Locomotive Crashworthiness Research

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Executive Summary

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13. ABSTRACT (Maximum 200 words)

Four reports on a study to evaluate whether various crashworthiness features, as defined in Public Law 102-365, can provide practical benefit to the occupants of freight locomotives are summarized. In particular, the benefit was assessed relative to the current industry standard, S-580. The work included: development and validation of computer models to simulate train collisions and the injury to cab occupants; generation of design concepts for the various features defined in the public law; and evaluation of the concepts in terms of cab crush, secondary impact, cost, and weight. Features that appear to provide benefit include stronger collision posts, crash refuges, and shatterproof windows.

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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.

As part of the response to Public Law 102-365, computer models were developed and related engineering calculations were made, to analyze the crashworthiness of the cab area in existing road freight locomotives and to provide quantitative estimates of the costs and benefits of the crashworthiness improvement features. The work was carried out by Arthur D. Little, Inc., under contract to the Volpe National Transportation Systems Center, from January 3, 1994, to March 31, 1995. The work was conducted as part of the Center's support to the Office of Research and Development, Federal Railroad Administration.

Details of the work are summarized in four volumes. Volume 1 covers model development and validation. Volume 2 covers the representation of proposed crashworthiness features, evaluation of their effectiveness in limiting cab intrusion, and evaluation of their influence on occupant survivability. Volume 3 discusses the pros and cons, and summarizes the estimated costs versus benefits, for each of the represented crashworthiness improvement features. Volume 4 extends the modeling to additional effects, and the analysis to higher closing speeds.

During the course of the study, further work was assigned to provide for additional studies of selected freight locomotive crashworthiness improvement features in collisions at higher closing speeds and for evaluation of the crashworthiness of the cabs in control cars used in passenger service. The additional freight locomotive studies will appear as volume 4 of this series. The work on control car cabs will be published as a separate report.
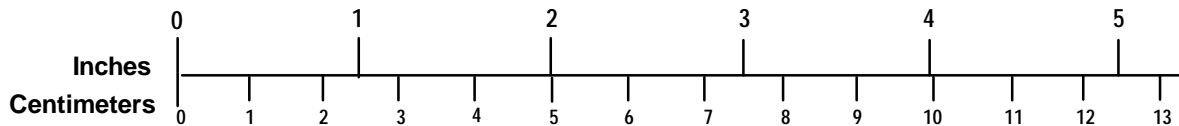
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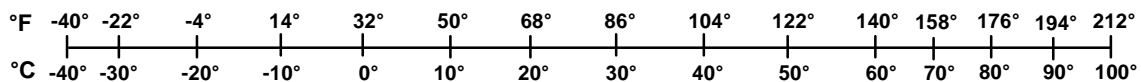
ENGLISH TO METRIC

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

Inches	0	1	2	3	4	5
Centimeters	0 1 2 3 4	5 6 7	8 9 10	11 12 13		

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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INTRODUCTION

Arthur D. Little and its subcontractors, Arvin/Calspan and Parsons Brinckerhoff, conducted studies of locomotive crashworthiness in support of the Federal Railroad Administration's (FRA) response to Public Law 102-365. This law includes a statement that the Secretary of Transportation shall conduct research and analysis to consider the costs and benefits associated with equipping locomotives with the following crashworthiness features:

• Braced collision posts
• Crash refuges
• Rollover protection devices
• Uniform sill heights
• Deflection plates
• Anticlimbers
• Shatterproof windows
• Equipment to deter post-collision entry of flammable liquids

The Arthur D. Little team was awarded a contract to conduct engineering analyses to identify and evaluate various design concepts for the features described above. In particular, the team was asked to perform this evaluation with respect to the currently applied Association of American Railroads (AAR) industry standard, S-580, summarized in table 1. This standard applies to new road-type locomotives built after August 1, 1990, and has requirements for three of the features listed in the public law: anticlimbers, collision posts, and the short hood structure, which can be considered, in part, as equipment to deter post-collision entry of flammable liquids.

Table 1. Summary of AAR's S-580 Standard on Locomotive Crashworthiness Requirements

Component	Requirement
Anticlimbers	Sustain an ultimate vertical load of 200,000 lbf at the short hood end
Collision posts	Two, each of which shall sustain an ultimate load of 200,000 lbf at 30 inches above the deck and 500,000 lbf at the deck
Short hood structure	The product of skin thickness and yield strength shall be at least 0.5 inches times 25,000 psi

Details of the project approach and results are described in a set of four reports (references [1] through [4]). Volume 1 summarizes the results of the structural damage and collision dynamics model development and validation; volume 2 describes the approach and results of the crashworthiness concept generation and evaluation as well as the occupant survivability model; volume 3 provides discussion on the advantages and disadvantages of each concept in terms of effectiveness, cost, and weight; and volume 4 provides the results of additional calculations to consider the separate effects of fewer locomotives, higher closing speed, and underframe bending.

