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AN ASSESSMENT OF THE CRASHWORTHINESS OF EXISTING URBAN RAIL VEHICLES
Volume I: Analyses and Assessments of Vehicles
Chapters 1 Through 7

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16. Abstract

The crashworthiness of existing urban rail vehicles (passenger cars) and the feasibility of improvements in this area were investigated by Calspan Corporation under contract to the Transportation Systems Center of the U.S. Department of Transportation in its role as systems manager for the Urban Mass Transportation Administration's Urban Rail Supporting Technology Program. Both rail-car structural configurations and impact absorption devices were studied. From this work, recommendations for engineering standards for urban rail vehicles will be developed.

This final report issued under the crashworthiness effort covers:

1. The development of analytical tools to predict passenger threat - environment during collision.
2. Criteria for predicting passenger injury due to train collisions.
3. An application of injury criteria and analytic models to predict passenger injuries resulting from collisions of trains that represent existing construction types.
4. A preliminary investigation of applying impact absorption devices to transit vehicles.
5. A design study of car structural configurations for improved impact energy management.
6. A review of engineering standards for Urban Rail Car Crashworthiness.

The report consists of three volumes:

Volume I: Analyses and Assessments of Vehicles, Chapters 1 Through 7
Volume II: Analyses and Assessments of Vehicles, Chapters 8 Through 12, Appendixes and References
Volume III: Train Collision Model User's Manual.

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PREFACE

In support of the Rail Technology Division of the Office of Research and Development of the Urban Mass Transportation Administration (UMTA), the Transportation Systems Center (TSC) has been assigned systems management responsibility for the UMTA Urban Rail System Supporting Technology Program.

As part of this program, TSC is conducting analytical and experimental studies directed towards improved urban rail system safety. A specific goal in the area of safety is reduction of both the number and the severity of injuries that may result from the collision of two trains.

On 16 August 1973, TSC contracted with Calspan Corporation to perform this study for the assessment of the crashworthiness of existing urban rail vehicles. This report presents a compilation of relevant background studies conducted prior to the start of this contract and an overall description of the work done during the course of this study conducted for the Rail Technology Division of the Urban Mass Transportation Administration under the TSC Urban Rail Supporting Technology Program.

This report is being published in three volumes. Volume I contains analyses and assessments of vehicles, chapters 1 through 7. Volume II contains chapters 8 through 12, all appendixes, and all references. Volume III contains a Train Collision Model User's Manual.

The authors take this opportunity to acknowledge the technical contributions to this report made by the program's technical monitor, Dr. Robert Raab of the Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts; and by the Program Manager, Mr. Frederick Rutyna, also of Transportation Systems Center.

The contributions of Mr. David J. Segal of Calspan Corporation are also recognized. Mr. Segal developed the computer program used for the analysis and applied this program to the many cases studied.

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1. INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

1.1.1 Background

It would be virtually impossible to eliminate all of the many circumstances that can, and sometimes do, lead to transit crashes. Such crashes, while they do not occur frequently, can produce a large number of fatalities and serious injuries. Until now, passenger rail cars have been designed for maximum occupant loading, comfort, and visibility. Relatively little attention has been paid to rail-car crashworthiness. Historically, safety efforts have been generally believed to be more effective when directed toward crash avoidance. Yet, work performed to date by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.) and cited herein indicates that it should be feasible greatly to increase the crashworthiness of passenger cars by employing relatively simple, low-cost structural design features.

What does rail-car crashworthiness really mean? Reviews of rail-crash data indicate that passengers are harmed directly by the initial collision itself -- i.e., by rail-car crushing or overriding during the accident -- or are killed or injured by excessive bodily stress incurred as the result of impacting some portion of the car's interior in the "second collision" following rail-car deceleration. In some cases, when cars are derailed and overturn, broken windows permit passengers to be ejected or partially ejected, subsequently crushing or severely lacerating them as the cars slide to a stop.

Thus, a crashworthy rail car is one which effectively serves as a safe passenger container and energy absorber during potentially survivable impact conditions and which also provides means for safe passenger exiting in a reasonable period of time following the accident -- regardless whether the car is upright or overturned. Ideally, "safe passenger container and energy absorber" implies that there is negligible chance that a passenger will be ejected through a car window, that all interior surfaces that could be impacted by a passenger are designed to distribute and not concentrate impact loads, that all interior materials are fire retardant and will not produce toxic gases if overheated, that precautions have been taken to guard against exposure of passengers to electrical hazards and fuel fires following the crash, that baggage and railroad equipment cannot become dislodged and impact a passenger during the accident, and that the car has adequate emergency exists and an emergency-lighting system.*

The Transportation Systems Center (TSC) of the U.S. Department of Transportation (DOT) has been assigned systems manager responsibility by the Urban Mass Transportation Administration's Office of Research and Development Rail Technology Division (UMTA) to conduct research, development, and evaluative efforts directed toward the introduction of improved technology in urban rail system applications. As part of this program, TSC is conducting analytical and experimental studies with a goal to reduce the number of passenger injuries and fatailities that can result from train accidents.

The purpose of this investigation is to assess the structural crashworthiness of existing urban rail vehicles, suggest structural improvements that are possible for such cars, and establish preliminary guidelines for the development of improved structural standards.

Analytical emphasis in this study is placed on frontal and front to rear collisions. Structural crashworthiness in such collisions is considered to include car penetration - leading to "penetration" or "first collision" injuries, and rigid body car acceleration, leading to internal passenger impacts causing "second collision" injuries. To investigate second collision injuries, the interior characteristics as well as the structural characteristics of the car are considered.

