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ANALYSIS OF OCCUPANT PROTECTION STRATEGIES IN TRAIN COLLISIONS

David C. Tyrell
Kristine J. Severson
Brian P. Marquis
Volpe National Transportation Systems Center
U.S. Department of Transportation
Cambridge, Massachusetts

ABSTRACT

A study of the occupant dynamics and predicted fatalities due to secondary impact for passengers involved in train collisions with impact speeds up to 140 mph is described. The principal focus is on the effectiveness of alternative strategies for protecting occupants in train collisions, including *friendly* interior arrangements and occupant restraints.

Head Injury Criteria (HIC), chest deceleration, and axial neck load were used to evaluate interior performance; the probability of fatality resulting from secondary impacts was evaluated for each of the interior configurations and restraint systems modeled based on these criteria.

The results indicate that compartmentalization can be as effective as a lap belt in minimizing probability of fatality for the 50th percentile male simulated. Compartmentalization is an occupant protection strategy that requires seats or restraining barriers to be positioned in a manner that provides a compact, cushioned protection zone surrounding each occupant. When occupants are allowed to travel large distances before impacting the interior, restrained occupants have a much greater chance of survival. Fatalities from secondary impacts are not expected in any of the scenarios modeled if the occupant is restrained with a lap belt and shoulder harness.

1. INTRODUCTION

This paper describes an evaluation of the occupant dynamics and predicted fatalities due to secondary impact for passengers involved in high-speed train collisions. The principal focus is on the influence of interior configuration, occupant restraint, and car crash pulse on fatalities resulting from secondary impacts. The car crash pulse varies with the impact speed, the position of the car within the trainset, and the structural design of the car.

Two alternative structural designs are compared to evaluate the effectiveness of each in minimizing secondary impact injuries. The first design studied is referred to as the conventional design. This denotes cars of uniform longitudinal strength. The second design is referred to as the crash energy management design. This term indicates cars designed with varying longitudinal strength, with higher strength in the occupied areas and lower strength in the unoccupied areas (Tyrell, et al., 1995).

2. ANALYSIS METHODOLOGY

The secondary collision occurs when the train rapidly decelerates due to the collision of the two trains, and the occupant continues to travel, in free flight, until he or she collides with an interior fixture, such as the seat back ahead. This dynamic motion was modeled with a detailed representation of human body dynamics, implemented in the computer program MADYMO (MADYMO, 1992).

2.1 Secondary Impact Model

Figure 1 shows a schematic from the model of a seated occupant in a train interior as analyzed in the simulation studies for passengers seated in rows. The analysis uses the deceleration time history of the vehicle predicted from the analysis of the dynamics and structural deformation under collisions described by Tyrell, et al. (1995). This deceleration is applied to the interior, and causes the occupant to move. At some point during the vehicle deceleration, an unrestrained occupant impacts an interior fixture, such as a seat back, a partition, or the floor.

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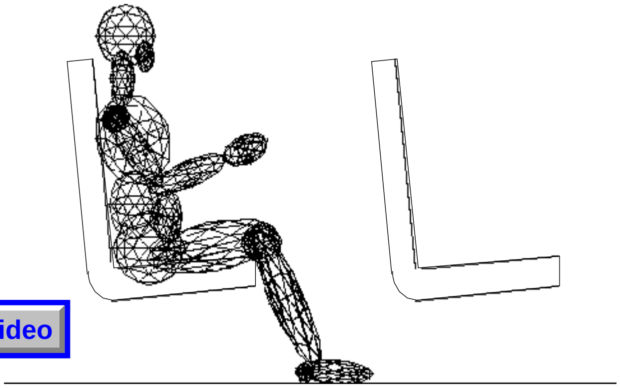


FIGURE 1. MADYMO HUMAN BODY MODEL

In the simulation the occupant is modeled as a system of interconnected, elliptically-shaped masses (ellipsoids) with parameters chosen to approximate the characteristics of a human. For this study, the parameters corresponding to a 50th percentile U.S. male were used. The 50th percentile male has a height that is just greater than half the male population of the U.S., a weight that is just greater than half that population, etc.

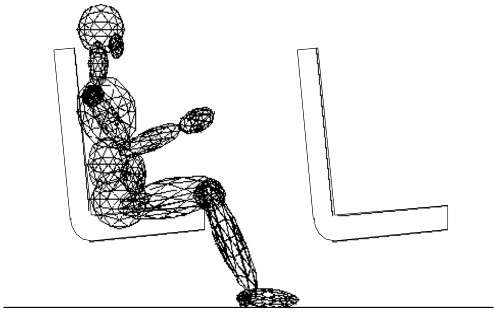
The model generates time histories for the displacement, velocity, and acceleration for all of the ellipsoids, including those corresponding to the head, and the forces and torques at the connections between the ellipsoids. Based on these motions and forces, injury criteria are calculated. Program outputs include data files for computer animations that depict the occupant motion during the collision. These animations allow the user to observe how different interiors, restraint systems, and structural train designs affect the occupant motion. MADYMO has been shown to produce results that are reasonable comparable to sled test results (O'Conner and Rao, 1990).

As in sled testing, the model assumes the occupant is passive during the collision. The increased duration of a train collision over an automobile collision allows the train occupants more time to react to the collision. Such reactions may influence the outcome of the secondary collisions; however, it is likely that such reactions are specific to particular individuals. It would be difficult to model these reactions and their potential influences on the outcome of the secondary collision.

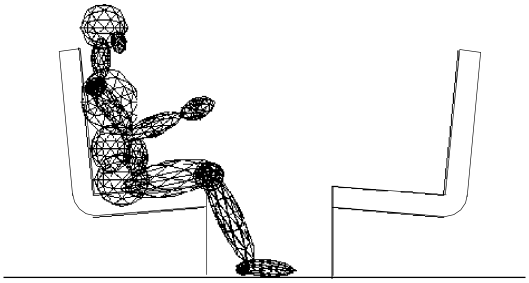
The program does not account for failure of interior components, i.e. seats and tables are assumed to remain intact. For the purpose of determining the occupant motion, the seats and tables are represented by planes with defined force/crush characteristics.

2.2 Interior Arrangements

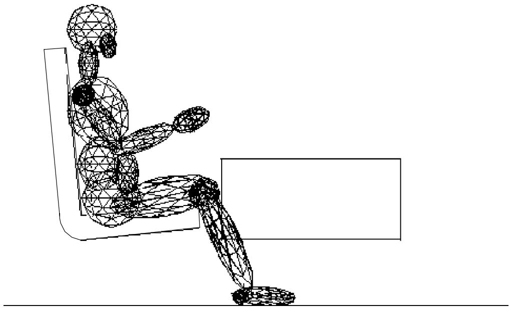
The interior configuration is the geometric arrangement and physical characteristics (stiffness, damping) of the seats, tables, and other fixtures in the occupant compartment of a passenger train. The three interior arrangements modeled -- forward-facing seats in rows, seats facing each other, and seats with tables -- are shown Figure 2.



a. Seats in Rows



b. Seats Facing



c. Seats and Table

FIGURE 2. INTERIOR CONFIGURATIONS

2.3 Occupant Protection Strategies

2.3.1 Compartmentalization. Compartmentalization is a strategy for providing occupant protection during a collision. The principal objectives of this strategy are to limit the occupant's range of motion and to assure that the interior surfaces are sufficiently soft to limit injury during occupant impact. If an occupant is not protected by a forward seat back, a restraining barrier must be provided that is sufficiently flexible, yet strong enough to maintain its integrity. This strategy provides occupant protection independent of any action taken by the occupant. The concept of compartmentalization was used by the National Highway Traffic Safety Administration (NHTSA) to justify the absence of safety belt requirements on large school buses (Federal Register, 1989).

