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Volpe National
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Cambridge, MA 02142-1093

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13. ABSTRACT (Maximum 200 words)

Models used to analyze locomotive crashworthiness are modified for application to control cab cars of the types used for intercity and commuter rail passenger service. An existing control cab car is analyzed for crashworthiness based on scenarios developed from two accidents. The peak strength of crashworthiness-related components is found to exceed the 49 CFR 221.141 requirements. Options for further improvement are analyzed.

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PREFACE

In September 1992, the Congress passed Public Law 102-365, the Railroad Safety Enforcement and Review Act, which required, in part, that the Secretary of Transportation conduct research and analysis to consider the costs and benefits of several types of crashworthiness improvement features. A major part of the work conducted in response was a study of the crashworthiness of the cab area in existing road freight locomotives. The results of that study were published earlier in four volumes and an executive summary.

During the course of study, further work was assigned to provide for evaluation of the crashworthiness of the cabs in control cars used in passenger service. This report summarizes the results of the cab car study. The work was carried out by Arthur D. Little, Inc., under contract to the Volpe National Transportation Systems Center, from March 15, 1995, to May 30, 1995. The work was conducted as part of the Center's support to the Office of Research and Development, Federal Railroad Administration.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F	=	y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

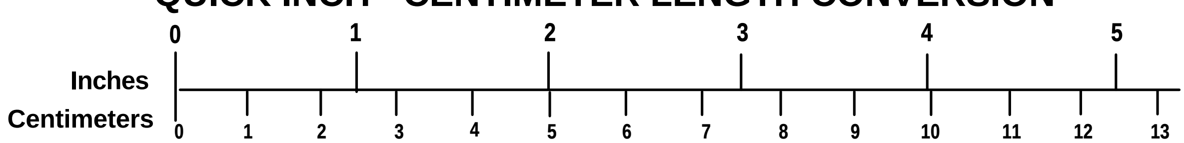
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

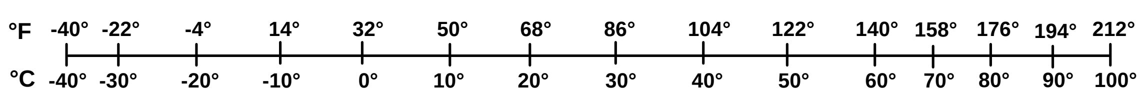
TEMPERATURE (EXACT)

[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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1. INTRODUCTION

Recently, a project was conducted to assess the crashworthiness of freight locomotives and to determine whether improvements could be practically made over that provided by current industry specifications [1]-[4]. The study included the development and application of a computer model to predict the amount of vehicle crush and the crash pulse, both of which are used to assess occupant survivability. Particular attention was placed on head-on collisions between two freight locomotives and the model was validated by applying it to actual accidents.

As part of this project, the crashworthiness of commuter train cab cars has also been investigated. By cab cars we mean the control car at one end of a train of several passenger cars that has a locomotive at the other end. This push-pull configuration requires a single locomotive that generally pulls during outbound trips and pushes during inbound trips so that the exhaust of the locomotive does not enter the terminal building of the primary metropolitan station. The concern with this type of train configuration is that the occupants of the relatively exposed cab car, including the engineer, are vulnerable to serious injury or fatality in the event of a collision with either a road vehicle at a grade crossing or with another train.

The objective of the cab car crashworthiness study reported here was to assess the crashworthiness of cab cars for particular types of collisions and to make a preliminary assessment of what effect changes in cab-end component strength might have on occupant survivability.

The literature on crashworthiness for this type of vehicle was reviewed and information was gathered from cab car manufacturers. The collision dynamics model developed in the previous study was modified for the cab car analysis, and two accident scenarios were selected to validate the model and investigate crashworthiness. Load-crush curves were generated for key components using finite element analysis, and the collision dynamics model was used to estimate the closing speed at which substantial crush would occur for both an in-line collision and a collision that challenges the corner post only.

The results suggest that extensive crush can occur for closing speeds in the range of 30-40 mph for what appears to be the most likely train-to-train collision involving cab cars in the push-pull mode. A collision in the upper end of this closing speed range is likely to eliminate substantial survivable volume at the impacted end and to induce accelerations for the remainder of the vehicle that will provide a significant probability of occupants sustaining a serious injury. Calculations also show that substantial increases in component strength are required to influence the outcome of the collisions modeled.

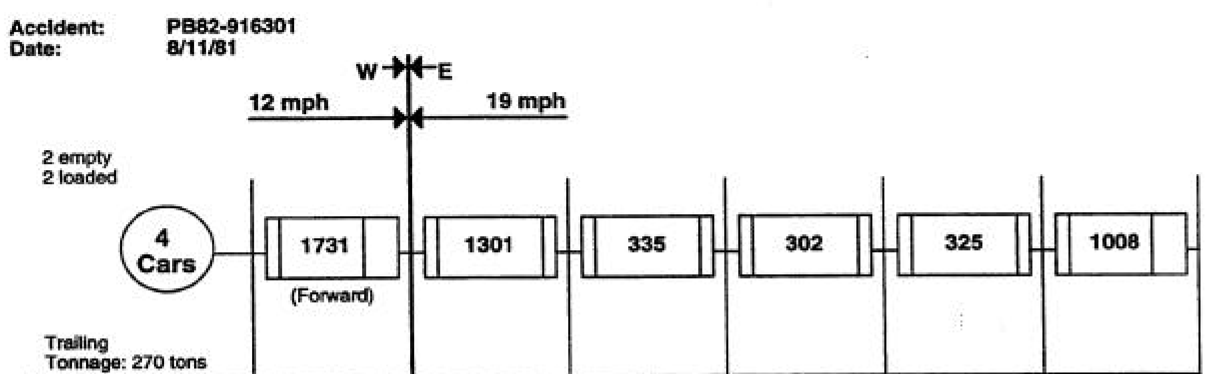
2. REVIEW OF ACCIDENTS

Several accident reports were reviewed in an effort to determine possible crash modes and component damage in collisions involving cab cars. These reports, together with a basic consideration of the manner in which many commuter trains operate, suggest that a collision between a cab car and a lead locomotive is a possible and challenging train-to-train collision.

Two accidents were selected for detailed consideration; the scenarios used to investigate crashworthiness were derived from these. The first collision, between a locomotive and a cab car, represents the type of accident possible in the common push-pull configuration discussed above. The second collision, between two cab cars, was one in which impact occurred between the corners of the vehicles. This is of interest because of the issue of corner post protection. These two accidents provided the primary impetus for formulating the crash scenarios with which to assess crashworthiness as described below.

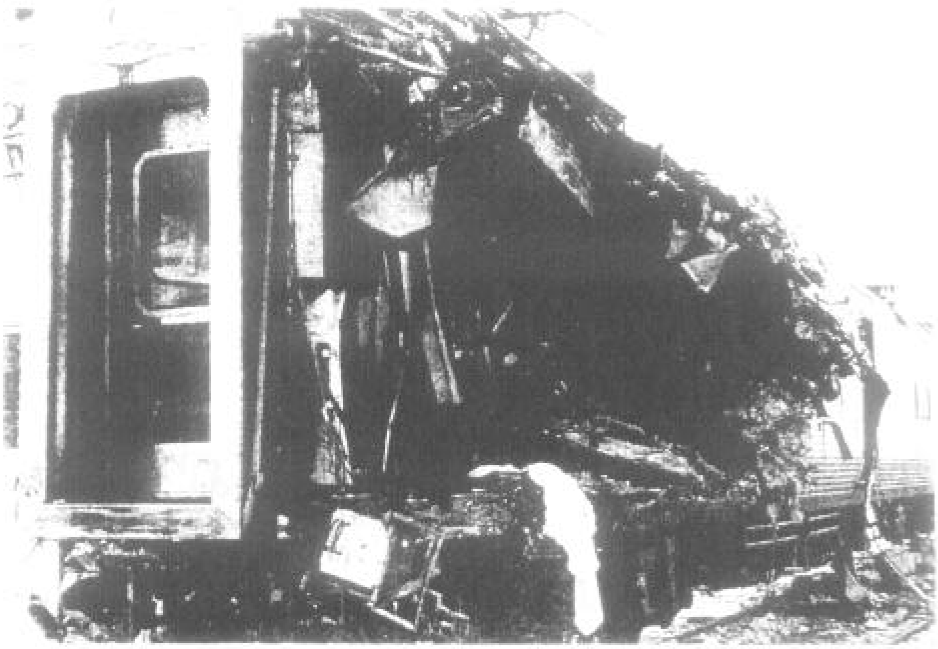
On August 11, 1981, there was a head-on collision between the Boston & Maine Corporation's Extra 1731 East and the Massachusetts Bay Transportation Authority's Train No. 570, on former Boston & Maine Corporation tracks located in Beverly, Massachusetts, causing several serious injuries [5]. This accident, depicted in figure 1, occurred at a closing speed of about 31 mph. The result was the severe deformation and fracture of the cab car underframe followed by override of the cab car onto the locomotive.

On January 18, 1993, near Gary, Indiana, the Northern Indiana Commuter Transportation District's Eastbound Train 7 and Westbound Train 12 collided on intersecting tracks that shared a bridge [6]. One of the trains was at rest and the other had a speed estimated to be 32 mph. The result was direct impact between the corners of the two lead cab cars that resulted in destruction of the corner posts, crush of approximately 25 ft on each vehicle side (figure 2), and seven passenger fatalities.