This executive summary provides a brief description of the approach and results.

APPROACH

The overall approach to the project is illustrated in figure 1. It included information gathering on locomotive design and crashworthiness, the development of computer models to evaluate crashworthiness, and the generation and evaluation of design concepts that could potentially improve locomotive cab survivability. No testing was included in the program. Rather, models were validated to the extent possible by comparing predicted results to reported accidents.

Information Gathering

Information gathering included review of the literature, discussions and visits with locomotive manufacturers, and review of accident reports. Members of the team also examined locomotives damaged in a head-on collision between two freight trains that occurred during the project.

The literature on freight locomotive crashworthiness dates primarily from the 1970-1980 time period during which the FRA supported much research (c.f. [5]). Considerable effort was placed into developing models, and load-crush curves were developed for some of the major components. Recommendations were also made to improve crashworthiness, including the implementation of a reinforced cab with a built-in front ramp to induce override of the cab without substantial crush [6].

The most recent study on freight locomotive crashworthiness, prior to the present study, was conducted by Illinois Institute of Technology Research Institute (IITRI) under support from the FRA [7]. The primary conclusion from this report was that override and cab crush could occur in a head-on collision between some freight trains at closing speeds as low as 22 mph. Results from the IITRI study also suggested that increasing the strength or energy absorption capability of the anticlimber has minor effect on the overall accident consequences. No other crashworthiness features were examined.
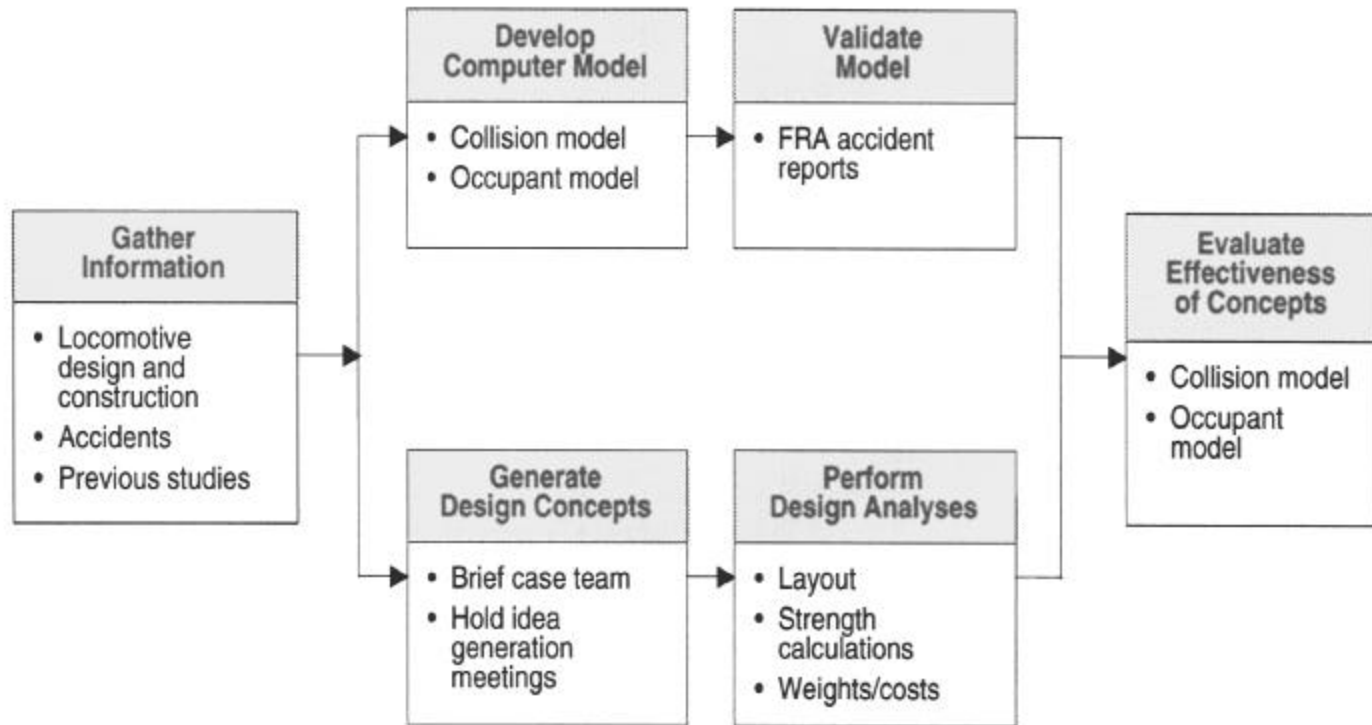
3

