Proceedings of RTDF2008
2008 ASME Rail Transportation Division Fall Technical Conference
September 24-25, 2008 Chicago, Illinois, USA

RTDF2008-74021

THE INFLUENCE OF MANUFACTURING VARIATIONS ON A CRASH ENERGY MANAGEMENT SYSTEM

Philip Mallon
Benjamin Perlman
David Tyrell
US Department of Transportation
Volpe National Transportation Systems Center
Cambridge, MA 02142

ABSTRACT

Crash Energy Management (CEM) systems protect passengers in the event of a train collision. A CEM system distributes crush throughout designated unoccupied crush zones of a passenger rail consist. This paper examines the influence of manufacturing variations in the CEM system on the crashworthiness of CEM passenger rail equipment.

To perform effectively, a CEM system must have certain features. A coupling mechanism allows coupled cars to come together in a controlled fashion and absorb energy. A load transfer mechanism ensures that the car ends mate and maintain contact. A principal energy absorber mechanism is responsible for absorbing the vast majority of crash energy. These components function by providing an increasing force-crush characteristic when they are overloaded. The force-crush behavior can vary due to manufacturing tolerances.

For the purposes of this research, the pushback coupler, the deformable anticlimber, and the primary energy absorber were the devices that performed these functions. It was confirmed in this study that the force-crush characteristic of the pushback coupler and the primary energy absorber have the greatest influence on crashworthiness performance.

To represent the influence of these parameters, the average force of the pushback coupler and the average force of the primary energy absorber were examined. A cab-led passenger train impacting a standing freight consist was represented as a one-dimensional lumped-mass model. The force-crush characteristic for each coach car end was adjusted to examine the effects of variation in manufacturing. Each car end was modified independently while holding all other car ends constant.

The model used in this study was designed to be comparable with a 30 mph, full-scale, train-to-train CEM test. Using crush distribution and secondary impact velocity as measures of crashworthiness, the standard CEM consist performance has a maximum crashworthiness speed limit of 40 mph. Percent total energy absorbed was used as a means of comparison between cars for each consist configuration.

When energy absorption levels are decreased at any particular car end, crush tends to be drawn towards this car end. Correspondingly, when available energy levels are increased at a car end, crush is drawn away from this car end. For both cases, the overall distribution of crush has more of an effect locally and less of an effect at other coupled interfaces. This paper shows that moderate variations in crush behavior may occur due to manufacturing tolerances and have little influence on the crashworthiness performance of CEM systems.

INTRODUCTION

CEM protects occupant space during a collision through transfer of collision energy. Load at the impacting car end of a consist is conveyed to sacrificial structures in unoccupied regions of a car. Recent research has demonstrated that both a CEM system [1] and a mixed CEM and conventional consist [2] will improve crashworthiness performance of passenger trains.

To work well, a CEM system must allow crush to be shared among car ends. A conventional car leading a consist absorbs most of the energy in a collision. [2,3] Crush is not passed through the consist to the trailing cars. Each car end with CEM equipment must function properly to distribute crush energy throughout the length of a train. Manufacture of a CEM system will inevitably introduce fabrication deviations and variation in material properties in CEM components. The purpose of this research is to understand the consequences of deviations in the behavior of components on CEM system performance.

The investigation uses computer simulation to investigate the influence of modifications to key elements of a CEM system. Adjustments made to the force-crush characteristic represent these modifications. Behavior exhibited by the consist as well as by the individual cars determine the effect of the variations. The overall crush at each car end and kinematic time history for each carbody can be translated into loss of occupied volume and secondary impact velocity (SIV) to assess crashworthiness.

BACKGROUND

To evaluate how well a CEM system performs, a reference must be established. Crush behavior of a conventional passenger train in a 30 mph collision with a freight consist is used as the reference for this study. The improvement in crashworthiness provided by CEM systems has been established for this case. This study investigates practical limits necessary to insure good performance.

Conventional Design

Historically, passenger railroad cars have been constructed with a stiff underframe and a relatively weak superstructure. Most passenger cars currently in service have similar construction. The force-crush characteristic of this design focuses crush on the colliding car.

The components making up the underframe of a conventional car are the center sill, the draft sill, the side sills, the draft gear, and the end beam. In a collision, the underframe of a cab-led conventional car is loaded until its draft gear is fully compressed. The draft sill is then loaded until it buckles, drastically reducing the load capacity. Once this happens, the colliding car is allowed to crush in an uncontrolled fashion. This behavior is characterized by the force-crush behavior depicted in Figure 1, derived from full-scale tests. The initial portion preceding the peak takes both the draft gear and coupler into account. Crush behavior beyond 5 feet can be extrapolated from test measurements to approximately half the length of the car [1].

