Factors Influencing Occupant Kinematics during Braking and Lane Change Maneuvers in a Passenger Vehicle

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Abstract The objective of this study is to evaluate the occupant's kinematics during emergency braking (velocity: 12 km/h and 50 km/h, peak frontal acceleration: 10 ms^{-2}) and lane change maneuvers with a series-production vehicle (velocity: 50 km/h, peak lateral acceleration: 10 ms^{-2}) taking into account influencing factors, e.g. seat and restraint system, physiological, anatomical and psychological factors. To quantify these factors two series of vehicle-based tests were performed. In the first series 24 male volunteers were seated in a modified seat restrained with a lap belt and kinematics were evaluated at three awareness conditions. In the second series 27 male and six female volunteers were evaluated. Lateral support plates were added to the seat. Volunteers were restrained with a conventional three-point belt. Retro-reflective markers were applied to anatomical landmarks and occupant kinematics were recorded using an infrared-based 3D motion-capture system. Vehicle kinematics were recorded from the vehicle CAN-bus system. The data analysis concentrates on the upper body kinematics. Marker trajectories were used to estimate the position and orientation of head and torso. The study shows distinct inter-individual differences in terms of occupant movement, especially for the lap-belt setup. The study further shows a strong influence of lateral support structures in the lane-change maneuvers. A complete set of results clustered according to the influencing factors is included in this paper.

Keywords Emergency braking, lane change maneuver, low g vehicle test, occupant kinematics, volunteers

I. INTRODUCTION

The safety level of passenger vehicles has increased considerably over the decades. A further increase through conventional passive restraint systems is seemingly limited. To meet the target of halving the road casualties from 2011 by 2020 [1] requires integral safety systems which support the driver during normal driving and in critical situations. Integral safety systems like Advanced Driver Assistance Systems are able to brake automatically and influence the vehicle's kinematics before impact and so they can avoid or mitigate accidents. Under these circumstances it is necessary to verify this potential. Therefore, in 2014 EuroNCAP introduced a test for accident-avoidance systems [2].

For development of passive safety systems anthropomorphic testing devices (ATD) can be used as muscle activity is considered as having a negligible effect on the occupant kinematics in moderate to severe accidents. For development of integral safety systems, though, muscle-induced, active movement of occupants exposed to low-level accelerations is crucial. Therefore simulation models which represent human kinematics for studying the pre-crash phase are needed, which in turn need a solid validation base of human movement during mild loading conditions.

Human kinematic response to different loading conditions occurring in driving maneuvers is typically studied on a sled or in-car. In a study by Szabo et al. [3], low-speed (nominal 16 km/h) rear impacts were carried out with five subjects (one female, four male) sitting in both the bullet and the target vehicle. The occupant kinematics were measured with acceleration sensors and recorded with a high-speed video camera mounted on the driver's side of the target vehicle. A forward motion between 58 mm and 110 mm for the head (ear target) and a maximum forward motion of 46 mm for the shoulder were measured.

Ejima et al. [4-6] studied the response of male and female subjects during low-speed sled tests. The kinematic response was recorded using an optical motion tracking system combined with EMG. In all studies by Ejima et al. [4-6] it was shown that individual muscle contributions have a considerable effect on the motion of the volunteer.

Kemper et al. [7] investigated the effect of pre-impact bracing on chest compression in low-speed frontal sled tests (5.0 g). The sternum deflection was measured and, additionally, a Vicon motion capturing system with 12 cameras was used to quantify the 3D kinematics of the subjects. They showed that the forward excursion of the elbows and shoulders was significantly reduced in the braced condition compared to the relaxed condition.

Low-speed frontal sled tests were also conducted in [8]. Here 34 (17 with acceleration of 2.5 g and 17 with acceleration of 5.0 g) dynamically-matched frontal sled tests were performed with five male volunteers, a Hybrid III 50th percentile male ATD and three post-mortem human surrogates (PMHS). 3D kinematics were measured with a Vicon motion analyses system. The study illustrated that human volunteers, ATD and PMHSs have different biomechanical response in low-speed frontal tests and demonstrated the importance of human volunteers.

In [9] the influence of a motorized seatbelt (MSB) in low-speed frontal impact tests (0.8 g) was studied. In a sled setup, three male subjects were tested and the difference between MSB and a modern three-point seatbelt was analyzed. The experiments were conducted in a relaxed and a braced state and the motion of the human body was recorded with a 3D motion capturing system. The MSB reduced the forward displacement y in the relaxed state dramatically.

Carlsson and Davidson [10] analyzed occupant kinematics during driver-initiated and autonomous braking in real traffic environments. Seventeen volunteers (eight females and nine males) were tested with a Volvo XC60 with an autonomous braking system with deceleration of 0.3 g, 0.4 g and 0.5 g. The subjects' motion was captured using different markers on the body and two cameras, one oriented towards the driver and one towards the passenger side. This study indicated that several properties (size and gender of the volunteers, position either in the driver or the passenger seat, vehicle deceleration and the seatbelt properties) seem to influence the forward motion. Taller volunteers had larger forward motion than shorter ones of the same gender, while females had a larger forward movement than males of the same sitting height. For most subjects the forward motion was larger in the passenger seat than in the driver seat and most of the subjects had the least forward motion at the lowest acceleration level.

Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pre-tensioned restraints were analyzed in [11]. Twenty subjects (11 male and nine female) were tested with a passenger car with two different braking test cases of 1.1 g. Kinematics were collected with a video- tracking system and muscle activity was measured with EMG. A significant reduction of head-forward movement was observed in pre-tensioned belt conditions.

Several studies with sled tests and vehicle setups were done to analyze human kinematics during low-load braking situations. There, the influence of belt systems, gender, anthropometric data and bracing conditions were studied.

