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# Evaluation of Rail Passenger Equipment Crashworthiness Strategies

David Tyrell and A. Benjamin Perlman

**Comparisons are made of the effectiveness of competing crashworthiness strategies -- crash energy management (CEM) and conventional passenger train design. CEM is a strategy for providing rail equipment crashworthiness that uses crush zones at the ends of the cars. These zones are designed to collapse in a controlled fashion during a collision, distributing the crush among the cars of the train. This technique preserves the occupied spaces in the train and limits the decelerations of the occupant volumes. Two scenarios are used to evaluate the effectiveness of the crashworthiness strategies: a train-to-train collision of a cab car-led passenger train with a standing locomotive-led passenger train, and a grade-crossing collision of a cab car-led passenger train with a standing highway vehicle. The maximum speed for which all the occupants are expected to survive and the predicted increase in fatalities and injuries with increasing collision speed are determined for both train designs. Crash energy management is shown to significantly increase the maximum speed at which all the occupants could survive for both the grade crossing and train-to-train collisions for cab car led trains, at the expense of modestly increasing the speeds at which occupants impact the interior in train-to-train collisions.**

Cab car led trains present a challenging situation in collisions. The presence of passengers as well as lighter weight and lower strength in comparison with locomotives exposes them to the most risk. In order to address this exposure, the Federal Railroad Administration (FRA) has conducted research on various modifications intended to improve the crashworthiness of cab cars [1, 2, 3, 4]. Modifications considered previously have focused on strengthening existing members of the cab car structure. This paper describes a 'clean-sheet' strategy for cab and coach car structural designs that is significantly different from conventional structural designs. This crash energy management (CEM) approach includes structural crush zones at the ends of the car that require less longitudinal force to collapse than the occupied areas.

## ALTERNATIVE CRASHWORTHINESS STRATEGIES

In designing for crashworthiness, the first objective is to preserve a sufficient volume for the occupants to ride out the collision without being crushed. Excessive forces and decelerations also present a potential for injury to the occupants. Relatively large forces and decelerations can occur when an unrestrained 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 second objective of crashworthiness is to limit these secondary collision forces and decelerations to tolerable levels.

Preserving occupant volume is accomplished with strength of the structure. If the occupant compartment is sufficiently strong, there will be sufficient space for the occupants. Secondary impacts are limited through a combination of structural crashworthiness and occupant protection measures. Allowing portions of the vehicle to crush in a predetermined manner can control the decelerations of the cars. Occupant protection measures include the use of restraints such as seatbelts and shoulder harnesses and strategies such as compartmentalization [5, 6, 7]. 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.

There is a tradeoff between increased occupant volume strength and secondary impact velocity. If a single car has uniform crush strength, increasing the crush strength increases the speed at which occupants impact the interior. For a train of cars the issue is more complex. The cushioning of the cars ahead and the pushing of the cars behind influence the deceleration of any particular car. In general, any crashworthiness strategy that better preserves the occupant volume will make the secondary impacts more severe for the occupants in the interior.

Conventional practice is oriented toward making the individual cars as strong as possible within weight and other design constraints. This approach attempts to control the behavior of individual cars during the collision. The crash energy management (CEM) approach is train oriented, apportioning the structural crushing to unoccupied areas throughout the train.

This paper includes descriptions of conventional and crash energy management crashworthiness approaches and a comparison of the effectiveness of each in selected collision scenarios. This evaluation is focused on the structural crashworthiness of the equipment, and for the comparison the interior occupant protection features are assumed to be the same for both crashworthiness approaches. The purpose of the paper is to develop the base of information needed to evaluate the potential economic benefits of the crash energy management approach.

### Conventional Practice

Figure 1 is a schematic illustration of the principal structural members of a conventional car subjected to the principal crashworthiness requirement since the 1940's, an 800 kip buff load [8]. The car must be able to support without permanent deformation an 800 kip longitudinal static load applied at the buff stops. This requirement is intended to assure at least a minimum strength of the occupied volume of the car. Although the buff stops are located approximately six feet from the end of the car, meeting this requirement using conventional design practices has resulted in structures that are nearly uniform in their axial strength. These car structures are as strong at the ends, outboard of the buff stops, as near the mid-length.