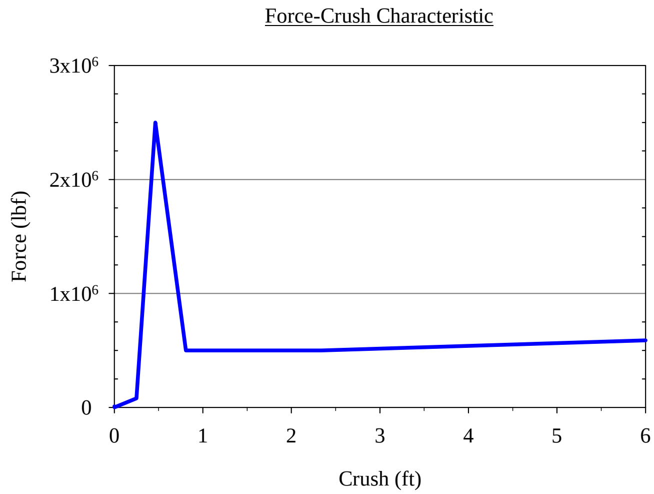

Figure 1. Conventional Force-Crush Characteristic

Trailing cars in a conventional consist absorb very little energy during an in-line collision with no override. After the draft gear is compressed, there is little structural crush. However, the car ends will tend to misalign as a result of the stiff link between cars. When a high longitudinal load is applied at the couplers, a small perturbation can make the cars move laterally away from each other. This phenomenon is known as saw-tooth buckling and is described in reference [1]. A CEM system inhibits this behavior.

When the draft sill buckles, as seen in the force-crush characteristic in Figure 1, the first car in the consist crushes and absorbs most of the collision energy. Little crush is passed on to trailing cars in the consist. Figure 2 illustrates the distribution for a 30 mph collision.

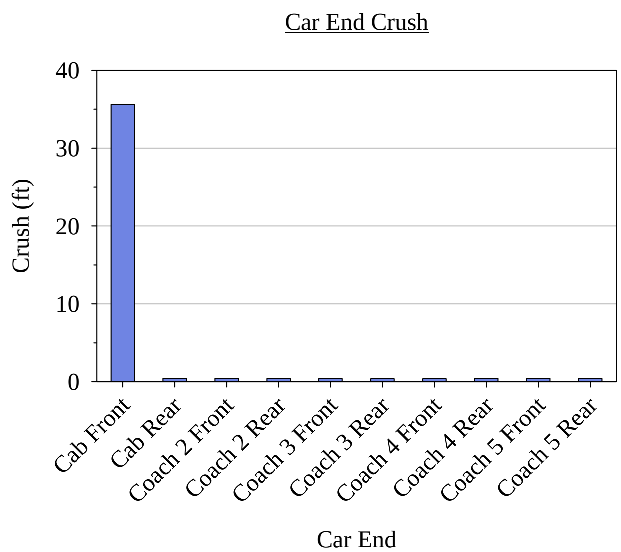

Figure 2. 30 mph Crush Distribution for a Conventional Consist

Crash Energy Management Design

The essence of the CEM rail car lies in the crush of unoccupied areas and the prevention of crush in the occupied volume. To produce a controlled crush situation, a sacrificial crush zone, similar to those found in modern-day passenger automobiles, can be placed at the ends of each car. A specific design based on these concepts was developed for the Federal Railroad Administration (FRA) by the Volpe National Transportation Systems Center (Volpe Center) [4]. A schematic of this design is presented in Figure 3.

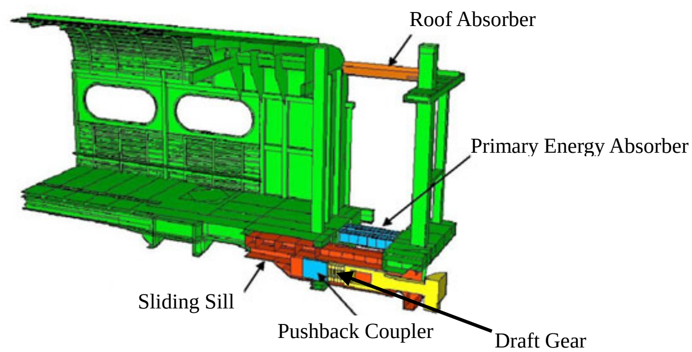

Figure 3. Finite Element Model of CEM System Design

Figure 4 shows a conceptual CEM force-crush characteristic of the schematic presented in Figure 3. It features distinct divisions symbolizing the individual parts that comprise this design.

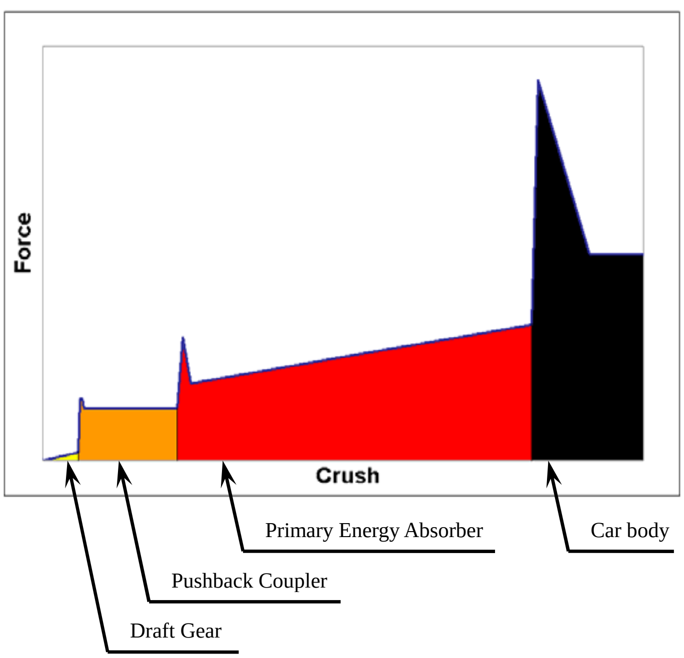

Figure 4. CEM Coach Car Force-Crush Characteristic

The shaded areas represent the energy associated with each component. These components are the draft gear, the pushback coupler, the primary energy absorber, and the occupied carbody. More force is required as each section is crushed, and crushing continues until the system is exhausted and the occupied volume is entered.