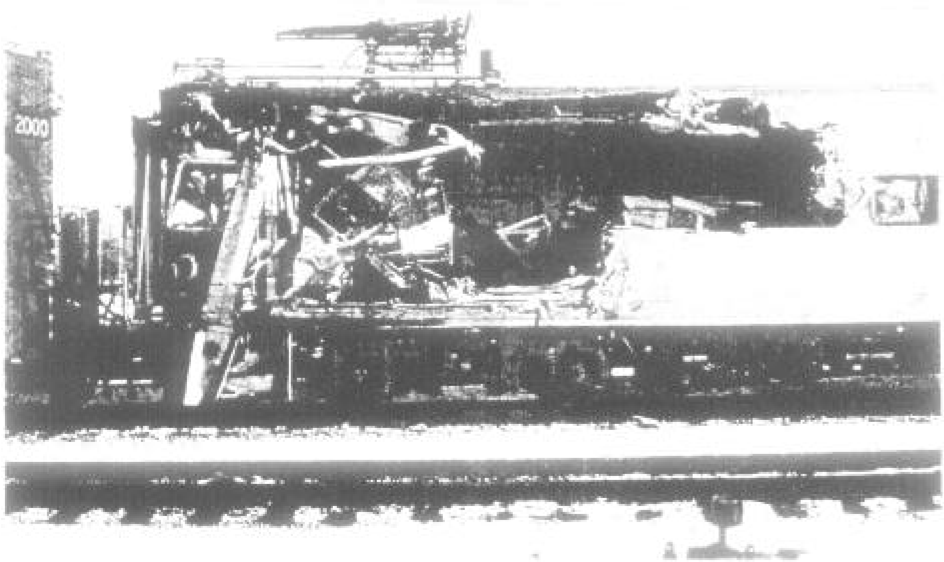


Vehicle Type	Freight Locomotive	Control Car	Coach Car	Coach Car	Coach Car	Freight Locomotive
Manufacturer	GP-9	Pullman Standard	Pullman Standard	Pullman Standard	Pullman Standard	F40 PH
Weight (lbf)	247,000	85,000	82,000	82,000	82,000	259,000
Year Built		1979	1979	1979	1979	
Injuries (crew)	2					
Fatalities (crew)	2	1				

Figure 1. Description of a Cab Car Accident in a Push-Pull Configuration



(a) Car 27 on train 7



(b) Car 36 on train 12

Figure 2. Photographs of a Collision in Which the Corner Post Was Impacted (January 18, 1993, collision between Northern Indiana Commuter Transportation District Eastbound Train 7 and Westbound Train 12, near Gary, Indiana)

3. CAB CAR DESIGN CONSIDERATIONS

There are a number of design characteristics that have an effect on a cab car's crashworthiness. A schematic illustration of the end structure of a cab car is shown in figure 3. Nearly all of the structure will participate in a head-on or rear-end collision, but the elements for which some aspect of the design is related to crashworthiness include the underframe, anticlimbing structure, collision posts, corner posts, and the truck-to-body connection.

Cab cars satisfy the federal requirements defined in 49 CFR, Part 229.141 [7], which states that all multiple unit (MU) locomotives in trains exceeding 600,000 lb include:

- a body structure that resists a minimum static end load of 800,000 lbf at the rear draft stops without developing any permanent deformation in any member of the body structure

- an anticlimbing arrangement at each end that can resist a vertical load of 100,000 lbf without exceeding the yield point when coupled MU locomotives are under full compression

- a coupler carrier and its connections that resist a vertical downward thrust from the coupler shank of 100,000 lbf for any horizontal position of the coupler, without exceeding the yield point

- two collision posts, each with an ultimate shear strength value of at least 300,000 lbf at a point even with the top of the underframe member and, if reinforcement is used to achieve this strength, possessing this strength value up to 18 inches above the underframe, tapering to nil required at a point approximately 30 inches above the underframe connection.

- a truck connection with an ultimate shear strength of at least 250,000 lbf.

Though not cited in 49 CFR, Part 229.141, it is common for cab car specifications to include a corner post ultimate strength requirement of 150,000 lbf at the underframe level.

As part of this program, we received drawing sets on two types of cab cars; one set from Bombardier and one set from Morrison Knudsen. The details from these drawings are proprietary, but some general comments can be made. For example, the structural members that would participate in a collision are usually made of steel with yield strength in excess of 50 ksi; however, aluminum is sometimes used for some of the members. Connections between these structural members are usually welded. In general, we did not evaluate the strength or ductility of these various connections but instead assumed that they were sufficient to enable several feet of crush deformation to occur in the primary structural members. The implications of connection fracture will be discussed in a later section.

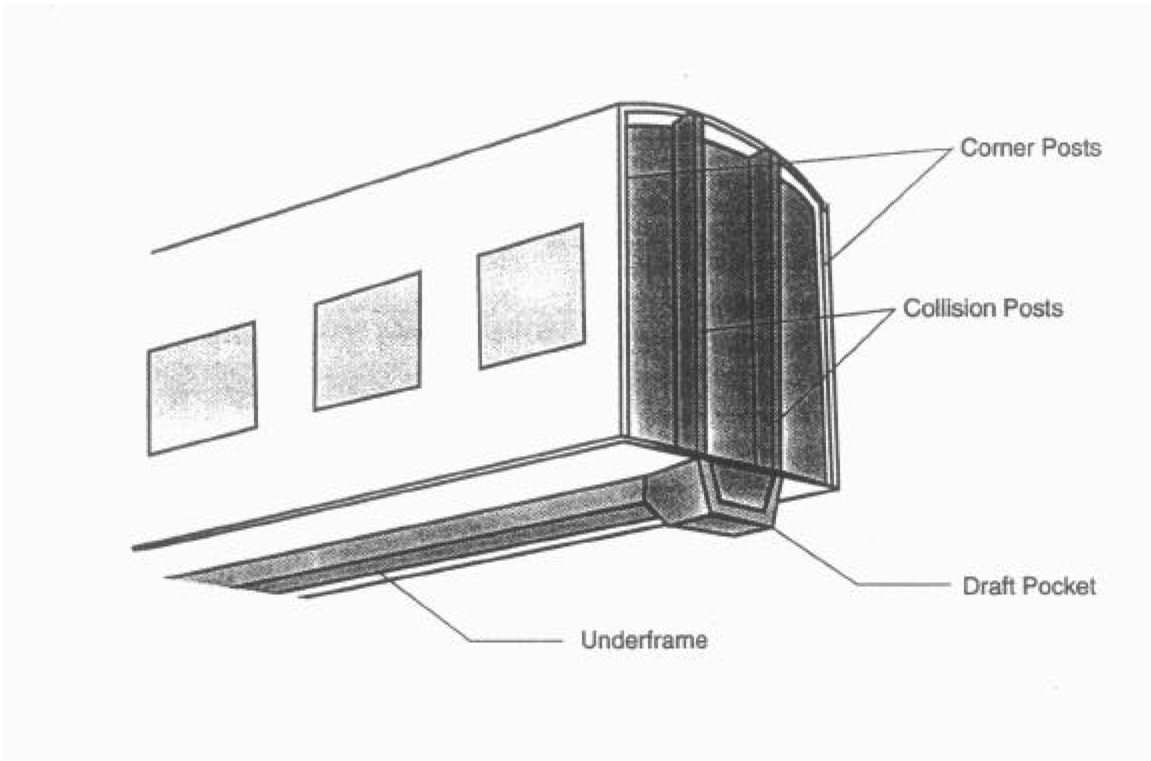


Figure 3. Illustration of Key Cab Car Structural Components for Crashworthiness

4. FRONT-END INTERACTIONS

It is important to understand the manner in which two rail vehicles interact in a collision, to ensure that the computer model properly simulates this behavior. In the case of a collision between a locomotive and a cab car whose longitudinal centerlines are collinear, it appears that the crush load in the cab car will be transferred to the overall structure primarily through the underframe. This interaction is illustrated schematically in figure 4. Because the underframe in cab cars is generally lower than that for locomotives, it is likely that, subsequent to coupler impact and deformation, the cab car underframe will be trapped between the protruding draft gear support structure and the underframe or anticlimber of the locomotive, as illustrated in figure 4. The draft gear support structure in locomotives has an ultimate strength of 2 to 3 x 106 lbf [1], and the locomotive underframe strength exceeds this range considerably. On the other hand, the cab car underframe, whose yield-based design strength is 0.8 x 106 lbf, has an ultimate strength of less than 2 x 106 lbf, as described below. The consequence of the trapping phenomenon and the locomotive/cab car structural strength difference is that the cab car underframe will be the primary component crushed. Such a loading situation appears to have occurred in the accident described earlier (figure 1).

Indeed, it is very unlikely that the cab car would be overridden in the locomotive/cab car collision situation because of the trapping phenomenon just described and the greater weight of the locomotive. Override is possible when two cab or passenger cars collide because of the similar weights and underframe heights. This case was not considered in the current study.

The second interaction we considered is one in which the corner post is directly loaded. In this case, the colliding locomotive and cab car have their longitudinal centerlines parallel but offset laterally. Such a condition can arise if one of the trains enters the mainline track from a turnout. In this case, the locomotive draft gear support structure, whose width is on the order of 20 inches, can be completely to the side of the cab car underframe. As a result, there is little opportunity for trapping and the locomotive underframe is likely to challenge the corner post directly, just at or above the cab car underframe. A similar situation occurred between two cab cars in the accident described in section 2.