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D. Tyrell, Volpe National Transportation Systems Center, Kendall Square, Cambridge, MA 02142. A. B. Perlman, Department of Mechanical Engineering, Tufts University, Medford, MA 02155

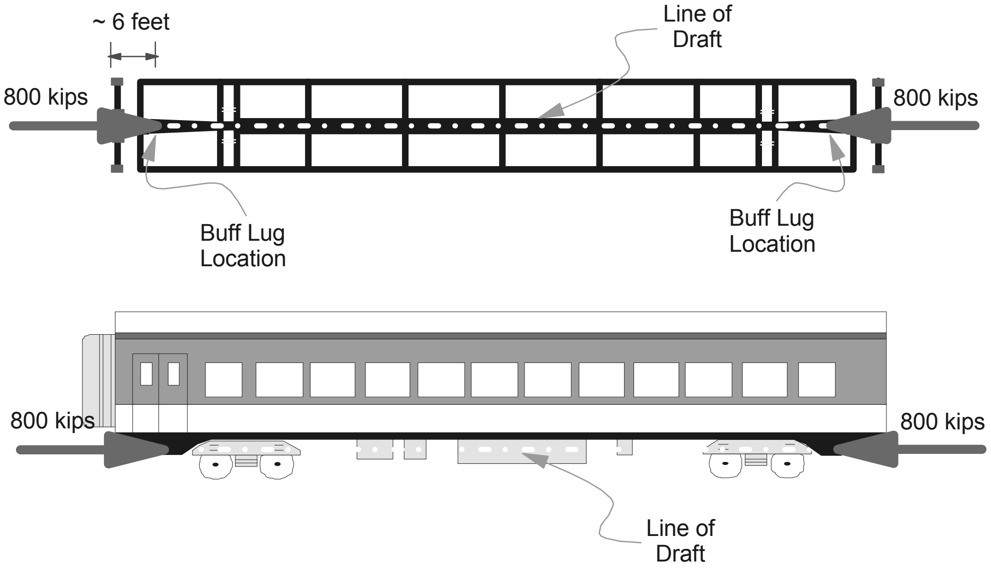

FIGURE 1. Schematic Illustration of conventional passenger rail car: (a) top view, (b) elevation view.

For most cars, applying a static load along the line of draft results in the floor being in compression and the roof being in tension. During a collision, the longitudinal dynamic load is likely to be applied to the structure above the line of draft, putting both the structure below the floor and in the roof into compression. The longitudinal dynamic load that initiates crushing of the car is significantly greater than the static buff load that can satisfy the condition represented in Figure 1.

Figure 2 is a schematic representation of the dynamic force/crush behavior of a conventional cab car, where the crush is the reduction in the cab car end-to-end length. It is based on measurements made during impact tests in which a single passenger car and two coupled passenger cars, were run into a fixed barrier (*9, 10*) and a test in which a cab car-led passenger train impacted a locomotive-led train. The measurements from all three tests show high initial peak loads, followed by significantly lower, approximately constant loads up to about eight feet of crush. After eight feet, the results of the train-to-train test indicate the load increases when the lead truck is engaged, and decreases rapidly when the body bolster fails. The initial portion – up to about six feet – of this force/crush behavior is qualitatively similar to the quasi-static force/crush behavior of an axially loaded beam with uniform cross-section [11].

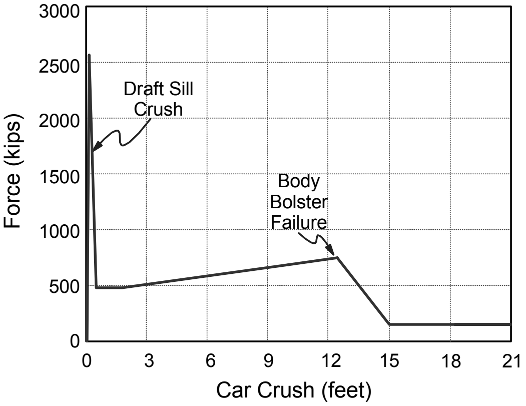

FIGURE 2. plot of force/crush characteristic for conventional passenger rail car main structure.