Figure 4 is adapted from the characteristic detailed in reference [5]. Other CEM design concepts with increasing levels of force are possible. The values in the FRA/Volpe design are used here as the standard for all adjustments.

The sliding sill is allowed to begin crushing the primary energy absorbers after the associated shear bolts fail at 1.3 x 10^6 lbf. The primary energy absorbers (PEA) begin crushing at 7.45 x 10^5 lbf and rise to 1.32 x 10^6 lbf over a stroke of 30 inches, yielding an average force of 1 x 10^6 lbf. Once the primary energy absorbers are exhausted, the carbody is loaded. Since no full-scale tests have been performed at a speed exceeding the maximum crashworthiness speed for this CEM design, not much is known about the structural crush exhibited by the passenger compartment at this time.

The pushback coupler (PBC) is designed to behave like a conventional coupler and thus be compatible with other couplers. It must behave well under normal use, but also must serve to initiate the crash energy management system. It will push back when the bolts holding it in place fail in shear at a force greater than 6 x 10^5 lbf. The coupler will then push back into an aluminum honeycomb energy absorber under a force of 5 x 10^5 lbf with a stroke of about 6 inches for the coach car.

Detailed force-crush characteristic curves for the conventional car, CEM coach car, and CEM cab car are compared in Figure 5.

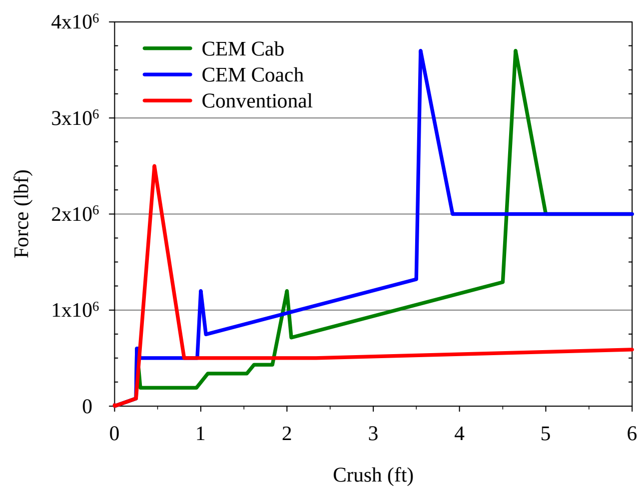

Figure 5. CEM and Conventional Force-Crush Characteristics

Note the increasing load required to compress the CEM cab and coach car ends. The differences in pushback coupler length for the coach and cab car can also be seen.

Figure 6 compares the energy absorbed by the crush of conventional and CEM railcars. The vertical dotted line denotes the limit of the unoccupied car end. At this level of crush, each CEM car end can absorb 4.2 MJ (3.10 x 10^6 ft-lbf) of energy, while the conventional car end can absorb 3.07 MJ (2.26 x 10^6 ft-lbf).

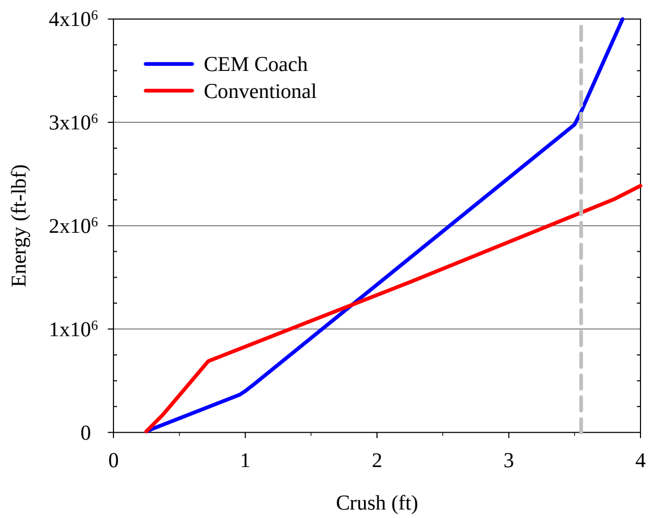

Figure 6. Energy Absorption of a CEM and Conventional Car

The points where energy absorption rate (slope) changes correspond to notable features on the associated force-crush curves. The conventional curve initially absorbs energy at a high rate that is significantly reduced once the peak load in the force-crush characteristic is reached, at approximately 6 inches. In contrast, the CEM coach has a successively increasing rate that will absorb more energy in increasingly severe collision conditions. The increase in slope at 1 foot of crush represents the exhaustion of the PBC and the triggering of the primary energy absorber (PEA). At this point, the conventional car has absorbed much more energy, but its performance degrades while the CEM system is resisting additional crush. The increase in slope at 3.55 feet of crush represents the exhaustion of the PEA. Both the conventional and CEM curves begin at 3 inches since the draft gear crushes elastically up to this point.

In this investigation, the energy capacity of a car end is used to evaluate efficiency. Comparison in terms of energy allows an evaluation of car ends whose force-crush characteristics are not the same. It is evident from Figure 6 that for car end crush of 2 feet or more, the CEM coach car end will absorb energy at a higher rate than the conventional car.