Figure 1. Illustration of the Locomotive Crashworthiness Research Project Approach

Most of the information obtained in our study from the locomotive manufacturers was on the design and fabrication of current locomotives; we used this information in constructing models and evaluating the practicality of various design concepts. However, we also had discussions on past and current efforts to improve crashworthiness and on the constraints that manufacturers face in making such modifications. We were provided with mechanical drawings and we were permitted to make tours of the locomotive fabrication facilities.

Numerous accident reports were reviewed to obtain information on the collision modes and types of structural damage that occur as a result of an accident. Emphasis was placed on the head-on collision because it was felt to represent the greatest threat to the cab occupants. A visit to the site of the Marathon, Texas, head-on collision, which occurred at a closing speed of over 60 mph, was also very instructive about the types of structural damage that occur in a collision. Three accidents, all head-on collisions, were selected for comparison to model results. Table 2 summarizes the characteristics of these accidents.

Table 2. Summary of Accidents Used for Validation of the Computer Model

FRA Report Number	Closing Speed (mph)	Crew Fatalities/ Injuries	Override?	Cab Crush?	S-580 Locomotive?
C-58-91	18	0/0	No	No	No
B-02-93	30	1/?*	Yes	Yes	No
C-10-94	43	*0/5*	Yes	No	Yes

* insufficient information

Characteristics associated with the second, 30 mph closing speed accident were selected for a baseline crash scenario. It included a five-locomotive consist traveling at 21 mph colliding with a two-locomotive consist traveling at 9 mph. Five of the locomotives had a weight of 200 tons and two had a weight of 140 tons. The lead locomotive of the 21 mph consist was overridden and the cab was severely crushed. This baseline scenario was used to determine the effectiveness of the various crashworthiness design concepts as will be described below.

Computer Models

Three computer models were developed to evaluate the effectiveness of the various crashworthiness features. The structural damage model was used to generate the load-crush curves for the important front-end structural components. These curves were then used as part of the lumped mass collision dynamics model, whose primary function was the calculation of the amount of cab crush and the cab acceleration vs. time, also called the crash pulse. The crash pulse was the primary input to the occupant survivability model, which was used to determine accelerations that a simulated occupant could experience.

The structural damage model was based on elastic-plastic finite element analyses carried out using the commercially available computer program ABAQUS [8]. Analyses were conducted for three sets of components: (1) the draft gear support structure/underframe; (2) the anticlimber/underframe; and (3) the short hood structure/collision posts. The geometry and material properties modeled depended on the particular configuration being analyzed, but the most important of these was a set of idealized geometries designed to either just satisfy (i.e., with no margin of extra strength) S-580 requirements - e.g., the collision posts - or to meet our understanding of general locomotive design requirements - e.g., the underframe. Analyses included the effects of plastic deformation and elastic and plastic buckling with crush values in excess of one to eight feet. Analyses made for actual components used on currently manufactured locomotives showed that the strength requirements of S-580 for anticlimbers and collision posts are substantially exceeded.

The collision dynamics model is a lumped mass model carried out using the commercially available computer program ADAMS [9]. Each locomotive in the consist is modeled as having three masses: the body and two trucks. These masses are connected by springs and dampers that include, for example, the effects of lift-off from the trucks during an override. The lead locomotives in the model include three impact elements to represent the important structural elements described in the previous paragraph.

An important feature of the collision dynamics model is that override is purposely initiated by including a ramp on one of the lead locomotive anticlimbers. This reflects our belief that, given sufficient collision force, the asymmetric deformation of components such as the couplers or the anticlimbers that occurs on impact leads to initiation of override even if the sill heights are nominally identical. However, the model does include a mechanism for override to be arrested if overall crush is limited.

For most of the calculations, motion is restricted to a vertical plane that includes the track; that is, no lateral motion is allowed. Separate calculations made in the study show that lateral buckling or derailment of trailing vehicles has little effect on the crush and crash pulse of the lead locomotive. (However, such derailment has a substantial effect on dissipating the energy of the trailing vehicles and is nearly always associated with head-on collisions of significant closing speed.) Separate calculations in this study also showed it was not necessary to include non-locomotive trailing vehicles in the collision dynamics model to predict the collision effects to the lead locomotive.

