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TRAIN CRASHWORTHINESS DESIGN FOR OCCUPANT SURVIVABILITY

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ABSTRACT

Studies were conducted evaluating the effectiveness of alternative strategies for providing crashworthiness of the vehicle structures. Conventional practice results in cars of essentially uniform longitudinal strength. The crash energy management approach requires varying strength through the train, with high strength in the occupied areas and lower strength in the unoccupied areas.

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

A method for developing the crush zone force/displacement characteristics and occupant volume strength required to limit secondary impact velocities and preserve occupant volumes is developed. Ideal force/displacement characteristics and occupant volume strength required to survive a 140 mph train-to-train collision are first determined; constraints on crush zone length and maximum occupant volume strength are then applied.

The two design approaches are evaluated in terms of occupant volume lost and secondary impact injury by applying a lumped-mass model, using the parameters associated with each design, for a range of collision scenarios.

1. INTRODUCTION AND BACKGROUND

There has been recent interest in high-speed passenger rail, with speeds in excess of 125 mph. The potential for collisions at increased speeds has renewed concerns about passenger rail vehicle crashworthiness. Studies have been conducted to evaluate the effectiveness of alternative strategies for providing crashworthiness of the vehicle structures at increased collision speeds. This paper describes comparisons of strategies for structural crashworthiness of rail passenger vehicles during collisions.

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, including occupants colliding with loose objects inside the train, such as baggage. 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 subsequently strikes some element of the wayside. Causes of fatality associated with the 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 sufficient occupant volume for the occupants to ride out the collision without being crushed, thrown from the train, or directly struck from something outside the train. The second objective is to limit the forces and decelerations imparted to the occupants to acceptable levels of human tolerance. Preserving 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 and not be crushed. Decelerations and forces are limited through a combination of structural crashworthiness measures, allowing portions of the vehicle to crush in a predetermined manner thereby limiting the decelerations of the vehicle; and other interior crashworthiness measures, including the use of occupant restraints, such as seatbelts and shoulder harnesses; and the application of strategies such as compartmentalization ("Federal Motor Vehicle Safety Standards; School Bus Passenger Seating and Crash Protection; Termination of Rulemaking," 1989).

Conventional practice is oriented toward making the individual cars as strong as they can be made, within weight and other design constraints; this approach attempts to control the behavior of individual cars during the collision. The crash energy management approach is train oriented, allowing structural crushing to be distributed throughout the train to the unoccupied areas in order to preserve the occupant volumes and to limit the decelerations of the cars. This approach attempts to control the behavior of the entire train during the collision. This 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 of crash energy management has received much attention in recent years in Japan (Ohnishi et al., 1993), France (Lacôte et al., 1993), and England (Glenn, 1987; Scholes, 1987; and Scholes et al., 1993).

2. CRASH ENERGY MANAGEMENT DESIGN METHODOLOGY

Figure 1 shows the location and length of the crush zones in each of the cars. The lengths shown are the reductions in length before intrusion into the occupied volumes. These crush zones are distributed throughout the car in order to control the progression of the structural crushing during the collision and to control the decelerations of the occupied volumes. By controlling the structural crushing the occupant volumes can be preserved, and by controlling the deceleration of the occupied volume the severity of the secondary impact can be limited.

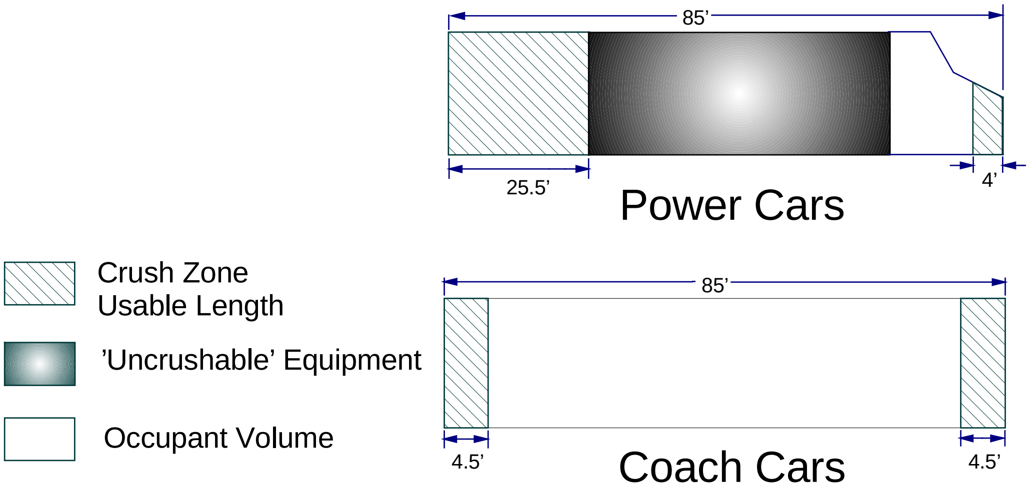

FIGURE 1. CRASH ENERGY MANAGEMENT DESIGN CRUSH ZONE LOCATIONS

The methodology used to determine the force/displacement characteristics for the crash energy management design is illustrated in Figure 2. The process starts with the desired deceleration time histories for each of the cars, from which ideal force/displacement characteristics are determined for a particular collision scenario. These characteristics are subsequently modified based on constraints on crush zone length and maximum occupant compartment strength. The constrained design is then evaluated to determine how well it approximates the performance of the ideal design.

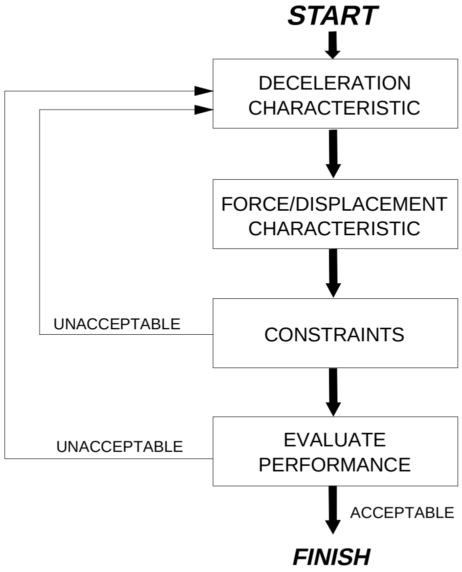

FIGURE 2. CRASH ENERGY MANAGEMENT DESIGN FORCE/DISPLACEMENT CHARACTERISTIC DEVELOPMENT

The ideal deceleration characteristics for the cars in a train during a train-to-train collision with a closing speed of 140 mph are shown in Figure 3. In order to limit the secondary impact velocity of an occupant 2½ feet from the seat back or interior barrier ahead of him or her to 17 mph, the initial occupant volume deceleration is limited to 4 G's for the first 0.20 second. Once the secondary impact has occurred, it is assumed that the occupant can safely withstand an occupant volume deceleration of 25 G's.

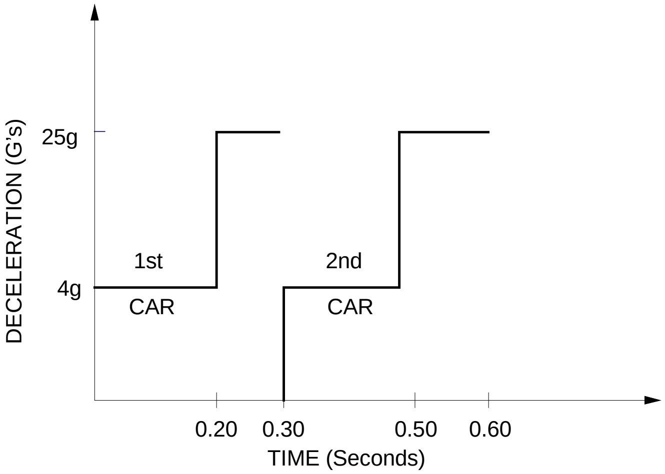

FIGURE 3. IDEAL DECELERATION CHARACTERISTIC

Ideally, each car undergoes its own collision independent of all the other cars in the train. For a hypothetical train collision into a brick wall, the first car impacts the wall and comes to rest before the second car starts to decelerate, i.e., ideally the car behind does not exert a force on the car ahead until the car ahead has come to rest. To achieve this deceleration characteristic for a train traveling at 140 mph colliding with a similar standing train (equivalent to a train colliding into a brick wall at 70 mph), the first car in the train would need a crush zone which imparts a deceleration of 4 G's to the car which allows 18 feet of crush; a crush zone which imparts a deceleration of 25 G's to the car which allows 4 feet of crush; and an occupant volume which is sufficiently strong to assure that it does not crush under 25 G's deceleration. The second car in the train, and all other trailing cars, would need a crush zone which would exert no deceleration (force) that is 9 feet long, in addition to the 4 G and 25 G crush zones. Figure 4 illustrates schematically the distribution of the crush zones along the length of the train.

