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ANALYSIS OF COLLISION SAFETY ASSOCIATED WITH CONVENTIONAL AND CRASH ENERGY MANAGEMENT CARS MIXED WITHIN A CONSIST

Kristine J. Severson
David C. Tyrell
Volpe National Transportation Systems Center
U.S. Department of Transportation
Cambridge, MA 02142

A. Benjamin Perlman
Tufts University
Department of Mechanical Engineering
Medford, MA 02155

ABSTRACT

A collision dynamics model of a passenger train-to-passenger train collision has been developed to simulate the potential safety hazards and benefits associated with mixing conventional and crash energy management (CEM) cars within a consist. This paper presents a comparison of estimated injuries and fatalities for seven collision scenarios based upon the variable mix of conventional and CEM cars. Based on the analysis results, recommended car placement when mixing cars within a consist is identified.

The model includes a 6 car cab car-led consist colliding with a 6 car locomotive-led stationary consist. The stationary consist is made up of all conventional cars. The moving consist has a variable mix of conventional and CEM cars. For comparison, the bounding scenarios are:

- a moving consist with all conventional cars, and
- a moving consist with all CEM cars.

The collision speed ranges from 15 to 35 mph.

Since the two car designs behave differently under impact conditions, there is a concern that there may be hazards associated with mixing the two designs in the same consist. In none of the cases evaluated is the mixed consist less crashworthy than the conventional consist. The modeling results indicate that the least crashworthy consists are ones in which a conventional cab car is leading any combination of vehicles. The conventional cab car incurs nearly all the damage and prevents trailing cars from participating in energy absorption, whether they are conventional or CEM. The most crashworthy consists are ones in which a CEM cab is leading. The CEM cab can absorb a significant amount of energy without intruding into the occupied volume. The CEM cab also allows trailing cars to participate in energy absorption, which provides further occupant protection.

The recommended strategy for car placement is to put the CEM car(s) at the leading end(s) and the conventional car(s) at the trailing end or in the middle of the consist in push-pull operation. There is also significant benefit to placing the seats in the leading CEM car or two so they are rear-facing. Rear-facing seats can reduce the severity of secondary impact injuries because the occupant is already in contact with the seat in the direction of travel and does not develop a significant velocity relative to the seat.

INTRODUCTION

Conventional passenger rail cars are designed to have a relatively uniform longitudinal strength, i.e., the strength at any cross-section along the length of the car is the same as the strength at any other cross-section. Like a long beam, a large force is required to initiate crushing, but after initiation, crushing continues at a much lower force. In a collision of conventional cars, the force/crush behavior results in the majority of the crush being isolated in the portion of the car nearest the impact.

In contrast, cars designed with crash energy management have sacrificial crush zones at the vehicle ends. These crush zones are designed to crush at a lower initial force, which allows energy absorption to be shared by multiple cars throughout the consist. The initially softer crush zones allow collision energy to be absorbed in areas that are typically unoccupied, while preserving the integrity of the occupied areas.

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. 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. 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 the speed with which the occupant strikes the interior. In general, any crashworthiness strategy that better preserves the occupant volume will make the secondary impacts occur at higher speeds, and therefore will make these impacts more severe. The combination of CEM for car structures and complimentary occupant protection measures allows optimizing the tradeoff between preserving the occupant volume and limiting the severity of secondary impacts.

Since passenger rail equipment has a useful life of 25 years or more, the implementation of CEM equipment is likely to result in CEM cars mixed in consists with conventional equipment. The purpose of this analysis is to realize the possible advantages or disadvantages associated with mixing equipment with different collision behavior within a consist, and to provide recommendations on car placement.

A limited number of scenarios have been selected to illustrate the safety associated with different train make-up conditions. Table 1 indicates the type of each car within the moving consist for each scenario. In each scenario, all the cars in the stationary consist are conventional. The cars in the moving consist vary from all conventional (scenario 1) to all CEM (scenarios 2 and 3). Scenarios 1 and 3 bound the range of possible outcomes in terms of fatalities. Other possible variations of train make-up would have fewer fatalities than scenario 1, but more fatalities than scenario 3. These scenarios bound the results because of the different force-crush behavior of each design.

Table 1. Conventional and CEM Car Placement

Legend:		Make-up of Moving Train						
		1	2	3	4	5	6	7
■	=Conventional	All Conv	All CEM	All CEM Cab rear-f	Cab Conv	1st Coach Conv	Cab CEM	1st Coach CEM
░	=CEM							
V = 15, 25, 35 mph	Cab	■	░	░	■	░	░	■
	Coach 1	■	░	░	░	■	■	░
	Coach 2	■	░	░	░	░	■	■
	Coach 3	■	░	░	░	░	■	■
	Coach 4	■	░	░	░	░	■	■
	Loco	■	■	■	■	■	■	■

This paper compares the collision safety of commuter trains with a variable mix of conventional and CEM cars. The comparison focuses on loss of occupant volume and probability of fatal injury as measures of occupant protection. The scenario in which all cars in both consists are conventional is used as a benchmark of current vehicle crashworthiness that must not be exceeded by mixing CEM and conventional cars within a consist.

