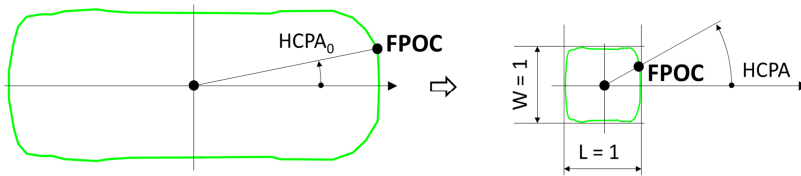
**Figure 4. Definition of VPARCC angles in host vehicle**

In the same way, the location of the FPOC on the opponent vehicle is defined as the original opponent collision point angle (called  $OCA_0$ ) using the local reference system of the opponent vehicle. By using a third angle in the horizontal plane, the heading direction of the opponent vehicle is defined relative to the heading direction of the host vehicle. This angle is called the opponent yaw angle (OYA) as indicated in Figure 5.



**Figure 5. Definition of VPARCC angles in host and opponent vehicle**

By using the definitions above, the description of the FPOC in terms of  $HCPA_0$  and  $OCA_0$  will be dependent on the vehicle width-to-length ratio. However, a more universal way of describing the angles is sought, therefore the vehicle dimensions including the FPOC are scaled to a square unit car as described in Figure 6. In this way, a transformed host collision point angle (HCPA) is defined for further use. The same procedure is applied to obtain the transformed opponent collision point angle (OCA).



**Figure 6. Description of transformation from actual appearance to square unit car system.**

The proposed method for describing crash configuration can be used as a tool for visualizing larger sets of crash configuration data to be considered in development of safety systems. In Figure 7, three examples of car-to-car collisions are used to explain how a crash configuration diagram can be created. Figure 7 shows how the transformed host and opponent collision point angles HCPA and OCPA combined with the opponent yaw angle OYA for the impact direction gives a graphic illustration of each crash configuration directly in the diagram. By using a variety of vehicle types, it was seen that their shape generally has a small influence on the crash configuration. However, some crash configurations defined using a rectangular car shape may differ from configurations where a vehicle with rounded corners is used.

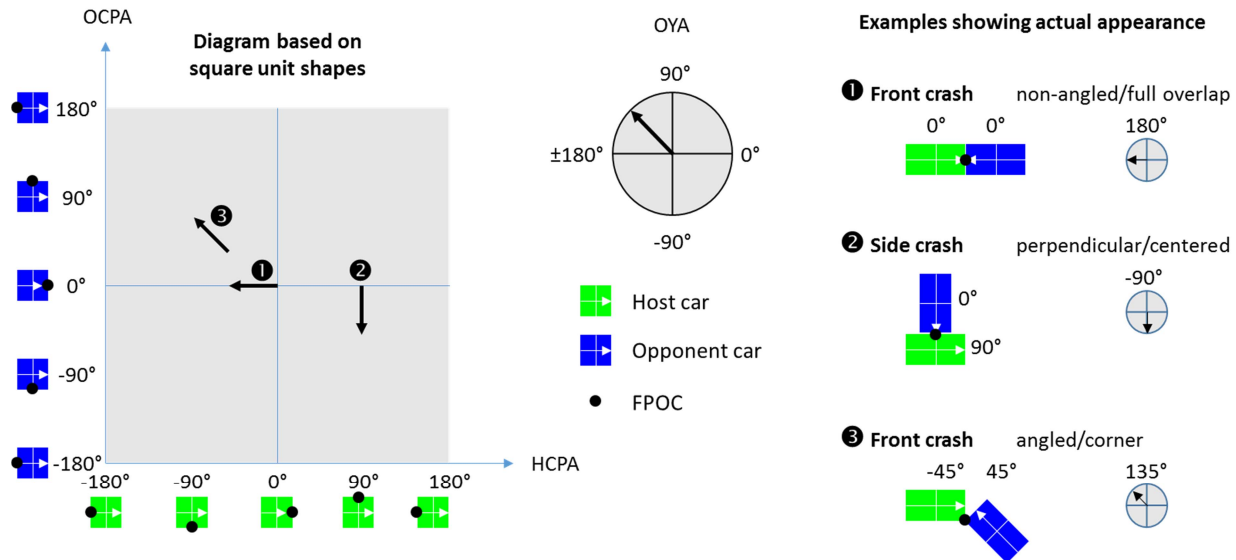
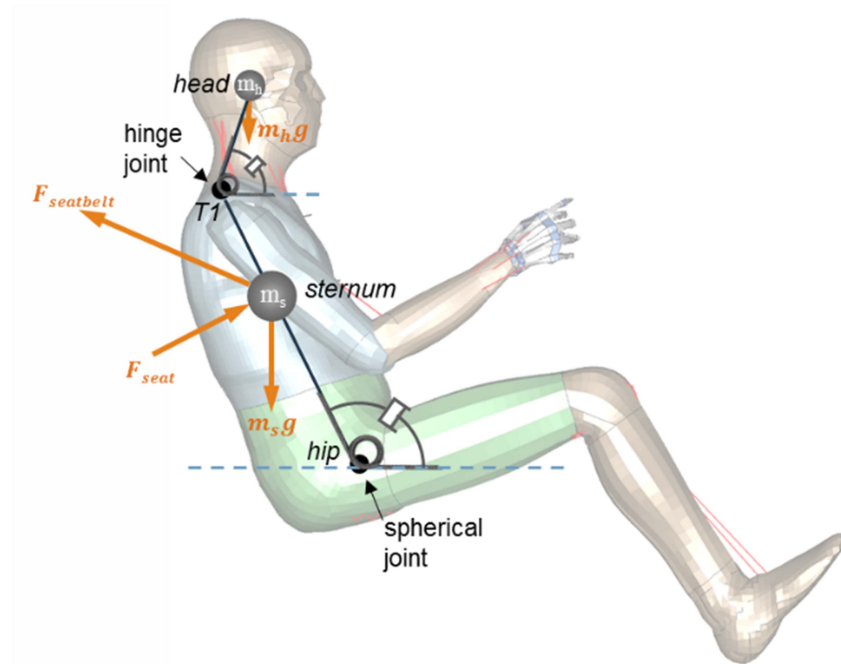


