Volunteer occupant kinematics during driver initiated and autonomous braking when driving in real traffic environments

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Abstract

When a vehicle is braking, the occupants are subjected to longitudinal forces which may influence their positions. The aim of this paper is to quantify the driver and passenger kinematics during medium harsh braking while driving in real traffic and to identify the influencing parameters.

The overall motions were relatively small during braking and the effect of seat belt locking was obvious. Mean forward motions were 55 ±26 mm for the chest and 97 ±47 mm for the head. This study indicates that several properties influence forward motion. Taller volunteers had a larger forward motion; females had a larger forward motion than males of the same sitting height. Passengers exhibited larger motions than drivers for most of the volunteers.

The result provides a deeper understanding of pre-impact conditions and adds knowledge to further improve the interaction of active and passive safety systems. It also provides valuable validation data for low-g occupant models, which can be used in studies of the effect of pre-impact braking on restraint interaction.

Keywords: integrated safety, kinematics, pre-impact braking, volunteer

I. INTRODUCTION

For some years, crash data analyses have been made to understand the circumstances that increase the occupant injury risk in car crashes. In particular, two studies have focused on the possible interdependence of the occupants' injury outcome relative to both different occupant characteristics and occupant position in the front seat. The first study focused on seat adjustment in the vehicle [1], and the other on gender [2]. Together these studies conclude that there are differences in injury outcome depending on the combination of these factors; both mention the position relative to, and interaction with, the restraint system. Clearly, seat adjustment directly influences the initial position relative to the restraints, whereas size and gender may also indirectly influence this position since drivers, for example, generally adjust the seat to encompass a proper interaction with the pedals and the steering wheel. In addition, during the past ten years, numerous systems have been introduced in the passenger car market, which aim to reduce the velocity in an impact as well as to prepare the vehicle for the impact [3]. These systems mostly intervene when the accident is unavoidable. In the future, with even more sophisticated sensors, there could be a possibility for primary safety systems to make interventions, e.g. autonomous braking, in a critical situation even if the accident might not be considered unavoidable. In such a scenario, a medium braking would probably be preferred. Velocity reductions introduce longitudinal forces on the occupants, which may influence their positions in the vehicle and the interaction with the restraint in case of a crash. This points to the delicate task of developing adaptive restraint systems which are capable of adapting to the occupants and the situation.

To determine occupants' various positions in a passenger car several field studies have been made in both Europe [4]–[6] and the USA [7], as well as volunteer studies [8]–[10]. Moreover, numerous volunteer tests have been made to obtain a better understanding of the occupants' positions and motions in a vehicle. In some of these, the aim was to obtain the volunteers' muscle activity, tensed or relaxed, and motion as a result of low-g acceleration (from 0.2 g to 1.0 g, maximum duration 600 ms); hence they were carried out in a laboratory environment [11]–[14]. Other studies have used a driving simulator to identify what effect the drivers' actions alone, in an emergency situation, have on their postures and positions, without any applied acceleration [15]–[19]. In addition, one of these studies carried out a complementary test in a real car on a test track to determine

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driver reaction in emergency braking [18]. Further volunteer tests have been carried out in real vehicles on test tracks (but with only one or two participants): passenger kinematics and forward displacement in emergency braking [20]–[21] and driver and passenger kinematics in lateral manoeuvres [22]. Additionally, two sets of volunteer tests have been performed with a large number of volunteers, 49 persons in each, in vehicles on test tracks. In the first, the drivers' behaviours in selected emergency situations were studied. For driver initiated braking, only a very small forward displacement of the driver's torso was noted. For combined braking and steering manoeuvring, a somewhat larger forward displacement of the driver's torso was observed [23]. In the second test set, the passengers were subjected to several pre-impact manoeuvres; one of these included straight forward emergency braking. The test showed that the longitudinal stability of the volunteers during emergency braking was dependent on leg and foot location as well as the level of bracing [24].

However, to the knowledge of the authors, no study has yet been carried out that quantifies and compares the effect of braking on driver and passenger kinematics in the same test which includes both genders, different sizes and different levels of braking.

The aim of the present study is to identify the position, motion and posture change of the driver and front seat passenger of different stature, when exposed to a braking with rapid onset, either controlled by the driver or initiated by the test-leader (denoted "autonomous braking"), and also to identify the parameters that influence this motion. This work will contribute in three ways; as validation data for the adaptation of mathematical human body models in low-g acceleration; in the development of adaptive occupant protection systems; and as input to decision models for interaction between primary and secondary safety, e.g. as previously outlined [25].

II. METHODS

In this volunteer study, driver and passenger motions, as a function of both driver and autonomous braking in real traffic scenarios, were studied. The study protocol was submitted to the Ethics Board of Gothenburg with the response that no formal application was necessary.

Volunteers and vehicle setup

Seventeen volunteers were selected to match the sitting height of the HIII family [26]–[27]: eight females and nine males, from 26 to 62 years old, Table 1. Informed consent was obtained before the test was carried out. Fifteen of the volunteers were employed at Volvo Car Corporation and were registered as willing to participate in this type of study. The remaining two were from Chalmers University of Technology. All of the volunteers participated in the test during their working hours but they received no additional compensation.

Although all of the volunteers usually drove regularly, there was a large spread in their estimated yearly driving: from 800 km/year to 45 000 km/year. All of the volunteers had driven the car make before: thirteen the exact model; three a slightly larger model; and one a somewhat smaller model. The volunteers wore light indoor clothing during the test drives and markers were placed on anatomical landmarks of interest: a film target close to the ear, in the Frankfurt plane, with marker centre about 35 mm from the auditory duct; black cross markers on the side of the forehead and the cheek; and a T-shaped holder with a film target on the upper part of the sternum Figure 1(b-c). The positions of these markers were recorded. The T-shaped holder for the thorax film marker placed the marker centre 30 mm in front of the thorax, Figure 1(b-c). No sensors were used and no instructions were given regarding the behaviour (tensed or relaxed), since the aim was to reproduce normal driving. Two interviews were conducted with all participating volunteers, one immediately after the test and one follow up interview.

