# OCCUPANT BEHAVIOR DURING A ONE-LANE CHANGE MANEUVER RESULTING FROM AUTONOMOUS EMERGENCY STEERING

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## ABSTRACT

The safety of vehicle occupants has evolved recently due to the market implementations of new sensing technologies that enables predicting and identifying hazardous road traffic situations and thus actively prevent or mitigate collisions. The obvious benefits of the active safety systems has also been recognized and acknowledged by the regulatory and consumer bodies responsible for transportation, and as a result, the new standards, regulations and public rewards are being introduced. The active safety systems can prevent or mitigate collisions by controlling the motion of the vehicles through autonomous actuation of either: braking, steering or both simultaneously. The autonomous control of the vehicle inevitably affects the motion of the travelling occupants with respect to the vehicle interior. Depending on the severity of the maneuver, the occupant motion may lead to non-optimal postures for the in-crash phase if the collision is unavoidable or may impair the capability of a driver to resume the control of a car after the autonomous evasive maneuver. These considerations create the direct need for developing the active systems together with passive systems with the ultimate objective to best protect the occupants. This paper presents a simulation methodology for developing new automotive safety systems in an integrative manner that ensures optimal exploitation of benefits of active and passive systems. It also presents the simulation results of the study into the occupant behavior during the emergency evasive maneuver. The investigation was performed using the combination of newly available simulation techniques for modelling the Advanced Driver Assistance Systems (PreScan software) and for modelling the real human behavior under low-g conditions (MADYMO software). The results obtained showed the severity of the out-of-position occupant postures created by the autonomous evasive system. It was also observed that the lateral acceleration, being the effect of the maneuver, may cause the driver to impact the b-pillar, and thus potentially impair the further driving capabilities. The study was performed based on the numerical simulations and some of the model components were not fully validated. Further investigations will follow and will be focused on additional validation of the method and its components and finally on quantitative assessment of the revealed problems.
The presented methodology and its application for investigating the occupant behavior under low-g loading shows the relevance of developing the new safety systems in an integrative manner.
The simulation methods and techniques will play significant role in the integrated safety systems development processes, allowing to test the conditions of high complexity in order to represent the real life scenarios and thus ensuring better occupant protection.

## INTRODUCTION

Despite the recent rapid technology advancements in the field of automotive safety, road accidents are still one of the main causes of severe injuries and premature deaths in contemporary societies. Introduction of driver assistance systems (ADA systems or ADAS) generates new opportunities to mitigate the damage caused by traffic accidents or, in many cases, prevents them from happening. ADA systems such as autonomous emergency braking (AEBS) or lane keeping assist (LKA) and lane change assist (LCA) support the driver in hazardous traffic situations by controlling longitudinal (by braking) and lateral (by steer torque) motion of the vehicle in case of collision risk. These systems, though relatively new to the market, have proved their significance for vehicle safety and are recognized already by legislative authorities and consumer bodies. The European Commission is introducing legislation for AEB and lane departure warning systems (LDW) in commercial vehicles [1]. The consumer testing protocols are currently being prepared for AEB systems, dedicated for city and interurban traffic and LDW, and will be introduced to the standard Euro NCAP protocol as of 2014. Several initiatives are working on developing standards describing system requirements and standard test programs. Some examples are the Crash Avoidance Metrics Partnership initiative (CAMP) and NHTSA confirmation test requirements. In Europe the EC funded projects such as PReVENT [2], eValue [3] and ASSESS [4] are working on standardization of test programs.

The above mentioned ongoing and upcoming standardization processes will finally lead to an increased performance of the longitudinal and lateral guidance assistance systems and popularization of them throughout all segments of the vehicle types. However, the AEB systems have their functionality limitations and there are traffic situations in which the obstacle appears suddenly on the driving path and braking is not efficient enough to avoid a collision. These situations could happen either in the city traffic conditions e.g. pedestrian intruding a street or in the fast moving, inter-urban and motorway conditions e.g. sudden lane change maneuver or suddenly stopped traffic. In these cases a steering intervention becomes the only measure to prevent a collision [5]. It should be considered as additional functionality of the emergency evasive system in which the algorithm, based on the criticality of scenario conditions, decides about which evasive actions should be taken: braking; steering or both simultaneously. Up to now, there have been several technology research level demonstrator projects carried out successfully, showing the potential of steering assist systems [6], [7], [8]. These systems present different approaches towards the decision characteristics: acting either as a driver support in which the system only corrects the maneuver initiated by a driver [6], or fully autonomously vehicle control that applies appropriate steering patterns [7].

The fully autonomous evasive steering intervention that is being discoursed within the paper requires a widespread and detailed understanding of the road situation. The system needs to classify all the detected participants that are currently in the region of interest (ROI), predict all the possible actions of all ROI participants , including the host vehicle itself, and finally assess the severity of the consequences of the possible evasive actions. The described situation evaluation flow sequence determines the parameters that need to be monitored by the controller to undertake appropriate actions. As explained in the [5], once the potential collision is detected, the system monitors the time to react (TTR) to determine the criticality of the situation. The TTR is the remaining time for a driver to avoid a collision by braking or steering, assuming the maximum performance (braking or lateral accelerations) of the vehicle resulting from each of the actions. Thus it can be computed as the maximum of time-to-brake (TTB) or time-to-steer (TTS) accordingly. This information is then being used by the controller to select the most suitable action to avoid the collision.

Though the accidentology studies justify the social need for developments of evasive systems and the research demonstrators proved their technological feasibility and effectiveness, product level implementations is not yet possible due to the potential product liability issues and lack of customer acceptance test results. It could be easily conceived that a driver needs to be capable to retain the control over the vehicle instantly after the autonomous maneuver is complete. This implicates that the yaw angle and yaw rate of the vehicle should be zeroed before the control is given back to the driver and that the lateral loadings resulting from autonomous maneuvering do not cause excessive misplacements of the occupants or/and contact interactions with the interior parts. This study is focusing on the latter, and tries to quantify the significance of the problem using simulation techniques and additionally depicts the potential out of position (OOP) problems in case of system failure and consecutive collision.