The regulations governing compartmentalization for school buses with a gross vehicle weight rating (GVWR) in excess of 10,000 lbs are contained in CFR 571.222 - School Bus Seating and Crash Protection (Code of Federal Regulations 49, 1993). This regulation requires that seat backs and partitions have a force/displacement characteristic within the bounds shown in Figure 3. When a sufficient amount of cushion and flexibility is provided in the surface of impact, the forces exerted on the occupant remain within a survivable level. For this study, the seat backs were assumed to have the softest force/displacement curve allowed in Figure 3.

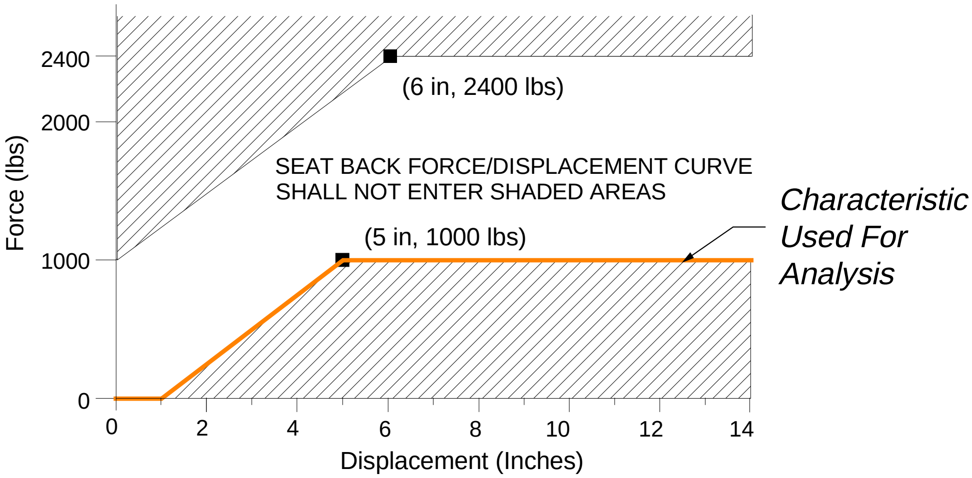


FIGURE 3. FORCE/DISPLACEMENT CHARACTERISTIC OF SEAT BACK

2.3.2 Occupant Restraint. Occupant motions in the seats-in-rows and the seats-facing interiors were evaluated with no restraint system, with a lap belt alone, and also with a lap belt and shoulder harness. The occupant motions in the interior with seats and table were evaluated only for the unrestrained occupant.

To model the shoulder harness and lap belt, an existing automobile belt model (MGA Research Corporation, 1991) was utilized. The belt model accounts for initial belt slack or pre-tension and for the potential rupture of belt segments if the force is greater than the strength of the belt. In the model, the anchorage for the upper end of the shoulder harness is defined as a fixed point in the interior space.

There may be substantial difficulties in designing an appropriate upper attachment point for the shoulder harness. Owing to similar difficulties, NHTSA does not require a shoulder harness in the center (inboard) position of automobile seats (Preamble to Amendment to FMVSS No. 222, 1989).

2.4 Vehicle Deceleration Time Histories (Crash Pulses)

Occupant response to a range of crash pulses (primary collision deceleration time histories) was analyzed to determine the influence of car position, primary collision impact speed, and structural crashworthiness. Crash pulses from two primary collision conditions were used in this study. The primary collision conditions were a power car-to-power car collision and cab car-to-power car collision. The consist makeup includes a power car, five coach cars, and a cab car as illustrated in Figure 4.

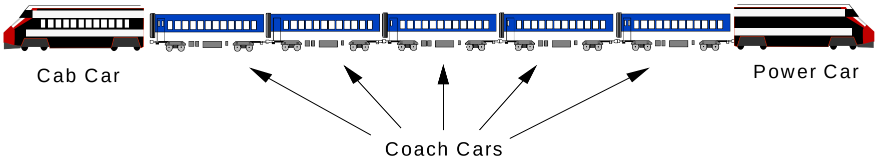
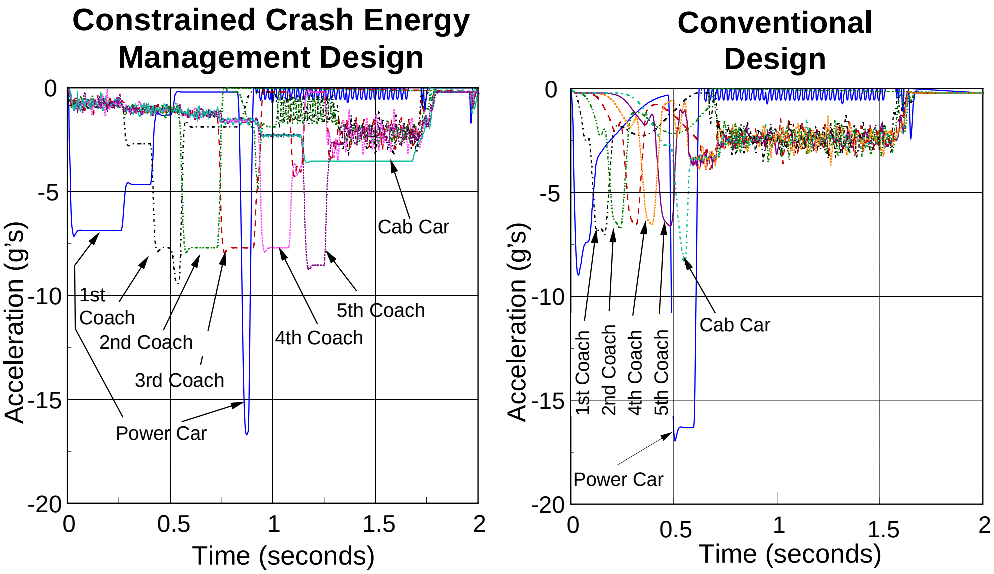


FIGURE 4. BASIC TRAINSET CONFIGURATION

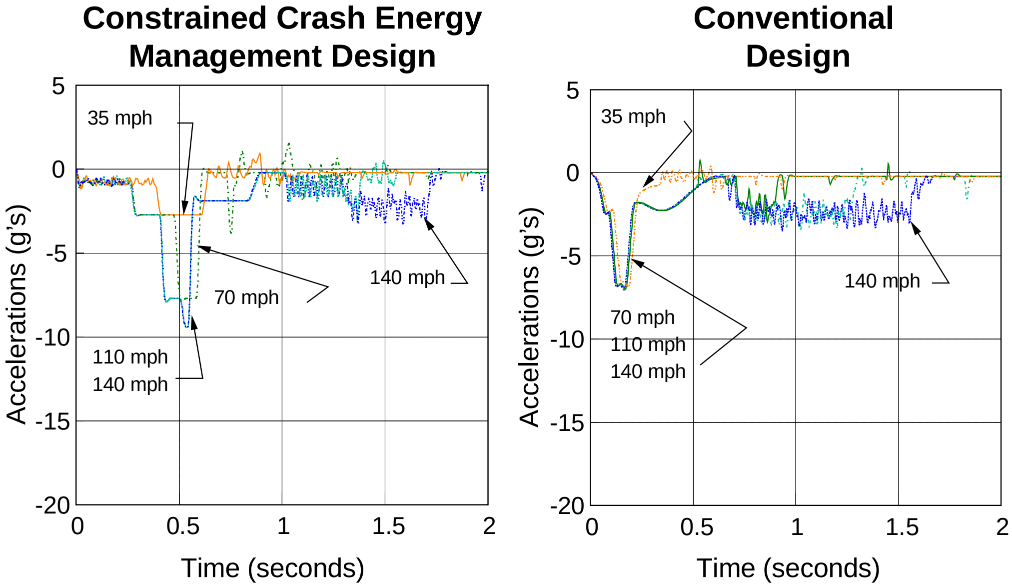
The crash pulse of the car is influenced by the car's position within the trainset. Figure 5 shows the crash pulses for each of the cars in the initially moving consist in a head-to-head collision with a 140 mph impact speed, for both the crash energy management design train and the conventional design train. For the crash energy management design train, the peak deceleration for each succeeding car occurs later and later (in time). For the conventional design train, the peak decelerations occur in rapid succession.