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* The Massachusetts Bay Transportation Authority and the Transportation Systems Center have successfully completed preliminary tests on a new type of solar energy transit car emergency lighting system. The tests were carried out by the MBTA with the cooperation and participation of the Transportation Systems Center acting as Systems Manager for the Urban Mass Transportation Administration Urban Rail Supporting Technology Program. The newly developed emergency lighting system has two special features: complete independence from existing electrical systems within the car and emergency power passively supplied by sunlight and then converted to electricity via advanced technology solar cells and stored in a small battery. The solar cells and battery are both an outgrowth of the nation's space program.

Oblique collisions, as in crossovers, and other collisions not necessarily involving straight longitudinal impact (e.g., impacting of derailed cars by other cars or against fixed objects) are far more difficult to analyze. In such situations, a more judgmental approach is used in considering structural improvements and improved standards.

Table 1-1 shows users of typical urban passenger rail cars (rail carriers) and the variety of cars they employ.

TABLE 1-1. REPRESENTATIVE PASSENGER RAIL CARS

NO.	ORIGINAL USER (AND USER'S/MANUFACTURER'S TYPE, IF ANY)	MANUFACTURER'S NAME AND ADDRESS	NO. BUILT	YEAR ORDERED	LENGTH*	DESIGN NO. OF PASSENGERS	PASSENGER LOADING (NO. PER FOOT OF LENGTH)
	RAPID-TRANSIT CARS						
→ 1A	(SAN FRANCISCO) BAY AREA RAPID TRANSIT DISTRICT	ROHR INDUSTRIES, CHULA VISTA, CAL.	150 (A)	1969 AND	74' 2-1/2"	120	1.6***
1B	(BART) (A AND B CARS)		100 (B)	1870·1973	69' 2-1/2"	132	1.9
2	CHICAGO TRANSIT AUTHORITY	ST. LOUIS CAR DIV., ST. LOUIS, MO.	160	1956	48' 0"	125	2.6
3	CHICAGO TRANSIT AUTHORITY	ST. LOUIS CAR DIV., ST. LOUIS, MO.	100	1958	48' 0"	125	2.6
4	CHICAGO TRANSIT AUTHORITY	PULLMAN-STANDARD DIV., CHICAGO, ILL.	180	1963	48' 0"	125	2.6
5	CHICAGO TRANSIT AUTHORITY	THE BUDD COMPANY, PHILADELPHIA, PA.	150	1967	48' 0"	100	2.1
6A	EXPO '67 (MONTREAL, QUEBEC, CANADA)	HAWKER SIDDELEY CANADA LTD., THUNDER BAY, ONT.	16 (A)	1966	76' 5-1/4"	200	2.6
6B	(A AND B CARS)		32 (B)	1866	74' 5/8"	200	2.7
7	MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA)	PULLMAN-STANDARD DIV., CHICAGO, ILL.	92	1962	69' 6"	275	3.8
→ 8A	MASSACHUSETTS BAY TRANSPORTATION	PULLMAN-STANDARD DIV., CHICAGO, ILL.	26 (A)	1968	69' 6"	228	3.3
8B	AUTHORITY (MBTA) (SILVERBIRD) (A AND B CARS)		26 (B)	1968	68' 6"	239	3.4
→ 9	NEW YORK CITY TRANSIT AUTHORITY (NYCTA, MTA) (R-33)	ST. LOUIS CAR DIV., ST. LOUIS, MO.	540	1962	51' 1-1/2"	180	3.5
→ 10A	NEW YORK CITY TRANSIT AUTHORITY (NYCTA, MTA) (R-44)	ST. LOUIS CAR DIV., ST. LOUIS, MO.	176 (A)	1970-1971	74' 8-1/2"	272	3.6
10B	(A AND B CARS)		176 (B)	1970-1971	74' 8-1/2"	280	3.7
11	PHILADELPHIA TRANSPORTATION COMPANY (SEPTA)	THE BUDD COMPANY, PHILADELPHIA, PA.	270	1959	55' 0"	115	2.1
12	PORT AUTHORITY TRANS HUDSON (PATH)	ST. LOUIS CAR DIV., ST. LOUIS, MO.	44	1966	51' 0"	140	2.7
13	PORT AUTHORITY TRANS HUDSON (PATH)	HAWKER SIDDELEY CANADA LTD., THUNDER BAY, ONT.	46	1970	51' 0"	139	2.7
14	TORONTO TRANSIT COMMISSION	HAWKER SIDDELEY CANADA LTD., THUNDER BAY, ONT.	76	1970	74' 5-5/8"	222	2.9
	COMMUTER CARS						
1	CHICAGO, BURLINGTON, AND QUINCY RR**	THE BUDD COMPANY, PHILADELPHIA, PA.	95	1964	85' 0"	148	1.7
2	CHICAGO, MILWAUKEE, ST. PAUL, AND PACIFIC RR**	THE BUDD COMPANY, PHILADELPHIA, PA.	40	1965	79' 11"	156	1.9
3	CHICAGO AND NORTH WESTERN RR**	PULLMAN-STANDARD DIV., CHICAGO, ILL.	172	1962-1965	85' 0"	155	1.8
→ 4	PENN CENTRAL RR, READING CO. (SEPTA) (SILVERLINER/208,280)††	THE BUDD COMPANY, PHILADELPHIA, PA.	127	1958, 1962	83' 8"	127	1.5
6	SOUTHERN PACIFIC RR**	PULLMAN STANDARD DIV., ST. LOUIS CAR DIV.	100+	1960-1865	85' 0"	164	1.9

* AS MEASURED BETWEEN ANTICLIMBERS OR BUFFERS

† USUALLY CARRIES ADDITIONAL, STANDING PASSENGERS NOT ANTICIPATED AT THE TIME OF DESIGN.