The occupant survivability model is based on the commercially available Articulated Total Body (ATB) model [10]. The occupant is simulated by a set of connected lumped masses designed to represent anatomical behavior of a 50th-percentile male. For most of the analyses, the occupant was modeled as lying face down, transverse to the direction of travel and in the rear of the cab to ride down the collision. The cab surfaces modeled included two seats with posts, two side-walls, and a front panel with an opening to represent the stairs down to the nose of the hood. The model uses the crash pulse as input and calculates the trajectory of the occupant and various force and acceleration values to which the occupant is subjected as he impacts various surfaces.

Occupant Survivability Measures

Three occupant survivability measures were used to evaluate the relative risk of injury or fatality: cab crush, the Head Injury Criterion (HIC), and the Resultant Chest Acceleration (CR). A crush of 6 ft beyond the tip of the short hood was taken as the value that would eliminate survivable space in the cab. This value corresponds approximately to crush up to the front console; however, we have assumed that for this crush, the debris forward of the console would be pushed into the cab, eliminating the survivable space. No secondary impact measures have been adopted for guided ground transportation so the HIC and CR values, currently used in the automotive and aircraft industries, were used here. It is not possible to assign values of the HIC and CR that correspond to fatality. Rather, these measures provide only a probability of experiencing a particular type of injury. For example, an HIC = 1000 corresponds to a 43% probability of sustaining a linear skull fracture and/or a state of unconsciousness lasting less than one hour, while a CR = 65 corresponds to a 60% probability of experiencing various rib fractures with or without hemothorax or pneumothorax.
(An HIC = 1000 and a CR = 65 are the maximum allowable values in the federally required 30 mph frontal impact test for automobiles.)

Model Validation

The collision models were validated by applying them to the three accidents described in table 2. To the extent possible, actual masses and component strengths were used for the specific locomotives involved in the accidents. Agreement between the model results and the observations from the accidents was generally very good.

The model predicted that only damage to the draft gear support structure should occur in the lead locomotives involved in the 18 mph closing speed collision. Override was predicted not to occur. Although no photos were available for this accident, damage was reported to be minor and override did not occur.

On the other hand, override and cab crush were predicted for the 30 mph closing speed accident as observed. In this case, the lead locomotive of a two-locomotive consist overrode the lead locomotive of a five-locomotive consist. The overridden locomotive did not entirely satisfy S-580 because its anticlimber did not span the full locomotive width. However, our calculations indicate that the strength of each collision post was just over 200,000 lbf at 30 inches above the deck. The predicted and observed cab crush were 10 ft and 7-8 ft, respectively.

The model was also successful in reproducing the results of the 43 mph closing speed collision that involved a three-locomotive consist impacting a single-locomotive consist. Override occurred in this accident but it was arrested by the collision posts, whose strength was approximately twice that required by S-580. Predicted crush was 4 ft in comparison to an observed crush of about 2 ft.

An important result of the model validation simulations for the last two accidents is the prediction of complete failure of the draft gear support structure of the overriding locomotive. This failure is largely responsible for enabling complete override to occur, since the

anticlimber/underframe of the overridden locomotive encounters no resistance below the underframe of the overriding locomotive. Figure 2, scenario A, illustrates this form of override. Side view photographs of the overriding locomotives in the last two accidents also show complete failure of the draft gear support structure [1]. Although we believe the front-end interaction illustrated as scenario B in figure 2 is possible, we have not yet modeled it nor have we found evidence of it in reported accidents.

In general, both model results and photographs from these accidents show that the anticlimber of the overridden locomotive is not challenged vertically during the head-on collisions. In fact, a vertical force of over 1,000,000 lbf would be required to raise the coupler of a 200-ton locomotive to the height of the anticlimber in a 30 mph closing speed collision; a force quite difficult to sustain by any front-end component. Rather, it seems likely that the anticlimber is crushed and then sheared by the opposing anticlimber/underframe structure. This suggests that the anticlimber is not effective in preventing override. Note, however, that the anticlimber is still probably very effective in preventing the rise of debris from grade-crossing-type collisions. In addition, our structural damage model analyses indicate that an anticlimber that satisfies S-580 can dissipate significant collision energy.

Design Concept Generation and Evaluation

The primary approach to the generation of crashworthiness design concepts was to hold several idea generation sessions with project team staff who had experience in crashworthiness, mechanical design, and railroad vehicle engineering. Two of the features listed on page 1 were discussed at each meeting, except the crash refuge feature, to which an entire meeting was devoted. Prior to each meeting, a general presentation was made by the project leader on what was known about locomotive design and fabrication constraints related to the feature in question. There were generally ten to fifteen ideas generated for each feature but only two or three of these were selected at the end of each meeting for further evaluation.