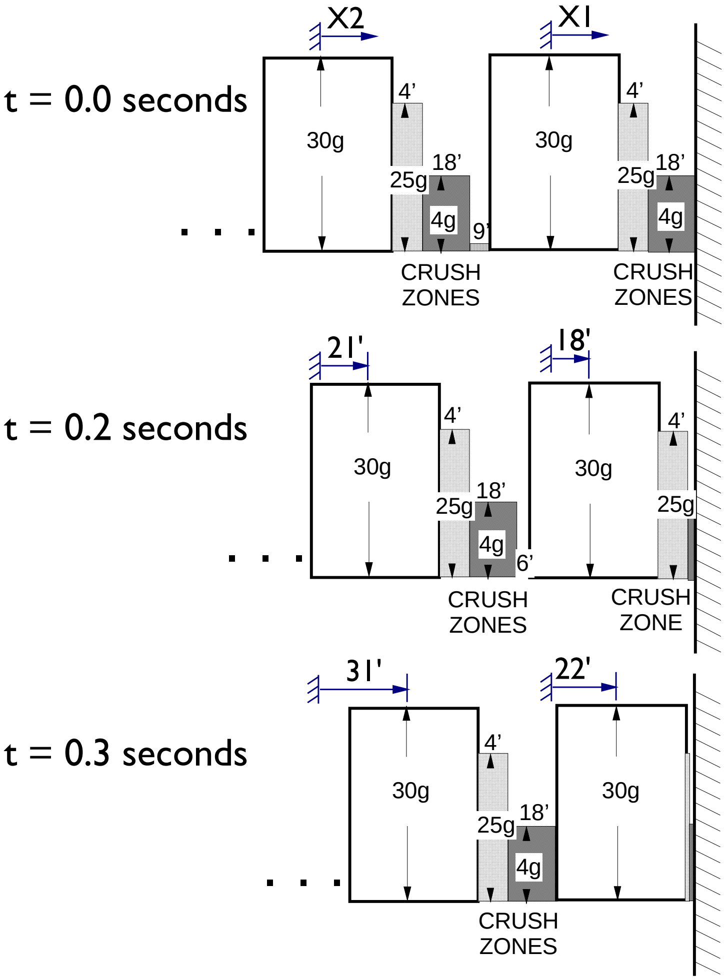

FIGURE 4. SCHEMATIC OF CRUSH ZONES REQUIRED TO IMPART IDEAL DECELERATION

The ideal deceleration characteristics must be modified in order to develop force/displacement characteristics which can be implemented in a vehicle structure. As soon as the first car starts to decelerate, a force must develop between the first and second car, owing to the connection between the cars. Figure 5 shows the deceleration characteristics of Figure 3 modified for a collision at 140 mph of a consist made up of a power car, five coach cars, and a cab car with an identical standing consist. In this scenario, the power cars are the first cars involved in the collision. The decelerations have been modified to have each of the cars start decelerating at the onset of the collision and to impart a greater deceleration to the operator during the initial portion of the collision. The assumption is that greater interior crashworthiness measures can be taken for the operator than for the passengers owing to the increased likelihood that the operator will be in his or her seat. This allows the operator's cab to be strengthened in order to preserve sufficient volume for the operator to survive, at the cost of increasing the deceleration imparted to the cab. These decelerations were numerically integrated to determine the velocity and displacement of each of the cars during the collision, and were used to determine the force/displacement characteristics necessary to produce the prescribed decelerations of the cars.

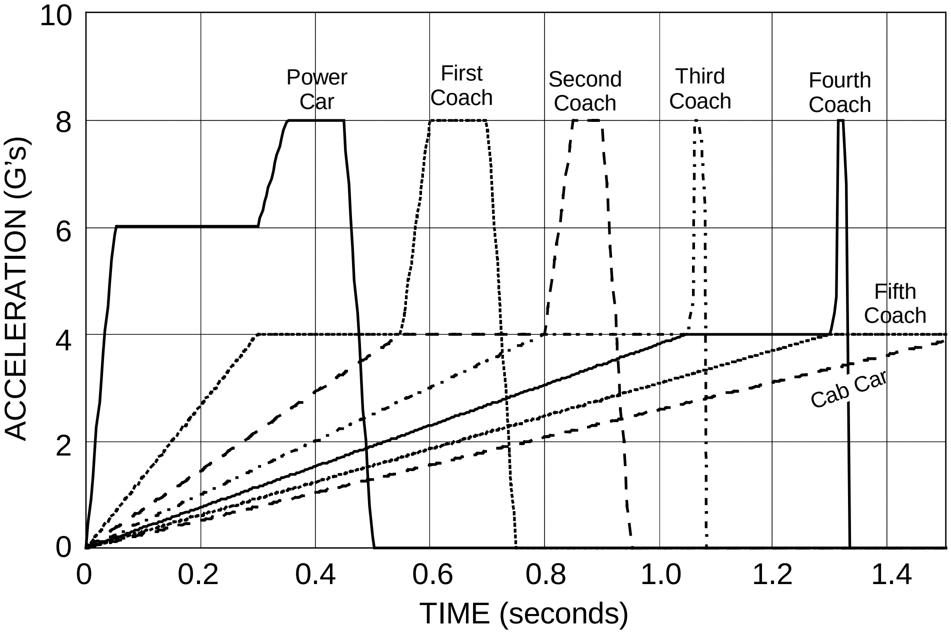

FIGURE 5. DESIRED DECELERATION CHARACTERISTIC FOR 70 MPH BRICK WALL COLLISION

The required and designed force/displacement characteristics have been developed for a consist made up of a power car, five coach cars, and a cab car which collides at 140 mph with an identical standing consist. The required forces are calculated directly from the desired decelerations and plotted against the displacement of each of the cars. The designed forces are initial estimates at "best" realizable force characteristics. The designed and required force/displacement characteristics for each of the cars in the train are shown in Figures 6, 7, and 8.

The crush zone characteristics shown in Figures 6, 7, and 8 will fully protect the operator and passengers in a train-to-train collision with a closing speed of 140 mph; however, these characteristics require occupant volume strengths of 3.0 million pounds and relatively long crush distances.[1] In order to be practical, constraints must be placed on the distances crushed and the forces developed, and the desired deceleration characteristics must be modified accordingly. For the coach cars, the longitudinal forces are constrained to be between 1.6 million lbs, presuming that greater strength would incur excessive vehicle weight, and 400 thousand lbs, presuming that less strength would impair the vehicle's ability to support service loads. For the power cars, the maximum force is constrained to 2 million lbs. This load is greater than for coach cars due to the substantially shorter occupant volume length in the power car. Constraints placed on crush distances include 4 feet of available crush distance ahead of the operator's cab in the front of each power car, 25.5 feet of available crush distance at the rear of the power car, and 4.5 feet of available crush distance at each end of all the coach cars. Additional constraints include symmetry, i.e.,

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[1] Actual crush zone length would need to be longer than the crush distances shown in the figures, in order to leave space for the crushed bulk material.

the train has to be able to withstand collisions in both directions, and a minimum number of crush zone characteristics, i.e., the force/displacement characteristics are constrained to require a single coach car design and a single power car design. The net result of these constraints is that the severity of the collision in which all occupants are expected to survive is reduced.