COLLISION DYNAMICS MODEL

A collision dynamics (CD) model has been developed using the Adams software program [1] to simulate an inline train-to-train collision. The CD model consists of 12 rigid masses connected by non-linear springs (see schematic in Figure 1). Each mass represents one rail car. The force/crush behavior for the connecting springs is based on a simplification of full-scale test data for the conventional cars [2, 3] and finite element analysis for the CEM cars [4]. Since the locomotive is significantly stronger than the cab and coach cars, its force/crush behavior is simplified as a linear spring with a spring constant of $1.2*10^7$ lb/ft.

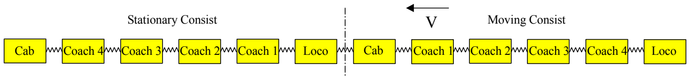

Figure 1. Schematic of Train-to-Train CD Model

Each mass is allowed only one degree of freedom – longitudinal translation. The cabs and coach cars weigh 104,000 lbs. and the locomotives weigh 263,000 lbs. The velocity of the moving consist ranges from 15-35 mph.

Figure 2 is a plot of the force/crush behaviors used in the conventional and CEM models. 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 [5]. The impacting end of the conventional train has a higher peak than the other car ends due to the dynamics of the impact. In the conventional curves, a large initial force is required to initiate buckling/crushing of the draft sill. Once the draft sill buckles, crushing continues at a much lower force. The gradual rise in crush force between 2 and 12 feet is due to a build-up of crushed material. The force fall-off after 12 feet indicates the vertical or lateral buckling that is likely to occur with sufficient collision energy.

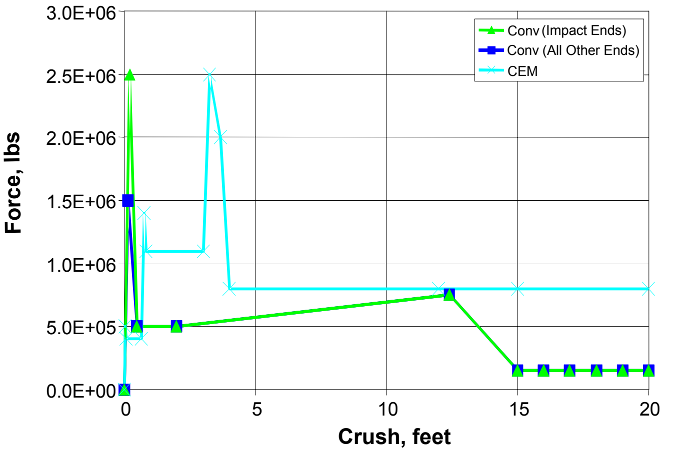

Figure 2. Force/Crush Behavior

In a collision, trains made up of conventional cars generally incur most or all of the crush at the point of impact. If two trains, which are made up of cars with the crush characteristics shown in Figure 2, collide, at best only the two colliding cars will crush. Indeed, only one of the colliding cars may crush if the other colliding car has a marginally greater peak crush load. This is principally due to the inability of a colliding car to push back with sufficient force to crush the car behind it. In the full-scale train-to-train test of conventional passenger equipment [6], the lead cab car sustained significant structural damage – its length was reduced by nearly 23 feet – while the impact locomotive suffered relatively minor damage and the trailing equipment in both trains suffered essentially no damage.

In contrast, the CEM curve has multiple tiers, or zones, of increasing crush force, representing a sacrificial crush zone at each end of the vehicle. One alternative for a CEM design is based on a sliding sill concept [4]. The initial slope is due to the loading of the shear back coupler. Once it fails, a block of aluminum honeycomb is loaded, resulting in a constant crush load of 400,000 lbs. over about 8 inches. Next, the crush load is transferred to the end beams. At a load of 1.4 million lbs. another set of shear bolts fail, and the primary energy absorbers are loaded. These absorbers are made up of two double box members, one on either side of the draft sill. The double box sections will crush about two feet under a 1.1 million pound load.

The crush zones are designed to crush in a successive manner, absorbing collision energy in unoccupied car ends before crushing the occupied areas inboard of the crush zones. The weaker crush zones allow the absorption of collision energy to be shared by multiple cars throughout the consist.