Figure 7. Example of how crash configurations are mapped into a diagram of OCPA vs. HCPA including OYA.

#### Simplified occupant kinematics model – SOCKIMO (element 4)

As previously stated, pre-crash simulations often consider a large amount of cases, typically more than a thousand for a specific conflict situation. To assess occupant pre-crash kinematics in these large datasets, the need for a computationally efficient model was identified as a tool that at an overall level describes how the pre-crash phase may affect occupant kinematics. In an internal development project it was therefore suggested to describe the upper body of a car occupant as an inverted pendulum constrained in the sagittal plane. This model was used for pure braking scenarios where the effect of AEB interventions could be quantified in terms of occupant pre-crash excursion. In the course of this work, a need for a model useful also in maneuvers including lateral accelerations was identified. This led to the initiation of a master thesis project aiming at describing the occupant as one or more inverted pendula free to move in three dimensions [22]. The studies concluded that a double pendulum model could be employed and using joint stiffness and damping parameters be tuned to fit the response of volunteers.



**Figure 8. Side view of driver HBM and corresponding simplified mathematical model, from [22].**

Figure 8 provides a graphical representation of how the simplified model was implemented. Rigid bodies are assumed between the head center of gravity, first thoracic vertebrae (T1), sternum, and the hip joint. These are positions that were all featured as tracking points in available volunteer data, later used for tuning and validating the model. A lower inverted pendulum was based in the occupant hip joint location and includes a point representing the sternum. At the upper end of the lower pendulum, corresponding to the center of the T1 vertebra, a hinge joint is defined. This hinge joint attaches to the upper pendulum that ends in the head center of gravity. By defining this hinge joint, the upper pendulum is constrained to movement in the plane initially defined by the hip joint, T1 and head center of gravity. Since this plane is updated corresponding to the displacement of the lower pendulum, the head center of gravity is free to move out of the initial sagittal plane.

The seat back was modeled as a contact to prevent the pendula model from tilting rearwards, using contact stiffness based on an FE model representing a typical passenger car seat. Seat belt forces were assumed to be applied in the point representing the sternum on a fixed distance between the hip joint and T1 as illustrated in Figure 8. In both the lower (spherical) joint and the upper (hinge) joint, two parameters were introduced characterizing the stiffness (Nm/rad) and the damping (Nm/rad/s).

In order to find appropriate joint parameters, volunteer tests performed by Chalmers University of Technology [23] were used and the model was tuned accordingly. This process enabled parameter sets representing a range of individual volunteer responses, and the final SOCKIMO included seven different such sets. The tuning process showed that the SOCKIMO can capture not only the magnitude of excursion but also the dynamic response as shown in Figure 9. The combined maneuver for which the model was tuned consisted of steering and braking with maximum accelerations of approximately 0.5 g.