Preliminary evaluation of the concepts involved making rough candidate designs and layout drawings to determine fit with current locomotives. These designs were also used to make approximate calculations of weight, cost, and strength. Various designs were reviewed and a single concept was selected for detailed evaluation for each feature. Again, the exception was the crash refuge feature, for which three concepts were evaluated in detail.

The final concepts selected were evaluated using the computer models and the baseline crash scenario described above. The basic approach was to compare occupant survivability measures for a lead locomotive that just satisfies S-580 to one that just satisfies S-580 *and* has the concept in question, both in the baseline crash scenario. Some calculations were made in which two or more of the concepts were implemented simultaneously, and some were made for closing speeds higher than 30 mph. Where necessary, new load-crush curves were generated. A modification to the model was also necessary to examine the deflection plate feature, whose purpose is to induce lateral motion of the locomotives. In this case, the vehicle trajectories were restricted to the horizontal plane that includes the track.

Scenario A

**Overriding locomotive draft
gear support structure fails.**
Complete override occurs.

Initial impact

ARREST POSSIBLE

Override initiation
Caused by ramping on couplers
or anticlimbers.

ARREST POSSIBLE

**Overridden locomotive draft
gear support structure fails.**
Trapping occurs.

ARREST POSSIBLE

**Overriding locomotive draft
gear support structure fails
or frame bending occurs.**
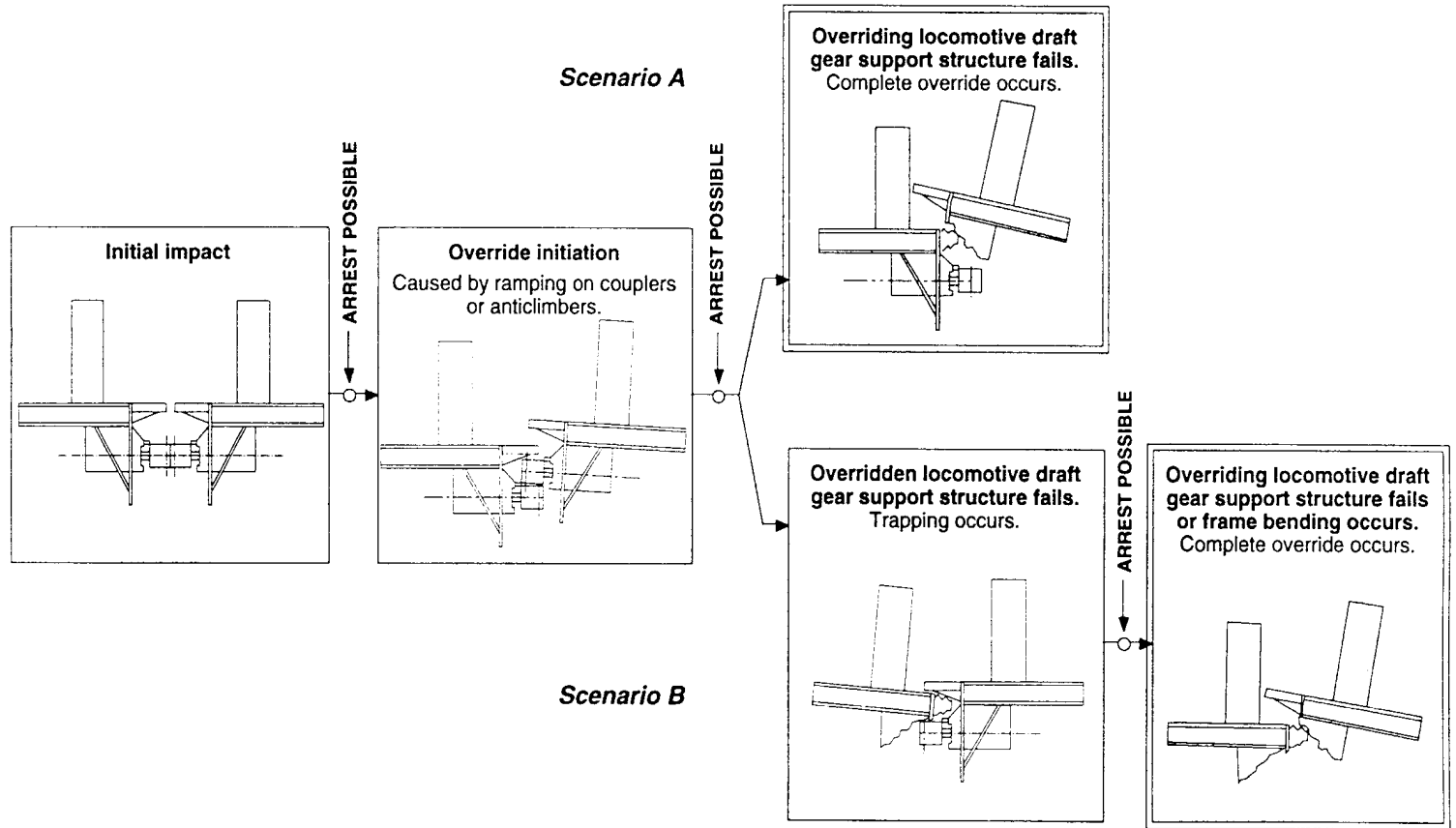Complete override occurs.

