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# Evaluation of Selected Crashworthiness Strategies for Passenger Trains

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## Abstract

There has been recent interest in high speed passenger rail. The potential for collisions at increased speeds has renewed concerns about the crashworthiness of passenger rail vehicles. Studies have been conducted to evaluate the effectiveness of alternative strategies for providing crashworthiness of the vehicle structures and interiors at increased collision speeds.

Conventional practice has resulted in cars of essentially uniform longitudinal strength. This approach has been found to be effective for train-to-train collision speeds of up to 31 m/s (70 mph). This uniform strength causes the structural crushing of the train to proceed uniformly, through both the unoccupied and occupied areas of the train. The crash energy management approach results in varying longitudinal strength, with high strength in the occupied areas and lower strength in the unoccupied areas. This approach attempts to distribute the structural crushing throughout the train to the unoccupied areas to preserve the occupant volumes and to limit the decelerations of the cars. The crash energy management approach has been found to offer significant benefits for higher speed collisions.

The interior crashworthiness analysis evaluated the influence of interior configuration and occupant restraint on fatality resulting from occupant motions during a collision. For a sufficiently gentle train deceleration, compartmentalization (a strategy for providing a "friendly" interior) can provide sufficient occupant protection to keep accepted injury criteria below the threshold values applied by the automotive industry. Seatbelts and shoulder restraints reduce the likelihood of fatality due to deceleration to near-certain survival for even the most severe collision conditions considered.

*Keywords:*
Structural Crashworthiness
Crash Energy Management
Interior Crashworthiness
Occupant Restraint

# 1. INTRODUCTION

There has been recent interest in high speed passenger rail, with speeds in excess of 56 m/s (125 mph). The potential for collisions at increased speeds and collisions involving passenger vehicles and vehicles with substantially different structures has renewed concerns about the passenger rail vehicle crashworthiness. Studies have been conducted to evaluate the effectiveness of alternative strategies for providing crashworthiness of the vehicle structures and interiors at increased collision speeds. This paper describes comparisons of strategies for structural crashworthiness of passenger vehicles and describes comparisons of strategies for interior crashworthiness for protection of occupants of the train during collisions.

## 1.1 Background

Trains may collide with objects which are relatively small, such as an animal on the tracks, to highway vehicles, to maintenance of way equipment, to another train. Most of these collisions can only occur in the normal running direction of the train, however, impacts into the side of the train can occur at grade crossings. Derailment can lead to the train rolling over, inducing high loads into the side of the cars and roof. Longitudinal collisions can occur at any speed up to the operating speed of the train. Highway vehicle collisions into the side of the train can occur for lower speeds.

In addition to the primary collision between the train and the impacted object, there is also a secondary collision between the occupants and the interior. Causes of fatality associated with the primary collision include crushing of the occupant compartment, in which the occupants themselves are crushed, local penetration into the occupant compartment, where an object intrudes into the occupant compartment and directly strikes an occupant, and occupant ejection from the occupant compartment, where an occupant is thrown from the train and strikes some element of the wayside. Causes of fatality associated with secondary collisions include excessive deceleration of the head or chest of the occupant and excessive forces imparted to the body, such as axial neck loads.

In designing for crashworthiness the first objective is to preserve a minimum occupant volume for the occupants to ride out the collision. Preserving the occupant volume is accomplished with strength of the structure, i.e., if the occupant compartment is sufficiently strong, then there will be sufficient space for the occupants to ride out the collision. The second objective is to limit the forces and decelerations imparted to the occupants to acceptable levels of human tolerance. Limiting the decelerations and forces is accomplished through a combination of structural crashworthiness measures, allowing portions of the vehicle to crush in a pre-determined manner thereby limiting the decelerations of the vehicle, and interior crashworthiness measures, including the use of occupant restraints, such as seatbelts and shoulder harnesses, and the application of strategies such as compartmentalization.

To evaluate the performance of a train in a particular collision, the collision mechanics of the train must to be estimated or determined, the likelihood of car-to-car over-ride and lateral buckling of the train needs to be known, and the forces acting between cars and the crushing behavior of the cars must be developed. Once the behavior of the train has been determined, the interior performance can be evaluated. (A detailed review of transportation crashworthiness practice and research, and its applicability to passenger rail transportation, is presented in reference [1].)

## 2. STRUCTURAL CRASHWORTHINESS

Conventional practice has resulted in cars of uniform longitudinal strength. The crash energy management approach results in varying longitudinal strength throughout the train, with high strength in the occupied areas and lower strength in the unoccupied areas. This approach attempts to distribute the structural crushing throughout the train to the unoccupied areas in order to preserve the occupant volumes and to limit the decelerations of the cars. This initial analysis compares the structural crashworthiness of passenger vehicles designed to conventional practice and passenger vehicles designed to allow the ends of the cars to crush. This strategy has received much attention in recent years in Japan [2], France [3], and England [4, 5, 6].

### 2.1 Analysis Approach

The collision scenario used to make the comparison between the two structural crashworthiness strategies is a head-on collision of two identical trains, one moving at speed and the other standing. In order to do the analysis and provide a basis for comparison, it is assumed that the collision mechanics of the train allow the trains to stay in-line and remain upright.

The model used in the analysis consists of lumped masses connected by non-linear force/crush characteristics. The comparison between the two strategies is accomplished by developing the non-linear force/crush characteristics for the cars and applying the model to determine the occupant volume lost and the secondary impact velocities for a range of collision speeds. The train modeled for the structural crashworthiness analysis is made up of a power car, six coach cars, and another power car, with the power cars each weighing 890 kN (200 kips) and the coaches 534 kN (120 kips).