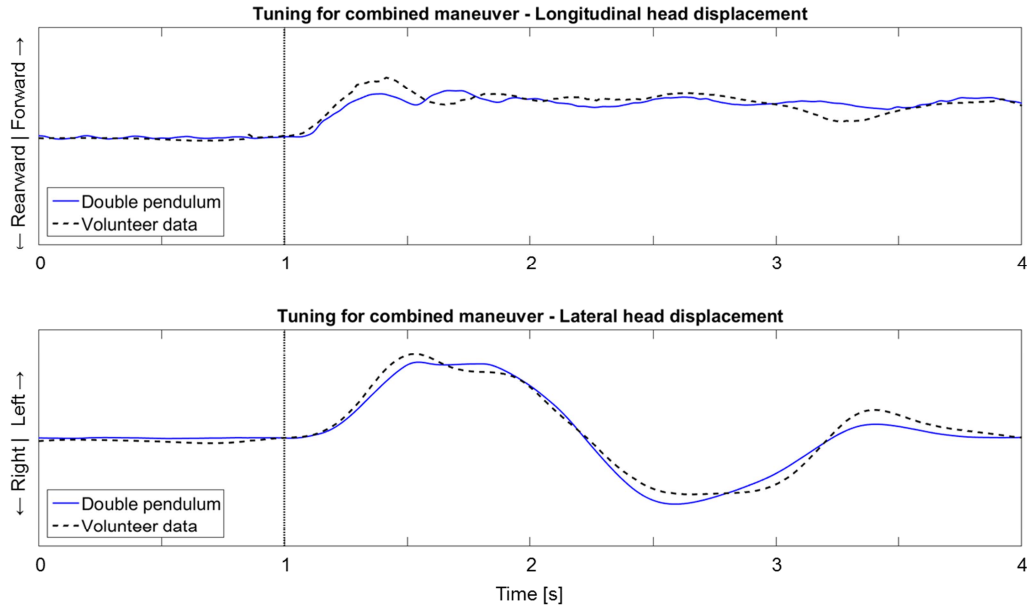


Figure 9. Example of tuned double pendulum model output compared to volunteer data, from [22].

The tuned SOCKIMO was thereafter validated by using a separate data set collected by Graz University data [14] as shown in Figure 10. From these volunteer tests, a corridor representing the and 0.16<sup>th</sup> and 0.84<sup>th</sup> quantiles of the response of 25 volunteers was used and compared to the model response.

