TRANSIT COOPERATIVE RESEARCH PROGRAM

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TCRP Synthesis 25

Light Rail Vehicle Compression Requirements

A Synthesis of Transit Practice

Transportation Research Board
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TRANSIT COOPERATIVE RESEARCH PROGRAM

Synthesis of Transit Practice 25

Light Rail Vehicle Compression Requirements

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213--Research for Public Transit. New Directions,* published in 1987 and based on a study sponsored by the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of vice configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U S Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academy of Sciences, acting through the Transportation Research Board (TRB), and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at anytime. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end-users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the Transit Development Corporation, the National Research Council, or the Federal Transit Administration of the U.S. Department of Transportation

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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PREFACE

A vast storehouse of information exists on many subjects of concern to the transit industry. This information has resulted from research and from the successful application of solutions to problems by individuals or organizations. There is a continuing need to provide a systematic means for compiling this information and making it available to the entire transit community in a usable format. The Transit Cooperative Research Program includes a synthesis series designed to search for and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in subject areas of concern to the transit industry.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to transit agency general managers, their planning, operations, engineering, and design staff, as well as to other LRV builders, operators, industry associations, and government organizations. Data summaries presented cover existing practice and include those related to design parameters. Compression test requirements are described, available information on the development of specifications and standards is presented, and examples of adjustments under particular circumstances are provided.

Administrators, practitioners, and researchers are continually faced with issues or problems on which there is much information, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered or not readily available in the literature, and, as a consequence, in seeking solutions, full information on what has been learned about an issue or problem is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to the available methods of solving or alleviating the issue or problem. In an effort to correct this situation, the Transit Cooperative Research Program (TCRP) Synthesis Project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common transit issues and problems and synthesizing available information. The synthesis reports from this endeavor constitute a TCRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to a specific problem or closely related issues.

This report of the Transportation Research Board makes use of existing surveys, reports, published literature, personal contacts, and interviews with experts in the field. It offers available LRV system information from North America, Europe, and Japan.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, available information was assembled from numerous sources, including a number of public transportation agencies. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Z.M. (Joe) Lewalski, D&D Engineering, Carson City, Nevada is responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Cameron Beach, Chief Operating Officer, Sacramento Regional Transit District; Stelian (Stan) Canjea, LRT Program Manager, New Jersey Transit Corporation; Frank J. Cihak, Chief Engineer and Special Projects Manager, American Public Transit Association; Harold S. Edris, Jr., Chief, Equipment Engineering, Maryland Mass Transit Administration; Ahmed Fazel, Manager of Engineering, Regional Transportation District, Denver; Henry Hide, Associate Director, TGM International Ltd., London; Russell E. Jackson, Senior Engineer, STV Incorporated, Philadelphia; Christopher W. Jenks, Senior Program Officer, Transportation Research Board; Jeffrey Mora, Transportation Systems Manager, Federal Transit Administration; Dennis Porter, Systems Engineering Director, Tri-Met, Portland, Oregon; and Peter L. Shaw, Ph.D., Public Transportation Specialist, Transportation Research Board.

This study was managed by Donna L. Vlasak, Senior Program Officer, who worked with the consultants, the topic panel, and the J-7 project committee in the development and review of the report. Assistance in topic panel selection and project scope development was provided by Sally D. Liff, Senior Program Officer. Linda S Mason was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Information on current practice was provided by many transit agencies. Their cooperation and assistance were most helpful.

LIGHT RAIL VEHICLE COMPRESSION REQUIREMENTS

SUMMARY

Light rail vehicle (LRV) compression resistance remains unchallenged as a major structural design criterion because it is a simple measure for specifying, designing, and testing vehicles. There is, however, wide variance in the LRV compression loads selected for vehicles with similar performance characteristics and operating environments in the transit industry today.

North American transit agencies generally specify that compression resistance be equal to approximately twice the empty weight of the LRV. European LRVs, particularly low-floor LRVs, have lower compression test requirements. A lower compression test requirement means that European LRVs generally are lower in weight, which translates into lower energy consumption and, potentially, reduced capital and operating costs. Respondents to a survey conducted for this synthesis believe that moderating the level of compression load requirements where feasible and safe would allow existing European weight-effective designs to be used in the United States, with little or no additional design engineering effort, thus reducing the development cost and potentially increasing competition among carbuilders.

It is argued that compression resistance, when increased, reaches a point beyond which its further increase loses merit; however, too many factors seem to be involved in a collision to identify this point analytically. (See *The Physics of Collision*, by Donald Raskin, for more information on collisions.) Therefore, to select compression resistance, engineers rely on comparing each other's experiences and on examining safety records of earlier designs. Survey results indicate that a stronger and more rigid car body does not necessarily provide better passenger protection.

Selected North American and overseas transit agencies and major carbuilders were surveyed with respect to LRV compression load, resistance, and strength (commonly known as "buff strength"). Comparisons of American and European compression statistics are presented. There seems to be a tendency in the United States to choose higher compression resistance. To a degree, this can be attributed to higher operating speeds and longer LRV trainsets. However, European agencies and carbuilders maintain that lower compression loads are acceptable if passengers are protected from the effects of a collision by such features as carend energy absorbers, collapsible vehicle ends, effective brakes, softly padded interiors, and automation of selected components of vehicle operation and by driver training.

Accounts of LRV operations in this synthesis convey the general perception that LRV operations are relatively safe. Accidents, when they do occur, are less destructive than collisions involving rapid transit and railroad cars or trains in terms of energy that is released and that needs to be absorbed or dissipated. The research results seem to point out the value of allowing transit agencies and design engineers to choose their own parameters, guided by the experiences of others in similar circumstances.

Survey findings also indicate that tailoring compression requirements to operating conditions rather than rigidly following traditional practice may yield potential benefits such as the following:

- Lower vehicle weight,
- Less wear on vehicle subsystems and components,
- Lower energy consumption,
- Reduced capital and operating costs, and
- Greater safety resulting from energy being absorbed by the car ends when a controlled crash is allowed in high-energy frontal impacts.

Transit agency comments seem to suggest that there may be benefits in studying specific vehicle and subsystem design standards, including the following:

- Trucks,
- Couplers,
- Lighting,
- Door operator and controls, and
- Brakes.

CHAPTER ONE

INTRODUCTION

PURPOSE AND SCOPE

This synthesis describes light rail vehicle (LRV) compression load requirements in the United States and Europe. Typically, these requirements are part of a larger set of requirements that include vertical load, serviceperson load on roof, loads of jacking and lifting, and other loads.

Specification requirements for compression load, resistance, and strength (commonly known as "buff strength") for LRVs in the United States generally range from 620 to 800 kN (140,000 to 180,000 lb). Typically, a North American transit agency will specify that compression strength be equal to approximately twice the empty weight of the LRV. However, traditional European LRVs, particularly low-floor LRVs, have lower compression test requirements, usually in the 180 to 440 kN (40,000 to 100,000 lb) range. A lower compression test requirement means that European LRVs generally are lower in weight, which translates into lower energy consumption and, potentially, reduced capital and operating costs.

The fact that strength of the car body is a factor in protecting passengers in a collision is understood. Less obvious is the fact that a stronger, heavier, and more rigid car does not necessarily provide better protection. Two facts support this assertion. First, the energy released in a collision is proportional to the masses involved *(1).* The smaller the masses, the lower the energy of destruction. Everything else being equal, a stronger car will be heavier; therefore, more energy will have be to dissipated in a collision. And the larger the amount of energy required to be dissipated, the larger the amount of damage done in the collision.

Second, increasing the compression strength of a car increases its longitudinal rigidity. What would happen if a car were perfectly rigid? Suppose two such cars are considered, each weighing 32 tons (70,000 lb), one crashing with a speed of 15 mph (25 km/hr) into the other at rest. The moving car would abruptly stop, and the initially stationary car would acquire a speed of 15 mph (25 km/hr). The transfer of energy between these perfectly rigid cars would take place within thousandths of a second. If the energy transfer occurred within 10 ms, the positive and negative accelerations of the cars would be on the order of 70 g *(1).*

These arguments lead to the conclusion that compression resistance, when gradually increased, reaches a point beyond which its further increase loses merit. Too many factors are involved in a collision to identify this point analytically. For this reason, engineers have to compare each other's experiences and practices to help them select compression resistance.

The engineer's search for a means to absorb energy (e.g., by allowing the end portion of a car to collapse to reduce accelerations) is based on an understanding of the limits of increased car body resistance to compression. The following components are used today for energy absorption: *(a)* coupler draft gears, *(b)* frangible tube coupler systems, and *(c)* nonrecoverable and recoverable (viscous) car-end energy absorbers.

Thus, the optimum car body structure will be neither too weak nor too strong. A certain amount of energy absorption is beneficial in that it provides cushioning between a passenger and the obstruction involved in a collision. Lighter cars generate less energy that requires dissipation in a collision.

APPROACH AND ORGANIZATION

For this synthesis, information on current LRV experience was collected. The synthesis reports on the following:

- Existing North American, European, and, to lesser degree, Japanese LRV compression requirements and related data;
- U.S. transit agencies adjusting or considering adjusting compression requirements under certain circumstances, such as for a new system design; and
- Related data such as
  - -- Compression load
  - -- Car weight
  - -- Consist type
  - -- Articulation
  - -- Maximum operating speed
  - -- Operating mode (mixed with street traffic or on an exclusive right-of- way)
  - -- Anticlimbers
  - -- Low-floor design.

These related data have been summarized in tables.

Parameters (compression load-to-LRV energy and compression load to car weight and speed) have been developed for all entries in the tables, and comparisons have been made of the entries in the diagrams. Any available background information on the development of specifications and standards have been included. Maximum use was made of existing surveys, reports, and published literature, as referenced.

Questionnaires were mailed to 48 selected North American and European transit agencies and carbuilders in Europe and Japan. The questionnaire appears in Appendix A. Transmittal of the questionnaires was followed by reminders. A draft of this synthesis was sent to all respondents for review and verification.

The relationships shown in Figures 1 through 6 (those between compression requirements on one side and vehicle weight, speed, and kinetic energy on the other) were selected because they illustrate the vehicles' dynamic characteristics well. Vehicle kinetic energy allows vehicles that vary in speed and weight to be compared.

To simplify tables and figures and facilitate cross-referencing, each vehicle has been assigned a number. These numbers, which are presented in the following list, are used in Tables 2 and 3 and in Figures 1 through 6. Appendix B provides detail on the survey respondents.

Vehicles Operating in the United States:

1. Baltimore (Adtranz, formerly ABB)
2. Boston 1 (Boeing Vertol)
3. Boston 2 (Kinki Sharyo)
4. Chicago (project canceled)
5. Dallas (Kinki Sharyo)
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG, part of Siemens Transportation Systems)
10. Portland 1 (Bombardier) 11. Portland 2 (DUEWAG, part of Siemens Transportation Systems)
12. Sacramento (DUEWAG, part of Siemens Transportation Systems)
13. San Francisco (Boeing Vertol)
14. Saint Louis (DUEWAG, part of Siemens Transportation Systems)
15. Santa Clara (UTDC, now Bombardier)

Vehicles Operating Outside the United States:

16. Chemnitz (Adtranz, formerly ABB)
17. Cologne (DUEWAG, part of Siemens Transportation Systems)
18. Düsseldorf 1 (DUEWAG, part of Siemens Transportation Systems)
19. Düsseldorf 2 (DUEWAG, part of Siemens Transportation Systems)
20. Frankfurt (DUEWAG, part of Siemens Transportation Systems)
21. The Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG, part of Siemens Transportation Systems)
24. Mannheim (DUEWAG, part of Siemens Transportation Systems)
25. Munich (Adtranz, formerly ABB, and before that, MAN)
26. Strasbourg (Adtranz, formerly ABB)
27. Toronto 1 (UTDC, now Bombardier)
28. Toronto 2 (UTDC, now Bombardier)
29. Toyama (Nippon Sharyo)
30. Vienna 1 (DUEWAG/Bombardier)
31. Vienna 2 (SGP, part of Siemens Transportation Systems)
32. Vienna 3 (SGP, part of Siemens Transportation Systems)

CHAPTER TWO

SURVEY RESPONSES

The survey responses provided information concerning 32 LRVs (Table 1). Overall, the rate of response to the inquiry was 40 percent.