## 2.2 Conventional Design

Figure 1. shows the car-to-car force/crush characteristic used for the conventional design train. This characteristic is based upon the force/crush characteristic developed for the Silverliner car [7], modified to allow for a shear-back coupler design and a more gradual crushing of the end structure. The maximum strength developed is the force required to cause gross yielding of the structure.

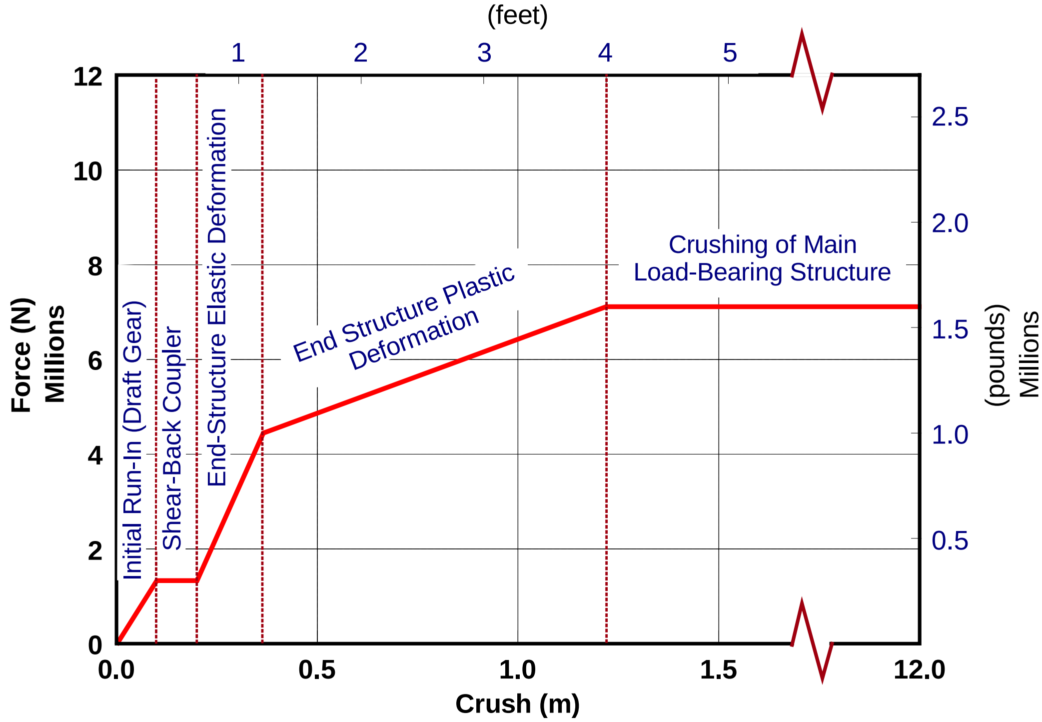


Figure 1. Conventional Design Crush Characteristic, for Power Car to Power Car, Power Car to Coach Car, and Coach Car to Coach Car.

## 2.3 Crash Energy Management Design

The crash energy management design force/crush characteristics were developed by determining the decelerations for each of the cars required to produce acceptable conditions for the occupants, and then determining the forces required between cars to produce those decelerations. These forces and decelerations were adjusted within constraints for the forces and the crush distances of the car structures. The forces were constrained to be between 7.1 MN (1.6 million lbs), presuming that greater strength would incur excessive vehicle weight, and 1.8 MN (400 thousand lbs), presuming that less strength would impair the vehicle's ability to support service loads. Constraints placed on crush distances include 1.2 m (4 feet) of available crush distance ahead of the operator's cab in the front of each power car, 7.77 m (25½ feet) of available crush distance at the rear of the power car, and 1.4 m (4½ feet) of available crush distance at each end of all the coach cars. Additional constraints include symmetry, i.e. the train has to be able to withstand collisions in both directions, and a minimum number of crush characteristics such that only one coach car structural design and one power car structural design are required. Figure 2. shows the force/crush characteristic between the standing and moving power cars, between the power car and first coach, and between the remaining coaches.