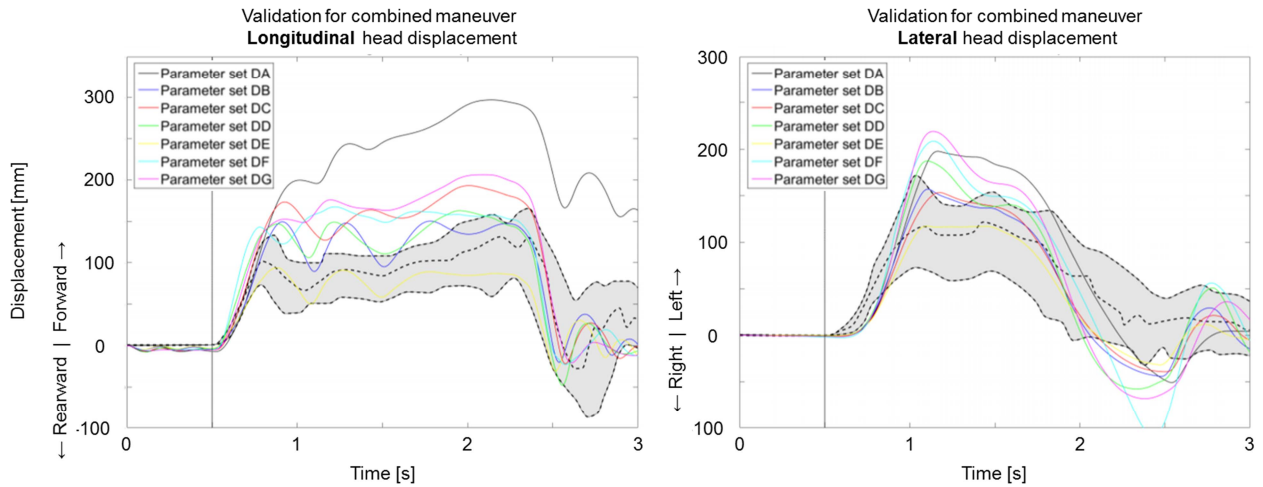


Figure 10. Validation in combined braking and steering maneuver

## EXAMPLE CASE

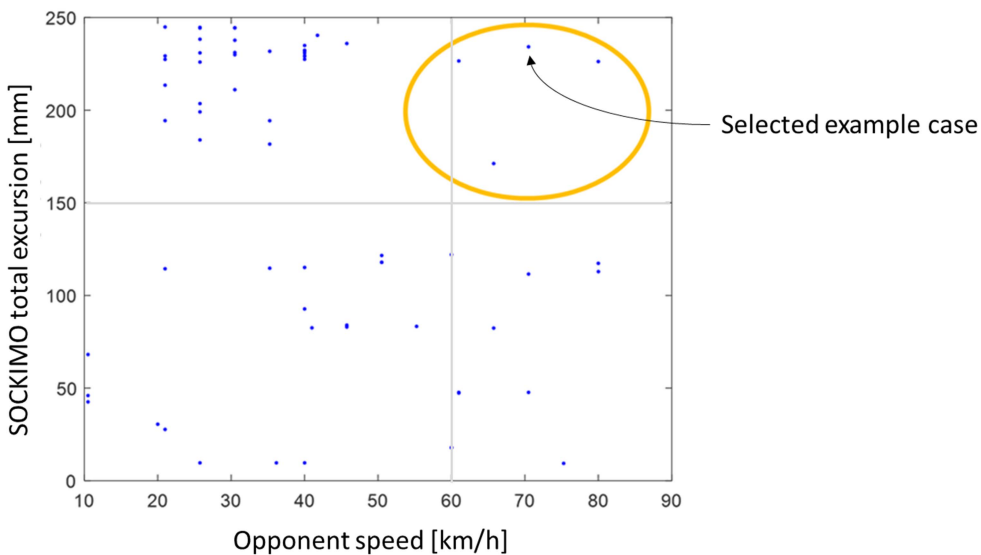
To demonstrate the methodology, an example case was selected from left turn / oncoming direction (LT/OD) conflict situations. These are characterized by the host vehicle turning left in a crossing and is struck by an oncoming vehicle that approaches from the direction opposite to the host vehicle initial direction, i.e. before the turn is initiated.

### Case selection (elements 1-6)

In the first stage, the Volvo Cars baseline generation framework was applied. First, crashes in Volvo Cars traffic accident database (VCTAD) were classified and LT/OD crashes were identified. Crash case analysis was performed on the pre-crash phase of each case in detail, and a dataset was generated from all cases. In this dataset, each crash was described numerically in a THd format where each time step, during 15 seconds before the crash or near-crash, depicts the vehicle trajectories, the road environment, the participants and their characteristics. In order to compensate for uncertainties in the data relating to case data quality and contingency of distributions, variations of parameters were implemented as synthetic cases in a THd-batch, comprising in total 940 cases for simulation.

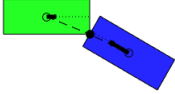
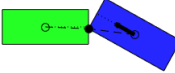
Pre-crash baseline and treatment simulations were performed as a next step. In the baseline setting, all cases resulted in a collision for which the host vehicle impact speed ranged from 4 to 30 km/h, and the opponent vehicle speed ranged from 4 to 131 km/h. By using a conceptual AEB system, a portion of the cases were completely avoided and in another portion there was no effect of the AEB system. In a third portion, mitigation of the crash was achieved by the AEB system. All remaining crashes were analyzed in further detail utilizing the crash configuration depicting method VPARCC and the SOCKIMO, and typical situations were identified for the case study.

The SOCKIMO was used to identify cases with large occupant pre-crash excursions in combination with a substantial crash severity. The SOCKIMO analysis was made with an average of the seven occupant parameter sets, Figure 10. Initially, a maximum SOCKIMO total head excursion above 150 mm during the complete pre-crash maneuver was used as filtering criterion. An additional filtering criterion was used to find one example case for which a substantial crash severity was present. Since the crash severity in the studied cases is highly governed by the impact speed of the opponent vehicle, cases with an opponent speed above 60 km/h were selected, see four encircled candidate cases in Figure 11. A case with a crash configuration notably modified by the AEB intervention was selected, resulting in the example case described in Table 1. Both baseline and treatment cases included a maximum vehicle lateral acceleration of 1.5 m/s<sup>2</sup> and maximum yaw velocity of 21 deg/s.