Figure 7 shows the crush distribution in the passenger cars for the 30 mph test case for a CEM train. While the front end of the cab car absorbs the most energy, the trailing CEM car ends all share in the energy absorption process. Each coach car end crushes between 2 and 2.5 feet. It is a goal of this research to understand how to insure that the CEM design will meet the performance targets.

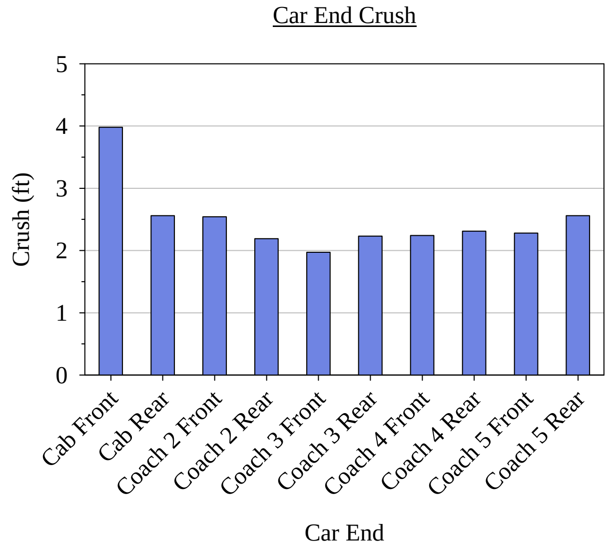

Figure 7. 30 mph Crush Distribution for a CEM Consist

Along with this change in crush distribution comes a change in car behavior. During a CEM collision, each car experiences its own collision until the cars have stopped. Where the conventional consist takes over 2 seconds to come to a stop, the CEM consist stops in less than 1 second. The process takes roughly half the time that the conventional train requires.

These larger decelerations lead to a harsher occupant environment [2]. In the passenger CEM train-to-train test, a secondary impact velocity of just under 20 mph was measured for the 30 mph collision. Although SIV is a determining factor in human safety during a collision, there are ways to protect against it already in use in other modes of transportation. Rear-facing seats in the cab car is one appropriate remedy to address this situation. [2]

RESEARCH APPROACH

The progression of this research began with the development of a collision scenario and continued with the setting of baseline values. From this reference, the change in crush distribution was determined for modifications in the force-crush characteristic of each car end.

Collision Scenario

A collision between a freight train and a passenger consist was chosen as the standard for this research. This type of collision is more severe than passenger consist to passenger consist collisions in which both trains will absorb energy. The impacting train model used in this research is a five passenger car, cab-led consist. The speed used in the reference case is 30 mph. This passenger train is made to crash with an initially resting freight train.

Model Details

The simulations during the course of this research were run with MSC.ADAMS. The characteristics of the passenger consist are based on those of the cars used in the Volpe Center's testing. [6] The cars are represented by a lumped mass model developed at the Volpe Center [2]. The coupling between them is characterized by nonlinear springs, including the locomotives. The trains are restricted to move only in the longitudinal direction on tangent track.

The freight consist used in this study is a 68-car freight train led by a locomotive weighing 263 kips. The first four cars each weigh 181 kips. The fifth car weighs 11,403 kips to represent the last 63 freight cars [7]. The passenger consist is made up of single-level cars, with each car weighing 75 kips and the locomotive weighing 263 kips. The test cars [6] were lighter than the weight of an empty passenger vehicle.

A side view of the model is shown in Figure 9. The masses on the freight train, represented as boxes, are connected to one another by stiff springs (1.2 x 10^7 lb/ft). Each passenger car end has a nonlinear spring characteristic force-crush curve defined in an external file. This file is imported through a FORTRAN subroutine within ADAMS. The coach characteristic was applied to all passenger car ends with the exception of the front of the cab and the rear of the fifth coach car. Cab car characteristics were applied at these ends. Table 1 contains a listing of parameters.

Table 1. Consist Details

	Coach Consist	Freight Consist
Car Weight	75 kips	181 kips
Consist Weight	638 kips	12,390 kips
Locomotive Weight	263 kips	263 kips
Locomotive Stiffness	12,000 kips/ft	12,000 kips/ft
Simulated Braking μ	0.2	0.2

Representations of the draft gear were included in the force-crush behavior of the ends of the locomotives since previous research has identified an influence on the distribution of crush [8].

Measures of Crashworthiness

Loss of occupied volume and secondary impact velocity have been used to estimate the fatality rate during a collision event. [2] This study aims at preserving the entire occupied volume. Secondary impact velocity will be examined in a subsequent investigation.

The end of each railcar, for both conventional and CEM cars, is assumed to be unoccupied and can suffer 3.55 feet of crush without incurring fatalities. This distance accounts for the shortening of the car and accumulation of crushed carbody structure. Simulations, as well as full-scale test results, show one car end at the coupled interface crushing more than its counterpart. This observation is true even though each car end is nominally identical. The timing of the crash pulse is often the cause for this behavior.

METHODOLOGY

This research looks into effects on CEM performance due to modifications in energy absorbing capabilities of the pushback coupler and the primary energy absorber. Comparisons were made based on the distribution of energy capacity throughout the train. Percent CEM utility is calculated by dividing the absorbed energy by the available energy. Figure 8 shows the distribution in the reference case. It is the translation of Figure 7 from crush in feet into crush in terms of percent energy utility.