TABLE 1

SURVEY RESPONSES

Target of the Questionnaire	Number of Surveys	Number of Responses
North American transit agencies	21	11
European transit agencies	11	2
Carbuilders (Europe and Japan)	16	7
Total	48	20

The results of the survey appear in Table 2 and in Figures 1 through 6, which are presented on the following pages.

For Figures 5 and 6, the kinetic energy in metric convention equals

$$E_k = (M \times V^2)/2$$

where

M = vehicle mass, kg;
V = vehicle maximum speed,m/sec; and
E_k = vehicle kinetic energy, Joules.

In traditional American units, the kinetic energy is equal to

$$E_k = (M \times V^2)/2g_c,$$

where

M = vehicle mass, IBM;
V = vehicle maximum speed, ft/sec;
g_c = the gravitational constant (2), 32.2 ($\text{lb}_m \times \text{ft}$)/($\text{lb}_f \times \text{sec}^2$); and
E_k = is vehicle kinetic energy, Ib_f ft.

Table 3 presents a summary of survey results.

TABLE 2

LRV COMPRESSION LOADS AND ASSOCIATED STATISTICS

Question	Vehicle	1. Baltimore	2. Boston 1	3. Boston 2	4. Chicago
1	Name of carbuilder	Adtranz (formerly ABB Traction Inc.)	Boeing Vertol	Kinki Sharyo	Project cancelled
2	Year of delivery; number of cars in the procurement batch	1991,35	1977/78, 135 cars	1986/87, 100 cars	Originally intended for 1998—2000, 45 cars
3	Compression load at the level of the end still of the underframe, (a) as specified, (b) as tested, kN (lbs)	a) 889.6 (200,000) b) 889.6 (200,000)	a) 596 (134,000) b) 596 (134,000)	a) 591.58 (133,000) b) 591.58 (133,000)	a) 440 (99,000) b) Project cancelled
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (lbs)	a) 444.8 (100,000) b) 498.1 (112,000)	a) 444.8 (100,000) b) 333.6 (75,000)	a) 444.8 (100,000) b) 400 (90,000)	a) 440 (99,000) b) Project cancelled
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Crush load	Empty car	Empty car	Crush load
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	49.37 (109,000)	30.35 (67,000)	38.95 (86,000)	40.77 (90,000)
7	Maximum vehicle speed, km/h (mph)	90 (55)	80 (50)	80 (50)	65 (40)

TABLE 2 (Continued)

	Vehicle	1. Baltimore	2. Boston 1	3. Boston 2	4. Chicago
8	Average operational vehicle speed (or system operational speed), km/h (mph)	34 (21)	40 (25)	40 (25)	Project Cancelled
9	Percentage (approximate of total vehicle route negotiated at the maximum speed	20%	20%	20%	Project Cancelled
10	Number of vehicle articulations, if any	One	One	One	Two
11	Type of vehicle floor: high floor, 70 % low floor, 100% low floor	High floor	High floor	High floor	Not determined
12	Does the car have anticlimbers?	Yes	Yes	Yes	Yes
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (lb/ft): (a) recoverable absorbers, (b) nonrecoverable absorbers	No	No	No	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	Yes, 101.7 (75,000)	Yes, 101.7 (75,000)	Yes, 101.7 (75,000)	Yes
15	The depth of the operator's cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1448 (57)	1524 (60)	1524 (60)	Not determined
16	Maximum number of cars in operational consist	Three	Three	Three	Two
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	45%	Less than 1%	Less than 1%	Project cancelled
18	Type of service, (a) downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 10% b) 17% c) 73%	a) 10% b) 90% c) 0%	a) 10% b) 90% c) 0%	a) 100% b) 0% c) 0%

TABLE 2 (Continued)

Question	Vehicle	5. Dallas	6. Los Angeles	7. New Jersey	8. Philadelphia
1	Name of carbuilder	Kinki Sharyo	Nippon Sharyo	Kinki Sharyo	Kawasaki
2	Year of delivery; number of cars in the procurement batch	1995/96, 40 cars	1990/92, 54 cars 1994/95, 15 cars	1998/2000, 50 cars	1981/82, 112 single ended (SE) 29 double ended (DE) cars
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested kN (lbs)	a) 978.6 (220,000) b) 978.6 (220,000)	a) 836.2 (188,000) b) 836.2 (188,000)	a) 392 (88,130) b) TBD	a) Not available b) 464 (104,000)

TABLE 2 (Continued)

Question	Vehicle	5. Dallas	6. Los Angeles	7. New Jersey	8. Philadelphia
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (lbs)	a) 444.8 (100,000) b) 448.8 (100,000)	a) 444.8 (100,000) b) 448.8 (100,000)	a) 432 (97,120) b) TBD	a) No requirements b) No requirements
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Crush load	Crush load	Crush load	Crush load
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	48.91 (108,000)	44.62 (98,500)	40.77 (90,000)	27 (59,600) DE
7	Maximum vehicle speed, km/h (mph)	105 (65)	90 (55)	80 (50)	80 (50) DE
8	Average operational vehicle speed (or system operational speed), km/h (mph)	50 (30)	32.4 (20)	TBD	30 (18) DE
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	15%	70%	TBD	10%
10	Number of vehicle articulations, if any	One	One	Two	None
11	Type of vehicle floor: high floor, 70% low floor, 100% low floor	High floor	High floor	70% low floor	High floor
12	Does the car have anticlimbers?	Yes	Yes	Yes	Yes
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (lb/ft): (a) recoverable absorbers, (b) nonrecoverable absorbers	No	No	Yes, TBD	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	Yes, 101 7 (75,000)	Yes, 101.7 (75,000)	Yes, TBD	Yes, 101.7 (75,000)
15	The depth of the operator's cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1752 (69)	Not available	TBD	1400 (55)
16	Maximum number of cars in operational consist	Three	Three	Two	Two
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	95%	Not available	TBD	Not applicable
18	Type of service, (a) downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 15% b) 85% c) 0%	a) 10% b) 90% c) 0%	a) 50% b) 50% c) 0%	a) 10% (DE) b) 90% (DE) c) 0%

TABLE 2 (Continued)

Question	Vehicle	9. Pittsburgh	10. Portland 1	11. Portland 2	12. Sacramento
1	Name of carbuilder	DUEWAG (Siemens Transportation Systems	Bombardier	DUEWAG (Siemens Transportation Systems	DUEWAG (Siemens Transportation Systems
2	Year of delivery; number of cars in the procurement batch	1985, 55 cars	1985/86, 26 cars	1996/98, 46 cars	1986/88, 26 cars 1990/91, 10 cars
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested, kN (lbs)	a) 765 (172,000) b) 650 (146,000)	a) 756 (170,000) b) 756 (170,000)	a) 756 (170,000) b) 756 (170,000)	a) 687.21 (154,500) b) 687.21 (154,000)
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (lbs)	a) 590 (133,000) b) 590 (133,000)	a) 445 (100,000) b) 445 (100,000)	a) 445 (100,000) b) 445 (100,000)	a) 445 (100,000) b) Not tested
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Crush load	Crush load	Crush load	Empty car
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	38.96 (86,000)	41.67 (92,000)	49.37 (109,000)	35 (77,260)
7	Maximum vehicle speed, km/h (mph)	83 (51) now reduced to 57 (35)	90 (55)	90 (55)	80 (50)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	28 (17)	36 (22)	36 (22)	31 (19)
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	10%	25%	25%	60%
10	Number of vehicle articulations, if any	One	One	Two	One
11	Type of vehicle floor; high floor, 70% low floor, 100% low floor	High floor	High floor	70% low floor	High floor
12	Does the car have anticlimbers?	Yes	Yes	Yes	Yes
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (lb/ft): (a) recoverable absorbers, (b) nonrecoverable absorbers	No	No	No	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	Yes, 120 (88,500)	Yes, 101.7 (75,000)	Yes, 101.7 (75,000)	Yes, 125 (92,185)
15	The depth of the operator's cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1900 (74.8)	1524 (60)	1524 (60)	1321 (52)
16	Maximum number of cars in operational consist	Three	Two	Two	Four

TABLE 2 (Continued)

Question	Vehicle	9. Pittsburgh	10. Portland 1	11. Portland 2	12. Sacramento
17	Percentage of service (approx-imate) when the train consist includes the maximum number of cars	Less than 10%	90%	90%	37%
18	Type of service, (a) downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 40% b) 60% c) 0%	a) 15% b) 85% c) 0%	a) 15% b) 85% c) 0%	a) 28% b) 72% c) 0%

TABLE 2 (Continued)

Question	Vehicle	13. San Francisco	14. Saint Louis	15. Santa Clara	16. Chemnitz (Variotram)
1	Name of carbuilder	Boeing Vertol	DUEWAG (Siemens Transportation Systems)	UTDC (now Bombardier)	Adtranz (formerly ABB)
2	Year of delivery; number of cars in the procurement batch	1980/82, 130 cars	1992, 31 cars	1987/88, 55 cars	1993, 16 cars
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested, kN (lbs)	a) 596 (134,000) b) Not available	a) 800 (180,000) b) 800 (180,000)	a) 854 (192,000) b) 854 (192,000)	a) 200 (45,000) b) 200 (45,000)
4	Compression load at the level of the coupler anchorage, (a) as Specified, (b) as tested, kN (lbs)	a) 333.6 (75,000) b) Not available	a) 445 (100,000) b) 445 (100,000)	a) 176.28 (130,000) b) Not tested	a) 200 (45,000) b) 200 (45,000)
5	Vertical load when tested with Compression loads in items 3 And 4, above (empty car, crush Load, or other load)	Crush load	22.65 ton (50,000) tested with item 3	Crush load	Crush load
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	30.35 (67,000) specified 29.54 (65,220) delivered	42.58 (94,000)	44.71 (98,700)	35 (77,300)
7	Maximum vehicle speed, km/h (mph)	80 (50)	90(55)	90(55)	80 (50)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	24 (15)	40(25)	32(20)	35 (22)
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	15%	35%	21%	25%
10	Number of vehicle articulations, if any	One	One	One	Four
11	Type of vehicle floor: high floor, 70 % low floor, 100% low floor	High floor	High floor	High floor	100% low floor
12	Does the car have anticlimbers?	Yes	Yes	Yes	No
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (b/ft): (a) recoverable absorbers, (b) nonrecoverable Absorbers	No	No	No	Yes, recoverable 2 x 20 (2x 14,750)

TABLE 2 (Continued)

Question	Vehicle	13. San Francisco	14. Saint Louis	15. Santa Clara	16. Chemnitz (Variotram)
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	Yes, 101.7 (75,000)	Yes, 101.7 (75,000)	Yes, 100 (73,750)	Yes, energy absorbing Integrated with bumpers
15	The depth of the operator's Cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1279(50)	1900(75)	1295(51)	1800 (71)
	Maximum number of cars in operational consist	Four	Two	Three	Two
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	Less than 10%	85%	2%	Data not available
18	Type of service, (a) downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 75% b) 25% c) 0%	a) 30% b) 70% c) 0%	a) 16% b) 84% c) 0%	a) 100% b) 0% c) 0%