** BI-LEVEL CAR

†† SELF-PROPELLED CAR

***ALTHOUGH CALLED A "RAPID-TRANSIT" CAR, THE BARTD CAR ACTUALLY SATISFIES COMMUTER-CAR DESIGN

→ CAR WHOSE CRASHWORTHINESS WAS ASSESSED IN THIS STUDY

NOTE

MOST RAPID-TRANSIT CARS EXIST IN BOTH "A" (SELF-PROPELLED) AND "B" (UNPOWERED) CONFIGURATIONS. HERE, A AND B CARS ARE INDICATED ONLY WHERE THERE ARE SIGNIFICANT DIFFERENCES IN LENGTH OR PASSENGER LOADINGS BETWEEN THE TWO CONFIGURATIONS

The rail cars listed in the table have been categorized on the basis of passenger accommodations and loadings. Both rapid-transit cars and commuter cars, collectively referred to as urban rail cars, are designed to accommodate some standing passengers and, therefore, have high passenger loadings or densities (expressed as the design number of passengers per foot of overall car length). Rapid-transit cars are designed to accommodate a high density of standing passengers as well as seated passengers and have passenger loadings ranging from 2.1 to almost 4.0 per foot of car length. Commuter cars are designed primarily for seated passengers but often have handholds on the seats to accommodate some standees during peak commuting hours; their passenger loadings are 1.5 to 1.9 per foot.

From the partial listing in Table 1-1, it is clear that it would be impractical to attempt to perform detailed crashworthiness investigations of all existing cars in this initial study. Therefore, a review was conducted early in the program to select for further study five cars which best represent existing variations in design.

Information for the five selected rail cars was obtained to form a basis for the simplified analytical representation of existing urban rail cars in specified collisions. The inherent complexity of car structures, and the complexity of failure modes involving very large post-elastic deformations prevents the accurate prediction of individual car force-deflection characteristics. A particularly difficult phenomenon to predict is the tendency of colliding rail cars to override one another in a severe collision, in such a manner that longitudinal structural material is not fully effective in resisting car penetration. In cases where override is severe, the structural resistance forces in the collision are significantly less than would be predicted by normal methods of stress analysis.

The approach used in this study is to make estimates of the force deflection characteristics of the five selected cars, based on a stress analysis of the car structures, supplemented by engineering judgment in estimating the degree to which particular elements of longitudinal structure will develop their full crush strength in a collision. From the force-deflection estimates of the study cars, a range of generalized force-deflection inputs is selected which is believed to be generally representative of existing cars.

The use of the generalized force-deflection inputs in a collision analysis provides an approximate estimate of the crashworthiness of existing urban rail cars as a group, and also provides useful design tools relating specific car characteristics or "collision inputs" (in particular, the effective car longitudinal strength to weight ratio and interior object crush distance) with car crashworthiness. However, in the absence of controlled tests validating these inputs, no attempts should be made to infer or predict the number of fatalities or injuries which will occur in a particular car under specified accident conditions.

1.1.2 Scope of Report

Studies have been performed in the following areas:

(1) Review of existing biomechanics injury data to correlate expected extent of rail-car passenger injuries with the ranges of accelerations, pressures, and forces that could be encountered by passengers in train crashes under specified conditions. (Refer to Chapter 3.)

(2) Construction and use of an integrated train/occupant model, of the analytical (mathematical) type, which incorporates the developed injury criteria noted above (Item 1) and which correlates the accelerations, pressures, and forces to which passengers are exposed in a crash with the accelerations and deformations to which an idealized rail-car structure is subjected in the crash. Thus, this model, given input data specifying the rail-car force-

deflection characteristics, number of cars in a train, and relative crash velocity of two colliding trains -- or one train and a fixed or movable obstacle -- predicts the expected extent of injuries (or fatality) for each passenger as functions of:

his car's location in the train (e.g., first car),

his location within the car (defined by his distance from a surface which he could impact),

the character of any surface which he impacts (as defined by the depth to which it can be crushed).

(Refer to Chapter 4)

(3) Selection and analysis of four transit cars and one commuter car (the Silverliner) representative of the urban rail cars in wide use today:

	User	Type	Manufacturer	No. In Service
(a)	Penn Central RR and Reading Co.	Silverliner	The Budd Company	61
(b)	New York City Transit Authority (NYCTA)	R-33A, B	St. Louis Car Div. General Steel Industries, Inc., St. Louis, Mo.	540
(c)	New York City Transit Authority (NYCTA)	R-44A, B	St. Louis Car Div. General Steel Industries, Inc., St. Louis, Mo.	240
(d)	San Francisco Bay Area Rapid Transit (BART)	A and B cars	Rohr Industries Chula Vista, California	250
(e)	Massachusetts Bay Transit Authority (MBTA)	Silverbird A, B (South Shore Rapid Transit)	Pullman-Standard Div., Pullman Incorporated, Chicago, Ill.	76

(Refer to Chapter 5)

(4) Definition of structural and interior inputs for use in the idealized train collision model, based on analysis of existing cars. (Refer to Chapter 6.)

(5) Using the idealized train collision model, establishment of relationships between impact speed, car body acceleration and deformation and passenger injury for impact speeds between 5 and 80 mph of trains consisting of one to ten cars representing the range of strengths and weights in use on existing systems. (Refer to Chapter 7.)

(6) Evaluation of the applicability of existing static and dynamic test data to validation of crashworthiness assessments. (Refer to Chapter 7.)

(7) Preliminary investigation of rail car override phenomenon, including history of representative collisions, identification and qualitative analysis of some fundamental override mechanisms, development of simplified analytical model for override, and identification of characteristics of existing cars which could lead to override. (Refer to Chapter 8.)

(8) Development of recommendations for the design of cost-effective improved structures and impact energy-absorption devices to increase the crashworthiness of urban rail cars. (Refer to Chapter 9.)

(9) Preliminary design study of the application of an impact energy absorption device to existing car structures. (Refer to Chapter 10.)