For this study a Volvo XC60 with automatic gearbox was used. All Volvo XC60s are equipped with a built in safety system, usually referred to as City Safety [28] which can avoid or mitigate low speed rear-end collisions by automatically applying the brakes. In the test vehicle this system was controlled by a separate laptop, denoted Autonomous braking in Figure 1(a), to allow the test leader to initiate brake activations.

Several film targets were mounted on the vehicle interior and their positions were registered by a 3-D system (FARO arm). The vehicle was equipped with two small video cameras to obtain side views of both the driver and the passenger, and a computer to collect the vehicle data and the video films, Figure 1(a-c). An extra camera to film the driving scenario and an extra rear-view mirror for the test leader were also installed.

TABLE 1

The characteristics of the volunteer groups as well as the individuals' characteristics and their differences in seating height as compared with representative Hybrid III dummies (HIII). Group A: small females, sitting height close to the HIII 5th percentile female dummy; Group B: large females, sitting height close to the HIII 50th percentile male dummy; Group C: midsize males, sitting height close to the HIII 50th percentile male dummy; Group D: large males, sitting height close to the HIII 95th percentile male dummy;

Volunteer groups	Gender	Stature (cm)	Weight (kg)	Sitting height (mm)	Age (years)	Deviation from the dummy's sitting height (mm)
A: F-5F	Female	155.0 ±0.8	54.3 ±4.9	817.8 ±7.3	43.8 ±8.3	30.8 ± 7.2
F-5F-1	Female	155	54	820	52	33
F-5F-2	Female	156	48	823	34	36
F-5F-3	Female	154	60	821	49	34
F-5F-4	Female	155	55	807	40	20
B: F-50M		168.0 ±4.1	68.0 ±5.4	879.8 ±0.5	42.8 ±2.4	-4.3 ±0.5
F-50M-1	Female	165	75	880	46	-4
F-50M-2	Female	174	62	880	41	-4
F-50M-3	Female	166	67	880	41	-4
F-50M-4	Female	167	68	879	43	-5
C: M-50M		174.8 ±6.8	77.8 ±10.5	888.5 ±5.2	56.3 ±6.8	4.5 ±5.2
M-50M-1	Male	171	87	893	62	9
M-50M-2	Male	187	91	892	62	8
M-50M-3	Male	171	62	886	46	2
M-50M-4	Male	171	73	880	62	-4
M-50M-5	Male	179	80	893	55	9
M-50M-6	Male	170	74	887	51	3
D: M-95M		177.0 ±1.7	72.0 ±8.2	937.0 ±24.0	29.7 ±3.5	17.0 ±24.0
M-95M-1	Male	178	81	964	33	44
M-95M-2	Male	178	65	918	30	-2
M-95M-3	Male	175	70	929	26	9
Hybrid III						
5th Female	–	148	50	787	–	–
50th Male	–	175	78	884	–	–
95th Male	–	185	101	920	–	–

Test procedure

Before the test started, the volunteers were informed about the purpose of the test and that the test leader could initiate autonomous brakings when that would be safe in the traffic situation. In addition, the driver was asked to brake hard unexpectedly, at times during the test drive. The driver was asked to adjust the seat and the steering wheel; after each test drive the positions of the seat and steering wheel were recorded. In contrast, the passenger was requested not to adjust the seat. The occupants were restrained by the standard vehicle seat belt locking at a vehicle deceleration of 0.5 g.

The test drives were carried out on ordinary roads, with speed restrictions from 30, to 90 km/h, in the day time, but rush hour was avoided. They were conducted in sets of two, allowing the volunteers to switch places, each part lasting for about 25 minutes with an accommodation time of 5 – 10 minutes.

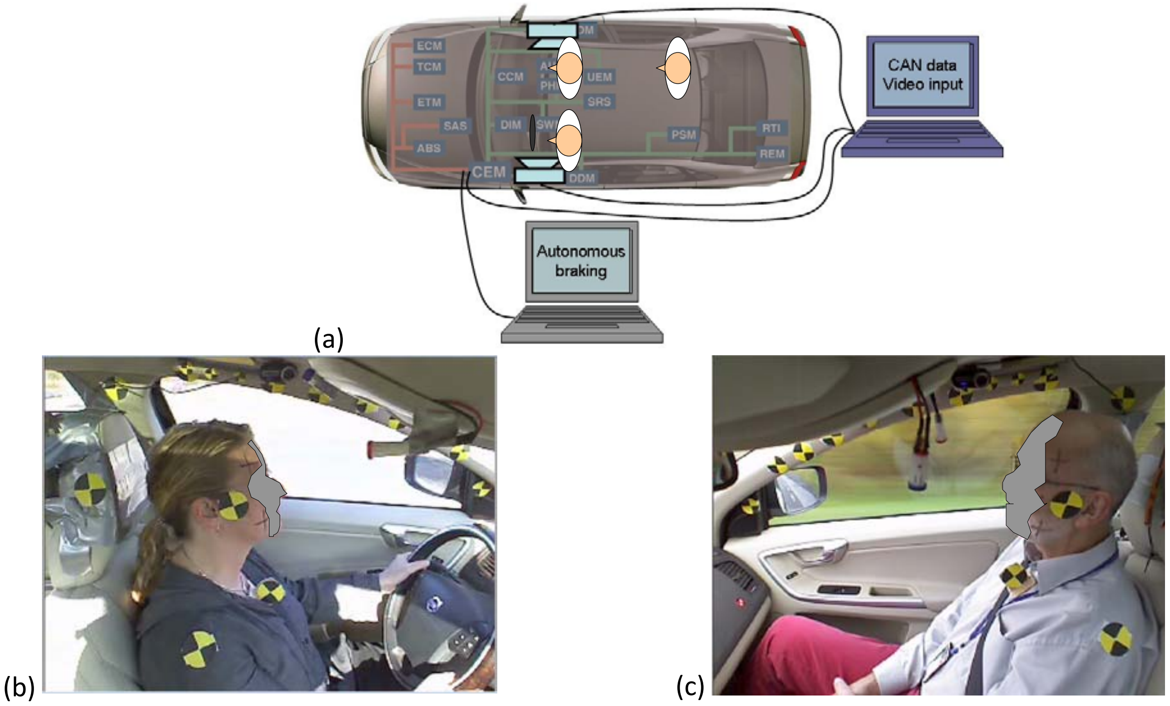


Figure 1. Principal test setup of the vehicle.: (a) Vehicle instumentation incl. driver, passenger and test leader positions; (b) Camera view of the driver; (c) Camera view of the passenger.