The static buff load requirement, in combination with the practice of designing car structures to have uniform axial strength, implies that at least 800 kips is required to initiate crushing of the car. Since the buff load is static and no permanent deformation is allowed, the dynamic load required to initiate permanent deformation will be greater than the 800 kips static buff load. Other than the peak load, the static buff load requirement does not influence the force/crush characteristic; rather the force/crush characteristic is governed by the nature of the sustained crush of the car structure. If the car structure crushes in a graceful manner, then the load for continued crush would remain high. If the car structure collapses, then the load for continued crush would be relatively low – lower than the 800 kip buff load requirement.

One implication of the force/crush characteristic shown in Figure 2 is that the crush will be focused on the colliding cars. The longitudinal force develops in the impacting cars first, and once the peak force is attained, the colliding car of a train will lose its the ability to push back on the trailing cars with sufficient force to crush those cars. In the collision test of two coupled cars [10], the lead car sustained nearly all of the structural damage at its lead end, with the car's length reduced by nearly six feet. Only minor scarring due to direct contact was observed at the interface between the trailing end of the lead car and the front end of the second car. Similarly, in the train-to-train test, nearly all of the damage was focused on the lead end of the colliding cab car, with only minor damage to the cab car's trailing end and to the trailing equipment. The colliding locomotive remained principally intact, although the anti-climber and bellmouth were damaged.

## Crash Energy Management

Figure 3 is a schematic of the concept of CEM, with crush zones at the ends of all of the cars of the train. If each zone can absorb three

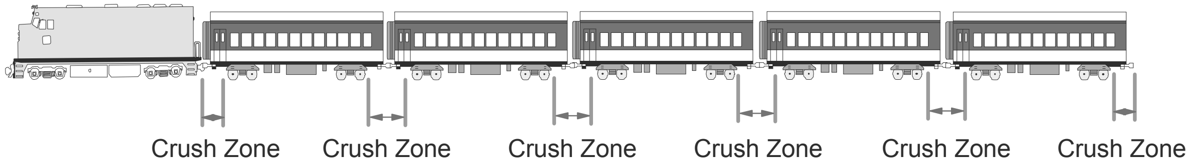

**FIGURE 3. Schematic Illustration of cush zone locations in commuter rail passenger train used in push/pull service.**

feet of crush, there is a total of six feet between coupled cars. The cab car and the coach cars are constrained to have the same force crush characteristic, to help allow the alternative use of the cab car as a coach car. In the event of an impact with a conventional locomotive, the cab car has only three feet of CEM crush at the impacting end to help absorb the impact. By controlling the structural crushing in the CEM zones of the trailing cars, occupant volumes can be preserved. Severity of the secondary impacts can be limited by managing the deceleration of the occupied volume with controlled structural crushing.

The operator and occupants of a cab car need to be protected. In a dedicated cab car, the operator could be moved back from the end of the car, allowing a larger crush zone than in a coach car. Such a design could provide even greater protection for both the operator and the passengers than for the CEM design discussed in this paper. However, operations that use cab cars as coach cars preclude moving the operator away from the end of the car. Eliminating the step well at the cab end provides additional area for structural elements to protect the operator. Recent equipment purchases have indicated that railroads are willing to eliminate the step well on the operator's side of the vestibule.

Figure 4 shows a schematic illustration for a CEM cab car that can also be used as a coach car. The operator's cab is surrounded by a strong cage, which can slide back as the energy dissipation elements are crushed. The area behind the operator is unoccupied, but could be used as a utility closet for brake or electrical equipment. This arrangement allows for preservation of the operator's volume in the event of a collision, but exposes the operator to higher deceleration than the passengers. To protect the operator, additional measures, such as seatbelts, airbags, or other inflatable structures, may be necessary.