Constrained Crash Energy Management Design

Conventional Design

FIGURE 5. DECELERATION OF EACH CAR IN THE CONSIST, HEAD-TO-HEAD COLLISION AT 140 MPH

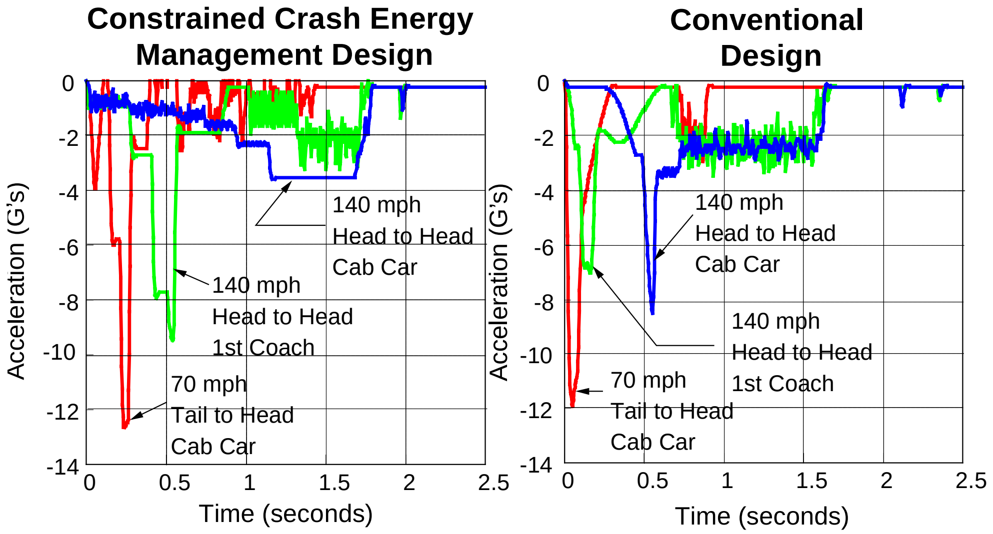
Figure 6 shows the influence of speed on the crash pulse. The principal characteristics of the crash pulse that are influenced by speed are its peak (maximum) value and its duration. For the crash energy management design, the peak deceleration of the crash pulse increases as the primary collision speed is increased, up to speeds of about 70 mph. At primary collision speeds above 70 mph, the peak value no longer increases, but the duration of the crash pulse increases. This influence of primary collision speed is due to the nature of the force/crush characteristic of the car. After some amount of crushing of the car, the force required to cause further crushing no longer increases; this constant force/crush characteristic effectively limits the maximum deceleration the car can achieve. The conventional design reaches its maximum deceleration for a primary collision closing speed of about 35 mph. For primary collision speeds above 35 mph, the only influence on deceleration of the first coach in the conventional design train is to increase the duration of the crash pulse.


Constrained Crash Energy Management Design

Conventional Design

FIGURE 6. INFLUENCE OF SPEED ON FIRST COACH CRASH PULSE, 140 MPH HEAD-TO-HEAD COLLISION

Six crash pulses were used in evaluating all of the interiors. These crash pulses are shown in Figure 7. The crash pulses were selected to represent the range of characteristics described by Tyrell, et al. (1995), including the peak deceleration and the time required to develop the peak deceleration.


Constrained Crash Energy Management Design

Conventional Design

FIGURE 7. CRASH PULSES USED IN SECONDARY COLLISION ANALYSES

The crash pulse input for MADYMO was idealized from the crash pulse predicted by the lumped-mass train model to eliminate high-frequency oscillations resulting from the computation method used in that model. Figure 8 shows an example of the lumped mass train model results and the input crash pulse used in the occupant simulation.

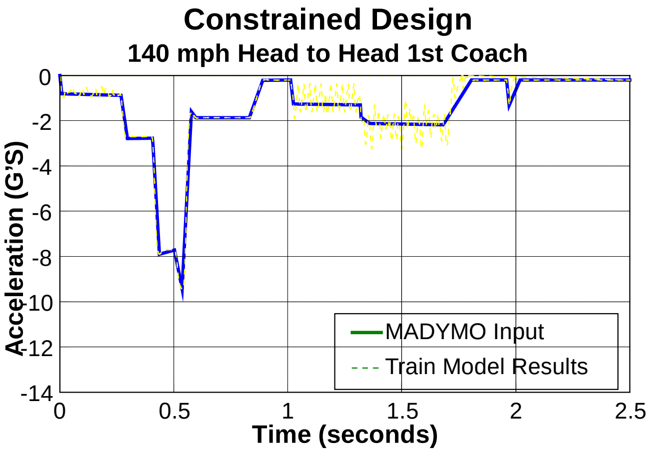


FIGURE 8. CRASH PULSE, FIRST COACH, 140 MPH HEAD-TO-HEAD COLLISION, CRASH ENERGY MANAGEMENT DESIGN, MADYMO INPUT AND TRAIN MODEL RESULTS

2.5 Injury Criteria

The head injury criteria (HIC), chest deceleration, and neck injury criteria were used to evaluate the mode and severity of predicted injuries. The Abbreviated Injury Scale (AIS), published by the American Association for Automotive Medicine (Pike, 1990), was used to provide a basis for comparison of HIC and chest deceleration. Table 1 lists the AIS Code and the corresponding values of HIC and Chest deceleration.

TABLE 1. AIS CODE, HIC, AND CHEST DECELERATION

AIS Code	HIC	Head Injury	Chest Deceleration	Chest Injury
1	135-519	Headache or dizziness	17-37 G's	Single rib fracture
2	520-899	Unconscious less than 1 hour; linear fracture	38-54 G's	2 to 3 rib fractures; sternum fracture
3	900-1254	Unconscious 1 to 6 hours; depressed fracture	55-68 G's	4 or more rib fractures; 2 to 3 rib fractures with hemothorax or pneumo-thorax
4	1255-1574	Unconscious 6 to 24 hours; open fracture	69-79 G's	greater than 4 rib fractures with hemo-thorax or pneumo- thorax; flail chest
5	1575-1859	Unconscious more than 24 hours; large hematoma	80-90 G's	Aorta laceration (partial transection)
6	>1860	Non-survivable	>90 G's	Non-survivable

The AIS is coded 0 through 6. AIS 0 indicates no injury, AIS 1 indicates minor injury, and so on. AIS 6 indicates the most severe injury which cannot be treated currently and is determined to be virtually non-survivable. For instance, a HIC of 620 corresponds with AIS code 2, where unconsciousness or linear skull fracture is possible due to head impact.