Three levels of autonomous braking were designed, medium braking with as quick onset rate as possible by the brake system with steady-state target acceleration of -3, -4 and -5 m/s^2. These braking levels have a set duration of 1.4 s. During each test drive at least two autonomous braking events per level were initiated by the test leader. The minimum values of the resulting longitudinal acceleration of the vehicle were: -4.68 ±0.34 m/s^2 for a level of -3 m/s^2, -5.69 ±0.33 m/s^2 for -4 m/s^2 and -6.73 ±0.40 m/s^2 for -5 m/s^2. The jerk, the derivative of the acceleration, was -19 m/s^3, Figure 2(a). A subset of the driver-initiated brakings, matching the characteristics of the -5 m/s^2 autonomous braking was chosen for further analysis, Figure 2(b).

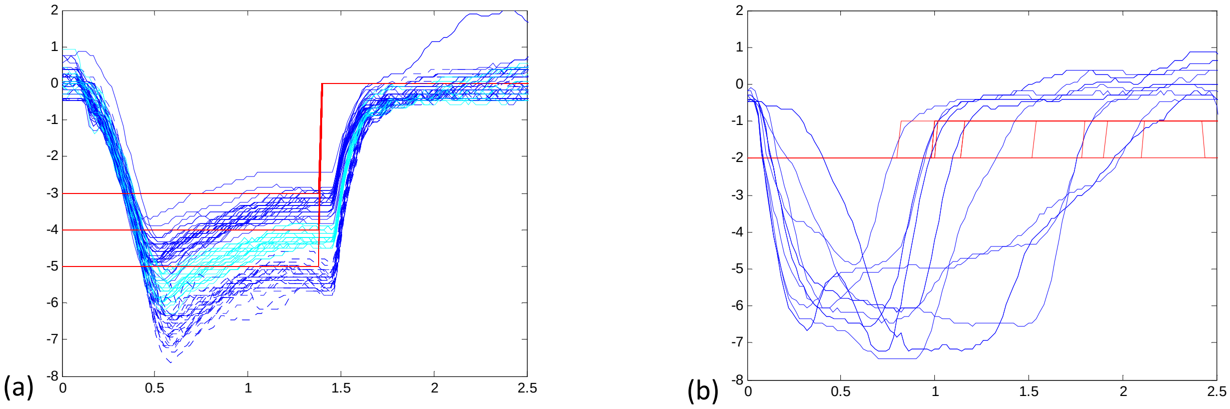


Figure 2. Recordings of the vehicle's longitudinal acceleration [m/s^2].: (a) The requested autonomous braking in red (-3, -4 and -5 m/s^2) and the vehicle's corresponding acceleration (dark and light blue); (b) Driver brakings that all had a maximum deceleration comparable to the autonomous braking level -5 m/s^2.

Data acquisition, processing and analysis

The vehicle data network includes fundamental information about the vehicle: speed, lateral acceleration, yaw rate, steering wheel angle and brake pedal status. It also includes information from the systems in the vehicle, e.g. brake pressure and the time at which the test leader activated the brake system. This information, together with the films from two video cameras (Philips SPC2050NC, 240 x 320 pixels, 60 fps) [29], was recorded time synchronized with a time stamp accuracy of 2 µs, using the vehicle measurement system CANape7.0 [30]. All vehicle signals were exported from CANape to MATLAB [31]. The film analysis was carried out using TEMA v3.12 [32] and then exported to MATLAB for further data analysis.

To compensate for the position of the cameras, different distances between the various photo targets and the cameras, downward angles, and the effect introduced by the use of two wide-angle lenses, a reference grid was printed and positioned in the appropriate planes inside the vehicle. Four reference images were captured by the video cameras, corresponding to the planes of ear and thorax motion in both driver and passenger seat. Based on these data and by using TEMA and the MATLAB image toolbox, four image transformation functions were developed to translate the pixel values for the film targets to "true positions" in the vehicle. This process yielded a very small resultant average error for the four main functions, the head and thorax film target areas of the driver and the passenger, less than 0.9 mm. For the analysis of the driver's position and motion relative to the steering wheel centre an additional image transformation was developed, which had a resultant average error of 2.40 mm, since this covers a larger area of the interior.

All coordinate systems have the reference for a positive x value in the forward direction of the vehicle and the reference for positive z value in the upward direction. Head and thorax film data were expressed with the origin of coordinates, set to the initial position of the ear and the thorax markers, for each volunteer. For the analysis of the driver's position and motion relative to the steering wheel centre, the origin of coordinates was set to the steering wheel centre. To study the head angle, the markers at the volunteer's ear, forehead and cheek were used to define two vectors, ear- forehead and ear- cheek. Either of these vectors was used in the analysis according to the visibility in the films.

In total 90 autonomous brakings were analyzed, giving video data for 55 driver and 82 passenger motions. In addition, 24 driver brakings were analyzed, giving data for 15 driver and 20 passenger motions, Appendix 1.

III. RESULTS

The volunteers' motions during the autonomous braking were captured by markers at the ear, forehead, cheek and thorax. The drivers' initial positions and trajectories during the autonomous brakings, for the ear and thorax markers relative to the steering wheel centre, are shown in Figure 3. Initial positions for the thorax markers varied within 200 mm; the variation of the ear markers' positions was 300 mm, Figure 3(a). The most rearward start position was for a 50th percentile male, while the most forward position of a thorax marker was a female of the same sitting height. This exemplifies that drivers adjust the seat to the steering wheel to match not only their size, but also their personal preferences and habits. The trajectories for all analyzed brakings are presented in Figure 3(b).