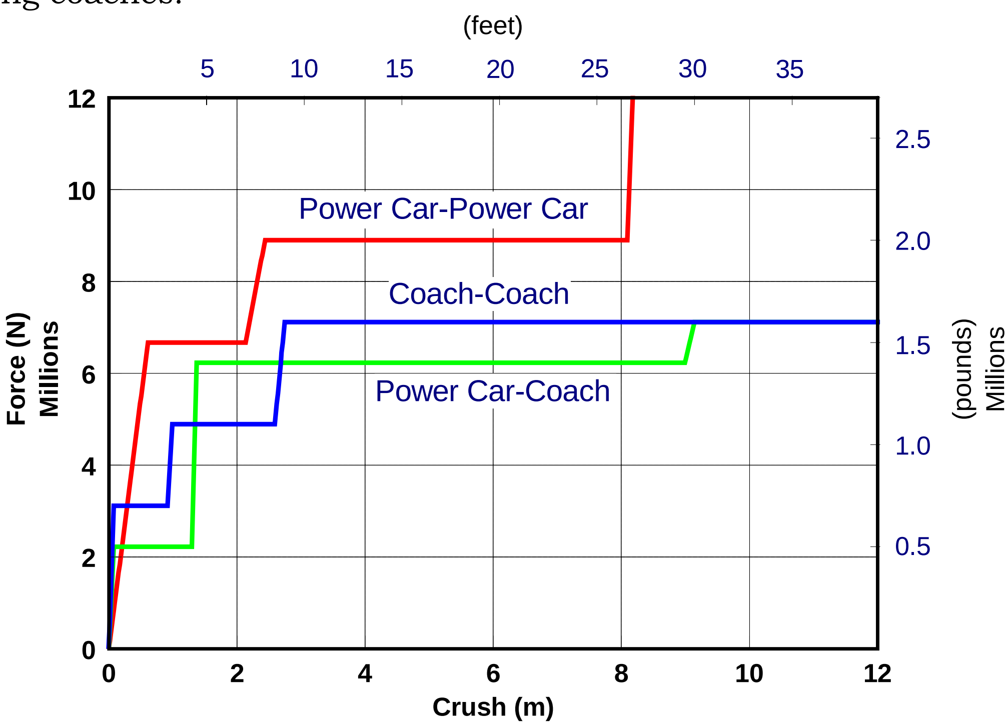


Figure 2. Crash Energy Management Design Force/Crush Characteristics

### 2.4 Analysis Results and Comparison

The scenario considered is a moving train colliding with a standing train. Both designs were analyzed for their performance in this scenario for a range of closing speeds. The basis for comparison is the loss of occupant volume and the deceleration imparted to the occupants during the secondary impact between the occupant and the seat back ahead of him.

#### *2.4.1 Occupant Volume*

Figure 3a. illustrates the occupant volume lost in each of the cars for the conventional design train for four closing speeds ranging from 16 m/s (35 mph) to 63 m/s (140 mph). Most of the occupant volume lost is in the first coach car. The figure shows that the crushing of the train starts at the front and proceeds toward the rear of the train. Figure 3b. illustrates the occupant volume lost in each of the cars for the constrained crash energy management design train for four closing speeds ranging from 16 m/s (35 mph) to 63 m/s (140 mph). The figure shows that this design approach is successful in distributing the crush throughout the train. The figures show that for closing speeds up to about 31 m/s (70 mph), the conventional design preserves all of the passenger volume, while the constrained crash energy management design preserves most of the passenger volumes up to 49 m/s (110 mph). The additional occupant volume lost for closing speeds above 31 m/s (70 mph) is much greater for the conventional design than the constrained crash energy management design.

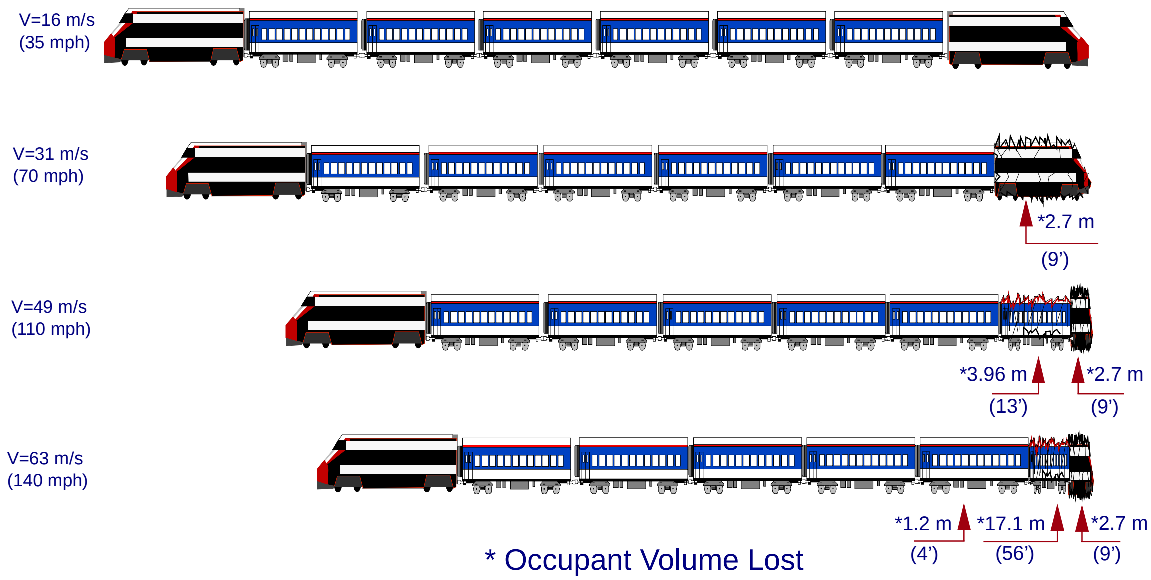


Figure 3a. Occupant Volume Loss for a Range of Closing Speeds, Conventional Design.