Figure 5 shows a CEM force/crush characteristic for the cab car and coach that allows the crush to be distributed throughout the cars of the train. As the crush increases, the force increases, remaining nearly constant in segments. This curve takes advantage of the buff stops being six feet from the end of the car. Between the buff lugs, a crash energy management car can be designed to support the 800 kip buff load, while requiring a lower force to crush the car outboard of the buff stops. Implementing the concept illustrated in Figure 4 in a rail car structure that can produce the force/crush characteristic shown in Figure 5 is a challenge. Coach cars, dedicated cab cars, and locomotives have been developed with structures that have force/crush characteristics that are qualitatively similar to the behavior shown in Figure 5 [12, 13, 14].

## COLLISION SCENARIOS

Two collision scenarios, a train-to-train collision and a grade crossing collision, are used to evaluate the potential effectiveness of passenger equipment incorporating CEM. The performance of a train with conventional equipment is compared to one with CEM structure. In both scenarios, the moving train consists of a cab car, four coach cars, and a locomotive, with the cab car leading. These scenarios are idealizations based on accidents that allow ready comparison of the performance of alternative structural crashworthiness design strategies. Accidents similar to the train-to-train collision scenario include the Beverly, Massachusetts accident on August 11, 1981 [15], the Secaucus, New Jersey accident on February 9, 1996 [16], and the Silver Spring, Maryland accident on February 16, 1996 [17]. Accidents similar to the grade crossing scenario include the Intercession City, Florida accident on November 30, 1993 [18], the Wakefield, Massachusetts, accident on January 16, 1996 [19], and the Portage, Indiana accident on June 18, 1998 [20].

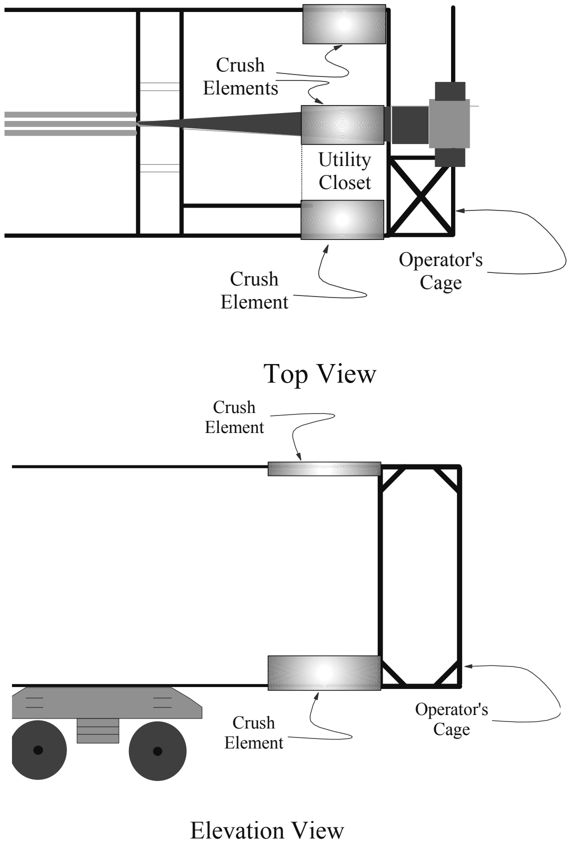

**FIGURE 4. Conceptual schematicfor CEM cab car.**

For the train-to-train scenario illustrated in Figure 6a, the initially standing train is made up of conventional equipment, and like the initially moving train, it includes a cab car, four coaches, and a locomotive. The standing train has the locomotive in the lead. In the simulations, the cab car of either another conventional train or a CEM train impacts the locomotive of the initially standing conventional train. The CEM train includes cab and coach

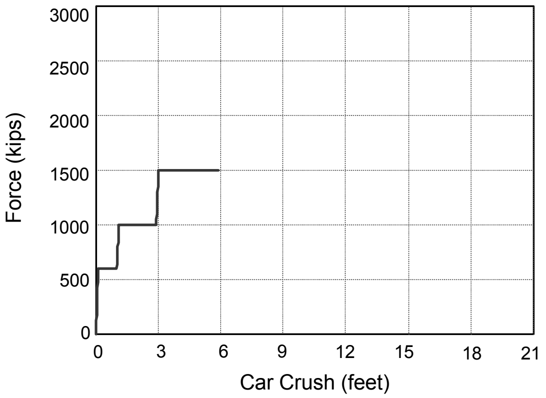

**FIGURE 5. Plot of force/crush characteristics for CEM passenger rail car.**

cars with crush zones as illustrated in Figure 3, while the locomotive does not include crush zones, i.e., the locomotive of the CEM train is a conventional locomotive.

