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An Overview of Passenger Equipment Fullscale Impact Tests: Results to Date

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1 Abstract

As part of the Federal Railroad Administration's Equipment Safety Research Program, a series of full-scale impact tests are being conducted on rail passenger vehicles. Three tests are intended to define the performance of current-design equipment in in-line collisions:

1. A single car impact with a fixed wall
2. A two coupled car impact with a fixed wall, and
3. A moving cab car led train impact with a standing locomotive-led train.

These tests are designed to first measure the crashworthiness of a single car, then the interactions of two cars when coupled, and finally the behavior of a complete train, including the interactions of the colliding cars. As part of these tests, interior configurations with forward facing unrestrained, forward facing restrained, and rear facing unrestrained test dummies are being used to measure potential occupant dynamics during a train collision. The first two tests have already been conducted. The third test is planned for the fall of 2001. Similar tests are currently being planned for crash energy management equipment. The crash energy management equipment is expected to perform significantly better in these tests than the conventional equipment.

While the principal objective of these tests is to determine effective strategies for improved structural crashworthiness and improved occupant protection, a secondary objective is to validate and improve the computer models that have been developed as part of the rail vehicle crashworthiness research. Results from the tests conducted to date show that the force reaches a high initial peak, and then decreases as the car crushes. The consequence of this decreasing force/crush characteristic is that the structural damage will be focused on the impacting cars in a collision, with very little damage to the trailing cars. Results from the occupant experiments show that the collision environment experienced by the occupants is different than assumed in early analyses. Earlier analyses and sled tests have assumed that the principal car motions influencing the occupants occurred longitudinally, and that the vertical and lateral car motions could be neglected. The vertical accelerations of the cars during the two-car test resulted in the heads of the test dummies rising over the seatbacks, and consequent high loads on the necks of the dummies. Such motions and loads were not been observed in previous sled testing.

2 Introduction

The Federal Railroad Administration (FRA) conducts research on rail equipment, track, and operation safety. Research areas include collision avoidance measures such as positive train control and strategies for minimizing operator fatigue, as well as equipment crashworthiness [1]. Keeping the trains separated is the first line of defense in assuring passenger and operator safety, while equipment crashworthiness is the last line of defense. The information from this research has been used to develop federal safety regulations for passenger equipment, which address emergency preparedness, fire safety, software safety, brakes, vehicle dynamic performance, and equipment crashworthiness [2].

In designing for crashworthiness, the first objective is to preserve a sufficient occupant volume for the occupants to ride out the collision without being crushed. Even when sufficient volume is preserved for the occupant to ride out the collision, excessive force or deceleration can still injure the occupant. These forces and decelerations principally occur, for an unrestrained occupant, when the occupant strikes the interior. (Occupant impacts with the interior or collisions between occupants and loose objects thrown about during the collision are usually termed secondary collisions; the primary collision being the collision between the two trains.) The second objective of crashworthiness is to limit the forces and decelerations imparted to the occupants to acceptable levels of human tolerance.

The overall objective of the rail equipment crashworthiness research conducted by the FRA is to develop design strategies with improved crashworthiness over existing designs. The approach taken in conducting this research has been to review relevant accidents, identify options for design modifications to improve occupant survivability, and to apply analytic tools and testing techniques for evaluating the effectiveness of these strategies.

As part of this research, computer models have been developed and applied to determine the response of rail equipment in a range of collision scenarios [3, 4, 5, 6, 7, 8]. In-line and oblique train-to-train collisions, as well as grade crossing collisions and rollover events subsequent to derailment have been modeled. The responses of locomotives, cab cars, and coach cars in a range of collision scenarios have been simulated.

To assess the validity of the models, results of these analyses have been compared with accident data, and component test results [9]. While providing useful information and some assurance of the validity of the models, accident data and component and subscale testing all have limitations. There is uncertainty about the initial conditions of any accident — the speeds and locations of the two colliding objects are never precisely known. The support and loading conditions in component tests can only approximate the actual conditions these components experience during a collision. Full-scale impact tests are necessary in order to know precisely the initial conditions and to provide the appropriate support conditions for the structures that crush during the impact.

3 Rail Passenger Train Accidents

The overall goal of the rail equipment crashworthiness research is to develop design strategies with improved crashworthiness over the strategies employed in existing designs. The accidents identify the conditions that, if possible, are to be survived. Some accidents happen under extreme circumstances – for instance at great speed -- that it is a practical impossibility to survive such collisions.