For validation of simulation models which represent human response during low-load maneuvers it is necessary to consider the volunteer's awareness condition, because of the difference between the occupant's states of anticipation and surprise at a maneuver. Furthermore, the kinematics is important for the design of restraint systems. Therefore volunteers using only a lap belt were also analyzed to get information of their movement patterns in this study. For further optimization of restraint systems it is also necessary to have information of the lateral movement of occupants during or before a critical situation and, therefore, lane change maneuvers were also analyzed in this study.

In this paper, results from a vehicle-based study are presented, where various frontal and lateral maneuvers were performed and the kinematic response of the occupants was captured using a 3D motion-capturing system. The influence of various subject-specific factors, awareness state and the seat-and-belt system are analyzed.

II. METHODS

A. Vehicle and maneuvers

Vehicle tests were performed in two series in a Mercedes-Benz S-500 (type: W221, width: 1.78 m, length: 5.23 m, wheelbase: 3.17 m, see Fig. 2) on a closed test track. Two types of maneuvers were studied: an emergency braking maneuver at two different velocities (12 km/h and 50 km/h) and a lane change situation at 50 km/h. In the braking maneuver the driver pressed the brake pedal at maximum effort, such that the brake-assist system was activated. In the lane change maneuver to the right, which was performed to closely resemble the first part of the VDA lane change [12], the driver turned the steering wheel to the right around 200°, followed by a counter-movement to the left approximately 360° and a rotation to the right to reach the neutral position, again at maximum effort. In the lane change maneuver to the left, similar levels of acceleration and steering wheel angles were reached, but in opposite directions.

In order to identify the vehicle driving state, velocity, vehicle speed, acceleration in lateral and frontal direction, steering wheel angle and angular velocity as well as the yaw rate were recorded from the CAN-Bus using a Dewetron Dewe5000. The steering wheel angle and angular velocity were sampled at 100 Hz, the velocity at 10 Hz, while the remaining channels were sampled at 50 Hz.

For the brake maneuver, the state of the brake pedal was used to define the starting of the maneuver, i.e. t=0. For the lane change maneuver, the first instance where the steering wheel angle exceeded 20° was identified. The steering wheel angular velocity at this point was then used to extrapolate to steering wheel angle 0° and the corresponding time was defined as t=0 (see also [13]).

B. Testing Series A – Rigid seat and a lap belt

For this series the standard seat was replaced with a modified seat (see Fig. 1), where the original seat frame was used, but the cushions were replaced by wooden plates, covered in artificial leather. The seat surface (width: 440 mm, length: 490 mm) was inclined by 10° and the distance between the rear edge and footwell level was 180 mm. The angle between back rest (width: 550 mm, length: 512 mm) and seat surface was 104° and the original headrest was used. Additionally, a lap belt only was used, where the original lower mounting points were utilized. The upper part of the belt was routed behind the seat and a clamp was placed close to the belt buckle to fix the length of the lap belt. The clamp was adjusted for each subject individually such that the belt was tight and pelvis movement was restricted. These measures were taken to facilitate the transfer of testing data to numerical simulation models and to simplify modeling the interaction between seat, belt and the occupant.

In this series emergency braking maneuvers with an initial velocity of 12 km/h and lane change situations with an initial velocity of 50 km/h were performed with 22 male subjects (mass: 77.4±6.7 kg, height: 179.4±4.3 cm, age: 32.2±8.6 y). All subjects held a valid driving license for operation of a passenger car and each subject gave written informed consent after an initial briefing about the test procedure. The tests were reviewed and approved by the local ethics committee. Three awareness conditions were realized: unaware (no information given to the subject), anticipated (maneuver could be inferred from contextual information) and an informed condition (maneuver was announced with a count-down from three). The maneuvers were performed in a fixed order and in arbitrary locations on the test track. In an informal questioning all subjects commented that the first maneuver surprised them.

C. Testing Series B – cushioned seat with lateral support and a three-point belt

In the second series the seat from Series A was further modified (see Fig. 1). Lateral support structures were added, where the geometry was close to the geometry of the original seat (Angle lateral support: 120°, distance between left and right piece: 314 mm). A layer of foam (thickness: 40 mm) was applied to the wooden plates at the seat surface and back rest as well as onto the lateral support structures. These were covered in artificial leather and a layer of light-absorbing material to reduce reflections in the infrared spectrum. The standard three-point belt was used with the pre-tensioner disabled.

Six female (mass: 63.0±10.4 kg, height: 169.0±4.1 cm, age: 31.5±9.3 y) and 27 male (mass: 77.8±8.4 kg, height: 179.1±4.7 cm, age: 25.4±9.6 y) subjects were tested in this series in various tests[1]. Since the number of subjects varies over the maneuvers, the specific properties for each subset are collected in Table I.

[1] Additionally combined braking and swerving maneuvers, braking during a stationary circle and maneuvers in a handling and slalom parcours were recorded, which are presented in [14].Only selected subjects of test Series B are included in this paper.

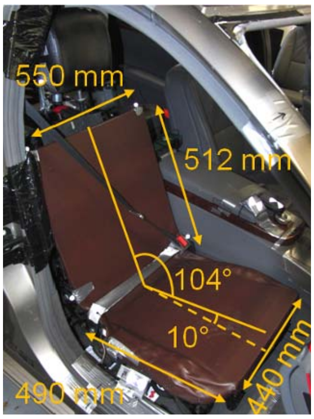

Fig. 1: Reference seats of Series A (left) and Series B (right). Note the lateral support structures in Series B.