TABLE 2 (Continued)

Question	Vehicle	17. Cologne (B80D)	18. Düsseldorf 1	19. Düsseldorf 2	20. Frankfurt
1	Name of carbuilder	DUEWAG (Siemens Transportation Systems)	DUEWAG (Siemens Transportation Systems)	DUEWAG (Siemens Transportation Systems)	DUEWAG (Siemens Transportation Systems)
2	Year of delivery; number of cars in the procurement batch	1973/96, 500 cars	1985/93,92alumi-num Stadbahn cars (B80D)	1995+,33 Tramcars (NFGT) ordered, 140 to be supplied	1995, 39 cars (U4)
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested, kN (Ibs)	a) 589 (132,419) b) 589 (132,419)	a) 800 (180,000) b) 800 (180,000)	a) 265 (59,577) b) 265 (59,577)	a) Not specified b) Not applicable
4	Compression load at the level of the coupler anchorage, (a) as Specified, (b) as tested, kN (lbs)	a) 392 (88,129) b) 392 (88,129)	a) 600 (135,000) b) 600 (135,000)	a) 265 (59,577) b) 265 (59,577)	a) 410 (92,175) b) 410 (92,175)
5	Vertical load when tested with Compression loads in items 3 And 4, above (empty car, crush Load, or other load)	Empty car + 2/3 max passenger load	Empty car	Empty car	Empty car
6	Weight of empty car, ready to Run (excluding vehicle operator And any attendants, if applicable), Metric Tons (lbs)	38.6 (85,210)	39.4 (86,975)	33.5 (74,000)	37.5 (82,780)
7	Maximum vehicle speed, km/h (mph)	80 (50)	70 (44)	65 (40)	70 (43)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	Not available	26 (16)	17 (10.5)	Not available
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	Not available	Not available	Not available	Not available

TABLE 2 (Continued)

Question	Vehicle	17. Cologne (B80D)	18. Düsseldorf 1	19. Düsseldorf 2	20. Frankfurt
10	Number of vehicle articulations, if any	One	One	Two	One
11	Type of vehicle floor: high floor, 70 % low floor, 100% low floor	High floor,	High floor	70% low floor	Medium high (870 mm or 34-1/4 inch
12	Does the car have anticlimbers?	No	No	No	No
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (lb/ft): (a) recoverable absorbers, (b) nonrecoverable absorbers	No	No	No	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	Yes, 65 (48,000)	Yes, 65 (48,000)	Yes, 15 (11,000)	Yes, 20 (14,750)
15	The depth of the operator's Cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1450 (57) Three	1500 (59) Three	1850 (73) Two	1333 (52) Three
	Maximum number of cars in operational consist				
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	Not available	Not available	Not available	Not available
18	Type of service, (a) downtown, Mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 30% b) 70% c) 0%	a) 30% b) 70% c) 0%	a) 80% b) 20% c) 0%	a) 0% b) 100% c) 0%

TABLE 2 (Continued)

Question	Vehicle	21. The Hague	22. Hong Kong	23. Karlsruhe	24. Mannheim (MGT6/8)
1	Name of carbuilder	BN (Brugge)	Kawasaki	DUEWAG (Siemens Transportation Systems)	DUEWAG (Siemens Transportation Systems)
2	Year of delivery; number of cars in the procurement batch	1981/94, 100 cars 1992/93, 47 cars	1992/93, 30 cars	1995/96, 22 cars	1995, 63 cars
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested, kN (lbs)	a) 200 (45,000) b) 200 (45,000)	a) 400 (99,000) b) Not tested	a) 250 (56,200) b) 250 (56,200)	a) Not specified b) Not applicable
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (lbs)	a) 100 (22,500) b) 100 (22,500)	a) 350 (79,000) b) Not tested	a) 250 (56,200) b) 250 (56,200)	a) 200 (45,000) b) Not tested
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Empty car	Crush load	Empty car	Empty car

TABLE 2 (Continued)

Question	Vehicle	21. The Hague	22. Hong Kong	23 Karlsruhe	24. Mannheim (MGT6/8)
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	37 (81,700)	30.75 (67,900)	38 (83,900)	32 (70,640)
7	Maximum vehicle speed, km/h (mph)	65 (40)	80 (50)	70 (43)	70 (43)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	22 (14)	Not available	Not available	Not available
9	Percentage (approximate) of total Vehicle route negotiated at the maximum speed	15%	Not available	Not available	Not available
10	Number of vehicle articulations, if any	Two	None	Two	Six
11	Type of vehicle floor, 70 % low floor, 100% low floor	High floor,	High floor	70% low floor	70% low floor
12	Does the car have anticlimbers?	No	Yes	No	No
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in (lb/ft): (a) recoverable absorbers, (b) nonrecov-erable absorbers	No	No	No	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	No	Yes, 53 (39,000)	Yes, 20 (14,750)	Yes, 20 (14,750)
15	The depth of the operator's cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1650 (65)	1500 (59)	1944 (77)	1400 (55)
	Maximum number of cars in operational consist	One	Two	One	Two
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	Not available	Not available	Not available	Not available
18	Type of service, (a) downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 20% b) 80% c) 0%	a) 0% b) 100% c) 0%c) 0%	a) 100% b) 0% c) 0%	a) 50% b) 50%

TABLE 2 (Continued)

Question	Vehicle	25. Munich	26. Strasbourg (Eurotram)	27. Toronto 1	28. Toronto 2
1	Name of carbuilder	Adtranz (formerly MAN)	Adtranz (formerly ABB)	Bombardier formerly UTDC)	Bombardier formerly UTDC)
2	Year of delivery; number of cars in the procurement batch	1994/97, 70 cars	1994/95, 25 cars	1977/81, 196 cars	1987/89, 52 cars

TABLE 2 (Continued)

Question	Vehicle	25. Munich	26. Strasbourg (Eurotram)	27. Toronto 1	28. Toronto 2
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b)as tested, kN (lbs)	a) 200 (45,000) b) 200 (45,000)	a) 200 (45,000) b) 200 (45,000)	a) 444.8 (100,000) b) 444.8 (100,000)	a) 444.8 (100,000) b) 444.8 (100,000)
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (Ibs)	No coupler	a) 200 (45,000) b) 200 (45,000)	No coupler	No coupler
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Empty car + 2/3 max Passenger load	Crush load	Empty car	Empty car
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (lbs)	30.8 (85,210)	40.3 (89,000)	22.65 (50,000)	36.64 (80,900)
7	Maximum vehicle speed, km/h (mph)	70(43)	60(37)	80(50)	80 (50)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	Not available	35(22)	16(10)	16 (10)
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	Not available	15%	3%	3%
10	Number of vehicle articulations, if any	Two	Six	None	One
11	Type of vehicle floor: high floor, 70 % low floor, 100% low floor	100% low floor	100% low floor	High floor	High floor
12	Does the car have anticlimbers?	Yes	No	Yes	Yes
13	Does the car have frontal collision energy absorbers? If so, what is their energy-absorbing capacity in kJ (lb/ft): (a) recoverable absorbers, (b) nonrecoverable absorbers	Yes, recoverable 2 x 5 (2 x 3,600)	Yes, recoverable 2 x 5.5 (2 x 4,000)	No	No
14	Does the car have couplers? If so, what is their energy-absorbing capacity, kJ (lb/ft)	No, emergency draw bars only	No, emergency draw bars only	No	No
15	The depth of the operator's cabin (from windshield to rear), or the depth of car's end area not occupied by passengers, mm (inch)	1300 (51)	.2700 (106)	1321 (52)	1321 (52)
	Maximum number of cars in operational consist	One	One	One	One
17	Percentage of service (approximate) when the train consist includes the maximum number of cars	Not applicable	Not applicable	Not applicable	Not applicable
18	Type of service, (a)downtown, mixed with automobile traffic, (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)	a) 100% b) 0% c) 0%	a) 70% b) 30% c) 0%	a) 97% b) 3% c) 0%	a) 97% b) 3% c) 0%

TABLE 2 (Continued)

Question	Vehicle	29. Toyama Chico Railway	30. Vienna 1 (Type T)	31. Vienna 2 (short ULF)	32. Vienna 3 (long ULF)
1	Name of carbuilder	Nippon Sharyo	DUEWAG/ Bombardier	SGP (Siemens Transportation Systems)	SGP (Siemens Transportation Systems)
2	Year of delivery; number of cars in the procurement batch	1993, 5 cars	1993/94, 68 cars	1995/2000, 150 cars	See column (31)
3	Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested, kN (lbs)	No requirements; actual capacity is approximately 200 (45,000)	a) Not specified b) Not tested	a) 200 (45,000) b) Not tested	a) 200 (45,000) b) Not tested
4	Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested, kN (Ibs)	No requirements	a) 400 (99,000) b) 500 (111,500)	a) 200 (45,000) b) 200 (45,000)	a) 200 (45,000) b) 200 (45,000)
5	Vertical load when tested with compression loads in items 3 and 4, above (empty car, crush load, or other load)	Not applicable	Empty car	Crush load	Crush load
6	Weight of empty car, ready to run (excluding vehicle operator and any attendants, if applicable), Metric Tons (Ibs)	17 (37,500)	36 (79,470)	31 (68,400)	44 (97,100)
7	Maximum vehicle speed, km/h (mph)	60 (37) design, 40 (25) operation	80 (50)	70 (43)	70 (43)
8	Average operational vehicle speed (or system operational speed), km/h (mph)	20 (12)	Not available	30 (18)	30 (18)
9	Percentage (approximate) of total vehicle route negotiated at the maximum speed	5%	Not available	Not available	Not available
10	Number of vehicle articulations, if any	None	Two	Two	Four
11	Type of vehicle floor: high floor, 70 % low floor, 100% low floor	High floor	70% low floor	100% low floor	100% low floor

Legend: Vehicles in U.S. ●

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo)
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland 1 (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf I (DUEWAG)
19. Düsseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto I (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna I (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

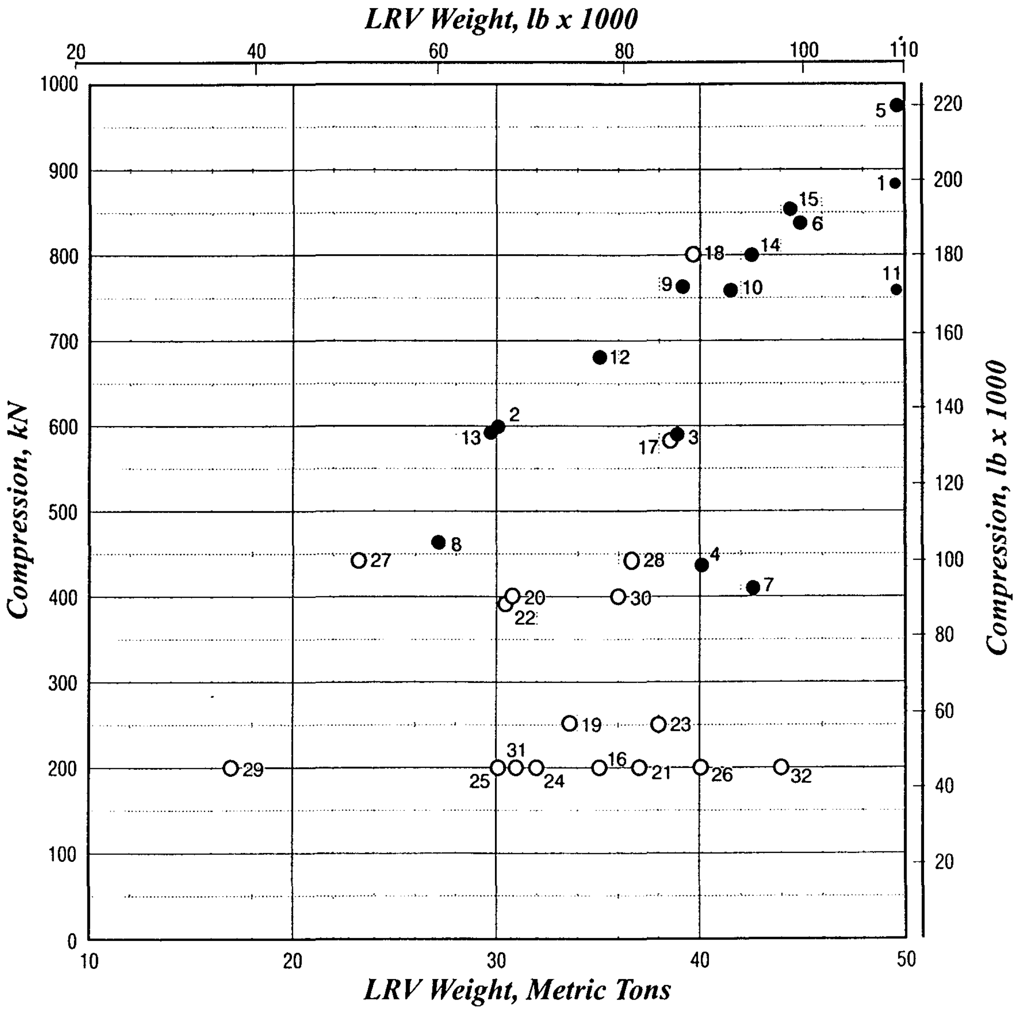

FIGURE 1 Compression versus LRV weight.