When a conventional car is leading in a collision, it absorbs most of the collision energy, no matter what kind of car is placed behind it. This behavior results in significant crush of the occupied area, especially at higher speeds. Therefore, the scenarios with a conventional car leading (scenarios 1, 4 and 7) all have nearly the same consequences.

Conversely, when a CEM car is leading, it can absorb almost three times as much energy as a conventional car without intruding into the occupied area. The CEM car can absorb 50% more energy than the conventional car at the impacting end, but the CEM car can also absorb a similar amount of crush at the trailing end, whereas the conventional car cannot pass crush back to the rear end of the car. By absorbing a significant amount of collision energy, a leading CEM car can protect trailing cars from incurring significant crush of the occupied areas, for the speeds considered in this paper.

Although the model is one-dimensional, it is capable of closely estimating the loss of occupant volume and the secondary impact velocities in a full-scale train-to-train impact test [6]. In that test, there was significant vertical override between the impacting cab and the locomotive; however, the vertical motion of the cab car was relatively small compared with its longitudinal motion. While that vertical motion isn't allowed in this model, the overall collision behavior is captured in the one-dimensional force/crush curve.

When compared against the conditions of the full-scale conventional test, the results from the collision dynamics model are in agreement with the test results in terms of car crush and secondary impact velocity (SIV).

At the vehicle ends, the CEM design has a higher average force per foot of crush than that of the conventional design, thus it can absorb more energy while incurring the same amount of crush. The higher average force in the CEM design results in a higher average acceleration of the car body, which results in a higher SIV for the occupants. The higher SIV is most significant in the leading cars. There is less disparity in the SIV between the CEM or conventional design in the trailing cars.

ANALYSIS RESULTS

The collision dynamics model was exercised under seven different scenarios of variable train make-up conditions. Results for each scenario were calculated for impact speeds of 15, 25, and 35 mph. The results demonstrate the range of collision outcomes, in terms of damaged occupant volume by car and secondary impact velocity by car. The car crush data are used to estimate the number of fatalities due to car crush. The SIV data are used to estimate the number of injuries and fatalities due to secondary impact. For this analysis, occupant injury is based on the cumulative probability of at least one injury to the head, chest or neck with AIS $\geq$ 3. Details on how the injuries/ fatalities were calculated can be found in the Appendix.

The SIV results are presented for the moving consist only. The SIVs in the stationary consist are all below 12 mph and are not expected to cause an injury of AIS 3 or greater. The leading locomotive on the stationary consist protects occupants from high SIVs and significant crush of occupied volume. Therefore, in the interest of simplicity, the secondary impact velocities are not presented for the stationary consist.

The crush results are only presented for the leading cab car and 1st coach car of the moving consist, because these are the only cars that experience damaged occupant volume in the moving consist. There is only one fatality estimated to occur in the stationary consist due to crush, that is in the 1st coach car of that consist for the case with a CEM car leading in the moving consist. No other fatalities due to crush (or SIV) are predicted to occur in the stationary consist for any case in the speed range studied here. The tables of injuries and fatalities include occupants from both the moving and stationary consists.

Table 2 presents a summary of the total fatalities due to crush and secondary impact velocity, according to train make-up and impact velocity. The results indicate that the most severe train make-up scenario at any impact velocity is one in which a conventional cab car is leading. When a conventional cab car is leading, its force/crush behavior prevents trailing cars from sharing in the energy absorption. After the initial peak is overcome, the conventional cab continues to crush at a much lower force, which can cause significant crush of the occupied volume at moderate impact velocities.

Table 2. Summary of Fatalities by Train Make-up and Impact Velocity

Total Number of Fatalities in Both Consists by Impact Velocity	Make-up of Moving Commuter Train						
	1	2	3	4	5	6	7
	All Conv	All CEM	All CEM Cab Rear-f	Cab Conv	1st coach Conv	Cab CEM	1st coach CEM
15 mph	5	0	0	0	0	0	0
25 mph	20	0	0	20	0	5	20
35 mph	60	15	10	60	19	29	60

15 mph Results

The 15-mph collision represents a fairly modest collision condition, however it still has a substantial amount of energy associated with it. The weight of the moving train is 783,000 lbs, which results in collision energy of nearly 6 million ft-lbs. About half of the total energy will be absorbed by car crush.

The occupant volume damaged, by car, is presented in the bar graph in Figure 3. The graph indicates that the only scenario in which there is any intrusion into the occupied area is scenario one, which has all conventional cars. The conventional cab car incurred two feet of damaged occupant volume, in addition to three feet of unoccupied area crushed at the leading end of the car.

