The influence of crash pulse shape on seat-occupant response in rear impacts

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Abstract - In road traffic accidents, a car-seat and its occupant can be subjected to various crash pulses in the case of a rear impact. This study investigates the influence of crash pulse shape on seat-occupant response and evaluates the corresponding risk of whiplash injury. For this purpose, a rigorously validated seat-occupant system model is used to study different car-seat designs and crash pulses. Two different car-seat concepts are also presented which can effectively mitigate whiplash injury for a wide range of crash severity. It is shown that for crash pulses of similar severity, the level of whiplash-risk depends strongly on the combined effects of seat design and crash pulse shape.

NOTATION

a_{mean}	mean acceleration
a_{peak}	peak acceleration
AWD	anti-whiplash device
Fsh	largest *OC*-shear-force
g	gravitational acceleration
G	the inertial coordinate system
HR	the typical-head-restraint model attached to all seats
HrCt	head restraint contact time
IIWPG	International Insurance Whiplash Prevention Group
IWG	IIWPG standard crash-pulse
IT	injury threshold value for NIC
JARI	Japan Automobile Research Institute
L, *M*	upper limits of *Fsh* for low and moderate neck-forces respectively
NIC	neck injury criterion
OC	occipital condyles or upper neck
OF	the outer-seatback-frame in RFWMS
P	translational AWD
R	rotational AWD of ROWMS and WMS, at the recliner
R^+	rotational AWD of RFWMS, at the recliner
$R*$	rotational AWD of RFWMS, connecting *OF* to the seatback
R^	the recliner joint of RONB
RFWMS	whiplash-mitigating car-seat concept with the inner-frame
RL	recommended limit for *HrCt*
RONB	the car-seat concept similar to a typical car-seat
ROWMS	a modified version of WMS
T1	the first thoracic vertebra
WMS	whiplash-mitigating car-seat concept
ΔT	duration of crash pulse
ΔV	change in the velocity of a vehicle subjected to a crash pulse

INTRODUCTION

The term “whiplash” is used to describe neck injuries (or disorders) in which the sudden differential movement between the head and torso, leads to damage of soft tissue in the neck. The highest risk of sustaining whiplash injury has been found to occur in rear-end crashes [1,2]. A common cause of whiplash is the formation of S-shape-like deformation in the neck due to retraction of the head (i.e. occipital condyles (*OC*)) relative to the upper torso (i.e. the first thoracic vertebra (*T1*)), as shown in Figure 1(a). The annual economic cost of whiplash injury has been estimated to be \$8.2 billion in the US [3] and £1.2 billion in the UK [2].

A head restraint with good stiffness and energy absorbing characteristics, positioned at the right height and with a small backset distance, would significantly decrease whiplash risk in rear-end crashes. However, research has shown that seats with good static head-restraint geometry do not always offer good protection dynamically [3,4]. In order to decrease whiplash risk, the head restraint must work in unison with the seat throughout the impact, providing early head support and reducing sudden differential movement between the head and the torso.

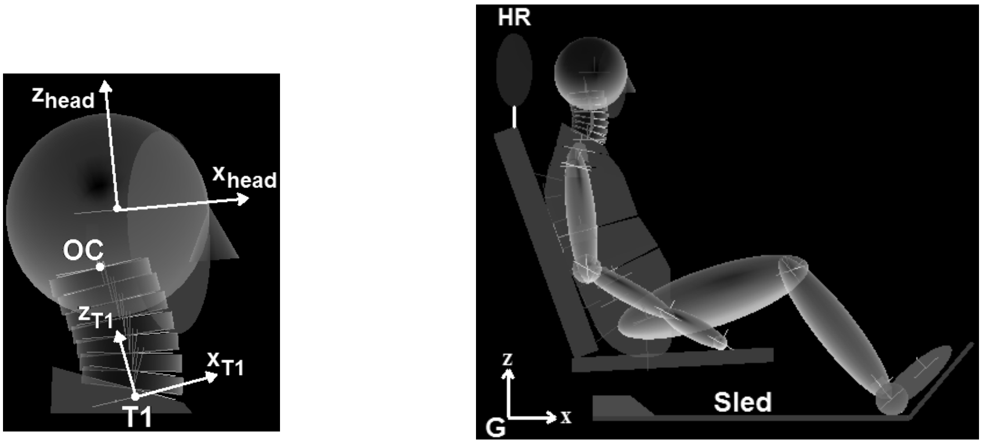
Statistically, whiplash is considered as a low-speed rear-impact injury. According to recent road-traffic accident data representing European rear-end crashes, single rear-impacts with almost full overlap (50% to 100%) represent the most common rear-impact configuration [5]. The data indicates that in single rear-impacts, 77% of the cars receive a ΔV lower than 15 km/h, 16% receive a ΔV between 15 and 25 km/h and 7% receive a ΔV higher than 25 km/h. (In accident analysis, the term ΔV is typically used to classify crash severity, and it is defined as the area under the acceleration-time curve of the struck vehicle over the course of the impact). It has been found that the highest risk of sustaining whiplash, occurs for a ΔV between 9 and 20 km/h. The risk of long-term (over one month) disablement due to whiplash, becomes significant for a ΔV between 13 and 27 km/h [5,6].

The crash pulses that a car-seat and its occupant are subjected to, can vary considerably in rear impacts depending on several factors such as the engagement level of the bumpers of the crash partners (e.g. override, underride, bumper-to-bumper), the degree of overlap, impact speed, the stiffness and the structure of the crash partners, the mass ratio and the type of energy absorbing element fitted to the bumper (e.g. crash-box, crushing pipe, hydraulic damper) [7-9]. Hence, for a complete seat-design and rear-impact whiplash assessment, one should consider a variety of crash pulse shapes and severities.

A SEAT-OCCUPANT SYSTEM FOR REAR IMPACT SIMULATION

A biofidelic seat-occupant system involving a 50th-percentile male multi-body human model, as shown in Figure 1(b), was developed using MSC VisualNastran-4D with Matlab-Simulink; and validated using the responses of seven healthy 50th-percentile male volunteers from the Japan Automobile Research Institute (JARI) sled tests [10,11]. The human model is composed of rigid bodies connected by rotational springs and dampers; and it successfully satisfies the rear-impact dummy biofidelity evaluation criteria [12]. The initial configuration of the human model, as shown in Figure 1(b), corresponds to the normal driving posture of a 50th-percentile male who is relaxed and unaware of the timing of the impact.

In validating the human model, the rigid-seat used in the JARI sled tests was modelled first and a contact model was developed to simulate the interaction of the human-body segments with the rigid seat surfaces. Based on the JARI rigid-seat, a generic multi-body car-seat model was developed at the same time to implement various energy absorbing devices, seatback, head restraint and recliner properties. A typical head-restraint (*HR*), attached to the seatback as shown in Figure 1(b), is also included in the seat-occupant system model. The seat model is able to simulate the mechanical function of a typical seatback foam and suspension. The developed seat-occupant system model helps to economically simulate different rear-impact scenarios and facilitate “what-if” tests [4].



(a) (b)

Figure 1. (a) S-shape-like deformation, (b) The seat-occupant system model

WHIPLASH-MITIGATING CAR-SEAT CONCEPTS

A typical car-seat is composed of a head restraint (*HR*), a seatback, and a seat-pan, as shown in Figure 2. In a typical car-seat, the recliner attaches the seatback to the seat-pan. The recliner is a mechanism that remains locked during normal daily use. When a rear impact occurs, the structure of the recliner mechanism deforms and this causes the seatback to rotate backwards with respect to the seat-pan. The rotation of the seatback can be coupled with some translational deformation at the recliner and at the base of the seat-pan. However, the dominant or typical mode of deformation is the rotation of the seatback around the rotation-centre of the recliner mechanism.

Using the seat-occupant system model, two different whiplash-mitigating car-seat concepts, namely WMS and RFWMS, were developed [4]. As shown in Figure 2, WMS and RFWMS are different than a typical car-seat as they employ anti-whiplash devices (AWDs) which control the relative motion between the structural members of the seat, to provide effective whiplash mitigation for a wide range of crash severity. Using these AWDs, a typical car-seat can be transformed into a seat which can offer improved protection in rear impacts. The AWDs, which are denoted by R, R^*, R^+ and P, are passive energy-absorbing devices composed of nonlinear spring-and-damper units and they become operational, only when the corresponding breakaway forces and/or torques are exceeded.

