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Passenger Rail Equipment Research in the U.S.

1 Introduction

In 1989 the Federal Railroad Administration (FRA) initiated a program of research into the safety aspects of high-speed passenger train systems. Collision safety – the balancing of collision avoidance measures of the system with the crashworthiness features of the train – was part of this program of research.

This program was initiated in response to growing interest in high-speed passenger rail. In the late 1980's high-speed passenger train service, with train speeds up to 320 kph (200 mph), was proposed (and subsequently cancelled) for Florida and Texas on a triangular route with San Antonio, Houston, and Dallas/Fort Worth at the corners. In the early 1990's Amtrak demonstrated the German ICE and Swedish X200 in the Northeast Corridor.

One of the first results of this research was a risk-based approach for assessing collision safety [1]. This approach was used in the development of the crashworthiness specifications for Amtrak's high-speed trainset, which is now in service in the Northeast Corridor. Additional studies of alternative crashworthiness approaches and occupant protection measures were also carried out to support the development of the high-speed trainset crashworthiness specifications [2, 3, 4].

The scope of the crashworthiness research was later broadened to include inter-city and commuter rail passenger trains operated at speeds less than 200 kph (125 mph). In 1996, a Rail Equipment Crashworthiness Symposium was held at the Volpe Center, with sessions on collision risk, structural crashworthiness, and occupant protection. Researchers from England and France made presentations, as did researchers from the U.S. [5]. This Symposium was held to support the development of the FRA passenger equipment safety standards. A number of other studies on occupant protection [6] and structural crashworthiness [7] were also carried out in support of this rulemaking effort.

The results of the FRA's research on rail equipment crashworthiness were made available to the American Public Transportation Association (APTA) for development of its Manual of Standards and Recommended Practices, by allowing ex officio representation of the FRA and Volpe Center on APTA Passenger Rail Equipment Safety Standard (PRESS) Construction/Structural Subcommittee and by conducting several studies requested by APTA, including cost/benefit analysis of alternative structural crashworthiness strategies and sled tests of commuter rail passenger seats.

Research studies on passenger equipment crashworthiness are being carried out to develop the base of information required for the next phase of rulemaking. Ongoing research into rail equipment crashworthiness ranges from field investigations of the causes of occupant injury and fatality in train accidents, to full-scale testing of existing and modified designs under conditions intended to approximate accident conditions [8, 9, 10, 11, 12, 13, 14, 15], to investigations of the fundamental mechanics of structural crush.

2 Research Areas

The overall objective of the passenger rail equipment crashworthiness research is to develop incremental improvements in the crashworthiness of passenger rail equipment. The approach taken in this research is:

1. Develop collision scenarios of concern
2. Evaluate the effectiveness of current-design equipment in the collision scenarios of concern
3. Propose and evaluate alternative approaches to crashworthiness
4. Compare the effectiveness of current equipment and alternatives
5. Recommend effective alternatives.

Areas of research include collision risk, the crush behavior of individual cars, the collision dynamics behavior of trains, and the dynamic response of occupants during collisions and derailments. The collision scenarios of concern are developed using risk analyses. The effectiveness of current design equipment is evaluated using accident information, analytic models, and test data. Alternatives are proposed for structural crashworthiness and for occupant protection. Alternatives include modifying existing designs –e.g., strengthening selected members – to development of 'clean sheet' designs. Alternative designs are evaluated using analytic models and testing. Comparisons are made in terms of fatality and the likelihood of injury.

2.1 Collision Risk

Risk analyses are performed in order to determine the collision scenarios of concern, as well as to help determine which crashworthiness alternatives are cost-effective. Figure 1 shows a general schematic for such risk analyses. There are two principal components to such risk analyses: the evaluation of the likelihood of collision and the evaluation of the consequences of collision. The likelihood of collision is determined from failure modes and effects analysis and the analysis of accident data. The results of such analyses are the collision scenarios of concern for a particular train operation. The information required to perform such an analysis include the traffic density, number of switches, the details of the signal system, the route, and any other information that may influence the possibility of a collision. The consequences of collision are determined from accident data and from simulation models of train collisions. Accident consequences include fatalities due to loss of occupant volume, and fatalities and injuries due to occupant impacts with the interior. The information required to develop the consequences include the structural details of the equipment, and layout and structural details of the interior.