(10) Study of the parametric tradeoffs of the rail-car structural improvements noted above to determine the interrelationships of vehicle structural parameters, cost, weight and passenger safety. (Refer to Chapter 11.)

(11) Summary of engineering design tradeoffs and design criteria for improving the structural crashworthiness of urban rail vehicles. (Refer to Chapter 11.)

(12) Recommendations for the development of engineering standards for the structural crashworthiness of rail rapid transit vehicles. (Refer to Chapter 12.)

1.2 SUMMARY

1.2.1 Train Crash Injury Criteria Development

To assess and improve the crashworthiness of existing urban rail vehicles, it was necessary to find a means of predicting the injuries that could result from crashes of original and modified rail cars over the likely range of crash conditions. Assuming that an analytical model could be developed to translate train accelerations and rail-car deformations to passenger accelerations, pressures, and forces (as discussed below), it was necessary to convert the resultant passenger stresses to degrees of injury that would be incurred by the passengers.

Therefore, biomechanics injury data available in the open literature were tabulated and reviewed to eliminate injury modes not applicable to train crashes. As the result, impact forces and associated acceleration limits were correlated with known levels of injury to the human head and chest. Next, from extensive study of many injury-severity criteria, a (injury) severity index was adopted that is based upon the integration, with respect to time, of a multiple of the passenger acceleration resulting from the crash. Curves of constant severity index were superimposed on a plot of passenger acceleration versus time for constant values of both the impacted-object crush (deflection) distance and the initial passenger impact velocity. Then, values of severity index were matched to a well-established injury-severity scale upon consideration of the head and chest injuries described for each category on the scale The result, a carpet plot defining the extent of passenger injuries as a function of the calculated conditions to which the passengers are exposed, was incorporated into an integrated train/occupant model (discussed below) for automatic prediction of injuries resulting from a train crash under specified conditions. Clearly, a broad analysis such as this requires numerous assumptions, and the following text repeatedly warns of the limitations which must be considered in interpretation of these predictions. It has been noted that there are many cases in which the crash events are not easily predictable. These include derailments resulting in additional car collisions, rollovers causing ejection and consequent lacerations or crushing of passengers, cases in which passengers impact small or sharp objects, each other, or are hit by unsecured baggage or railroad equipment,and cases in which passengers are injured or killed by fire, drowning, or electrical or other hazards. Such cases are not readily modeled but can be evaluated to some degree through an engineering review of train crash accident reports.

1.2.2 Rail Car Crashworthiness Analyses

An analytical model has been developed which determines the effects of parametric variation of rail-car number/location, weight, force versus deflection characteristics and impact closing velocity on the severity of passenger injuries resulting from a longitudinal train collision for assumed occupant spacings (distances from objects they could impact) and impacted object crush distances.

This model consists of a train-collision model and an occupant model and incorporates the bodily-injury criteria summarized above. The train-collision model accepts inputs defining the collision (closing velocity, number and types of cars in each train, and design data for each type of car) and predicts the accelerations and deformations of each car. The latter information is the input to the occupant model, which determines the magnitudes and durations of the resultant passenger accelerations and compares these values with the stored bodily-injury criteria to predict probable extent of injuries and fatalities among the passengers as functions of car structural characteristics and car location in train, passenger location within car, and crash conditions.

Generalized car force-deflection curves, based on a crush strength analysis of the five study cars, were used as structural inputs in the train collision model. These curves represented a range of effective car strength to weight ratios from 4 to 12. At each strength to weight ratio, the car interior characteristics (space between occupant and impacted surface, crush distance of impacted surface and length of car end space unoccupied by passengers) were systematically varied. The collision simulations were run for train closing velocities to 80 mph, occupant spacings from 2 to 24 feet, and impacted-object crush distances of 1/4 to 12 inches.

The major outputs obtained from the train collision model were (1) the length of passenger compartment crush distance, from which penetration or "first collision" fatalities were computed and (2) the degree of "second collision" injury severity throughout the train.

To assess qualitative aspects of train behavior in accidents (e.g., climbing), a review of representative train collisions was conducted. The major findings obtained from the car structural analysis, implementation of the collision model and accident review were:

(1) The effective longitudinal strength to weight ratio is the most significant structural parameter influencing car structural performance in frontal and front to rear collisions.

(2) First collision fatalities at relatively high closure speeds can be eliminated by a proper combination of effective car strength to weight ratio and passenger-free end space. For example, if train crush takes place almost entirely in the colliding cars (typical of actual accidents) first collision fatalities at closure speeds up to 40 mph can be eliminated if cars have effective strength to weight ratio of about 12, and if the end car has passenger-free end space of about 9 feet. If cars can be designed such that sharing of crush between cars takes place, required free end space at the end car can be reduced significantly. Higher strength to weight ratios

require less free end space. The optimum combination of strength to weight ratio and free end space is dependent on cost factors. (See summary in following section, 1.2.3, "Cost Effectiveness of Structural Improvements").

(3) The four transit cars which were studied fall in an estimated strength to weight ratio range of 5 to 10. The one commuter car which was studied has an estimated strength to weight ratio of about 15. The relatively low magnitude of the transit car range is illustrated by the fact that, at a strength to weight ratio of 5, about 22 feet of crush in each train is required to absorb the collision energy of identical 8 car trains at a closure speed of 40 mph.

(4) The type of car construction (e.g., as in the five car types which were selected for study) does not limit the strength to weight ratio which can be obtained. For all existing cars, primary structural material comprises a very small percentage of total car weight. The low specification strength levels for transit cars have not required the efficient orientation of structural material for development of longitudinal strength. Therefore significant increases in strength can be obtained with small increases in car weight, and in some cases can be obtained with no increase in car weight.