**Figure 11.** SOCKIMO max head excursion (mean of 7 occupant parameter settings, mm) vs. opponent speed (km/h).

**Table 1. Example case crash configurations and AEB description for Baseline and Treatment, respectively.**

	Crash configuration						Pre-crash intervention
	Appearance	Host speed (green)	Opponent speed (blue)	OYA	HCPA	OCA	
<b>Baseline</b>		15 km/h	70 km/h	150°	-45°	11°	None
<b>Treatment</b>		~0 km/h	70 km/h	151°	-6°	45°	AEB: Max longitudinal acceleration 12 m/s <sup>2</sup>

The selected case was then simulated using the SAFER HBM occupant model positioned in the host vehicle in four different combinations of PCVK and crash pulse as described in Table 2. Simulations BB and TT describe the cases from the CA-CAE tool shown in Table 1, and simulations denoted nB and TB were included in order to study the individual effects of PCVK and crash pulse, respectively. The FE structural crash simulations were performed using two identical mid-size passenger cars to provide the crash pulse needed for the FE A-HBM occupant simulation.

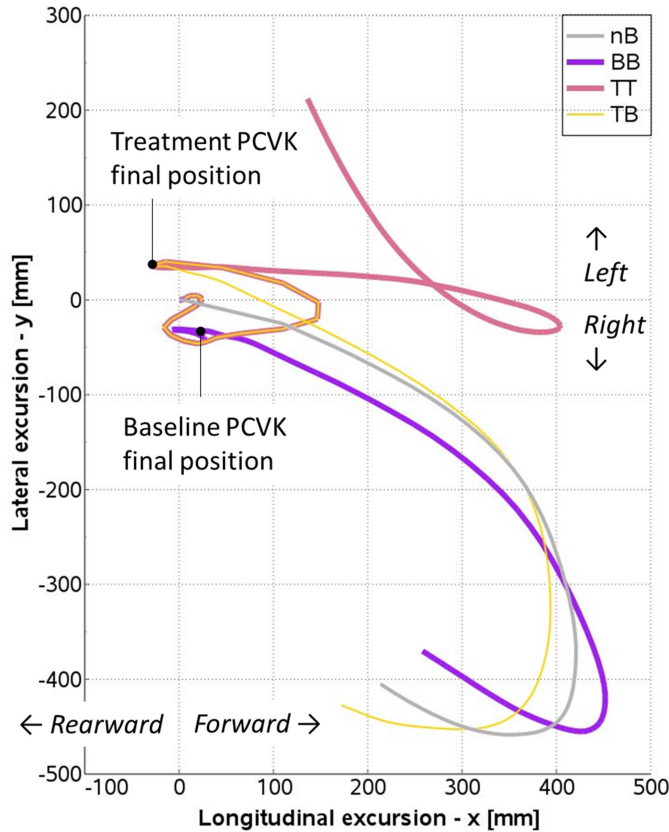
**Table 2. Overview of simulations**

Simulation code	PCVK	Crash pulse
nB	(none)	Baseline
BB	Baseline	Baseline
TT	Treatment	Treatment
TB	Treatment	Baseline

#### **Output from FE A-HBM occupant simulation – element 7**

A clear effect from the pre-crash maneuver as well as crash configuration on driver head trajectory in a vehicle-fixed coordinate system could be seen, Figure 12. The measured effect of the Baseline PCVK is a maximum excursion of 28 mm forward (x) and 44 mm to the right (y). The Treatment PCVK results in a maximum excursion 148 mm forward (x) and 46 mm to the right (y). However, the Treatment PCVK final position is 30 mm rearward (x) and 36 mm to the left (Y) of the origin. A more detailed illustration of the occupant pre-crash kinematic response in the four simulations can be found in Appendix 1.

By further analyzing the head center of gravity trajectories in Figure 12 during the crash phase, it was found that the effect of introducing the Treatment crash had a considerable effect. The Baseline crash pulse introduced a substantial lateral component to the crash pulse, which leads to occupant excursion that has approximately the same magnitude to the right as forward. In the Treatment crash (see Table 1), the opponent vehicle overlaps the host vehicle to a lesser extent, thereby reducing the lateral acceleration component of the host vehicle during the crash phase. The Treatment crash pulse leads to an occupant excursion with low deviation from the vehicle longitudinal direction and increases the lateral excursion only during rebound. Further details on the occupant kinematic response during crash can be found in Appendix 2.



**Figure 12.** Complete sequence trajectories of SAFER HBM driver head center of gravity, vehicle-fixed coordinate system.

When comparing the three simulations where the Baseline crash pulse was used (nB, BB and TB), it was found that although the initial positions for the crash phase differed, the head trajectory during crash was similar. The maximum lateral head displacement in simulations nB, BB and TB was approximately the same at 450-460 mm. The TB simulation results however suggested that an outboard/rearward initial crash position (i.e. to the left of and behind the origin) led to a longer duration of the interaction with the driver airbag reducing the maximum forward displacement compared to nominal position in the nB simulation. In contrast, the BB simulation results suggested a shorter airbag interaction duration, which was associated with a larger maximum forward displacement.