Figure 9, (Prasad and Mertz, 1985) illustrates the relationship between injury criteria and the probability of fatality (percentage of life-threatening injury). If the HIC is determined to be 1000, this would be categorized as an AIS code 3, and approximates an 18 percent risk of life-threatening injury. This means that for a group comprised of 50th percentile U.S. males subjected to the collision, 18 percent would not be expected to survive. This should not be interpreted to mean that the remaining 82 percent are unharmed; it is likely that the remaining 82 percent will have injuries, but their injuries are not expected to be life threatening. AIS codes are superimposed on the HIC graph; a similar plot can be developed for chest deceleration.

2.5.1 Head Injury Criteria (HIC). The Head Injury Criteria (SAE J885, 1986) is defined as:

$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5} \qquad (1)$$

where

a = resultant acceleration of the head in g's
t_1 = start of time interval in seconds
t_2 = end of time interval in seconds

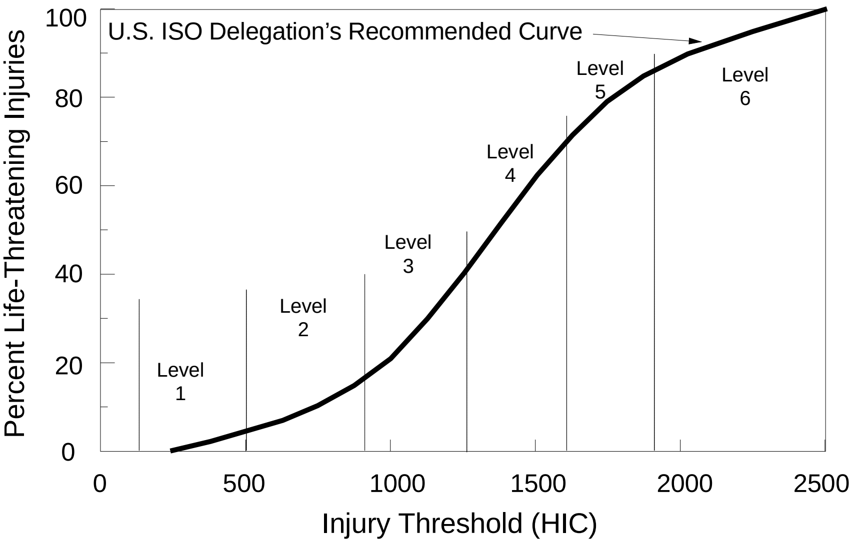


FIGURE 9. PROBABILITY OF FATALITY VS. HEAD INJURY CRITERIA

Using this equation, the maximum HIC is calculated from the acceleration time history of the occupant's head, i.e., t_1 and t_2 are chosen to maximize the HIC calculation. Time intervals greater than 36 milliseconds are not employed. The HIC calculation includes the influence of the duration of the acceleration.

2.5.2 Chest Injury Criteria. The chest deceleration injury criteria is based on the maximum resultant deceleration of the chest. Spikes in the chest deceleration time-history are discounted if they are less than 3 milliseconds in duration. For automobile crashworthiness testing, NHTSA specifies the maximum chest deceleration as 60 g's, which corresponds to a HIC of approximately 1,000 for level of expected injury.

2.5.3 Neck Injury Criteria. The axial neck load criteria (SAE J885, 1986) are used to assess injury when loads are imparted to the top of the head, in line with the spinal cord. A negative load represents a compressive force, and a positive load represents a tensile force. In this study, this condition occurs when the unrestrained occupant in the facing-seat interior impacts the rearward-facing seat. This seating configuration causes the occupant to dive head first into the seat, incurring large neck loads, even in cases with a gentle crash pulse.

This injury condition may also occur, in varying degrees, to occupants restrained with lap belts alone in the seats in rows interior. While the occupant's body is partially restrained, the head builds up angular acceleration and strikes the seat back with the top of his head. The severity of the neck injury depends principally on the length of the occupant's torso and the distance separating the seats.

In collisions with no head impact (usually occurring when the occupant is restrained with a lap belt and shoulder harness), the tensile neck load can be used to assess neck injury.

Figures 10a and 10b illustrate the neck injury criteria for axial compressive and tensile neck loads, respectively, proposed but not implemented by NHTSA (Pike, 1990). For the purpose of this paper, the criteria is used to compare the potential for neck injury between occupants involved in conventional and constrained crash energy management train collisions. In both figures, the plots show the boundary between tolerance regions; i.e. neck loads for a given duration occurring below the boundary are survivable, while neck loads above the boundary are virtually non-survivable.

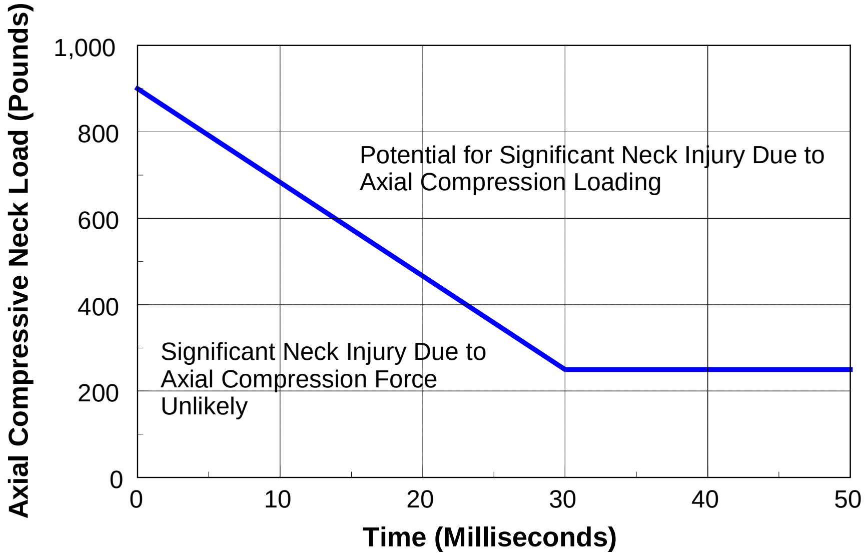


FIGURE 10a. INJURY CRITERIA FOR COMPRESSIVE NECK LOADS

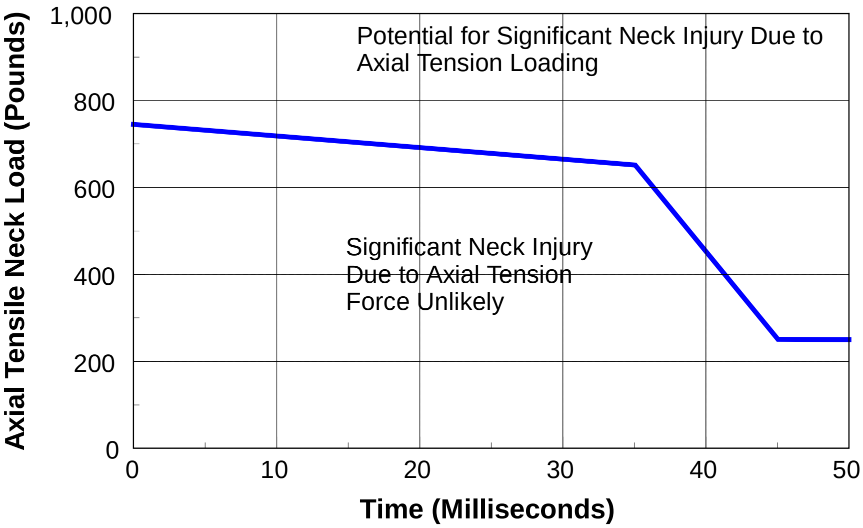


FIGURE 10b. INJURY CRITERIA FOR TENSILE NECK LOADS

3. RESULTS

3.1 Seats in Rows Interior

3.1.1 **Compartmentalization.** Figure 11 shows the computer-simulated occupant motions for the unrestrained occupant in the interior with forward-facing seats in rows. Figure 12 shows the kinematic response of the unrestrained occupant in the seats in rows interior during a 140 mph head-to-head collision for the conventionally designed train (left) and the constrained crash energy management train (right). The initial portion of the constrained crash energy management pulse is sufficiently gentle such that friction forces between the occupants' feet and the floor are large enough to keep the feet from sliding forward, causing the occupant to begin to stand up during the collision. The initial portion of the conventional pulse is sufficiently abrupt such that the occupants' feet slide on the floor.