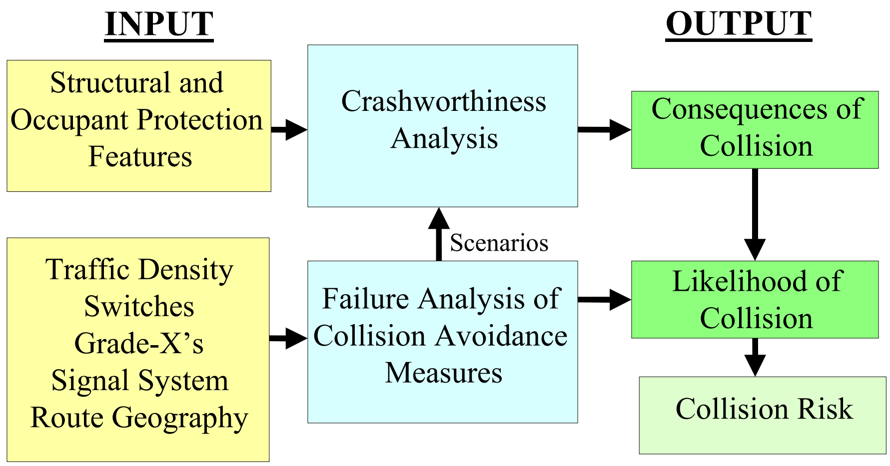

Figure 1. Schematic of Collision Risk Analysis.

2.2 Crashworthiness Strategies

Structural crashworthiness strategies ranging from strengthening vertical end structure members on cab cars to shear-back couplers with crush-zones have been considered. Figure 2 shows the distribution of crush among the cars for a conventional design train and a crash-energy management design train in a train-to-train collision at 25 mph. Crash energy management is expected to have significant benefits..

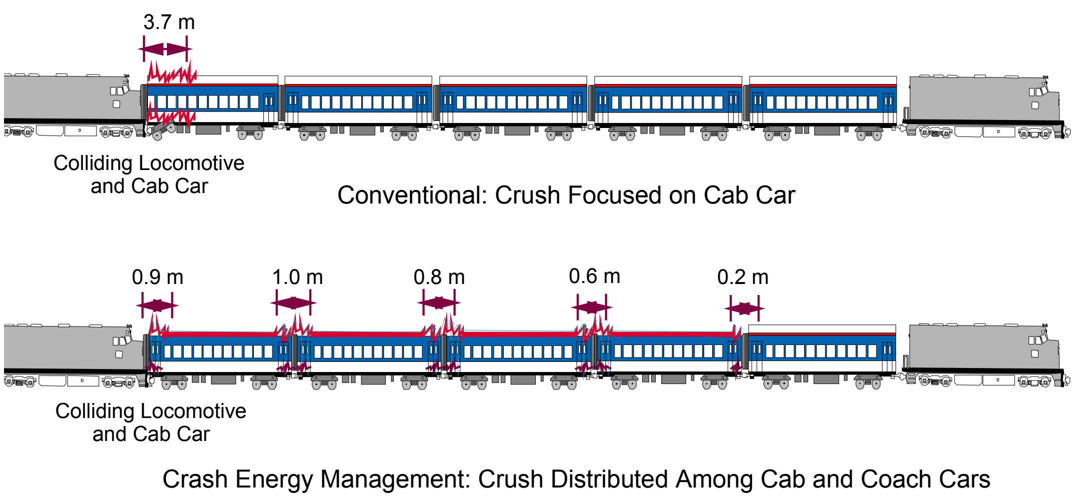

Figure 2. Comparison of the Crush of Alternative Crashworthiness Approaches in a Train-toTrain Collision.

Occupant protection strategies ranging from compartmentalization to lap and shoulder belts have been considered. Compartmentalization is a strategy for providing occupant protection during a collision. The principal objectives of this strategy are to limit the occupant's range of motion and to assure that the interior surfaces are sufficiently soft to limit injury during occupant impact. This strategy requires relatively little modification to existing seat designs. Development has been required to implement Lap and shoulder belts, as the loads associated with the shoulder belt must be supported through the seatback. Figure 3 shows an intercity passenger seat incorporating lap and shoulder belts that was tested during recent full-scale testing. A three-position commuter rail passenger seat incorporating lap and shoulder belts has recently been developed.