Of particular concern are collisions involving cab cars as one or both of the impacting cars. In comparison to locomotives, cab cars are exposed to more risk in collisions. The presence of passengers, the cab car being lighter weight and weaker strength than the locomotive, and the cab operator being placed at the extreme end of the car, with essentially no structure ahead of him or her, render the car vulnerable. Cab cars are used in all commuter operations in the US, either in push-pull operation with a locomotive pushing or in multiple-unit operation, where most of the cars are self-powered.

The consequences for the cab car and its occupant can be especially sever if a cab car led train collides with a locomotive-led train. One such accident occurred on August 11, 1981, when the cab car of a commuter train struck the locomotive of a freight train [10]. Figure 1 shows the colliding cab car and locomotive shortly after the accident. The passenger train was traveling at approximately 58 km/h (36 mph), and the freight train was traveling at approximately 19 km/h (12 mph). There were four fatalities and three serious injuries. During the collision, the cab car overrode the locomotive, resulting in substantial underframe damage to the cab car. The portion of the cab car frame ahead of the truck was essentially peeled away from the cab car. The locomotive was long hood forward, and the sheet metal of the long hood was removed in the collision. The engine and generator on the locomotive remained essentially intact.

Figure 1. Post-accident photograph, lead cab cab and lead locomotive, Beverly, Massachusetts collision.

Other accidents in which a cab car-led train collided with a locomotive-led train include a collision in Secaucus, New Jersey on February 9, 1996 [11], where the trains collided obliquely at a switch and a collision in Silver Spring, Maryland on February 16, 1996 [12], where the trains collided again at a switch, but nearly head-on. There were three fatalities and twelve serious injuries in the Secaucus accident, and eleven fatalities and twenty-six injuries in the Silver Spring accident. In both accidents there was substantial structural damage to the cab cars.

4 Crashworthiness Strategies

Conventional practice is oriented toward making the individual cars as strong as they can be made, within weight and other design constraints. This approach attempts to control the behavior of individual cars during the collision. The crash energy management (CEM) approach is train oriented, apportioning the structural crushing throughout the train to the unoccupied areas in order to preserve the occupant volumes and to limit the decelerations of the cars. This approach attempts to control the behavior of the entire train during the collision.

4.1 Conventional Approach

Figure 2 shows a schematic illustration of the principal structural members of a conventional single-level passenger rail car. The principal crashworthiness requirement for North American rail passenger equipment since the 1940's has been the 3.56 MN (800 kip) buff load requirement [13]. The buff load requirement is intended to assure a minimum strength of the occupied volume of the car.

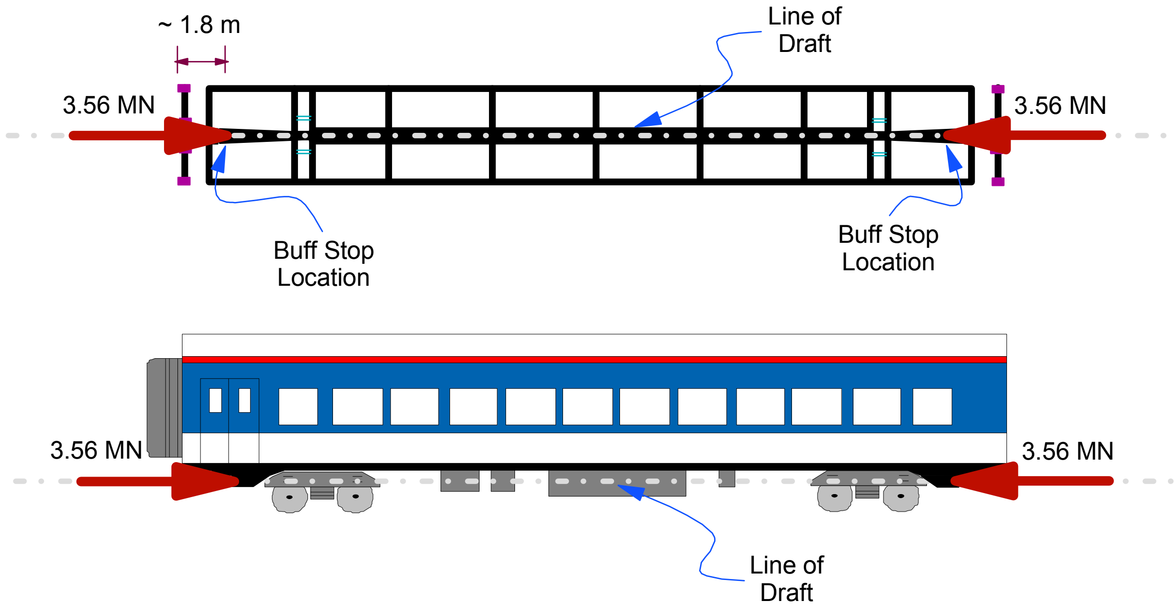

Figure 2. Schematic Illustration of conventional passenger rail car.