In the grade crossing collision scenario, a moving cab car led train, made up of either conventional or CEM equipment, collides with a highway vehicle standing at a grade crossing. The highway vehicle weighs 100 kips. The highway vehicle and load are assumed to be rigid and do not crush during the impact. Figure 6b is a schematic illustration of the grade crossing collision.

## COMPARISON OF THE EFFECTIVENESS OF ALTERNATIVE CRASHWORTHINESS STRATEGIES

A one-dimensional, multiple-degree-of-freedom model is used to compare lost occupant volume and secondary impacts for the two structural crashworthiness strategies. This model and evaluation approach is similar to those described in references [6, 21]. The model is appropriate when the lateral and vertical displacements of the car are small in comparison to the longitudinal displacements.

Fatalities due to loss of occupant volume are assumed to be proportional to the reduction in length in each car. The model is used to calculate the crush at the ends of each car. Volume occupied by the crushed material is taken into account by assuming that it is 40% of the reduction in car length. Simple structures such as thick-walled columns can be crushed to approximately 20% to 30% of their undeformed height [22]. 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. Fatalities begin when three feet of car length is lost at an end. There are three passenger seats in the first row and five seats (three by two seating) in each successive row.

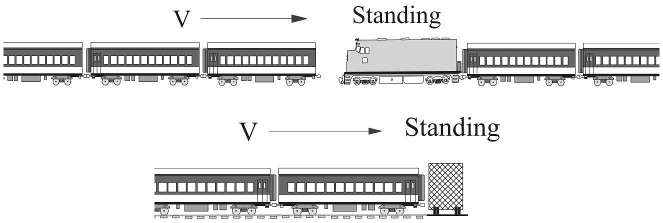

**FIGURE 6. Schematic Illustrations of train-to-train collision and Grade Crossing Collision Scenarios.**

Fatalities from occupant impact with the interior depend on the secondary impact velocity -- the speed with which the occupant strikes the interior. The occupants are assumed to go into free flight at the start of the collision. After traveling some distance, the occupants strike a seat or wall. The occupants are assumed to be seated in consecutive rows of forward facing seats so that there is a distance of 2 feet from the forehead of an occupant to the seat back ahead of him or her. The seat back is assumed to have some amount of padding and flexibility. Given the seat back force/deflection characteristic [23] 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 while in contact with the seat can be used to calculate the Head Injury Criteria (HIC) [24], an injury criteria widely applied in the automotive and aircraft industries to evaluate test and analysis data. Both the conventional and CEM equipment are assumed to have the same interior configuration.

### Train-to-Train Collision

Figure 7 compares the distribution of crush among the cars in the CEM and conventional trains for a cab car-led train, initially moving at 25 mph, colliding with a standing locomotive-led train. For the conventional train the crush is focused on the front of leading cab car. The front end of the car crushes substantially more than three feet, resulting in significant loss of occupant volume. It is assumed that after one foot of crush, the operator space is lost. For the 12 feet of crush predicted for the conventional train, the space for five rows of passenger seats is gone. With three seats in the first row and five in each succeeding row, the survival space for 23 passengers would be crushed.

For the CEM train, crush is largest at the front of the cab car, but is distributed to all of the passenger cars. At a closing speed of 25 mph, no end of a car is crushed as much as three feet so that the space for all of the passengers and all of the crew is preserved. Significant crush occurs at the rear of the cab car, at the front and rear of the first coach car and at the front of the second coach car. The total crush distance at the interface between the cab and the first coach is greater than between the colliding cab car and locomotive. Both the trailing end of the cab car and the leading end of the first coach have a crush zone, while there is a crush zone at the lead end of the cab car, but none in the locomotive. Preservation of the operator's survival volume is predicated on the implementation of the concept illustrated in Figure 4.