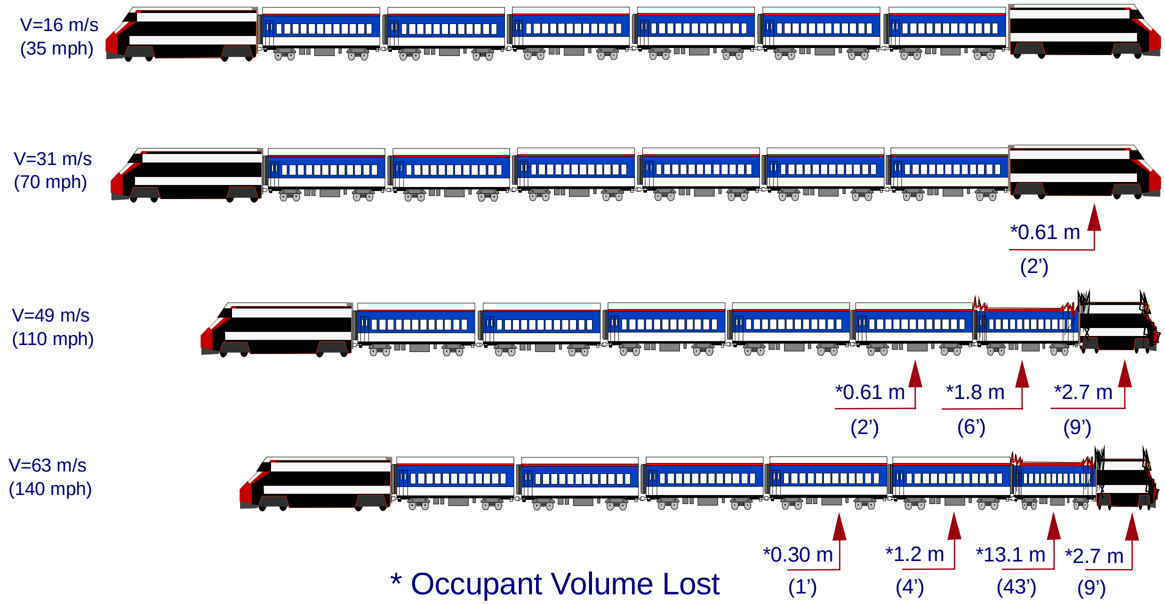


Figure 3b. Occupant Volume Loss for a Range of Closing Speeds, Constrained Crash Energy Design.

### *2.4.2 Occupant Deceleration*

When sufficient volume is preserved for the occupant to ride out the collision, the occupant can still be injured by excessive deceleration or forces. These forces and decelerations principally come about, for an unrestrained occupant, when the occupant strikes the interior. How hard the occupant strikes the interior depends upon the deceleration of the train itself during the collision and the 'friendliness' of the interior. In order to provide a basis for comparison between the decelerations generated by the conventional design and by the constrained crash energy management design, a simplified model of an occupant is used to calculate the decelerations of the occupant's head, and these decelerations are then compared with accepted injury criteria.

The occupant model is based on the assumption that the occupant goes into free flight at the start of the collision and subsequently strikes the interior. The occupant is assumed to strike the seat back ahead of him, which has some amount of padding and flexibility. Given the seat back force/deflection characteristic and the nominal mass of the head, the deceleration of the head can be calculated from the velocity with which the head impacts the seat back. The head deceleration can then be evaluated based upon generally accepted injury criteria. The deceleration time history of the head can be used to calculate the Head Injury Criteria (HIC)[8], an injury criteria widely applied in the automotive and aircraft industries to evaluate test and analysis data. The seat back force/deflection characteristic used in the analysis is the softest characteristic described in the National Highway Traffic Safety Administration (NHTSA) standard 49CFR571.222 - School Bus Seating and Crash Protection [9].

Figure 4. shows plots of occupant velocity relative to the vehicle as a function of displacement relative to the vehicle for both the constrained crash energy management design and conventional design at 45 m/s (100 mph). The distance from the occupant's nose to the seat back ahead of him is assumed to be 0.76 m (2½ feet) -- the seat pitch (longitudinal distance between two seats one row apart) is assumed to be 1.1 m (42 inches), the occupant's head is assumed to be 0.20 m (8 inches) deep, and the padding on the seat is assumed to be 0.10 m (4 inches) thick.

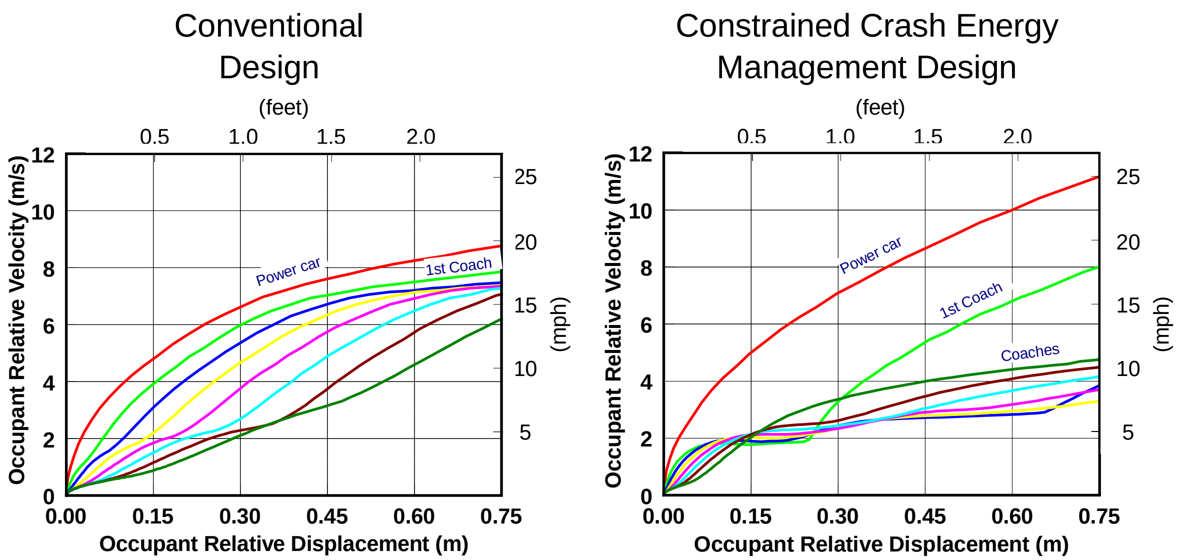


Figure 4. Occupant Relative Displacement vs. Occupant Relative Velocity.