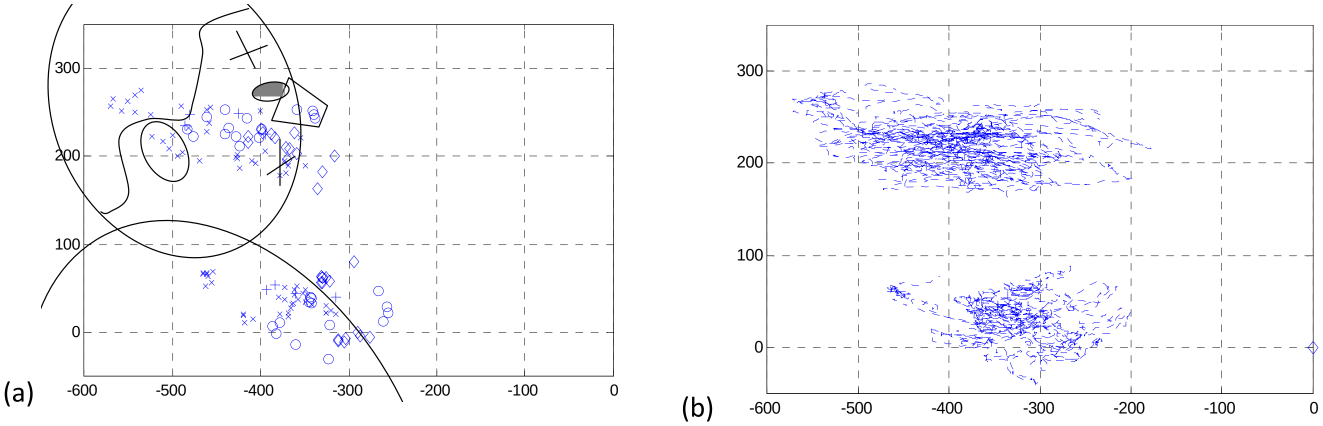


Figure 3. Driver ear and thorax marker relative to the steering wheel center in all analyzed autonomous brakings. [mm]: (a) Startpositions (o:F-50M, ◊:F-5F, x: M-50M, +: M-95M); (b) Trajectories

During autonomous braking the volunteer's torso was effectively restrained by the seat belt after about 500 ms from the initiation of the braking while the head continued forward. Maximum forward head displacement occurred at about 600 ms, Figure 5 which was the time for maximum vehicle deceleration, Figure 2. During this braking phase, the head angle appeared to oscillate within a few degrees from initial head angle for most volunteers, Figure 4(a-b). For a majority of the volunteers a flexion angle was apparent; slight for the drivers and more pronounced for the passengers, Figure 4(a-b). After a while some of the volunteers moved their heads slowly backwards. When the brake was released, the torso's rebound phase started, head and torso moving as one unit. When the torso reached the seatback, the head continued to rotate rearward and induced neck extension.

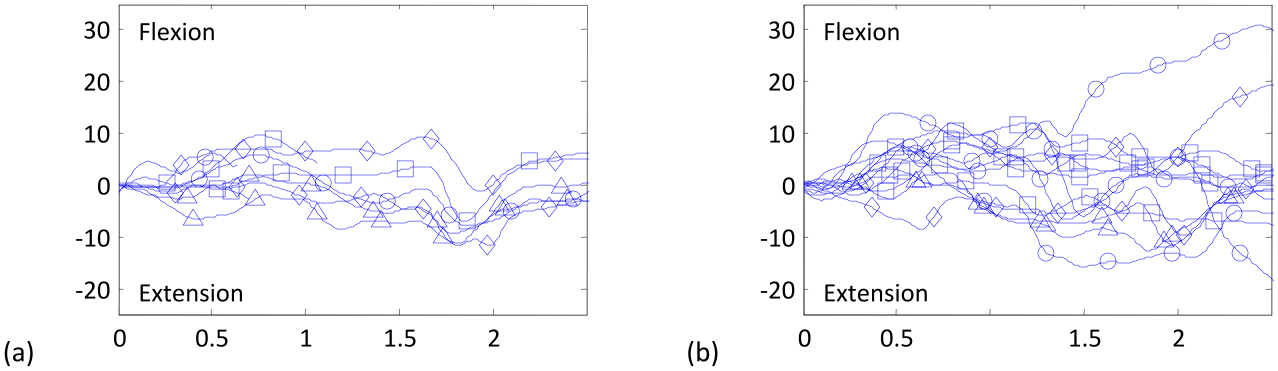
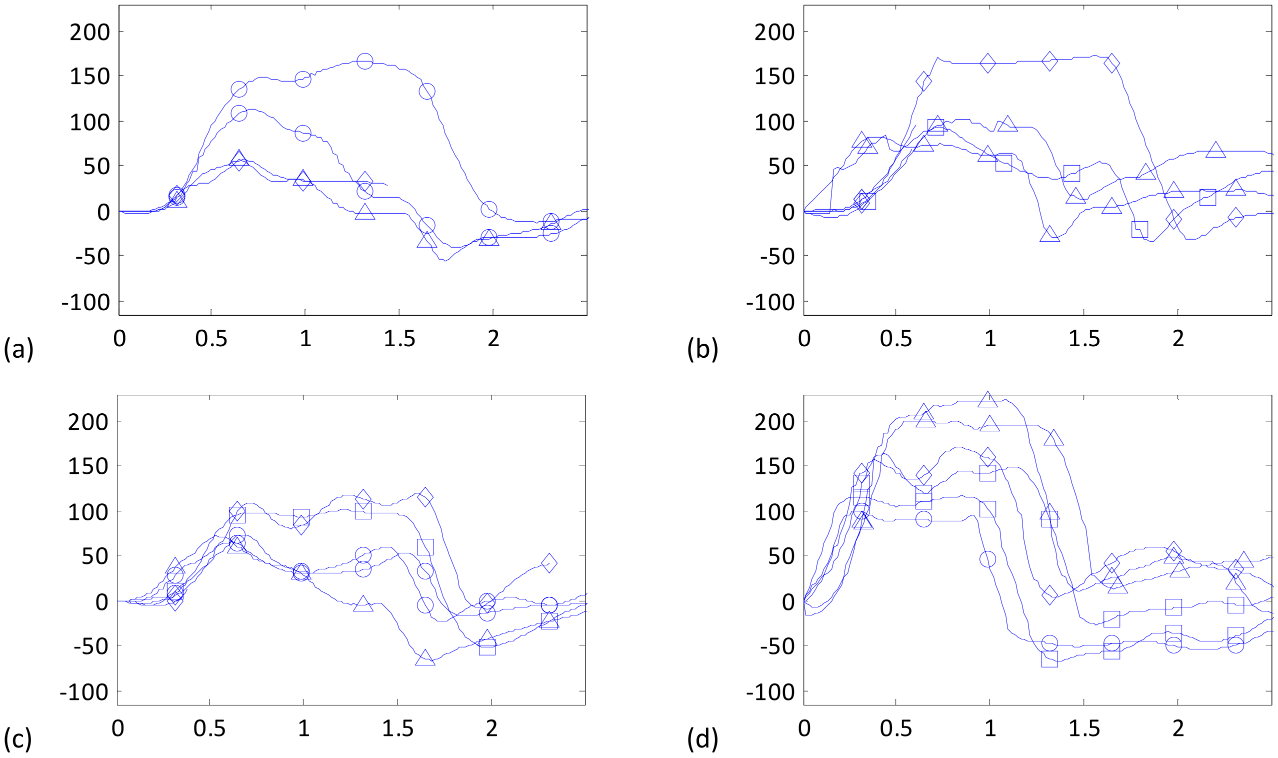