TABLE I
PARAMETERS OF THE MANEUVER AND SUBJECT PROPERTIES

series	maneuver	velocity [km/h]	awareness	seat - belt system	peak acc. [m/s2]	#subjects	#male	#female	height [cm]		weight [kg]		age [y]	
A	Br	12	un	lap belt	-10.2	22	22	0	179.4	±4.3	77.4	±6.7	32.2	±8.6
	Br	12	an		-10.2	22	22	0	179.4	±4.3	77.4	±6.7	33.2	±8.6
	Br	12	in		-10.2	22	22	0	179.4	±4.3	77.4	±6.7	32.2	±8.6
	Lr	50	un		-10.2	22	22	0	179.4	±4.3	77.4	±6.7	32.2	±8.6
	Lr	50	an		-10.2	20	20	0	179.2	±4.2	76.9	±6.7	31.5	±8.3
	Lr	50	in		-10.2	21	21	0	179.1	±4.1	76.9	±6.5	32.2	±8.7
B	Br	12	un	standard three-point belt	-10.8	14	10	4	176.3	±5.5	75.9	±12.0	28.8	±4.2
	Br	12	re		-10.8	9	6	3	177.0	±6.1	76.4	±11.3	27.7	±4.6
	Br	50	un		-10.8	10	6	4	176.5	±5.9	76.5	±11.1	31.1	±8.4
	Ll	50	un		10.1	5	2	3	175.2	±5.2	68.2	±9.1	29.0	±6.4
	Lr	50	un		-9.9	4	2	2	176.5	±5.0	71.8	±5.1	27.5	±6.2

Maneuver: Br…braking, Lr…Lane change right, Ll…Lane change left
Awareness: un…unaware, an…anticipated, in…informed, re…repetition

D. *Occupant kinematics*

Occupant kinematic data were captured using a Vicon V612 motion-capturing system featuring eight near-infrared cameras (see Fig. 2). Positions of retro-reflective markers on specific locations on the occupant's body were recorded at a sample frequency of 100 Hz and reconstructed to give their 3D positions. All data sets were synchronized with vehicle kinematics and time-shifted such that t=0 corresponds to the onset of the maneuver in consideration.

The occupant's upper part of the torso and head were considered as rigid and selected markers were assigned to those body segments. A purpose-built gap-filling algorithm was applied, which allowed reconstruction of missing marker trajectory if at least three markers on the subject were visible. Using rigid body constraints, displacements of these body segments were determined. A reference posture of the occupant was defined as the posture that occurred at t=0. For further analysis, displacements with respect to this reference position were used. Note that no smoothing procedure was performed except for the implicit low-pass filtering that is inherent to the orientation estimation procedure.

11 markers on the head (bilateral: forehead, back of the head, ear, cheek bone; central: top of head, C1, chin) and 12 markers on the torso (bilateral acromion, pectoralis, clavicle, scapula; central: C7, T1, T10, sternum) were used to compute characteristic points of the head and upper torso segment in each video frame. These are referred to as center points and displacements ($\Delta r^{Head|Torso}_{x|y|z}$) with respect to t=0 are reported, where the superscript denotes the body region and the subscript denotes the x, y or z component of the displacement

vector. The coordinate system was chosen such that the H-point of the unmodified seat refers to the origin, the x-axis points towards the rear of the vehicle, the y-axis to the right and the z-axis up.

(a) (b) (c)

Fig. 2. Setup of vehicle and subjects. The vehicle was equipped with eight Vicon infrared motion-capturing cameras. Note that the windshield and the passenger window were removed (a). Subjects wore a skin-tight motion-capturing suit and reflective markers attached onto the suit (b) and (c).

In the subsequent analysis, the maximum excursions of the center point displacements during the initial kinematic response are considered. For braking maneuvers, the minimal value Δr_x in the interval $0 \leq t \leq 0.6$ s is considered. For lane change maneuvers to the right the minimal value Δr_y in the interval $0 \leq t \leq 1.2$ s is taken, while for lane change maneuvers to the left the maximum value Δr_y in the same interval is taken.

Maximum excursions are then analyzed using analysis of variance (ANOVA). In case of significance (significance level: 0.05) of the categorical variables, a pair wise comparison using the Tukey test was performed. For Series A, three factors were taken into account in ANOVA: *segment* (indicating the body segment head or torso), subject *height* and the *awareness* state (“unaware”, “anticipated” and “informed”). For the braking maneuvers in Series B, factors *segment* and *height*, *gender* and *maneuver* (one of the three maneuvers: brake at 12 km/h first and second maneuver and brake at 50 km/h) were considered. Additionally different subsets of data and factors were analyzed. For the very small sample (n=9) of lane change maneuvers in Series B the factors *segment*, *height* and *direction* (of the maneuver) were used in ANOVA. Finally the two Series A and B were jointly analyzed, where factors *segment*, *height* and *belt/seat* (i.e. the rigid seat with lap belt in Series A or the cushioned seat with lateral support and three-point belt in series B) were considered.

III. RESULTS

A. Description of maneuver

In Figs. 3-5 a representative subject for each maneuver was chosen and relevant quantities of occupant and vehicle kinematics were displayed. In both maneuvers a clear principal direction of the acceleration can be identified. In the braking scenarios, the acceleration points are mainly in the negative x-direction, while in the lane change to the left scenarios, the acceleration is predominantly in the negative y-direction (and in the positive y-direction in the maneuvers to the left). In the braking maneuvers at 12 km/h, peak frontal accelerations of -10.0±0.3 m s^{-2} were reached and the vehicle stopped after 0.48±0.05 s. In braking maneuvers at 50 km/h, peak frontal accelerations of -10.5±0.3 m s^{-2} were reached and the vehicle stopped after 1.6±0.13 s. In the lane change maneuver peak lateral accelerations of -10.0±0.2 m s^{-2} were reached and after 0.95±0.05 s the initial part of the maneuver was finished (i.e. the lateral acceleration changed the sign). Also, the center point displacements predominantly point in the principal direction of the acceleration. Therefore, the displacement values in the principal direction of the maneuver are considered for analysis.