## METHODOLOGY

Previous studies have shown that autonomous systems, such as AEB or autonomous steering, can lead to a non-optimal occupant posture and position resulting in reduced performance of the occupant restraint systems in case of a collision [9]. Consequently, these active safety systems cannot be developed independently of the passive safety systems without risking suboptimal safety performance of the occupant restraint system (airbags, seatbelts). Instead, they need to be developed and assessed in an integral manner, considering it one complete integrated safety system. At the same time, the increasing presence of surround sensors allows for an improved performance of the passive safety systems by using information from before the crash. This information can be used to trigger restraint systems during the pre-crash phase e.g. pre-pretentioning of safety belts to reduce the occupant misalignments during pre-crash lateral or longitudinal loadings.

Currently, no experimental methods or simulation tools exist for evaluating the effects of pre-crash dynamics on the occupant injury risk during the crash phase. In the paper, the use of two software packages that together provide the potential to cover all critical aspects of the design of an integrated safety system is shown. One of the software packages (PreScan) focuses on the sensing and active control systems of a vehicle, and the other package (Madymo) predicts an occupant response and injury risk throughout the whole pre- and potential in-crash event.
The methodology used in this study has been previously presented [10] when applied for the investigation into the frontal collision load case with pre-crash autonomous braking and the side collision load case with pre-crash triggered restrained systems [11]. In the current study, the methodology was appropriately adjusted to best represent the phenomena characteristic for the problem of low-g lateral loading during autonomous evasive steering (See Figure 1).

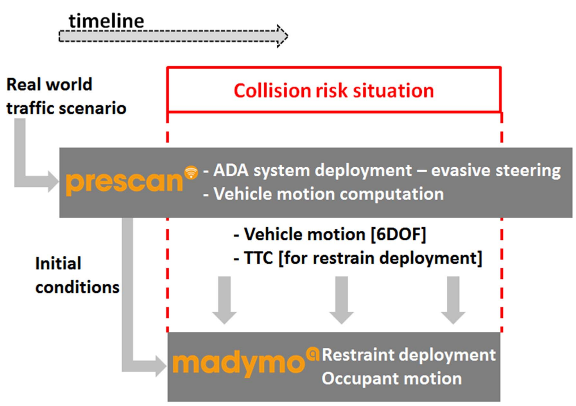


*Figure 1*. Methodology setup for integral analysis of autonomous steering maneuver.

The principles of the method remained the same as in case of frontal or side collision application. The real world traffic situation is represented in PreScan in which the vehicle model under investigation, equipped with the ADA system with evasive steering capabilities, is exposed to the collision risk situation. Once the evasive steering ADA system model detects and classifies the collision risk, Madymo simulation is initiated with the initial conditions imported from PreScan. The system actuation (applied evasive steering torque) is computed by PreScan and the resulting vehicle motion is being continuously sent to the Madymo simulation. Simultaneously, the estimated time to collision (TTC) information calculated from the surround sensor model outputs is used to timely deploy on-board restraint systems (e.g. belt pre-pretensioners) that accompany the evasive steering maneuver. Madymo uses the above listed information to calculate the deployment of restraints (if present in the system) and computation of the occupant's motion as an effect of loadings created by autonomous vehicle control. The outputs from Madymo analysis is used to quantify the significance of occupant's misalignments and thus out of position postures for potentially following collision, and to evaluate the driver capabilities to take over the vehicle control instantly after the autonomous actions are finished.
The presented method is applied in the following paragraphs for the analysis of an autonomous evasive steering maneuver deployed due to collision risk situation with a suddenly cutting-in vehicle on a high speed road.

**Scenario Identification**

80% of rear-end collisions happen on straight roads and one of the most common scenario is the one in which both vehicles drive at relatively high speed [12]. In 62% of the rear-end collisions the driver took an evasive action, this including braking or steering prior to impact, attempting to avoid the collision. Dedicated active safety systems [6] can assist the driver while attempting to avoid the rear-end collision by applying the necessary braking pressure or the necessary steering torque. More advanced systems can autonomously take actions on the vehicle, in order to minimize any risk of collision in case of driver distraction or inability to react/acknowledge a risky situation.
In this paper the effect of pre-braking (either autonomous or not) is neglected and the worst case scenario is selected, in which the driver would not react to the collision, and would be passively subject to a severe lateral loading caused by an autonomous steering maneuver.

A traffic scenario has been represented in PreScan software, in which a vehicle equipped with a radar sensor and an autonomous steering controller (host vehicle) drives at the velocity of 70 km/h (host vehicle). On the adjacent lane a second vehicle (target vehicle) drives at the speed of 50 km/h. Due to a road construction on its lane, it suddenly steers onto the left lane where the host vehicle is driving (See Figure 2). Behind the host vehicle and on its left lane no other vehicles are driving, thus leaving all the necessary space for a safe evasive steering maneuver. The velocities of both vehicles are kept constant during the maneuver and it is supposed that the vehicles keep driving at the same speed after the maneuver has been completed.

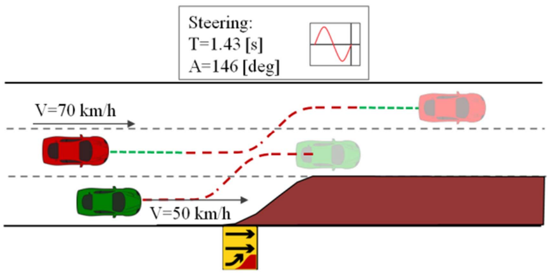


*Figure 2*. Traffic scenario setup.

**Maneuver Identification**

As already mentioned in the introduction, the computation of TTB and TTS is used by the controller to select the most suitable action to avoid the collision. The severity of the maneuver increases when no prior actions are taken either by the vehicle (autonomous braking) or by the driver (attempt to brake and/or steer), as the magnitude of the steering angle has to ensure one lane change in a shorter time, thus becoming critical. As a result, the vehicle is heavily loaded laterally, thus increasing the risk of lateral slip and/or rollover, as well as occupants' injuries due to contact interactions with the passenger compartment. In addition, no risk of single-vehicle or vehicle-to-vehicle collision shall exist due to the application of such maneuver.
In conclusion, provided that no collisions with third parties (other vehicles or environment) would result from the execution of the evasive maneuver, four main factors shall be addressed when evaluating an autonomous evasive steering system:

1. Ability to assure the necessary lateral displacement of the host vehicle which would prevent the collision with the cutting-in vehicle.
2. Ensure vehicle's lateral stability.
3. Ensure that the occupants' misalignment does not result in injuries.
4. Ensure driver's capability of taking control over the vehicle after the maneuver.