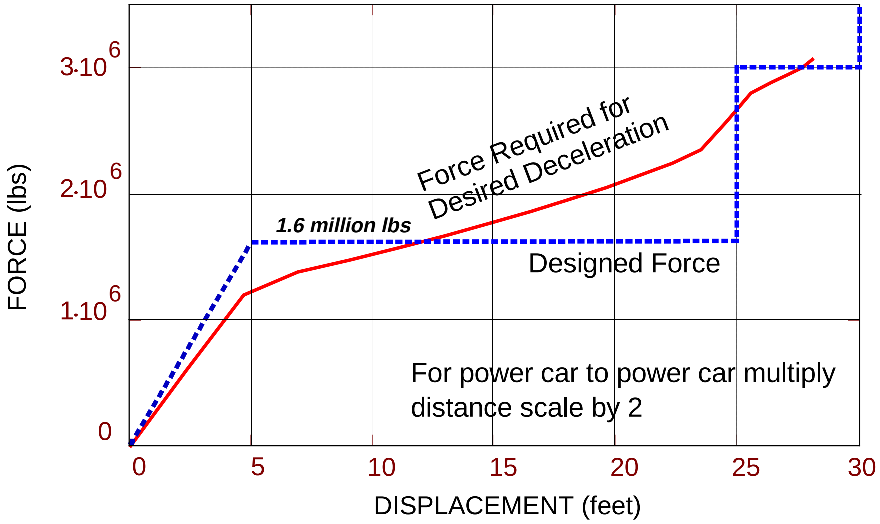

FIGURE 6. POWER CAR TO POWER CAR CRUSH ZONES FORCE DISPLACEMENT CHARACTERISTIC REQUIRED TO ASSURE OCCUPANT SURVIVAL IN 140 MPH TRAIN-TO-TRAIN COLLISION

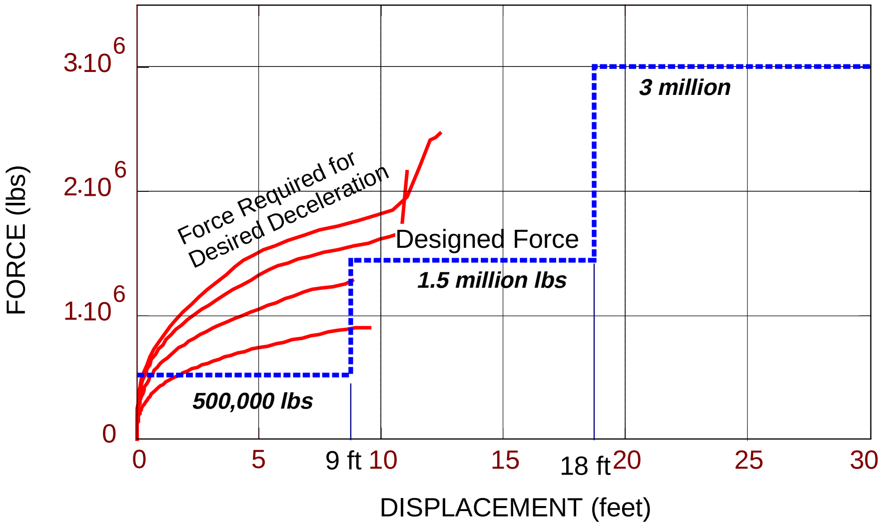

FIGURE 7. COACH CAR TO COACH CAR CRUSH ZONES FORCE DISPLACEMENT CHARACTERISTIC REQUIRED TO ASSURE OCCUPANT SURVIVAL IN 140 MPH TRAIN-TO-TRAIN COLLISION

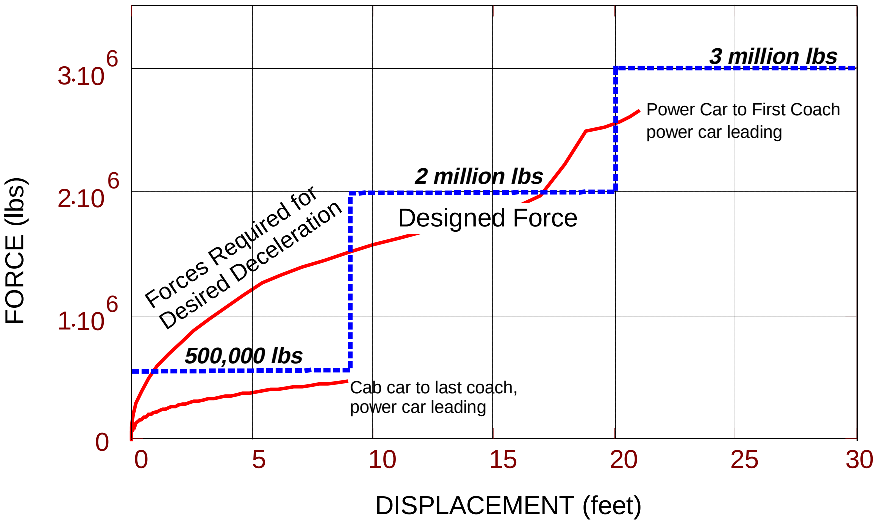

FIGURE 8. POWER CAR TO FIRST COACH AND FIFTH COACH TO CAB CAR CRUSH ZONE FORCE DISPLACEMENT CHARACTERISTICS REQUIRED TO ASSURE OCCUPANT SURVIVAL IN 140 MPH TRAIN-TO-TRAIN COLLISION

Figure 9 shows deceleration time histories which result in force/displacement characteristics which meet the desired constraints for the power car-six coach car-power car consist in a 45 mph collision into a brick wall (or 90 mph train-to-train collision). These decelerations were developed iteratively by calculating the forces and distances required to generate the decelerations shown in the figure, and manually modifying the decelerations and collision speed to produce the desired change in forces and distances.

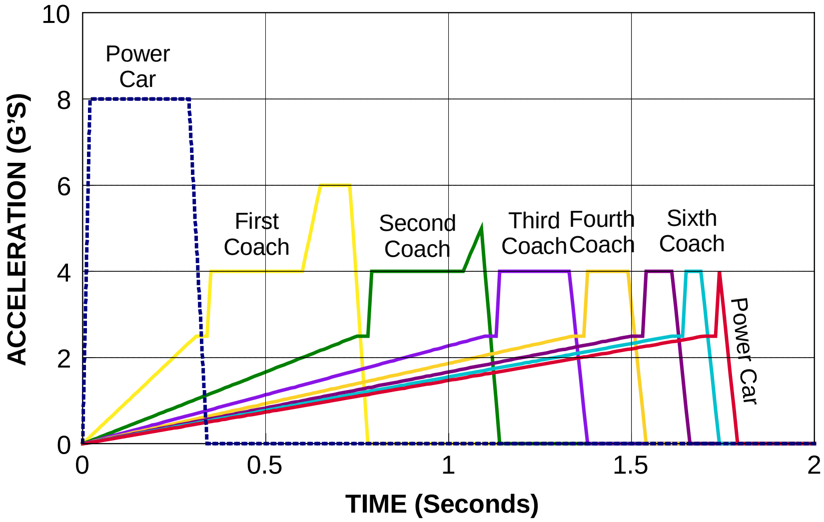

FIGURE 9. POWER CAR-SIX COACH-POWER CAR CONSIST DECELERATION CHARACTERISTIC, 45 MPH BRICK WALL COLLISION

The design forces were developed by approximating the forces required for the desired deceleration, in the same manner as the design forces shown in Figures 6, 7, and 8. The design force/displacement characteristics for the constrained design for the brick wall collisions of the power car-six coach cars-cab car consists are shown in Figure 10.