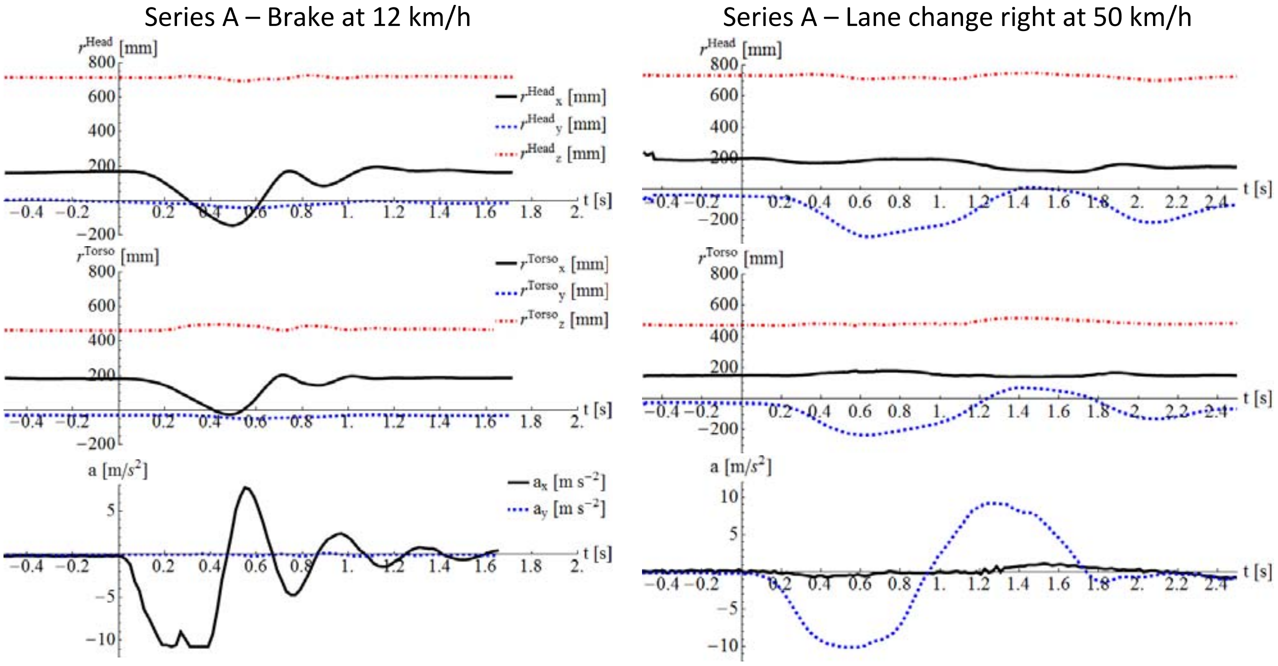

Fig. 3: Vehicle kinematics and the kinematic response of a braking (left) and a lane change (right) maneuver of a sample subject from Series A are plotted against time. Coordinates of the center point displacements of head and torso are displayed in the first two rows (x-coord.: solid black line, y-coord.: dashed blue line, z-coord.: dot-dashed red line), the corresponding accelerations (x-comp.: solid black line, y-comp.: dashed blue line) are plotted in the third line. Note that in both maneuvers the acceleration is almost parallel to the x- and y-axis, respectively, and also that the kinematic response occurs mainly in this direction.

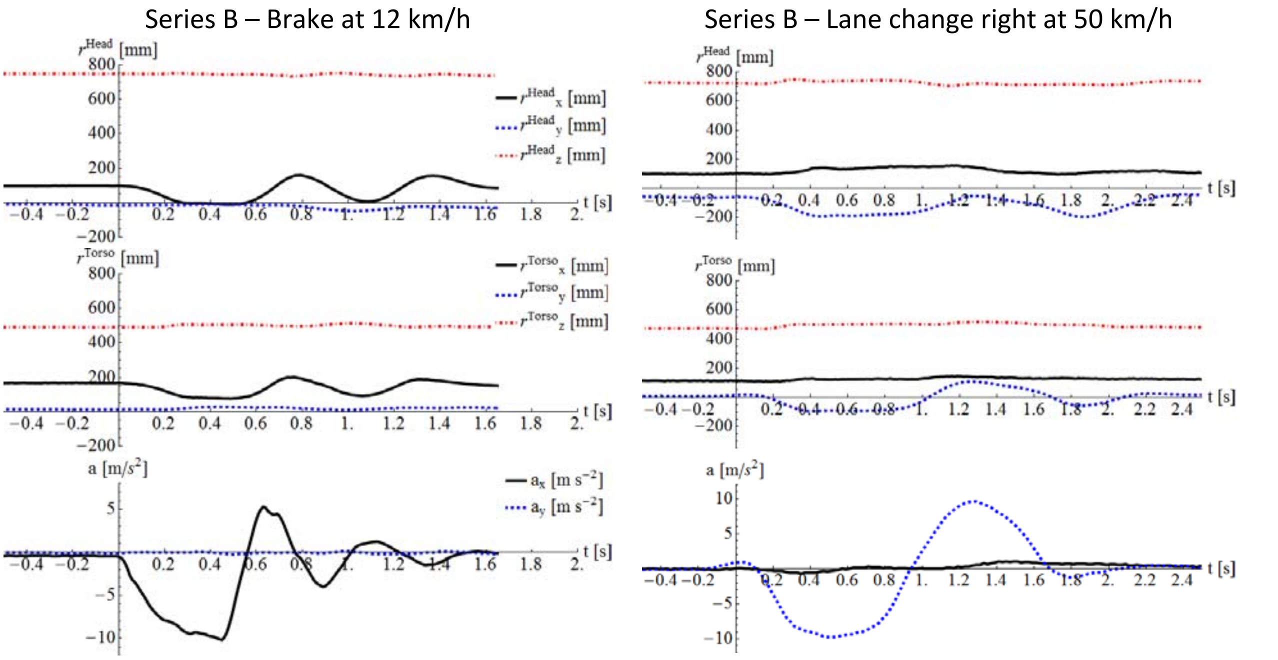

Fig. 4: Vehicle kinematics and the kinematic response of a braking (left, 12 km/h) and a lane change (right) maneuver to the right of a sample subject from Series B plotted against time. Coordinates of the center point displacements of head and torso are displayed in the first two rows (x-coord.: solid black line, y-coord.: dashed blue line, z-coord.: dot-dashed red line), the corresponding accelerations (x-comp.: solid black line, y-comp.: dashed blue line) are plotted in the third line.