Figure 4. Change of head angle, filtered by CFC60, for volunteers in group C: M-50M when subjected to autonomous brakings of -5 m/s^2 [degrees]: (a) Driver position; (b) Passenger position

Figure 5 presents the analysis of volunteer forward motions of the ear marker during autonomous brakings of -5m/s^2 in both driver and passenger positions. The change of head angle (head rotation) during this motion was mostly within +/- 10 degrees, but in a few cases it exceeded +/- 20 degrees. The motions for the individual volunteers were relatively repeatable for the same deceleration and in the same position, as illustrated in Figure 5 by the curves for individuals in the different volunteer groups. The spread in forward motion for the autonomous brakings was smaller in the driver position than in the passenger position for the two volunteer groups of the same sitting height, Figure 5(c-d) and (e-f). However, this was not obvious either for the large males in Figure 5(g-h) or for the small females, Figure 5(a-b). The female volunteers seemed to experience a larger forward motion than the males of the same size, Figure 5(e-c) and (f-d). Furthermore, males and females of the same sitting height seemed to have a different motion pattern in driver, Figure 5(e-c) as well as passenger, Figure 5(f-d) positions. The forward ear motion of the male volunteers seemed to follow the deceleration pulse, with only a short time at the turning-point, whereas the females stayed in the most forward position for a longer period, until the brake released. Comparison of these females' motion patterns for three decelerations showed that at the deceleration of -3 m/s^2 some, but not all, of the individual forward ear motions seemed to follow the deceleration pulse, which is similar to the behaviour of the male volunteers.