The correct operation of the system (first two factors) has been represented using PreScan software; the modeling assumptions are discussed in the following paragraphs. Further on, the risk of occupants (driver and front-seat passenger) injuries is discussed.

**Vehicle Dynamics Model** A mid-class vehicle has been identified for this study and the simple vehicle dynamics model available in PreScan software [13] has been adopted to reproduce the vehicle loading resulting from the application of the identified maneuver. The Bicycle Model representing the longitudinal and lateral vehicle motion is combined with a simplified model for the computation of the roll motion (See Figure 3).
In the model it is assumed that:

1. The tires characteristic is linear, i.e. only small slip angles are applied.
2. The tires can always generate the maximum available lateral force.
3. Only small roll angles (±5°) are applied.
4. The vehicle rolls with respect to the ground level.
5. An equivalent resistant rolling torque representing the reaction of the four suspensions is applied.
6. ESC system (Electronic Stability Control) is not represented.

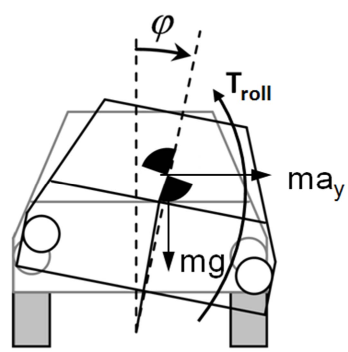


*Figure 3.* PreScan rolling vehicle model.

**Maneuver Dynamics** The adopted steering wheel angle profile is modeled as a single sine wave curve (Equation 1).

$$\boldsymbol{\delta = A \cdot \sin(\omega \cdot t)} \qquad (1).$$

In order to assess the severity of the evasive steering maneuver in terms of lateral loading, the NHTSA New Car Assessment Program (NCAP) Rollover resistance rating has been consulted [13], [14]. In order to evaluate the rollover risk of a vehicle for untripped rollovers (those in which tire/road interface friction is the only external force acting on a vehicle that rolls over), a dynamic test is carried out in order to evaluate whether and/or how much the resulting lateral loading causes a vehicle's inside tires to be lifted while performing a severe single-lane change maneuver (Fishhook maneuver).
The amplitude and angular frequency of the sine wave steering wheel angle profile have been identified by following the procedure defined by ECE-R13H and FMVSS126 [16,17] this being similar to the one defined by NHTSA. The amplitude

of the steering wheel angle profile has been increased until the single-lane change would let the car avoid the collision and require a lateral loading within the limits found in the NHTSA road tests (lateral accelerations of 0.8-0.9 [g]). Since the steering wheel angle profile here identified is intended to reproduce a single-lane change maneuver, it has been expressed as a simple sine wave profile, thus being simplified with respect to the Fishhook maneuver; however, the consequent lateral loading applied to the vehicle is comparable with the one measured on cars tested by NHTSA which have successfully passed the rollover test (i.e. no wheel lift or wheel lift below the required limit of 2 inches) with deactivated ESC system.
The capability of the host vehicle to successfully evade the collision with the cutting-in vehicle has been evaluated by means of simulation only, by monitoring the relative lateral displacement of the two vehicles. As a result, the amplitude of the sine wave was set to 146 [deg.], the angular frequency to 4.398 rad/s and the period to 1.43 s (See Figure 4).

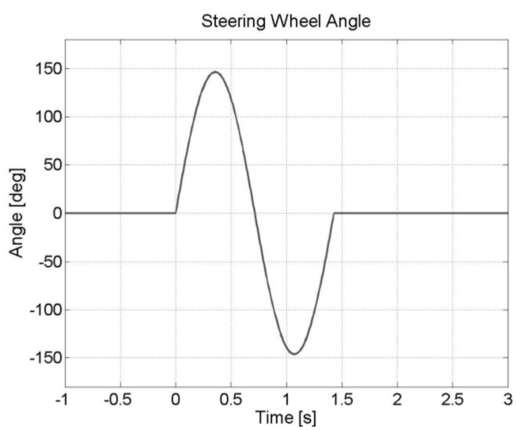


*Figure 4*. Steering wheel angle profile.

The above defined maneuver is optimized for this particular scenario and vehicles velocities, and is applied as soon as the emergency maneuver is triggered by the controller.

In order to prove the maneuver feasibility without the assistance of an ESC system, not available in the vehicle model, the vehicle loading subsequent to the identified evasive steering maneuver has been correlated to the CarSim base model's response, prior customization with the vehicle inertia properties of the PreScan model. The same steering wheel angle profile discussed before has been used as input to both models; the lateral loading at the vehicle velocity of 70 km/h has been simulated (See Figure 5).

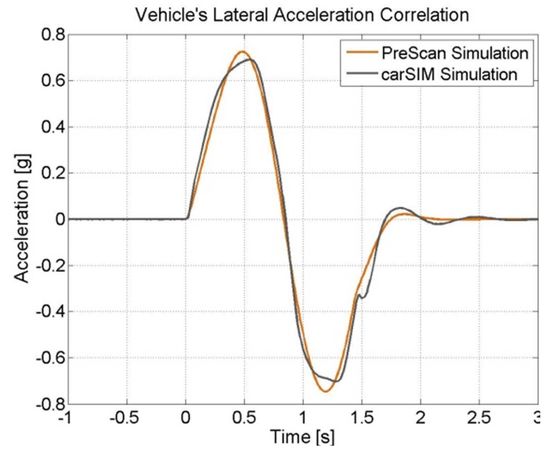


*Figure 5*. Vehicle's lateral acceleration correlated against CarSim model.