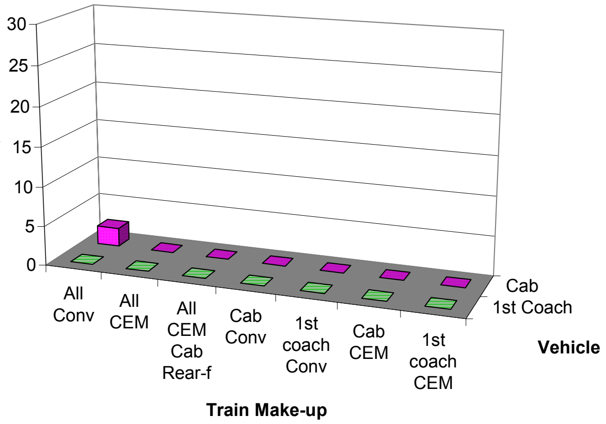

Figure 3. Damaged Occupant Volume in 15 mph Collision

Secondary impact velocity for the 15-mph collision is presented in Figure 4. The maximum SIV of 14.4 mph occurs in the 1st coach of scenario 4, which has a conventional cab leading four CEM coach cars and a locomotive. This low SIV is not expected to cause serious injury.

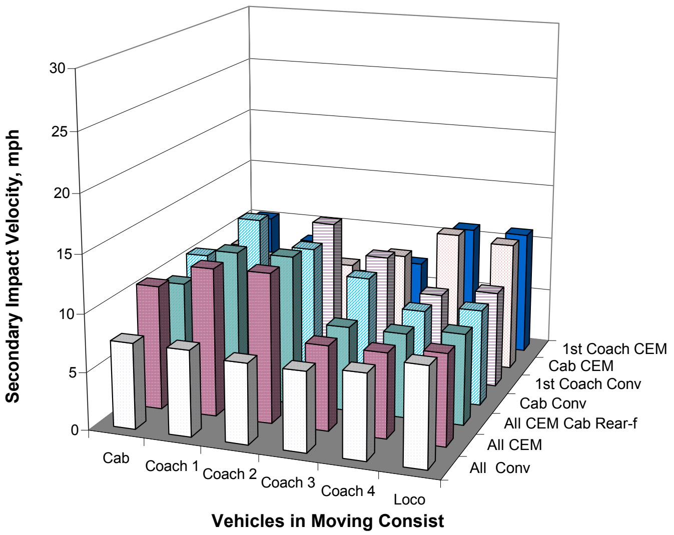

Figure 4. Secondary Impact Velocity in 15 mph Collision

The injuries and fatalities for each scenario are presented in Table 3. As discussed above, the only expected fatalities are caused by damage to the occupied volume in scenario one. The methodology for calculating fatalities due to crush is presented in the Appendix.

Table 3. Injuries and Fatalities for 15 mph Collision

Impact Velocity is 15 MPH	Make-up of Moving Commuter Train						
	1	2	3	4	5	6	7
	All Conv	All CEM	All CEM Cab Rear-f	Cab Conv	1st coach Conv	Cab CEM	1st coach CEM
# of occupants with injury >= AIS 3	0	0	0	0	0	0	0
# of fatal secondary impact injuries	0	0	0	0	0	0	0
# of fatalities due to crush	5	0	0	0	0	0	0
Total # of fatalities	5	0	0	0	0	0	0

25 mph Results

The 25-mph collision represents a moderately severe train collision, with over 16 million ft-lbs of kinetic energy. Severe injuries or fatalities due to occupant impacts are predicted for all of the scenarios. Excessive crush of the occupied volume can only cause fatality.

Figure 5 presents the occupant volume damaged by car for the 25-mph collision. There is significant crush of the cab car in scenarios 1, 4 and 7. Each of these scenarios has a conventional cab car leading. There is a small amount of occupant volume damage (less than 1 foot) in the cab and first coach of scenario 6.

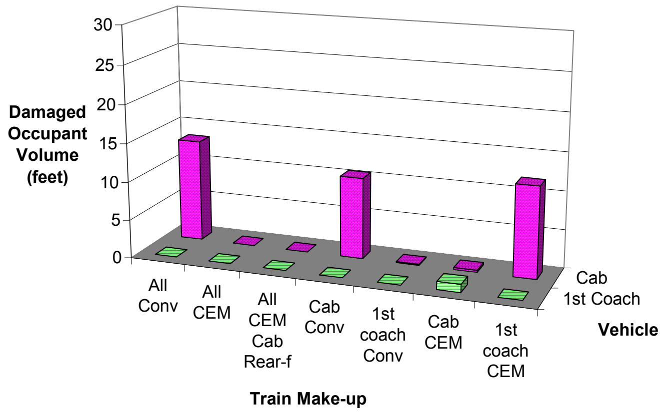

Figure 5. Damaged Occupant Volume in 25 mph Collision

The SIV for the 25-mph collision is presented in the bar graph in Figure 6. The maximum SIV at this impact speed is 18.7 mph and occurs in the scenario in which all cars are CEM cars. This SIV is not sufficient to lead to fatality.