For most cars, applying the load along the line of draft results in the floor being in compression and the roof being in tension. During a collision, the longitudinal load is likely to be applied to the structure above the line of draft, putting the structure below the floor and in the roof into compression. The load required to initiate crushing of the car structure is significantly greater than the static buff strength requirement, in part owing to this difference in load application.

4.2 Crash Energy Management Approach

The CEM approach employs crush zones at the ends of the cars which are designed to collapse in a controlled fashion during a collision, consequently distributing the crush among the cars of the train [14, 15, 16, 17]. Figure 3 shows the location of the crush zones at the ends of each of the cars of the train.

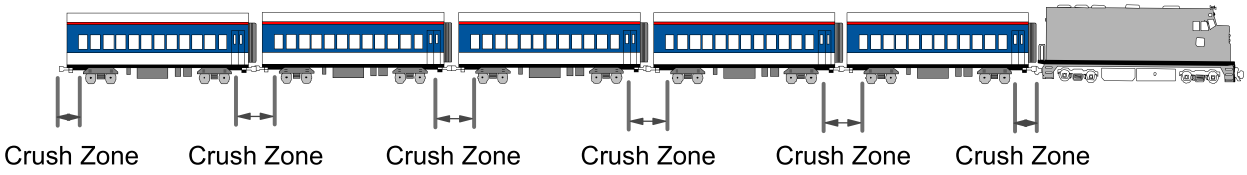

Figure 3. Schematic Illustration of cush zone locations in rail passenger train used in push/pull service.

5 Evaluation of Crashworthiness Strategies

Evaluation techniques – both numerical simulation and destructive testing techniques – are available for evaluating:

1. the behavior of the entire train during a collision,
2. the crush of the cars under prescribed loading conditions, and
3. the response of occupants inside the train.

These evaluation techniques are illustrated in Figure 4.

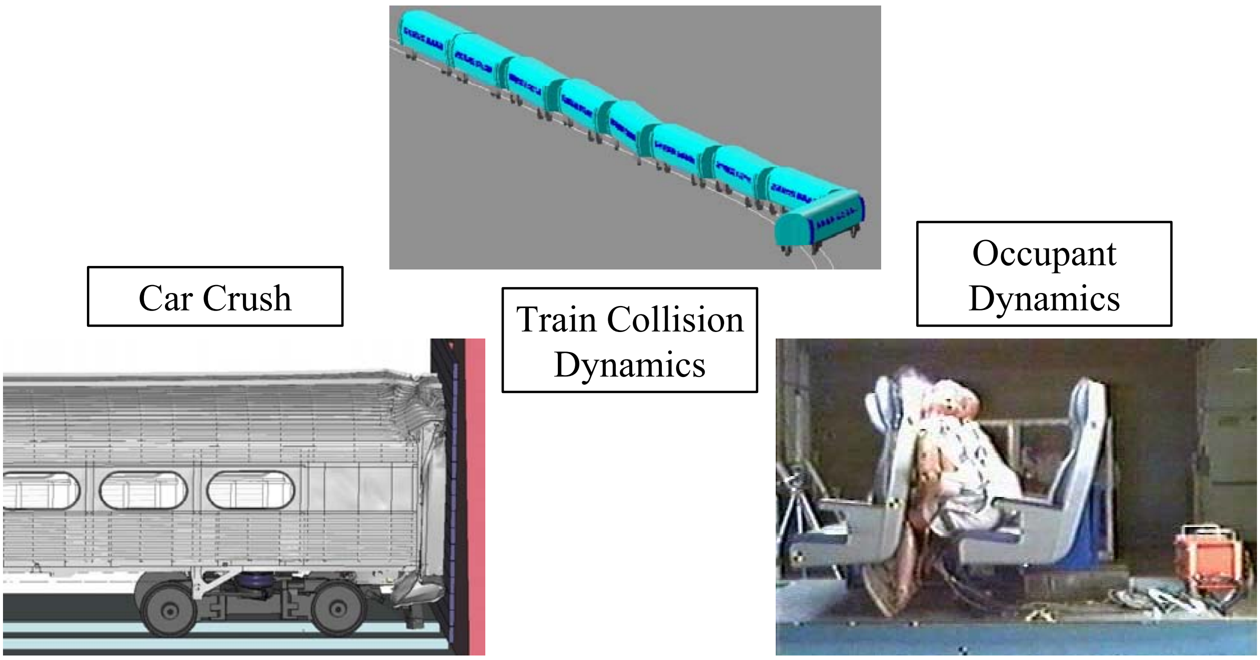

Figure 4. Illustrations of crashworthiness evaluation techniques.