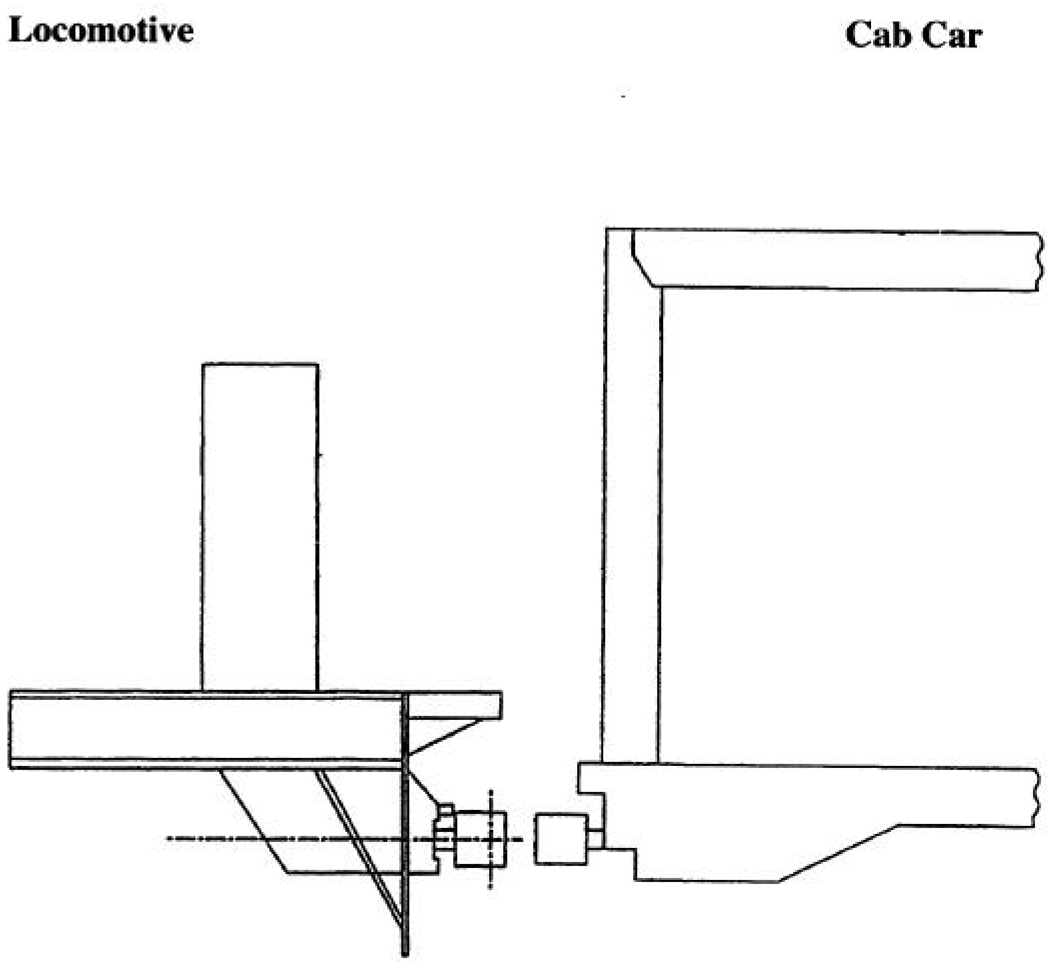


Figure 4. An Illustration of Locomotive and Cab Car Structures for Purposes of Envisioning Their Interaction in a Collision

5. **BASELINE CRASH SCENARIOS**

The two crash scenarios utilized in this investigation to assess the crashworthiness of cab cars are based on the first accident discussed in section 2 and the front end interactions discussed in the previous section. They are depicted in figure 5. Both have the same train configurations. The difference between the two is the lateral offset. The speeds of the individual trains shown was used for initial calculations, but calculations were also conducted for other values of closing speed. The ratio of the velocities, V_1/V_2 , was kept constant for all calculations, rather than keeping the speed of one consist the same.

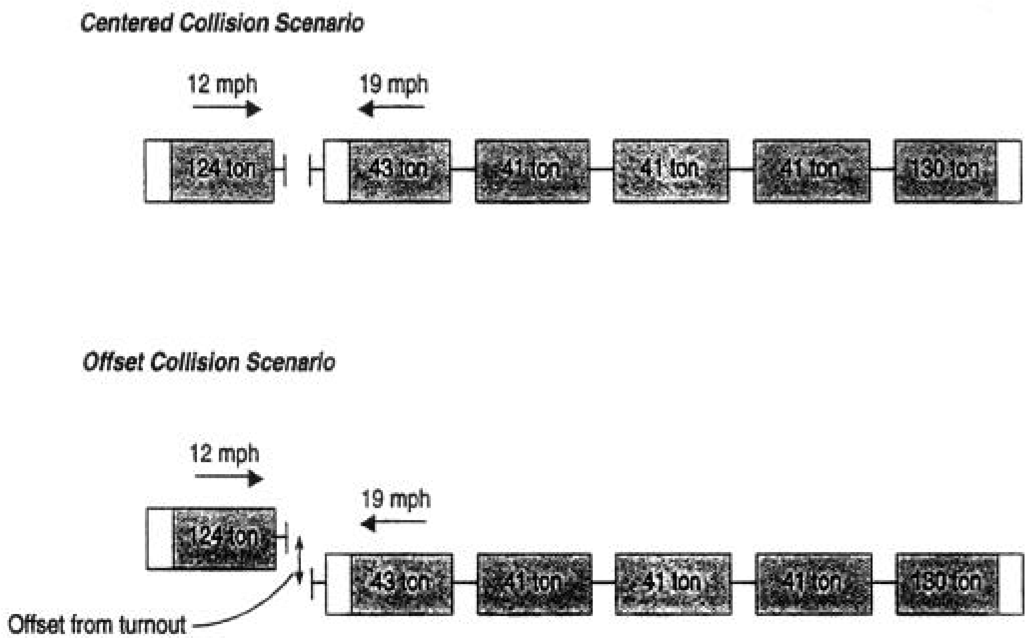


Figure 5. Description of the Two Crash Scenarios Used to Investigate Cab Car Crashworthiness

The underframe load-crush curve used in the collision dynamics analysis was generated from several considerations. The federal requirement 49 CFR, Part 229.141, states that the buff, or compressive, load at which any part of the underframe first reaches its yield strength shall be at least 800,000 lbf. Thus, the load-crush curve we generate should just satisfy this criterion. Our calculations on the vehicle structure modeled showed that the load at which first yield occurred was greater than 800,000 lbf. Therefore, all load values in the calculated load-crush curve were scaled by the ratio of 800,000 lbf to the load actually calculated to cause first yield.

Figure 6 shows the underframe load-crush curve used in the collision dynamics model. The form of the initial part of the curve, to approximately 1 ft crush, is the same as that calculated for the actual structure, but the magnitude has been adjusted as described in the previous paragraph. The peak load response is predicted by finite element analysis. Figure 7 shows a deformed underframe mesh resulting from peak load application through the draft stop (about 2.5 ft of crush). The remainder of the curve is an interpolation between the load at 1 ft of crush and zero load at 6 ft of crush, which is our rough approximation of the crush of the underframe in the Beverly, Massachusetts, accident. Although the effects of fracture were not directly accounted for in the generation of the underframe crush curve, comparison of predicted average strains in various structural members to uniaxial tensile test data suggests that some of the structural members will fracture at a crush of about 2 ft.

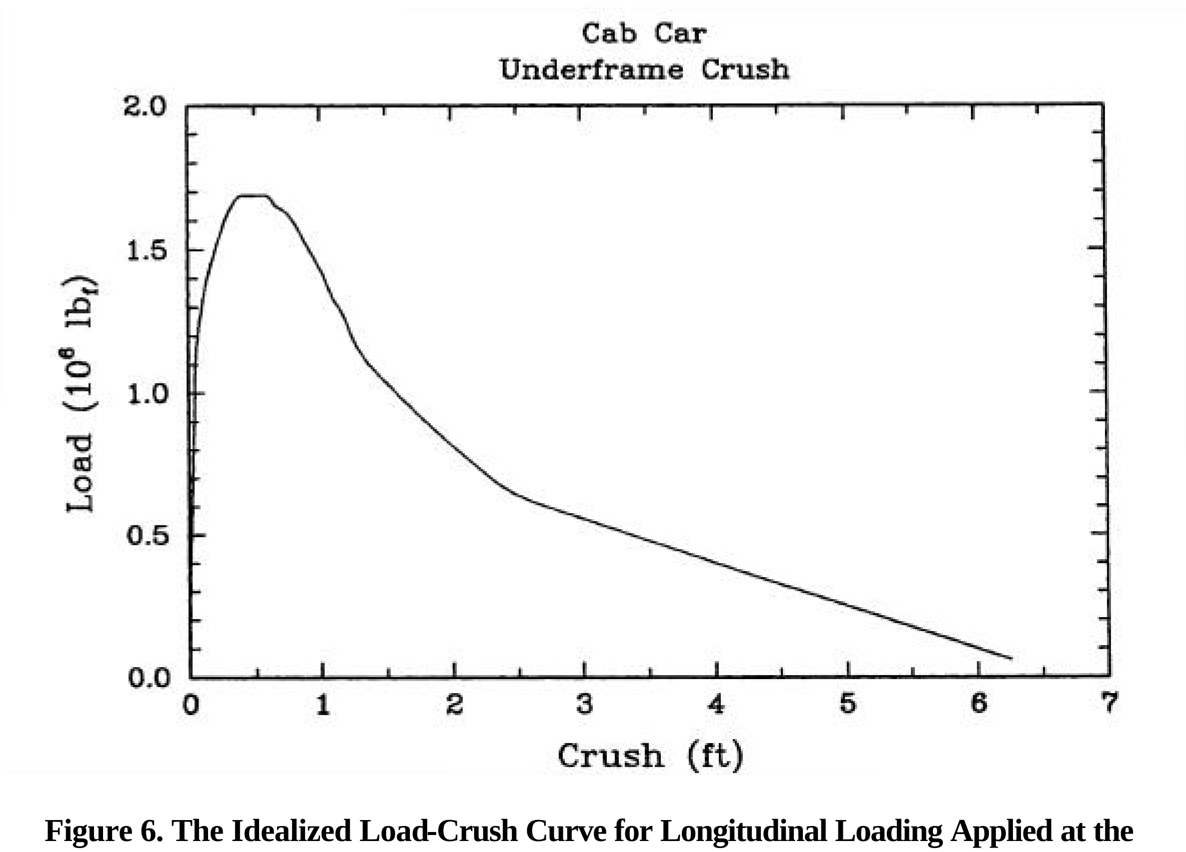


Figure 6. The Idealized Load-Crush Curve for Longitudinal Loading Applied at the Draft Stop of the Underframe