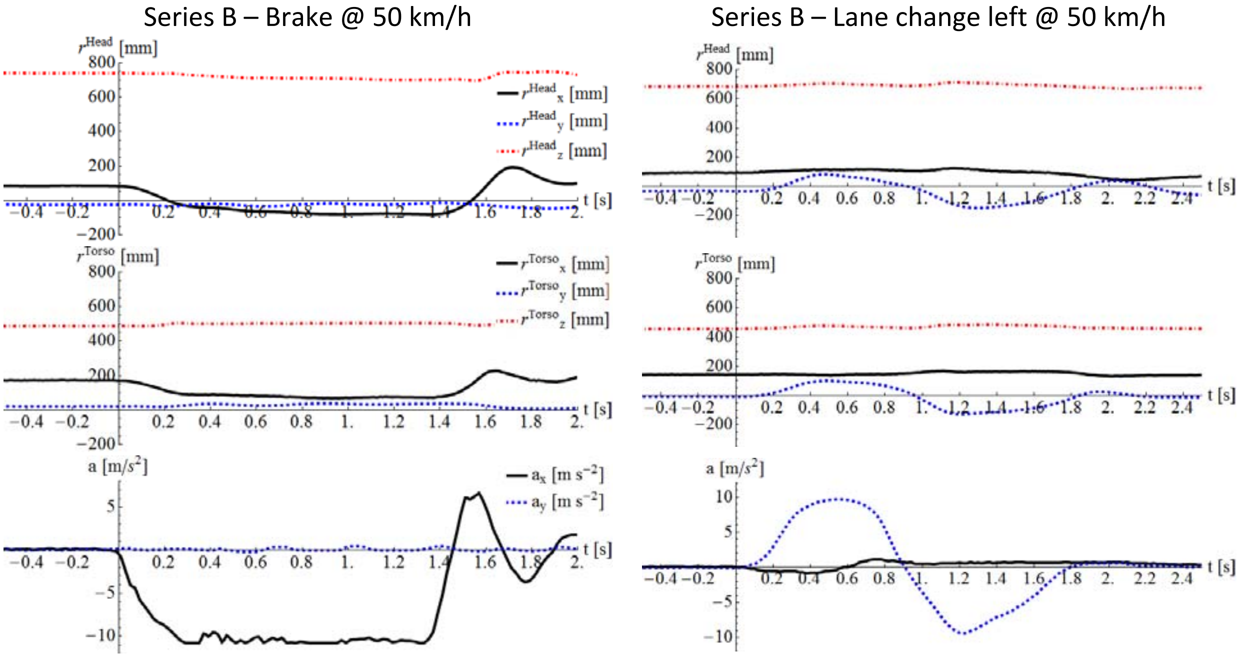

Fig. 5: Vehicle kinematics and the kinematic response of a braking (left, 50 km/h) and a lane change (right) maneuver to the right of a sample subject from Series B plotted against time. Coordinates of the center point displacements of head and torso are displayed in the first two rows (x-coord.: solid black line, y-coord.: dashed blue line, z-coord.: dot-dashed red line), the corresponding accelerations (x-comp.: solid black line, y-comp.: dashed blue line) are plotted in the third line.The kinematic response to a braking (50 km/h, left) and a lane change (right) maneuver to the left of a sample subject from Series B.

The braking maneuver can be split into two main phases, a forward movement and a rebound phase. In Series A with a lap belt only the forward movement starts after around 100 ms and reaches the maximal excursion after around 500 ms. Thereafter, a backward movement takes place, lasting approximately 250 ms. The vehicle reaches a full stop after around 550 ms, although some residual motion due to the suspension is also present after 1.5 s. In Series B, a qualitatively different behavior is observed, where the forward movement of head and torso is restricted.

The lane change maneuver can be split into four phases. In the first 200 ms, no relevant lateral movement is observed (below 5% of maximum movement). Thereafter, the lateral movement to the outside of the turn sets in and the maximum lateral excursions are typically reached after 650 ms. At around 1200-1400 ms, the peak lateral excursion in the direction opposite to the initial movement is reached and the upright starting position is crossed after 1100-1300 ms. In the final backward movement phase, a large variation among the subjects is observed and no consistent pattern is found.

In Tab. II, statistical quantities for the maximum forward and sideward (phase two) movements are collected and a graphical representation thereof can be found in Fig. 6 and Fig. 7.

TABLE II
MAXIMUM EXCURSIONS OF HEAD AND TORSO CENTER POINTS IN VARIOUS MANEUVERS

series	maneuver	velocity [km/h]	direction	awareness	seat - belt system	Δr^{Torso}_x [mm]		Δr^{Head}_x [mm]	
A	Brake	12		un	lap belt	-201	±60	-316	±99
				an		-157	±71	-280	±108
				in		-141	±93	-254	±146
B	Brake	12		un	three-point belt	-115	±26	-208	±58
				re		-90	±18	-154	±45
		50		un		-93	±20	-151	±43
						Δr^{Torso}_y [mm]		Δr^{Head}_y [mm]	
A	Lane	50	right	un	lap belt	-208	±61	-257	±100
				an		-209	±66	-271	±110
				in		-167	±67	-214	±84
B	Lane	50	left	un	three-point belt	107	±27	101	±21
			right	un		-115	±34	-144	±39

awareness: un…unaware, an…anticipated, in…informed, re…repetition

B. *Braking maneuver*

1) *Series A*

Maximal forward excursion of the center point of both torso and head decreased with increasing alertness. For Δr^{Torso}_x values of -201±60 mm, -157±71 mm and -141±60 mm were observed for the unaware, anticipated and informed states, respectively, while values of-316±99 mm, -280±108 mm and -254±146 mm were determined for Δr^{Head}_x.