In WMS, the rotational anti-whiplash denoted by R is positioned at the recliner and it enables the seatback to rotate with respect to the seat-pan. The translational anti-whiplash device denoted by P is placed under the seat-pan and it permits the whole seat to translate backwards a short distance during rear impact.

The main difference between RFWMS and WMS is that in RFWMS, the seatback (which the torso directly interacts with) functions as an inner-frame and it is pivoted to the outer-seatback-frame (*OF*) using another rotational anti-whiplash denoted by R^*. Besides, *OF* is connected to the seat-pan by the rotational anti-whiplash device R^+. When the breakaway torque at R^* is overcome due to the pressure applied by the torso on the seatback, a rotation at R^* occurs in the opposite direction to the rotation at R^+.

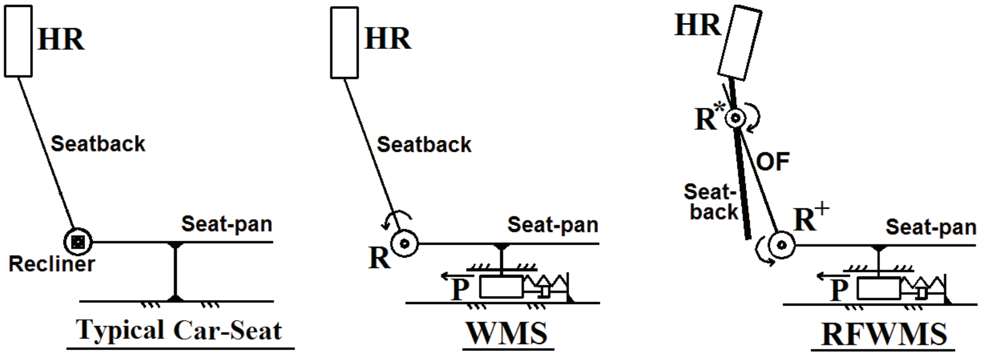


Figure 2. Schematic drawings of a typical car-seat and the car-seat concepts

Table 1. Operational ranges of the anti-whiplash devices

	7 km/h ≤ ΔV< 10 km/h	10 km/h ≤ ΔV≤ 13 km/h	ΔV > 13 km/h
WMS	R	R , P	R , P
RFWMS	R^+	R^+, P	R^+, P , R^*

The mechanical properties of the AWDs were determined using a wide range of ΔV (between 4.5 and 35 km/h) and variety of crash pulses [4]. The applied set of crash pulses also included the low, medium and high-severity crash pulses employed in the European New Car Assessment Programme (EuroNCAP) whiplash tests [13]. As shown in Table 1, the AWDs become operational in succession, according to the severity of the rear impact. No AWD becomes operational for a ΔV value less than 7 km/h to prevent activation during normal daily use.

Himmetoglu et al. [4] demonstrated that the whiplash-mitigating car-seat concepts (i.e. WMS and RFWMS) could successfully mitigate whiplash injuries for a wide range of crash severity (between 4.5 and 30 km/h of ΔV) through coordinated motion of seat components. For the highest severity considered, the seat-pan displacement and seatback rotation were limited to 6.4 cm and 32 deg, respectively. This helped to limit the ramping of the unbelted occupant and the rearward displacement of the seat. RFWMS performed better than WMS at all severities, since the rotational AWD denoted by R^* controls the rotation of the seatback more effectively and provides relatively earlier head-restraint contact. The performances of the whiplash-mitigating car-seat concepts were also compared with those of the typical car-seats without any whiplash-mitigating feature. For this purpose, all of the car-seat models were subjected to the IIWPG (International Insurance Whiplash Prevention Group) standard crash-pulse [14]. The numerical simulations indicated that both WMS and RFWMS represented a significant improvement over the typical-car-seat models although all of the seats had the same head restraint (*HR*) with the same static geometry (as shown in Figure 1(b), with a backset distance of 60 mm) prior to impact. For example, for WMS and RFWMS, the neck shear-forces were about three times lower in comparison with the typical-car-seat models.

CRASH PULSE SHAPES IN REAL-WORLD AND LABORATORY REAR-IMPACTS

Hynd and Willis [9] have made a literature survey on low-speed rear-impact crash pulses which have been recorded using crash pulse recorders in laboratory rear-impact tests (car-to-car and barrier-to-car) and in real-world rear-end crashes involving current production cars. It has been found that the reported crash pulse data is limited and it is available only for a limited number of car models. Considering the available data, rear-impact crash pulses have typically either unimodal or bimodal sinusoidal shapes. Unimodal shapes are commonly characterised by an initial sudden rise followed by a gradual descent in acceleration, whereas the bimodal ones are commonly characterised by an initial sudden rise with a high peak, followed by a lower peak and a gradual descent in acceleration. The trapezoidal pulses do not seem to represent real-world crash pulses in rear impacts.

Crash pulse recorders employ accelerometers whose outputs are filtered so as to reveal the main characteristics of crash pulses. For the rear-impact crash pulses reported in the literature, different channel-frequency-class (CFC) filters have been applied by different researchers [7-9]. Consequently, the shapes of the crash pulses are affected, to some degree, by the type of filtering applied.

In this study, in order to investigate the effects of rear-impact crash pulse shape on seat-occupant response, nine different crash-pulses are derived from the available data in the literature, including typical and generic pulses. These nine different crash-pulses, as shown in Figure 3, all have a ΔV of 16 km/h but with different shapes. The ΔV is chosen as 16 km/h for the following reasons. In a recent European road-traffic accident study, front-seat occupants who were involved in single rear-impacts and also suffered from whiplash injuries, were analysed [5]. The results showed that 35% of the injured occupants received a ΔV lower than 9 km/h, 55% experienced a ΔV between 9 and 20 km/h, and 10% received a ΔV higher than 20 km/h. For a ΔV between 13 and 27 km/h, long-term symptoms were found to be significant [6,9]. Therefore, rear impacts with a ΔV of 16 km/h, fall fairly well within the ΔV interval where most of the whiplash injuries occur and at the same time, they can represent rear-end crashes where there is long-term whiplash risk. The IIWPG also conducts whiplash sled-tests using a single crash-pulse with a ΔV of 16 km/h.

Figure 3 and Table 2 present the nine crash-pulses used in this study. The crash pulse denoted by IWG is the unimodal sinusoidal (or triangular) pulse used as the standard crash-pulse in the IIWPG whiplash evaluation protocol [14]. The crash pulse denoted by BMHL is a bimodal sinusoidal pulse with a high peak followed by a lower peak. BMLH has the reverse shape of BMHL while the higher and lower peak acceleration values are the same for both. BMHL and BMLH are derived from the study by Zuby and Avery [15]. TALH and ISOSC are generic crash-pulses created for this study.

TALH is a triangular crash-pulse which has a uniformly increasing acceleration profile followed by a sharp drop, once the peak value is reached. ISOSC is a crash pulse which has the shape of an isosceles triangle. IWG, BMHL, BMLH, TALH and ISOSC pulses have the same ΔV, the same duration (ΔT), and the same peak acceleration (a_{peak}) and mean acceleration (a_{mean}) values, however their shapes differ considerably. It should be noted that a_{mean} is calculated by $\Delta V / \Delta T$.

The crash pulse HPLL has a very high initial peak acceleration of 18g which is followed by relatively much lower levels of acceleration. HPLL is adapted from the data obtained by Heitplatz et al. [8] in car-to-car laboratory rear-impact tests. HPLL represents the acceleration pulse of a Ford-Ka which was struck by a Ford-Focus with 100% overlap.

The crash pulse EPBM which has an early peak acceleration, can be considered as a bimodal pulse on the whole. EPBM is adapted from the work by Linder et al. [7] in which barrier-to-car rear-impact tests were conducted with 100% overlap. It can be seen that both HPLL and EPBM have the same ΔV and a_{mean} as IWG, BMHL, BMLH, TALH and ISOSC pulses, but their peak accelerations are higher.

The crash pulses TRP1 and TRP2 are generic trapezoidal pulses created for this study. TRP1 has the same ΔV and a_{mean} as IWG, BMHL, BMLH, TALH, ISOSC, HPLL and EPBM pulses, but it has a lower a_{peak} value. TRP2 has the same ΔV as the other pulses, but it has the longest duration and lowest a_{peak} and a_{mean} values, as shown in Table 2.