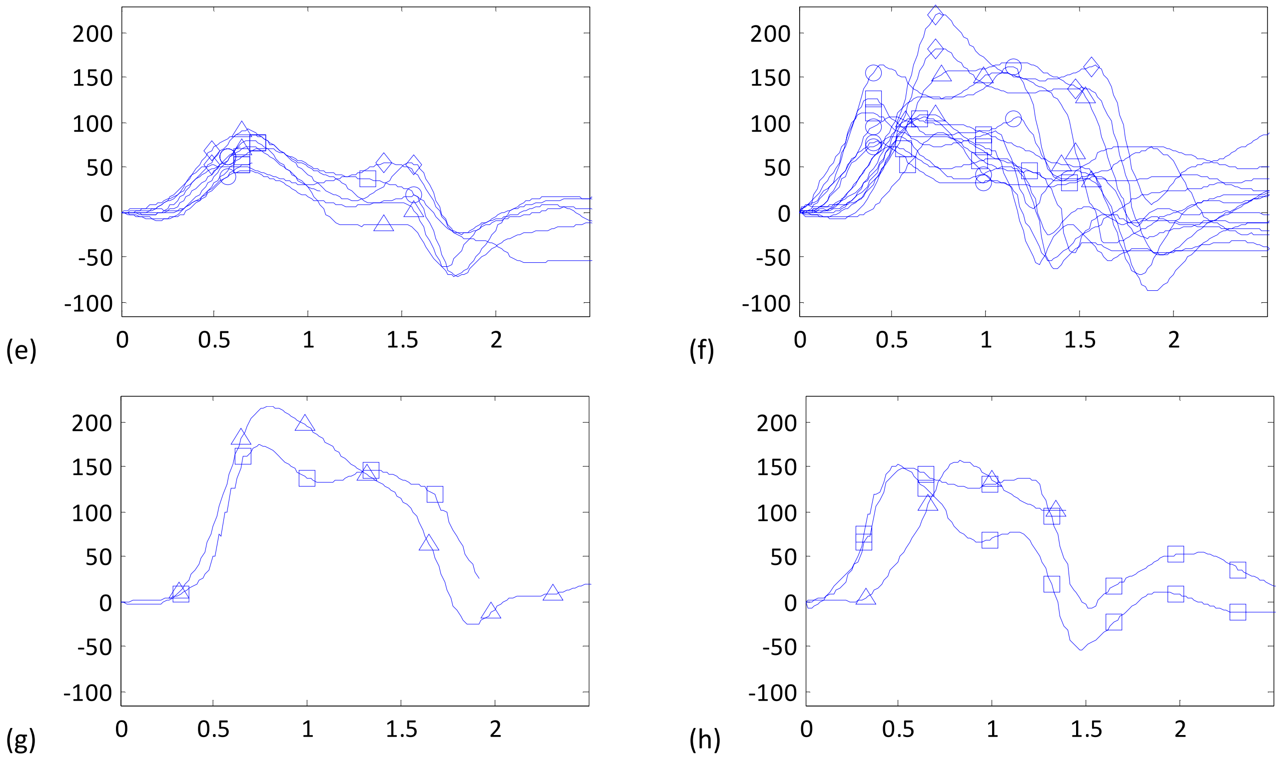


Figure 5. Forward motions of the ear-marker of the volunteers in the four volunteer groups in the two positions when subjected to autonomous brakings of -5 m/s^2 [mm]. For each individual, a specific marker is used: (a) Group A, F-5F, Driver; (b) Group A, F-5F, Passenger; (c) Group B, F-50M, Driver; (d) Group B, F-50M, Passenger; (e) Group C, M-50M, Driver; (f) Group C, M-50M, Passenger (g) Group D, M-95M, Driver; (h) Group D, M-95M, Passenger

When the drivers did the braking themselves, the motions of their ear markers were very small and in one case even negative, Figure 6(a), and the change of head angle was smaller than for autonomous braking of the similar deceleration. Still, the passengers experienced comparable forward motions for comparable braking levels, independent of the source of the braking, Figure 5(f)-Figure 6(b) and Figure 5(d)-Figure 6(c).

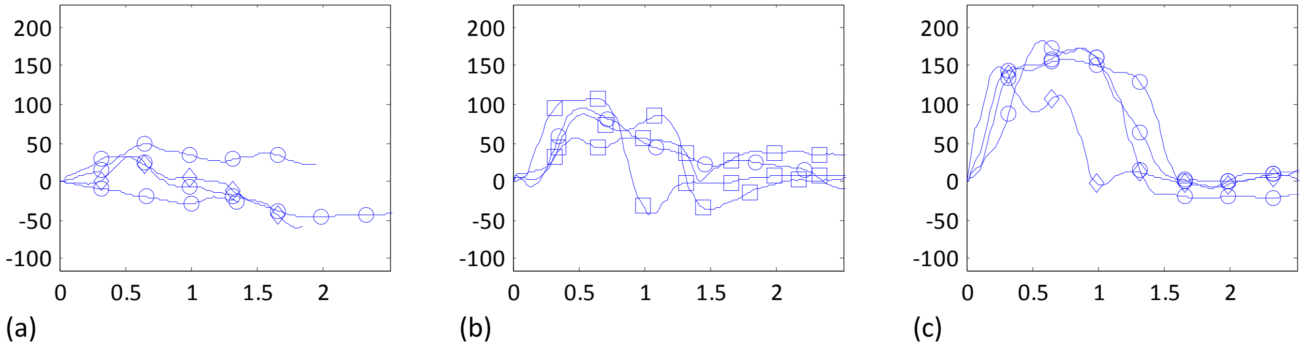


Figure 6. Forward motions of the volunteer ear-markers in the two positions, subjected to driver braking with maximum deceleration comparable to the 5 m/s^2 autonomous braking [mm]. For each individual, a specific marker is used: (a) Group C, M-50M, Driver; (b) Group C, M-50M, Passenger; (c) Group B, F-50M, Passenger

For each volunteer the mean value of the forward displacement was calculated for each autonomous braking level, followed by calculation of the mean value for each volunteer group, presented in Figure 7 and Appendix 2. The volunteer groups' mean forward excursion of the ear marker in the three braking situations varied from 19 mm for the small female to 197 mm for the large male. The variation in the thorax motion was smaller, from 20 mm to 82 mm. The overall mean forward motion for the volunteer groups was 52 mm for the thorax marker and 97 mm for the ear marker. All of the volunteer groups experienced a larger forward excursion in the passenger seat than in the driver seat, except for the group of large males. Also, the taller volunteer groups had a larger forward motion of the ear marker than the smaller ones of the same gender, Figure 7 (Group B vs. Group A and Group D vs. Group C). This difference was even more pronounced when comparing the forward motion between the large males and the small females, Figure 7 (Group D vs. Group A). The female volunteer group experienced a larger forward displacement of the ear marker than the male volunteer group with the same sitting height in both positions and all deceleration levels, Figure 7 (Group B vs. Group C). Furthermore, the vehicle deceleration appeared to affect the posture change. The forward motion was the smallest at the level of -3 m/s^2 and the largest at the level of -5 m/s^2 for three of the volunteer groups in the passenger position Figure 7 (Group B, C and D), although the same behaviour did not occur for the driver position. The small females had another motion pattern with a minimum at the deceleration level of -4 m/s^2; this behaviour was consistent for both ear and thorax markers in both driver and passenger positions, Figure 7.

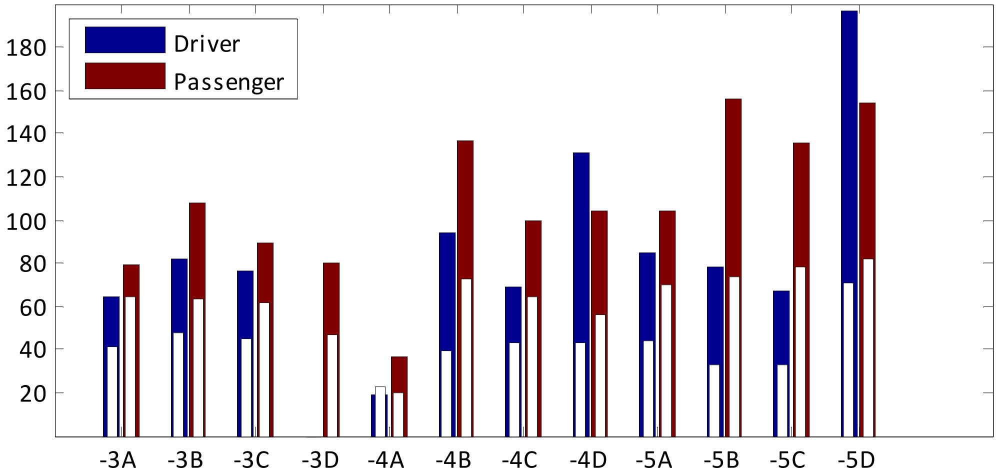


Figure 7. The mean forward motion for the four volunteer groups, when exposed to the three levels of autonomous brakings (-3, -4 and -5 m/s^2) [mm]. The ear marker's forward motion is illustrated according to the legend, and the corresponding thorax displacement is shown by a white bar. The volunteer groups: Group A:F-5F, Group B: F-50M, Group C:M-50M, Group D:M-95M.