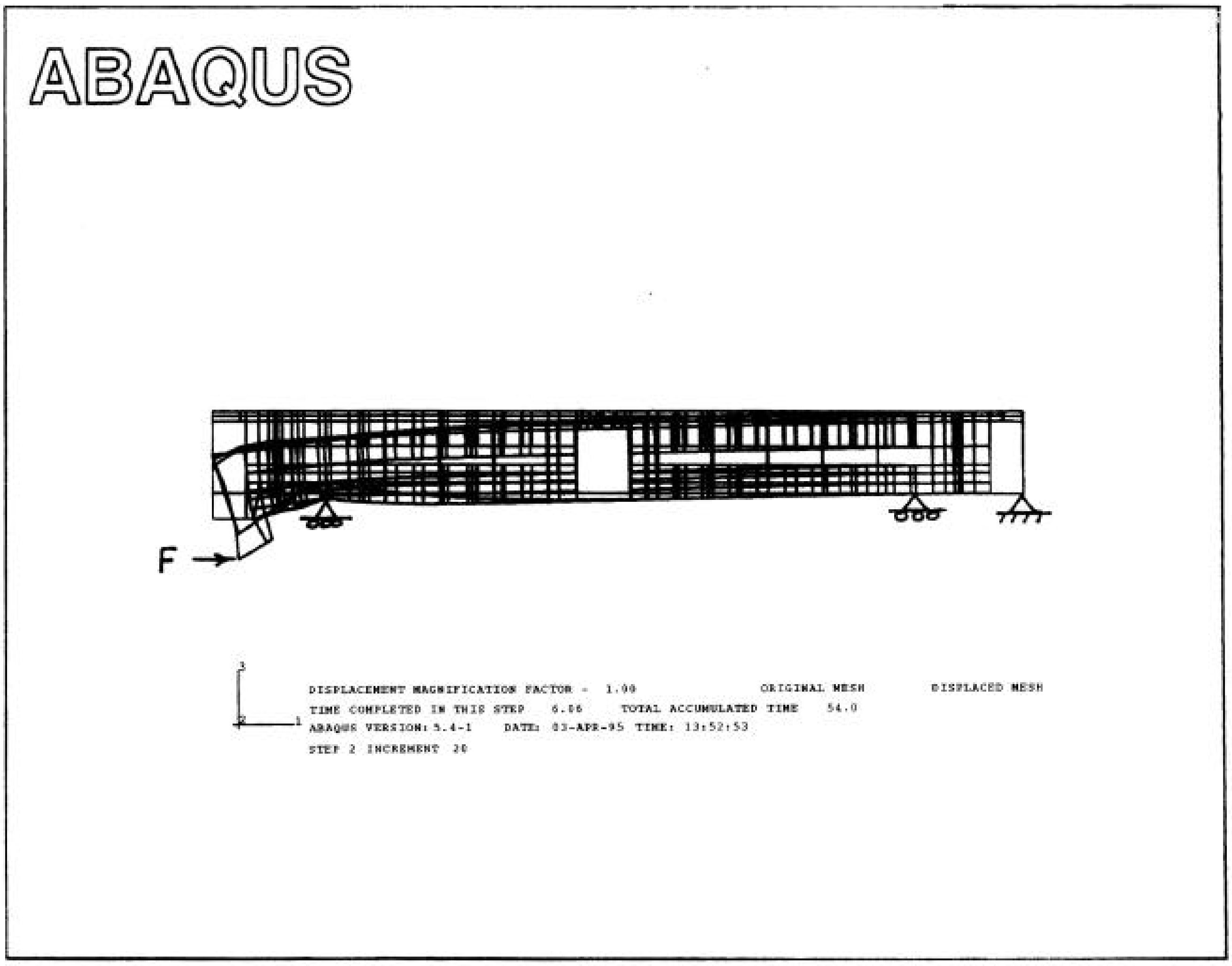


Figure 7. An Example of Predicted Cab Car Underframe Deformation for a Load Applied to the Draft Stop (about 2.5 ft of crush)

The curve we derived for underframe crush reaches an ultimate load of nearly 1.7 x 10^6 lbf, which is over twice the buff load that causes yielding. The deformation associated with this loading includes both an indenting deformation of the underframe at the draft stop and substantial down-bending of the entire vehicle end structure. This type of underframe deformation is consistent with the deformation observed in the accident on which the in-line crash scenario is based. The underframe of the cab car in the accident was evidently crushed, bent downward, and then torn away from its superstructure, permitting relatively uninhibited override of the colliding locomotive.

The load-crush curve used in the collision dynamics analysis for the corner post case is shown in figure 8, and an example of the deformed mesh for this type of loading is shown in figure 9. Plastic deformation occurs at around 100,000 lbf for the case modeled, and the load rises until it reaches the 150,000 lbf strength requirement. This idealized curve was generated by truncating the calculated curve at a load of 150,000 lbf and then continuing the curve at this load level for substantial crush. Such a curve satisfies the 150,000 lbf ultimate load requirement cited in some cab car specifications. Again, the fracture of the corner post or its connections was not accounted for in the generation of this curve. However, our finite element analysis results suggest that fracture of the post could begin at about 1 ft of crush. As a note, the ultimate strength of the corner post modeled for a load applied at the roof line was in excess of 80,000 lbf.

The load-crush curve used in the collision dynamics analysis for the two collision posts, when loaded at 18 inches above the top of the underframe, is shown in figure 10; a deformed mesh for this type of loading is shown in figure 11. Again the curve for the idealized component is forced to reach a plateau, in this case at the required 600,000 lbf for the two posts, even though calculations on the actual structure show that the required ultimate strength is exceeded. This particular curve is shown for reference only, since it was not used in the collision dynamics analyses presented below.

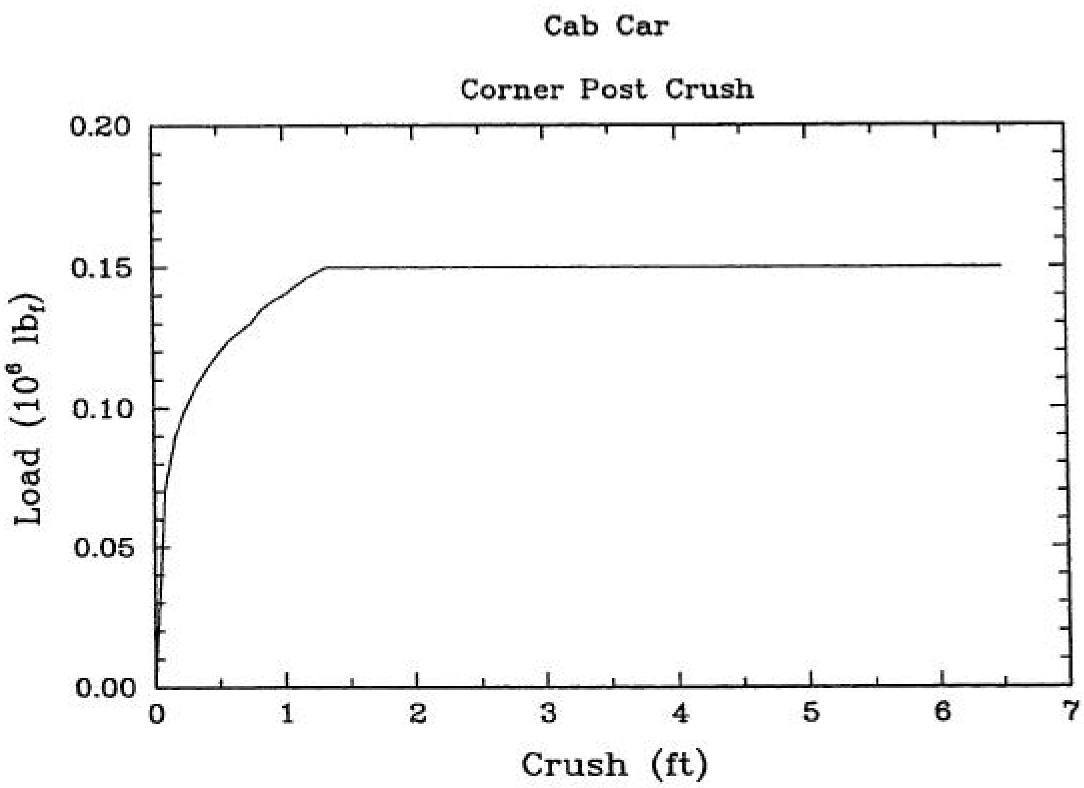


Figure 8. The Idealized Load-Crush Curve for Longitudinal Loading Applied Near the Base of a Corner Post