(5) Override (in which the primary longitudinal structure below the floor of one colliding car is overriden by the other colliding car) can have the effect of significantly reducing calculated strength to weight ratios. The review of accident history showed that severe or total override can occur between similar or identical colliding cars. Experience indicates that conventional transit car anti-climbers may be effective at low closure speeds, but not at high closure speeds of 30 mph, 40 mph or greater. Failure results indicate that severe override is associated with severe vertical deformation of the car which can occur in an area extending as far back as the truck bolster. Design characteristics which appear to be conducive to override can be identified, but more analysis and experiment is required to understand the phenomenon adequately and to assess its magnitude in relatively high speed transit car collisions.

(6) Maximum second collision injury levels in frontal and front to rear collisions are dependent primarily on (a) total car speed change in the collision, and (b) the crush distance or "compliance" which occurs in the interior object which the passenger impacts. "Ride down" in which the passenger strikes the constraining interior object before the car has come to a stop (i.e., at an impact speed less than total car speed change in the collision) is not a major factor in determining maximum second collision injury severity for standing passengers. Therefore, increases in car strength to weight ratio (which affect car deceleration rate in a collision but not total car speed change) will not for all practical cases affect maximum second collision injury severity. Increases in strength to weight ratio however might be expected to increase minor and moderate injuries to seated passengers in some cases.

(7) In collisions between similar trains at closure speeds up to about 40 mph, severe second collision injuries to standing passengers can be prevented at all car strength to weight ratios provided that interior objects in the car have compliance characteristics equivalent to those of relatively well designed existing equipment. When closure speeds are increased to levels significantly higher than 40 mph, second collision environment becomes rapidly more severe. At 60 mph closure speeds, required interior object compliance to prevent all severe injuries to standing passengers may increase by a factor of two or three. Compartmentalization (barriers at 6 foot spacing or less) can reduce these interior equipment compliance requirements significantly at these speeds, but only if used with cars having strength to weight ratio at the lower end of the present range (about 4 to 6). Because of the large car penetration at these low strength levels, it is concluded that more benefits can be obtained from the development of interior equipment with sufficient compliance to prevent severe second collision injuries at closure speeds in excess of 40 mph.

(8) When collisions occur between trains having significantly different weights, (large difference in numbers of cars in train) the total change in velocity of the light train is relatively high, causing maximum second collision injury severities in the light train to be correspondingly high. Therefor, if other variables are held equal, maximum closure velocities which can occur in such accidents without resulting in severe injuries are reduced as differences in the number of cars of colliding trains increase. (For example, closure velocity of 40 mph in a collision between a 2 car train and a 6 car train produces the same velocity change in the 2 car train (V = 30 mph) as a closure velocity of 60 mph produces in collisions of identical trains.)

The most significant findings from the rail car crashworthiness analysis are that existing transit cars have strength levels which are generally less than half of the strength levels for commuter and inter-city cars designed to FRA standards, and for this reason can be expected to experience over twice as much penetration in frontal and front to rear collisions. (Item 3.) Transit cars can be designed to have significantly more strength with little or, in some cases, no increase in car weight (Item 4). Strength to weight ratio can be increased from maximum levels in existing transit cars with no increase in maximum second collision injury severities, and in most collisions at closure speeds up to about 40 mph severe second collision injuries to standing passengers are preventable at all strength to weight ratios. (Item 7 and 8.)

1.2.3 Cost Effectiveness of Structural Improvements

Cost effectiveness of structural improvements represents an approximation of the cost per life saved based on the cost of the structural improvements. Three areas for improvement in car crashworthiness are identified in Chapter 9 as being worthy of further investigation:

(1) Achievement of controlled and predictable force deflection properties.

(2) Provision of energy absorption ability

(3) Improvement of car interior for increased safety

Results of the collision simulations (Chapter 7) show that most existing cars can be made more crashworthy by providing an increased level of effective longitudinal strength. This can be achieved by (1) more efficient use of structural materials, at no increase in weight, or (2) the addition of more structural material. In addition, the car design must be such that significant override does not occur.

Assuming that the addition of structural material is used to provide increased longitudinal strength, the cost of providing increased crashworthiness is calculated in Chapter 11. For a cost in the range of one dollar to three dollars per pound of added structural material, and assuming that only one frontal collision (at 40 mph) occurs in the nation (during the rush hours) every 20 years,* the calculations indicate, generally, that a cost efficiency may be achieved such that the cost per life saved would be significantly less that 200,000 dollars.

A useful baseline for comparing costs was found, see Chapter 9, to be the cost of providing passenger-free end space. Also, that a vehicle having the lower strength/weight ratio, see paragraph 5.6, must have more passenger-free crush space in order to provide equivalent passenger safety.

The best cost efficiency is a combination of strength-to-weight ratio and passenger-free end space and is dependent on the relative costs of:

(1) obtaining added car strength and

(2) providing additional cars to compensate for passenger capacity decrease due to passenger-free end space

Assuming a cost of 400,000 dollars per additional car, the optimum combination of end space and strength-to-weight ratio is yielded from structural costs in the range of one dollar to three dollars per pound:

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* Severe collisions such as this have occurred more frequently on commuter lines than on transit properties (e.g., 1972 front to rear collision at closure speed of approximately 45 mph on commuter section of the Illinois Central Gulf Railroad and two similar collisons between commuter cars on Long Island Railroad in the 1950's). To estimate the incidence of such severe collisions on transit properties would require accident records for a period of time significantly greater than 20 years. Adequate records are not available.

Cost of Structure (dollars per lb.)	Optimum Strength to Weight Ratio	Space Required (feet)
3	7	15.5
2	9	12
1	14	7.7

The required passenger-free space is based on the assumption of:

(1) the elimination of fatalities in a 40 mph closure speed collision where vehicle/vehicle penetration is involved

(2) all crush taking place at the front end of the colliding cars.