## DISCUSSION

This study aims to describe a CAE methodology that allows for estimation of the combined safety effects from collision avoidance and injury prevention systems. In a demonstration case, combinations of pre-crash maneuver and subsequent crash was presented as an example of the feasibility of the method. The present methodology constitutes a framework for dealing with the large data sets that can be generated through CAE pre-crash simulations of collision avoidance technologies applied to real-world traffic situations. A crash configuration definition for setting up crash simulations or physical crash tests was introduced and a simplified occupant kinematic model for filtering out cases for detailed analysis was presented.

All elements of the methodology are subject to further refinement, for instance the vehicle dynamics model in the pre-crash CAE tool may need further details when studying avoidance maneuvers with significant three-dimensional effects. In this initial study, the SOCKIMO provided an indication of large occupant pre-crash excursion that was also reflected when using the SAFER HBM. For future analyses, the SOCKIMO may need to be further refined along with the interpretation of its output. For some traffic situations, a human body model with more details than the SOCKIMO but not as detailed as an FE HBM may be desirable.

In this study, cases were filtered out when the largest SOCKIMO excursion exceeded 150 mm, regardless when this maximum excursion occurred during the pre-crash maneuver. The excursion at the time of crash initiation may prove to be a better metric for occupant pre-positioning relevant for injury prediction. On the other hand, once a large occupant excursion has occurred, this could be associated with non-linear effects that the SOCKIMO is not able to capture. Such an example could be seat belt interaction where the effect on occupant kinematics could be studied in a more realistic way using the A-HBM, for which also the effect of electrical reversible retractors (ERR) can be studied. There is a risk that the SOCKIMO will point out cases where the occupant excursion is not a problem in terms of predicted injury risk during the crash phase. This depends on the combination of pre-crash maneuver and type of crash. For some crashes, certain pre-crash maneuvers may actually be beneficial for improving the occupant interaction with the restraint system, in some cases unfavorable. Another factor that influences the occupant pre-crash excursion is whether the arms are used for bracing against the steering wheel or other vehicle interior components. In the current implementation, the SOCKIMO is tuned for front seat passengers for which no bracing is present, while the SAFER HBM was run as a driver with hands on the steering wheel and active arm muscles simulating this bracing. This could be one reason why the SOCKIMO head excursion exceeds that of the driver A-HBM. (SOCKIMO ca 230 mm in Figure 11 vs A-HBM approximately 150 mm, Figure 12). An additional reason for this may be found when observing validation data suggesting that several of the seven parameter sets of the SOCKIMO lead to pre-crash motions larger than the volunteer corridors as shown in Figure 10. Occupant excursion as predicted by the SOCKIMO may not be accurate as a prediction of actual occupant excursion but rather as an indicator when comparing sets of pre-crash vehicle kinematic data.

The crash simulation phase in this study was performed using a rigid sled, i.e. assuming no compartment intrusion. Although modern passenger cars often exhibit minimal intrusion, there are and will still be situations where this is not the case. Typically, this assumption could not be made when intrusion occurs in the direct surrounding of the occupant such as in side impacts. In such cases, a deformable sled where intrusions are recorded from full-scale structural FE crash simulations and then applied to the virtual sled with the A-HBM may be useful. Alternatively, the A-HBM can be placed directly in the full-scale model, however this approach is currently judged as unfeasible due to the large simulation effort that would further limit the number of studied cases.

The proposed crash configuration method VPARCC was shown to be sensitive to changes based on pre-crash AEB interventions. Although the provided example case displayed large differences in terms of VPARCC parameters and subsequently significantly different resulting crash pulses, the methodology is detailed enough to describe also subtle geometrical changes in crash configuration not captured in established methods using e.g. CDC [8]. VPARCC was demonstrated in car-to-car crash situations, however it can also be applied to collision objects such as trucks or vulnerable road users. In order for the method to remain generic, the shape of the traffic objects should be defined in such a way that only one point is intersected at a time when a vector is swept the full 360 degrees around the object center as described in the crash configuration section.

The approach in the presented methodology would not be possible using simplified occupant models only since these lack details needed for in-depth analysis of the interaction between the occupant and vehicle interior. In contrast, using only detailed models would lead to a limited ability to cover a wide range of traffic situations due to the great simulation effort associated with FE HBMs. Further methodology validation should be conducted and usage expanded to other combinations of pre-crash maneuvers and crashes.