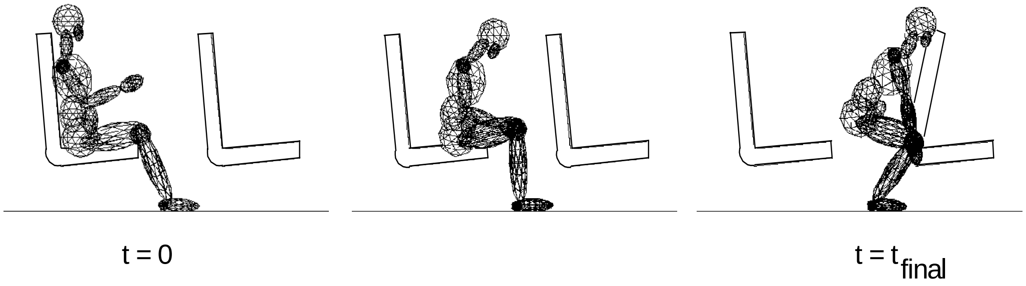


FIGURE 11. OCCUPANT MOTION, UNRESTRAINED, SEATS IN ROWS INTERIOR

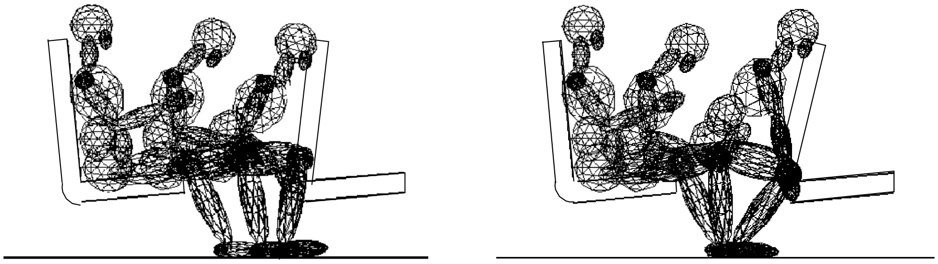


FIGURE 12. HUMAN BODY KINEMATIC RESPONSE TO INITIALLY ABRUPT AND INITIALLY GENTLE CRASH PULSE, SEATS IN ROWS INTERIOR

Figure 13 plots the deceleration time histories for the unrestrained occupant’s head and the first coach car during a 140 mph head-to-head collision. The occupant’s peak deceleration is substantially greater than the car’s, and occurs during the secondary impact, when the occupant is abruptly decelerated.

Figure 14 shows plots of the unrestrained occupant’s and the first coach car’s inertial velocity time histories for a 140 mph head-to-head collision. The more abrupt deceleration of the first coach car of the conventional design results in the occupant going into free flight, maintaining a speed of approximately 140 mph until the occupant impacts the forward seat. In general, this results in a more severe deceleration of the occupant’s head. The initially gentle deceleration of the first coach car of the constrained crash energy management design allows the occupant to begin to decelerate from 140 mph before impact with the seat. In general, this results in a less severe secondary impact.

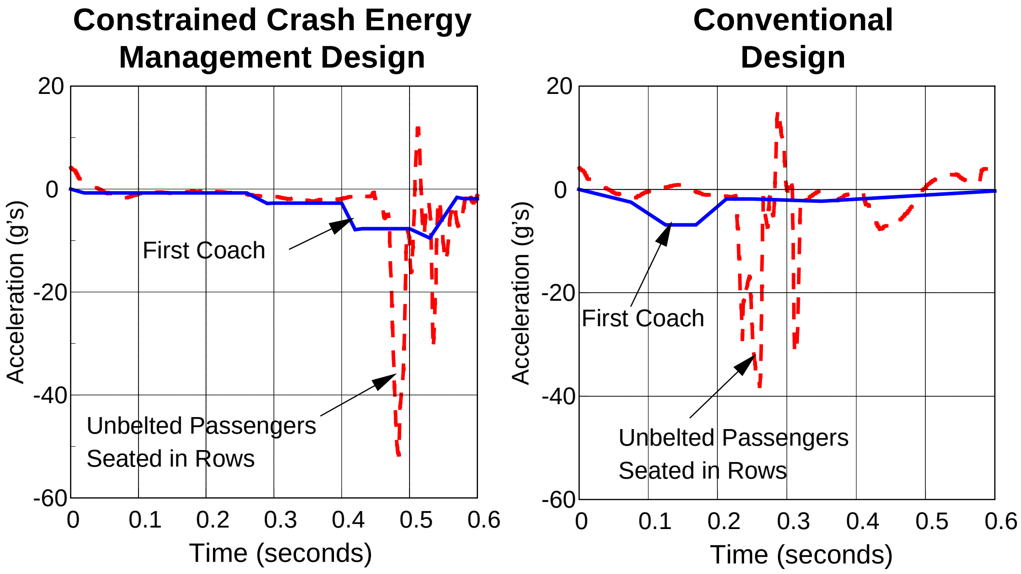


FIGURE 13. UNRESTRAINED PASSENGER AND VEHICLE DECELERATIONS, 140 MPH HEAD-TO-HEAD COLLISION

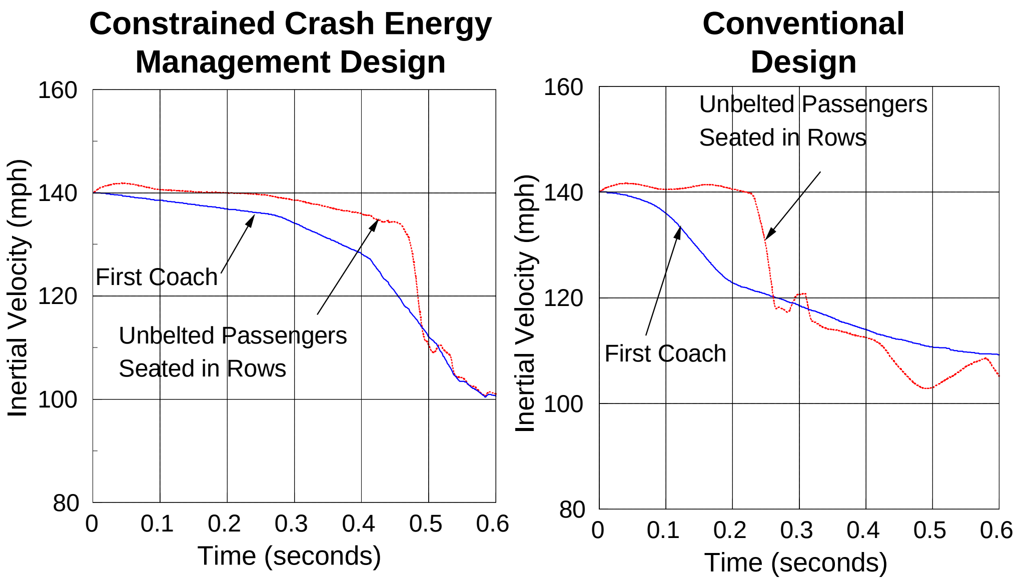


FIGURE 14. UNRESTRAINED PASSENGER AND VEHICLE VELOCITIES, 140 MPH HEAD-TO-HEAD COLLISION

In Figure 15 the relative velocity is plotted against the relative displacement for an occupant in a seats in rows interior in each car in a 140 mph head-to-head collision. The constrained crash energy management design results in substantially lower secondary impact velocities as compared to the conventional design, especially for cars behind the second coach car.