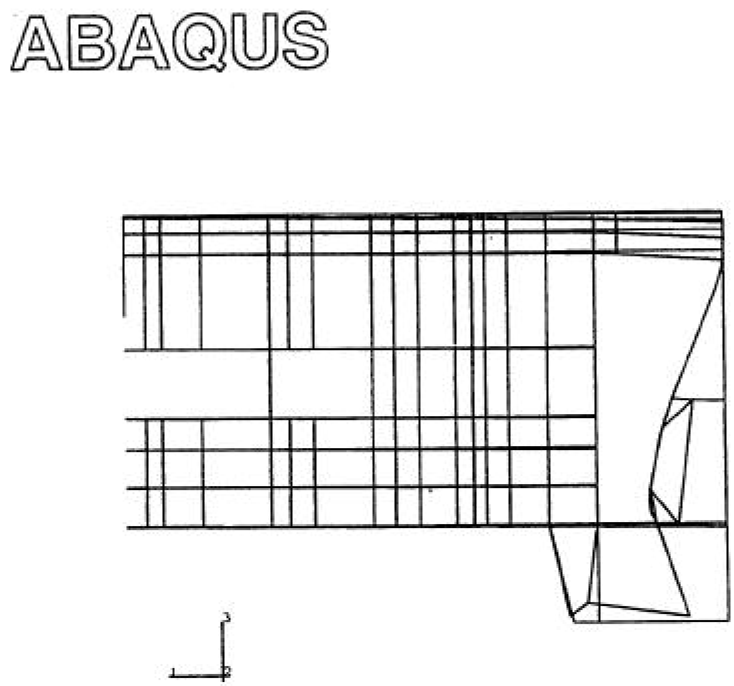


Figure 9. An Example of Predicted Corner Post Deformation

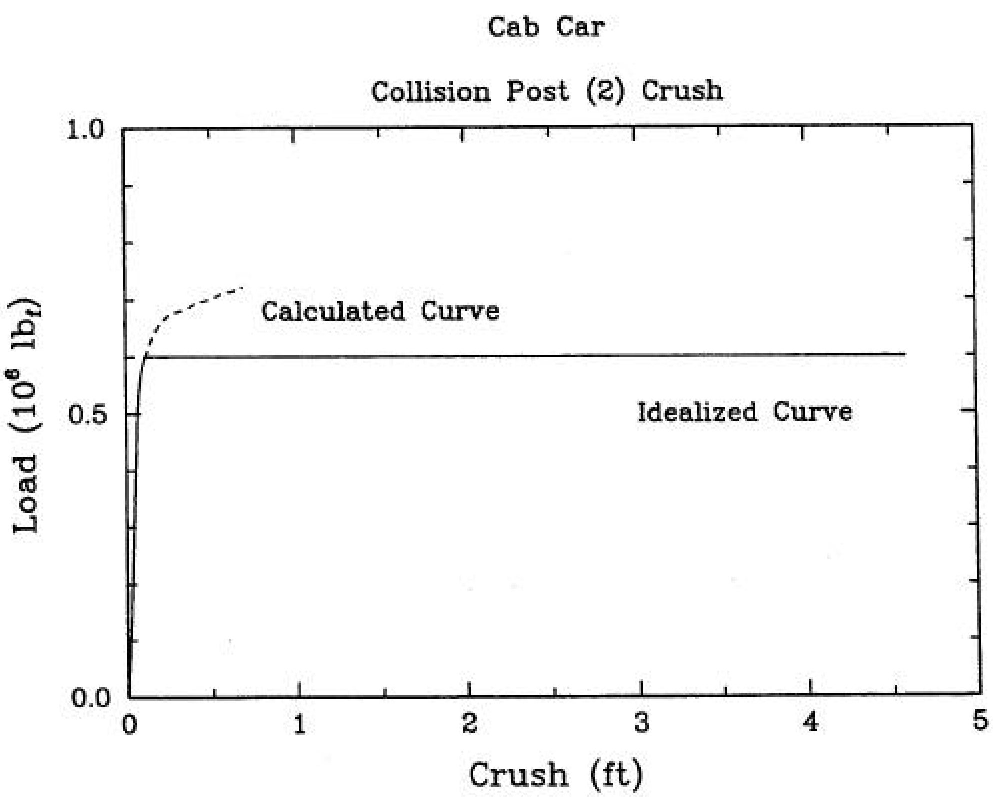


Figure 10. The Idealized Load-Crush Curve for Longitudinal Loading of Two Collision Posts

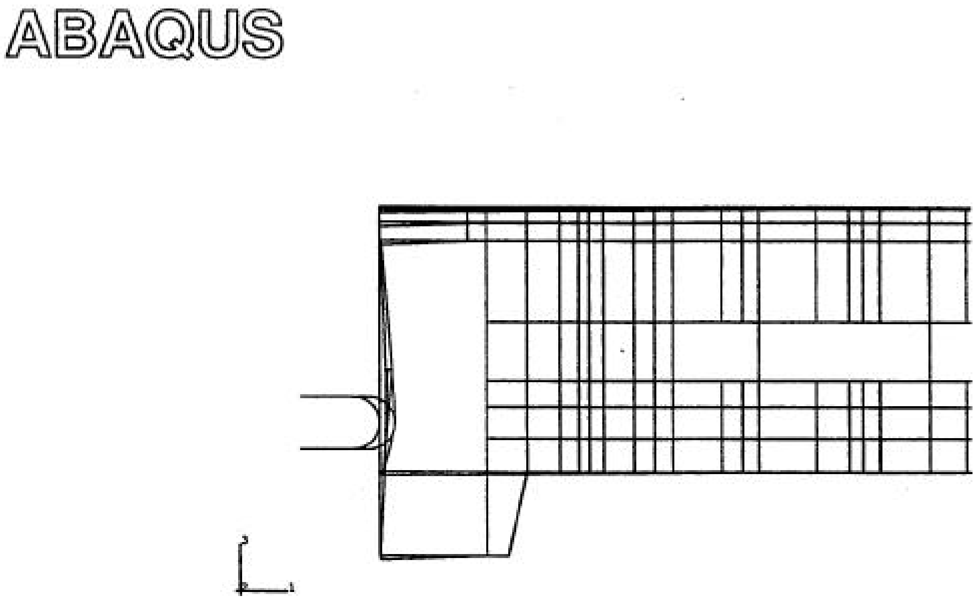


Figure 11. An Example of Predicted Collision Post Deformation

Our idealizations exhibit a peak load that is maintained with substantial crush deformation for both the corner and collision posts. Clearly a point will be reached at which either shear or tensile failure will occur in the members or their connections and the load is likely to drop precipitously at this point; some comments are provided about the crush at which this effect might initiate. It is not possible to identify this deformation for a generic cab car that meets current federal requirements or the purchase specifications against which the cars are designed and built. As a result, the collision dynamics analyses that utilize these curves will necessarily be an approximation. Nevertheless, we feel that analyses based on these curves provide some information on the crush response with respect to closing speed.

The coupler load-deformation curve was idealized as a triangular curve with a peak load of 0.45 x 106 lbf and a maximum deformation of 0.33 ft. The curve was derived to provide approximately the same energy absorption characteristics as a cab car draft gear whose characteristics were provided by a manufacturer of cab car draft gear.

7. COLLISION DYNAMICS ANALYSES

7.1 MODEL DESCRIPTION

Relatively minor modifications were made to the collision dynamics model previously used to simulate freight locomotive collisions [1]. Briefly, the lumped mass model idealizes the cab car as three masses: the body and the two trucks. Each truck-to-body connection consists of a vertical spring and damper, in parallel, and a longitudinal spring. The trucks are constrained to motion along a line, representing the track, and motion of the body is restricted to the vertical plane. Motion was also restricted to the vertical plane for the offset collision because we believe that the relatively small crush loads, $\leq$ 150,000 lbf, will induce little yaw motion. Dimensional, mass, and inertial properties for these three masses were selected to correspond to either a locomotive or a cab car, each of whose overall weight corresponds to that given for the accident scenario.

The crush response of the lead cab car and all other vehicles modeled is embodied in impact elements that are located at the ends of each vehicle. These impact elements are one-dimensional and possess the load crush response derived from the finite element analysis described in the previous section. An exception to this is the draft gear support structure and underframe load-crush response for the locomotive, which was taken as that for the baseline freight locomotive from the previous study [1]; the locomotive collision post response was not needed here. The lead cab car includes two impact elements for the analyses carried out in these studies (figure 12): (1) the coupler and draft gear; and (2) the underframe *or* the corner post. (Recall that impact with the cab car collision posts was not considered in the present study.) Trailing vehicles include only a single impact element, which has the load-crush response corresponding to the coupler and underframe. Unlike the model for the freight locomotive collisions, no ramp is included to allow override to initiate, consistent with the discussion of section 4.