Figure 8 compares the amount of crush at the lead end of the cab car as a function of closing speed for the train-to-train collision. At closing speeds greater than 12 mph, there is sufficient energy to overcome the initial peak of the force/crush characteristic for the conventional car. As the closing speed increases above this threshold, the crush increases rapidly. The rate of increased crush of the lead end of the cab car with increased collision speed is much lower for the CEM design than for the conventional equipment. Even though the crush zone on the lead end of the cab car is exhausted at 25 mph, the crush zones at the trailing end of the cab car and at both ends of the coach cars are not. For closing speeds greater than 25 mph, most of the additional crushing is transferred backward to the trailing end of the cab car and to the

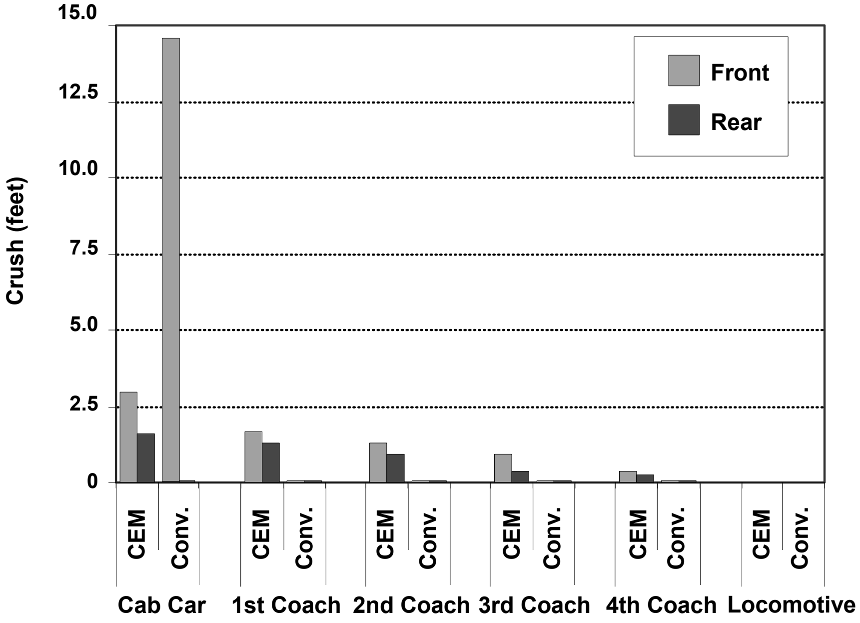

**Figure 7. Distribution of crush among cars in the train, conventional and crash energy management trains, train to train collision at 25 mph.**

coach car crush zones. In the train-to-train collision scenario, loss of occupant volume is expected for the conventional train at collision speeds greater than 12 mph, and for the CEM train at collision speeds greater than 25 mph.

Figure 9 compares the secondary impact velocities for the cars in the CEM and conventional trains for a cab car-led train, initially moving at 25 mph, colliding with a standing locomotive-led train. These plots show the relative speed for conventional and CEM designs at which an unrestrained occupant would travel in the interior of the car. Seated, forward-facing passengers would impact the seatback in the next row after traveling a relative distance of approximately two feet.

Given the seat back force/deflection characteristic, the mass of the head, and the secondary impact velocity, a range for the deceleration time-history of the head can be calculated. This range depends on the manner in which the head rebounds from the seat. The deceleration time-history of the head can be used to calculate the HIC. The HIC is related to the likelihood of injury and fatality. The likelihood of injury is greater as the secondary impact velocity increases. Since a range for the deceleration time history of the head is calculated, a range for the likelihood of fatality is predicted. All of the cars in the conventional design train have nearly the same secondary impact velocity. They are all approximately the same because the crushing of the lead car decelerates all of the cars together. More effective preservation of the occupant volume in the CEM design train comes in exchange for higher secondary impact velocities in the passenger cars. For the CEM design train, the cab car and the first coach have distinctly higher secondary impact velocities than the other coaches and trailing locomotive.