As noted in paragraph 1.2.2, this space can be reduced if car designs are made such that some crush is distributed to other car ends.

The structural cost figure of $3.00 per pound is an approximation of the total cost of a fabricated structure which provides a more efficient use of structural material with a minimized increase of weight. The cost figure of $1.00 per pound is an estimate (relatively high) of the cost of structural material where additional strength is accomplished by adding materials and weight. Since additional longitudinal strength can be provided by increasing the thickness of primary longitudinal members, the addition of new structural members and joints may be excluded, at some point, as not required in this method. Therefore, the real cost of providing added strength is believed to be closer to the material cost.

If added strength is obtained by increasing structural efficiency, rather than by adding to structural weight, added costs of material could be negligible or zero. In such cases, a prudent upper limit on strength to weight ratio should be established based on minimizing minor and moderate second collision injuries.

Suggested design concepts for minimizing or eliminating override are discussed in Chapter 9. The design concepts emphasize the use of rigid transverse elements in the car structure which serve to maintain the transverse rigidity of the full monocoque section (e.g., underframe, sideframe and roof) during the collision. Because of the relative inefficiency of transit car structures, it appears to be possible to offset the added weight of the transverse members by more efficient use of longitudinal structure.

Energy absorbers are investigated in chapters 9 and 10. The cost and potential of vehicle energy absorbers (supported by one or two trucks forward of the lead car) were compared to the cost and potential of absorbers cantilevered forward from the lead car. For closure speeds up to approximately 50 mph the cantilevered absorber, supplemented by passenger-free end space, was found to be more cost beneficial than the vehicle energy absorber. Calculations included the cost of providing unoccupied end space.

Further investigation of the cantilevered absorber is described in Chapter 10. The factors which limit absorption capacity are (1) maximum crush force compatible with basic car structure, and (2) maximum available length. The upper limit of available length for usable stroke is limited to about 8 feet, based on lateral clearance for a system with a minimum curve radius of 145 feet. This can be reduced by particular car design requirements, such as location of truck or operators' cab. For a car strength to weight ratio of 7 (the high end of the transit car specification range) cantilevered absorbers having 5 to 8 feet of usable stroke are capable of absorbing the full energy (in crashes between identical 8 car trains) of collisions from approximately 20 mph to 25 mph.

The ultimate cost effectiveness of an externally mounted energy absorber, compared to provision of unoccupied space within the normal car body outline, is dependent on the additional amount of anti-climbing strength which must be provided in the basic car shell, and the operational cost induced in the particular transit system. Further analysis and experiment would be necessary to determine the former; the latter depends very strongly on particular transit system operational procedures and facilities.

1.2.4 Specifications and Standards

No single structural standard covering transit cars exists. Individual transit authorities produce their own structural specifications as part of total design specifications for new cars. Structural specifications of the study cars plus 12 additional representative transit cars were reviewed (Chapter 12). Major findings were

(1) Most current transit car structural specifications are direct or indirect offshoots of the original Association of American Railroad (AAR) standards and current federal (FRA) standards. Like the FRA standards, the transit car standards are design oriented, requiring in most cases specific static strength levels locally for particular components and joints, but not requiring demonstration of strength throughout the structure. Also like the FRA standards, the only exception to this is the requirement for longitudinal or "buff" load, where static test is required for proof of overall strength.

(2) Wide differences in the individual transit authority specifications exist, both in terms of amount of coverage and strength levels required. The differences are not attributable to differences in car size, weight, or performance requirements.

(3) In those specifications where longitudinal strength and weight are specified, longitudinal strength requirements are given in terms of yield strength or "zero permanent deformation" strength. The resulting yield strength to weight ratios fall in a range from 3 to 7. Though it is possible to develop peak crush strength which is significantly higher than yield strength, it is also possible to develop average crush strength levels (averaged over crush distance) which are significantly lower than yield strength. It is concluded that existing specifications permit cars to be built with extremely low strength levels, in terms of crush distance required to absorb collision energy. At a strength to weight ratio of only 3, the crush distance required in each train to absorb the collision energy of two identical 8 car trains at closure speed of 40 mph is approximately 36 feet.

Basic approaches to the generation of uniform transit system standards and guidelines for car construction are discussed in Chapter 12. The relative merits of design guidelines, design standards, and performance standards are reviewed.

The approximate calculations given in Chapter 12 show that the cost impact of performance standards which require destructive tests for proof of compliance is much higher in the transit car industry than in the automobile industry, when viewed in terms of individual car costs and total sales.

A methodology employing non destructive tests for demonstration of compliance to standards is described in Chapter 12. In this methodology, the standards and the compliance test procedures are based on a prior program of analysis and validation experiments.

Because of the time required to develop the methodology described, it is recommended in Chapter 12 that interim uniform standards be formulated. To provide a basis for formulation of the interim standards, small scale tests as well as full scale barrier tests should be considered.

The most comprehensive transit car standards now in existence appear to be the recent standards of the New York City Transit Authority which apply to the R-46 cars. (These cars are to be placed in service shortly.) These standards include relatively rigorous longitudinal strength requirements, as well as relatively rigorous collision post and corner post requirements.

2. MAJOR CONCLUSIONS AND RECOMMENDATIONS

2.1 MAJOR CONCLUSIONS

1) By employing a relatively simple one dimensional dynamic train collision model, it is possible to estimate theoretical car penetration and second collision injury environment in cars where effective force versus deflection characteristics and interior characteristics are known. For transit cars with seated and standing passengers, employment of the model indicates that large increases in effective transit car strength can reduce penetration (first collision) fatalities very significantly without significantly increasing second collision injury severity. This conclusion should be confirmed and refined by a more detailed analysis of colliding cars and by analysis of and experiments on existing and improved interior equipment.