In the CEM design, the trade-off in preserving the occupant volume is that the occupants experience a larger secondary impact velocity in the cars nearest the point of impact. However, even in the scenarios with CEM cars leading, no fatalities due to secondary impact velocity are expected.

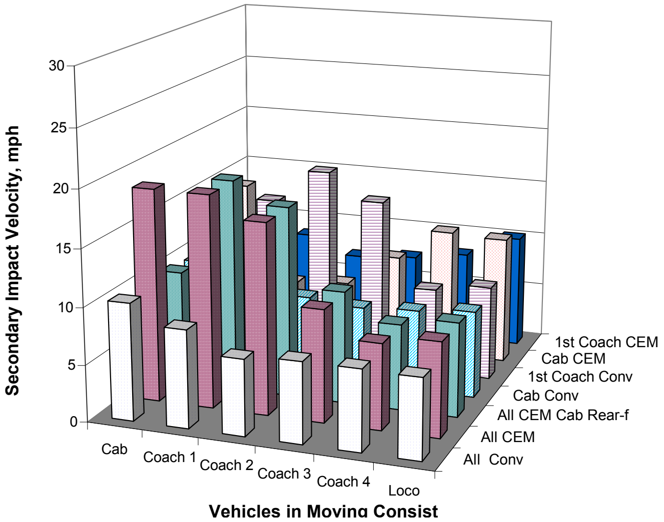

Figure 6. Secondary Impact Velocity in 25 mph Collision

Table 4 presents the summary of injuries and fatalities for the 25-mph collision. The only fatalities predicted are caused by crush of the occupied volume. The scenarios in which a conventional cab car is leading result in the greatest number of fatalities. The conventional design incurs nearly all the crush at the point of impact because of its force/crush behavior, resulting in significant damage to the occupant volume. In scenario 6 the five fatalities occur in the 1st coach car, which is conventional. The CEM cab car cannot quite absorb enough energy by itself to preserve all of the occupied volume of the trailing conventional car.

Table 4. Injuries and Fatalities for 25 mph Collision

Impact Velocity is 25 MPH	Make-up of Moving Commuter Train						
	1	2	3	4	5	6	7
	All Conv	All CEM	All CEM Cab Rear-f	Cab Conv	1st coach Conv	Cab CEM	1st coach CEM
# of occupants with injury >= AIS 3	0	4	2	0	2	0	0
# of fatal secondary impact injuries	0	0	0	0	0	0	0
# of fatalities due to crush	20	0	0	20	0	5	20
Total # of fatalities	20	0	0	20	0	5	20

35 mph Results

The occupant volume damaged is presented in Figure 7 for the cab car and coach car. This higher collision speed results in significantly more damage to the occupied volumes. The relationship between collision speed and occupant volume damaged is not linear, because the kinetic energy developed in a collision, and thus the crush, is proportional to the square of the velocity.

In scenarios 1, 4 and 7, the occupied volume of the leading conventional cab car is expected to incur 38 feet of damage. This amount of damage is consistent with the results from a full-scale conventional train-to-train test in which the 30-mph collision resulted in 23 feet of damage to the leading cab car.

In scenarios 5 and 6, the leading CEM cab cannot quite absorb enough energy in the unoccupied car ends to prevent intrusion into the occupied areas of the leading cab and the 1st coach car. Since the 1st coach in both scenarios is conventional, it absorbs the rest of the energy at the leading end of the car, resulting in 6-12 feet of damaged occupant volume.

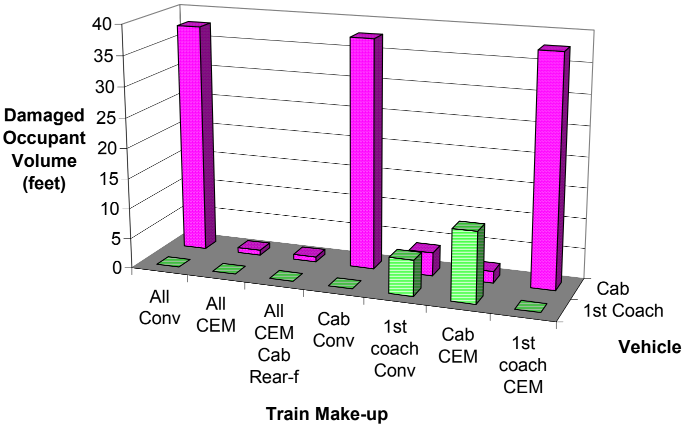

Figure 7. Damaged Occupant Volume in 35 mph Collision

The SIVs for the 35-mph collision are presented in Figure 8. Scenarios 2, 5 and 6, which have CEM cab cars leading, have the highest SIVs, particularly in the first three cars. Again, this is the trade-off for preserving nearly all the occupant volume in the leading CEM cars. The largest SIV is 27.3 mph and occurs in the CEM cab car of scenario 2, and is high enough to result in some fatalities. If occupants in the lead cab car were seated in rear-facing seats (scenario 3), the SIV in that car could be reduced to 10.2 mph, and not high enough to lead to fatalities. For occupants in rear-facing seats, there are about