Legend: Vehicles in U.S. •

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo)
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland I (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf I (DUEWAG)
19. Düsseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto 1 (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna I (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

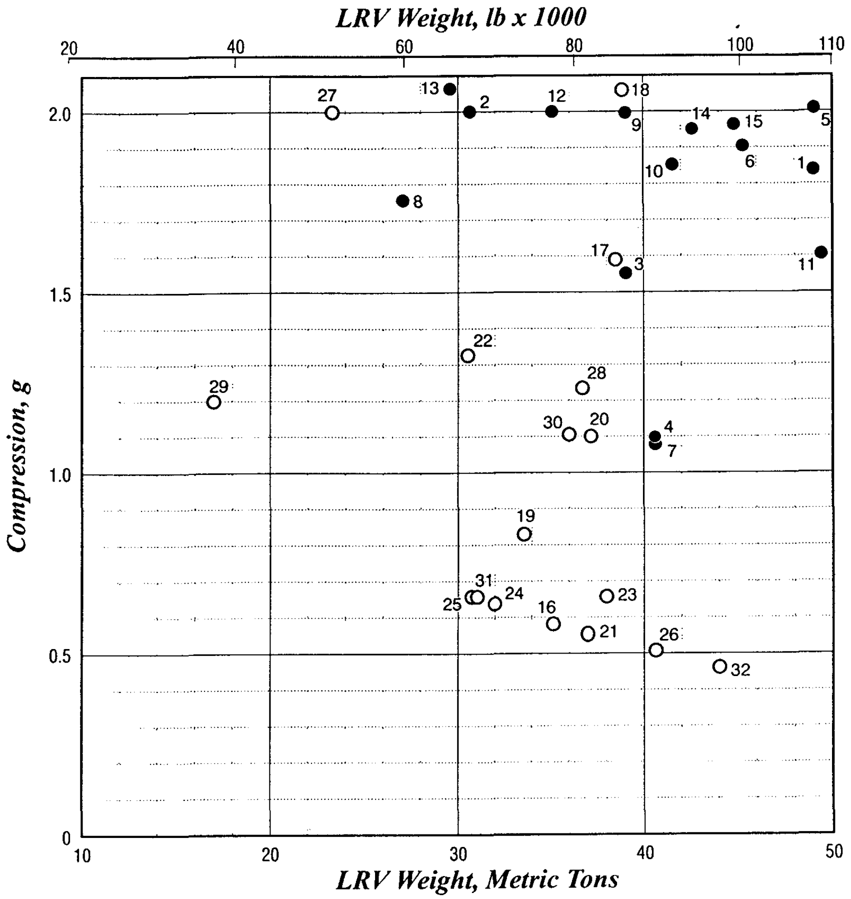

FIGURE 2 Compression in *g's* versus LRV weight.

Legend: Vehicles in U.S. •

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo)
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland 1 (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf I (DUEWAG)
19. Düsseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto I (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna I (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

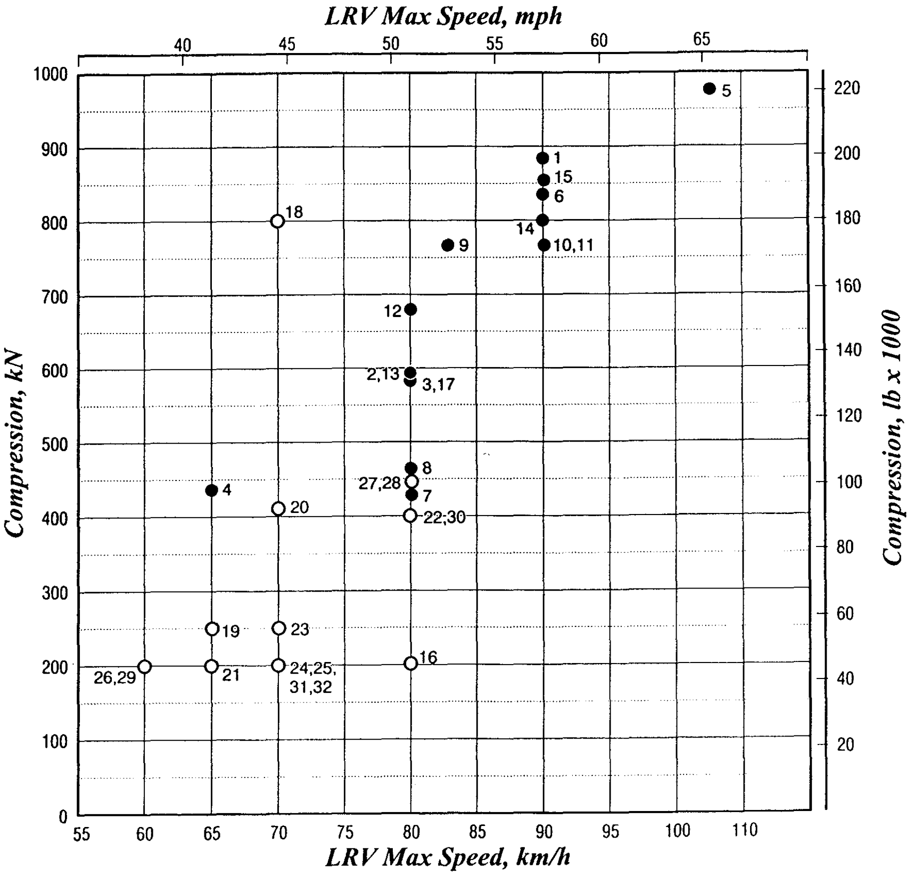

FIGURE 3 Compression versus LRV maximum speed.

Legend: Vehicles in U.S. •

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo)
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland 1 (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf 1 (DUEWAG)
19. Düsseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto I (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna 1 (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

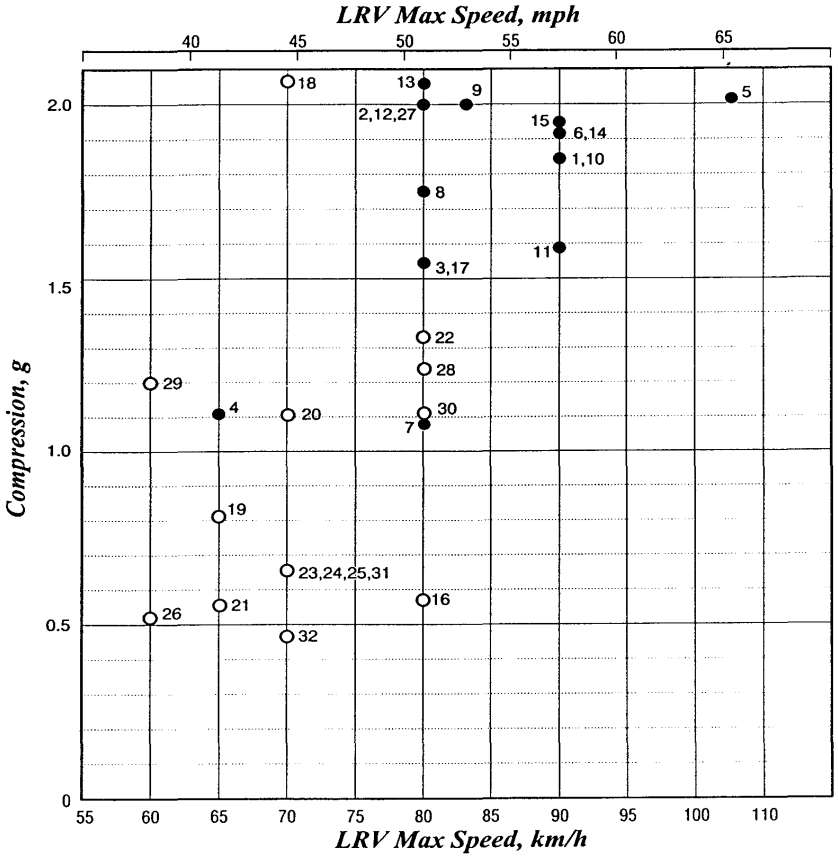

FIGURE 4 Compression in *g's* versus LRV maximum speed.

Legend: Vehicles in U.S. •

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo) - not shown
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland 1 (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf I (DUEWAG)
19. Düisseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto 1 (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna I (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

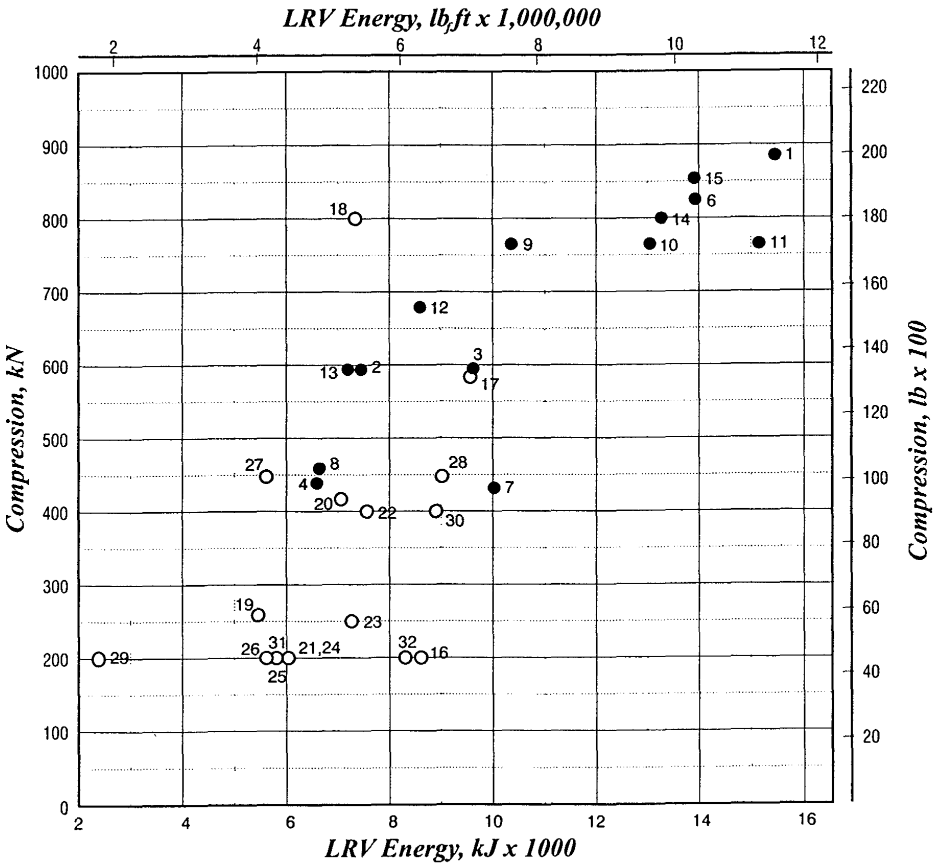

FIGURE 5 Compression versus LRV energy.