The principal objectives of the train collision dynamics evaluation are to determine the distribution of the crush among the cars in the train, and to determine the trajectories of the cars during the collision, including the decelerations of the occupied areas. The principal objectives of the car crush evaluation are to determine the load required to crush the car (i.e., the force/crush characteristic) and the mode crush, i.e., the changing geometry of the structure as it crushes. The principal objective of the evaluation of the occupant response is to determine if the forces and decelerations imparted to the occupants remain within survivable levels.

5.1 In-Line Fullscale Impact Testing

The conditions for the in-line fullscale impact tests are schematically illustrated in Figure 5. The first three tests define the crashworthiness of conventional equipment [18]. The performance of CEM equipment is to be measured in three additional tests that are similar to the tests of conventional equipment. This arrangement tests allows comparison of the conventional equipment performance with the performance of improved-crashworthiness equipment. These tests are intended to measure the crashworthiness of a single car, the interactions of two such cars when coupled, and finally the behavior of complete trains, including the interactions of the colliding cars.

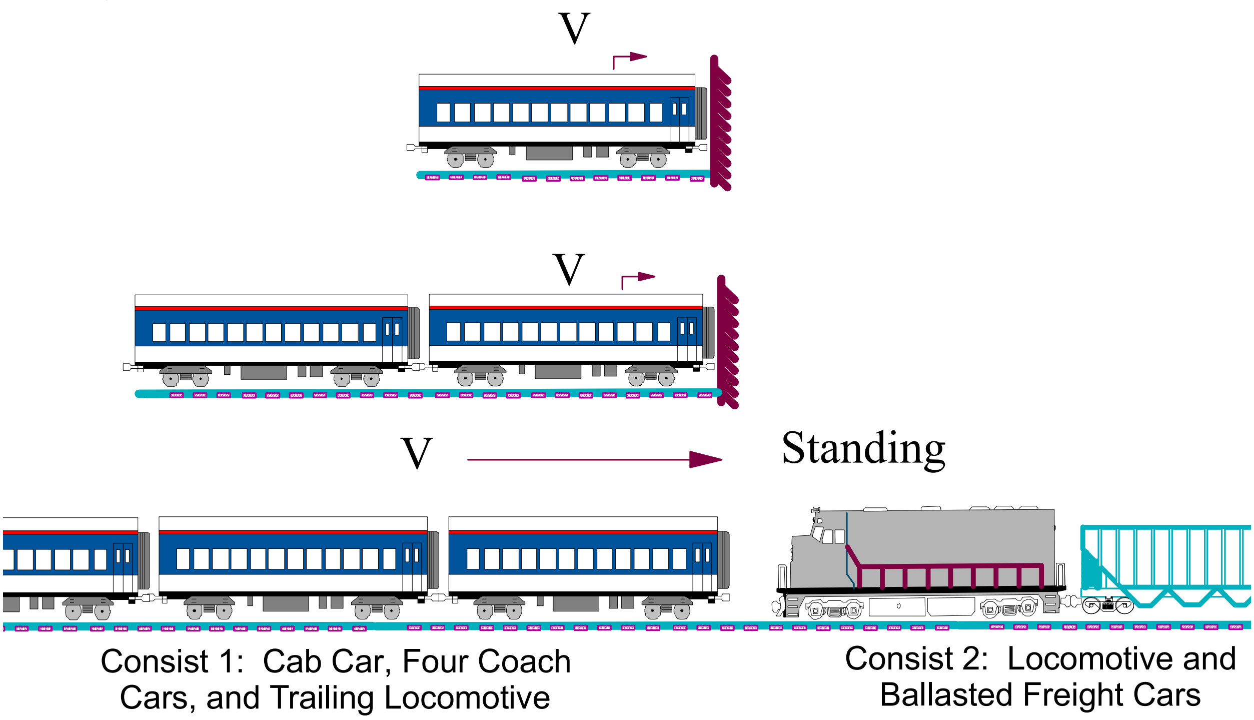

Figure 5. Schematic illustrations of single-car, two-car, and train-to-train impact tests.

Figure 6 shows schematic illustrations of the passenger protection strategies tested in the single-car and two-car tests [18]. All three strategies were included in the single-car test and in the leading car in the two-car test. The trailing car in the two-car test also included the forward facing unrestrained occupant protection strategy. It is currently planned that all three passenger protection strategies will be part of the train-to-train test. The principal objective of these occupant protection experiments is to measure the responses of instrumented dummies in several interior configurations.