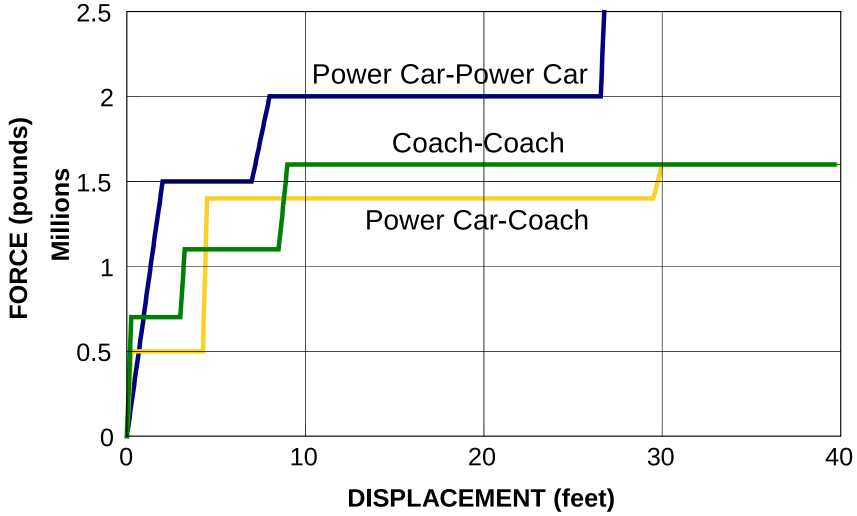

FIGURE 10. CAR-TO-CAR FORCE/DISPLACEMENT CHARACTERISTICS, POWER CAR-SIX COACH CARS-POWER CAR CONSIST

3. CONVENTIONAL DESIGN FORCE/DISPLACEMENT CHARACTERISTICS

Figure 11 shows the car-to-car force/displacement characteristic used for the conventional car in the analysis. This characteristic is based upon the force/displacement characteristic developed by Calspan for the Silverliner car (Romeo and Cassidy, 1974), modified to allow for a shear-back coupler design and a more gradual crushing of the end structure. It should be noted that the maximum strength developed is the force required to cause gross yielding of the structure, which is considerably higher than the force required to cause permanent deformation. If the car is crushed beyond the initial run-in, then the car will eventually rebound.

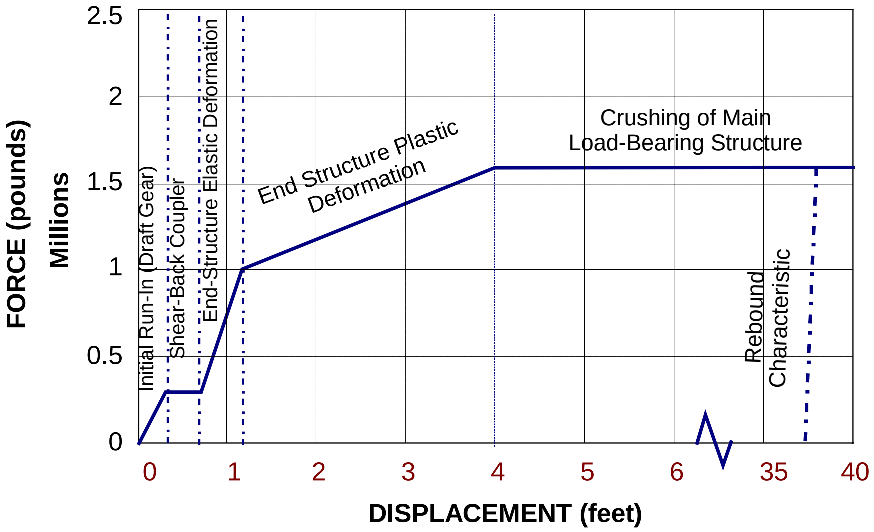

FIGURE 11. CONVENTIONAL DESIGN CAR-TO-CAR FORCE/DISPLACEMENT CHARACTERISTIC

4. ANALYSIS RESULTS AND COMPARISON

The scenario considered is a moving train colliding with a similar standing train. The conventional and crash energy management 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 or her. The analysis approach for determining loss of occupant volume and occupant deceleration is described in the Appendix.

Figure 12a shows the time histories for the accelerations of each of the cars in both trains for a collision of a train moving at 100 mph into a standing train, for the conventional design, and Figure 12b shows a similar plot for the constrained crash energy management design. These figures show that each design goes through the collision in substantially different ways. For the conventional design, there is substantial overlap in the deceleration time histories of the cars, while for the crash energy management design there is a large degree of separation between the deceleration time histories of each of the cars. The deceleration time history plot shows a large deceleration at approximately 1 second for the lead power cars; this large deceleration is a consequence of the cars being crushed solid.

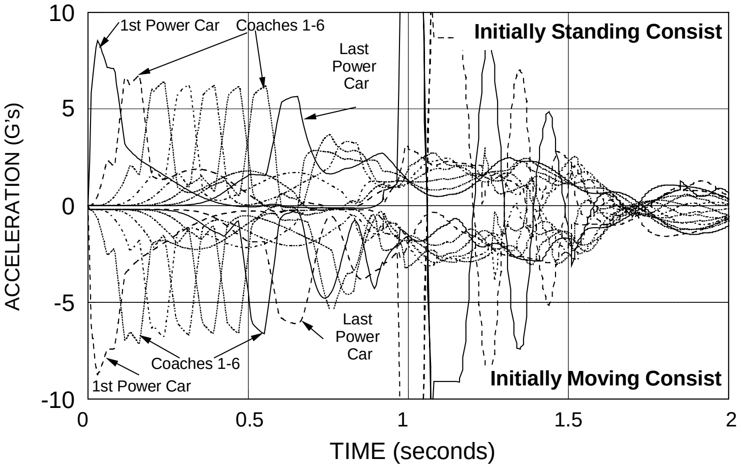

FIGURE 12a. DECELERATION TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CONVENTIONAL DESIGN

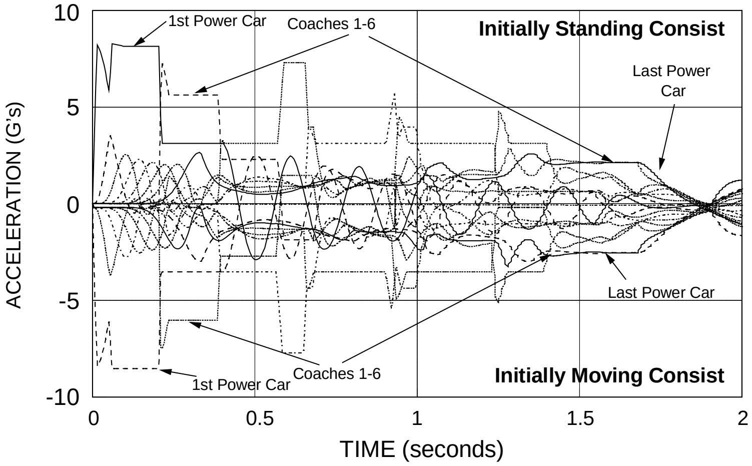

FIGURE 12b. DECELERATION TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CRASH ENERGY MANAGEMENT DESIGN

Figure 13a shows the velocity time histories for each of the cars in both the initially standing and initially moving trains for the conventional design, and Figure 13b shows a similar plot for the constrained crash energy management design. This figure also shows that each design goes through the collision in substantially different ways; for the conventional design, the train essentially acts as a single unit during the collision, while for the crash energy management design, each car largely undergoes its own collision.