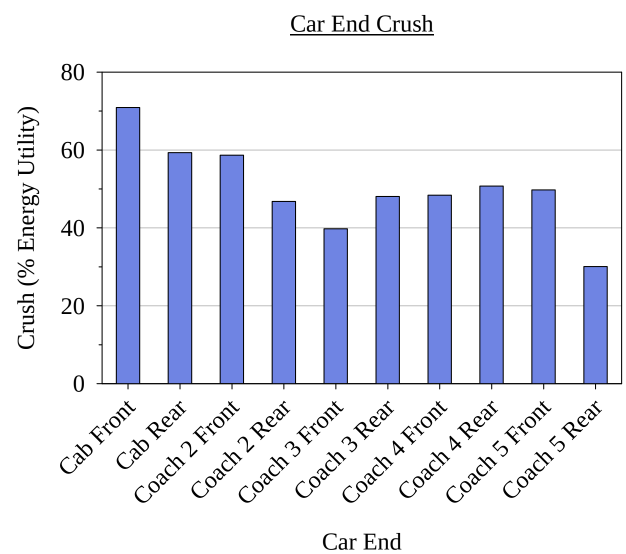

Figure 8. 30 mph Crush Distribution for a CEM Consist in terms of Percent Energy Utility

Cab car characteristics were used at the colliding interface of the passenger consist and for the rear end of the fifth coach at the interface with the trailing locomotive. All three cars between these two are coach cars. The associated force-crush curves for these cars can be found in Figure 5. From this point of reference, a single part of the curve was modified at a time with all the other features at their reference values.

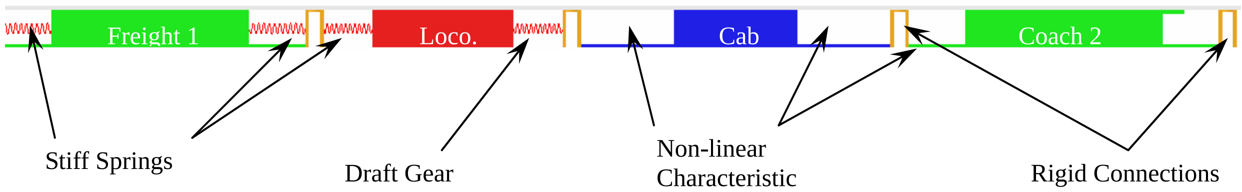

Figure 9. ADAMS Model of the Train-to-Train Collision

The ADAMS model has a range of adjustable items, which are listed in Table 2.

Table 2. Components Available for Modification

Component	Parameter Modified
Draft Gear	Stroke Length
	Slope of Operating Force
Pushback Coupler	Activation Force (1)
	Average Operating Force (2)
	Slope of Operating Force
	Stroke Length
Primary Energy Absorber	Activation Force (3)
	Average Operating Force (4)
	Slope of Operating Force
	Stroke Length
	PEA Average to PBC Average Ratio
Occupied Volume	Activation Force (5)
	Average Carbody Strength

The numbers in the table refer to the arrows in Figure 10 that identify the feature of the force-crush characteristic associated with the parameter.

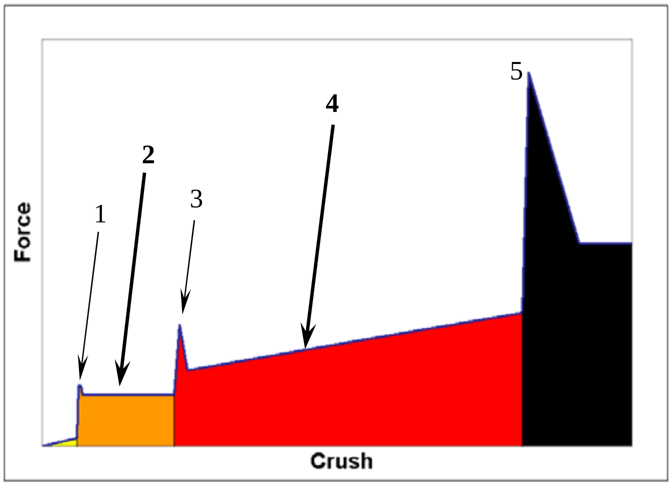

Figure 10. Parameter Modification Locations

Some of these parameters have more influence than others. For example, neither the slope nor the length of the draft gear was shown to have any significant effect on crashworthiness [8]. The carbody is required by the FRA to have a static buff strength of 800 kips. Measurements in dynamic tests suggest a much higher dynamic capacity. In this investigation, 3,700 kips was assumed for the activation force of the carbody. This activation force influences the maximum crashworthiness speed, which is the highest speed at which no occupant volume is lost. In this study, intrusion into the occupant volume was assumed when the dynamic load reached the peak activation force. The maximum crashworthiness speed depends on this value.

The average pushback coupler force is more important to its performance than its other characteristic parameters. The average force of the primary energy absorber has also been shown to produce significant effects. However, the ratio of these two values has the greatest effect [3]. In that study, changes in these parameters were applied to every passenger car in the consist. In this research, effects of modifications to individual car ends were examined.