2) Specifications for existing transit cars are widely divergent in amount of coverage (structural characteristics dealt with) and strength levels required. In those specifications where longitudinal strength and weight are specified, strength requirements are given in terms of yield strength or "zero permanent deformation" strength. The resulting yield strength to weight ratios fall in a range from 3 to 7. These specifications permit cars to be built with sustained crush strength levels which permit high car penetration in frontal and front-to-rear collisions.

3) By the more efficient configuration of structural materials now used in transit cars, it is possible in many cases to obtain significantly increased car strength with no increase in car weight or cost. Assuming that added strength is obtained by increasing the amount of structural material (i.e., providing more structural material in existing inefficient designs from a crashworthiness aspect) collision model results and cost analyses indicate that the cost of providing added strength in all new transit cars is generally significantly less than $200,000 per life saved, for unit costs of $1.00 to $5.00 per pound of added structure. This is based on only one frontal collision (at 40 mph) occurring once in the nation (during rush hours) every 20 years.

4) Severe override can occur in frontal collisions of similar or identical cars. This has the effect of causing large reductions in effective strength/weight ratio. Existing transit car anti-climbers are believed to be effective at low speeds, but their effectiveness at higher speeds is questionable. Further analysis supplemented by experiment is required to obtain an adequate understanding of override between similar transit cars and the design characteristics which affect it.

2.2 RECOMMENDATIONS FOR FURTHER STUDY

1) A more refined one dimensional analytical model should be applied to the colliding cars in a frontal collision in order to provide an elementary basis for prediction of car structural behavior.

2) The one dimensional analytical model should ultimately be expanded to a three dimensional model to provide an improved basis for prediction of car behavior, and an adequate understanding of override and other three dimensional effects. The model should be validated by a series of controlled static and dynamic experiments starting with relatively simple two or three dimensional structures and progressing to actual car structures.

3) A combined analytical and experimental program should be formulated to provide a basis for the design of interior equipment with adequate compliance characteristics in second collisions. Since second collision severity depends on car crush strength level as well as interior characteristics, final definition of an optimum car strength/weight ratio range will depend on the findings from the interior equipment program.

4) Because of the time period required for (1), (2) and (3), and because of the generally low magnitude of and high variation in existing transit car strength requirements, it is recommended that uniform interim structural standards be formulated. To provide a basis for formulation of the interim standards, it is recommended that small scale tests as well as

full scale tests be considered. The most comprehensive of the existing transit car standards should be used as the initial baseline (e.g., the NYCTA standards for the R-46 car).

3. INJURY - PREDICTION METHODOLOGY FOR TRAIN CRASHES

3.1 INTRODUCTION

Assessment and improvement of the crashworthiness of existing urban rail vehicles requires determination of passenger (and crew) injuries that could result from crashes of original and modified rail cars over the likely range of crash conditions. Determination of the expected injuries is based on review of existing crash biomechanics tolerance data and relation of these data to the train crash environment.

The first step in injury prediction -- correlation of injuries with the accelerations, jerks (onset rates of accelerations), pressures, and forces that could be encountered by passengers in train crashes is discussed in this section. The final step -- correlation of the accelerations, pressures, and forces to which passengers are exposed in crashes with the accelerations and deformations to which a given rail car structure is subjected in crashes (as defined by the crash conditions specified) -- is performed by analytical modeling, discussed in Chapter 4.

3.2 PRESENT INJURY CRITERIA AND THEIR APPLICABILITY TO RAIL-CAR CRASHWORTHINESS

The injury criteria available in the open literature are presented in Table 3-1. In generating the listing, reference sources were given which are easily obtainable, and the table includes a reference or source listing for each value presented. "Biomechanics and its Application to Automotive Design"* was selected as a primary source as it presents a compilation of many of the injury criteria listed and constitutes perhaps the best single source of injury criteria available. For the injury criteria not listed in Reference 1, original papers have been cited where possible.†

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* A complete list of references is given at the end of this report. The first 12 references are cited in Table 3-1, as well; other documents cited in this section are footnoted for easy reference.

†See page 3-16 at end of this chapter.