Calculations were always carried out using the vehicle configuration shown in figure 12 - a single locomotive colliding with a train of four cab cars and a trailing locomotive. Initial analyses used individual velocities of V_1 = 19 mph for the passenger train, and V_2 = -12 mph for the individual locomotive. The ratio of these two velocities, V_1/V_2 = -1.6, was maintained for all subsequent calculations with the results reported in terms of closing speed. The model was run for a simulated time ranging from 0.25 to 0.50 seconds after initial impact, depending on the amount of time required to complete the crush deformation in the lead cab car. Output included the amount of cab car underframe or corner post crush and the acceleration pulse of the cab car.

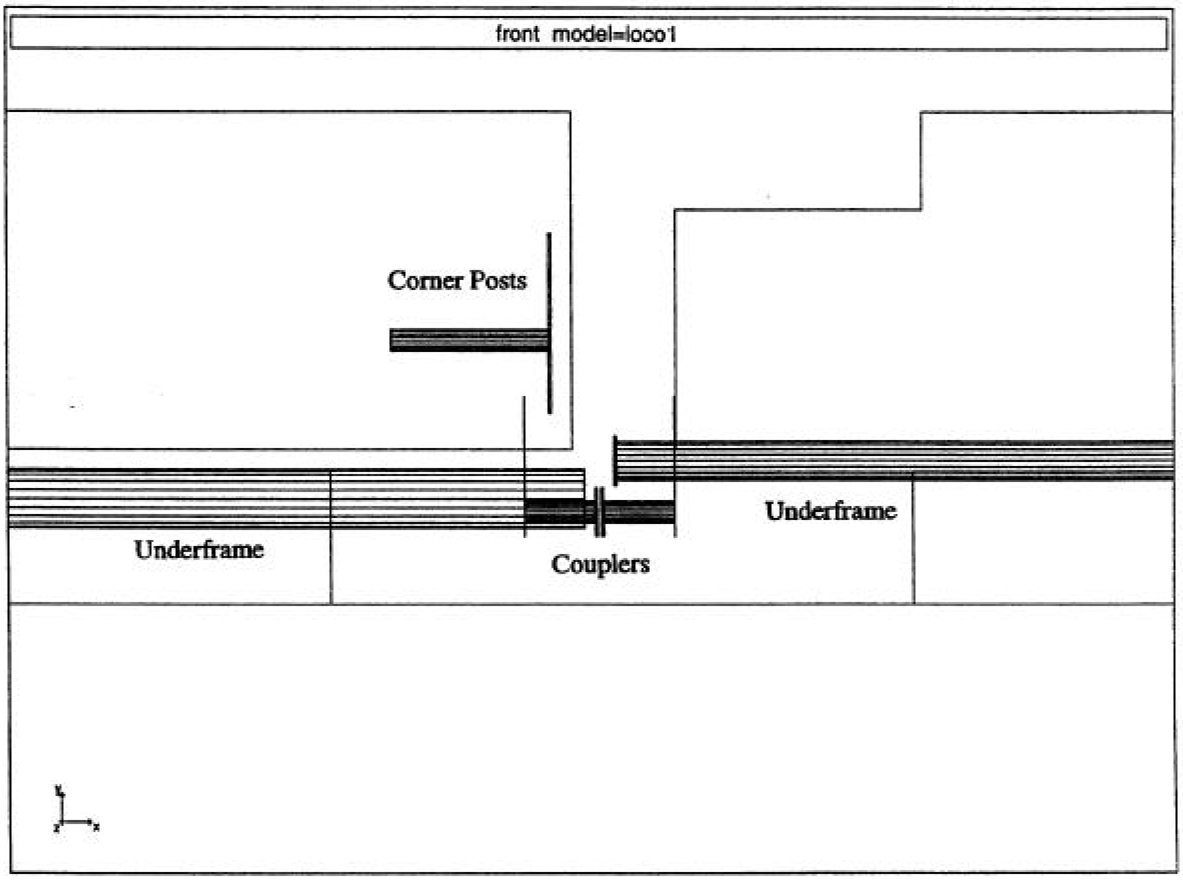


Figure 12. An Illustration of the Vehicle Components Included in the Collision Dynamics Model

7.2 RESULTS

7.2.1 Centered Collision Crash Scenario

The predicted cab car underframe crush vs. closing speed for a velocity ratio, $V_1/V_2 = -1.6$, is shown in figure 13. A crush of 1 ft is reached at a closing speed of about 25 mph and the crush becomes very large - greater than 6 ft - at closing speeds above about 35 mph. This asymptotic behavior is a result of the assumed underframe load-crush curve, which decreases monotonically after the peak strength is achieved (figure 6). The closing speed at which substantial crush occurs would be increased if the cab car structure was somehow designed and built to maintain the peak load for substantial crush.

The predicted response for underframe crush in figure 13 is in reasonable agreement with the outcome of the accident on which the simulation was based. In the accident, which is reported to have occurred at a closing speed of about 31 mph, there was also substantial underframe crush, including fracture between the underframe and superstructure.

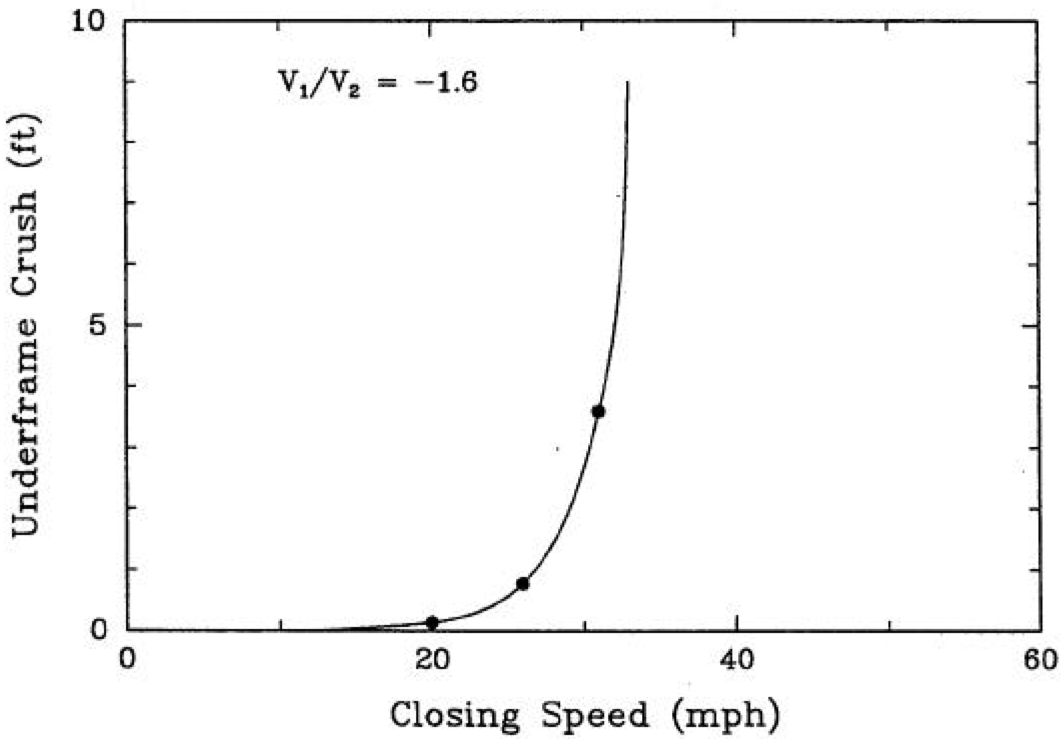


Figure 13. Predicted Cab Car Underframe Crush vs. Closing Speed for Cab Car/Locomotive Crash Scenario

The peak acceleration for a centered collision at 31 mph is lower than what is theoretically possible for the cab car modeled. The calculated crash pulse, shown in figure 14, indicates a maximum acceleration of approximately 10 g's, comparable to the peak accelerations we calculated for freight locomotive collisions at these closing speeds. While the accelerations calculated in the freight locomotive case were found to be relatively mild in terms of causing secondary impact injuries to someone lying prone on the floor of the freight locomotive cab, they exceed the 6 g value that has been discussed as an acceptable value for passenger rail vehicles [9]. Although the issue of secondary impact is of academic interest for occupants located near the forward end of the cab car in this simulated collision, the issue is important for occupants in other parts of the vehicle predicted not to crush.

Of note is the peak acceleration derived from a consideration of the maximum possible crash load, which is reached at the front end during this collision. It is:

a_{max}= 1.7 x 10^6 lbf/85 x 10^3lb = 20 g's.

The difference between this value and that computed in the collision dynamics model is due to the substantial load that acts at the rear of the cab car at the same time that the peak collision force acts at the front end. However, such a difference may not prevail for other collision conditions and component load-crush responses.