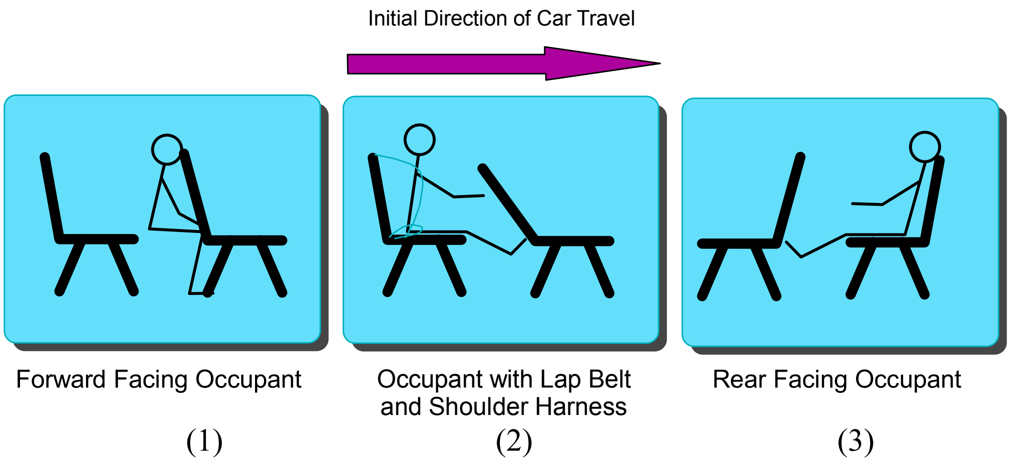

Figure 6. Schematics of passenger protection strategies tested during impact tests.

Figure 7 shows a schematic illustration of the locomotive operator's interior environment to be included in the train-to-train test. The objectives of this experiment are to observe the kinematics of the test dummy and to measure the test dummy response.

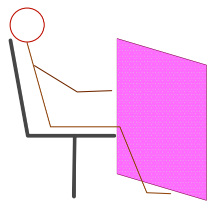

Figure 7. Schematic of locomotive operator interior test.

Table 1 summarizes the critical measurements for each of the three tests. While the overall objective of these tests is to demonstrate the effectiveness of CEM equipment, the test data are also being used for comparison with analyses and modeling results.

Table 1. Test Descriptions and Critical Measurements

Test Description	Critical Measurement
Single-Car Dynamic Crush Test	- Dynamic crush force - Loss of occupant volume - Occupant volume deceleration, - Effectiveness of compartmentalization, rear-facing seats, and seats with lap and shoulder belts
Test of Two Coupled Cars	- 'Sawtooth' lateral buckling of coupled cars, - Influence of trailing car on maximum occupant volume deceleration, - Effectiveness of compartmentalization, rear-facing seats, and seats with lap and shoulder belts
Train Test	- Lateral buckling of coupled cars, - Override of colliding cars - Effectiveness of compartmentalization, rear-facing seats, and seats with lap and shoulder belts - Measurement of operator secondary collision environment

The measurements will be used to refine these analyses approaches and models, and to assure that the factors influencing the response of the equipment and test dummies are taken into account. The table lists the measurements that are critical to assuring the appropriate modeling and analysis of the equipment and test dummies.

6 Results to Date

To date, the single car test and the two-car test have been conducted for conventional equipment. The train-to-train test of conventional equipment is planned for the autumn of 2001. Analysis of car crush from the single-car test of conventional equipment is nearly complete, while train collision dynamics analysis of the two-car test is continuing. Occupant protection analysis of the data from these tests is ongoing.

6.1 Car Crush

Figure 8 shows the force/crush characteristics developed from measurements made during impact tests of a single passenger car and of two coupled passenger cars into a fixed barrier [19, 20]. Both of these curves have high initial peak loads followed by significantly lower loads, which are approximately constant, for continued crush.