Table 1. lists the range of HIC values expected on the moving train for several collision speeds, for both the crash energy management and conventional design trains. The crash energy management design results in substantially lower HIC values. This is a result of the lower secondary collision velocities for most of the cars in the consist.

Table 1. HIC Values, Conventional and Crash Energy Management Designs

| Primary Collision Speed (m/s)* | | HIC Coaches | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Conventional Design | 63 | 230-480 | 190-430 | 180-400 | 180-400 | 160-360 | 120-250 |
| | 49 | 230-480 | 190-430 | 180-400 | 180-400 | 160-360 | 120-250 |
| | 31 | 230-480 | 190-430 | 180-400 | 180-400 | 160-360 | 120-250 |
| | 16 | 200-440 | 180-400 | 180-400 | 180-400 | 170-375 | 160-350 |
| Crash Energy Management Design | 63 | 240-490 | 40-80 | 20-50 | 30-70 | 50-110 | 60-140 |
| | 49 | 235-485 | 40-80 | 20-50 | 30-70 | 50-110 | 60-140 |
| | 31 | 230-480 | 30-70 | 20-50 | 30-70 | 50-110 | 60-140 |
| | 16 | 160-350 | 10-40 | 10-40 | 30-70 | 40-120 | 50-130 |

* 1 m/s = 2.2 mi/h

### 2.5 Structural Crashworthiness Analysis Conclusions

For train-to-train collisions at closing speeds above 31m/s (70 mph), the constrained crash energy management design is more effective than the conventional approach in preserving occupant volume. For closing speeds below 31m/s (70 mph), both strategies are equally effective in preserving occupant volume. The constrained crash energy management design does result in gentler secondary impacts than the conventional design, for train to train collisions at all speeds analyzed.

# 3. INTERIOR CRASHWORTHINESS

The objective of the interior analysis was to evaluate the influence of interior configuration, seat belts, and seat belts with shoulder harnesses on fatality resulting from occupant motions during a collision. Three different interior configurations were analyzed: forward facing consecutive rows of seats, facing rows of seats, and facing rows of seats with a table. Both the forward facing consecutive rows of seats and facing rows of seats interiors were evaluated with the occupant unrestrained, restrained with a seat belt alone, and restrained with a seat belt and shoulder harness.

As part of this analysis, the effectiveness of "compartmentalization" as a means of occupant protection was evaluated. Compartmentalization is a strategy for providing a "friendly" interior for the occupants to survive the secondary collision. By providing a sufficient amount of cushion and flexibility in the surface of impact (e.g. the seat back), the impact force experienced by the occupant can be reduced to a survivable level. NHTSA concluded that this strategy justifies the absence of seat belts in school buses [10].

## 3.1 Collision Conditions

The train modeled for the interior crashworthiness analysis is made up of a power car, five coach cars, and cab car. This train model was exercised for a range of collision conditions and the results which describe the decelerations of the cars in the train during the collision were used in evaluating train interior performance. The three different interior configurations were evaluated for their performance with respect to secondary impacts, using six different crash pulses. These collision conditions are listed in Table 2.

Table 2. Train Collision Conditions for Interior Analysis

| Constrained Crash Energy Management Design | Conventional US Design |
|---|---|
| **First Coach**<br>Power Car to Power Car Collision<br>63 m/s* Impact Speed | **First Coach**<br>Power Car to Power Car Collision<br>63 m/s Impact Speed |
| **Cab Car** (Last Car)<br>Power Car to Power Car Collision<br>63 m/s Impact Speed | **Cab Car** (Last Car)<br>Power Car to Power Car Collision<br>63 m/s Impact Speed |
| **Cab Car** (Leading Car)<br>Cab Car to Power Car Collision<br>31 m/s Impact Speed | **Cab Car** (Leading Car)<br>Cab Car to Power Car Collision<br>31 m/s Impact Speed |

* 1 m/s = 2.2 mi/h

## 3.2 Analysis Approach

The analysis was performed using MADYMO, a computer simulation program developed for evaluating the performance of automobile interiors during frontal automobile collisions [11]. The computer program produces a detailed representation of human body kinematics and dynamics. Program outputs include a number of criteria for evaluating occupant fatality. For this evaluation, the HIC, chest deceleration, and axial neck load were used to evaluate the performance of the interior.

Computer simulations were made of each of the interior configurations for each of the crash pulses. A total of 42 computer simulations were made. The occupant modeled for each of these simulations was the 50th percentile male (The US male whose physical features are the median, e.g. half the male population is taller and half is shorter, half is heavier and half is lighter, etc.).

The analyses results described in this paper are for the nominal male, and may be different for occupants of a different size or age. The initial position of the occupant may also have an influence on these results, as well as the conscious response of the occupant to the collision. The model implemented in MADYMO is based on the assumption that the occupant is passive during the collision. (It should also be noted that the principal cause of fatality is expected to be loss of occupant volume, which may account for approximately 75% of the fatalities during a collision [12].)

### *3.2.1 Injury Criteria*

The HIC is a function of the relative acceleration of the head during impact. It can be used to predict the probability of fatality resulting from head injury [13]. As required in standard 49CFR571.208 by NHTSA, the HIC value shall not exceed 1000 for a vehicle impacting a fixed collision barrier at 13 m/s (30 MPH). This corresponds to a predicted fatality rate of approximately 18% for the 50th percentile male.

In addition to HIC, chest deceleration and neck load were also evaluated as part of the interior crashworthiness analysis. Chest deceleration is also used by NHTSA and the FAA to evaluate crashworthiness performance, with the commonly accepted maximum value of 588 $m/s^2$ (60 G's). This deceleration corresponds approximately to a 22% fatality rate for the 50th percentile male. The compressive and tensile neck load limits used in the analysis were proposed as regulations by NHTSA, but were not implemented [14].