A good level of correlation has been observed (only the lateral acceleration is here commented) and neither lateral slip, nor rollover have been observed in CarSim. Therefore, it can be assumed that the limitation of not having any ESC system represented in the vehicle model does not compromise the occupant loading investigation.

The steering wheel angle profile was used as input to the PreScan vehicle dynamics model to produce the vehicle motion. Due to steering, at the velocity of 70 km/h, the vehicle is laterally loaded for two seconds and a maximum lateral acceleration of 0.72 [g] is observed (See Figure 6). A maximum roll angle of 2.3 [deg.] (See Figure 7) and a lateral displacement of 2.7 [m] (See Figure 8) are also observed.

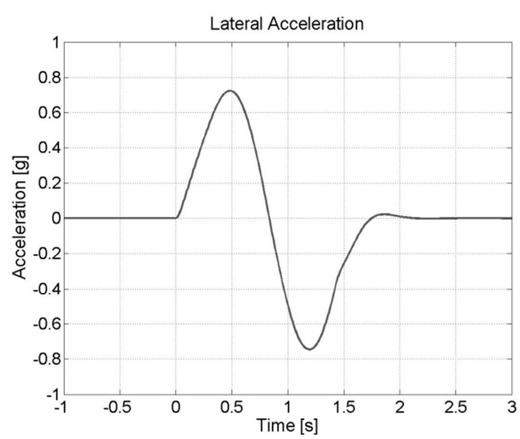


*Figure 6.* Vehicle's lateral acceleration.

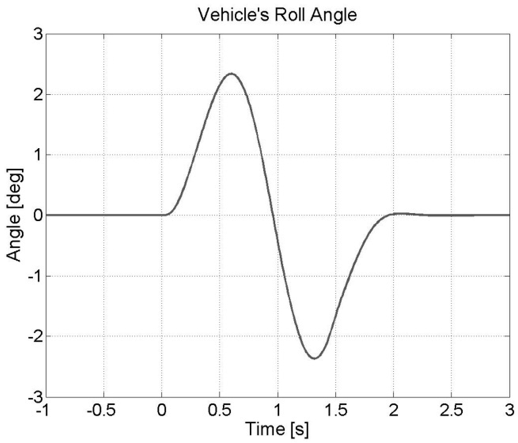


*Figure 7*. Vehicle's Roll Angle.

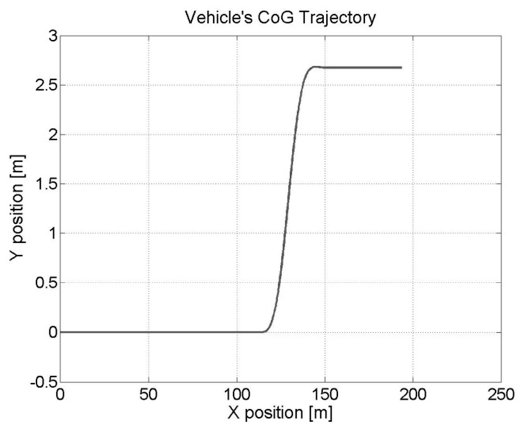


*Figure 8.* Vehicle's CoG (Centre of Gravity) trajectory.

The above mentioned maneuver dynamics characteristics have been used to load the occupants.

**Controller Principles and Sensor Model**

A controller and a sensor have been modeled to reproduce the autonomous performance of the vehicle maneuver in case of risk of collision with the cutting-in vehicle. This study wants, however, to investigate the consequences of an emergency maneuver to the resulting occupants' motion, rather than the reasons why or the way the maneuver would be applied. Therefore, only a simplified triggering logic and an ideal sensor have been modeled in PreScan, using Matlab/Simulink as main platform for the sensor's readings processing by the logic. The actuator is represented by the steering module of the Simulink-based simple Vehicle Dynamics model.
It is assumed that the host vehicle is equipped with one sensor only, placed in the middle of the vehicle, right on the front grid. The sensor model acts as a ground-truth detector which monitors whether/when the CoG of an object comes into a predefined FoV (Field of View), a cone beam with an aperture of 50 [deg.] and a maximum range of 30 [m] (See Figure 9).

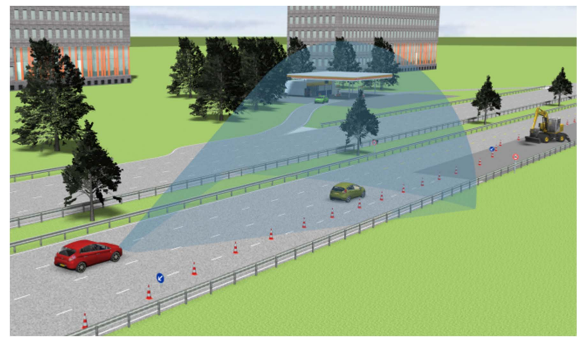

*Figure 9*. Vehicle's sensor model FoV.

The sensor model ideally reproduces a SRR (Short Range Radar) sensor and is scanning the area in front of the vehicle. No other sensors have been modeled, which would scan the areas on the sides and the rear of the vehicle, thus monitoring the whole area around the car. It is in fact assumed that there is only one potentially collidable vehicle and that no other vehicles are driving behind the host vehicle and/or overtaking it. With these assumptions, the controller could be further simplified and no traffic monitoring, nor object tracking had to be implemented.
Furthermore, since the cutting-in vehicle is not sensor-tracked before and during the maneuver, the steering wheel angle profile is built-in into the controller and applied as soon as the detected vehicle comes close to the host vehicle. No driver warnings are deployed.
The system acts in four main steps (See Figure 10). By means of the sensor model, the area in front of the vehicle is scanned and the relative lateral velocity of the detected object is continuously monitored; the control system identifies hazardous situation when the target vehicle cuts-in and triggers the emergency steering maneuver to avoid the collision.