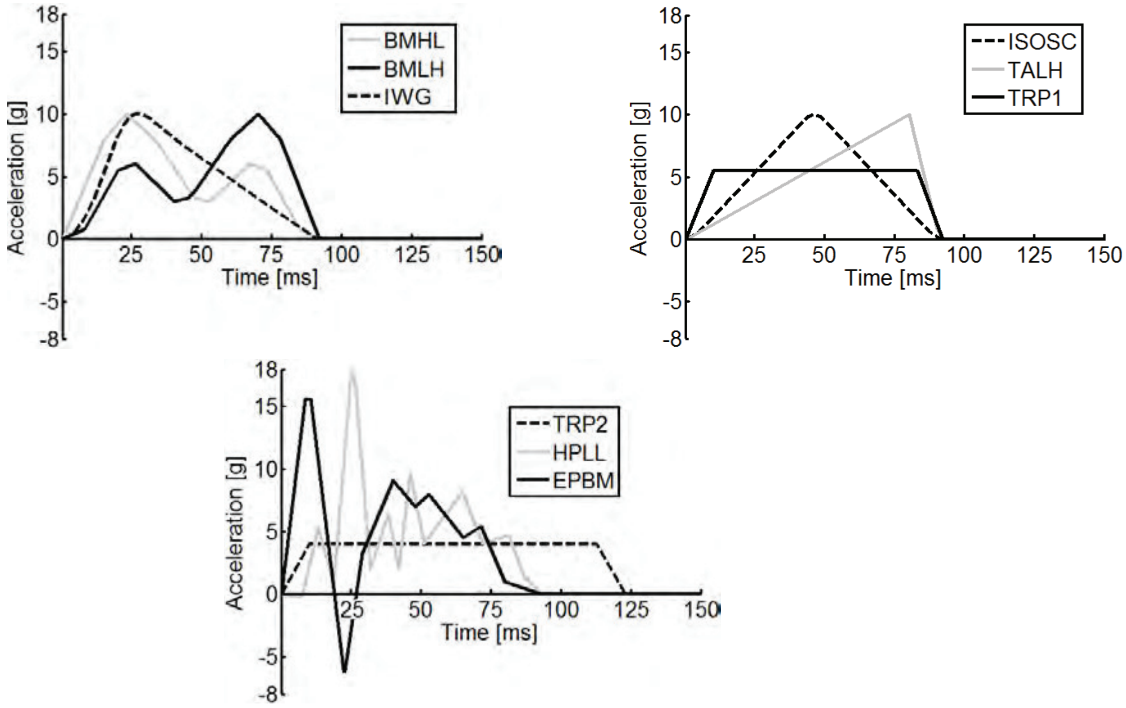


Figure 3. Crash pulses, all with ΔV=16 km/h

Table 2. Crash-pulse test matrix

Pulse	ΔV [km/h]	a_{mean} [g]	a_{peak} [g]	ΔT [ms]		Pulse	ΔV [km/h]	a_{mean} [g]	a_{peak} [g]	ΔT [ms]
IWG	16	4.95	10	92		TRP1	16	4.95	5.5	92
BMHL	16	4.95	10	92		HPLL	16	4.95	18	92
BMLH	16	4.95	10	92		EPBM	16	4.95	15.5	92
TALH	16	4.95	10	92		TRP2	16	3.675	4	123
ISOSC	16	4.95	10	92						

It must be noted that trapezoidal crash-pulses are not found to be representative of the real crash-pulses in low-speed rear-impacts, whereas sinusoidal type crash-pulses having shapes similar to those of IWG, BMHL, HPLL and EPBM are the most prevalent ones in the literature. Among the bimodal sinusoidal crash-pulses, the ones which have a lower peak followed by a higher peak, such as BMLH, are rare. The shapes of ISOSC, TALH, TRP1 and TRP2 may not be realistic enough but they can be of great use in testing the sensitivity of seat designs to different crash pulse shapes.

CAR-SEAT CONCEPTS FOR CRASH PULSE SHAPE ANALYSIS

In order to investigate the effects of crash pulse shape on seat-occupant response, four different car-seat concepts (RONB, ROWMS, WMS, RFWMS) are considered, as shown in Figure 4. The mechanical properties of these car-seat concepts are given in Figure 5. The dimensions and masses of the individual seat components are the same for all the car-seat concepts, and they are representative of the typical car-seats on the market [16].

Mechanical properties of WMS and RFWMS

WMS and RFWMS are whiplash-mitigating car-seat concepts as described previously. The stiffness and damping characteristics of the translational anti-whiplash device *P*, as shown in Figure 5(c), are the same for these two car-seat concepts; but the breakaway forces are 5 kN and 4.25 kN for WMS and RFWMS respectively. For the rebound (forward) motion, *P* applies high damping (30 kNs/m) to limit forceful rebound of the seat-pan.

WMS and RFWMS have some differences regarding the stiffnesses of the rotational AWDs situated at the recliner, as shown in Figures 5(a) and 5(b). It can be seen that R^+ of RFWMS is softer than *R* of WMS. RFWMS performs better than WMS at all crash severities [4] since R^+ is used in conjunction with R^* as indicated in Table 1.

For rearward rotations at *R* and R^+, a constant damping coefficient of 1 Nms/deg is used. This is an estimation of the rotational damping coefficient for the deformation of the recliner-mechanism in typical car-seats [17]. *R* and R^+ apply high damping (15 Nms/deg) when the seatback (in WMS) and *OF* (in RFWMS) start rotating forward (rebound motion), hence limiting rebound.

Figure 5(d) shows the stiffness and damping characteristics of the rotational anti-whiplash device R^* which has a breakaway torque of 1.35 kNm. A damping coefficient of 0.1 Nms/deg is applied by R^* for the reverse (rebound) motion.

Mechanical properties of ROWMS and RONB

ROWMS is a modified version of WMS; they both have the same anti-whiplash device *R*, but in ROWMS the seat-pan is rigidly fixed to the floor (or sled - see Figure 1(b)). The car-seat concept RONB is a modified version of ROWMS and it has got a recliner joint denoted by $R^\wedge$. As shown in Figures 5(a) and 5(b), the only difference between RONB and ROWMS is that in RONB, $R^\wedge$ does not incorporate any breakaway torque. The damping characteristics of $R^\wedge$ are the same as *R* and R^+.

In RONB, the stiffness characteristics of $R^\wedge$ are very similar to the deformation characteristics (i.e. static-torque versus seatback-rotation) of typical car-seat recliners as obtained in the quasistatic seat-tests conducted by Viano [18]. Therefore, RONB can be considered as a model of a typical car-seat without any particular whiplash-mitigating feature. In the quasistatic tests by Viano [18], the torque values increased up to 25-to-30 deg (on average) of seatback-rotation and for further rotational deformations, there were drops in torque, associated with the failure of the structure of the recliner mechanism (i.e. plastic deformation). On the other hand, in RONB and the other car-seat concepts, the torque values increase rapidly at around 25 deg as shown in Figures 5(a) and 5(b); this helps to limit ramping of the unbelted occupant in high severity rear impacts.