Three-factorial ANOVA revealed a significant effect of factors *segment* ($F(1,131)=46.387$, $P=0.00$) and *awareness* ($F(2,131)=4.322$, $P=0.02$), while *height* was not significant ($F(1,131)=2.325$, $P=0.13$). Pairwise comparison for the awareness factor shows a significant difference between the “aware” and “informed”states.

2) *Series B*

In the Series B lower excursions of -115±26 mm for the torso and -208±60 mm for the head were measured in the first maneuver at 12 km/h. In the second braking maneuver at 12 km/h and at 50 km/h, the corresponding values dropped to -90±18 mm and -154±45 mm and -93±20 mm and -151±43 mm, respectively.

A four-factor analysis was performed revealing a significant effect for the three factors *segment* ($F(1,65)=64.874$, $P=0.00$), *gender* ($F(1,65)=4.961$, $P=0.03$) and *maneuver* ($F(2,65)=9.129$, $P=0.00$), while *height* showed no significant effect ($F(1,65)=1.320$, $P=0.26$). Omitting the factor *gender*, however, resulted in a significant influence of the height.

An additional two-factorial ANOVA on the *segment* and *velocity* factors for the second braking maneuver at 12 km/h and the braking maneuver at 50 km/h resulted in a significant influence of the *segment* factor ($F(1,37)=30.934$, $P=0.00$) only, while the factor *velocity* showed no influence ($F(1,37)=0.001$, $P=0.97$).

3) *Series A & B*

In order to compare both series of braking test a three-factorial ANOVA was performed. The *segment* factors ($F(1,197)=69.949$, $P=0.00$) remained highly significant and also the factors *seat-and-belt* system ($F(1,197)=43.416$, $P=0.00$) and *height* ($F(1,197)=3.974$, $P=0.05$) were significant.

C. *Lane change maneuver*

1) *Series A*

In contrast to the braking maneuver in Series A no strict trend of decreasing excursions could be found. The observed lateral excursions for the torso were found to be -208±61 mm, -209±66 mm and -167±67 mm for the unaware, anticipated and informed awareness states, while values of -257±100 mm, -271±110 mm and -

214±84 mm were observed for the head.

Similary to the braking maneuvers, a three-factorial ANOVA in this series indicates a significant effect of factors *segment* (F(1,135)=13.569, P=0.00) and *awareness* (F(2,135)=4.794, P=0.01). In the pairwise comparison there is a significant difference between “aware” and “informed” states as well as between “anticipated” and “informed”. The factor height is not significant here (F(1,135)=1.776, P=0.18).

2) Series B

In Series B, lower lateral excursions were measured in both directions of the maneuver than in Series A. Maneuvers to the left lead to excursions of 107±27 mm and 101±21 mm of torso and head, while values of -115±34 mm and -144±39 mm were observed for the corresponding values in the maneuver to the right.

In contrast to all other maneuvers, the three-factorial ANOVA does not show any significant influence of factors *segment* (F(1,17)=0.510, P=0.49) *direction* (F(1,17)=4.107, P=0.06) or *height* (F(1,17)=1.682, P=0.22). Note that only absolute excursions are compared here, such that the maneuver to the left leads to the same excursion in the initial phase as the maneuver to the right.

3) Series A & B

Comparing both series of tests in a four-factorial ANOVA reveals that the three factors *segment* (F(1,153)=13.873, P=0.00), *awareness* (F(2,153)=5.275, P=0.01) and *seat-and-belt* system (F(1,153)=31.351, P=0.00) are highly significant, while the *height* factor is not (F(1,153)=0.000, P=0.98). Similary to the Series A pairwise comparison indicates significant differences between the “aware” and “informed” states as well as between “anticipated” and “informed”.