Scenario B

Figure 2. Two Potential Head-On Collision Override Scenarios

RESULTS

Table 3 lists the concepts that were finally evaluated, the occupant survivability results, and the estimations of weight and cost increases over that which would be provided on a locomotive that just satisfies S-580. This table should be referred to in reviewing the discussion below.

*The **baseline locomotive**,* which is modeled to just satisfy S-580, is predicted to experience override and a cab crush of 8 ft, which would eliminate the cab survivable volume. We note that this result is little different from that observed in the accident from which the baseline scenario was derived, even though the overridden locomotive in that accident did not satisfy S-580. The reason for this, as described in the section on model validation, is that the anticlimber does not appear to be challenged vertically and appears to be ineffective in preventing total override in head-on collisions at all but the slowest speeds. The critical closing speed, defined here as the closing speed at which survivable cab volume is lost, is predicted to be approximately 30 mph for the baseline configuration studied. The secondary impact measures are also reported for this case for comparison to values to be presented below, even though they are technically not relevant when survivable space is eliminated. Nevertheless, their small magnitude indicates a low probability of injury to the crew if cab crush had not occurred for this crash pulse.

Stronger collision posts appear to provide substantial practical benefit to crashworthiness. Our concept consisted of collision posts whose shape resembles a tapered, wide flange beam. Implementation of posts whose strength is approximately four times that required by S-580 and for which the strength is maintained for significant crush, is predicted to reduce the cab crush to only 1 ft in the baseline crash scenario, thus maintaining substantial survivable volume. The critical closing speed for the baseline configuration is predicted to increase by about 10 mph, to 40 mph, through implementation of this concept alone. In addition, the secondary impact measures, while greater than those in the baseline locomotive, are still relatively low, suggesting a high probability of escaping serious injury.

Our estimates suggest that the design concept collision posts result in no increase in weight over what is required to satisfy S-580. However, a cost increase of about $1,000 per locomotive is estimated to cover a stronger connection to the underframe and higher fabrication costs for what would be a more complicated geometry. We note that current locomotives include collision posts whose strength is two to three times that required by S-580, achieved primarily by using high strength materials.

We note also that there is a collision post strength above which there is no added benefit, since bending of the underframe will eventually become the controlling deformation mechanism. We estimate this value to be between about 1,000,000 and 1,500,000 lbf per post. Finally, a calculation was carried out for a configuration, derived from the baseline case, in which three locomotives collide with a single locomotive at a closing speed of 30 mph. The results showed that reducing the number of locomotives, as could be done with AC motor technology, reduced the cab crush in a locomotive just satisfying S-580 to about 1 ft, i.e., the same crush as with seven locomotives and the implementation of the strong collision post concept.