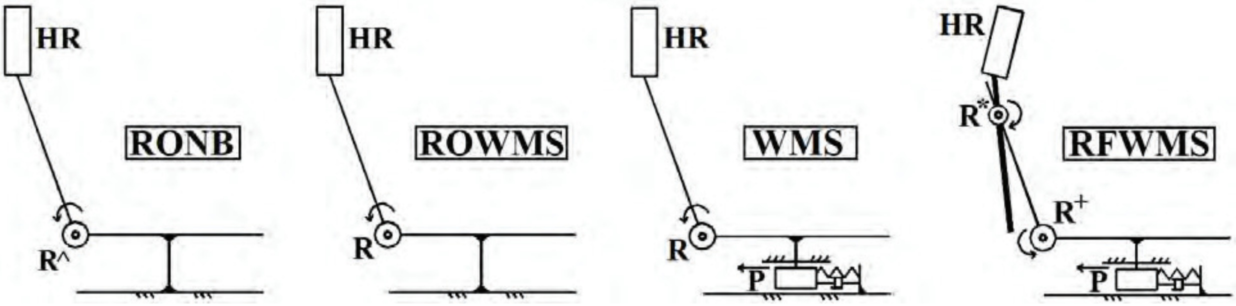


Figure 4. The car-seat concepts used in the analysis of crash pulse shape

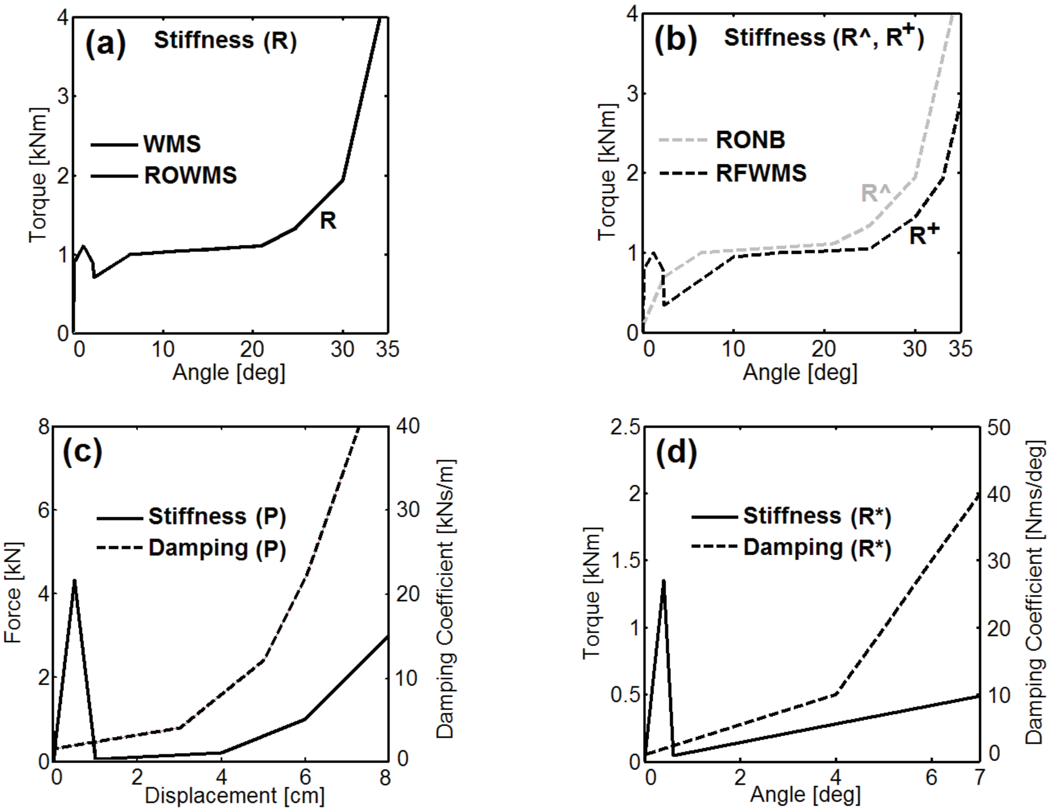


Figure 5. The mechanical properties of the car-seat concepts

TEST PROCEDURE

The car-seat concepts are subjected to the nine crash-pulses whose properties are specified in both Figure 3 and Table 2. Prior to rear impact, the hands and arms of the human model are positioned as shown in Figure 1(b) to adopt a posture similar to the one practiced in dynamic whiplash sled-tests [14]. As in the JARI sled tests, the initial seatback angle is set to 20 deg from the vertical and no seatbelt is used. In order to simulate the frictional resistance between a typical car-occupant and a typical car-seat upholstery, a friction coefficient of 0.35 is used in the simulations for all contacts between the human and car-seat models [16].

The head restraint *HR* is attached to all of the car-seat concepts and it satisfies the minimum height requirement set by the European standard (UN-ECE Regulation No.17) [3]. Nevertheless, an additional vertical height of 35 mm is added to compensate for spine straightening. This value corresponds to the average upward displacement of *T1* as observed in the JARI volunteer sled tests [11]. Thus, the top of *HR* becomes level with the top of the head as shown in Figure 1(b). It is considered that backset values less than 45 mm could cause discomfort. Therefore, the backset of *HR* is set to 60 mm to allow head comfort. This backset value is within the range of a good static head-restraint geometry as specified by IIWPG [14].

For the dynamic rating of the car-seat concepts, the parameters set by the IIWPG are used which are head restraint contact time, *T1* maximum forward-acceleration, maximum *OC*-shear-force and maximum *OC*-tension-force. Additionally, NIC (Neck Injury Criterion) is also calculated [19]. NIC is associated with the formation of S-shape-like deformation in the neck and is based on the relative acceleration and velocity between the *OC* and *T1*.

In order to rate the *OC* forces, the IIWPG neck force classification, as shown in Figure 6, is used. IIWPG recommends a head restraint contact time of 70 ms and a *T1* forward-acceleration limit of 9.5g for energy absorbing seats subjected to the IIWPG standard crash-pulse. The proposed injury threshold value for NIC is 15 m^2/s^2 [19].

The maximum *T1* forward acceleration is taken as the highest acceleration of *T1* in the x-direction, as expressed in the inertial coordinate system *G*, as shown in Figure 1(b). In the human model, the positive shear and the positive normal-forces acting on the head at the *OC*, are defined in the directions of +x and +z axes of the head coordinate system respectively. Therefore, the *OC*-tension force acting on the head is negative by definition. The head coordinate system is located at the head centre of gravity as shown in Figure 1(a).

RESULTS

The simulations have revealed that the shape of the crash pulse can have considerable effects on seat response and the associated whiplash-risk in rear impacts. For all the car-seat concepts, Figure 7 shows the variation of *Fsh* (the maximum (i.e. largest) *OC*-shear-force), *HrCt* (head restraint contact time) and maximum-NIC with respect to the nine crash-pulses which can be considered to be of similar severity. In Figure 7(a), *M* and *L* represent the upper limits of the *OC*-shear force for the moderate and low neck-force regions (see Figure 6) respectively. In Figure 7(b), *RL* indicates IIWPG's recommended limit for head restraint contact time. In Figure 7(c), *IT* represents the injury threshold value for NIC.

RONB and RFWMS are the worst and the best performing car-seat concepts, respectively. WMS is the second best performing car-seat concept whereas the performance of ROWMS is only moderate. In Figure 8, the responses of RONB and WMS to the crash pulse HPLL are presented in order to show the typical differences between seats which have higher and lower whiplash-risks respectively. Figures 9 and 10 show the responses of ROWMS and RFWMS to the crash pulses BMHL, BMLH and EPBM.

For each crash-pulse, Figures 8, 9 and 10 show frozen frames from the simulations at 40 ms (i) before the human model fully sinks into the seatback foam; the instant (ii) when the head first contacts the head restraint; the instant (iii) when the maximum seatback-rotation occurs (the maximum penetration of the head into the head restraint also occurs at around this moment); and the instant (iv) when the head just leaves the head restraint.

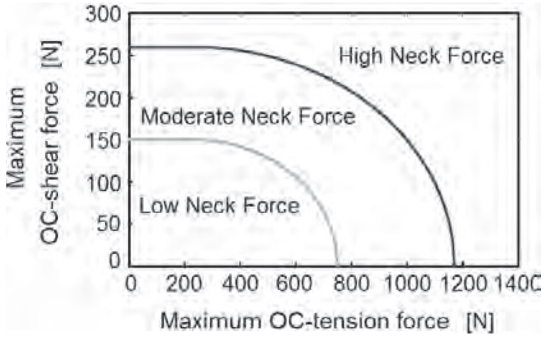


Figure 6. IIWPG neck force classification (adapted from IIWPG [14])