Figure 3. Inter-city passenger seat incorporating lap and shoulder belts.

2.3 Analysis and Test Techniques

Evaluation techniques – both numerical simulation and destructive testing techniques – are available for evaluating car crush under prescribed conditions, behavior of the entire train during a collision, and the response of occupants inside the train. These evaluation techniques are illustrated in Figure 4. 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 of crush (i.e., the changing geometry of the structure as it crushes.) 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 objective of the evaluation of the occupant response is to determine if the forces and decelerations imparted to the occupants remain within survivable levels.

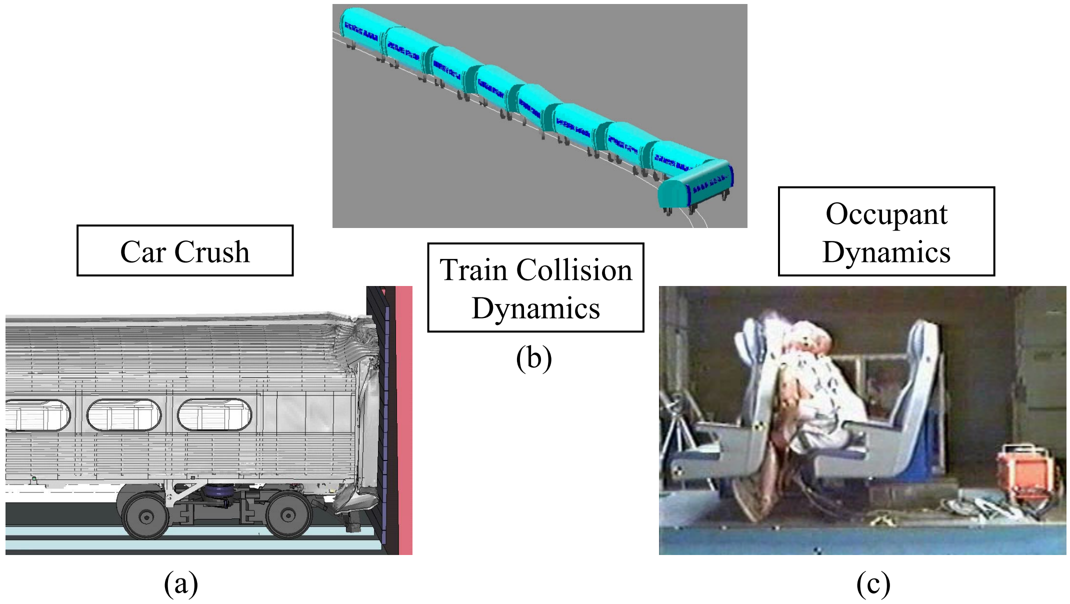

Figure 4. Rail Equipment Collision Evaluation Techniques.

Car crush can be analyzed using closed-form limit-load analysis for relatively simple geometries and loading conditions; more complex geometries and loading conditions require detailed elastic-plastic large-deformation finite element analysis [16, 17]. Car crush can be destructively tested either in full-scale or subscale using substructure components as test specimens [18], or entire cars [8, 11, 13, 14]. If subscale or substructure testing is done, analyses can be used to extend the test results to full-scale or the entire structure. Figure 4(a) shows a detailed finite element analysis of a passenger car impacting a fixed barrier. The principal results of the car crush evaluation – the force crush characteristic and the mode of crush -- are used to develop the train collision dynamics analysis.

Train collision dynamics can be analyzed using lump-mass parameter models, with non-linear force characteristics developed from crush analysis of the cars [3, 4, 11, 13, 19, 20]. Such models may be one-dimensional, planar, or three-dimensional, depending upon the details of the equipment and collision condition being analyzed. Analyses based on conservation of momenta and conservation of energy can also provide useful information on the trajectories and crush of the equipment during a collision. Train collision dynamics can also be evaluated in full-scale [11, 13, 14] and subscale [21] tests. Figure 4(b) shows a three-dimensional lumped-parameter model of a passenger train impacting a fixed barrier. The barrier has been removed from the figure to show the behavior of the train. Results of train collision dynamics evaluations include loss of occupant volume, which can be used to estimate the number of fatalities. Results also include decelerations of the occupant volumes, which are used in test and analysis of occupant dynamics.