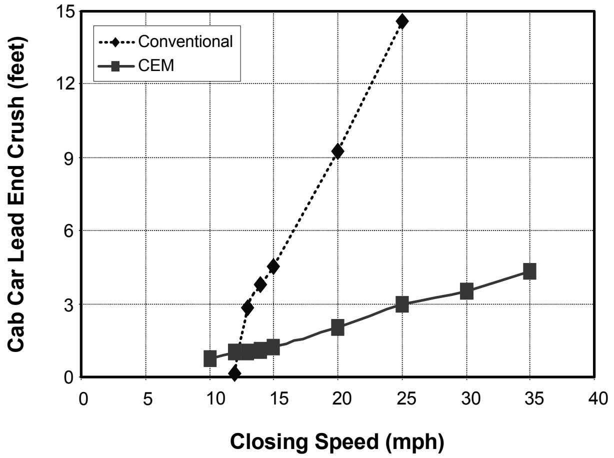

**FIGURE 8. influence of train to train closing speed on Cab Car Lead End crush, conventional and crash energy management designs**

No fatalities are expected for secondary impact velocities below 20 mph. For collision speeds up to 35 mph, secondary impact velocities above 20 mph are predicted only in the cab car of the CEM train. A potentially greater level of occupant protection can be achieved in the cab car by having the seating face the rear of the car or by providing seatbelts [6, 7]. When facing rearward, the occupants do not impact the interior, but are instead restrained by the seatback.

For the conventional design equipment, there is just sufficient energy to crush the operator's volume at 12 mph. Intrusion into the passenger volume is initiated at 14 mph. No intrusion into either the operator or passenger volume is predicted until the closing speed has reached 25 mph for the CEM equipment. At 35 mph the crush of the CEM cab car exceeds three feet and the survival volume for the operator and three passengers is lost. In addition, the secondary impact velocity exceeds 20 mph for the occupants of the CEM-design cab car. As a consequence, a range of one to eight fatalities is expected in the CEM-design cab car when the closing speed of the train-to train collision is 35 mph. No fatalities due to secondary impacts are expected in the conventional-design cab car. By using crash energy management, the maximum safe speed for the operator can be more than doubled, while it is nearly doubled for the passengers.

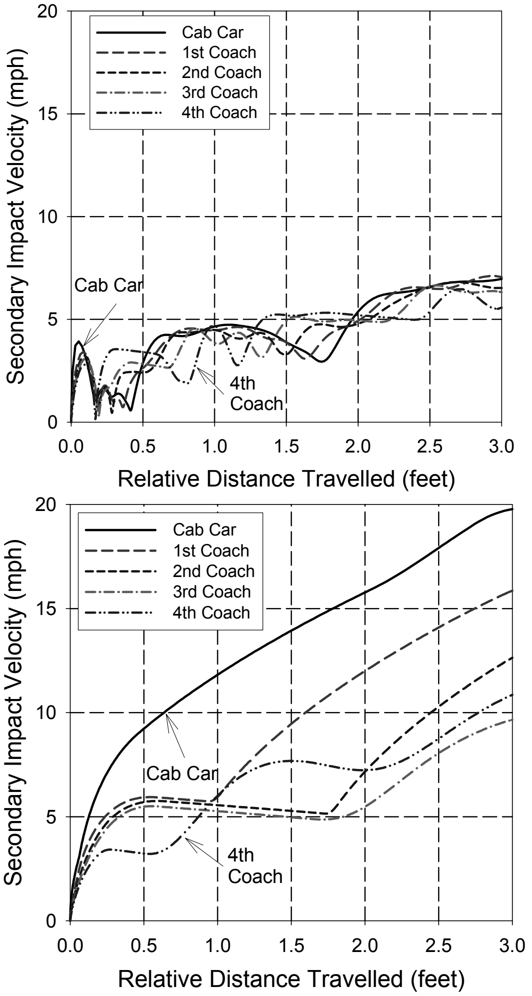

**Figure 9. Secondary Impact velocities, conventional and crash energy management trains, train to train collision at 25 mph.**