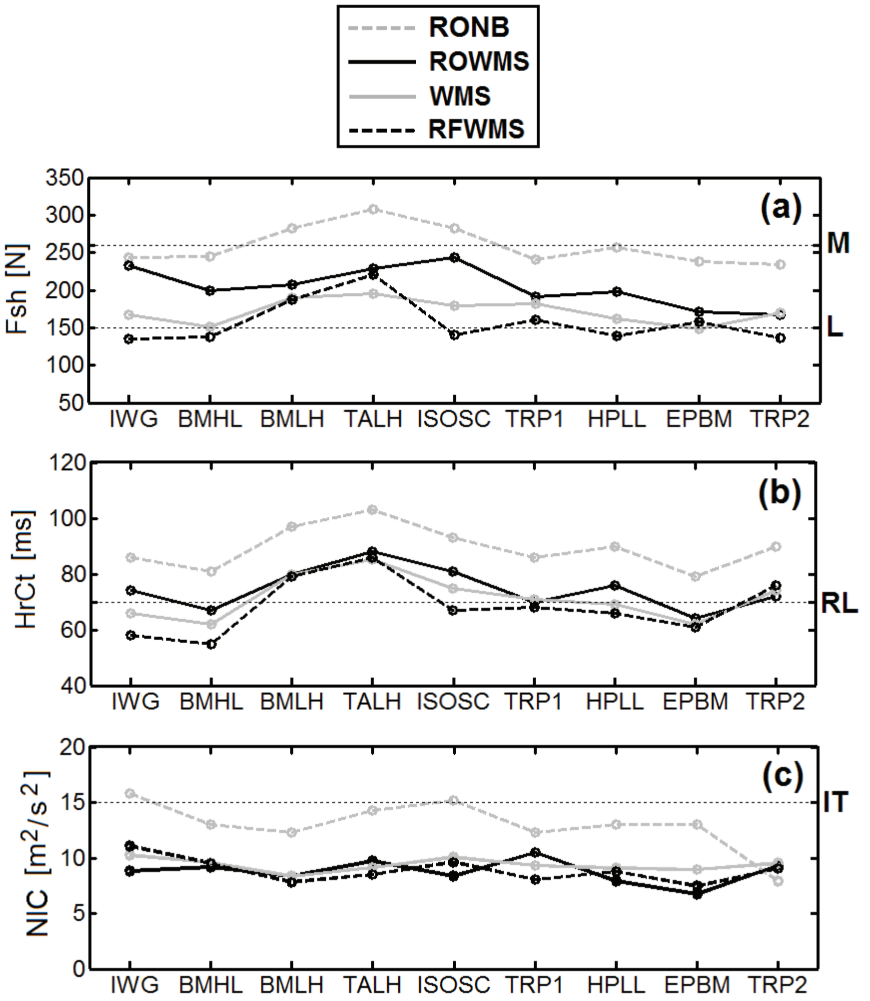


Figure 7. Comparison of seat-occupant responses to the nine crash-pulses

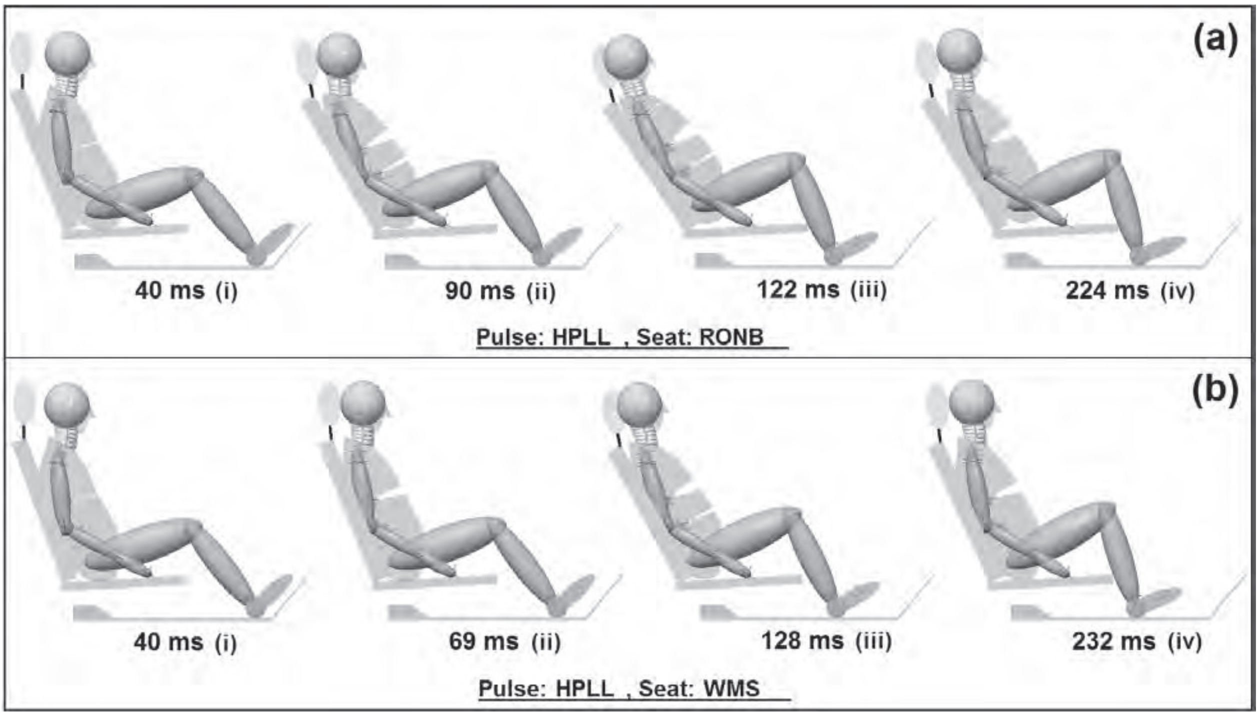


Figure 8. Comparison of seat-occupant responses (RONB vs WMS) to the crash pulse HPLL

DISCUSSION

Performance of RONB

The performance of RONB is quite distinct from the other car-seat concepts as shown in Figure 7. For all of the nine crash-pulses, RONB produces the highest risk of whiplash. *Fsh* values are either high or around the borderline between high and moderate neck-force regions. Figure 7(b) shows that *HrCt* values are also well above the recommended limit. The maximum-NIC values are either close or just above the injury threshold value for the majority of the crash-pulses. The values of the maximum *OC*-tension forces vary between 270 N and 450 N. The pulses ISOSC and TALH produce the highest *OC*-tension forces. For more than half of the nine crash-pulses, the maximum *T1*-forward-acceleration values reach or exceed the 9.5g limit.

The poor performance of RONB stems from the fact that the seatback of RONB begins to rotate early and rapidly after the onset of the impact, leading to poor support of the head and torso throughout the impact as shown in Figure 8(a). During the initial stages of the impact, the seatback starts to rotate considerably while the human model is still sinking into the seatback foam. The excessive rotation of the seatback during the first 90 ms causes the head to flex significantly relative to the upper torso; thus head restraint contact time is extended excessively. Consequently, the head interacts with the head restraint severely (see instant (iii) in Figures 8(a) and 8(b)).

RONB does not have any particular whiplash-mitigating feature. The recliner-joint *R^* is only involved in energy absorption and since *R^* is not strong enough by itself, the seatback yields quite easily and ineffectively. Another shortcoming of RONB is the lack of breakaway torque in the mechanical properties of *R^*. A relatively small breakaway torque at the recliner can enable the torso to sink into the seatback structure without excessive rotation of the seatback at the start of the impact.

The performance of ROWMS, WMS and RFWMS

The results indicate that for ROWMS, WMS and RFWMS, the maximum-NIC values are less than 10.5 m^2/s^2 (see Figure 7(c)) and this is lower than the proposed injury threshold value of 15 m^2/s^2. No car-seat concept is better than the others regarding the NIC responses. For these three car-seat concepts, the *OC*-tension forces are less than 250 N, which is considered to be low (see Figure 6). However, ROWMS exhibits relatively higher *OC*-tension forces in comparison to WMS and RFWMS.

The maximum *T1*-forward-acceleration values rank these three car-seat concepts in the same way as *Fsh*. WMS and RFWMS do not exceed the 9.5g limit for all the crash pulses, whereas ROWMS exceeds the limit for IWG, BMLH and ISOSC pulses.

ROWMS performs worse than both WMS and RFWMS as indicated by the *Fsh* and *HrCt* responses, as shown in Figures 7(a) and 7(b), respectively. For ROWMS, *Fsh* (largest *OC*-shear-force) values are in the moderate-force region for all the crash pulses and this indicates a relatively higher risk of whiplash. On the other hand, WMS and RFWMS produce *Fsh* values less than 195 N (i.e. *Fsh* is either low or moderate). For WMS, *Fsh* values are in the low-force region for only two of the crash pulses whereas RFWMS produces low *Fsh* for five of the crash pulses.

ROWMS has extended *HrCt* in comparison to WMS and RFWMS, for four of the crash pulses (IWG, BMHL, ISOSC, HPLL). For these four crash-pulses, ROWMS produces considerably higher *Fsh* as well. The reason is that the head and the torso are not supported effectively enough by ROWMS. On the other hand, WMS and RFWMS control the rotation of the seatback more effectively and provide earlier head-restraint contact.

Among all the whiplash assessment parameters used in this study, *Fsh* is the clearest indication of whiplash risk induced by the combined effects of seat design and crash pulse. Thus, *Fsh* is able to distinguish between the car-seat concepts with more precision. Considering the *Fsh* responses in

Figure 7(a), WMS and RFWMS show more robust performance than ROWMS, since they have less sensitivity to variations in the crash pulse shape (apart from BMLH and TALH).