Legend: Vehicles in U.S. •

1. Baltimore (Adtranz)
2. Boston (Boeing)
3. Boston (Kinki Sharyo)
4. Chicago (project cancelled)
5. Dallas (Kinki Sharyo) - not shown
6. Los Angeles (Nippon Sharyo)
7. New Jersey (Kinki Sharyo)
8. Philadelphia (Kawasaki)
9. Pittsburgh (DUEWAG)
10. Portland 1 (Bombardier)
11. Portland 2 (DUEWAG)
12. Sacramento (DUEWAG)
13. San Francisco (Boeing)
14. St. Louis (DUEWAG)
15. Santa Clara (UTDC)

Outside U.S. O

16. Chemnitz (Adtranz)
17. Cologne (DUEWAG)
18. Düsseldorf I (DUEWAG)
19. Düsseldorf 2 (DUEWAG)
20. Frankfurt (DUEWAG)
21. the Hague (BN, Brugge)
22. Hong Kong (Kawasaki)
23. Karlsruhe (DUEWAG)
24. Mannheim (DUEWAG)
25. Munich (Adtranz)
26. Strasbourg (Adtranz)
27. Toronto I (UTDC)
28. Toronto 2 (UTDC)
29. Toyama (Nippon Sharyo)
30. Vienna I (DUEWAG/Bombardier)
31. Vienna 2 (SGP)
32. Vienna 3 (SGP).

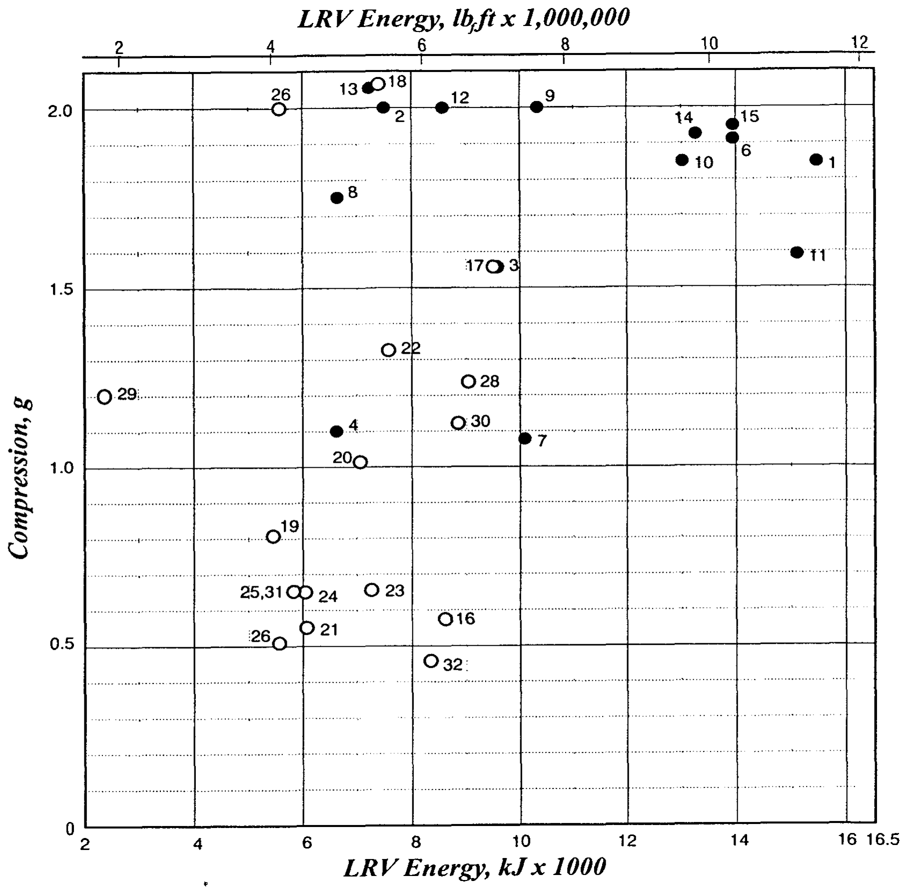

FIGURE 6 Compression in *g's* versus LRV energy.

TABLE 3
SUMMARY OF STATISTICS

Description	Weight (kg)	Weight (lb) (1)2,205	Speed (km/h)	Speed (m/sec) (3)1000,3600	Speed (mph) (3).621	K Energy (joules) (1)(4)(4)/2	K Energy (lbf.ft) (6).738	Buff (Newton)	Buff (lbs)	Buff (g) (9)/(2)
United States										
1. Baltimore (Adtranz)	49,370	108,861	90	25.00	55.89	15,428,125	11,385,956	889,600	200,000	1.84
2. Boston 1 (Boeing)	30,350	66,922	80	22.22	49.68	7,493,827	5,530,444	596,000	134,000	2.00
3. Boston 2 (Kinki Sharyo)	38,950	85,885	80	22.22	49.68	9,617,284	7,097,556	591,580	133,000	1.55
4. Chicago (project cancelled)	40,770	89,898	65	18.06	40.37	6,645,573	4,904,433	440,000	99,000	1.10
5. Dallas (Kinki Sharyo)	48,920	107,869	105	29.17	65.21	20,807,986	15,356,294	978,600	220,000	2.04
6. Los Angeles (Nipon Sharyo)	44,620	98,387	90	25.00	55.89	13,943,750	10,290,488	836,200	188,000	1.91
7. New Jersey (Kinki Sharyo)	40,770	89,898	80	22.22	49.68	10,066,667	7,429,200	432,000	97,120	1.08
8. Philadelphia (Kawasaki)	27,000	59,535	80	22.22	49.68	6,666,667	4,920,000	464,000	104,000	1.75
9. Pittsburgh (DUEWAG)	38,960	85,907	83	23.06	51.54	10,354,762	7,641,815	765,000	172,000	2.00
10. Portland 1 (Bombardier)	41,670	91,882	90	25.00	55.89	13,021,875	9,610,144	756,000	170,000	1.85
11. Portland 2 (DUEWAG)	49,370	109,000	90	22.22	55.89	15,428,125	11,385,956	756,000	170,000	1.56
12. Sacramento (DUEWAG)	35,000	77,175	80	22.22	49.68	8,641,975	6,377,778	687,210	154,000	2.00
13. San Francisco (Boeing)	29,540	65,136	80	22.22	49.68	7,293,827	5,382,844	596,000	134,000	2.06
14. Saint Louis (DUEWAG)	42,580	93,889	90	25.00	55.89	13,306,250	9,820,013	800,000	180,000	1.92
15. Santa Clara (UTDC)	44,710	98,586	90	25.00	55.89	13,971,875	10,311,244	854,000	192,000	1.95
Outside the United States										
16. Chemnitz (Adtranz)	35,000	77,175	80	22.22	49.68	8,641,975	6,377,778	200,000	45,000	0.58
17. Cologne (DUEWAG)	38,600	85,113	80	22.22	49.68	9,530,864	7,033,778	589,000	132,419	1.56
18. Düsseldorf 1 (DUEWAG)	39,400	86,877	70	19.44	43.47	7,448,302	5,496,847	800,000	180,000	2.07
19. Düsseldorf 2 (DUEWAG)	33,500	73,868	65	18.06	40.37	5,460,552	4,029,887	265,000	59,577	0.81
20. Frankfurt (DUEWAG)	37,500	82,688	70	19.44	43.47	7,089,120	5,231,771	410,000	92,175	1.11
21. The Hague (BN-Brugge)	37,000	81,585	65	18.06	40.37	6,031,057	4,450,920	200,000	45,000	0.55
22. Hong Kong (Kawasaki)	30,750	67,804	80	22.22	49.68	7,592,593	5,603,333	400,000	90,000	1.33
23. Karisruhe (DUEWAG)	38,000	83,790	70	19.44	43.47	7,183,642	5,301,528	250,000	56,200	0.67
24. Mannheim (DUEWAG)	32,000	70,560	70	19.44	43.47	6,049,383	4,494,444	200,000	45,000	0.64
25. Munich (Adtranz)	30,800	67,914	70	19.44	43.47	5,822,531	4,297,028	200,000	45,000	0.66
26. Strasbourg (Adtranz)	40,300	88,862	60	16.67	37.26	5,597,222	4,130,750	200,000	45,000	0.51
27. Toronto 1 (UTDC)	22,650	49,943	80	22.22	49.68	5,592,593	4,127,333	444,800	100,000	2.00
28. Toronto 2 (UTDC)	36,640	80,791	80	22.22	49.68	9,046,914	6,676,622	444,800	100,000	1.24
29. Toyama (Nippon Sharyo)	17,000	37,485	60	16.67	37.26	2,361,111	1,742,500	200,000	45,000	1.20
30. Vienna 1 (DUEW/Bomb)	36,000	79,380	80	22.22	49.68	8,888,889	6,560,000	400,000	90,000	1.13
31. Vienna 2 (SGP)	31,000	68,355	70	19.44	43.47	5,860,340	4,324,931	200,000	45,000	0.66
32. Vienna 3 (SGP)	44,000	97,020	70	19.44	43.47	8,317,901	6,138,611	200,000	45,000	0.46

CHAPTER THREE

LRV COMPRESSION LOAD DESIGN PRACTICES

COMPRESSION LOAD DEFINED

Car body compression load is a major vehicle design criterion. Resistance to compression is the major factor responsible for car body structural integrity in case of vehicle impact. Compression load is a proven and favorite design criterion because it provides a simple measure for assessing the strength of a car's structure and is convenient to use in stress calculations and easy to apply in testing.

In vehicle engineering practice, the term "compression load" is used interchangeably with "buff load." Under this load, the vehicle displays compression (or buff) strength (or resistance).

As a minimum, vehicle compression loads are defined for design purposes. Routinely, however, these loads are also applied in compression stress testing.

There are various opinions and practices regarding whether the compression load should be applied by itself or in combination with the vertical forces representing payload. In the United States, the maximum passenger (crush) load is routinely added to compression forces, even though cars are sometimes compressed when empty. During compression testing in Europe, cars are either crush loaded, empty, or vertically loaded some other way (e.g., to the level of two-thirds the crush passenger load).

COMPRESSION TESTING

Supporters of compression testing car shells when empty indicate that, in particular cases, passenger weight, acting downward, may relieve compression load stresses that deform the center of the vehicle upward.

The compression test is performed on a bare car body structure. The weight of equipment, interior finish components, and passengers, if required, are simulated by distributed sandbags, water containers, other weights, or hydraulic cylinders acting vertically.

In LRV design practice, compression load is applied either at the middle of the anticlimbers over a specified pressure surface (e.g., A x B mm), against the coupler anchors along the axis of the draft, or both. In the absence of anticlimbers, which is typical outside North America, compression load is applied against the end sills of the underframe.