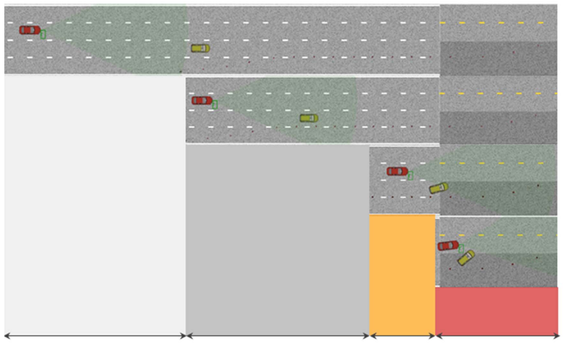


*Figure 10*. Logic overview.

**Internal compartment and restraint system models**

The difference in the prediction of the occupants (driver and front-seat passenger) behavior resulting from the emergency maneuver when using two different models, the Madymo active human model $50^{th}$ percentile and the Madymo ES-2 Q Dummy, has been investigated and is here discussed.
The ES-2 ellipsoid dummy is a well-established ATD (Anthropometric Test Device), typically used in all lateral crash test protocols. It is extensively validated in numerous component, full scale and full system tests and is best suited for all types of conceptual and development side crash analysis [18].
The active human model has an improved biofidelity and includes muscle activity and posture maintenance activation: the neck, spine, elbows and hips can be controlled in order to try to maintain the initial position under the influence of external loading. The active human model is validated for occupant pre-crash simulation with volunteer and PMHS (Post Mortem Human Subject) test data [19], [20].
In this study, for both the human occupant models, the neck and the spine are activated, while only the driver human model has active elbows, as he holds the steering wheel. The occupants' responsiveness (null in case of unaware occupant, maximum in case of full awareness) has been set to 70%, thus representing a normal driving conditions.
The model of the host car occupants, its environment and safety restraint systems have been built in Madymo software. The model of the vehicle interior compartment represents the interior of the generalized mid-size class passenger car and consists of: seats cushion and structure, knee bolster, dashboard, floor and foot rest, A-pillar and B-pillar covers and door-trims. The geometry of all vehicle compartment elements is represented using ellipsoids technique and the compliance of the elements (seat cushions, knee bolster) is represented by means of force-penetration characteristics, representative of a generic vehicle. Furthermore, the door trims have rigid properties.
The belt model represents the functionality of a conventional belt system. The retractor is locked under a vehicle's lateral acceleration of 0.4 [g]. The pre-tensioning action, intended to reduce the misalignment of the occupants under low-g loading, has not been investigated within this study.

**Simulation Approach summary – Data Flow**

By means of PreScan software, the traffic scenario is represented and the sensors readings are generated. In Matlab/Simulink software (running simultaneously with PreScan) the simple controller model processes the sensors inputs and initiates the evasive steering maneuver; the vehicle dynamics model reproduces the actuation of the steering wheel and the consequent vehicle motion (longitudinal and lateral position of the center of gravity, together with vehicles pitch, roll and yaw angle profiles).
The so generated vehicle motion data is imported into MADYMO software and applied to the compartment model, thus resulting in occupants loading. The occupants' kinematics and resulting contacts with the vehicle internal compartment (if any) are analyzed and commented in the paragraph below.

**RESULTS - OCCUPANTS KINEMATICS ANALYSIS**

The simulation results of the occupants' behavior are here presented and discussed. The kinematic behavior during to the emergency maneuver is first analyzed with the Active Human models and then with the ES-2 dummy models. The head accelerations, together with head and chest displacements are reported and commented in order to evaluate injury risks on the occupants. In conclusion, the difference between the motion of the ES-2 dummy and the Active Human models is highlighted.
The evasive maneuver causes significant motion of both occupants and brings them out of position. Two main phases can be identified: vehicle steers to the left in order to evade the obstacle and then steers back to the original direction (See Figure 11). Both phases show a considerable motion of the upper torso of the AHMs, while the lower body is well restrained by the seat bolsters.

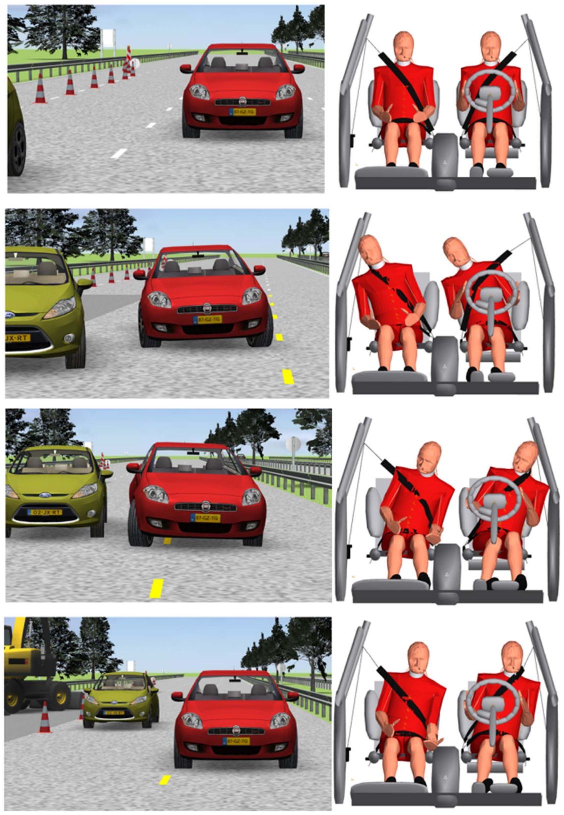

*Figure 11.* Sequence of events (AHM).

The restraining action of the passenger's shoulder belt is predominant in phase 1, although it cannot prevent the head from coming into contact with the B-pillar (See Figure 12), thus producing a peak acceleration of 8.45[g] and a HIC value of 2.4. The driver is less restrained by the shoulder belt, as the relative slip with the torso in phase 1 brings him severely out of position, thus causing a higher head acceleration when impacting the B-pillar (phase 2), with a peak value of 24.50[g] and a HIC value of 62.6.