6 inches of travel distance between the occupant's head and the seat back. During a collision, the occupant develops a velocity relative to the seat while this gap is traversed. The SIV's in the conventional cab car and all of the coach cars – both CEM and conventional – are not sufficient to lead to fatality.

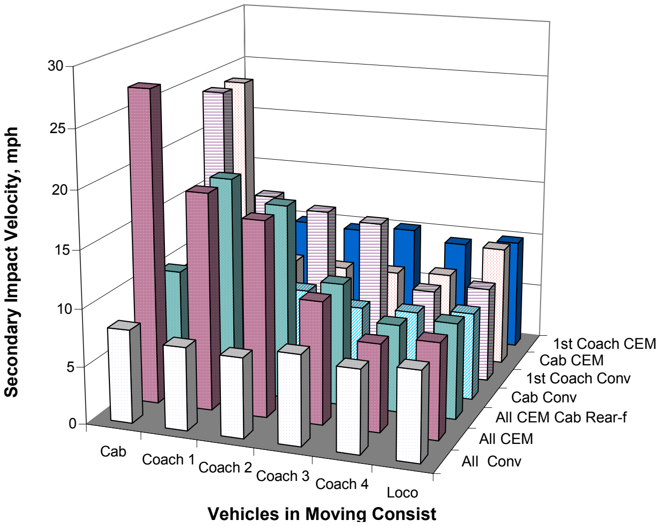

Figure 8. Secondary Impact Velocity in 35 mph Collision

The estimated injuries and fatalities for the 35-mph collision are presented in Table 5. The scenarios with a conventional cab car leading (1,4,7) have significantly more fatalities than in the scenarios with a CEM cab car leading (2,3,5,6). The optimal scenario is #3 – there are no fatal injuries due to secondary impact and ten expected fatalities due to crush. Five fatalities due to crush in scenarios 2 and 3 occurred in the 1st coach of the stationary consist.

Table 5. Injuries and Fatalities for 35 mph Collision

Impact Velocity is 35 MPH	Make-up of Moving Commuter Train						
	1	2	3	4	5	6	7
	All Conv	All CEM	All CEM Cab Rear-f	Cab Conv	1st coach Conv	Cab CEM	1st coach CEM
# of occupants with injury >= AIS 3	0	50	3	0	42	42	0
# of fatal secondary impact injuries	0	5	0	0	4	4	0
# of fatalities due to crush	60	10	10	60	15	25	60
Total # of fatalities	60	15	10	60	19	29	60

While the scenarios with a CEM cab car leading may result in more serious injuries, the injuries occur at the expense of drastically reducing the number of fatalities due to crush in the lead car.

SUMMARY AND CONCLUSIONS

The modeling results demonstrate that there is great benefit to placing even a single CEM car at the leading end of a consist. By simply replacing a conventional cab car with a CEM cab car, fatalities can be reduced by 50% for 20% of the cost (when compared to replacing all five passenger cars in a consist). More CEM cars would provide additional benefit, but with a lesser cost/benefit ratio.

The CEM design is much more effective at preserving occupied volume during a collision, when the CEM car(s) are at or near the point of impact. The monotonic increase in the force/crush behavior of CEM cars allows trailing cars to participate in energy absorption. The initial spike in the conventional force/crush behavior is what causes all the crush to be isolated at the lead end when the impacting car is conventional. This behavior prevents the energy-absorbing capabilities of the CEM cars from being utilized if the CEM cars are placed away from the point of impact.

Thus, placing CEM cars at the leading end(s) of the train would provide the most benefit from the high energy-absorbing cars. When CEM cars are placed in the middle of the consist, they do not provide much improvement over conventional cars. The leading conventional car bears most of the damage from the collision, and doesn't allow the trailing cars to share in the energy absorption.

In a train made up of all CEM cars, the SIVs are highest near the impacting end, and decrease incrementally for each of the trailing cars. The SIV of the trailing cars is lower because of the cushioning effect of the leading cars. In a CEM train collision, an occupant in any of the cars behind the first three cars would have an SIV close to that of an occupant in a train made up of all conventional cars.