## Grade Crossing Collision

For the grade crossing collision scenario, the crush is focused on the cab car for both the conventional car and the crash energy management design. Some of crush is transferred to the rear of the cab car for the CEM design. Figure 10 shows the crush of the cab car as a function of closing speed for the grade crossing collision for both the conventional and CEM trains. At low speeds, there is less crush for the conventional than for the CEM design. As indicated by Figures 2 and 5, the conventional design absorbs more energy in the first foot of cab car crush. At higher speeds, more energy is absorbed in the CEM design than in the conventional design, since the force is larger as the crush increases. In the grade-crossing collision scenario, loss of occupant volume is expected for the conventional train at collision speeds greater than 20 mph, and for the CEM train at collision speeds greater than 35 mph.

No fatalities or injuries are expected due to secondary impacts for the grade crossing collision. Since the mass of the highway vehicle is small relative to the mass of the train, the change in velocity of the moving train is much lower in the grade crossing collision than in the train-to-train collision. For a 40 mph primary collision velocity, the secondary impact velocities for the cars in the conventional train are all about 5 mph. For the CEM design, the cab car has a higher secondary impact velocity than the other coaches since the cars crush with some degree of independence. In a 40 mph grade crossing collision, the secondary impact velocity in the cab car of the CEM train is estimated to be 9 mph, not sufficient to cause fatality for a forward-facing unrestrained passenger.

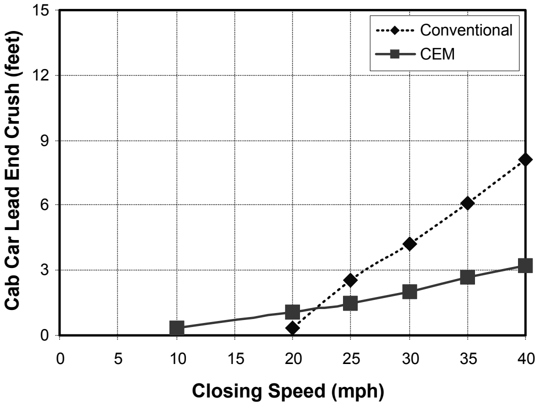

Figure 10. influence of grade crossing collision closing speed on Cab Car Lead End crush, conventional and crash energy management designs

The CEM design is effective in protecting the operator and passengers at closing speeds up to 35 mph. The maximum safe speeds for the operator and for the passengers in the conventional design are 20 and 25 mph, respectively. By using crash energy management, the maximum safe speed for the operator can be nearly doubled, and increased by nearly half for the passengers.

## CONCLUSIONS AND RECOMMENDATIONS

Crash energy management provides a significant increase in crashworthiness over the conventional approach for cab car-led trains in train-to-train and grade crossing collisions. The crash energy management design evaluated in this paper has a maximum safe speed (the greatest collision speed at which all occupants survive) more then two times greater than the maximum safe speed for conventional equipment for a train-to-train collision with a cab car leading. This crash energy management design also has a maximum safe speed nearly twice the conventional design in a grade crossing collision with a heavy highway vehicle. Crash energy management is more effective in preserving the survival space for the occupants than the conventional approach, at the expense of modestly increasing the speeds at which occupants impact the interior in train-to-train collisions.

Potentially even greater increase in maximum safe speed could be achieved with a dedicated cab car, which has a longer crush zone and the operator is some distance from the impact. A longer crush zone would increase the maximum safe speed for both the operator and the passengers by absorbing more of the collision energy. By moving the operator away from the end of the cab car, the impact would also inflict a less severe secondary collision environment upon the operator.

Detailed structural analyses and testing are required in order to develop structures that implement the crash-energy management force/crush characteristics described in this paper [25]. More detailed analyses are also required to develop the operator's cage, and to assure that it performs appropriately. The cage must be capable of surviving oblique train-to-train collisions, as can occur at a switch, as well as head-on train-to-train collisions and grade crossing collisions.

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