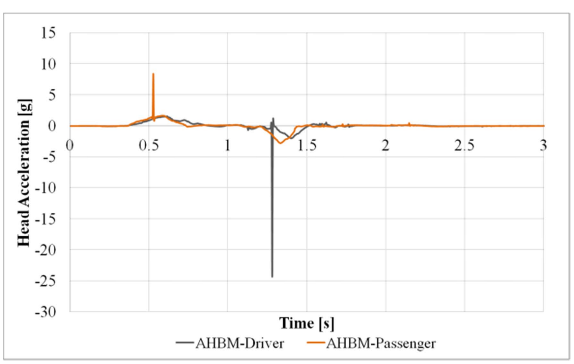


*Figure 12.* Driver and Passenger head accelerations (AHM).

The occupants' absolute displacements differ in the two phases of the maneuver, with higher values when they move towards the center of the cockpit (See Table 1). The maximum head lateral displacement has been observed for the driver during phase 1, with the value of 0.311 [m], and for the passenger in phase 2, with the value of 0.299 [m]. The maximum chest lateral displacement of 0.228 [m] has been observed for the driver during phase 1, and of 0.176[m] for the passenger during phase 2. Therefore, phase 1 is the most critical in terms of driver's lateral displacements, while the passenger undergoes the highest lateral displacements in phase 2 (See Figure 13 and Figure 14). The occupants do not come into contact with each other.

One second after the maneuver has been completed, the residual head lateral displacement is 0.121 [m] for the driver and 0.115 [m] for the passenger, and the residual chest lateral displacement is 0.111 [m] and 0.095 [m], respectively: neither of the occupants is back to the initial position.

**Table1.**
**Occupants' lateral displacements and head acceleration during the first and second phases of the maneuver (AHM)**

| | AHBM *Driver* | | AHBM *Passenger* | |
|---|---|---|---|---|
| | ***Phase 1*** | ***Phase 2*** | ***Phase 1*** | ***Phase 2*** |
| **Head Displacement [m]** | 0.311 | 0.303 | 0.243 | 0.299 |
| **Chest Displacement [m]** | 0.228 | 0.195 | 0.165 | 0.176 |
| **Head Lat. Acceleration [g]** | 1.58 | 24.50 | 8.45 | 2.80 |

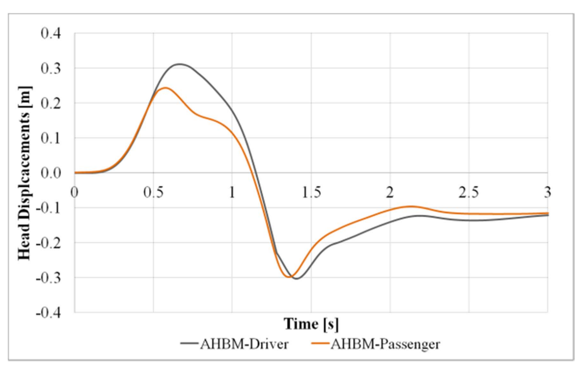


*Figure 13.* Head displacements (AHM).

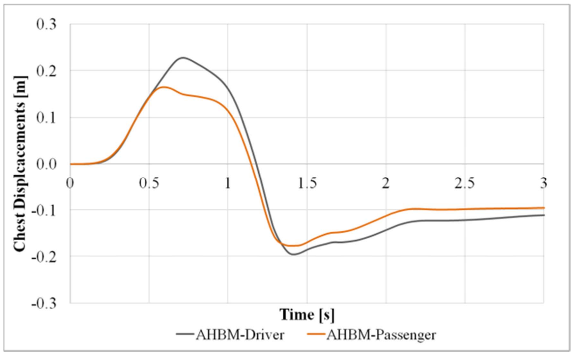


*Figure 14*. Chest displacements (AHM models).

When using the ES-2 dummy models less pronounced absolute displacements of both occupants has been observed, with the consequent avoidance of head impact with the B-pillar (See Figure 15). The shoulder belts restrained the occupants more effectively during the whole maneuver.

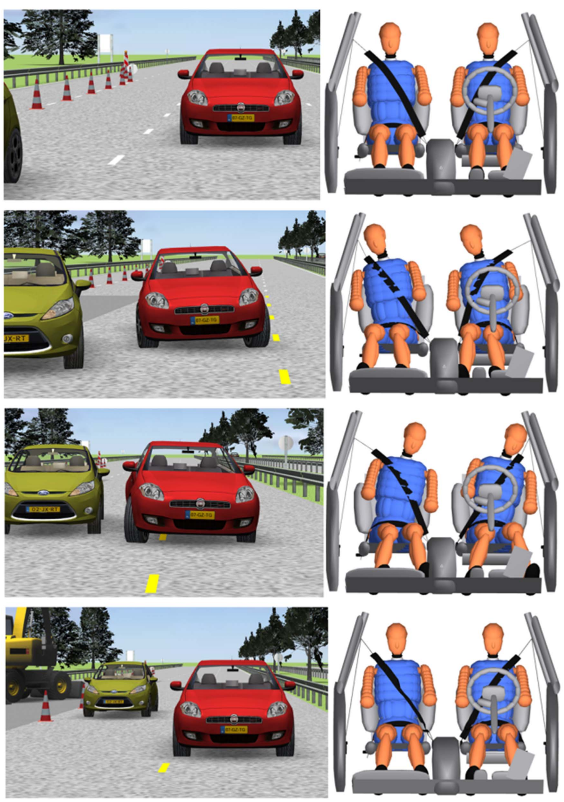

*Figure 15*. Sequence of events (ES-2 dummy model).

The maximum head lateral displacement has been observed for both the occupants during phase 2, with the value of 0.216 [m] and 0.218 [m], respectively (See Table 2). The same trend applies to the chest lateral displacements, with values of 0.084 [m] for the driver and 0.086 [m] for the passenger. In contrast to what observed with the AHM models, phase 2 is the most critical in terms of head accelerations and occupants lateral displacements for both driver and passenger (See Figure 16 and Figure 17). The occupants do not come into contact with each other. One second after the maneuver has been completed, the residual head and chest lateral displacements are negligible, with the maximum value of 0.004 [m] for the driver's head: both the occupants are back to their initial position.