Occupant dynamics can be evaluated using lumped-parameter models, with non-linear characteristics to represent the behavior of human joints under impact conditions [2]. A relatively simple one-dimensional model can also be used to evaluate the potential for head injury due to impact with a compliant surface [4]. Dynamic sled tests of interior configurations, with instrumented test dummies to measure the forces and decelerations that would be imparted to occupants can also be used to evaluate occupant dynamics [6]. Interior configurations with test dummies can also be used as part of the full-scale tests of rail cars and trains [9, 10, 12, 15]. Figure 4(c) shows a photograph from a sled test of rows of commuter passenger seats. Results of occupant dynamics evaluations include the forces and decelerations that would be experienced by occupants under the conditions analyzed or tested. The likelihood of injury and fatality can be estimated from the forces and decelerations experienced by the occupants [3, 4].

3 Ongoing Research

Ongoing studies range from a field study of occupant injury in train collisions, to studies of material behavior under impact conditions, to development of a three-position passenger seat design incorporating lap and shoulder belts, to development of crush zone design for passenger coaches and cab car, to full-scale impact testing of equipment. The field study and the full-scale testing are being used to provide as complete a picture as possible on how casualties occur in train collisions.

3.1 Field Study of Occupant Injury

The FRA, with the cooperation of the National Transportation Safety Board, is conducting a study of occupant injury during train collisions. The objectives of this study are to determine:

1. The range of severity of the injuries that occur in train collisions and derailments,
2. the types of injuries that occur,
3. where these injuries occur on the train, and
4. the causal mechanisms for these injuries.

The results of this study will be used to focus the research efforts on occupant protection and to provide information for benefit/cost analyses of potential occupant protection measures, such as lap and shoulder belts for seated occupants.

As part of the study, detailed observations are made of the train interior locations where injuries occurred, and interviews are conducted with the survivors and medical personnel treating the survivors. Observation of the train interior, with its associated forensic evidence, allows development of the causal mechanisms for casualties.

Three accidents have been investigated as part of this study:

1. A derailment in Lake City, North Carolina on August 21, 2000
2. A passenger train collision with a freight train in Syracuse, New York on February 5, 2001
3. A passenger train derailment in Nodaway, Iowa on March 17, 2001

It is currently planned that three more accidents will be investigated in such detail.

3.2 Full-scale Testing

Two series of fullscale test are planned, one based on a head-on collision scenario, in which a cab car-led train collides with a locomotive-led train, and the second based on a grade-crossing collision scenario, in which a cab car-led train collides with a tractor trailer carrying a coil of sheet steel. The conditions and the sequence of the tests are listed in Table 1.

Table 1. Planned Sequence of Full-scale Passenger-Equipment Impact Tests.

Test Conditions	Conventional-Design Equipment	Improved-Crashworthiness Design Equipment
Single-car impact with fixed barrier	November 16, 1999	Test 6
Two-coupled-car impact with fixed barrier	April 4, 2000	Test 7
Cab car-led train impact with locomotive-led train	January 31, 2002	Test 8
Single-car impact with steel coil	Test 4	Test 5

Figure 2 shows a schematic representation of the in-line collision scenario. Examples of such collisions include the Prides Crossing, Massachusetts collision between a commuter train and a freight train [22] and the Silver Spring, Maryland collision between a commuter train and an intercity passenger train [23].

Figure 5 shows a schematic representation of the grade crossing collision scenario. Examples of such collisions include the Portage, Indiana collision between a cab-car led commuter train and a tractor-tandem trailer carrying coils of steel [24] and the Yardley, Pennsylvania collision between a cab-car led commuter train a tractor semi-trailer carrying coils of steel [25].

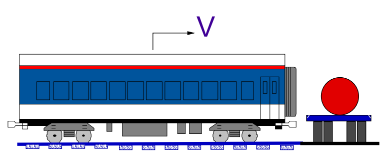

Figure 5. Schematic of Grade-Crossing Collision Scenario.