The motion at the first braking was compared with the motions at later brakings of the same level in order to study the occupants' becoming accustomed to the autonomous brakings, Figure 8. Of three passenger motions analyzed, two passengers had a smaller forward displacement of the ear marker in the first autonomous braking, but the third one had the opposite behaviour. The variation is less than the inter-subject variation for these volunteers, Figure 8(b). In comparison, one driver's forward motions of the ear marker in brakings two and three are very different from each other. In the second braking the forward motion was somewhat larger, but in the third braking it was clearly smaller, Figure 8(a).

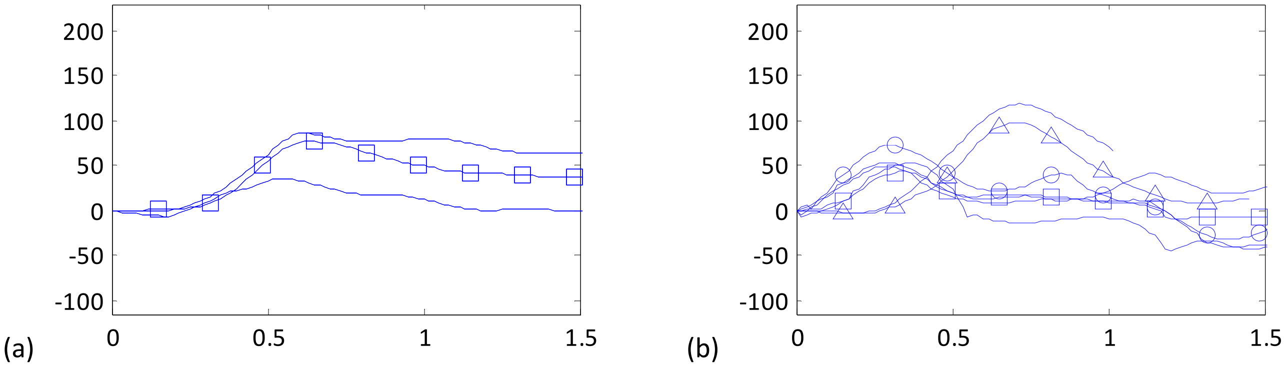


Figure 8. The forward motion of the ear marker during the first -3 m/s^2 autonomous braking (showed by markers) and later brakings of the same deceleration (solid lines): (a) One driver, M-50M-1; (b) Three passengers: M-50M-2: ○, M-95M-1: □ and M-95M-3 Δ.

Even if the study does not find any accommodation in the physical motion, it was noted that the occupants reacted with great surprise at the first autonomous braking but not for the succeeding ones. Still, the drivers reacted by checking the rear-view mirror at almost every braking. In addition it was found that in 12% of the autonomous brakings analyzed, the driver braked during or immediately after this event, Table 2.

TABLE 2

Count of driver brakings with immediate timing to the autonomous brakings.

Autonomous braking		Count of driver actions		Driver
Level	Number of	No action	Braking	braking
- 5 m/s2	33	29	3	9%
- 4 m/s2	24	20	2	8%
- 3 m/s2	36	30	6	17%
Total :	93	79	11	12%

IV. DISCUSSION

When a vehicle is braking, the occupants are subjected to longitudinal forces which may influence their positions. The aim of this study is to quantify drivers' and passengers' positions and kinematics during medium harsh braking while driving in real traffic and to identify the influencing parameters.

As the drivers were asked to adjust the seat and steering wheel to suit their preferred sitting posture, the start positions of the ear and thorax are relatively varied. This variation is clearly not only size dependent but also an effect of the individuals' habits, as suggested also by others [5]–[7]. For this reason the results are presented in two coordinate systems: the seat frame and a frame that has its origin in the initial position of the ear and thorax markers. The former presents the distance to the interior of the vehicle and the restraint in case of a crash. The latter presents the volunteer response to longitudinal vehicle decelerations and could be used to assess mathematical models of the human, used in the development of integrated safety systems.

Earlier volunteer studies have shown the effect of muscle activity, relaxed or tensed, on the volunteers' motion when exposed to accelerations [11]–[14]. In this study the volunteers were not given any instructions about being tensed or relaxed, in order to reproduce normal driving, but of course the volunteers were aware of the test situation and reacted to it. One of the volunteers clearly stated that he tried to be as relaxed as possible; consequently, he had a larger forward motion than the others. This was a large male with the initial most forward thorax position of the males; he also exhibited the most forward position of the ear marker.

The average motion of the volunteers due to the autonomous braking was relatively small and was found to be related to the amplitude of the vehicle deceleration applied. This was apparent until the seat belt locked and restrained the chest, which had then moved about 5 cm (mean value). When the seat belt had locked, the head continued its forward motion, having a total forward motion of about 10 cm (mean value) at the turning-point; thereafter, the head moved rearward. When the brake was released the chest and the head rebounded rather quickly. For most of the volunteers the change of head angle during this whole motion was less than 10 degrees in extension and flexion, only in a few occasions it exceeded 20 degrees. Most of the volunteers exhibited a flexion motion at the rebound. This head angle did not increase monotonically during the event; the head angle data indicate that the occupants tried to balance the head, possibly to keep the line of sight.