Table 3. Summary of Crashworthiness Concept Evaluation Results

Concept	Description	Weight Increase*	Cost Increase*	Occupant Survivability Measures	Change in Predicted Survivability
Baseline (S-580)	Collision post strength: 200,000 lbf (each) at 30 inches Anticlimber vert. strength: 200,000 lbf Short hood: 0.5 inch x 25,000 psi yield	-	-	Peak loco accel.: 11 g's Crush: 8 ft HIC: 160 C_R: 20	• Loss of survivable volume • 5% Prob. AIS 2 • 30% Prob. AIS 3
1. Strong Collision Posts	Increase strength from 200,000 lbf/post at 30 inches by four times; ensure strength for significant deformation	0-400 lb	$1,000	Peak loco accel.: 11 g's Crush: 1 ft HIC: 330 C_R: 36	• Survivable volume maint'd • 15% Prob. AIS 2 • 40% Prob. AIS 3
2. Rotating Seat Crash Refuge	Requires locking mechanism and some other protection measure in this list	300 lb	$10-15,000	Peak loco accel.: 11 g's Crush: (Depends on accompanying feature) HIC: 95 C_R: 28	• 3% Prob. AIS 2 • 35% Prob. AIS 3
3. Rotate & Drop Seat Crash Refuge	Requires locking and drop mechanism as well as some other protection measure	600 lb	$15-20,000	Peak loco accel.: 11 g's Crush: (Depends on accompanying feature) HIC: 62 C_R: 21	• 2% Prob. AIS 2 • 30% Prob. AIS 3
4. Trench Crash Refuge	Lever-action drop down floor panel in rear of cab exposes trench	400 lb	$2,000	Peak loco accel.: 11 g's Crush: (Depends on accompanying feature) HIC: 165 C_R: 15	• 5% Prob. AIS 2 • 20% Prob. AIS 3
5. Interlocking Anticlimber	Casting welded to front; replaces and also acts like anticlimber	2,000 lb	$5,000	Peak loco accel.: 15 g's Crush: 0 HIC: 925 C_R: 50	• Survivable volume maint'd • 45% Prob. AIS 2 • 50% Prob. AIS 3
6. Deflection Plates	Angled plates on front of each locomotive derail one or both locomotives	2,000 lb	$5,000	Analysis suggests this feature is not effective	• NA

Table 3. Summary of Crashworthiness Concept Evaluation Results (Cont.)

Concept	Description	Weight Increase*	Cost Increase*	Occupant Survivability Measures	Change in Predicted Survivability
7. Roll Bar	Frame near front of cab	3,000 lb	$10,000	Not calculated	• Not determined
8. Shatterproof Windows	Semitempered glass/polycarbonate with spall shield	Negligible	$1,000	Provides 4-5 times the impact resistance	• Not determined
9. Equipment to Deter Post-Collision Entry of Flammable Liquids	Shatterproof windows; opening (e.g., light) covers; doors that open out	Negligible	Negligible (currently in use)	Provides 4-5 times the impact resistance	

HIC : Head Injury Criterion
C_R: Resultant Chest Acceleration
AIS: Abbreviated Injury Scale (volume 2)

* Compare with typical weight and cost of freight locomotives:

        Locomotive weight: 400,000 lb - 6 axle
                        260,000 lb - 4 axle
       Cost: $1.5 - 2M (per new locomotive)

Notes: • 50% probability of serious injury values
               • Crush: 6 ft
               • HIC: 1090
               • C_R: 46

Three different concepts were evaluated for the ***crash refuge*** feature. Two of these are related, and consist of a seat that would rotate and lock in a position that faces the rear of the locomotive thus allowing the occupant to ride down the collision against the back of the seat. In one of these concepts the seat simply rotates and locks; in the other it rotates, locks and drops to the floor. The third crash refuge concept consists of a trench that opens in the rear of the cab and includes a front facing panel, against which the occupants could ride down the collision.

All three of these concepts are only effective if significant crush of the cab can be prevented, therefore, their evaluation by implementing them without some other feature is not technically meaningful. Nevertheless, the calculated secondary impact measures are reduced substantially for the crash pulse corresponding to the baseline crash scenario. Furthermore, relatively low values of HIC and CR were obtained from calculations in which the rotating seat crash refuge was combined with strong collision posts and the interlocking anticlimber concepts at closing speeds above 50 mph.

The added weight and cost for the crash refuge concepts varies. In general, there is little estimated weight increase, but we estimate that the added cost could be as high as $20,000 for such things as stronger and better cushioned seats and reliable locking and drop mechanisms. Some redesign of the cab would also probably be required to accommodate the extra room needed, particularly for the trench concept.

The concept evaluated for the ***anticlimber*** feature is an interlocking device intended to ensure that substantial crush occurs in the underframe. We considered a design that replaced current anticlimbers with a cast piece of steel that includes protruding tangs, two on one side of the locomotive front, separated vertically by approximately 10 inches, and one on the other side positioned vertically to fit between the two other tangs so that interlocking would occur on impact with an opposing locomotive fitted with a similar device. Variations of this concept can be envisioned, for example, such as the continuous channels used on some mass transit cars. We assumed that the interlocking anticlimber would project in front of the locomotive far enough to: (1) prevent debris from rising up to the cab in a grade crossing collision; and (2) to induce some overlap - but no load - when opposing locomotives were in the full buff position. The width of the anticlimber would also be limited to prevent contact in curves.