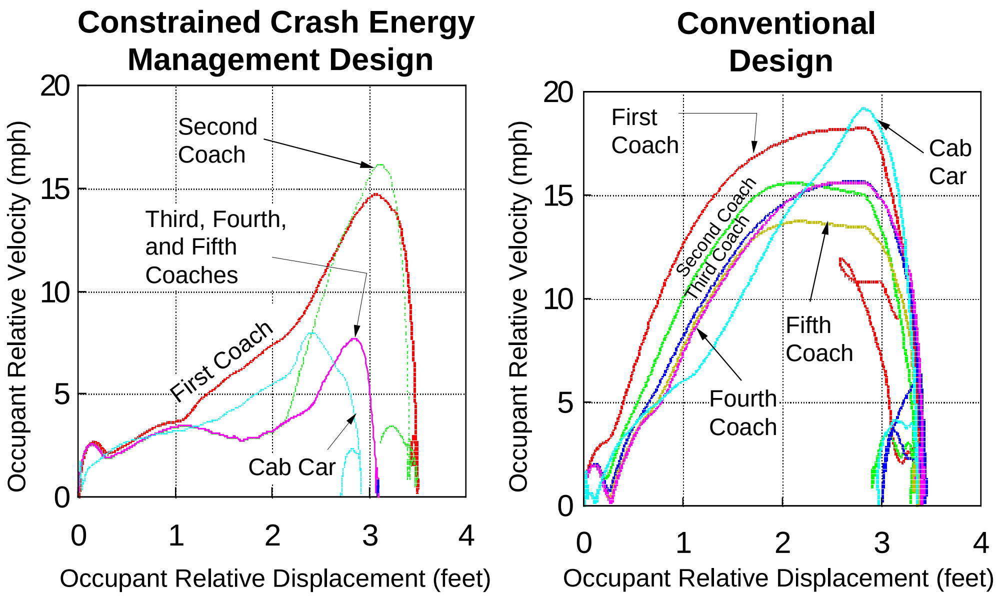


FIGURE 15. SECONDARY IMPACT VELOCITIES FOR OCCUPANTS BY PASSENGER CAR

Table 2 lists the corresponding injury criteria for an unrestrained occupant in the seats in rows interior in each of the passenger cars involved in a 140 mph head-to-head collision.

TABLE 2. INJURY CRITERIA FOR SECONDARY COLLISIONS OF UNRESTRAINED OCCUPANTS, SEATS IN ROWS INTERIOR

		HIC	**Chest G's**	**Neck Load (lbs)**
		Unbelted	**Unbelted**	**Unbelted**
Conventional Design	1st Coach	167	24	-386
	2nd Coach	77	19	-454
	3rd Coach	109	25	-436
	4th Coach	59	16	-475
	5th Coach	135	28	-368
	Cab Car	223	36	-529
Constrained Crash Energy Management Design	1st Coach	221	38	-536
	2nd Coach	313	33	-367
	3rd Coach	17	10	-301
	4th Coach	17	7	-244
	5th Coach	17	7	-244
	Cab Car	11	7	-229

3.1.2 Occupant Restraint.

Figure 16 shows how the occupant motion is influenced by the two restraint systems. The lap belt alone cannot prevent the head of a 50th percentile male from striking the forward seat with a 42-inch seat pitch. For taller occupants, or for the same occupant in an interior with the seats positioned closer together, an occupant restrained with only a lap belt could potentially suffer greater injuries than an unrestrained occupant, owing to the nature of the head impact. The combined lap belt and shoulder harness are effective in preventing the occupant from striking the forward seat.

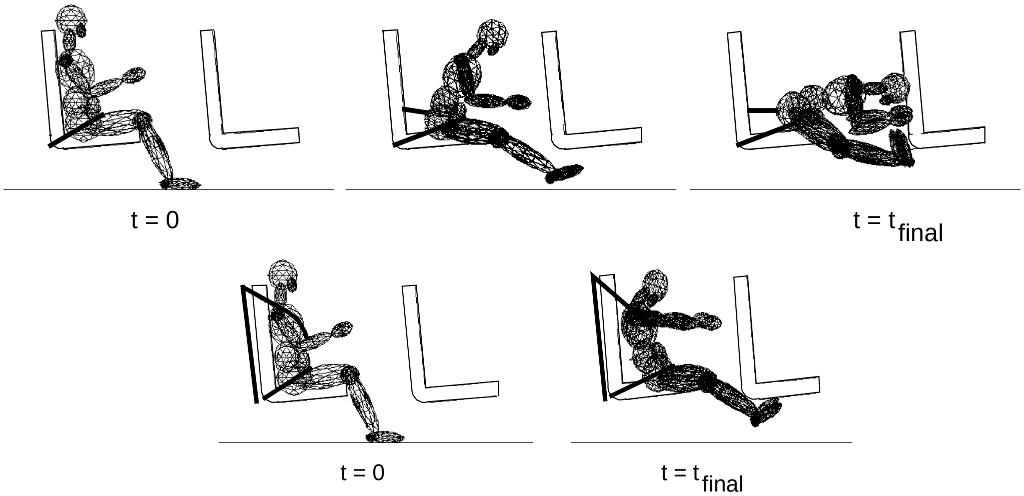


FIGURE 16. OCCUPANT MOTION, RESTRAINED WITH SEAT BELT ALONE, AND WITH SEAT BELT AND SHOULDER HARNESS, SEATS IN ROWS INTERIOR

Figure 17 shows the deceleration time history of the occupant restrained with a lap belt, in addition to the unrestrained occupant and car deceleration time histories. The figure shows a substantial decrease in the head deceleration of the restrained occupant over the unrestrained occupant for the same collision conditions.

Figure 18 shows the velocity time history of the occupant restrained with a lap belt, in addition to the unrestrained occupant and car velocity time histories. The initially gentle slope of the occupant time history (equal to the acceleration) for the crash energy management design indicates that the occupant begins to decelerate slowly before he experiences rapid deceleration during the secondary impact. This allows the occupant time to travel and strike the interior with a relatively low impact velocity. This is particularly beneficial for occupants in cars behind the second coach, because of the delayed onset of the trailing car's peak deceleration. Consequently, there is more time for the occupant to travel with a low deceleration and contact the forward seat with a low impact velocity, thus minimizing injury.