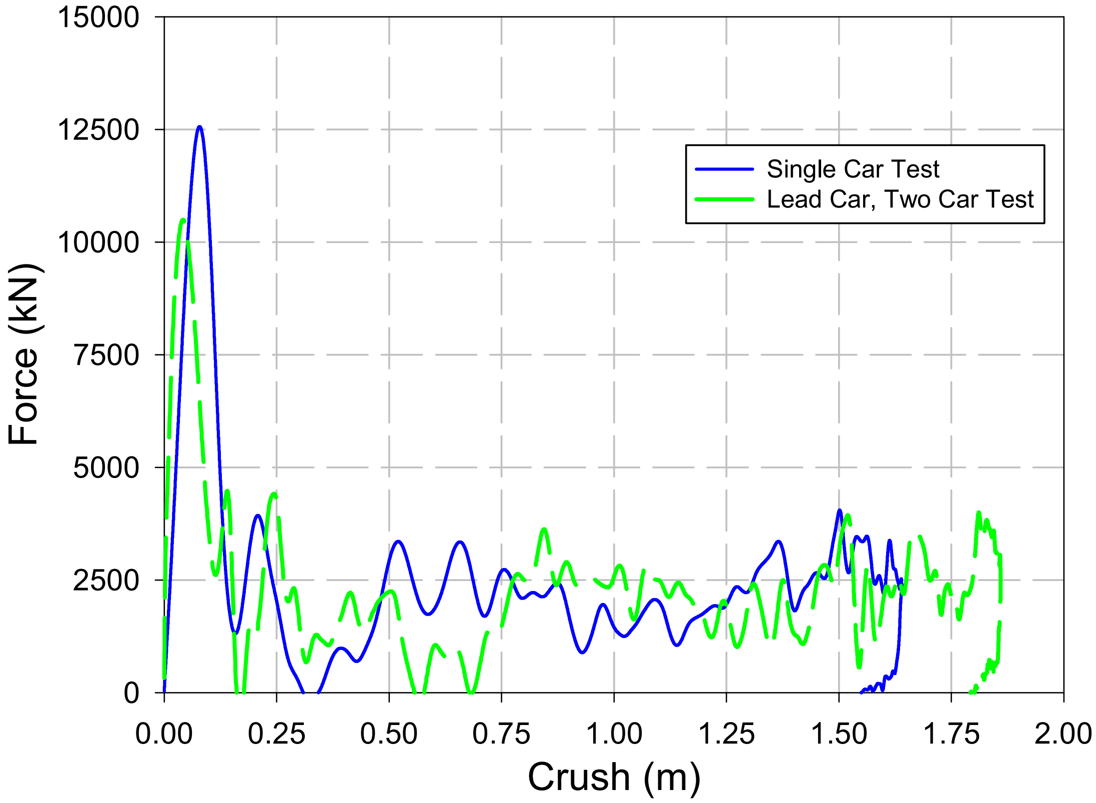

Figure 8. Force/crush curves, typical U.S. passenger equipment.

One implication of the force/crush characteristic shown in Figure 8 is that the crush will be focused on the colliding cars. Once the impacting car has crushed by 100 mm (4 inches), the most force it can exert is significantly less than the peak force, while any cars behind can apply up to the peak force. The shape of this characteristic is why, in the test of two coupled cars impacting with a fixed barrier, the lead car sustained significant structural damage while the front end of the trailing car sustained only minor scarring due to the direct contact with the trailing end of the lead car.

Figure 9 shows frames of the high-speed film taken during the single car test [19, 21, 22]. In addition to the high-speed film frames, the figure also shows three frames taken from an animation of the post-test analysis. The model developed in this effort closely agrees with the measurements for the force/crush behavior the cab car, the mode of structural deformation, and the cab car gross motions.