The results of the computer evaluation, which were based on the assumptions that locking would definitely occur and that underframe bending is possible, indicate that this concept can also increase the critical closing speed by about 10 mph over that provided by a locomotive just satisfying S-580, in the configuration studied. When the interlocking anticlimber is combined with the strong collision post concept, the critical closing speed is increased by 15 to 20 mph over the baseline case. The calculations also show that the secondary impact measures are increased substantially, for an occupant in the prone position, as a result of having to absorb the large impact forces associated with crushing of the underframe. Thus, for the crash pulse of the baseline crash scenario, there would be a relatively high probability of severe injury without implementation of some type of crash refuge.

Our assessment of the **uniform sill heights** feature is closely related to that of the interlocking anticlimber. Calculations show that more energy is dissipated into the underframes, the more closely aligned are the neutral axes of the colliding underframes. This greater dissipation certainly occurs when the interlocking anticlimber is present, but it also occurs at closing speeds greater than about 40 mph even when override initiation is permitted. However, the maximum benefit to be achieved will be limited by vertical offsets determined by such effects as wheel wear, manufacturing tolerances, and dynamic effects just prior to collision. The 10 mph increase in critical closing speed given earlier is based on a four-inch offset with the interlocking anticlimber and strong collision posts.

A concern with the interlocking anticlimber is the engineering required for the structure to deform in a controlled manner under such high (>6,000,000 lbf), localized loads.

Our estimates for the added weight and cost of the interlocking anticlimber are 2,000 lb and $5,000, although the cost figure may be affected by the engineering and testing required to demonstrate its effectiveness.

The concept evaluated for the **deflection plates** was similar to the interlocking anticlimber except the cast metal pieces are inclined with respect to the axis of the locomotive in an effort to deflect the opposing locomotive to the side. Layout drawings indicated that an angle of about 15 degrees could be accommodated without significantly lengthening the underframe. However, collision dynamics model results showed that with such a small angle, the collision would behave exactly like the previous interlocking anticlimber case; that is, no significant side deflection would result prior to arrest of the collision. In fact, the angle had to be increased to about 45 degrees before substantial side deflection occurred and even in this case, track resistance to lateral movement was not simulated and the crush force was still nearly 6,000,000 lbf. Substantial underframe lengthening would almost certainly be required for such large angles. In light of these results, the concept and feature were considered ineffective and impractical and were not pursued further.

The concept evaluated for the **rollover protection** feature was a single roll bar located at the front of the cab. This feature, as well as the next two to be discussed, could not be evaluated using the collision modeling approach used to evaluate the other concepts because the feature provides no direct additional protection in the baseline crash scenario. Instead, roof and side loads were selected from a consideration of the possible load support and dynamic effects in a rollover event. The roof and side load used, not acting simultaneously, was 200,000 lbf for a 200-ton locomotive. It turns out that a side load applied at the roof line near the front of the cab governs the size of the structural shape section required to prevent substantial crush. We estimate that the added weight and cost associated with this roll bar concept is 3,000 lb and $10,000, respectively. For comparison, we estimate that the side load strength of current cabs is less than 20,000 lbf.

The concept selected for the **shatterproof windows** feature is a semi-tempered glass/polycarbonate laminate with a spall shield. This system appears to possess four to five times the impact and penetration resistance of currently used glass/polyvinyl butyral systems. We estimate that this improved effectiveness comes with little or no weight penalty but with

an additional cost of about $1000 for a locomotive, which includes some modification of the frames to resist the higher impact forces.

The final feature considered was **equipment to deter post-collision entry** *of* **flammable liquids.** The concepts examined for this feature included the glazing and associated framing with improved impact resistance just discussed, the use of inside covers over openings in the short hood and cab such as at lights, and the use of doors that only open outwards. It is our understanding that at least one of the U.S. manufacturers currently applies some of these concepts. No quantitative evaluation was made of these concepts. We estimate the added cost of the glazing and covers to be comparable to that for the glazing just discussed.

SUMMARY NOTES

Our study suggests that it is feasible to provide practical improvement to freight locomotive crashworthiness by making modifications to some of the features listed in the Public Law. In particular, an increase in the strength of the collision posts over that specified in S-580 appears to provide the clearest benefit and, in fact, is currently being used or pursued by various railroads. This increase in strength would need to be accompanied by a demonstration of ductility and strength retention for a significant amount of crush; a specification not currently included in S-580. Implementation of a deliberate crash refuge and use of glazing with higher penetration resistance also appear to be feasible for practically improving crashworthiness. Finally, an interlocking anticlimber combined with closely matching underframe neutral axes (rather than sill heights) provides increased protection against cab crush, particularly when used with the stronger collision post concept.

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