## 3.3 Results

### *3.3.1 Seated Rows*

Figure 5. shows the computer simulated occupant motions for the unrestrained, belted, and belted and harnessed occupant in the interior with forward facing consecutive rows of seats. (In the interest of reducing the computations required to generate the graphical output, these results are generated from just the human-body kinematics and do not show the deformations of the body components, such as the head, neck, chest, etc. or the deformations of the seat. As a consequence, the seat back appears to intrude into the occupant's head in the figure for the unrestrained occupant. In the simulation itself this intrusion is not allowed to occur; it is an artifact of the simplified graphical output.)

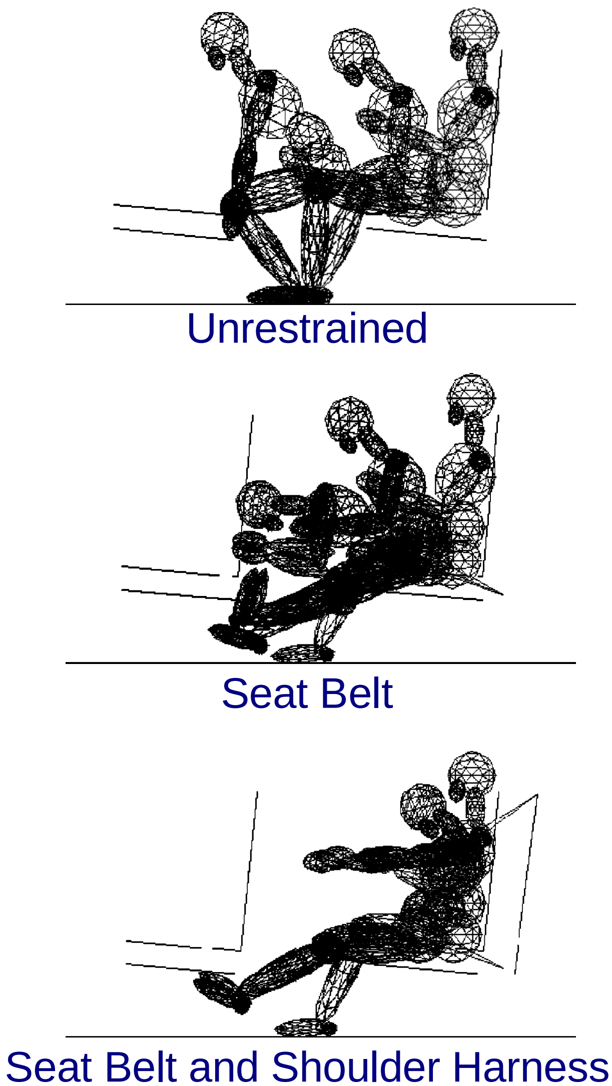


Figure 5. Occupant Motion, Seated Rows Interior.

The analysis results show that the motions of the occupant during a collision are insensitive to the crash pulse. These motions depend principally on the interior configuration and the occupant restraint or lack of restraint. The instantaneous velocity of the occupant at any given time during his or her motion is sensitive to the crash pulse. The mode of injury depends upon the interior and the type of occupant restraint, but whether or not the forces or decelerations imparted to the occupant are sufficient to cause injury depends upon the crash pulse and the force/deflection characteristic of the impacted surface.

Table 3. lists the values for the selected injury criteria and the associated probabilities of fatal injury for unrestrained, belted, and belted and shoulder harnessed occupants in the row seat 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. 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 seat and shoulder belts.

Table 3. Injury Criteria and Fatality Rates For Secondary Collisions Seated, Rows

| Crash Pulse | | HIC | | | Chest Accel. ($m/s^2$)* | | | Neck Load (N)** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Belted | Harness | Unbelted | Belted | Harness | Unbelted | Belted | Harness | Unbelted |
| Conventional Design | 1st Coach 63 m/s Power Car to Power Car | 45 (0%) | 21 (0%) | 167 (0%) | 117 (0%) | 88 (0%) | 235 (2%) | -1290 (0%) | 310 (0%) | -1720 (0%) |
| | Cab Car 63 m/s Power Car to Power Car | 18 (0%) | 13 (0%) | 196 (0%) | 107 (0%) | 98.1 (0%) | 353 (4%) | 627 (0%) | 310 (0%) | -2350 (0%) |
| | Cab Car 31 m/s Cab Car to Power Car | 74 (0%) | 42 (0%) | 662 (4%) | 186 (0%) | 167 (0%) | 520 (16%) | -2540 (0%) | 761 (0%) | -1710 (0%) |
| Crash Energy Management Design | 1st Coach 63 m/s Power Car to Power Car | 75 (0%) | 15 (0%) | 221 (0%) | 196 (0%) | 98.1 (0%) | 373 (4%) | -2380 (0%) | 310 (0%) | -2380 (0%) |
| | Cab Car 63 m/s Power Car to Power Car | 0 (0%) | 0 (0%) | 13 (0%) | 20 (0%) | 20 (0%) | 69 (0%) | 76 (0%) | -71 (0%) | -1020 (0%) |
| | Cab Car 31 m/s Cab Car to Power Car | 170 (0%) | 22 (0%) | 587 (2%) | 265 (2%) | 127 (0%) | 481 (13%) | 3050 (0%) | 380 (0%) | -1490 (0%) |

* 1 $m/s^2$ = 0.10 G's
** 1 N = 0.22 lbf

### *3.3.2 Facing Seats*

Figure 6. shows the computer simulated motions for an occupant that is unrestrained, belted, and belted with a shoulder harness in the interior with

facing rows of seats. For this analysis, only the forward seat is occupied. The occupant travels a substantial distance before impacting the seat back of the facing seat. This distance allows the occupant to build up speed relative to the interior, resulting in a severe impact.