## CONCLUSIONS

A methodology for predicting the performance of safety systems with a combined effect from collision avoidance and injury prevention features was presented. In this process, methods for describing crash configurations was introduced. This method supports detailed descriptions of crashes and is sensitive to changes in configurations based on pre-crash maneuvers. Further, a simplified occupant kinematics model (SOCKIMO) was introduced as a tool for filtering out cases where considerable occupant pre-crash excursion can be suspected to occur. The feasibility of the individual elements of this methodology to function together was demonstrated in an example case where autonomous emergency braking led to a considerable change in the crash configuration and was predicted to introduce substantial occupant pre-crash excursion. In addition, in this example case it was shown that the present A-HBM tool is able to cover the complete sequence of events from pre-crash maneuvers to crash in one single simulation, thereby demonstrating how the tool chain efficiently contributes to evaluating the injury prevention effects from both pre-crash and crash countermeasures in the vehicle.

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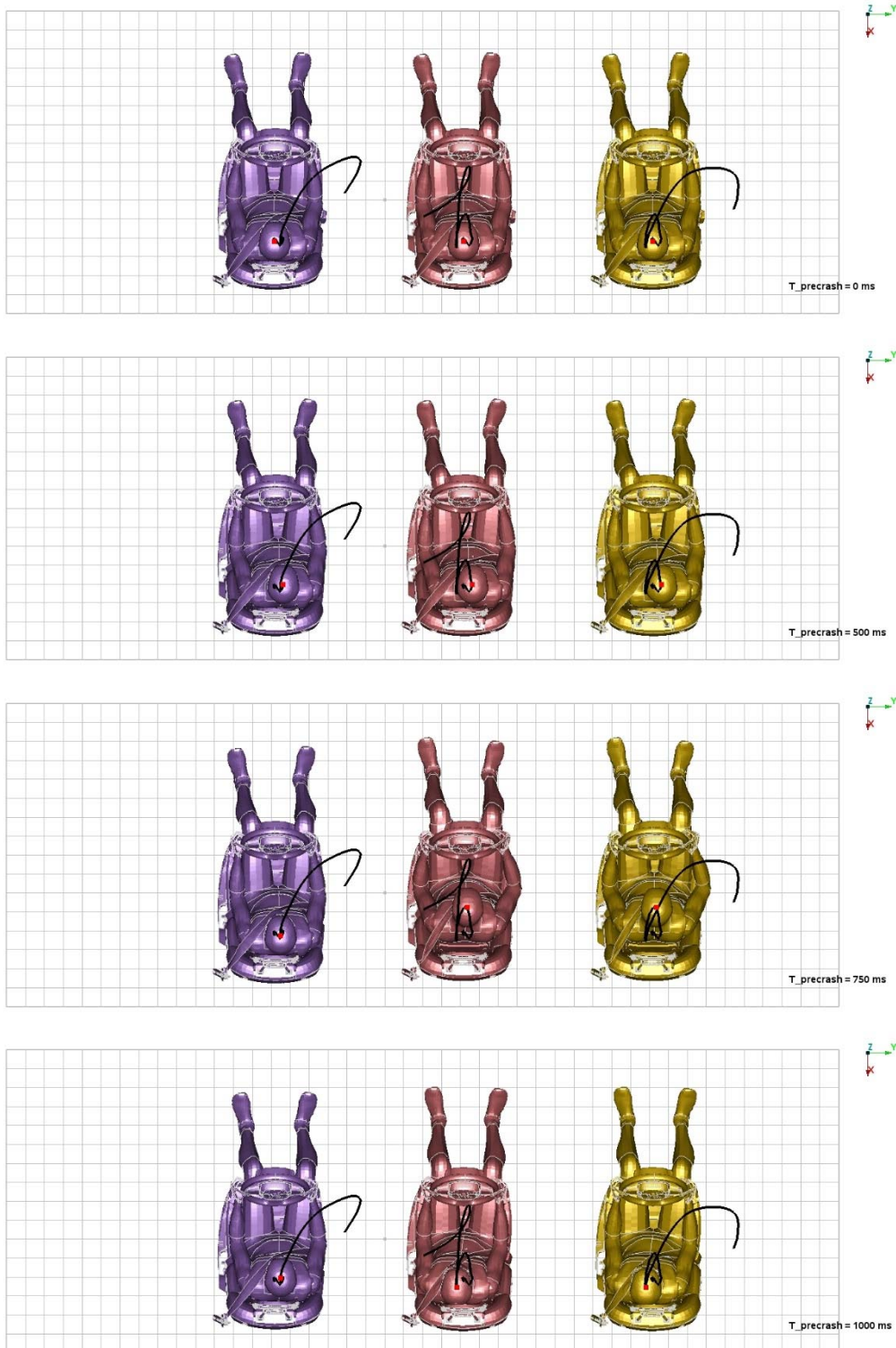
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## APPENDIX 1

Occupant response in example case during pre-crash maneuver.