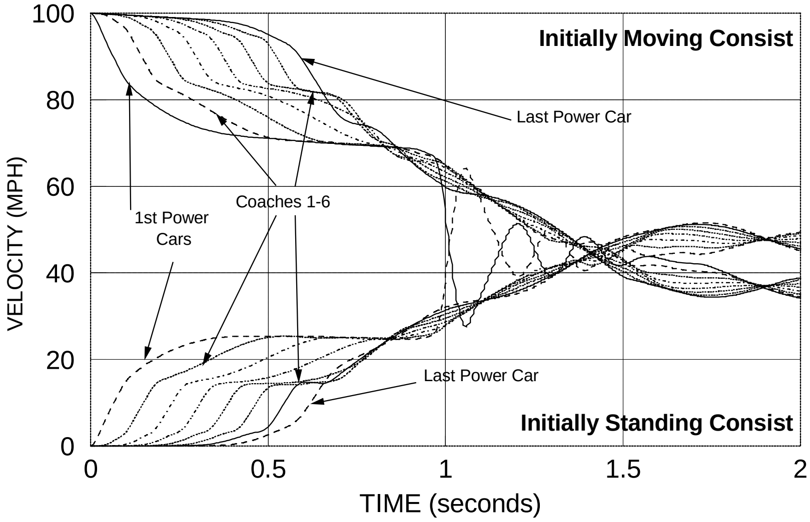

FIGURE 13a. VELOCITY TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CONVENTIONAL DESIGN

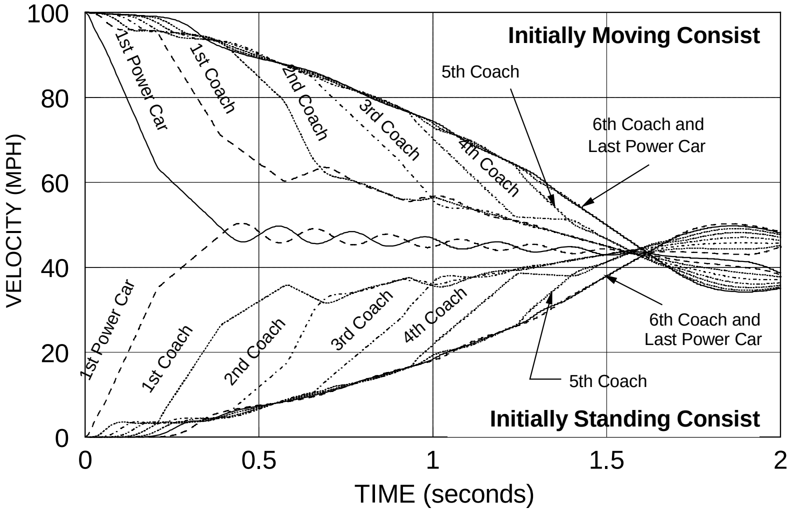

FIGURE 13b. VELOCITY TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CRASH ENERGY MANAGEMENT DESIGN

Figure 14a shows the relative displacements between the centers of gravity of each of the cars in both trains for a collision of a train moving at 100 mph into a standing train, for the conventional design. Figure 14b shows a similar plot for the constrained crash energy management design. Essentially, for the conventional design, the crush progresses from the front of the train toward the rear of the train during the collision, moving through both occupied and unoccupied portions of the train. For the constrained crash energy management design, a substantial amount of crush is moved to the unoccupied areas between the cars which are away from the point of impact. Loss of occupant volume is calculated from the relative displacement of the cars, as described in the Appendix.

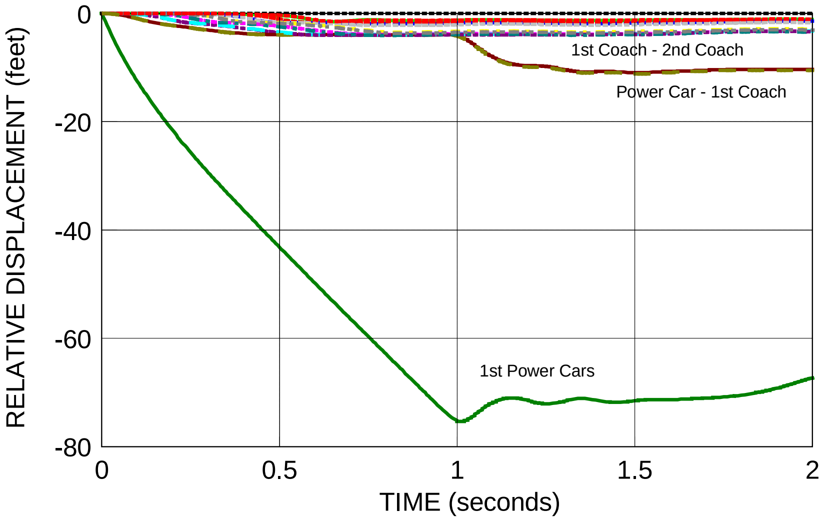

FIGURE 14a. RELATIVE DISPLACEMENT TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CONVENTIONAL DESIGN

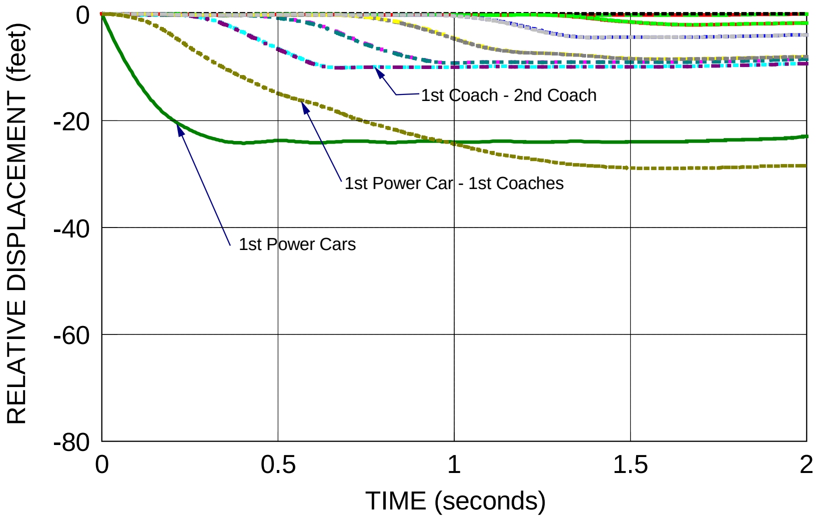

FIGURE 14b. RELATIVE DISPLACEMENT TIME HISTORIES, EACH CAR IN THE CONSIST, 100 MPH CLOSING SPEED, CRASH ENERGY MANAGEMENT DESIGN

4.1 Occupant Volume

Figure 15a illustrates the occupant volume lost in each of the cars for the conventional design train for four closing speeds ranging from 35 mph to 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 15b illustrates the occupant volume lost in each of the cars for the constrained crash energy management design train for four closing speeds ranging from 35 mph to 140 mph. The figures show that for closing speeds up to about 70 mph, the conventional design preserves all of the passenger volume, while the constrained crash energy management design preserves most of the passenger volume up to 110 mph. The additional occupant volume lost for closing speeds above 70 mph is much greater for the conventional design than for the constrained crash energy management design.

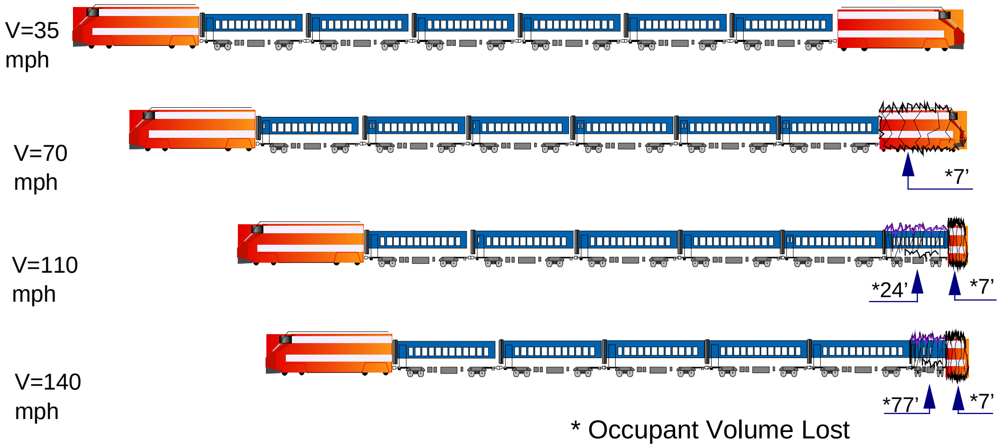

FIGURE 15a. OCCUPANT VOLUME LOSS FOR A RANGE OF CLOSING SPEEDS, POWER CAR TO POWER CAR COLLISION, INITIALLY MOVING CONSIST, CONVENTIONAL DESIGN