**Table2.**
**Occupants' lateral displacements and head acceleration during the first and second phases of the maneuver (ES-2 dummy model)**

| | **ES2 *Driver*** | | **ES2 *Passenger*** | |
|---|---|---|---|---|
| | ***Phase 1*** | ***Phase 2*** | ***Phase 1*** | ***Phase 2*** |
| **Head Displacement [m]** | 0.146 | 0.216 | 0.144 | 0.218 |
| **Chest Displacement [m]** | 0.055 | 0.084 | 0.057 | 0.086 |
| **Head Lat. Acceleration [g]** | 1.67 | 2.15 | 1.32 | 2.09 |

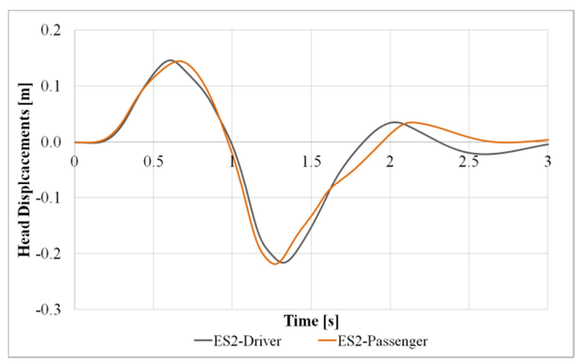


*Figure 16*. Head displacements (ES-2).

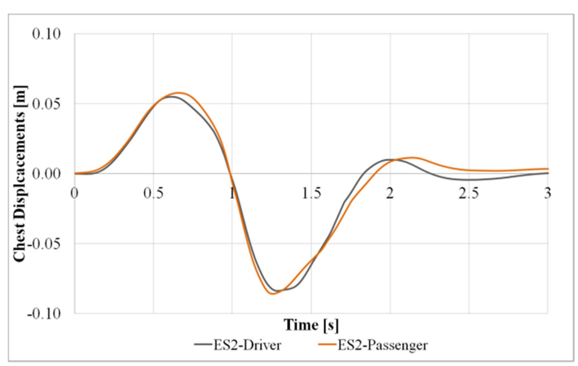


*Figure 17*. Chest displacements (ES-2).

The two selected occupant models show different behavior in the kinematics resulting from the applied lateral loading. By selecting the worst case phases, namely phase 1 for the driver and phase 2 for the passenger, the observed chest and head lateral displacements have been compared. Assuming the AHM response as reference (i.e. 100% displacement), the adoption of the ES-2 dummy model would result, for the driver, in a reduction of the estimated lateral displacements as big as 53% (head) and 76 % (chest) (See Figure 18). Similarly, for the passenger, the observed reduction of the head lateral displacement is equal to 27 %, the reduction of the chest lateral displacement to 51 % (See Figure 19).

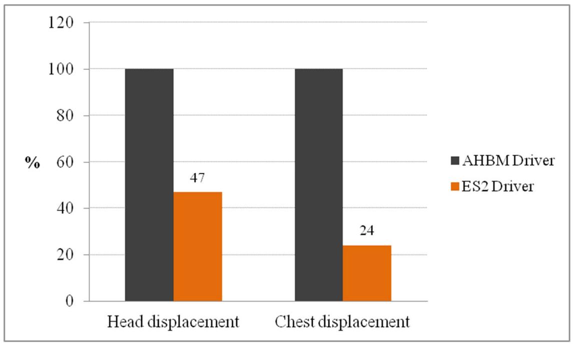


*Figure 18*. Phase 1_Driver's head and chest lateral displacements comparison (ES-2 dummy model vs. AHM).

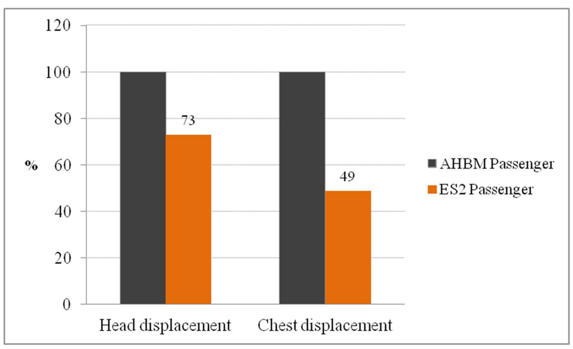


*Figure 19*. Phase 2_Passenger's head and chest lateral displacements comparison (ES-2 dummy model vs. AHM).

Due to the different kinematics, the position of the occupants during and at the end of the maneuver show significant difference in the out of position. One second after the end of the maneuver, the AHM models are still out of position, while the ES-2 models are back to the upright position (See Figure 20).

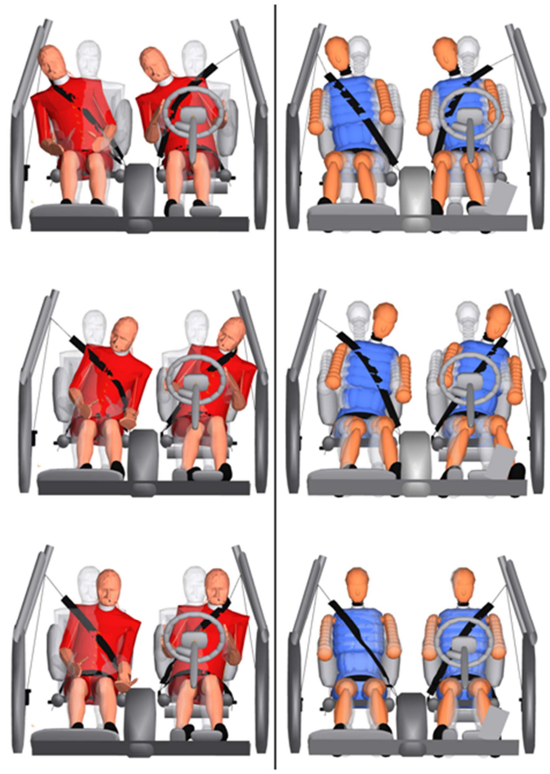

*Figure 20*. Occupants' OOP comparison (AHM vs. ES-2 dummy model).