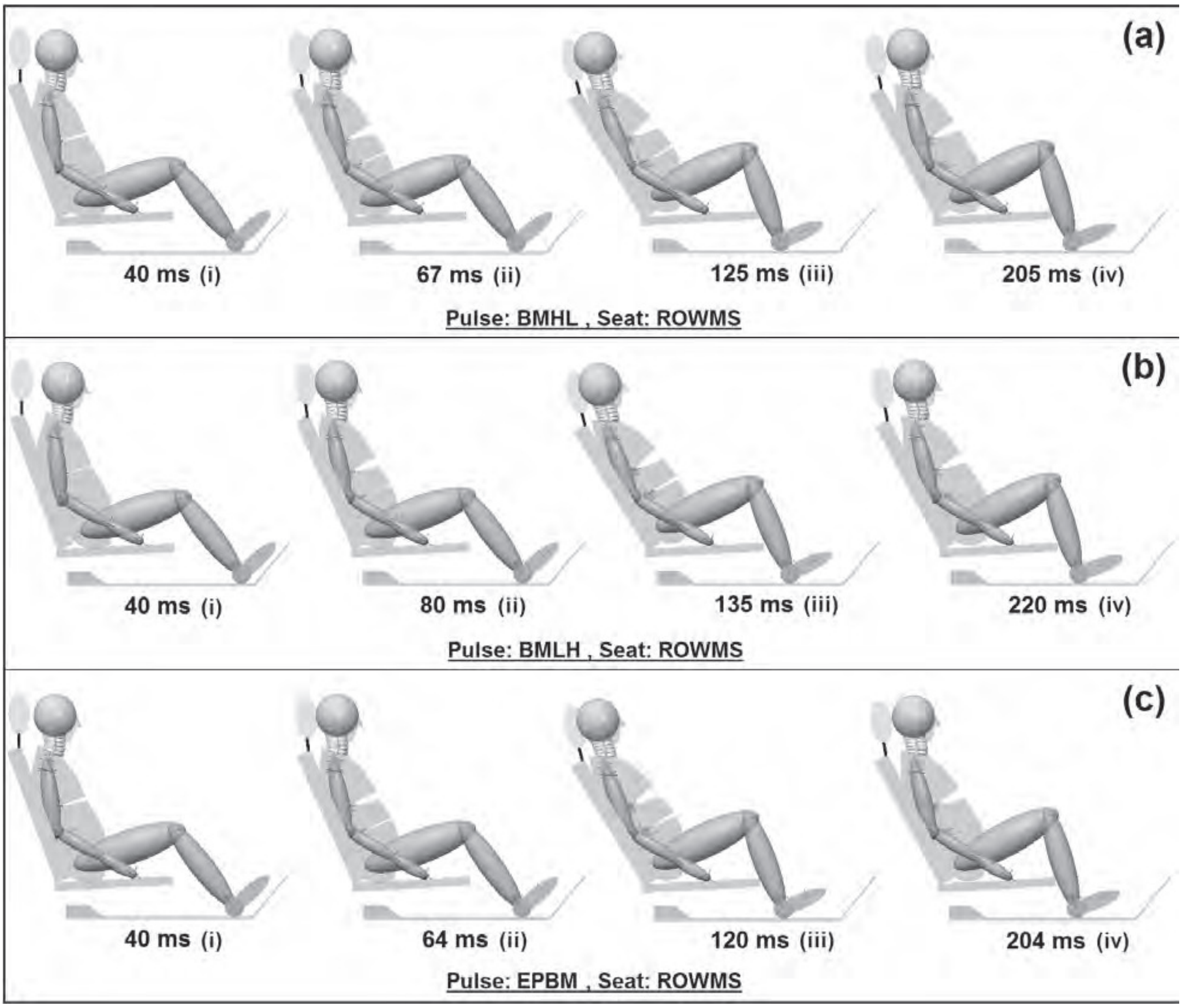


Figure 9. ROWMS-response to selected crash-pulses

Response of ROWMS

The only difference between RONB and ROWMS is the breakaway torque that ROWMS has for the anti-whiplash device (*R*) at the recliner (see Figures 5(a) and 5(b)). This relatively small breakaway torque improves seat performance appreciably (in comparison to RONB). IWG, TALH and ISOSC are the most injurious (or severe) pulses whereas EPBM and TRP2 are the least injurious ones for ROWMS, as indicated by the *Fsh* responses. The pulses BMHL, BMLH, TRP1 and HPLL are equally severe and compared with the ISOSC pulse, they produce *Fsh* which are 45 N lower on average.

For BMLH, TALH and ISOSC, head restraint contact is delayed considerably (see Figures 7(b) and 9(b)) due to low levels of acceleration in the first 40 ms, 45ms and 30 ms of these pulses respectively. For HPLL, the peak acceleration which occurs at 25 ms, is quite high but short in duration. Therefore, as shown in Figures 7(a) and 7(b), HPLL does not produce earlier head-restraint-contact and also it is not as severe as IWG, TALH and ISOSC.

As shown in Figures 7(b) and 9(c), the earliest head-restraint contact occurs for the pulse EPBM since the torso sinks quickly into the seatback foam owing to the high levels of acceleration that occurs in the first 20 ms of the impact. But then, between 20 and 40 ms, reverse and lower levels of acceleration take place. EPBM is the least injurious pulse along with TRP2, since the seatback does not rotate early and rapidly which helps to support the head and torso more effectively.

TRP2 is the weakest pulse. The maximum seatback-rotation during impact is only 8.45 deg for TRP2 whereas for the rest of the pulses, it varies between 11.4 to 12.9 deg for ROWMS, as shown in Figure 10. When subjected to TRP2, ROWMS supports gently the head and torso throughout the impact. These results can be explained by the fact that TRP2 has the lowest mean acceleration value and the lowest levels of acceleration.

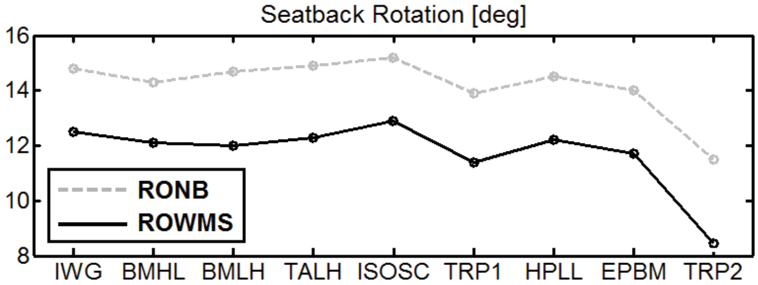


Figure 10. Maximum seatback-rotations during impact (RONB vs ROWMS)

Response of RFWMS

RFWMS has three different anti-whiplash devices that control the motion of the seat components and it is the best performing car-seat concept on the whole. RFWMS achieves this performance by utilising an inner-frame which controls the rotation of the seatback more effectively and provides relatively earlier head-restraint contact.

The pulses IWG, BMHL, ISOSC and HPLL are relatively strong pulses for ROWMS, but RFWMS respond successfully to these pulses since the corresponding *Fsh* values are in the low-force region. In RFWMS, the seat-pan motion (at *P*) and the inner-frame rotation (at R^*) prevent excessive rotation of the seatback and at the same time, provide early and more effective head-support.

RFWMS can be considered to have underachieved for the pulses BMLH and TALH since *Fsh* and *HrCt* values are the highest for these two pulses. The reason is that during the first 50 ms, BMLH and TALH have low levels of acceleration and this causes considerable time-delays in the responses of the anti-whiplash devices R^* and *P*. Hence, RFWMS is not able to fully realise its whiplash-mitigating potential due to inefficient operation of the AWDs and its performance becomes closer to that of ROWMS for BMLH and TALH.

The responses of RFWMS to the pulses BMHL and BMLH, are compared in Figures 11(a) and 11(b). For BMLH, *HrCt* is extended by 24 ms; besides the rotation at the recliner (R^+), seat-pan displacement (at *P*) and inner-frame rotation (at R^*) are delayed by 15 ms, 10 ms and 55 ms respectively in comparison with BMHL. Figure 12 presents the responses of the AWDs when RFWMS is subjected to the pulses IWG and BMLH. In comparison with IWG, the pulse BMLH causes 12 ms, 20 ms and 53 ms of delays for R^+, *P* and R^* respectively. The main reason for the degraded performance of RFWMS (when subjected to the pulses BMLH and TALH) is that the inner-frame (controlled by R^*) does not become operational early enough.