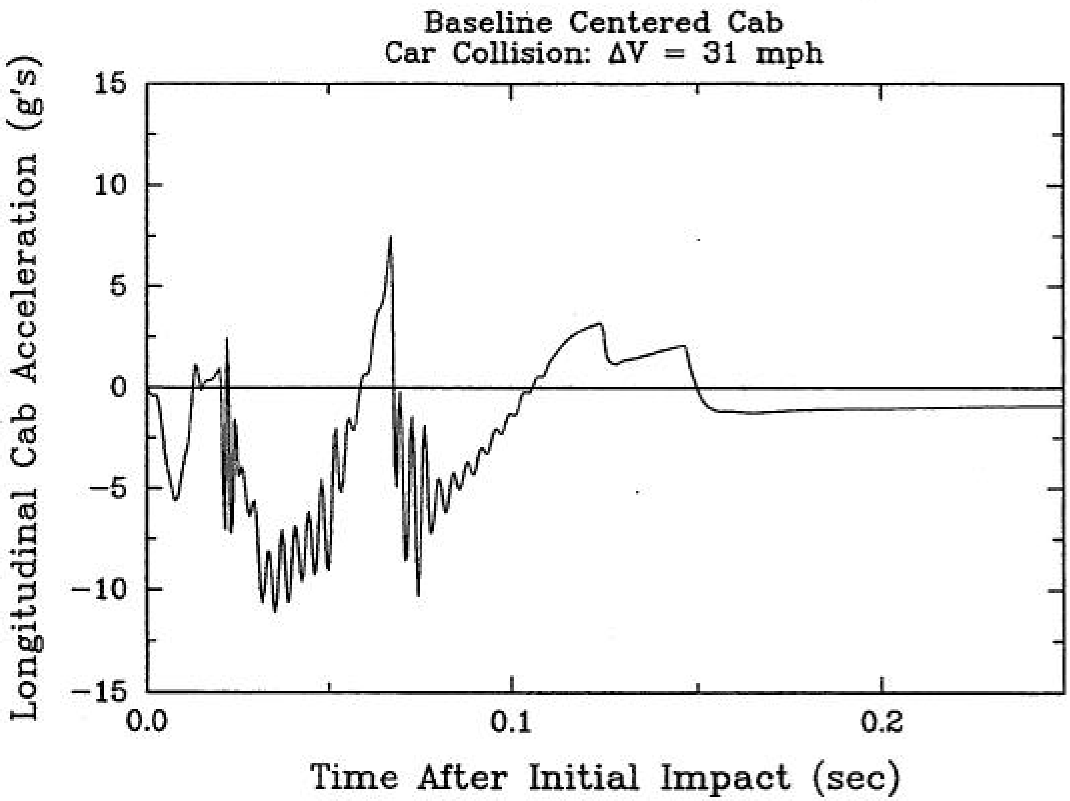


Figure 14. The Cab Car Crash Pulse Corresponding to the Centered Cab Car/Locomotive Collision at a 31 mph Closing Speed

7.2.2 Offset Collision Crash Scenario

The closing speed at which substantial crush of the corner post occurs in the offset collision crash scenario is much lower than that corresponding to underframe crush. Figure 15 shows that substantial corner post crush occurs when the closing speed is above 15 mph.

Although we were unable to locate an accident corresponding to corner post impact between a locomotive and a cab car, the corner post collision accident between two cab cars described in section 3 offers an opportunity for comparison to the offset collision predictions. The consequence of that approximately 32 mph closing speed collision was destruction of the corner posts followed by about 25 ft of crush along the sides of each cab car. Although the predicted results in figure 15 do not extend to 25 ft of crush, substantial crush would certainly be predicted at AV = 32 mph. Thus, the predictions of ADAMS model are consistent with the accident observations.

A crash pulse for the offset collision at 10 mph closing speed is shown in figure 16. The peak acceleration in this case is 5 g's, which corresponds to impact between couplers. The second, extended peak in acceleration of about 1.5 g's closely matches the value estimated from the simulated plateau strength of the corner post:

$a_{max} = 0.15 \text{ x } 10^6 \text{ lbf}/85 \text{ x } 10^3 \text{ lb} = 1.76 \text{ g's}.$

Thus, the accelerations for this collision scenario are relatively mild, suggesting that there may be room for increasing strength without greatly increasing the risk of secondary impact injuries for this type of collision.

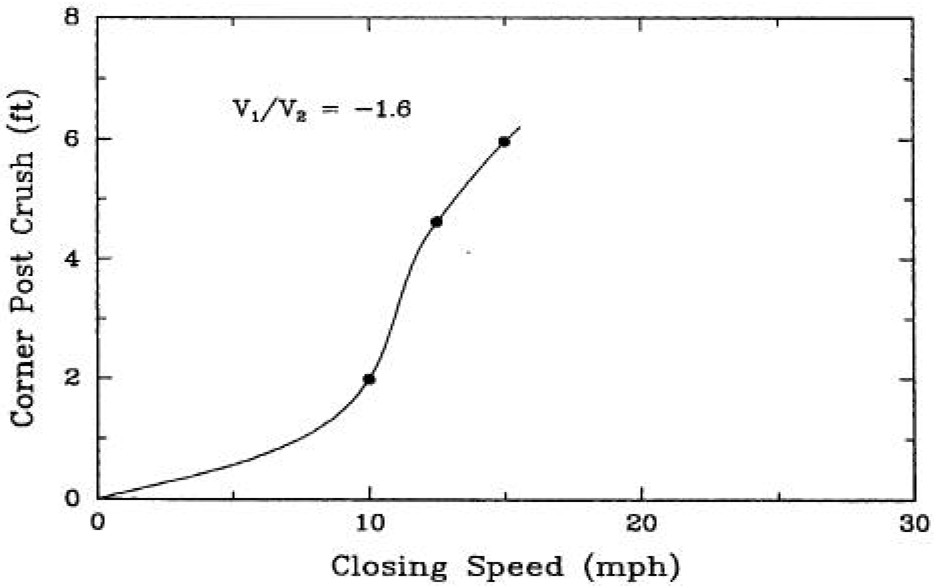


Figure 15. Predicted Cab Car Corner Post Crush vs. Closing Speed for Cab Car/Locomotive Crash Scenario

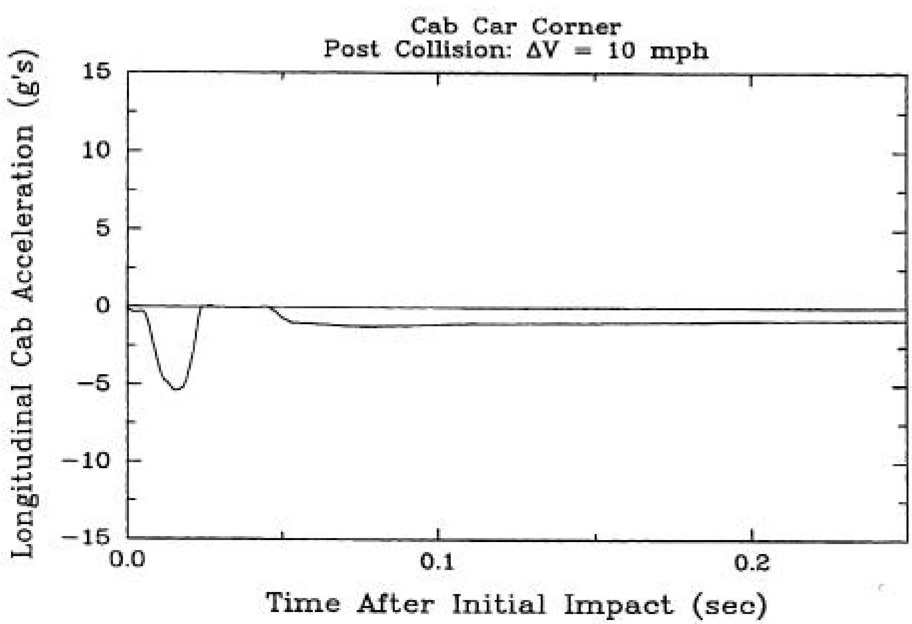


Figure 16. The Cab Car Crash Pulse Corresponding to the Corner Post Collision at a 10 mph Closing Speed

7.3 THE EFFECT OF INCREASED COMPONENT STRENGTHS

Two sets of collision dynamics calculations were carried out to assess the effects of increasing component strength on degree of crush. These were:

1. An increase in the underframe strength of 50%, applied over the entire range of crush. This corresponds to a peak underframe strength of 2.6 x 106 lbf.

2. An increase in the corner post strength by a factor of four, to 600,000 lbf, thus matching the combined, currently required strength of two collision posts.

The results of the collision dynamics calculations utilizing these higher strength load-crush curves are shown in figures 17 and 18 for the two crash results; data for the baseline component strengths are also shown in these figures. The data in figure 17, for the centered collision, suggest that the closing speed at which very large vehicle crush will occur is in the range of 40-45 mph, about 10 mph greater than that for the baseline component strengths. Similar increases in the closing speed needed to induce substantial crush are obtained for the offset collision scenario, for which the range is increased from 10-15 mph to 20-25 mph.