The trade-off in preserving the occupant volume in the CEM design is a higher SIV than with the conventional design in the leading cars. This trade-off could be mitigated by using rearward-facing seats in the leading car(s). Rearward-facing seats reduce the SIV because the occupant is already in contact with the seatback, so the occupant doesn't develop a significant velocity with respect to the vehicle.

The results of this analysis depend upon the accuracy of the assumed force/crush behavior of the conventional and CEM designs. The force/crush characteristic for the conventional analysis is based on test data, and the modeling approach used compares closely with test measurements. The CEM force/crush behavior calculated using finite element analysis will be verified with the planned full-scale impact test using CEM equipment.

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APPENDIX – CALCULATING INJURIES/FATALITIES

In this paper, the amount of car crush is used to estimate the number of fatalities due to loss of survivable occupant volume. Loss of occupant volume is based on damage to the occupied areas of the car. For this analysis, it is assumed that there are three feet of unoccupied area at each car end. If more than three feet are crushed at either end, then loss of occupant volume occurs.

In a leading cab car, the operator occupies this space at the end of the car. To allow for a 3-foot crush zone while preserving survivable space for the operator, a unique concept has been proposed for the operator’s end of the cab. The operator’s cab can be surrounded by a strong cage, which can slide back as the energy dissipation elements are crushed. 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. Additional work is planned to determine if this concept can be practically implemented.

For the purpose of calculating fatalities due to crush, it is assumed that all passenger cars are loaded to full capacity. The cab cars and coach cars all have 25 rows of 5 seats each (2x3 seating), which amounts to a seat pitch of 38 inches, or 3.16 feet. This seating arrangement is typical of coach and cab cars used in commuter service.

Fatalities due to crush are calculated as follows:

1. Subtract 3 feet from the total car crush, to account for the 3 feet of unoccupied space at the car end.
2. Multiply the occupant volume crushed by 1.4, to account for the volume occupied by the crushed material.
3. Divide the result in step 2 by the seat pitch to calculate the number of rows of seats damaged. If more than 25% of a row is damaged, all occupants in that row are assumed to have suffered fatal injuries.
4. Multiply the number of rows of seats damaged by the number of seats per row, in this case 5, to calculate the number of fatalities.

For example, if the model calculated 10 feet of car crush for a particular car, the number of rows of seats crushed would be (10-3)*1.4/3.16, or 3.1 rows. Since only 10% of the 4th row was damaged, round down to 3 rows and multiply by 5 seats per row to calculate 15 fatalities due to crush.

In processing the model results, car crush beyond 30 feet is disregarded because the model is not reliable for greater crush distances. The one-dimensional model is not sufficient to simulate such scenarios. Due to the unrepeatable nature of such chaotic events, it would be difficult for any model to predict the results accurately.

Secondary impact velocity is used to calculate injuries caused by an occupant impacting an interior part of the car. SIV refers to the velocity at which an occupant strikes some part of the interior, in this analysis the forward seat back. The SIV is calculated as the occupant’s velocity relative to the vehicle interior when the occupant’s head has traveled two feet. This is approximately the distance between the occupant’s head and the forward seat, when seated in forward-facing rows of seats that are placed 38 inches apart. This is a common seating configuration used in commuter passenger trains.

To estimate occupant injury in a simple manner, test data have been used to correlate SIV with head, chest and neck injury. The graph in Figure 9 is used to correlate SIV with the severity of injury to an occupant’s head, chest or neck. The curves in the graph are based on test data taken from instrumented crash test dummies during sled testing and full-scale train testing. Each curve is normalized to a particular injury threshold, as discussed below.

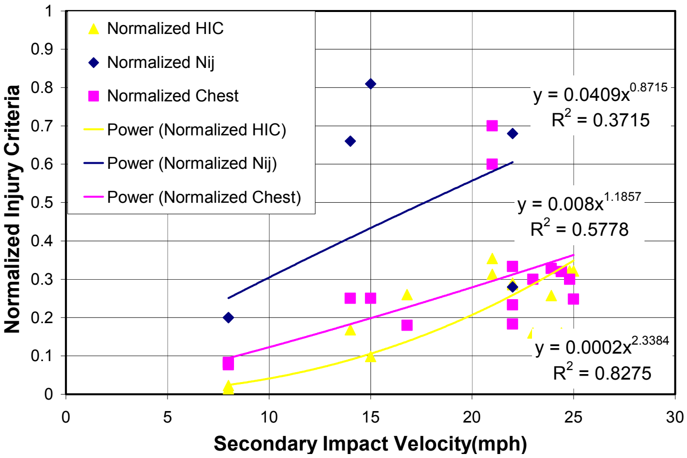

Figure 9. Normalized Injury Criteria Based on SIV

Head Injury Criteria (HIC) addresses the risk of injury to the head, and is estimated as a function of SIV in Equation 1. The HIC is normalized to a value of 700. A HIC of 700 with a duration of 15 milliseconds is the limit for the Hybrid III test dummy, as established by the National Highway Traffic Safety Administration (NHTSA) in FMVSS No. 208[7]. In Equation 1, the threshold value of the HIC, 700, has been taken out of the coefficient. The threshold value is exceeded when the term in parenthesis exceeds 1.