## CONCLUSIONS

The simulation results of the passenger head and chest lateral displacements, presented in the Table 1, correlate well with the experimental test results obtained in the previous studies [9] in which comparable loading conditions were applied (double lane change maneuver defined by ISO 3888-2). The maximum averaged values obtained in the road experiments amount to 275mm and 165mm for the head and chest lateral displacement respectively, which should be compared to the maximum 299mm and 174mm obtained in the simulated tests with active human model (AHM). Assuming the modeling limitations, and the possible boundary conditions differences (differences in the seat shape, occupant anthropometry, clothing, seat belt response), it can be concluded that the overestimations of 5-8% for the simulation model are of a good representation.
The results of the head accelerations and consequently HIC values resulting from the contact interaction with the B-pillar during maneuvering should not be treated quantitatively due to the simplified representation of the vehicle interior model and b-pillar contact characteristics. It should be perceived as a an incidental parameter, indicating

that the head contact with B-pillar or roof rail is possible and should be considered for further testing on the customer acceptance and driving capabilities. However, the obtained results of HIC=62 would correspond to the abbreviated injury scale value (AIS) below AIS=1, that potentially can create headache or/and dizziness. This would further imply that the driver capabilities of taking over the control of the vehicle after the maneuver may be impaired. The analysis of a passenger and a driver motion shows, that the total lateral displacement of a driver is more pronounced than the one of a passenger. This is characteristic for a type of a maneuver (evasion to the left) and the fact that a driver is first misplaced towards the center of a vehicle (Phase 1- to his or her right hand side) and then to the B-pillar direction (Phase 2). The differences are more significant in Phase 1 of the maneuver (over 20%) and less pronounced for the Phase 2. This indicates that the potential predictive countermeasure systems for restraining the occupant motion during autonomous maneuvering should take into account the direction of intended steering and apply countermeasures accordingly per occupant and a driver.
Within the conclusive analysis of the results presented above, it should be noted that the limitations of the models and the approach used in the investigation may affect the results and thus conclusions. The quantitative assessment of the lateral occupants' displacements can be affected by modifying the executed maneuver and the critical model components: seat geometry and characteristics, interior part contact characteristic, interior geometry, occupant activation level and the occupant model itself. The components used in the study were generalized to observe the significance of the hypothesized problems globally; however they become a limitation in case the phenomena under investigation are required to be studied in a greater detail. Though the simulation results show very good correlation with the real experimenting [9], the selection of AHM activation settings (awareness, neck co-contraction, delay time, head-neck alignment) may not be representative enough for determining the problems globally and thus the aforementioned conclusions may have limited transferability. To address this, further studies into the sensitivity of the displacements results to the human activation level are needed.

The original hypothesis that the emergency autonomous evasive steering may result in significant occupants' misplacements during the maneuver has been confirmed in the above presented simulation results. This can pose a potential problem for customer acceptance of such systems due to the discomforting experience and/or potential risk of impaired driving capabilities instant after the maneuver. Implementation of autonomous evasive steering systems would then require application of additional measures to reduce the occupant motion during the highly dynamic maneuvering e.g. belt pretensioners or inflatable side bolsters, deployed prior to the steering execution. Those should partially reduce the misplacements to an adequate level. The other problem is the potential risk of impaired driver capabilities to continue driving due to the excessive misplacement or interaction with the B-pillar or roof rail. This requires a dedicated investigation that includes volunteer testing to validate and quantify the observed incidents.

As concluded in the previous studies [9], the dynamic loadings resulting from autonomous operations of a vehicle (braking or steering) may lead to out of position (and thus reduced protection of restraint systems in case of a collision. In case of a lateral displacement of such magnitude as presented in the study and depicted in the results paragraph, the problem can be easily conceivable as significant for potential frontal, lateral or rear collision. The displacements of occupants misalign their position with respect to the frontal airbags, and back- and head-rests. Additionally, the belt routing geometry is also altered from intended placement. As a result the effectiveness of the complete passive restraint system in case of a frontal collision can be significantly reduced due to altered injury mechanisms or/and potential contact with the instrument panel resulting from misaligned interaction with an airbag. Similarly for the other direction collisions, the misplaced position of occupants can reduce effectiveness of head rests in case of a rear impact, or impair the intended operation of the side protection systems (door trim or side/curtain airbags). Further studies are needed to quantify the problem and determine acceptable levels of displacements with respect to the intended position that are necessary to ensure optimal protection from the passive safety systems perspective. Definition of acceptance corridors will enable to define requirements for potential preventive systems meant to reduce the occupant misplacement due to autonomous vehicle control and thus addressing both problems: capability to take over vehicle control after the maneuver and sub-optimal protection in case of a collision. This can be only ensured when both active safety systems and passive safety systems are developed in an integrated manner.

The objective of the analysis performed with the ES-2 dummy model was to illustrate the potential differences between the human and anthropometric test device (ATD) models in capturing occupant response to the low-g loading conditions. Both models, used as tools in the same analysis process, exposed to the same loading conditions, show significantly different responses. The differences in lateral head and chest displacements vary between 23% and 76%, and can be considered as highly significant and are of paramount importance for any subsequent studies and conclusions. The significant differences can be explained by the fact that ATDs were designed and built to replicate human behavior under high-g, crash level loadings and cannot represent well the flexibility of a human body under lower loadings. These observations impose the requirements on the methodologies for integrated safety developments to use either human model simulations or volunteer tests for determining pre-crash occupant motion. Additionally it is expected that ATDs may not be suitable to represent human behavior accurately enough in the in-crash phase if initially set to out of position resulting from pre-crash loading (due to their limitations in representing human kinematics for other than standardized initial settings). However this hypothesis requires further investigation and verifications.

The increasing presence of autonomously operating vehicle control systems exposes the occupants of these vehicles to the highly dynamic loadings during the traffic situations with high risk of collision when these ADA systems are operating. This generates the need to develop the countermeasure systems that can control occupants' unfavorable motion and thus reduce the misplacements of the occupants with respect to their intended positions at which the passive systems are the most effective.
The work presented within this paper shows the importance of including the effect of ADA system operation on the occupants' misplacements into the system integration development processes and presents the complete simulation methodology that enables conceptual investigations into the required functionalities of current and future integrated safety system.

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