The overall objective of these tests is to demonstrate the effectiveness of improved-crashworthiness equipment. The first series of four tests define the crashworthiness of conventional equipment in the in-line [8, 9, 10, 11, 12, 13, 14, 15, 26] and grade-crossing collision scenarios. The performance of improved-crashworthiness equipment is to be measured in the second series of four tests. This arrangement of the tests allows comparison of the conventional-equipment performance with the performance of improved-crashworthiness equipment. The in-line collision tests are intended to measure the crashworthiness of a single car, then the interactions of two such cars when coupled, and finally the behavior of complete trains, including the interactions of the colliding cars. The grade-crossing collision tests are intended to measure the effectiveness of the car end structure in preventing intrusion during a grade-crossing collision. The requirements for these tests are currently being developed.

4 Discussion

The overall objective of the crashworthiness research is to develop strategies for improvements in crashworthiness over existing equipment. A wide range of research efforts is conducted in order to develop these strategies and means of implementing them. The results of this research are used in the development of rail passenger equipment regulations and safety standards.

Results of studies on collision risk and on crash energy management were used in the development of the crashworthiness specifications for Amtrak's high-speed trainset, which is now in service in the Northeast Corridor. Subsequent to developing that specification, the FRA was directed by Congress to develop rail passenger equipment safety standards in two phases. Several studies were conducted to support the development of the safety standards; the first phase of rulemaking has been completed, and the rules were issued in 1999 [27]. The FRA is currently planning development of the second phase of passenger equipment rules, and it is anticipated that the ongoing research will provide the technical basis for these second phase rules. The results of the FRA's research on rail equipment crashworthiness were also made available to American Public Transportation Association (APTA) for development of its Manual of Standards and Recommended Practices. APTA's first manual was also published in 1999 [28], and is currently undergoing revision. The rail passenger equipment research effort has evolved to help develop the technical basis for the development of these regulations and standards.

5 References

1. Bing, A., 1993, "Collision Avoidance and Accident Survivability, Volume 4: Proposed Specifications" DOT/FRA/ORD-93-02.IV, FRA, U.S. Department of Transportation.
2. Tyrell, D.C., Severson, K.J., Marquis, B.J., 1995, "Analysis of Occupant Protection Strategies in Train Collisions," ASME International Mechanical Engineering Congress and Exposition, AMD-Vol. 210, BED-Vol. 30, pp. 539-557.
3. Tyrell, D.C., Severson, K.J., Marquis, B.J., 1995, "Train Crashworthiness Design for Occupant Survivability," ASME International Mechanical Engineering Congress and Exposition, AMD-Vol. 210, BED-Vol. 30, pp. 59-74.
4. Tyrell, D.C., Severson, K.J., Marquis, B.J.,1998, “Crashworthiness of Passenger Trains”, U.S. Department of Transportation, DOT/FRA/ORD-97/10.
5. Tyrell, D.C., Rubin, A., editors, 1998, “Proceedings of the Symposium on Rail Vehicle Crashworthiness, June 1996”, U.S. Department of Transportation, DOT/FRA/ORD-97/08.
6. Tyrell, D., Severson, K.J., “Crashworthiness Testing of Amtrak’s Traditional Coach Seat”, U.S. Department of Transportation, DOT/FRA/ORD-96/08, October 1996.
7. Tyrell, D.C., Severson, K.J., Mayville, R.A., Stringfellow, R.G., Berry, S., Perlman, A.B., 1997, "Evaluation of Cab Car Crashworthiness Design Modifications," Proceedings of the 1997 IEEE/ ASME Joint Railroad Conference, IEEE Catalog Number 97CH36047.
8. Tyrell, D., Severson, K., Perlman, A.B., March, 2000, “Single Passenger Rail Car Impact Test Volume I: Overview and Selected Results,” U.S. Department of Transportation, DOT/FRA/ORD-00/02.1.
9. VanIngen-Dunn, C., March 2000, “Single Passenger Rail Car Impact Test Volume II: Summary of Occupant Protection Program,” U.S. Department of Transportation, DOT/FRA/ORD-00/02.2.
10. Tyrell, D., Severson, K., Perlman, A.B., Brickle, B., VanIngen-Dunn, C., “Rail Passenger Equipment Crashworthiness Testing Requirements and Implementation,” presented at the 2000 International Mechanical Engineering Congress and Exposition, November 6, 2000, Orlando, Florida.
11. Severson, K., Tyrell, D., Perlman, A.B., “Rail Passenger Equipment Collision Tests: Analysis of Structural Measurements,” presented at the 2000 International Mechanical Engineering Congress and Exposition, November 6, 2000, Orlando, Florida.
12. Tyrell, D., Zolock, J., VanIngen-Dunn, C., “Rail Passenger Equipment Collision Tests: Analysis of Occupant Protection Measurements,” presented at the 2000 International Mechanical Engineering Congress and Exposition, November 6, 2000, Orlando, Florida.
13. Severson, K., “Development of Collision Dynamics Models to Estimate the Results of Full-scale Rail Vehicle Impact Tests,” Tufts University Master’s Thesis, November 2000.
14. Tyrell, D., Severson, K., Zolock, J., Perlman, A.B., January, 2002, “Passenger Rail Two-Car Impact Test Volume I: Overview and Selected Results,” U.S. Department of Transportation, DOT/FRA/ORD-01/22.I.
15. VanIngen-Dunn, C., January 2002, “Passenger Rail Two-Car Impact Test Volume II: Summary of Occupant Protection Program,” U.S. Department of Transportation, DOT/FRA/ORD-01/22.II.