Compression load usually is applied by means of hydraulic cylinders, and the effect of compression on the car body is measured by strain gauges. Strain gauges are applied in the critical areas of the car body and are wired to an electronic apparatus that automatically records the stresses in the locations tested.

A typical test includes a number of compression applications, starting from lower loads and gradually increasing to the highest load specified. After each application of the consecutive compression loads, the load is removed and the results of the test are evaluated before testing is resumed. This cautious technique ensures that engineers will be warned about approaching problems and that the tested car shell will not be damaged unintentionally because of an error in design.

Stresses in the structure under the action of the specified compression load should not cause a permanent deformation of any component of the structure. This means that stresses may not exceed the yield of the structural material.

AMERICAN PRACTICES

It is not clear when compression load was recognized as a major design criterion, where the magnitude of this load was originally formulated and with what justification, or when its validity was acknowledged by including it in vehicle contract specifications.

Today in the United States, the most common practice is to refer to earlier specifications. Until recently, compression loads equal to two times the empty car weight have been favored. This practice is frequently referred to as specifying compression at the level of 2g.

The compression resistance of early American streetcars is unknown. Only one complete set of specifications for the PCC car, which was the standard car design in the United States for 20 years starting in 1936, was located. However, the specifications do not include compression load.

An actual value for an LRV compression load in the United States was first mentioned in a 1971 Municipal Railway of the City and County of San Francisco (MUNI) specification. The following quotation, which specifies compression load, is taken from this source *(3)*:

> A and B body section--compression load on center-line of anticlimber (cab-end) and equivalent of center-line (non-cab end) with no yielding of structure--100,000 lb.

The International Organization for Standardization (ISO) unit equivalent for this load is 445 kN.

At approximately the same time, the Massachusetts Bay Transportation Authority (MBTA) decided to purchase new light rail equipment. Taking advantage of this opportunity, the then Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation encouraged both transit agencies, MUNI and MBTA, to develop a common vehicle procurement document. In this document, the following requirement was formulated for design compression load (4):

> Under the combined maximum vertical load and an end load, applied horizontally at the end sills, equivalent to 2g (two times the actual empty car weight).... stress in the principal framing members shall be not greater than the yield point of the material.

This was the first time, as far as research for this synthesis has been able to establish, that the concept of a 2g compression load was proposed and included in a specification.

The 2g principle was later reinforced when UMTA contracted with a consultant, N.D. Lea & Associates, Inc. (predecessor of Lea + Elliot Transportation Consultants), to write the *Light Rail Transit Car Specification Guide*, based on experience with LRV specifications for San Francisco and Boston. This document, published in 1981, included the following requirement regarding compression load *(5)*:

> - Under the combined maximal vertical load and an end load, applied horizontally at the end sills, equal to two times the empty car weight (AW0), the following conditions shall be met:
>
> > --Stress in the principal framing members shall be not greater than the guaranteed minimum yield point published by the manufacturer of the materials; or for materials whose yield point is not clearly defined, the 0.2 percent offset yield method shall be used.
> > --After removal of load, any residual strain readings as indicated by the applied strain gauges shall be within the overall accuracy of the strain instrumentation.

The following points are relevant:

- The described principle of using a 2g or, in practice, near-2g design compression load is limited to LRVs only and only those in the United States.

Overseas licensees of the successful PCC design have used their own standards for car body compression loads. For instance, the double-articulated, standard high-floor, PCC-based cars delivered by BN (now Bombardier Eurorail) for the city of The Hague from 1981 to 1984 and 1992 to 1993 (Vehicle 21 in Tables 2 and 3 and in the figures) were built to a buff load of 200 kN (45,000 lb_f). For a car that weighs 37 tons, this translates to an equivalent load of 0.55g.

Similar to this example, everywhere else, including Europe and Japan, and for every other type of rail vehicle, the compression load is specified as an absolute force rather than as a component of car body weight. For instance, for mainline railroad coaches in the United States, compression load tests are conducted at 3560 kN (800,000 lb_f). For rapid transit cars, 890 kN (200,000 lb_f) usually is specified.

- The reasons for specifying LRV compression load at 2g in the United States are unknown.
- The N.D. Lea & Associates guideline was conceived as a guide, not as a national standard.
- The Lea document allowed complete flexibility in establishing technical specifications. This is stated in the abstract of the document, which is quoted here in full:

> This Light Rail Transit Car Specification Guide is not a procurement document in itself. It is intended to be used as a guide by light rail transit operators and purchasers of such equipment in the preparation of technical specifications. Because of differing site-specific needs, this Specification Guide has been organized ***to provide ample freedom of choice among a wide range of options*** [emphasis added]. Thus both an operator whose needs dictate a sophisticated vehicle and the operator whose requirements can be met by a very simple vehicle, can use this document as a guide in drafting their individual specifications.
>
> This Car Specification Guide has evolved from the original U.S. Standard Light Rail Vehicle (SLRV) Specification developed in 1972, and incorporates a number of revisions reflecting: 1) changes which may reduce vehicle purchase costs and complexity; 2) provisions for a number of purchaser-selected options; 3) a wider specification so that a new vehicle design is not required and permits designs of vehicles which are already in passenger service; and 4) clarification of requirements so that compliance with the specification can be measured or proven to be met.

A significant influence on the development of American LRV compression requirements has been General Order 143 of the Public Utilities Commission of the State of California. This document, which was adopted in June 1978, was amended in June 1991 and again in May 1994 as General Order 143A. Section 6.03 stipulates that LRV compression load be "equal to twice the unladen car body weight applied longitudinally at the end sills." Because of the document's title, what was initially thought to be within "ample freedom of choice" became understood as an order.

EUROPEAN PRACTICES

As was the case for the United States, this study did not identify the earliest sources of prevailing practices regarding LRV compression loads in Europe.

The first document identified as addressing these concerns was the German standard VÖV 6.030.1/1977, which recommends a load of 200 kN (45,000 lb_f). Information gathered in Europe indicates that other countries (e.g., Austria and Poland) have followed the recommendations of this German source. An updated version of this document was adopted in 1992; it currently is in use under the name VDV Recommendation 152, Structural Requirements to Rail Vehicles for Public Mass Transit in Accordance with BOStrab.

An effort to develop an international standard for compression loads for rail vehicles in Europe was made in March 1995 when the European Common Market Committee for Standardization (CEN) issued the draft document Structural Requirements of Railway Vehicle Bodies *(6)*. This document is expected to become the standard in all 18 European Community member countries. Table 4, taken from this document, summarizes recommended compression values for passenger rolling stock.

Table 4 does not reflect the emerging new category of vehicles that, using the proposed terms of reference, would be located between Categories III and IV. These vehicles can be considered LRVs, but are designed to perform in a service of mixed operations with mainline railroad traffic (i.e., with trainsets of much higher compression loads and speeds, those belonging to Categories I and II). An agreement is emerging

TABLE 4

EUROPEAN COMPRESSION LOADS FOR RAIL PASSENGER VEHICLES

	Passenger Rolling Stock				
Description	Category I	Category II	Category III	Category IV	Category V
Category	Coaches, Locomotives	Fixed Consist Trainsets	Underground Rapid Transit	Suburban Cars	Tramways
Compression	2,000 kN (450,000 lbf)	1,500 kN (340,000 lbf)	800 kN (180,000 lbf)	400 kN (90,000 lbf)	200 kN (45,000 lbf)

among rail engineers in Europe that these vehicles can be built to a compression load requirement of 600 kN (135,000 lb_f). Examples of this new type of LRV are Siemens Transportation Systems LRV for Karlsruhe, Germany and Bombardier Eurorail LRV for Saarbrücken, Germany.

The 600-kN (135,000-lb_f) compression category also includes self-propelled diesel units designed to fulfill the needs of a regional commuter service. These cars, which are allowed to operate in mixed traffic with railroad vehicles, can be used as a start-up service for systems that are considering full-size light rail transit operations. The middle section of the floor of these cars has been lowered to 530 mm to 550 mm (21 to 22 in.), their maximum speed has been raised from a typical 80 km/hr to 100 km/hr (50 to 60 mph) or more, and their braking capabilities have been upgraded to those of LRVs by the addition of track brakes. Examples of these designs are Siemens Transportation Systems' Regio Sprinter and LINT vehicle by Linke Hoffman Busch (now part of GEC Alsthom).

In summary, there is a practice in Europe of using three major levels of compression loads:

- 200 kN (45,000 lb_f)--streetcars operating at relatively low speeds (maximum 40 mph (60 km/hr) and in mixed traffic with automobiles. This type of operation prevails in North America, in cities such as San Francisco, Toronto, and New Orleans.
- 400 kN (90,000 lb_f)--for LRVs with a higher maximum speed of 50 mph (80 km/hr) or so, operating partially on an exclusive right-of-way. In Germany, this type of operation recently has been referred to as Stadtbahn. In the United States, a similar type of operation can be found in Los Angeles, Sacramento, and St. Louis.
- 600 kN (135,000 lb_f)--for LRVs intended to operate partially on a right-of-way in traffic mixed with railroad trains. However, this category has not been incorporated in the first draft of the European standard now being prepared.

These compression load categories, which are lower than those in the United States, reflect European recognition that LRVs are not subject to major head-on collisions involving high speed, high energy, and vehicle overriding. Several reasons for this are the use of better brakes in LRVs (which include track brakes), lower operational speeds of LRVs, and the fact that LRVs use shorter trainsets than those used in other rail modes.

There is general agreement in Europe that the aforementioned levels of compression must be assessed by the transit agency every time and, if necessary, modified to be higher or lower, depending on the type of operations intended. Some aspects of operations that govern such modifications may include average operational speed, major right-of-way grade crossings that are unprotected by safety gates, the presence of steep grades in the system, and the particular culture in which the vehicles operate. Currently, the authority for establishing the level of compression load belongs to the operating agency or its designated representative, in cooperation with the carbuilder.

DIFFERENCES BETWEEN AMERICAN AND EUROPEAN EXPERIENCES

The European approach to establishing compression loads, the main feature of which is fitting car body strength [200 kN, 400 kN, 600 kN, (45,000 lb_{ft}, 90,000 lb_{ft}, 135,000 lb_{ft}) or in between] to local operating conditions, has been emphasized in this synthesis because it differs from the U.S. approach. In the United States, prevailing practice is for a transit agency to refer to the *Light Rail Transit Car Specification Guide (5),* which suggests a compression load equal to two times the empty car weight (2g). Although this compression load is considered to be a guideline only, allowing for ample freedom of choice, such freedom has not been exercised in practice, and the document has acquired the force of a standard.

As shown in Table 3, there have been deviations from the 2g practice. Typically, these deviations have occurred because the carbuilder had difficulty delivering a car with the weight as specified.

Only recently, because of the emergence of new LRV designs that incorporate low floors, which complicate the structure, has a lower compression load been specified. This occurred with the unsuccessful attempt to launch the construction of a light rail system in Chicago and with the New Jersey Transit--Hudson Bergen LRT system currently in development. In both cases, LRV compression loads were targeted at values between 400 and 450 kN (90,000 and 100,000 lb_f), rather than the 725 to 905 kN (160,000 to 200,000 lb_f) typically found in the United States.

CHAPTER FOUR

SELECTED PERFORMANCE OBSERVATIONS

BEHAVIOR OF EXISTING LRVs IN COLLISIONS

Compression load in LRV design is considered along with vehicle behavior in collisions and derailments. The underlying concern is that the value of the compression load selected should depend on the nature of service.

The original questionnaire that was distributed to transit agencies and carbuilders included a set of questions regarding car body shell performance in collisions and related situations. However, the answers received on this subject were inconsistent. In most cases, the information was not available. In the rest, it was found that information had been collected differently at various agencies, and some respondents preferred to share their impressions in narrative form rather than as statistics. Ultimately, it was decided to summarize the information available in concise accounts rather than in systematized statistical data.