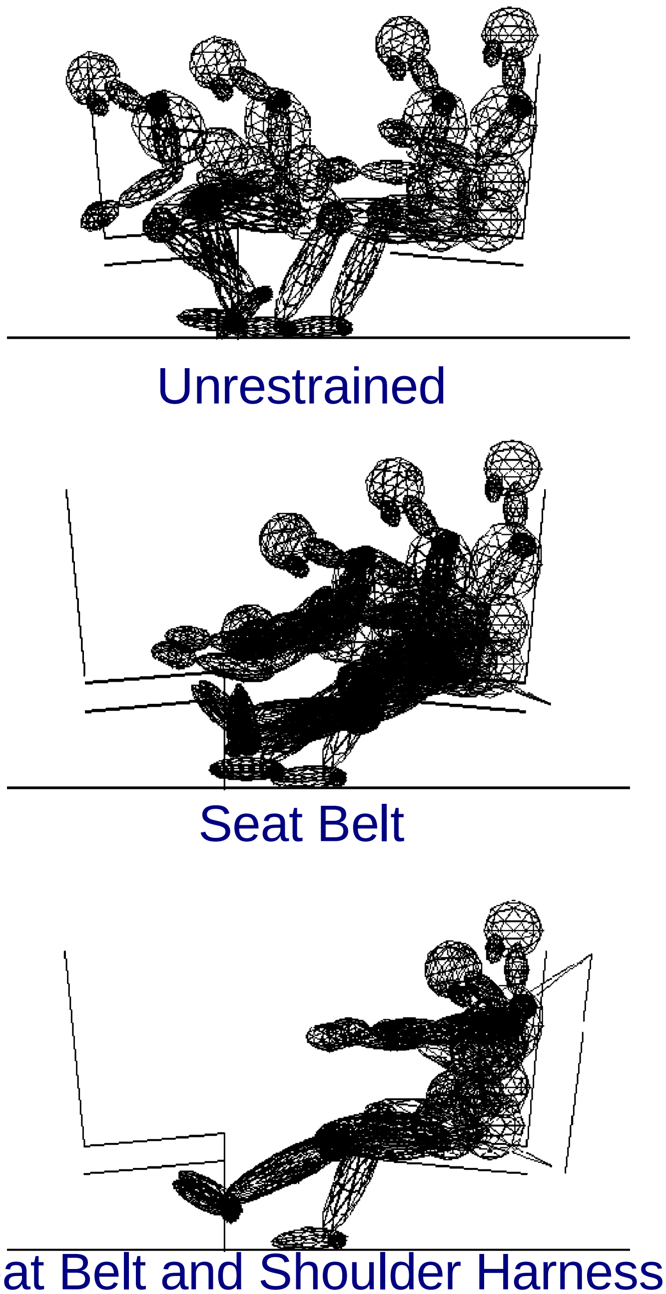


Figure 6. Occupant Motion, Facing Seats Interior.

Table 4. lists the values for the selected injury criteria and the associated probabilities of fatal injury for occupants that are unrestrained, belted and belted with a shoulder harness in the facing seats interior. This interior was

the worst performing interior evaluated. There is certain fatality in this interior configuration for all crash pulses considered for an unrestrained 50th percentile male occupant facing forward with the assumed initial position. (The outcome of the secondary collision is likely to be influenced by the occupant's size and initial position, as well as the occupant's response to the collision. These results are not sufficient to justify the conclusion that all passengers with sufficient occupant volume to survive are killed by the secondary collision.) The most severe crash pulse for this interior is for the cab car when it is leading during the collision, similar to the interior with rows of seats all facing the same direction. 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 the deceleration for all the crash pulses used in the evaluation if the occupant is restrained with a lap belt combined with a shoulder belt.

Table 4. Injury Criteria and Fatality Rates For Secondary Collisions
Facing Seats

| Crash Pulse | | HIC | | | Chest Accel. ($m/s^2$) * | | | Neck Load (N) ** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Belted | Harness | Unbelted | Belted | Harness | Unbelted | Belted | Harness | Unbelted |
| Conventional Design | 1st Coach 63 m/s Power Car to Power Car | 34 (0%) | 21 (0%) | 490 (3%) | 108 (0%) | 88 (0%) | 245 (1%) | 782 (0%) | 310 (0%) | -6140 (100%) |
| | Cab Car 63 m/s Power Car to Power Car | 18 (0%) | 13 (0%) | 1019 (18%) | 98.1 (0%) | 98.1 (0%) | 324 (3%) | 605 (0%) | 310 (0%) | -11410 (100%) |
| | Cab Car 31 m/s Cab Car to Power Car | 1668 (75%) | 42 (0%) | 3263 (100%) | 255 (2%) | 167 (0%) | 432 (8%) | -2860 (0%) | 761 (0%) | -5262 (100%) |
| Crash Energy Management Design | 1st Coach 63 m/s Power Car to Power Car | 502 (3%) | 17 (0%) | 4044 (100%) | 216 (0%) | 98.1 (0%) | 628 (35%) | -1530 (0%) | 310 (0%) | -23280 (100%) |
| | Cab Car 63 m/s Power Car to Power Car | 0 (0%) | 0 (0%) | 151 (0%) | 20 (0%) | 20 (0%) | 265 (2%) | 76 (0%) | -71 (0%) | -9043 (100%) |
| | Cab Car 31 m/s Cab Car to Power Car | 1247 (38%) | 26 (0%) | 1616 (68%) | 196 (0)% | 118 (0)% | 304 (3%) | 1650 (0%) | 410 (0%) | -5974 (100%) |