16. Tyrell, D.C., Martinez, E.E., Wierzbicki, T., "Crashworthiness Studies of Locomotive Wide Nose Short Hood Designs," Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems, American Society of Mechanical Engineers, AMD Vol. 237/BED Vol. 45, 1999.
17. Martinez, E., Tyrell, D., "Alternative Analyses of Locomotive Structural Designs for Crashworthiness," presented at the 2000 International Mechanical Engineering Congress and Exposition, November 6, 2000, Orlando, Florida.
18. Mayville, R.A., Hammond, R.P., Johnson, K.N., 1999, "Static and Dynamic Crush Testing and Analysis of a Rail Vehicle Corner Structural Element," Proceedings of the 8th ASME Symposium on Crashworthiness, Occupant Protection and Biomechanics in Transportation November 14-19, 1999; Nashville, Tennessee.
19. Mayville, R.A., Rancatore, R.J., Tegler, L. 1999, "Investigation and Simulation of Lateral Buckling in Trains," Proceedings of the 1999 IEEE/ASME Joint Railroad Conference, April 13-15, 1999, IEEE Catalog Number 99CH36340, ASME RTD Volume 16.
20. Mayville, R.A.,Stringfellow, R.G., Rancatore, R.J., Hosmer, T.P., 1995, "Locomotive Crashworthiness Research, Volume 1: Model Development and Validation" DOT/FRA/ORD-95/08.1.
21. Holmes, B.S. and J.D. Colton, "Application of Scale Modeling Techniques to Crashworthiness Research," Kenneth J. Saczalski, et al. Editors, Aircraft Crashworthiness, Charlottesville, VA: University Press of Virginia, 1975.
22. National Transportation Safety Board, "Railroad Accident Report: Head-On Collision of Boston and Maine Corporation Extra 1731 East and Massachusetts Bay Transportation Authority Train No. 570 on Former Boston and Maine Corporation Tracks, Beverly, Massachusetts, August 11, 1981," PB82-916301, NTSB-RAR-82-1, 1982.
23. National Transportation Safety Board, "Collision and Derailment of Maryland Rail Commuter MARC Train 286 and National Railroad Passenger Corporation AMTRAK Train 29 Near Silver Spring, MD February 16, 1996", RAR-97-02, 06/17/1997.
24. National Transportation Safety Board, "Collision of Northern Indiana Commuter Transportation District Train 102 with a Tractor-Trailer Portage, Indiana June 18,1998", RAR-99-03, 07/26/1999.
25. National Transportation Safety Board, "Collision of Reading Company Commuter Train and Tractor-Semitrailer, Near Yardley Pennsylvania, June 5, 1975", RAR-76-4, 03/03/1976.
26. Brickle, B., "Single Passenger Rail Car Impact Test Volume III: Test Procedures, Instrumentation, and Data," DOT/FRA/ORD-01/02.3, May 2000.
27. U.S. Department of Transportation, Federal Railroad Administration, "49 CFR Part 216 et al., Passenger Equipment Safety Standards; Final Rule," Federal Register, May 12, 1999.
28. American Public Transportation Association, Member Services Department, Manual of Standards and Recommended Practices for Passenger Rail Equipment, Issue of July 1, 1999.