Equation 1. $HIC = (0.0002 \cdot SIV^{2.3384}) \cdot 700$

The risk of injury due to thoracic spinal acceleration is addressed by the 3-millisecond clip value. The NHTSA chest acceleration limit for thoracic injury criteria is 60 Gs for the Hybrid III test dummy [7]. Equation 2 relates the SIV to the clip value, normalized to 60 Gs.

Equation 2. $CLIP = (0.008 \cdot SIV^{1.1857}) \cdot 60$

The neck injury criteria, Nij, is based on a linear combination of neck loads and moments. The NHTSA limits for neck tension, compression, extension and flexion are normalized for each dummy size such that the Nij limit for the Hybrid III test dummy is 1 [7]. Equation 3 correlates SIV to Nij.

Equation 3. $Nij = (0.0409 \cdot SIV^{0.8715})$

Once the secondary impact velocities have been converted to injury criteria, the injury criteria are then related to the likelihood of injury. The Abbreviated Injury Scale (AIS) is used as a basis of comparison for head, chest and neck injuries. The AIS is a universally accepted injury severity scaling system [8]. It was developed as a simple numerical method for ranking and comparing the severity of injuries. The AIS is coded 0 through 6. AIS 0 indicates no injury, AIS 1 indicates minor injury, and so on. AIS 6 indicates the most severe injury which is determined to be virtually non-survivable.

For this analysis, occupant injury is based on the cumulative probability of at least one injury to the head, chest or neck with AIS $\geq$ 3. The probabilities for an injury of AIS $\geq$ 3 to the head and chest are given in Equations 4 and 5, respectively [9, 10].

Equation 4.

$$PAIS3+(HIC) = \frac{1}{\left[1 + e^{\left[\left(3.39 + \frac{200}{HIC}\right) - 0.00372 \cdot HIC\right]}\right]}$$

Equation 5. $PAIS3+(CLIP) = \dfrac{1}{\left[1 + e^{(3.1493 - 0.0630 \cdot CLIP)}\right]}$

For this analysis, the neck injury risk curves presented in [10] were modified to estimate the cumulative probability of a neck injury of AIS $\geq$ 3. The AIS 3+ injury risk curve presented in Reference 9 assumed the injury response to be dichotomous (AIS<3 and AIS >=3). The AIS 3+ injury risk curve assuming injury response to be polytomous (AIS<2, AIS=2, AIS=3, AIS=4, and AIS>=5) is given in Equation 6:

Equation 6. $PAIS3+(Nij) = \dfrac{1}{\left[1 + e^{(2.1897 - 1.1955 \cdot Nij)}\right]}$

These equations calculate the probability of injury as a function of the respective injury criteria. They are based on logistic regression methods, fitting a curve to available test data. The curves are not necessarily applicable near the tails, where the injury criteria are exceptionally small or large. For instance, Equation 6 results in a curve that crosses the abscissa at 10.1%. Clearly, the probability of an AIS 3 or greater injury cannot be 10% for an Nij value of zero. To correct for this curve-fitting error, minimum injury thresholds for the chest and neck have been applied.

Based on the test data used to develop the curves, it is assumed that a chest acceleration below 20 Gs cannot cause a chest injury of AIS 3 or greater. Similarly, it is assumed that a Nij value below 0.6 cannot cause a neck injury of AIS 3 or greater. These cut-offs are based on the fact that there isn't a single data point indicating injury below these thresholds. Without this error correction, the probability of injury would be grossly overstated.

The final step is relating the probability of an AIS 3 or greater injury to the likelihood of fatality. There is little data taken from actual train accidents that relate the secondary impact injuries to fatalities. However, such data was compiled from a 30mph head-on train collision between a crowded commuter train and a freight train in Placentia, CA on April 23, 2002 [11]. There were 20-25 people who suffered injuries of AIS 3 or greater. Two of these injured people suffered fatal injuries. Based on the Placentia accident, the ratio of two fatal injuries to 20 AIS 3 or greater injuries, or 10%, has been used in this analysis to calculate the number of fatal injuries due to secondary impact.