* 1 $m/s^2$ = 0.10 G's
** 1 N = 0.22 lbf

### *3.3.3 Seats and Table*

Figure 7. shows the occupant motions for the unrestrained forward facing occupant. The table itself acts a restraint, with a relatively short distance between the occupant and table, which does not allow the occupant to build up much speed before impacting the table. One concern is how the forces between that table and the occupant are distributed. There is the potential of severe

internal abdominal injuries if the forces are too concentrated, i.e., if the table edge acts as a knife edge.

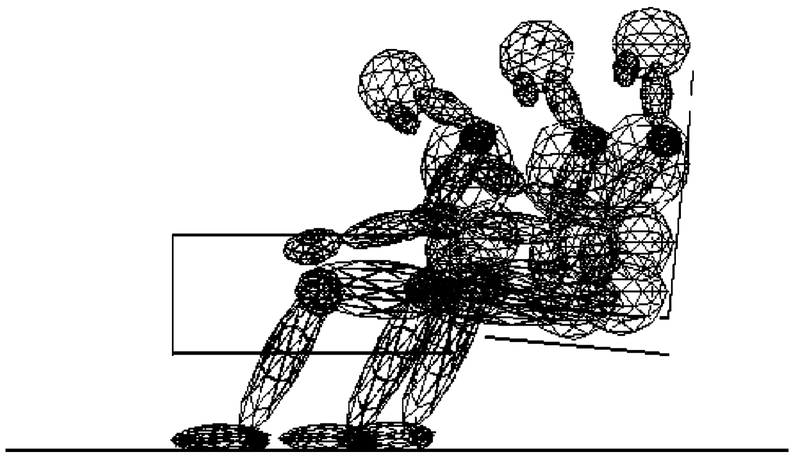

Figure 7. Occupant Motion, Seats and Table

Table 5. lists the values for the selected injury criteria and the associated probabilities of fatality for the forward facing occupant in the interior with seats and table. The probability of fatality from deceleration is less than 10% for all the crash pulses considered except the crash pulse for the conventional design train with the cab car leading, where the likelihood of fatality is near certain.

Table 5. Injury Criteria and Fatality Rates For Secondary Collisions
Seats and Table

| Crash Pulse | | HIC | Chest Acc. ($m/s^2$) * | Neck Load (N) ** |
|---|---|---|---|---|
| Conventional Design | 1st Coach 63 m/s head to head | 311 (0%) | 412 (7%) | 2680 (0%) |
| | Cab Car 63 m/s head to head | 186 (0%) | 324 (3%) | 2030 (0%) |
| | Cab Car 31 m/s tail to head | 702 (7%) | 500 (14%) | 3500 (100%) |
| Crash Energy Management Design | 1st Coach 63 m/s head to head | 110 (0%) | 235 (1%) | 1280 (0%) |
| | Cab Car 63 m/s head to head | 16 (0%) | 157 (0%) | 725 (0%) |
| | Cab Car 31 m/s tail to head | 415 (2%) | 392 (5%) | 2670 (0%) |

* 1 $m/s^2$ = 0.10 G's
** 1 N = 0.22 lbf

### 3.4 Interior Crashworthiness Analysis Conclusions

The analysis results show that seatbelts and seatbelts with shoulder harnesses are an effective means of providing occupant protection for a wide range of collision conditions. Seatbelts with shoulder harnesses provide sufficient occupant protection to assure near certain survival for all the collision conditions analyzed. The analysis results suggest that, under some conditions, occupants may potentially suffer greater injury with lap belts than without, as a result of the occupant's head impacting the top of the seat back ahead of him. These conditions include seats in rows that are more closely spaced than considered in the analysis. The analysis results also show that compartmentalization can be an effective means of providing occupant protection for a limited range of collision conditions. This strategy provides a level of protection at least as great as required for automobiles and for aircraft for all the conditions analyzed except when the cab car is leading during the collision and for the facing seats.

## 4. CONCLUSIONS

For the conditions considered, both the crash energy management design and the conventional design preserve sufficient volume for the occupants to survive in train-to-train collisions below 31 m/s (70 mph). For collisions above 31 m/s (70 mph), the crash energy management approach is significantly more effective than the conventional approach in preserving occupant volume. For the full range of collision speeds, the crash energy management design provides a significantly gentler initial deceleration than the conventional design.

For a sufficiently gentle initial train deceleration, compartmentalization provides sufficient occupant protection to keep accepted injury criteria below the threshold values used by the automotive and aircraft industries in evaluating interior crashworthiness performance. Seatbelts and shoulder restraints reduce the likelihood of fatality due to secondary collision to near-certain survival for all the occupants not killed due to loss of occupant volume for all collisions considered.

The crash energy management design presented in this paper was designed against a particular collision scenario and should not be considered a universal or global optimum. The optimum force/crush characteristics will depend upon the details of the collisions which must be survived. If a range of collisions must be survived (i.e., collisions with freight trains, with maintenance of way equipment, with highway vehicles, etc.) a number of force crush characteristics should be evaluated against this range of collisions in order to determine the optimum for a particular application.

## 5. ACKNOWLEDGMENTS

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