For the reasons described above, the pushback coupler operating strength was varied first. It was kept within a realistic range for the ratio of pushback coupler strength to primary energy absorber strength ratio. For this reason, modifications to the pushback coupler strength were kept at 50 percent of the original value. The peak activation force was adjusted by the same amount of force as the pushback coupler average force.

Adjustments made to the primary energy absorber, since it is the component with the highest energy capacity, tend to have the greatest impact on collision behavior. Once again, the relationship between average strengths of pushback coupler and primary absorber is critical. Consequently, these adjustments were held at 20 percent of the reference strength.

Maximum crashworthiness speed was determined for each adjustment in the pushback coupler or primary energy absorber capacity. Behavior was examined between 20 and 50 mph at a resolution of 5 mph and between 35 and 40 mph, a 1 mph resolution was used.

In summary, the selected component variations described above were applied successively to each car end, and the performance of each is measured in terms of crush distribution and maximum crashworthiness speed. The percentages by which each component was modified reflect the greatest changes that could reasonably be made to the components and do not necessarily represent products of variations in manufacturing.

RESULTS

Primary Energy Absorber

The PEA is the last to deform before the carbody itself is loaded. After the draft gear and pushback coupler have been exhausted, the primary energy absorber triggers at 1.20 x 10^6 lbf and operates at a slope of 2.36 x 10^5 lbf/ft, with an average value of 1.03 x 10^6 lbf. Strength levels were offset above and below the reference value by 20 percent. Behavior for an increased PEA level at each car end independently was examined first. The slope for the PEA was held constant. Figure 11 provides a visualization of the changes made. Though the primary energy absorption slopes are identical to those used in the coach car design, the trigger load for the reference case is 7.13 x 10^5 lbf and the average operating load is 1.03 x 10^6 lbf for the cab car.

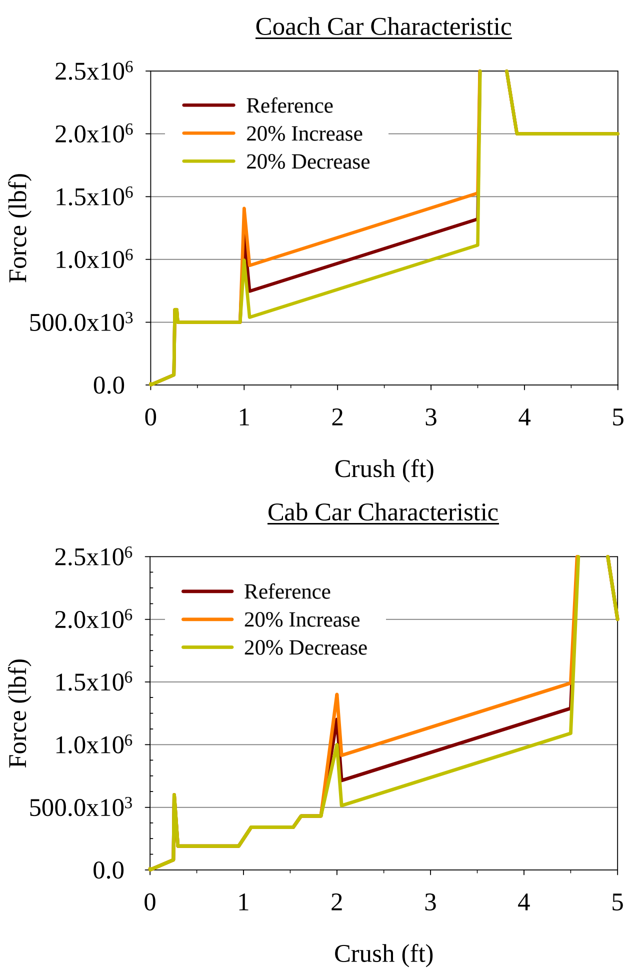

Figure 11. Primary Energy Absorber Adjustment

Table 3 summarizes the changes made to each coach car. The total energy capacity of the CEM system and the loading (but not failure) of the carbody is also included for each case, as the available energy differs for each.

Table 3. Primary Energy Absorber Adjustment

	Trigger (lbf)	Average (lbf)	Slope (lbf/ft)	Total Energy (ft-lbf)
Reference	$1.20(10)^6$	$1.03(10)^6$	$2.36(10)^5$	$3.10(10)^6$
20 % Increase	$1.41(10)^6$	$1.24(10)^6$	$2.36(10)^5$	$3.63(10)^6$
20 % Decrease	$9.94(10)^5$	$8.26(10)^5$	$2.36(10)^5$	$2.58(10)^6$

For a given adjustment to each car end, there is an associated reaction in the car end with which it is coupled. For instance, if the rear end of the leading cab car has a primary energy absorber strength 20 percent lower than usual, the front end of the first coach car experiences less crush than in the reference configuration. Furthermore, the PEA at the rear of the cab car begins to load before the one on the coupled car end.

Running the model for each case produces a series of graphs like Figure 8, with crush in terms of percent CEM utility for each car end. These plots were concatenated to produce the three-dimensional plot shown in Figure 12. Crush is plotted on the vertical axis and car end is on one horizontal axis. The crush distribution plot, or "slice," for each run made is along the "Car End Modified" axis. The assembly of crush distribution plots reveals patterns that depend on the variations in component behavior. Slices for each car end show how performance is changed as the PEA on car ends are weakened. In general, the only substantial change is at the coupled interface where the component has been adjusted. Reducing the PEA strength by 20 percent produces a 50 to 60 percent increase in percent utility since the end has a lower energy capacity. The distinct peaks form a diagonal ridge in the plot, highlighting the local effect of the weak component.