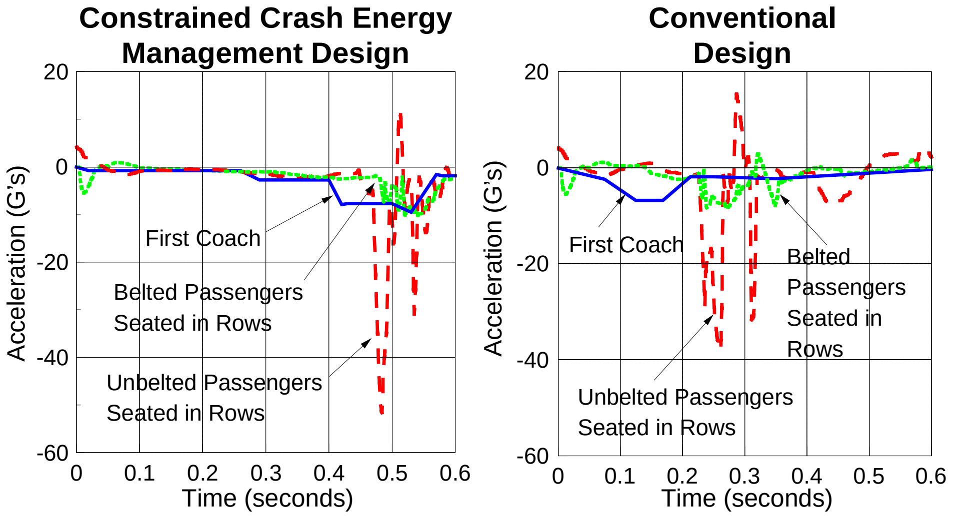


FIGURE 17. RESTRAINED PASSENGER AND VEHICLE DECELERATIONS

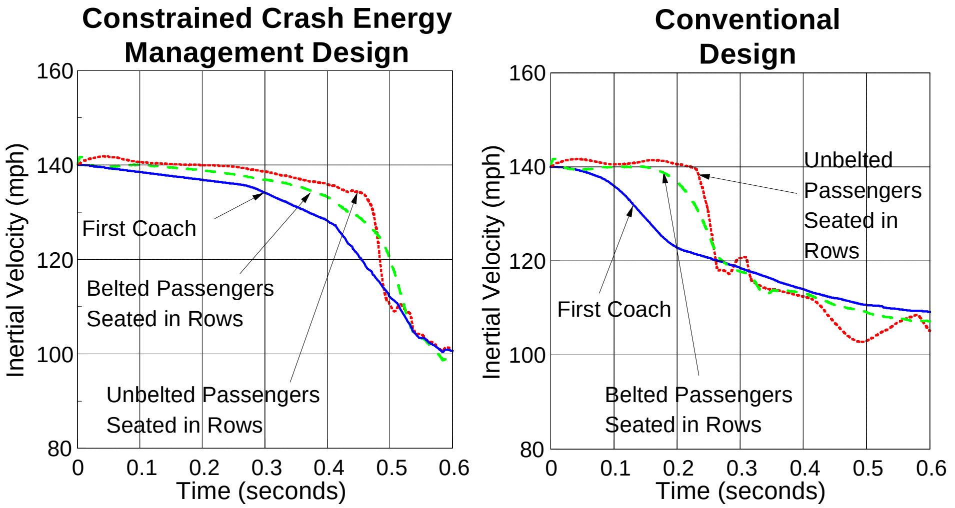


FIGURE 18. RESTRAINED PASSENGER AND VEHICLE VELOCITIES

3.1.3 Summary of Seats in Rows Results. Table 3 presents the injury criteria and the associated probability of fatal injury for unrestrained, belted, and belted-and-harnessed occupants in the seats in rows interior. The table shows that the most severe crash pulse for this interior is for the cab car when it is leading during the collision, even at a lower impact speed. The table also shows that the nominal occupant is expected to survive the deceleration in all the collision scenarios evaluated if he is restrained with lap and shoulder belts.

TABLE 3. INJURY CRITERIA AND FATALITY RATES FOR SECONDARY COLLISIONS, SEATS IN ROWS

		HIC			Chest G's			Neck Load (lbs)		
		No Belt	Lap Belt	Harness	No Belt	Lap Belt	Harness	No Belt	Lap Belt	Harness
Conven-tional Design	1st Coach 140 mph head to head	167 (0%)	46 (0%)	21 (0%)	24 (2%)	12 (0%)	9 (0%)	-386 (0%)	-290 (0%)	70 (0%)
	Cab Car 140 mph head to head	196 (0%)	18 (0%)	13 (0%)	36 (4%)	11 (0%)	10 (0%)	-529 (0%)	141 (0%)	69 (0%)
	Cab Car 70 mph tail to head	1009 (18%)	252 (0%)	90 (0%)	53 (16%)	19 (0%)	17 (0%)	-384 (0%)	-570 (0%)	171 (0%)
Constrained Crash Energy Manage-ment Design	1st Coach 140 mph head to head	221 (0%)	75 (0%)	15 (0%)	38 (4%)	20 (0%)	10 (0%)	-536 (0%)	-536 (0%)	70 (0%)
	Cab Car 140 mph head to head	13 (0%)	0 (0%)	0 (0%)	7 (0%)	2 (0%)	2 (0%)	-229 (0%)	17 (0%)	-16 (0%)
	Cab Car 70 mph tail to head	449 (2%)	170 (0%)	22 (0%)	49 (13%)	27 (2%)	13 (0%)	-335 (0%)	686 (0%)	85 (0%)

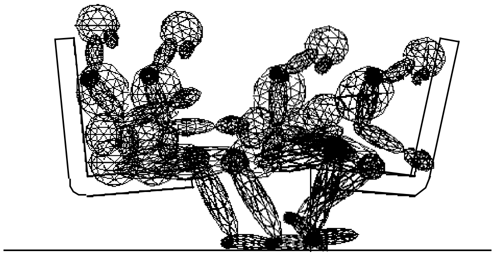
3.2 Seats Facing

Figure 19 depicts the simulated motion for an occupant that is unrestrained, belted, and belted and harnessed in the seats facing interior. For this analysis, only the forward-facing seat is occupied. It is assumed that the addition of a rearward-facing occupant in the opposing seat would increase the level of injury.

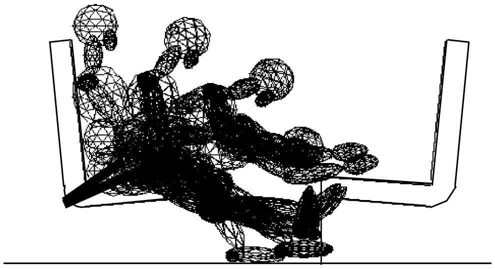
The unrestrained occupant travels a substantial distance before impacting the facing seat. This distance allows the occupant to build up speed relative to the interior, resulting in a severe impact. Due to the position of the body at impact, the inertial mass of the body follows the head into the seat, creating considerably large forces on the head and neck that are nearly unsurvivable.

The motion of the occupant restrained with only a lap belt is restricted, but the lap belt alone cannot prevent the occupant's head from striking the forward seat. The seat pan is not designed to deform very much from this type of load application, and can impart a significant force to the occupant's head.

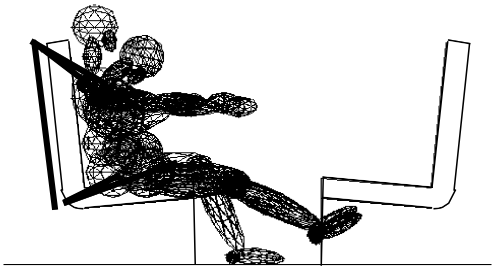
The lap belt and shoulder harness is effective at preventing contact with the forward seat. With this restraint system, the occupant experiences the same motion as in the seats in rows interior.



a. Unrestrained



b. Seat Belt



c. Seat Belt and Shoulder Harness

FIGURE 19. MOTIONS FOR OCCUPANTS IN FACING SEATS INTERIOR

Table 4 lists the probability of fatal injury for occupants that are unrestrained, belted, and belted and harnessed in the seats facing interior. This interior performed the worst among the interiors evaluated. There is near-certain fatality for the unrestrained occupant in the seats facing interior for each crash pulse considered in this evaluation. The most severe crash pulse for this interior is also for the cab car in a tail-to-head collision. For this crash pulse, there is a substantial probability of fatality even for occupants with lap belts alone. The table also shows that the nominal occupant is expected to survive for each crash pulse evaluated if he is restrained with a lap belt and shoulder belt.