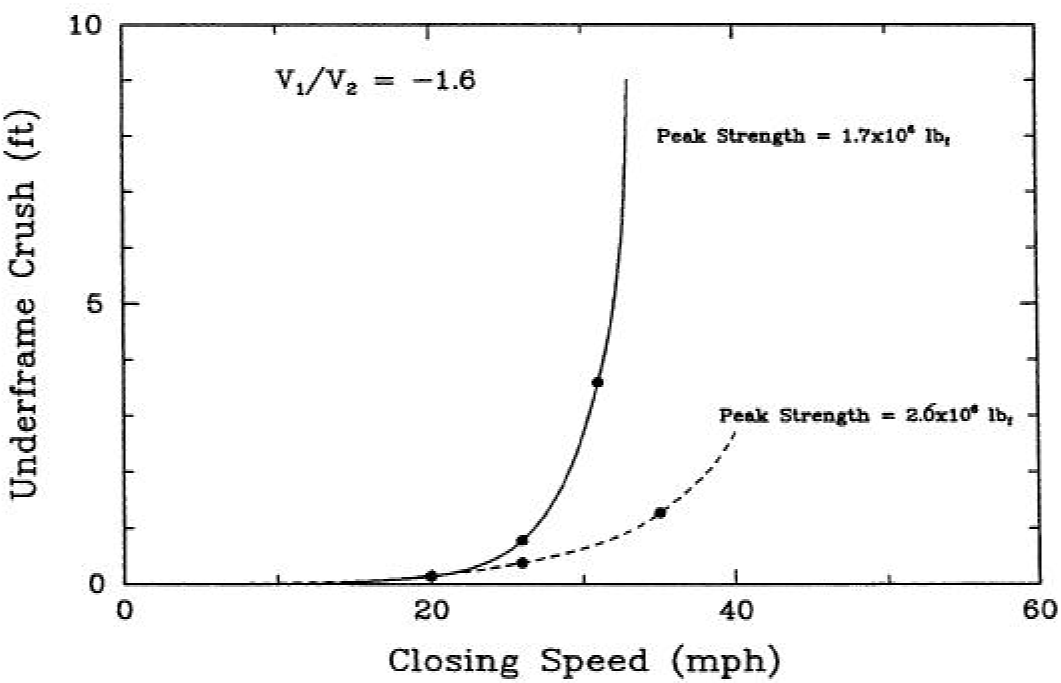


Figure 17. Predicted Cab Car Underframe Crush vs. Closing Speed for the Baseline and Stronger Underframe Cases

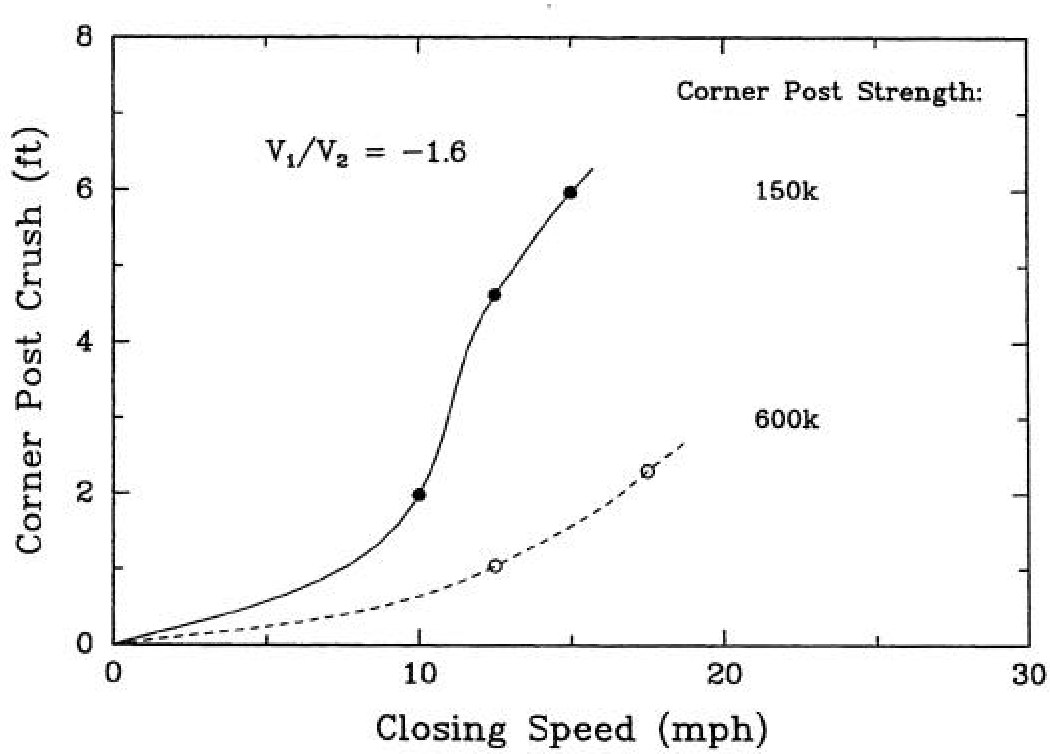


Figure 18. Predicted Cab Car Corner Post Crush vs. Closing Speed for the Baseline and Stronger Corner Post Cases

8. DISCUSSION

This investigation has provided information with which the crashworthiness of cab cars can be assessed. Generally, the results indicate that for commuter train configurations of the push-pull type in which a cab car and locomotive are involved in a head-on collision, it would be unlikely that the cab car could sustain an accident at a closing speed in excess of 35 mph without experiencing substantial crush to both the control cab and the passenger compartment. The result of such crush would likely cause severe injury or fatality of the vehicle occupants. This is based on calculations for a crash scenario in which the cab car collides with a 124-ton locomotive, as well as on observations from an actual accident. The closing speed for this scenario at which only loss of control cab survivable space would occur is about 30 mph, which corresponds to about 3 ft of crush.

Substantial cab car crush is predicted to occur at even lower closing speeds when the collision forces are resisted by components other than the underframe, such as the collision posts or a corner post. However, it is difficult to envision a collision interaction in which a locomotive would interact primarily with the collision posts and not the underframe.

It is also possible to comment on the outcome of a cab-car-to-cab-car collision using the results of this study. In such a collision, we may, to a first approximation, assume that both trains would share the collision energy equally. This assumption alone would suggest that higher closing speed collisions could be sustained than for the case of impact with the locomotive, for which the cab car must absorb nearly all of the collision energy; the locomotive absorbs very little energy. In fact, since the energy that must be absorbed in a collision - the collision energy - is given by:

$$\text{Collision energy} = 0.5[m_1(m_1 + m_2)](V_1 - V_2)^2$$

where m_1, m_2, V_1, and V_2 are the masses and velocities of train 1 and train 2, respectively, we might expect an increase in collision closing speed by a factor of 1.4 (2).

However, a different front end interaction is possible, and perhaps likely, in the cab-car-to-cab-car collision. Namely, it is now possible for the underframe of one cab car to override the underframe of the other car, resulting in impact with one vehicle's collision posts. Since collision posts that just satisfy the federal requirements appear to possess lower energy absorption capability than the underframe, this interaction will tend to diminish the benefit of a shared collision energy.

The analyses conducted in this study include an aspect that is not actually part of the federal requirements related to crashworthiness: the assumption of component ductility. The load-crush curves calculated and idealized, as discussed in section 5, allow for several feet of crush and there is some engineering basis for this. However, 49 CFR, Part 229.141, specifies only that components shall achieve certain strength values. Under such circumstances it is technically possible that a structure satisfying these requirements would be capable of absorbing very little energy, thus having a dramatic effect on the consequences of a collision.

Finally, while no specific occupant survivability calculations were conducted in this cab car crashworthiness study, as they were in the freight locomotive study, it appears that the crash pulse magnitudes are high but not extreme for the cab car collisions in which substantial crush does not occur (less than about 30 mph for the configuration modeled). Occupant survivability calculations have been conducted for passengers seated in cab cars for a crash pulse whose peak was approximately 7 g's [10]. The analyses in that study gave a Head Injury Criterion (HIC) of 620 and a Resultant Chest Acceleration (CR) of 53 for seated and unrestrained passengers. These values correspond to probabilities of experiencing certain severe injuries (see [2]) of about 30% for the HIC value and 55% for the CR value.

Freight train collision crash pulses whose peak was approximately 10 g's resulted in predicted small probabilities of sustaining a serious injury for occupants lying prone on the cab floor; such a situation could prevail for the engineer of the cab car who may exit the control compartment and lie on the floor prior to a collision. The 10 g acceleration in the freight locomotive case produced a HIC of 390 and a CR of 44. Thus, it appears that occupants are at greater risk of sustaining serious injuries due to loss of survivable volume rather than secondary impact for the collision conditions modeled in this study. However, the severity of secondary impact will increase as the strength of the underframe or other components is increased.

We note that there is a trend in European passenger rail vehicle design to specify crashworthiness in terms of energy absorption and to limit peak car body strengths so that secondary impact intensities will be limited [9].

9. CONCLUSIONS

Several conclusions can be drawn from this investigation on cab car crashworthiness:

- The peak strength of crashworthiness-related components in current cab cars is greater than that required by 49 CFR, Part 221.141.

- The collision dynamics model appears to provide a good simulation of collisions involving cab cars.

- Substantial crush appears likely at closing speeds above approximately 35 mph for the situation in which a cab car, just satisfying the federal requirements, is in a push-pull configuration and collides with a locomotive.

- Crush is limited for closing speeds less than approximately 30 mph when the cab car underframe is the primary component transmitting the collision force.

- The closing speed at which substantial crush occurs is in the range of 15-20 mph when a single corner post just satisfying a 150,000 lbf ultimate strength requirement must carry the bulk of the collision force.

- The crash pulse in a 30 mph closing speed collision in which the cab car underframe carries the collision force appears severe enough to result in passenger injuries. However, the predicted extent of these injuries was not investigated.

- Increasing underframe strength by 50% has the effect of increasing the predicted closing speed at which substantial crush occurs to approximately 40 mph. This will increase the propensity for secondary impact injuries to passengers.

- Increasing the single corner post strength by four times, to 600,000 lbf, which is the federal requirement for two collision posts, increases the predicted closing speed for substantial crush to about 25-30 mph.

- The strength-only specifications of the federal standards provide no assurance of substantial energy absorption in collisions.

- The closing speed at which substantial crush occurs in cab-car-to-cab-car collisions depends on whether override occurs. In cases for which the underframes carry the bulk of the collision force, we expect the closing speed for substantial crush to be above that for a cab-car-to-locomotive collision.

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