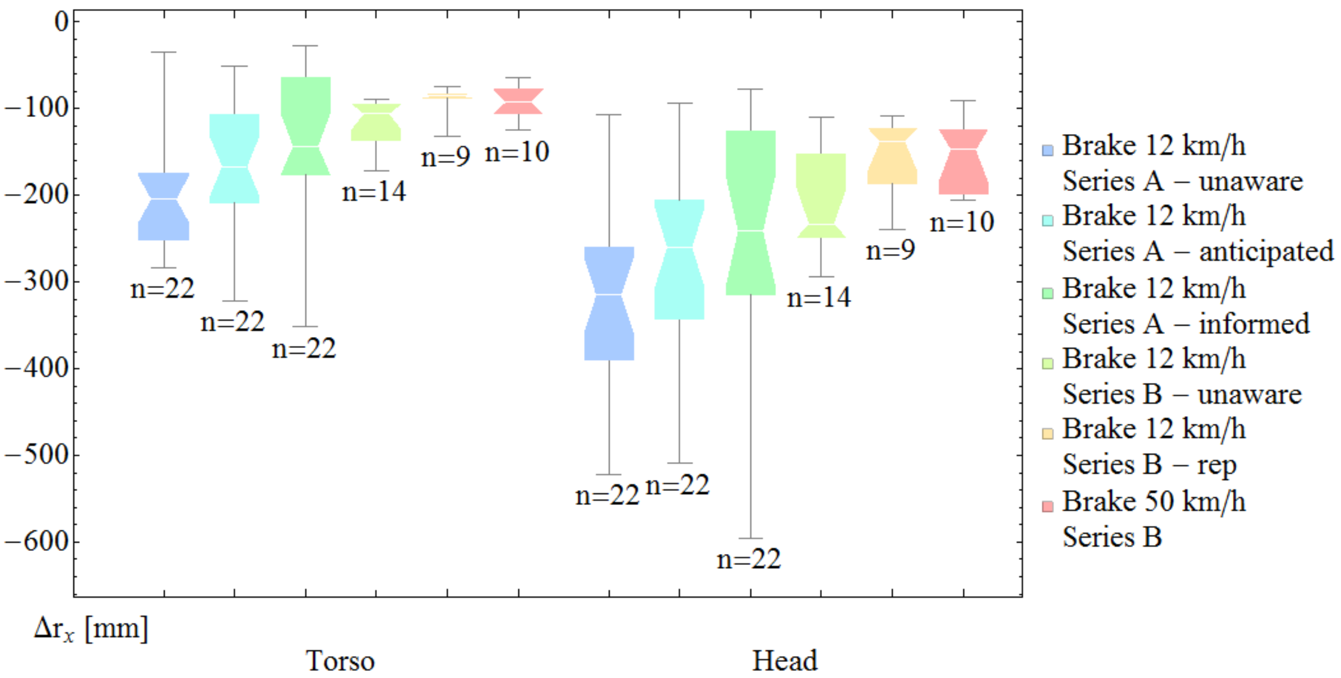

Fig. 6: Maximum excursion of torso (left) and head (right) in frontal direction during various braking maneuvers. For each set of subjects, the median (white line in the center of the colored box) confidence interval of the median estimator (notches in the colored box), 1st and 3rd quartile (lower and upper limit of the box) and extreme values (error bars) are displayed. The corresponding number of subjects is included in each plot item.

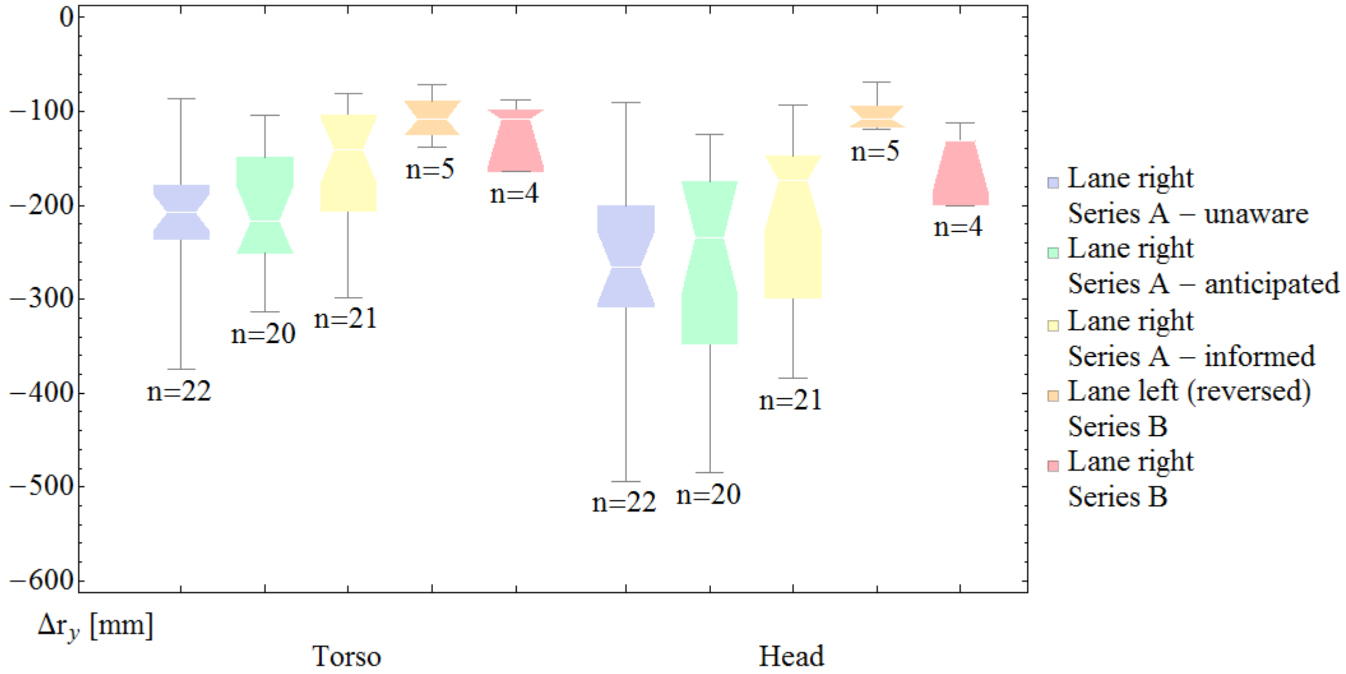

Figure 7: Maximum excursion of torso (left) and head (right) in a lateral direction during various lane change maneuvers. Note that, for the sake of comparison maximum excursions in the maneuver to the left are displayed on the negative axis.

IV. Discussion

A. Braking maneuver

In the braking situation with a lap belt only large forward excursions and inter-individual differences of head (up to -316±99 mm) and torso (up to -201±60 mm) were found. Significantly smaller values of -208±60 mm for the head and -115±26 mm for the torso were found with a three-point belt. Òlafsdòttir et al. [11] measured an average forward excursion for male subjects of 209±32 mm for head and 137±17 mm for the thorax (first thoracic vertebra, T1) using a three-point belt. For female subjects the average forward excursion for head was 209±16 mm and 146±14 mm for the thorax when the standard three-point belt was used. [3] measured an average forward excursion for male subjects of 87±29 mm for head with standard seat and an average forward excursion of 91±18 mm for a modified head restrain system (2 inches of padding added). A forward excursion of 100 mm for the head with the modified head restrain system was measured with one female subject. Also [8] analyzed different forward excursion for five male subjects. For relaxed subjects a forward excursion of 169±14 mm at the head center of gravity (CG) and 130±15 mm at the seventh cervical vertebra (C7) during 5.0 g acceleration was observed. For braced subjects forward excursions of 106±20 mm (Head CG) and 61±25 mm (C7) were measured. The forward excursion for head (Center of gravity) was 123±9 mm and for thorax (C7) was 89±5 mm during a 2.5g impact. Occupants in modern cars are exclusively restrained with three-point belts. Nevertheless, the difference in kinematic response between the lap belt and three-point belt provides validation data for numerical simulation models for the pre-crash phase. Additionally, data from the lap belt situation may be useful for other areas of application, e.g. airplane and train safety, where restraint systems are not as sophisticated as in passenger vehicles.