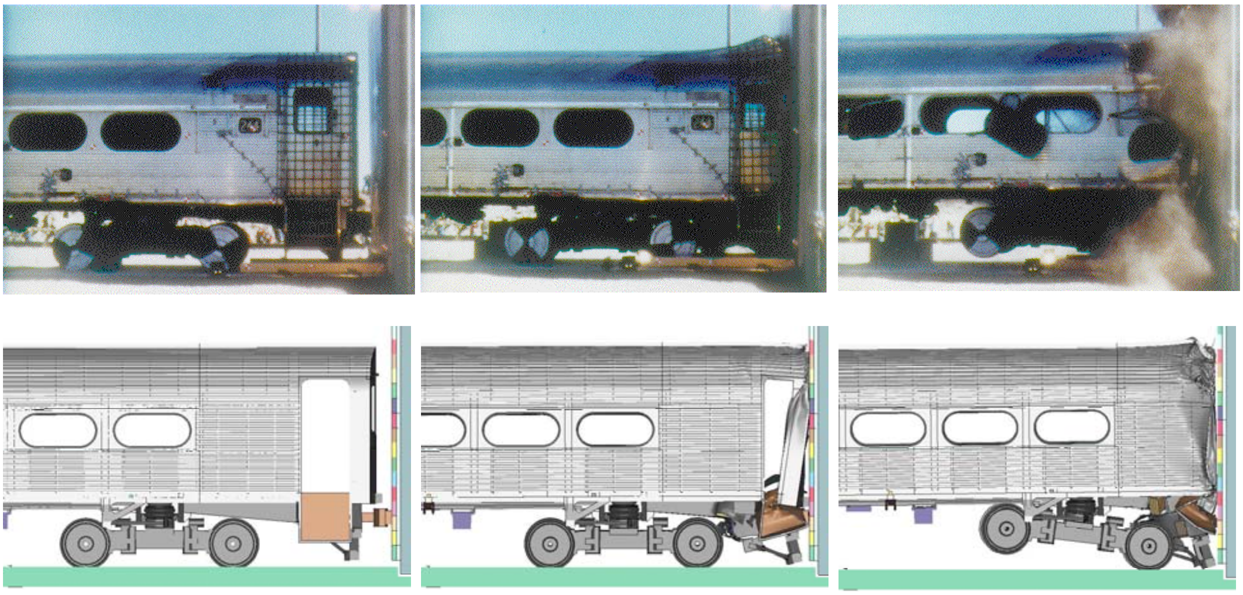

Figure 9. Car crush, single-car test and post-test analysis.

6.2 Train Collision Dynamics

During the two-car test, the cars remained coupled, but buckled in a saw-tooth mode. This buckling is due to the linkage behavior of the couplers used on North American passenger equipment. These couplers form a rigid link between cars; when there is a high longitudinal load present, with only a small perturbation, the link formed by the couplers pushes laterally on the ends of the cars. As a result, the ends of the cars are laterally offset from each other when they contact. The maximum lateral displacement between the cars during the collision was approximately 762 mm (30 inches). The final lateral displacement was 381 mm (15 inches). The left track buckled under the lateral load from the front truck of the trailing car, allowing the right wheels of the front truck of the trailing car to drop. Figure 10 shows the coupled connection between the two cars at their final lateral displacement.

Once the cars are misaligned, the high longitudinal force acting on one car exerts a significant lateral component on an adjacent car. Consequently, the train will continue to buckle out into a relatively large amplitude zig-zag pattern if there is sufficient energy from the collision. Depending on the severity, this mode may progress until the cars have side-to-side impacts. The results of this behavior have been observed in accidents [23, 24, 25]. The progression of the cars from in-line, to the sawtooth lateral buckling pattern, then to the zigzag pattern has been simulated [26] with computational models. The progression from in-line to sawtooth buckling was observed and measured in detail during the two-car test [20].

Figure 10. Photograph of coupled connection after two-car test.

6.3 Occupant Protection

The occupant environment during a collision is defined by the interior configuration, its associated engineering details, and the deceleration imparted to that configuration. During an in-line train collision, the greatest decelerations are longitudinal. However, significant lateral and vertical accelerations that influence the motions of the occupants can arise.

Figure 11 shows a response during the two-car test for a test dummy initially in a forward-facing seat, without any restraints [27]. In this particular experiment, the test dummy's face impacted the upper seat back, followed by the head going over the top of the seat. Upon returning to its seated position, the chin caught on the top of the seat back. The middle photograph in Figure 11 shows all three of the dummies' heads above the top of the seatbacks.

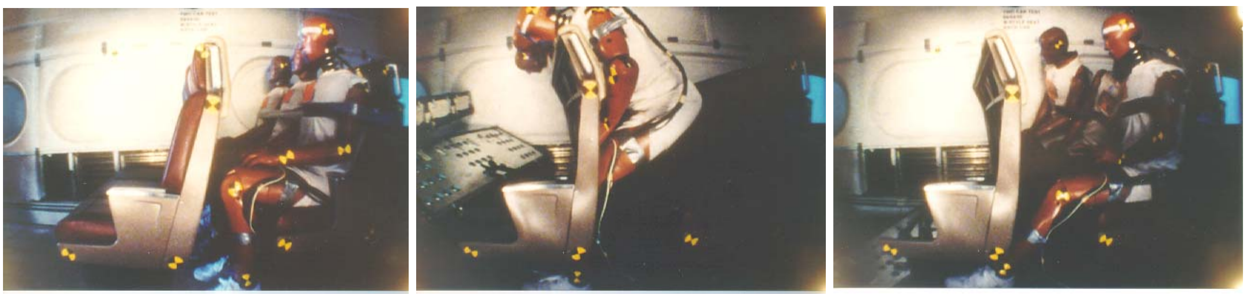

Figure 11. Time-sequence for forward facing rows of seats, trailing car, two car test.

In previous sled testing of the same model seat, lack of vertical motion led to the dummies' heads impacting the seatback near the top. The downward vertical motion of the car in the fullscale test apparently influenced the dummies heads' to rise above the seatback. The forces and decelerations were within survivable limits in the sled testing, while the neck loads exceeded the limits used by the US automotive industry in the two-car fullscale test.