AGENCY COMMENTS

The Massachusetts Bay Transportation Authority (MBTA) provided the following information:

- MBTA's light rail system (Green Line) does not use automatic train protection. There are block signals with wayside aspect indication on the reserved sections of the system only.
- From 1977 to 1990, the Green Line averaged one significant collision per year. From 1990 to the present, the average has been one every 2 years. The term "significant" is meant to describe an incident involving LRVs only, one that results in heavy damage to the cars. Generally, the damage consists of bent main longitudinal frame members and a crushed cab and end frame. There were no crew or passenger fatalities associated with these collisions, and most injuries were relatively minor.
- There have been several hundred incidents involving LRVs and automobiles and trucks. The damage to the LRVs generally was minor.
- There have been several hundred derailments. In most cases, the cars suffered only minor damage, even when the situation called for unconventional rerailing methods, such as diagonal jacking.
- The most notable fact is the zero fatalities. MBTA attributes this in large part to the overall structural design of its cars. Although the agency is aware that other transit agencies, particularly those in Europe, operate equipment with lower compression strength, it will not alter its present design standards. MBTA believes that to do so would result in an increased risk to passengers and operating crews.

Dallas Area Rapid Transit noted that, as of the end of January 1996, the agency had not yet had an accident. In terms of crash avoidance routines, its new high-speed system, not in revenue service at the time of the survey, will use block signals with automatic train stops.

The Los Angeles County Metropolitan Transit Authority provided information about the Blue Line light rail transit system for the period July 1989 to January 1996:

- Ninety percent of the transit authority's operations are on exclusive rights-of-way, 10 percent in mixed street traffic.
- In the 6 and a half years of the reporting period, there were 283 accidents involving 32 vehicles coming in contact with automobiles or persons. Seventy-three accidents (25 percent of the total) involved damage to the car shell paint only; 28 of the incidents (10 percent) resulted in damage to the car body front and underframe; and 53 accidents (19 percent) caused damage to the side. In three cases, the damage occurred to the doors.
- Twenty-three injuries to passengers were reported, all of them minor.
- An automated train protection system is in place.

The Municipal Railway of the City and County of San Francisco reported information covering 3 years, 1993 to 1995. In this period, 303 accidents occurred, 204 in the yard and 99 in the streets. Two-thirds of the total number of recorded incidents were derailments. The source did not have access to information about injuries. The railway has cab signaling equipment in place in the nine-station subway portion of the system.

Information from the Saint Louis Bi-State Development Agency covered the period from July 1993 to January 1996. During this time, one LRV-auto collision occurred at a crossing, resulting in severe damage to one low-level door and step well. An unspecified number of minor injuries were reported. The system uses cab signaling with forced braking to zero speed. The Transportation Agency of Santa Clara County (California) reported the accidents that occurred from 1987 to 1995. In this 9-year period, there were no collisions between LRVs, but there were 202 LRV/auto collisions and 38 others. Approximately 94 percent of the collisions resulted in paint damage only, 3 percent in front body and underframe damage, 6 percent in door damage, and 2 percent in side damage between doors. No injuries to passengers inside the LRVs were reported. The system uses automated train protection over its 9.5-mi length. In addition, signals to indicate an approaching LRV are installed at all street intersections.

Rheinische Bahngesellschaft AG Düsseldorf advised of the existence of an automated train operation system in a tunnel section in the center of the city. The respondent did not have accident statistics readily available.

The Adtranz Design Center, in Derby, England, provided information about the accident record for the early operations of the Strasbourg Eurotram. In the period covering November 1994 to January 1996, there were 104 accidents, mostly involving automobiles. Twelve (9 percent) of the accidents resulted in the LRV being withdrawn from service. There were no injuries requiring hospitalization, and no record of minor injuries exists. The system features switch selection protection, constant radio communication between drivers, and a control center that monitors the movement of all LRVs.

Adtranz Engineering Center, in Berlin (formerly ABB Henschel AG), wrote that it is not the vehicle design compression load that is important to consider in predicting a car's behavior in accidents, but the capacity to absorb collision energy through a bumper system such as that used on the Variotram LRV (Vehicle 16 in Tables 2 and 3 and in the figures).

The former technical director of The Hague Tramway Company in the Netherlands shared his experience concerning the operation of PCC-type LRVs. These double-articulated cars, which were delivered in the 1980s and early 1990s, were built to a 200-kN compression load. The structural integrity of the cars, which operated in a street environment, was good. In a few of the severe collisions, a limited deformation of the front-end structure was experienced, but rarely in the area of an articulated joint. The main floor structure always remained intact.

These accounts of light rail operations reinforce the perception that LRV operations are relatively safe. Accidents, when they happen, are less destructive than collisions involving rapid transit and railroad cars, in terms of the energy that is released and that needs to be absorbed or dissipated.

In the questionnaire, a question was asked regarding fatalities of LRV passengers caused by impact. None of those surveyed reported a fatality. Although it is true that such cases would be admitted reluctantly, their total absence among the answers received supports the common perception that LRVs are structurally safe. In contrast, fatalities resulting from collapsing car body structures on railroads are widely reported.

FURTHER COMMENTS

Major data from the survey are summarized in Table 3. Figures 1 though 6 illustrate a tendency in the United States to choose compression loads at the higher end of the scale. This tendency is partially justified by the higher speeds and larger LRV trainsets in the United States, compared with those in Europe. However, if the Toronto rigid-body LRV (Vehicle 13 in Tables 2 and 3 and in the figures), with its almost 100 percent low-speed operation in the streets, had been built in Europe, its compression load most likely would have been 200 kN instead of 445 kN.

Similarly, for San Francisco's Boeing Vertol LRV (70 percent of whose operations are in the streets and which has a 24-km/hr average system speed and automated train control at higher tunnel speeds), the resulting compression load most likely would be substantially lower than its specified 596 kN if the car had been designed for Europe. Furthermore, the European design centers defend and demonstrate the safety of such reduced compression load designs. These conclusions are based on the information supplied by European respondents.

In one response to the questionnaire, the Italian Firema Consortium responded by letter instead of by questionnaire. To supplement the statistical tables, excerpts from the letter follow:

> With reference to your request of 21 January 1996, I am pleased to inform you that until now, due to the specification of the Italian Department of Transportation. the static compression load of Italian LRVs has been 500 kN (110,000 lb).
>
> We consider the above value too high when compared to the other European countries' specifications.
>
> In the recent tenders for the new LRVs for Milan and Rome a compression load of only 300 kN (66,000 lbf) is required.
>
> For the new LRVs for the city of Oslo (Norway) we are considering a compression load of 300 kN (66,000 Ibf) and an energy absorber for crashes up to 10 km/h (6 mph).

CHAPTER FIVE

CONCLUSIONS

LRV compression resistance as a major structural design criterion seems to remain unchallenged because it provides a simple measure for specifying, designing, and testing vehicles. However, industry practice reveals wide differences in compression loads selected for vehicles with similar performance characteristics and in similar operating environments. Specifically, U.S. compression requirements are two to four times higher than those in Europe. Some reasons for this situation are as follows:

- First, part of the difference between U.S. and European compression requirements is the result of longer trainsets in the United States and their higher speeds.
- Second, LRV compression resistance is only one measure to be considered in protecting passengers from the effects of a collision. Other measures include car-end energy absorbers, collapsible vehicle ends, effective brakes, softly padded interiors, automation of selected components of operation, and drivers' training. A comparable level of safety can be reached by using various combinations of these measures.
- Third, compression resistance, when gradually increased, reaches a point beyond which its further increase is no longer beneficial to the safety of the vehicle. Too many factors are involved in collisions to identify this point analytically. Therefore, to select compression resistance, engineers rely on comparing each other's experiences and on examining the safety records of earlier designs. Thus, the choice of LRV compression resistance is, to a considerable degree, a matter of judgment. The differences in compression resistance selected for vehicles of comparable weights and speeds reflect the variations in such judgments.

The survey did not find differences in compression requirements applied to single- or multiple-articulation LRVs and high- or low-floor LRVs in Europe.

Data gathered for this synthesis can help transit agencies establish vehicle compression loads that are most appropriate for their type of operations. Survey findings lead to the conclusion that tailoring compression requirements to operating conditions instead of rigidly following the 2g practice (i.e., compression equal to twice the weight of the empty vehicle) may result in several benefits. Although 2g may be appropriate for larger vehicle consists and higher speeds, statistics show that, in some circumstances, absolutely safe operations are conducted with vehicles built to compression requirements as low as 0.5g.

The potential benefits from lower compression load are lower vehicle weight, less wear of vehicle subsystems and components, lower energy consumption, reduced capital and operating costs, and greater safety resulting from energy being absorbed by the car ends when a controlled crash is allowed in high-energy frontal impacts.

This synthesis demonstrates the value of conducting future surveys on rail vehicle design and development. There are two approaches to this development:

- Issue specific design standards concerning vehicle dimensions, weights, performance goals and limits, and the like.
- Allow engineers to choose design parameters from among those already used by development centers and proven in practice. This synthesis summarizes practices in selecting LRV compression loads and demonstrates that strictly adhering to only one standard value (e.g., 2g compression in the United States) may lead to optimum solutions being missed.

In conclusion, future studies similar in scope to this one might synthesize the design practices of such subsystems as the following:

- Trucks,
- Couplers,
- Lighting,
- Door operators and controls,
- Brakes, and
- Other major vehicle subsystems.

REFERENCES

1. Raskin, D., *The Physics of Collision*, Transit Development Corporation, Urban Mass Transportation Administration Monograph Series 500, document 500-6 (October 1974).
2. Baumeister, T., editor, *Standard Handbook for Mechanical Engineers*, McGraw Hill, New York (1967).
3. Contract Proposal No. MR-586R for Electric Multiple-Unit Subway-Surface Rail Cars. City and County of San Francisco, California (November 1971).
4. *Standard Light Rail Vehicle Specification,* prepared by the Massachusetts Bay Transportation Authority and the San Francisco Municipal Railway for the Urban Mass Transportation Administration, United States Department of Transportation (October 1972).
5. Lea and Associates, N.D., Inc., *Light Rail Transit Car Specification Guide,* prepared for Transportation Systems Center, Washington, D.C. (December 1981).
6. European Common Market Committee for Standardization (CEN), *Structural Requirements of Railway Vehicle Bodies*, Draft (March 1995).

APPENDIX A

QUESTIONNAIRE AND COMMENTARY

COMMENTARY

The first four questions do not require explanatory comments.

Question 5, about the vertical load applied to a car shell during the compression test, is of interest because there is no agreement on whether the test should be performed on an empty or a crush-loaded car. Those who prefer testing empty cars argue that such a condition is more rigorous because a car compressed at its underframe bends upward in the middle more severely. A crush load at condition of compression levels the underframe and may lower the stresses.

Answers to Question 6, about maximum vehicle speed, will allow the comparison of kinetic energies of vehicles in motion. Questions 7 and 8, about average operational speeds and the percentage of total vehicle route negotiated at the maximum speed, have the same intention, with an emphasis on averages rather than extremes. The selection of compression load will be affected to a degree by the average system operational speeds and how frequently the maximum speed is used.

Question 10, regarding the number of articulations in a design, was asked to assess whether the presence of articulations affects the selection of compression loads.

Question 11, on the type of vehicle floor (high or 70 or 100 percent low), was asked to determine the influence of these types of design choices on the compression load selected.

Question 12, regarding the presence of anticlimbers in a design, is self-explanatory.

Question 13, on the use of frontal collision energy absorbers, was included because such absorbers are the latest development in LRV design and potentially very valuable.