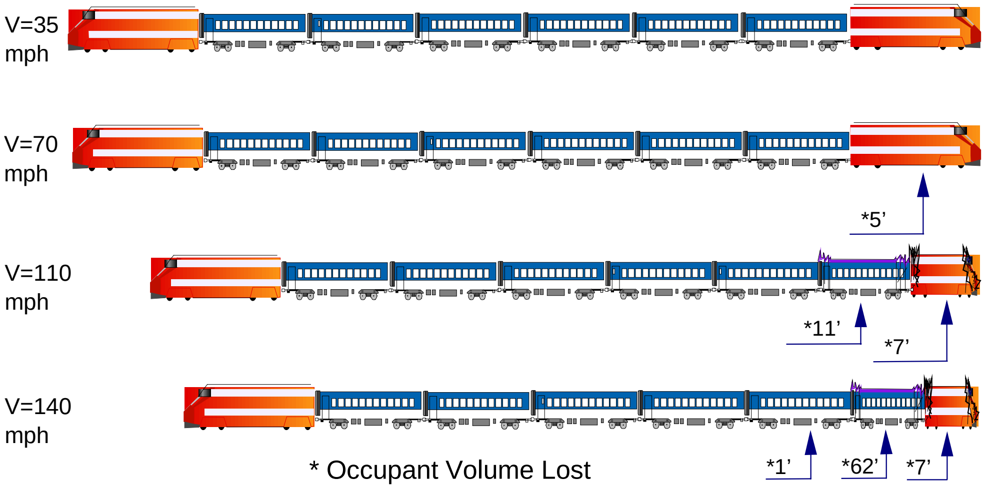

FIGURE 15b. OCCUPANT VOLUME LOSS FOR A RANGE OF CLOSING SPEEDS, POWER CAR TO POWER CAR COLLISION, INITIALLY MOVING CONSIST, CRASH ENERGY MANAGEMENT DESIGN

4.2. Occupant Deceleration

Figure 16 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 for a 100 mph train-to-train collision. The distance from the occupant's nose to the seat back ahead of him or her is assumed to be 2½ feet. The seat pitch (longitudinal distance between two seats one row apart) is assumed to be 42 inches, the occupant's head is assumed to be 8 inches deep, and the padding on the seat is assumed to be 4 inches thick.

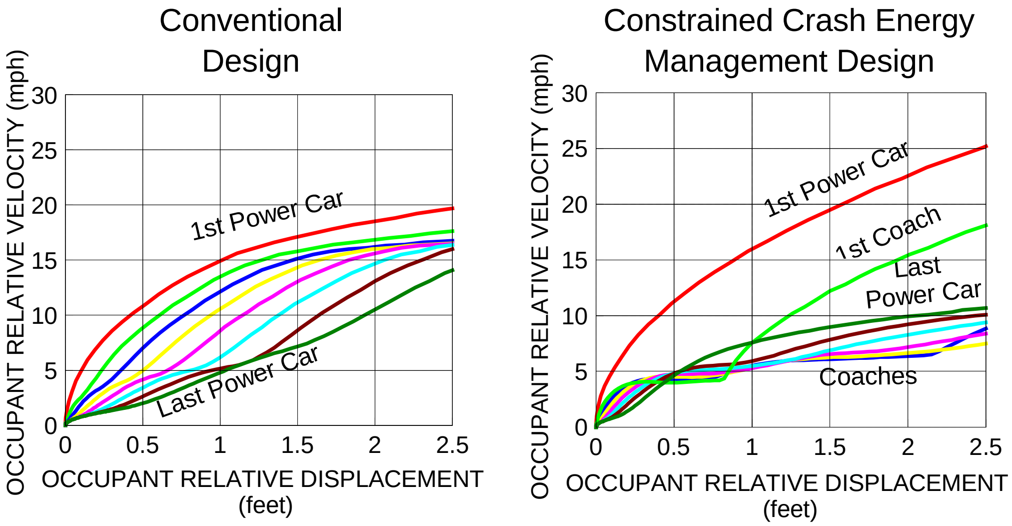

FIGURE 16. OCCUPANT RELATIVE DISPLACEMENT VS. OCCUPANT RELATIVE VELOCITY, INITIALLY MOVING CONSIST

Figure 17 shows bar charts of the secondary impact velocities for each of the cars in the initially moving consists, for both the crash energy management design and the conventional design trains, for primary collision speeds of 140, 110, 70, and 35 mph. As shown in the bar chart, the secondary impact speed does not change significantly for collision speeds above 35 mph for the conventional design while they do not change significantly for speeds above 70 mph for the crash energy management design. Secondary impact velocities are not strongly influenced by the primary collision speed because the secondary impact speed is principally a function of the first portion of the deceleration crash pulse, i.e., the secondary collision occurs soon after the primary collision starts and well before the primary collision ends. Increasing speed has a greater influence on the final portion of the crash pulse than on the initial portion.

For most of the coaches and the trailing power car, the crash energy management design develops significantly lower secondary impact velocities, which is correspondingly expected to result in fewer fatalities and injuries due to secondary impacts of the occupants with the interior. The crash energy management design was developed with the assumption that greater secondary collision protection measures can be taken for the operator in the lead power car, owing to the increased likelihood that the operator will be in his or her seat, and as a consequence the secondary impact velocity is greater in the crash energy management design. The secondary impact velocities in the first coaches are essentially the same for both designs.

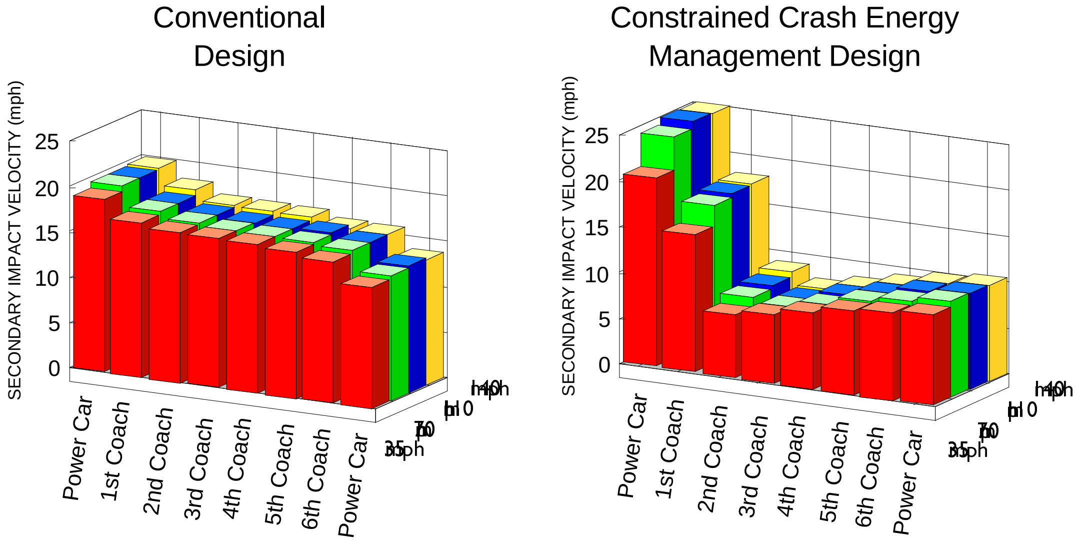

FIGURE 17. OCCUPANT SECONDARY IMPACT VELOCITIES, INITIALLY MOVING CONSIST

4.3 Fatalities

Fatality is calculated from loss of occupant volume and occupant head deceleration, as described in the Appendix. Fatality due to loss of occupant volume is calculated from the length of occupant volume lost in each car, assuming that fatalities are proportional to this reduction in occupant volume. Fatality due to occupant head deceleration is evaluated using the head injury criteria (HIC) (SAE J885, 1986), an injury criteria widely applied in the automotive and aircraft industries to evaluate test and analysis data.

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 the occupants in most of the cars in the consist.