Head center of gravity described by red marker and trajectory by thick black line.



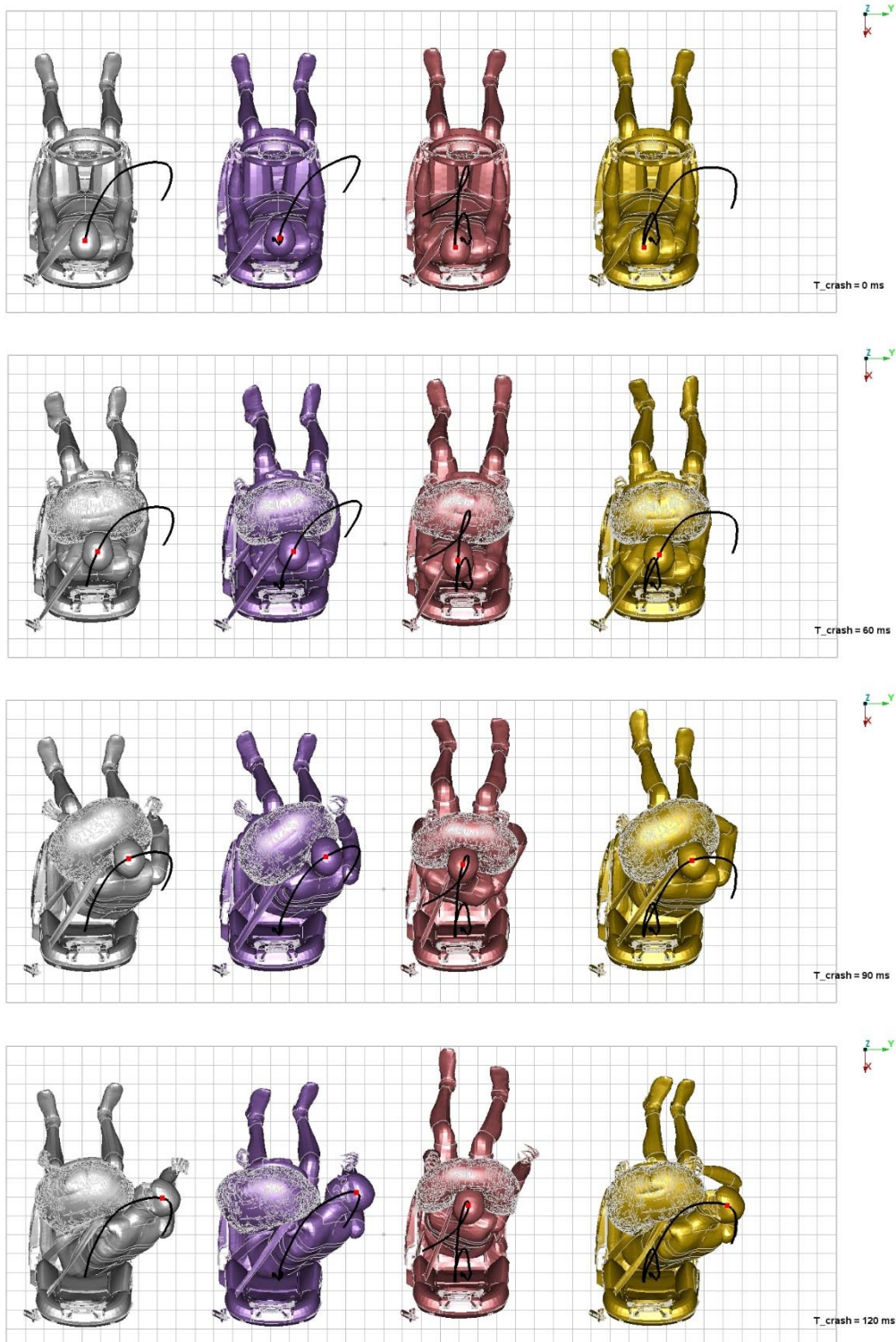
From left: Simulations BB / TT / TB (grid size = 100 mm)



## APPENDIX 2

Occupant response in example case during oblique crash.

Head center of gravity described by red marker and trajectory by thick black line.



From left: Simulations nB / BB / TT / TB (grid size = 100 mm)