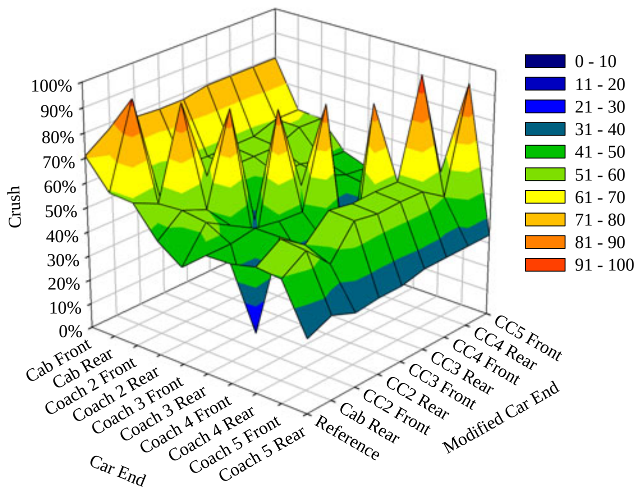

Figure 12. 30 MPH Car-end crush results of sequentially tested PEA ratings lowered 20 percent

Figure 13 shows the results when PEA strength is raised sequentially at each car end. A valley is formed in the plot to indicate where the modification was made. Also note that the front end of the cab car maintains a steady 80 percent utility of the CEM system for any change from the reference configuration.

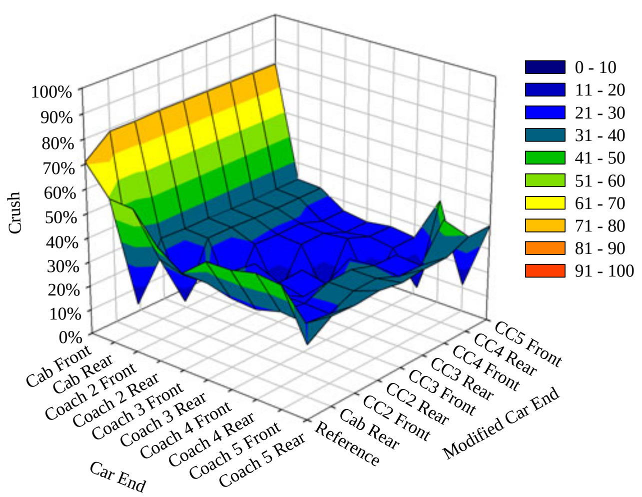

Figure 13. 30 MPH Car-end crush results of sequentially tested PEA ratings raised 20 percent

In both of the above three-dimensional graphs, it is of note that the cab car ends at both the colliding interface and at the rear of the fifth coach car exhibit relatively constant crush percentages. Although the crush distribution changes with each slice, the “weak spot” is always the lowered force car end at the adjusted interface. For the 30 mph cases with PEA level adjustments of 20 percent upward and downward, there is no entry into the occupied volume.

The results due to the addition of the draft gear on the ends of the locomotives were observed. Previous research details the effects the draft gear has on the behavior of the consist during a collision. However, it was found that the addition of draft gear to the ends of the locomotives had only a small effect on CEM performance.

Pushback Coupler

After compression of the draft gear, the pushback coupler is designed to engage at an activation force of 6 x 10^5 lbf and operate at a force of 5 x 10^5 lbf. Variations of an operating load raised 50 percent of the original value were made to each car end. Table 4 summarizes these adjustments. The results qualitatively are similar to those for adjustments made to the PEA.

Table 4. Pushback Coupler Adjustment

	Trigger (lbf)	Operating (lbf)
Reference	$6(10)^5$	$5(10)^5$
50 % Increase	$8.5(10)^5$	$7.5(10)^5$
50 % Decrease	$3.5(10)^5$	$2.5(10)^5$

Figure 14 displays the changes applied to the pushback couplers.

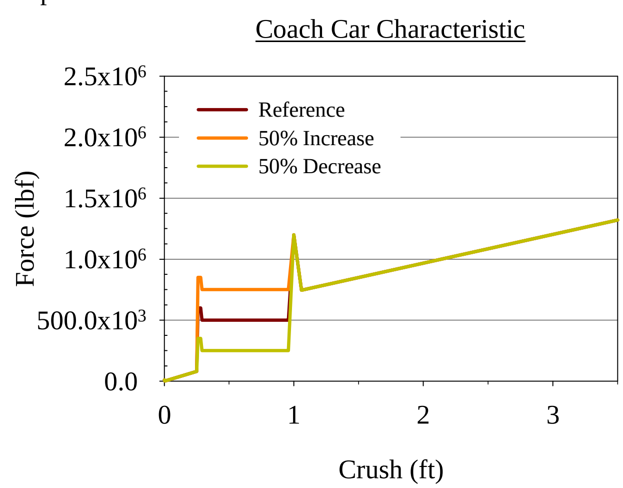

Figure 14. Pushback Coupler Adjustment

The draft gear has little effect on CEM performance at the speeds considered.