TABLE 1. HEAD INJURY CRITERIA (HIC), CAB CAR TO POWER CAR COLLISION, INITIALLY MOVING CONSIST, CONVENTIONAL AND CRASH ENERGY MANAGEMENT DESIGNS

Primary Collision Speed		HIC Coaches					
		1	2	3	4	5	6
Conventional Design	140	220-475	195-420	185-405	185-400	180-395	175-375
	110	215-470	195-420	185-405	185-400	180-390	170-370
	70	215-470	195-420	185-405	185-400	180-390	170-370
	35	200-440	185-405	185-400	185-400	180-385	165-355
Crash Energy Management Design	140	235-505	40-85	25-55	35-75	45-100	55-120
	110	225-485	35-75	25-55	35-75	45-100	55-115
	70	215-465	30-65	25-55	35-75	45-100	55-115
	35	150-325	20-45	25-55	35-75	45-95	50-105

Table 2 lists the predicted fatalities owing to occupant volume loss and secondary impacts for a train with the power car leading colliding with the power car of a standing train. Most of the fatalities are predicted to be due to loss of occupant volume; this prediction is consistent with the outcomes of actual collisions (Reilly et al., 1978). The crash energy management design provides significant benefits in this scenario for all speeds considered; this design is consistently more effective in preserving occupant volume and limiting fatalities due to secondary impacts.

TABLE 2. SECONDARY IMPACT FATALITIES, CONVENTIONAL AND CRASH ENERGY MANAGEMENT DESIGNS

Speed	Conventional Design			Crash Energy Management Design		
	Seats Lost	Secondary Impact Fatalities	Total	Seats Lost	Secondary Impact Fatalities	Total
140 mph	76	0-4	76-80	67	0	67
110 mph	25	0-5	25-30	13	0-1	13-14
70 mph	2	0-5	2-7	2	0-1	2-3
35 mph	0	0-5	0-5	0	0-1	0-1

5. CONCLUSIONS

For collision speeds below 70 mph, for two similar trains colliding, both the crash energy management design and the conventional design preserve sufficient volume for the occupants to survive. For collisions above 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.

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/displacement characteristics will depend upon the details of the collisions that 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 displacement characteristics should be evaluated against this range of collisions in order to determine the optimum for a particular application.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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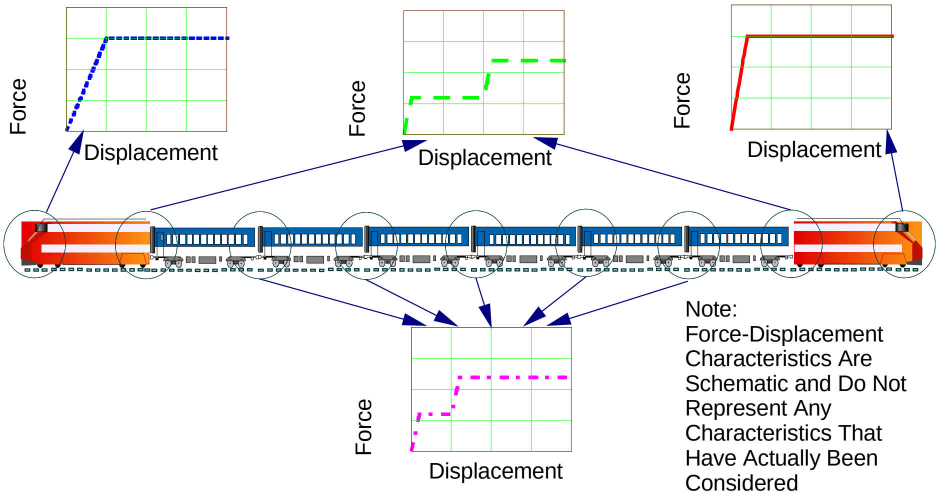
8. APPENDIX: ANALYSIS APPROACH

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 override 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 cars and 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 Galganski (1993).)

The comparison between the two structural crashworthiness strategies is accomplished by developing the force/displacement characteristics for the cars and applying a lumped-mass model to determine the occupant volume lost and the secondary impact velocities for a range of collision scenarios. It is assumed that the train stays in line and that individual cars can crush solid. Secondary impact velocities are calculated assuming that the occupants are seated in consecutive rows of forward facing seats, with 2½ feet from the occupant's forehead to the seat back ahead of him or her and that the occupant remains at the initial train speed until he or she impacts an interior surface. Figure 18 shows a schematic of a lumped-mass train model, representative of the models used in the analysis.

The distributed mass and stiffness of each car is approximated by a lumped mass and a non-linear force/displacement characteristic. Each car may only crush a maximum amount, that is, after some amount of displacement the car becomes essentially solid metal. At the displacement at which the car is crushed solid, the force increases rapidly with a small increase in displacement. The crushed structure is expected to have some amount of resiliency, and so the cars are allowed to rebound, with a large change in force for a small change in displacement. In order to allow substantial crushing of the cars (crush distances greater than 50% of the initial car length) the mass is lumped at the rear of the car and the force/displacement characteristic is placed ahead of the mass.



Note:
Force-Displacement
Characteristics Are
Schematic and Do Not
Represent Any
Characteristics That
Have Actually Been
Considered

FIGURE 18. STRUCTURAL CRASHWORTHINESS ANALYSIS MODEL

Table 3 lists the weights associated with each car type considered in the analysis. For the same car type, both the conventional and the crash energy management design are assumed to have the same weight. The moving train is assumed to be in emergency braking at a rate of 0.2 G's. Each car in the standing consist is assumed to develop the braking force associated with a wheel/rail coefficient of friction of 0.2.

TABLE 3. WEIGHT OF EACH CAR TYPE

Car Type	Weight
Power Car	180 kips
Cab Car	120 kips
1^{st} Class, Coach, and Food-Service Cars	120 kips

8.1 Loss of Occupant Volume

Fatality due to loss of occupant volume is estimated by calculating the length of occupant volume lost in each car and assuming that fatalities are proportional to this reduction in occupant volume. The model, implemented in a FORTRAN computer program, is used to calculate the crush between cars. This crush (reduction in car length) is allocated to the two cars according to crush zone strength—the weakest zones crush first—and the front-to-back crushing of a structure with uniform strength. Each of the coach cars can crush to a minimum length of 25 feet, and the power cars can crush to a minimum length of 46.5 feet. The volume occupied by the crushed material is 40% of the reduction in car length.[2] The reduction in occupant volume is the initial occupant volume less the reduction in car length and less the volume occupied by the crushed material. Table 4 lists the number of seats and initial occupant volume lengths for each of the car types considered. Fatality is calculated assuming that all of the seats in the train are occupied.

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[2] Simple structures such as thick-walled columns can be crushed to approximately 20% to 30% of their undeformed height (Wierzbicki, 1990). For this analysis, the portion of the rail car structure that is crushed is assumed to take 40% of its initial length owing to end structure characteristics and nonstructural material in the crush zone which may impede close folding of the crushable structure.

TABLE 4. NUMBER OF SEATS IN EACH CAR TYPE

Car Type	Number of Seats	Initial Occupant Volume Length	
		Conventional Design	Crash Energy Management Design
Power Car	2	9	9
1st Class Car	44	77	72
Coach Car	74	77	72
Food-Service Car	74	77	72

8.2 Secondary Impact

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 occur, for an unrestrained occupant, when the occupant strikes the interior. (Occupant impacts with the interior or collisions between occupants and loose objects thrown about during the collision are usually termed secondary collisions; the primary collision considered here is the collision between the two trains.) How hard the occupant strikes the interior depends upon the deceleration of the train itself during the collision and the degree of “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.

A sketch of the occupant model is shown in Figure 19. The occupant model is based on the assumption that the occupant goes into free flight at the start of the collision and, subsequently, after traveling some distance, strikes the interior. The occupant is assumed to strike the seat back ahead of him or her, 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 deceleration time history of the head can be used to calculate the Head Injury Criteria (HIC) (SAE J885, 1986), an injury criteria widely applied in the automotive and aircraft industries to evaluate test and analysis data. The distance from the occupant’s nose to the seat back ahead of him or her is assumed to be 2½ feet, i.e., the seat pitch is assumed to be 42 inches, the occupant’s head is assumed to be 8 inches deep, and the padding on the seat is assumed to be 4 inches thick.