7 Expected Overall Results of Train-to-Train Tests

Figure 12 shows preliminary estimates for the train-to-train tests of conventional equipment, with the impact occurring at 40 km/h (25 mph). The results were obtained with a one-dimensional multi-degree of freedom train collision dynamics model. For conventional equipment, the crush is expected to be focused on the cab car. Consequently, there is substantial loss of occupant volume. In this analysis, the operator's cab and four rows of passenger seats are crushed. Since there is a strong potential for the either the cab car to override the locomotive or vice versa, efforts are ongoing to analyze the test with three-dimensional models.

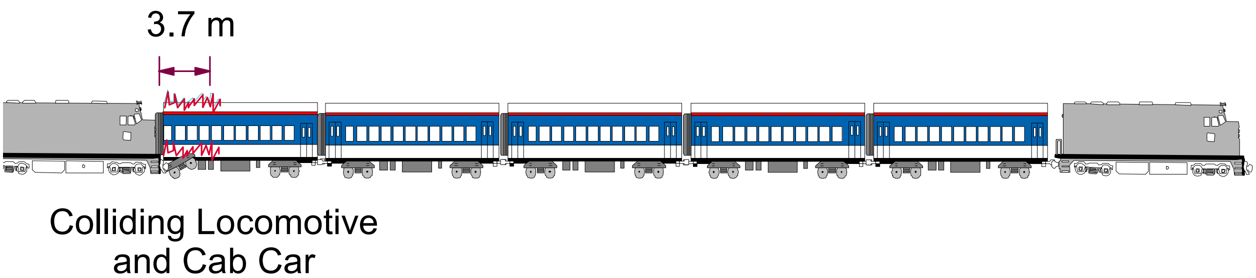

Figure 12. Expected results for conventional equipment in train-to-train test.

Figure 13 shows preliminary estimates for the train-to-train tests of CEM equipment, with the impact occurring at 40 km/h (25 mph). For the CEM equipment, there is no loss of occupant volume for the passengers. There is potentially loss of volume for the operator. However means of protecting the operator, such as an operator's cage that gets pushed back into a utility closet in the event of a collision, are being investigated.

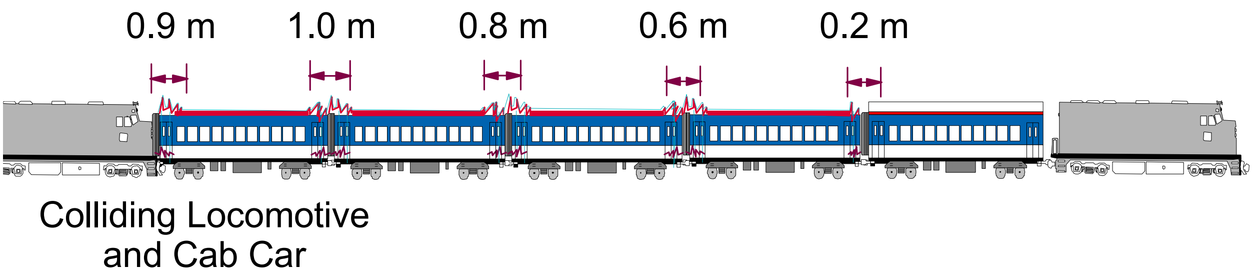

Figure 13. Expected results for CEM equipment in train-to-train test.

The occupant environment during the train-to-train test of the CEM equipment is expected to have slightly higher longitudinal accelerations, but lower vertical and lateral accelerations than during the train-to-train test of the conventional equipment. Overall, the occupant environments in the two test should be approximately equivalent, in terms of the likelihood of occupant injury.

8 Future Plans

Preliminary analyses of the single-car test and two-car test structural and occupant protection measurements have been completed. The structural measurements are currently being used to refine simulation models. The occupant protection measurements are being used to evaluate the influence of the vertical and lateral accelerations on occupant response, by comparing them with previous sled test measurements. Efforts are continuing to finalize the requirements and implementation of the train-to-train test of conventional equipment.

Preparations are also underway for testing crash energy management design equipment. For the two-car test of crash energy management equipment it is anticipated that the car crush will be distributed among the leading and trailing ends of the leading car and the leading end of the trailing car. As a result, there should be no intrusion into the occupant volume. In the two-car test of the conventional equipment, the crush was focused on the leading end of the leading car, resulting in loss of occupant volume for the first row of passenger seats [16].

Plans for fullscale tests based on a grade-crossing collision with a heavy rigid object are also being implemented. These tests are intended to evaluate the structure above the floor of the cab car. Two such tests are currently planned, one of a conventional cab car and another of a cab car with the end structure vertical elements – the corner posts and collision posts -- tightly tied together with transverse elements. These tests are planned for the autumn of 2001.

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