Maximum Crashworthiness Speed

The maximum speed at which there is no occupant volume loss for the reference model was 40 mph. It is important to note that not every absorber has been completely exhausted at this speed.

The maximum crashworthy speed was determined for each modification to the baseline configuration. The results of this research are in Figure 15. This speed was unchanged for all adjustments in the PBC. Most PEA configurations were also safe up to 40 mph. The few that fell below this mark only decrease by about 10 percent in maximum crashworthiness speed. Nearly all of the cases with reduced safe speed occur for changes of the interface between the 4th and 5th coaches. These reductions occur whether the strength is raised or lowered.

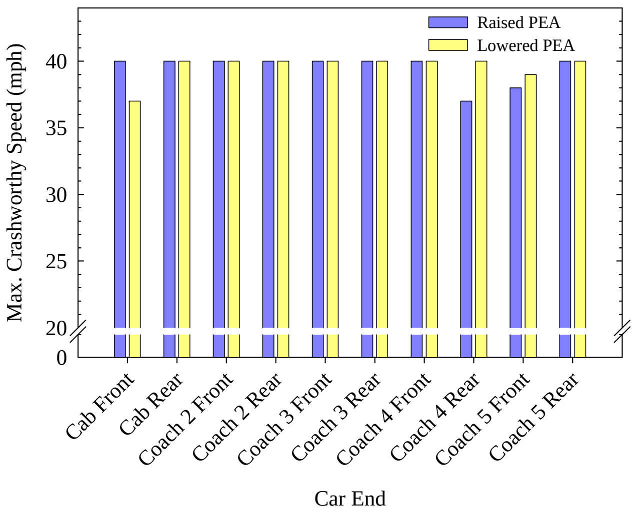

Figure 15. Maximum Crashworthiness Speed for Adjustment in PEA Strength

In general, the colliding cab car end limits the maximum crashworthy speed. When the occupant volume is intruded in the trailing cars [9], it is associated with the interaction at the rear end locomotive-coach interface.

SUMMARY AND CONCLUSIONS

The CEM system has been shown to be robust. Large changes in energy absorption at one car end have little effect on the overall crashworthiness of the train.

Adjustment of the pushback coupler operating strength by as much as 50 percent of the reference value makes little difference in the crush of the colliding interface and of the rear of the last coach car. There are local changes in the amount of crush at the location of coach car modifications.

20 percent adjustments of the primary energy absorber mechanism have more of an effect on overall consist behavior. Local variations result in energy utility differences from 30 to 40 percent for decreased PEA levels. For increased PEA levels, a difference of 20 to 30 percent is observed.

This research examined the effects of modifications to individual portions of the reference force-crush characteristic when applied to a single car end. This represents the effect of variations in the manufacture of the CEM components. This research also aided in the determination of the influence each modification had on the crashworthiness of the consist during a collision event. This research has shown that even if the CEM force-crush characteristic is modified from the reference, the overall consist behavior will still be more desirable with respect to the conventional consist. Crush is drawn away from the lead car, and is focused on unoccupied space.

ACKNOWLEDGEMENTS

The work described in this paper was part of a Tufts University Department of Mechanical Engineering Undergraduate Thesis. Some of this work was done as part of the Federal Railroad Administration's Equipment Safety Research Program. The authors thank Professor Behrouz Abedian, Department of Mechanical Engineering, Tufts University, for his discussions, questions, and recommendations as a member of the thesis committee. The authors would also like to thank Eloy Martinez, Program Manager, Federal Railroad Administration, for his helpful comments and flexibility in allowing access to information from the Equipment Safety Research Program.

REFERENCES

1. Tyrell, D., "Passenger Rail Train-to-Train Impact Test Volume I: Overview and Selected Results," DOT/FRA/ORD-03/17.1, U.S. Department of Transportation, Washington, DC, July 2003.
2. Severson, K., Tyrell, D., Perlman, B., "Analysis of Collision Safety Associated with Conventional and Crash Energy Management Cars Mixed Within a Consist," American Society of Mechanical Engineers, Paper No. IMECE2003-44122, November 2003.
3. Priante, M. "Influence of Train Parameters on Crashworthiness Performance of Passenger Trains." Tufts University Undergraduate Honors Thesis, May 2004.
4. Mayville, R, Stringfellow, R., R., Johnson, K., Tyrell, D., "The Development of a Rail Passenger Coach Car Crush Zone," American Society of Mechanical Engineers, Paper No. JRC2003-1653, April 2003.
5. Jacobsen, K., Tyrell, D., Perlman, A.B., "Impact Test of a Crash-Energy-Management Passenger Rail Car," American Society of Mechanical Engineers, Paper No. RTD2004-66045, April 2004.
6. Tyrell, D., Jacobsen, K., Martinez, E., "A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment: Structural Results," American Society of Mechanical Engineers, Paper No. IMECE2006-13597, November 2006.
7. Parent, D., Tyrell, D., Perlman, A.B., "Crashworthiness Analysis of the Placentia, CA Rail Collision," Proceedings of ICrash 2004, International Crashworthiness Conference, San Francisco, California, July 14-16, 2004.

8. Carolan, M. "Performance Efficiency of Crash Energy Management Systems." Tufts University Undergraduate Thesis, May 2006.
9. Mallon, P. "Influence of Manufacturing Variations on a Crash Energy Management System." Tufts University Undergraduate Honors Thesis, May 2007.