TABLE 4. INJURY CRITERIA AND FATALITY RATES FOR SECONDARY COLLISIONS, FACING SEATS

		HIC			Chest G’s			Neck Load (lbs)		
		No Belt	Lap Belt	Harness	No Belt	Lap Belt	Harness	No Belt	Lap Belt	Harness
Conventional Design	1st Coach 140 mph head to head	490 (3%)	25 (0%)	21 (0%)	25 (1%)	11 (0%)	9 (0%)	-1392 (100%)	176 (0%)	70 (0%)
	Cab Car 140 mph head to head	1019 (18%)	18 (0%)	13 (0%)	33 (3%)	10 (0%)	10 (0%)	-2564 (100%)	136 (0%)	69 (0%)
	Cab Car 70 mph tail to head	3263 (100%)	1668 (75%)	90 (0%)	44 (8%)	26 (2%)	17 (0%)	-1183 (100%)	-644 (0%)	171 (0%)
Constrained Crash Energy Management Design	1st Coach 140 mph head to head	4044 (100%)	502 (3%)	17 (0%)	64 (35%)	22 (0%)	10 (0%)	-5233 (100%)	-345 (0%)	70 (0%)
	Cab Car 140 mph head to head	151 (0%)	0 (0%)	0 (0%)	27 (2%)	2 (0%)	2 (0%)	-2033 (100%)	17 (0%)	-16 (0%)
	Cab Car 70 mph tail to head	1616 (68%)	1247 (38%)	26 (0%)	31 (3%)	20 (0%)	12 (0%)	-1343 (100%)	371 (0%)	93 (0%)

3.3 Seats and Table

Figure 20 shows the occupant motion for the unrestrained forward-facing occupant. Restraints were not evaluated for this interior. As the figure shows, the table itself acts as a restraint, with a relatively short distance between the occupant and the table. This short distance does not allow the occupant to build up much speed before impacting the table, resulting in a more benign impact. One concern, however, is how the forces are distributed as they are imparted to the occupant. There is the potential of severe internal abdominal injuries if the forces are too concentrated, i.e. the table edge acts as a knife edge.

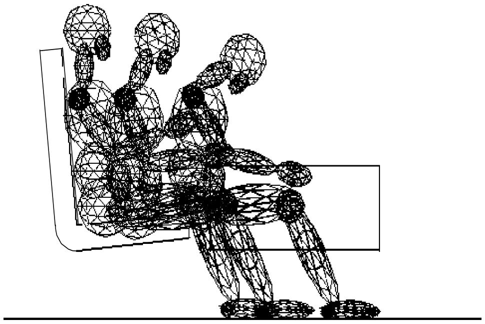


FIGURE 20. MOTIONS FOR OCCUPANTS IN SEATS AND TABLE INTERIOR

Table 5 lists the probability of fatality for the forward-facing occupant in the interior with seats and table. The probability of fatality is less than 10 percent for all the crash pulses considered except the crash pulse for the conventionally designed train with the cab car leading, where the likelihood of fatality is near certain, due to neck injury.

TABLE 5. INJURY CRITERIA AND FATALITY RATE FOR SECONDARY COLLISIONS, SEATS AND TABLE

		HIC	Chest G's	Neck Load(lbs)
Conventional Design	1st Coach, 140 mph head to head	311 (0%)	42 (7%)	602 (0%)
	Cab Car, 140 mph head to head	186 (0%)	33 (3%)	456 (0%)
	Cab Car, 70 mph tail to head	702 (7%)	51 (14%)	787 (100%)
Constrained Crash Energy Management Design	1st Coach, 140 mph head to head	110 (0%)	24 (1%)	288 (0%)
	Cab Car, 140 mph head to head	16 (0%)	16 (0%)	163 (0%)
	Cab Car, 70 mph tail to head	415 (2%)	40 (5%)	601 (0%)

4. CONCLUSIONS

4.1 Compartmentalization

The results illustrate that the judicious placement of the impact surface can be effective in reducing injuries. By placing the seats reasonably close together, the occupant will have less distance in which to build up speed relative to the occupant compartment. In the seats in rows configuration, the occupant has less than 3 feet to travel before impacting the forward seat back, while in the facing seats configuration, the occupant travels about 5 feet before impacting the seat face of the forward seat. The expected rate of fatality was found to be substantially higher in the facing seats configuration. In most cases, the occupant's relative velocity increases until he or she is stopped by the forward seat. Therefore, the impact velocity relative to the interior will be reduced as the travel distance is reduced.

In the seats and table configuration, the table acts to arrest the occupant's motion before relative velocities high enough to cause fatality can be attained. Provided that the table edges are sufficiently blunt (so as not to impart severely concentrated forces on the occupant's abdomen), the table can be an effective compartmentalization strategy.

4.2 Occupant Restraint

Current U.S. practice requires no occupant restraint system for train passengers. In some configurations modeled (i.e. seats in rows), compartmentalization can be as effective as occupant restraint for the 50th percentile male. A restraint system is most effective in train interiors that do not employ suitable compartmentalization strategies, such as the facing seats interior. In interiors where there are large distances between seats, restrained occupants have a much greater chance of survival. Fatalities from secondary impacts are not expected in any of the scenarios modeled if the occupant is restrained with a lap belt and shoulder harness.

The analysis suggests that it may be more hazardous for an occupant of larger stature to be restrained with a lap belt alone than to be unrestrained in some interiors. For instance, in the seats in rows interior, potentially large axial neck loads may be encountered when the occupant's upper torso rotates around the lap belt, and the occupant's head strikes the forward seat. This adverse situation may also occur for an average size occupant if the seats are positioned with a seat pitch less than the 42 inches modeled.

4.3 Crash Pulse

Car position has a significant influence on the vehicle's crash pulse. While the peak decelerations are slightly higher and the durations longer for the crash energy management design than for the conventional design (see Figure 5), the timing of the peaks has a more critical affect on the secondary impact an occupant experiences. For occupants seated in rows, in cars behind the second coach car, the delayed timing of the crash energy management design crash pulse peaks gives the occupant sufficient time to travel in free flight and undergo the secondary impact before the car experiences a rapid deceleration. When an occupant is in contact with the interior, the occupant will experience a deceleration nearly equal to that of the train.

As seen in the results for the 140 mph head-to-head collision for unrestrained occupants seated in rows (see Table 2), the values for injury criteria are relatively low for all cars for both the conventional and the crash energy management design. However, the injury severity for occupants in the crash energy management design cars decreases sharply after the second coach car. Injuries experienced by occupants in cars behind the second coach are classified on the AIS injury scale as Code 0, or no injury, based upon HIC and chest deceleration.

In the conventional design, occupants in cars away from the initial train-to-train collision do not experience a less severe secondary impact than occupants in cars near the collision. Occupants in each car except the fourth coach experience injuries classified as AIS Code 1, or minor injuries. The results from the crash energy management design indicate that the AIS Code can be reduced to zero.

5. ACKNOWLEDGMENTS

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