Question 14, regarding the use of couplers with energy absorbing capacities, also allows better assessment of a car's vulnerability in lower energy collisions.

Answers to Question 15, on the depth of the cab, provide information on a vehicle's capacity to shield passengers in the most severe, high-energy collisions. The entire depth of the car ends not used by patrons effectively acts as a protective crush zone. Incidentally, providing a means for an operator in danger to evacuate rapidly is one of the concerns to be addressed in design.

Answers to Question 16, about the maximum number of cars in an operational consist, and to Question 17, on the percentage of service during which the train consist includes the maximum number of cars, will allow better sizing of the kinetic energies of particular LRVs while in operation.

Finally, Question 18, on the type of operations, whether in mixed traffic or on a right-of-way, was asked to acquire a sense of the probability and severity of accidental LRV contact with other traffic in the transit corridor.

TRANSIT COOPERATIVE RESEARCH PROGRAM
SYNTHESIS TOPIC SC-5

Questionnaire

LIGHT RAIL VEHICLE COMPRESSION REQUIREMENTS

Your Name____
Your Title____
Organization____
Telephone______________________ Address____________________

Please use a separate questionnaire for each type of LRV servicing your system. Please photocopy the questionnaire if needed.

* * *

1. The name of the carbuilder
………………………………………………………………………………………...
2. Year of delivery; number of cars in the procurement batch
…………………………………………………………………
…………………………………………………………………
3. Compression load at the level of the end sill of the underframe, (a) as specified, (b) as tested
………………………………………………………………………………………
………………………………………………………………………………………
4. Compression load at the level of the coupler anchorage, (a) as specified, (b) as tested
………………………………………………………………………………………
5. Vertical load when tested with compression loads in items 3 and 4, above (empty car, crash load, or other load)
………………………………………………………………………………………

6. Weight of empty car, ready to run (excluding driver and any attendants, if applicable)
………………………………………………………………………………………
7. Maximum vehicle speed
………………………………………………………………………………………
8. Average operational vehicle speed (or system operational speed)
………………………………………………………………………………………
9. Percentage (approximate) of total vehicle route negotiated at the maximum speed.
………………………………………………………………………………………
10. Number of vehicle articulations, if any
………………………………………………………………………………………
11. Type of vehicle floor: high floor, 70% low floor, 100% low floor
………………………………………………………………………………………
12. Does the car have anticlimbers?
………………………………………………………………………………………..
13. Does the car have frontal collision energy-absorbers? If so, what is their energy-absorbing capacity (kN of lbft):
(a) recoverable absorbers
…………………………………………………………………….…………
(b) nonrecoverable absorbers
……………………………………………………………………………
14. Does the car have couplers? If so, what is their energy-absorbing capacity (kN of lbft):………………………………………………………………………………
15. The depth of the operator's cabin (from windshield to rear), or the depth of car's end area no occupied by passengers
……………………………………………………………………………………

16. Maximum number of cars in operational consist ………………………………………………………………………..

17. Percentage of service (approximate) when the train consist includes the maximum number of cars……

18. Type of service, (a) downtown, mixed with automobile traffic (b) suburban, on right-of-way, or (c) mixed with mainline rail; percentage of each (100% total)…………………………………………………
……

19. If they are available, enclosing the statistics of the collisions occurring in your LRV system would be highly appreciated. An example of the information sought is summarized below:

    1. Time period in which collisions reported have occurred, (from: …., to: ….)

    2. Type of operation (street, yard),

    3. Vehicle involved (LRVs only, LRVs/automobiles or other)

    4. Number of LRVs involved in collisions

    5. Number of collisions

    6. Ratio: collisions/LRV

    7. Type of damage to LRV:
        a) Paint damage only (actual number and % of total)
        b) Body/underframe damage, front/rear (actual number and % of total)
        c) Doors damaged (actual number and % of total)
        d) Body damage to the side (actual number and % of total)

8. Number of personal injuries sustained in collisions in the reporting period: (a) light (no hospitalization involved), (b) serious (hospitalization), (c) fatal. Only injuries to passengers inside the LRV to be counted.

9. Are there any crash avoidance routines (such as automatic train protection) in place in your system?

Please return this completed questionnaire and any additional information by January 26, 1996 to:

Z.M. “Joe” Lewalski
D & D Engineering
5575 Ethel Drive
Carson City, Nevada 89701

THANK YOU VERY MUCH FOR YOUR PARTICIPATION

APPENDIX B

SURVEY RESPONDENTS

The following numbers correspond with the numbers used in Tables 2 and 3 and Figures 1 through 6 to identify the LRVs on which survey information was obtained.

1. Principal Engineer, MTA, 6 St. Paul St., Room 724, Baltimore, MD 21202, tel: 410-767-3319, fax: 410-333-4810

2-3. Manager, Rail Vehicle Engineering, Massachusetts Bay Transportation Authority, 80 Broadway, Everett, MA 02149, tel: 617-222-5161, fax: 617-387-2384

4. Conformed RFP Vehicle Specification for Chicago Circulator LRV, by L.T. Klauder, dated May 19, 1994

5. Project Management, Dallas Area Rapid Transit, 1401 Pacific Ave., Dallas, TX 75266-7206, tel: 214-7492833, fax: 214-749-3664

6. LTK Engineering Services, 811 W. 7th St., Suite 1200, Los Angeles, CA 90017, tel: 213-683-1495, fax: 213-683-0503

7. Manager, Light Rail, New Jersey Transit, One Raymond Plaza West, Newark, NJ 07102, tel: 201-491-8859, fax: 201-491-8849

8. Senior Staff Officer, Initial Design Department, Kawasaki Heavy Industries, Ltd., 2-1-18, Wadayama-Dori, Hygo-Ku, Kobe, Japan, tel: 011-81-78-682-3042, fax: 01181-78-682-3050

9. Senior LRV Engineer, Port Authority of Allegheny County, 100 Village Ave., Pittsburgh, PA 15241, tel: 412-8547354, fax: 412-854-7316

10.-11. Project Engineer, LRVs, TRI-MET, 710 N.E. Holladay St., Portland OR 97232, tel: 503-239-2142, fax: 503-239-2286

12. Systems Design Manager, Regional Transit District, 2811 "O" St., Sacramento, CA 95816, tel: 916-321-3858, fax: 916-454-6016

13. Senior LRV Engineer, Municipal Railway of the City and County of San Francisco, 425 Geneva Ave., San Francisco, CA 94112, tel: 415-337-2223, fax: 415-3372365

14. Superintendent, LRV Maintenance, Bi-State Development Agency, 700 S. Ewing Ave., St Louis, MO 63103, tel: 314-189-6822, fax: 314-189-6888

15. Senior Systems Engineer, Transportation Agency of Santa Clara County, 101 W. Younger Ave., San Jose, CA 95110, tel: 408-299-8978, fax: 408-295-4359

16. Adtranz, Mirau Str. 30, D-13509, Berlin, Germany, tel: 011-49-30-4098-395, fax: 011-49-30-4098-457

17. DUEWAG AG Düsseldorf (part of Siemens Transportation Systems), Königsberger Str. 100, 40231 Düsseldorf, Germany, tel: 011-49-211-9844-510, fax: 01149-211-9844-205

18.-19. Chief Engineer (ret.), Rheinische Bahngesellschaft AG Düsseldorf, Rilkestrasse 52, D-40668 Meerbusch, Germany, tel: 011-49-2150-4911, fax: 011-49-21505633

20. See 17

21. Former Technical Director, The Hague Transit Authority, Ocarinalaan 598, 2287 SK Rijswijk (zh), Netherlands, tel: 011-31-70-394-5547

22. See 8

23.-24. See 17

25. Staff Engineer, Sonderaufgaben, Stadtwerke München, Werkbereich Verkehr, Einsteinstrasse 28, D-80207 Munich, Germany, tel: 011-49-89-2191-2104, fax: 011-49-89-2191-2155

26. Chief Mechanical Engineer, ADtranz, J Shop Office, Litchurch Lane, Derby, England DE24 8AD, tel: 011-44-1332-266266, fax: 011-44-1332-266258

27.-28. Manager, Maintenance Engineering, Toronto Transit Commission, 1900 Yonge St., Toronto, Ontario M4S 1Z2, Canada, tel: 416-393-3162, fax: 416-397-8306

29. Deputy Chief Engineer, Nippon Sharyo, 2-20 Honohara, Toyokawa, Aichi 442, Japan, tel: 011-81-5338-54115, fax: 011-81-5338-4-9484

30.-33. Senior Staff Engineer, Siemens Transportation Systems, P.O. Box 3240, D-91050 Erlangen, Germany, tel: 011-49-9131-7-46249, fax: 011-49-9131-7-21966

APPENDIX C

TYPICAL WORDING OF A CRASHWORTHINESS SPECIFICATION

Typical wording used in the United States regarding car body crashworthiness appears in the following excerpt taken from the Chicago Transit Authority specification. This specification applies to Chicago rapid transit cars, the design of which has been derived from the American PCC LRV.

> **Car Behavior Under Collision Conditions**
>
> The car structure items preceding and following this paragraph have as their intent the design of a car with maximum energy-absorbing capability within the general strength parameters indicated. The desired behavior is the crushing of the structure at the extreme ends first, with crush progressing toward the bolster It is also intended that the entire end stay together and remain attached to the roof and floor, even though it is bent or buckled. This should result in pulling down the end of the roof in a severe collision. The design of the car shall be such as to make telescoping of one car into another virtually impossible. Special care shall be exercised in the design and execution of all structural welds to ensure maximum weld integrity under collision conditions.

APPENDIX D

OTHER CHARACTERISTICS CONTRIBUTING TO LRV SAFETY

Car body longitudinal strength as defined by compression requirements is only one of the measures to be considered in protecting passengers from the effects of a collision. Other available means of protection include the following:

- The use of car-end energy absorbers, recoverable or nonrecoverable. This is a relatively new development in LRV design but already has been found to be very effective. For instance, in information received from the Strasbourg Transit Authority, the agency emphasized the positive role of car-end recoverable energy absorbers in protecting its Eurotram LRV (Vehicle 26 in Tables 2 and 3 and Figures 1 through 6) against the effects of most common LRV/auto collisions.
- Collapsible vehicle ends for crush energy absorption and control of collision phenomena. This car body capability is addressed in more detail in Appendix C. Opportunities for quick evacuation of the operator before an imminent collision should be considered part of this strategy.
- Effective brakes. For instance, a trade journal (*3*, p. 19) reports that the German Office of Standards VDV. with the German Ministry of Transportation, allows LRV-type vehicles intended for joint operation with railroads to be built to LRV compression requirements rather than those of railroads. on the strength of their braking performance of 3 m/sec^2 (6.7 mphps). Railroad decelerations are half that.
- Softly padded and collapsible interior components. Typical solutions are the use of cushioned seat headrests, padded vertical stanchions, and carpeted floors.
- Automated vehicle protection providing for the continuous separation of vehicles. Such a system, depending on the specifics of the operation, may automatically engage brakes when sensing an obstacle on the track or receive such an order from an automatic locator of trains on the track. This measure may provide the ultimate solution to protecting passengers from the effects of a collision. For instance, because of its application, the high-speed Japanese Shinkansen railroad trainset is allowed to have a compression resistance similar to that of a Dallas LRV.
- Operational procedures and techniques, including grade crossing gates, safe speeds, and operator training. A comparable level of safety can be reached by using various combinations of these measures.

Other safety measures were considered but were found to be impractical in public transit. Safety belts and inflatable air bags, both of which restrain the free movement of passengers in a collision, were two of these measures. Also judged impractical was the idea of dedicating the first car in the consist, empty in this case, as a buffer that would absorb energy in case of collision.

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