The data show that most of the volunteers exhibited a larger forward motion in the passenger seat than in the driver seat. This could be due to a variety of reasons, mental as well as physical. The driver is likely to be more mentally active and aware of the situation, being responsible for the driving task and, as such, to react faster than the passenger. As a consequence of the driving task, the muscle activation level was probably higher for the average driver than the passenger and could, in conjunction with the fact that the driver has a steering wheel to be used for bracing, influence the forward motions. In addition, the drivers were asked to adjust the seat and steering wheel. As the passengers were asked not to change the seat adjustments, their positions were not optimized to the seat belt or the footrest. However, studies of real life driving [7] and epidemiology [1] show that it is relatively common that the passenger does not adjust the seat position. In addition, the results also show that size affects the forward motion; taller volunteers exhibit a larger motion than smaller ones of the same gender. More surprisingly, gender appeared to affect the peak forward motion. Females had larger forward displacements than males of the same size, and they remained in the forward position for a longer period, in most of the situations until the brake released. Finally, the vehicle deceleration affects the posture change, so that the forward motion is the smallest at the level of -3 m/s^2 and the largest at the level of -5 m/s^2

for three of the volunteer groups. One group deviated from this pattern, the small females, with a minimum at the level of -4 m/s^2. This could be an effect of the volunteers' weight and the seat belt locking properties.

Predictably, the drivers' motions when performing a quick and hard braking themselves were extremely small, since they were obviously prepared for the deceleration forces. On the other hand, the passengers experienced forward motions similar to those in the matching autonomous braking.

In all volunteer tests some sort of accommodation is expected. In this study the occupants reacted with great surprise at the first autonomous braking but not for the succeeding ones, which indicates an accommodation, even if the study does not find any accommodation in the physical motion. Still, during autonomous braking the drivers continued throughout the test series to look through the rear-view mirror.

Although the study contained a limited number of volunteers, the narrow selection of consistent sizes supports representative results for these sizes. Cameras were used to study the motions of the volunteers, which introduced the need of compensation for errors due to: different distances to the film targets; cameras mounted non-perpendicular to the plane of motion and wide angle lenses. More advanced measurement systems could possibly give more detailed information. The method, to first calculate each volunteer's mean forward displacement in the different situations and, based on this, to calculate the volunteer groups' mean forward displacement, does not yield any good statistical measures, however it was chosen because it allows every volunteer the same impact on the result. Finally, although this paper presents a relatively simple test method, it was shown to be useful, and it could probably be implemented in other studies.

While this paper illustrates some of the individual parameters that influence an occupant's motion when subjected to an autonomous braking, it does not determine whether there is one parameter that is predominant. To achieve this, a test with more volunteers would be needed. Still, seat belt performance is shown to be one of the key parameters. Finally, this study provides valuable validation data for low-g occupant model development and for studies of the effect of pre-impact braking on restraint interaction.

V. CONCLUSIONS

In the future, integrated safety systems will intervene in critical situations that could lead to a crash, one possible action being medium autonomous braking. When a vehicle is braking, the occupants are subjected to longitudinal forces which may influence their positions. In the present study, driver and front seat passenger volunteers were exposed to low-g longitudinal decelerations with rapid onset in a production vehicle on ordinary roads. The study compares the effect of these medium autonomous brakings on driver and passenger kinematics and includes genders, different sizes and different levels of braking.

The observations in this study indicate that several properties seem to influence the forward motion: size and gender of the volunteers, the position either in the driver or passenger seat, the vehicle deceleration and seat belt properties. First, the taller volunteers had a larger forward motion than shorter ones of the same gender, while females had a larger forward motion than males of the same sitting height. Second, for most of the volunteers, the forward motion was larger in the passenger seat than in the driver seat, with exception of the large males. Third, most of the volunteers had the smallest forward motion at the lowest of the three deceleration levels, with the exception of the small females who had the minimum of forward motion at the midlevel of the applied brakings.

The overall motion is relatively small and the effect of seat belt locking is obvious, with a mean forward motion of the chest of only about 5 cm and a mean forward motion of the head of about 10 cm. The head rotation is relatively small during the braking, with a maximum when rebound occurs. Surprisingly, some females not only experienced a larger forward motion than comparable males, but also seemed to stay in the forward position for a longer period.

The results give a deeper understanding of pre-impact conditions and add knowledge for further improving the interaction of active and passive safety systems. It also provides valuable validation data for low-g occupant mathematical human body model development to study the effect of pre-impact braking on restraint interaction.

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VIII. APPENDICES

APPENDIX 1

Number of films analyzed for autonomous and driver initiated brakings in driver and passenger positions. The number of volunteers in brackets.

Volunteer group	Position	Autonomous braking, requested deceleration level			Driver braking, comparable to
		-5 m/s^2	-4 m/s^2	-3 m/s^2	-5 m/s^2
A. F-5F	Driver	4 (3)	1 (1)	3 (2)	7 (3)
A. F-5F	Passenger	6 (3)	1 (1)	2 (2)	3 (1)
B. F-50M	Driver	6 (4)	2 (2)	4 (3)	4 (3)
B. F-50M	Passenger	6 (4)	9 (4)	9 (4)	7 (4)
C. M-50M	Driver	10 (4)	6 (5)	15 (6)	4 (2)
C. M-50M	Passenger	15 (5)	6 (4)	13 (5)	6 (3)
D. M-95M	Driver	2 (2)	2 (2)	0	0
D. M-95M	Passenger	3 (2)	5 (2)	7 (3)	4 (2)

APPENDIX 2

Mean forward motion of ear and thorax markers for the four volunteer groups in driver and passenger positions, when exposed to three levels of autonomous brakings.

Volunteer group	Position	Autonomous braking, requested deceleration level					
		-5 m/s^2		-4 m/s^2		-3 m/s^2	
		Ear	Thorax	Ear	Thorax	Ear	Thorax
A. F-5F	Driver	85	44	19	23	64	41
A. F-5F	Passenger	104	70	37	20	79	64
B. F-50M	Driver	78	33	94	39	82	48
B. F-50M	Passenger	156	74	137	73	108	63
C. M-50M	Driver	67	33	69	43	76	45
C. M-50M	Passenger	136	78	100	64	89	62
D. M-95M	Driver	197	71	131	43	--	--
D. M-95M	Passenger	154	82	104	56	80	47