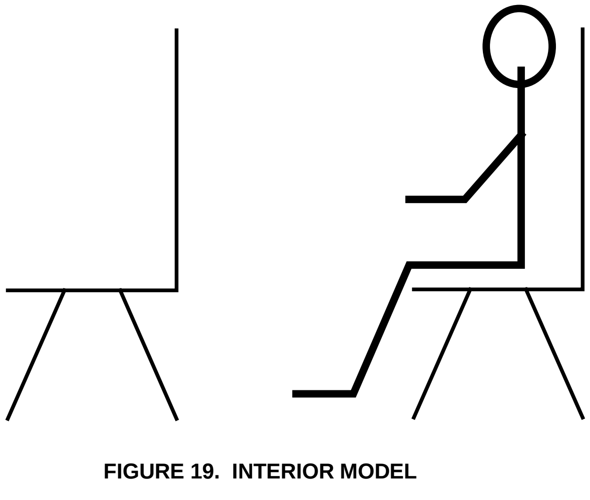

FIGURE 19. INTERIOR MODEL

The seat back force/displacement characteristic used in the analysis is shown in Figure 20. The characteristic used in the analysis is the softest characteristic described in the NHTSA standard 49CFR571.222 - School Bus Seating and Crash Protection (Code of Federal Regulation 49, 1993).

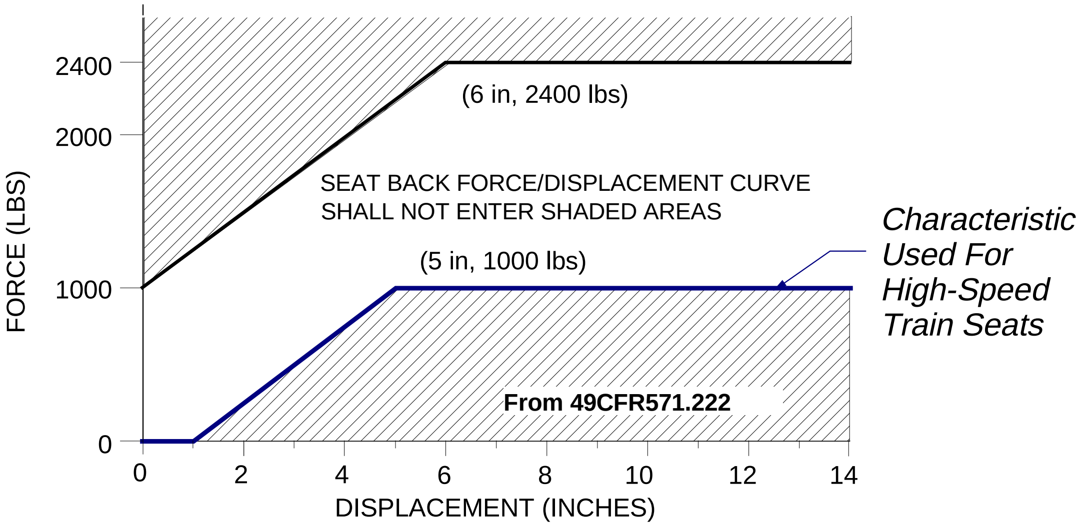

FIGURE 20. SEAT BACK FORCE/DEFLECTION CHARACTERISTIC (CODE OF FEDERAL REGULATION 49, 1993)

Figure 21 shows a plot of HIC as a function of secondary impact velocity for the seat back force/displacement characteristic shown in Figure 20. The force/displacement shown in Figure 21 does not fully describe the seat back behavior; the seat back may behave in either of two different extremes, or in some combination of those two extremes. In an elastic secondary collision, the occupant is fully pushed back into his or her initial secondary impact position; in a plastic secondary collision the seat back does not push back at all.

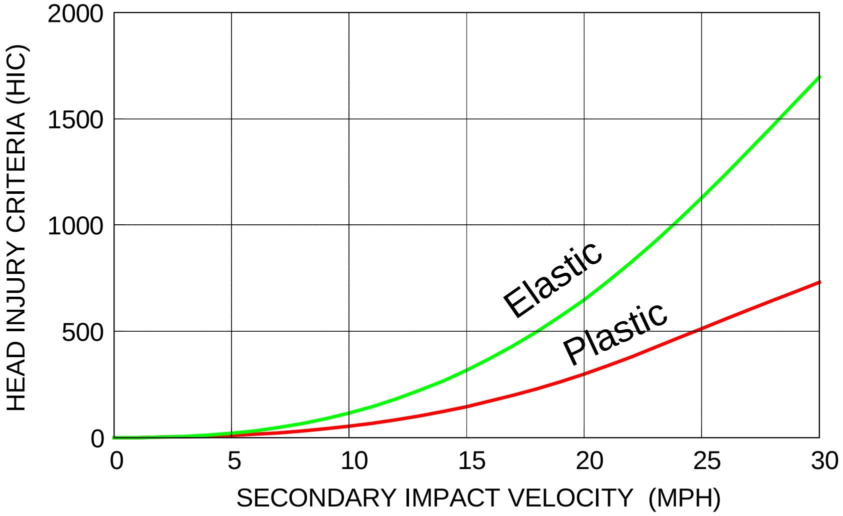

FIGURE 21. HEAD INJURY CRITERIA AS A FUNCTION OF SECONDARY IMPACT VELOCITY FOR ASSUMED INTERIOR CONDITIONS

The HIC is a function of the relative acceleration of the head during impact and is used to predict the probability of fatality resulting from head injury. A HIC of 1,000 corresponds to a predicted fatality rate of approximately 18% for the 50th percentile male. Figure 22 from Prasad and Mertz (1985), shows a plot of the probability of fatality as a function of HIC.

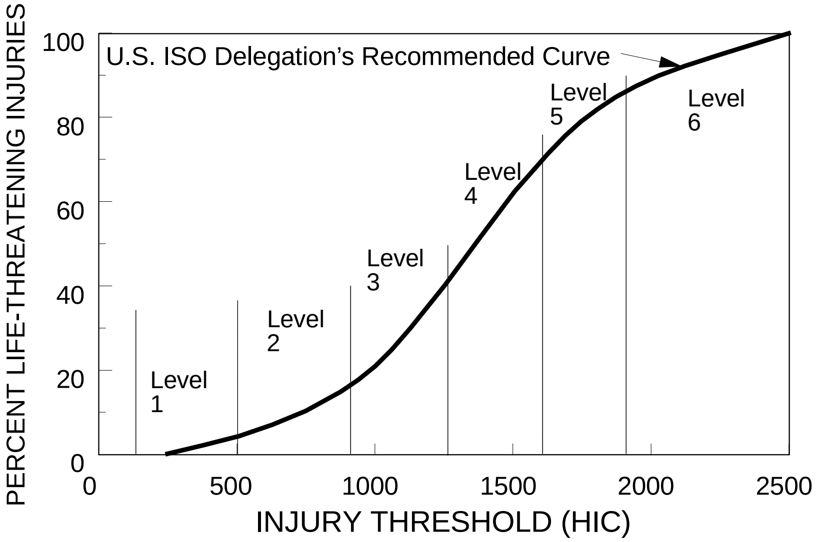

FIGURE 22. PROBABILITY OF FATALITY AS A FUNCTION OF HEAD INJURY CRITERIA (PRASAD AND MERTZ, 1985)

The occupant's secondary impact velocity relative to the car is calculated from a lumped-mass train collision model. This velocity is then used to determine the range of injury criteria, from Figure 21. The injury criteria is then used to determine the probability of fatality for the 50th percentile male, from Figure 22. Fatality due to secondary collision is then calculated by taking the percentage of occupants with sufficient occupant volume to survive the collision. (The analysis only allows the occupants to be killed by loss of occupant volume or by the secondary collision, not by both.) Fatality for the occupants in the train is determined by repeating this procedure for each car in the train.