For the pulse EPBM, the inner-frame rotation (at R^*) is delayed by 40 ms in comparison to BMHL, as shown in Figures 11(a) and 11(c). For EPBM, the seat-pan motion (at *P*) initiates 10 ms earlier than that of BMHL; besides the seat-pan motion is much more rapid and this compensates for the delay in the response of the inner-frame rotation. A similar situation occurs for the pulse TRP1. Therefore, RFWMS shows good performance when subjected to EPBM and TRP1 as well.

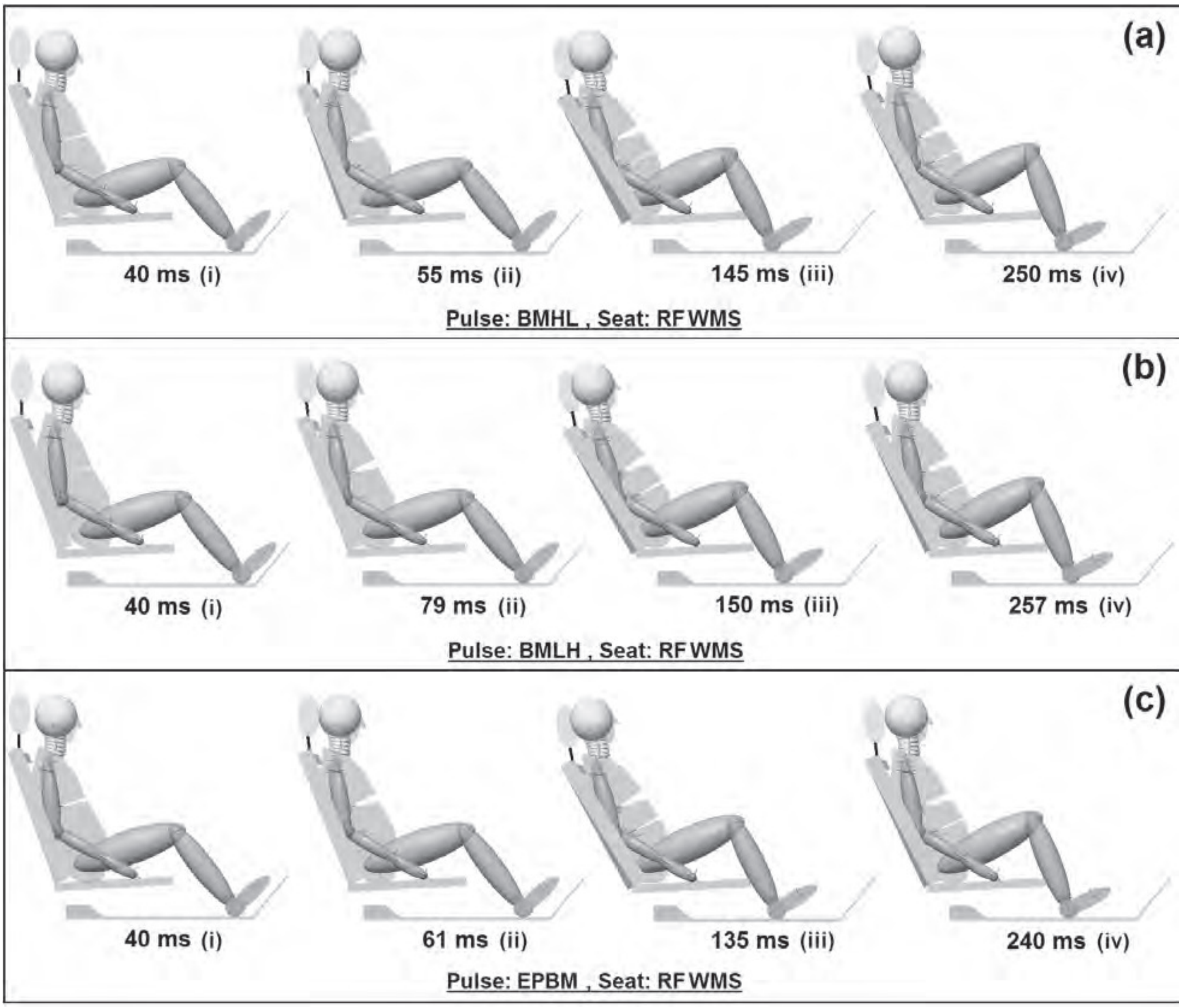


Figure 11. RFWMS-response to selected crash-pulses

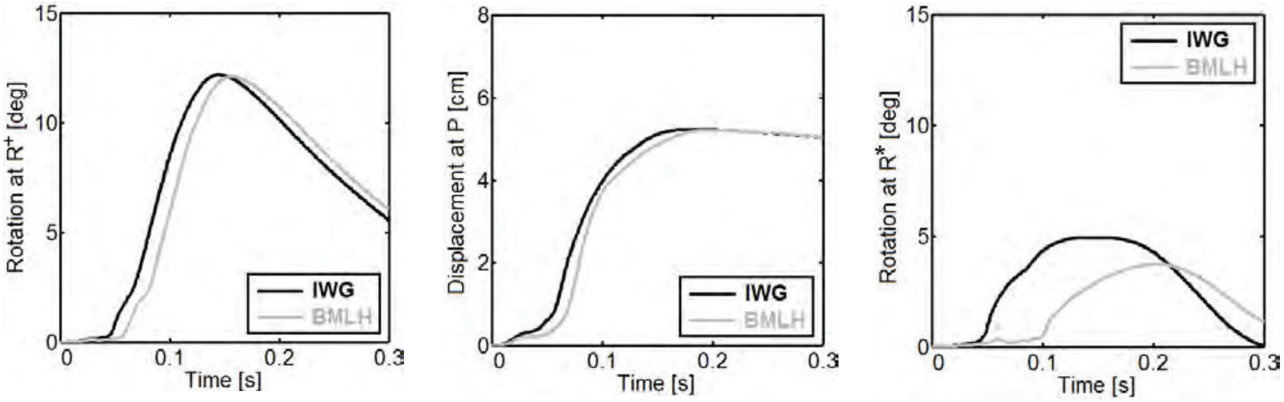


Figure 12. Comparison of AWD responses (seat: RFWMS; crash pulses: IWG, BMLH)

In its first 30 ms, ISOSC has low levels of acceleration which then increases continuously until 50 ms. The acceleration profile in the first 50 ms of ISOSC is strong enough to activate all of the AWDs without much delay i.e. the AWDs react sufficiently on time to keep both *HrCt* and *Fsh* low.

For the pulse TRP2, the translational anti-whiplash device *P* does not become operational at all. The rotation of the inner-frame is delayed excessively until 165 ms. Hence, the maximum rotation at *R** is only 1.65 deg and RFWMS behaves like ROWMS throughout the impact. However, the seatback of RFWMS rotates 3.6 deg more in comparison with ROWMS. The reason is that the rotational anti-whiplash device R^+ (at the recliner) is designed to be more compliant than the rotational anti-whiplash device R of WMS and ROWMS. TRP2 is a weak pulse, thus RFWMS provides effective head and torso support even when the anti-whiplash devices P and R^* are not operational.

Crash pulse shape effects on seat-occupant response

The seat-occupant responses in Figure 7 indicate that the pulses IWG, BMHL, ISOSC and HPLL, are able to differentiate between better and worse seat-designs more clearly; in other words seat performance is sensitive to these four pulses. This is evident in both *Fsh* and *HrCt* responses.

On the contrary, the pulses BMLH, TALH, EPBM, TRP1 and TRP2 are not able to differentiate between seat designs (note that RONB can be disregarded in this comparison since it is already a quite poor design). As mentioned in the previous sections, these five pulses have acceleration profiles which are not able to overcome promptly the breakaway force and torque of P and R^* respectively. Hence, the performances of WMS and RFWMS become closer to those of ROWMS for these five pulses as indicated by the *Fsh* and *HrCt* responses. Among these five pulses, EPBM, TRP1 and TRP2 are relatively weaker (i.e. less injurious) pulses, thus the performances of WMS and RFWMS are still good despite the mentioned problems. For EPBM, TRP1 and TRP2, the maximum seatback-rotations during impact are also the lowest for both ROWMS and RONB (see Figure 10).