The significant influence of the *seat-and-belt* factor in both maneuver types can be attributed to the strong interaction of the occupant with the upper part of the three-point belt in the braking maneuver and the contact of the occupant with the lateral support structures in the lane change maneuver.

For Series A, a significant influence of the awareness state was found. The maneuvers were performed in fixed order, so for the informed condition there may be an entanglement of information and a habituation effect. In Series B a significant influence of the awareness state was also found. Nevertheless, no comparison should be made between the anticipated state in Series A and B. In Series B, a more complicated trajectory on the test track was driven and the frequency of maneuvers was slightly higher. Therefore, anticipation of the maneuver from contextual information was arguably harder in Series B than in Series A.

For Series B, a significant influence of the vehicle velocity was also revealed, which vanished when the first braking maneuver was excluded. Although we compare the first higher-speed maneuver with the second lower-speed maneuver, it can be argued that the awareness state is comparable, since no information about the maneuver was given.

A significant influence of the subject height was only present in the full set of tests A and B, while in Series B it only emerged when gender was not considered. The latter effect can be explained by the strong correlation of gender and height in the test population.

B. Lane change maneuver

Large lateral excursions and large inter-individual differences for both head (up to -271±110 mm) and torso (up to -209±66 mm) were recorded, where the absolute values were smaller than in the braking maneuver, but the relative variation was larger. For the significant influence of the awareness state, the same limitations as in the braking maneuvers occur. In Series B, the lateral excursion was significantly reduced, most probably by the use of lateral support structures in the seat. In contrast to any other maneuver, there was no more significant difference between excursions of the head and torso segments, which might also be attributed to the lateral support structures. Note the limited number of subjects in these maneuvers (Lane change left: five subjects, Lane change right: four subjects). No significant influence of the subject height was observed in any of the maneuvers

C. Limitations

Although maneuvers were performed in a vehicle and, thereby, one step towards realistic driving scenarios was made, the subjects are still in an explicit experimental situation due to subject preparation, the missing windshield and preparation of the vehicle, driving on a closed test track and a high frequency of maneuvers. Furthermore, only a difference in the awareness states “unaware”, “anticipated” and “informed” in Series A can be made, but no distinction between habituation effects and the difference in information given to the subject (between the “anticipated” and the “informed” state). This is due to the fixed sequence in which the tests were performed.

V. CONCLUSIONS

The occupant response during two main emergency scenarios was recorded in various full vehicle tests. Large absolute values and large inter-subject variability of head and torso excursions were observed, where the largest values were found in a reference seat without lateral support structures and using a lap belt only. In line with expectations the frontal and lateral excursions were reduced by using a modified seat with added lateral support structures and a three-point belt. These data are very valuable for validating active human models.

Statistical analysis revealed various influencing factors on the maximum excursions. Besides the obvious influence of the restraint system, a significant influence of the awareness condition on occupant kinematics can be shown.

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VII. REFERENCES

[1] European Commission: Towards a European road safety area: policy orientations on road safety 2011-2020, 20-7-2010.

[2] Euro NCAP: Autonomous Emergency Braking, http://de.euroncap.com/de/testsexplained/aeb.aspx access to website: (11-3-2014)

[3] Szabo TJ, Welcher JB. Human subject kinematics and electromyographic activity during low speed rear impacts. *SAE International,* 1996, pp. 295-315.

[4] Ejima S, Ono K, Holcombe S, Kaneoka K, Fürstenberg K. A study on occupant kinematics behaviour and muscle activities during pre-impact braking based on volunteer tests. *Proceedings of IRCOBI Conference,* 2007, Maastricht, The Netherlands.

[5] Ejima S, Zama Y, et al. Prediction of the physical motion of the human body based on muscle activity during pre-impact braking. *Proceedings of IRCOBI Conference,* 2008, Bern, Switzerland.

[6] Ejima S, Ito D, et al. Effects of pre-impact swerving/steering on physical motion of the volunteer in the low-speed side-impact sled test. *Proceedings of IRCOBI Conference,* 2012, Dublin, Ireland.

[7] Kemper AR, Beeman SM, Duma SM. Effects of pre-impact bracing on chest compression of human occupants in low-speed frontal sled tests. *Proceedings of 22th International Conference on the Enhanced Safety of Vehicles, 2011,* paper no. 11-0193.

[8] Beeman SM, Kemper AR, Madigan ML, Franck CT. Occupant kinematics in low-speed frontal sled tests: Human volunteers, Hybrid III ATD, and PMHS. *Accident Analysis and Prevention,* 2012, 47:128-139.

[9] Daisuke I, Ejima S, et al. Occupant kinematic behavior and effects of a motorized seatbelt on occupant restraint of human volunteers during low speed frontal impact: Mini-sled tests with mass production car seat. *Proceedings of IRCOBI Conference,* 2013, Gothenburg, Sweden.

[10] Carlsson S, Davidsson J. Volunteer occupant kinematics during driver initiated and autonomous braking when driving in real traffic environments. *Proceedings of IRCOBI Conference,* 2011, Krakow, Poland.

[11] Òlafsdòttir JM, Östh J, Davidsson J, Brolin K. Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pre-tensioned restraints, *Proceedings of IRCOBI Conference*, 2013, Gothenburg, Sweden.

[12] Verband der Automobilindustrie: VDA Lane Change Test; http://www.vda.de/de/verband/fachabteilungen/technik/infos/vda-spurwechseltest.html access to website: (12-3-2014)

[13] Huber P, Christova M, et al. Muscle activation onset latencies and amplitudes during lane change in a full vehicle test. *Proceedings of IRCOBI Conference,* 2013, Gothenburg, Sweden.

[14] Huber P, Kirschbichler S, Prüggler A, Steidl T. Three dimensional occupant kinematics during frontal, lateral and combined emergency maneuvers. *Proceedings of IRCOBI (submitted),* 2014.