In general, the pulses BMLH, TALH and ISOSC produce the most extended *HrCt* since they have initially low levels of acceleration. They lead to increased *Fsh* as well. BMLH and TALH also cause inefficient operation of the AWDs in WMS and RFWMS. For the pulses BMLH and TALH, the performances of WMS and RFWMS are lowered significantly because the mechanical properties of the AWDs are optimised [4] using mainly the sinusoidal type (unimodal or bimodal) crash-pulses which are prevalent and characterised by an initial sudden rise followed by lower levels of acceleration as in IWG, BMHL, HPLL and EPBM. The initial levels of acceleration in BMLH and TALH are not high enough to activate the AWDs on time.

The results indicate that head support within the first 75 ms of the impact is essential for lower whiplash-risk. However, early *HrCt* does not always ensure low *Fsh*. For example, ROWMS has *HrCt* less than 75 ms for IWG, BMHL, TRP1 and HPLL but *Fsh* values are between 195 and 235 N (in the upper half of the moderate neck-force region) for these four pulses as shown in Figures 7(a) and 7(b).

Considering the results given in Figure 7, the most injurious pulses can be selected as IWG, TALH and ISOSC (note that TALH is a more severe version of BMLH). For these three pulses, the maximum seatback-rotations during impact are also the highest for both ROWMS and RONB (see Figure 10). The car-seat concepts WMS and RFWMS respond successfully to these three pulses although their performance is lowered when subjected to BMLH and TALH. A careful observation reveals that these three pulses (i.e. IWG, TALH and ISOSC) have sustained levels of relatively high acceleration for a prolonged period of time. IWG, TALH and ISOSC have accelerations greater than 4.5g for at least 50 ms such that 80% of the total ΔV takes place within 50 ms between t_1 and t_2, as shown in Figure 13. Hence between t_1 and t_2, these three pulses have a ΔV of 12.8 km/h and an a_{mean} of 7.25g. Between t_1 and t_2, the seatback rotates more rapidly and this increases dynamic backset (i.e. moves the head restraint away from the head) which leads to stronger interaction of the head with the head restraint for the rest of the impact and causes higher whiplash-risk.

It can be seen that the most injurious pulses i.e. IWG, TALH and ISOSC have a great proportion of total ΔV concentrated in a period of only 50 ms (due to higher levels of acceleration within this period) considering that the duration of the pulse is 92 ms. This observation is in agreement with the results of other studies. Linder et al. [20] reported that starting from the late 1990s, the rear structures of cars became stiffer and this caused an increase in the number of whiplash injuries. Stiffer rear-structures typically produce crash pulses with higher acceleration levels and shorter pulse duration [20].

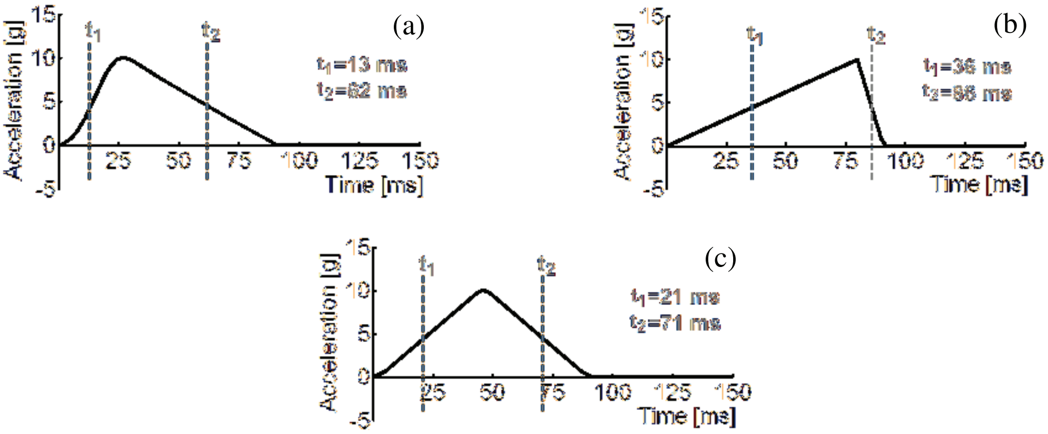


Figure 13. The most injurious pulses (a) IWG, (b) TALH, (c) ISOSC

Medium severity crash-pulses for dynamic assessment of car-seats

This study provides valuable information for the evaluation and selection of medium-severity crash-pulses (with ΔV=16 km/h) that can be used in consumer whiplash-tests. The selected crash pulse(s) should be able to distinguish clearly between different car-seat designs and test their sensitivity to variations in crash severity and pulse shape. The crash pulses IWG, BMHL, ISOSC and HPLL are suitable for this purpose as explained in the previous section.

IWG, BMHL and HPLL rate the performances of the four different car-seat concepts similarly (see Figure 7) but IWG can be considered to be slightly more injurious and it can be more easily generated by typical laboratory sled test equipment [9] as it is a unimodal pulse. Therefore, IWG is a good choice to dynamically assess the rear-impact performance of car-seats. IWG is already the medium severity crash-pulse in the EuroNCAP whiplash-test procedure [13]. ISOSC is also a good choice to classify car-seats. Though ISOSC is an uncommon rear-impact crash-pulse, it can be used to evaluate the effects of initially low levels of acceleration that may be seen in the time-history of crash-pulses.

There are numerous car-seats on the market specifically developed to reduce whiplash injuries and for such seats, it is important to have whiplash mitigating features which can respond optimally to crash pulses of different severity and shape. For example, the whiplash-mitigating car-seat concepts WMS and RFWMS show relatively lower performance for the pulses BMLH and TALH since these two pulses have initially low levels of acceleration which are not high enough to activate the AWDs promptly. It can be shown that if the AWDs were designed to become operational without delay for BMLH and TALH as well, then the performances of WMS and RFWMS would be considerably worse for the typical (or prevalent) rear-impact crash-pulses which have an initial sudden rise followed by lower levels of acceleration.

Some car-seats on the market employ pro-active devices (e.g. pro-active head-restraints) triggered by crash sensors. The acceleration level at which the pro-active device is triggered, is a critical point in the rear-impact performance of the car-seat. Therefore, the pulses BMLH, TALH and ISOSC are good candidates to test whether such active devices respond early enough in the case of a rear-impact.

According to the reported data in the literature, low-speed rear-impact crash-pulses having the shapes of BMLH, TALH and ISOSC are uncommon. However, it is still possible to have a variety of crash pulses in rear-impacts due to several factors as described in the Introduction. Crash pulses such as BMLH, TALH and ISOSC should also be used to evaluate the extent of delay in the activation of whiplash-mitigating devices because such delays can lower the performance of the seat. TALH and ISOSC are easier to implement in laboratory tests as they have simple triangular shapes. Therefore, in addition to IWG, either TALH or ISOSC (see Figure 13) should be used in medium-severity consumer whiplash-tests.

CONCLUSIONS

In this paper, the influence of rear-impact crash pulse shape on seat-occupant response is investigated in a systematic manner using four different car-seat concepts. The developed multi-body models are efficient tools which can be used to interpret the rear-impact dynamics of the seat-occupant system practically. The crash-pulses which are used in this study, include generic and uncommon pulses as well, so as to make a comprehensive analysis of crash pulse shapes and the associated seat-occupant responses. In order to analyse the effects of crash-pulse-shape alone, the ΔV and the pulse duration are kept the same for the crash-pulses (except TRP2) so that the mean acceleration is the same for all while the peak acceleration is varied.

This study indicates that the amount of whiplash-risk depends strongly on the combined effects of seat design and crash pulse shape. It is shown that the shape of the crash pulse is quite influential and has to be considered along with the parameters that describe the overall characteristics of the crash pulse such as ΔV, a_{mean} and a_{peak}. The results indicate that early head-support is important but does not always guarantee lower whiplash-risk if there is ineffective energy-absorption by the seatback. For all of the nine crash-pulses, the car-seat concepts WMS and RFWMS have significantly lower whiplash-risk in comparison with RONB and ROWMS which can be considered to represent typical car-seats.

This study proposes two different medium-severity crash-pulses for consumer whiplash-testing. The first one is IWG which is currently being employed in the EuroNCAP and IIWPG dynamic whiplash-tests. The second one can be chosen as either TALH or ISOSC which are both easier to implement in laboratory tests. The initially low levels of acceleration in TALH and ISOSC, can be of great help in testing the performance of active and passive whiplash-mitigating devices which are available in many car-seats on the market today. Hence, using two different crash-pulses as suggested, can provide a complete assessment of the dynamic performance of car-seats in medium-severity rear-impacts.

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