TABLE 3-1. INJURY CRITERIA

AREA	TEST METHODS	SUBJECT	PARAMETER AND LEVEL	INJURY	REFERENCE
HEAD: H_x	IMPACT, FLAT PLATE	CADAVER	80 g's	CONCUSSION	
	↓ ↓ ↓	↓	40 g's	NONE	↓
H_y	SLED, BELTS	HUMAN	46 g's	MINDR	83
α	ROTATION	ANIMALS	50 rad/sec	50% CHANCE DF CDNCUSSIDN	82
α	↓	↓	1800 rad/sec^2	↓ ↓ ↓ ↓	↓
HSI	CALCULATED	–	f(a,t) 1000	DEFINED AS NDN INJURIDUS	86
HIC	↓	–	↓ ↓	↓ ↓ ↓	69 ↓
FACE: FRONTAL	IMPACT, UNPADDED, 28 IN.^{2}	HUMAN	400 lb	NONE	80
(FOREHEAD)	PADDED 28	↓	285	↓	↓
	5	CADAVER	2000	FRACTURE (THRESHDLD)	89
	1		900		↓
TEMPOROPARIETAL					
(TEMPLE)	1		450		80
ZYGOMATIC	5		480		↓
(CHEEK)	1		250		89
	1		200		↓
MAXILLA	1		160		80
(UPPER JAW)	1		150		89
MANDIBLE	5		600		80
(LOWER JAW)	1		275		↓
MANDIBLE x	1		400		89
MANDIBLE y	↓ ↓ 4 ↓	↓	200 ↓	↓	89 ↓
NECK: HYPERTENSION	STATIC LOADING	CADAVER	42 ft-lb	LIGAMENTOUS DAMAGE	80
HYPERFLEXION	↓ ↓	↓	140 ↓ ↓	NDNE	↓
CHEST: C_x	FREE-FALL, IMPACT PADDED	HUMAN	49 g's, 10 sec	NDNE	81
	SLED, BLETS	↓	45 g's, 23 sec	MINOR	80
	IMPACT, 28 IN.^{2}	CADAVER	1200 lb	RIB FRACTURE	↓
	SLED, VEST, 140 ↓	HUMAN	3300 lb	NONE	85
C_z	SEAT EJECTION TESTS	↓	25 g's	OCCASIDNAL VERTEBRAL FRACTURE	83
C_R	CALCULATED	–	60 g's 3 ms	DEFINED AS NON-INJURIDUS	69
CSI	↓	–	f(a,t) 1000	↓ ↓ ↓	↓
PELVIS	SLED, BELTS	HUMAN	2800 lb	NDNE	80
	↓ ↓	↓	5000 ↓	↓	↓
LOWER EXTREMITIES					
FEMUR	CALCULATED	–	1700 lb	DEFINED AS NON INJURIOUS	69
	IMPACT, PADDED, 28 IN.^{2} AXIAL	HUMAN	1050	NDNE	80
	↓ ↓	CADAVER	1700 ↓	FRACTURE	↓
	STATIC LOADING IN TORSIDN		102 ft-lb		90
PATELLA	IMPACT, UNPADDED, 28 IN.^{2}		1700 lb		80
TIBIA	STATIC LOADING IN TORSIDN		50 ft-lb		86
	BENDING		166		↓
	TORSIDN		55		90
FIBULA	↓ ↓ ↓ ↓	↓	7 ↓ ↓	↓	↓
UPPER EXTREMITIES					
HUMERUS	STATIC LOADING IN TORSION	CADAVER	46 ft-lb	FRACTURE	90
RADIUS			14		
ULNA	↓ ↓ ↓ ↓	↓	9 ↓ ↓	↓	↓
WHOLE BDDY	SLED, BELTS	HUMAN	45 g's 23 sec	MINOR	80
	RE-ENTRY COUCH		126 g's	NDNE	88
	FREE-FALL, IMPACT PADDED		49 g's 10 sec		81
	SLED, BELTS	↓	DNSET RATE		84
			1000 g's sec	↓	

TABLE 3-1. INJURY CRITERIA (Cont.)

REFERENCES

1. Anon., "Biomechanics and its Application to Automotive Design," Publication P-49, Society of Automotive Engineers, Inc., New York, N.Y., January 1973.
2. Anon., "Occupant Crash Protection in Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Busses," Publication FMVSS 208, National Highway Traffic Safety Administration, U.S. Dept. of Transportation, revision of 17 February 1972.
3. Mertz, H.J. and Gadd, C.W., "Thoracic Tolerance to Whole-Body Deceleration," Paper Published in Proceedings of Fifteenth Stapp Car Crash Conference, Coronado, California, 17 November 1971.
4. Ommaya, A.K., et al., "Comparative Tolerances for Cerebral Concussion by Head Impact and Whiplash Injury in Primates," SAE Paper 700401, 1970 International Automobile Safety Conference Compendium, Society of Automotive Engineers, Inc., New York, N.Y., 1970.
5. Robbins, D.H., Snyder, R.G., and Roberts, V.L., "Injury Criteria Model for Restraint System Effectiveness Evaluation," Report BioM-70-7, Highway Safety Research Institute, Ann Arbor, Mich., October 1970.
6. Eiband, A.M., "Human Tolerance to Radially Applied Acceleration," Memo 5-19-59 E, National Aeronautics and Space Administration, June 1959.
7. Gurdjian, E.S., "Experiences in Head Injury and Skeletal Research," Published in Proceedings of Symposium on Impact Acceleration Stress (held at Brooks Air Force Base, November 27-29, 1961), Publication 977, National Academy of Sciences, National Research Council, 1961.
8. Bahniuk, Eugene, Mack, Robert P., Burstein, Albert H., and Frankel, Victor H., "The Biomechanics of Contemporary Ski Bindings," Journal of Safety Research, December 1972
9. Anon., "Human Tolerance to Impact Conditions as Related to Motor Vehicle Design," Recommended Practice SAE J885a, published in 1966 SAE Handbook, Society of Automotive Engineers, Inc., New York, N.Y., October 1966.
10. Anon., "Military Troop Seat Design Criteria," Technical Report TCREC TR-62-79, Aviation Crash Injury Research Division, Flight Safety Foundation, Inc., Fort Eustis, Va., November 1962.
11. Schneider, D.C. and Nahum, A.M., "Impact Studies of Facial Bones and Skull," Paper presented at Sixteenth Stapp Car Crash Conference, November 1972.
12. Evans, F. Gaynor, Ph.D., Stress and Strain in Bones - Their Relation to Fractures and Osteogenesis, Charles C. Thomas, Publisher, Springfield, Ill., 1957.

Table 3-1 summarizes the injury criteria available in the literature and, in so doing, provides a point of departure for a discussion of these criteria with regard to train crash injury. First, some general comments are presented to provide an overview; then, the specific items presented in the table are discussed.

The study of train crash occupant injury can be divided into cases of whole-body accelerations and cases of bodily impact. Pure g-load injury can be defined as occurrences of internal body strain resulting from acceleration of the body as a whole. This condition could occur for the case of body deceleration by a complete restraint system. Train crash acceleration magnitudes, as we shall see, suggest that this type of injury is not the primary problem in practically all occurrences of train crash. Only when the conditions of completely adequate restraint have been met (which is no simple matter), and when no impact occurs, should we address ourselves to the concern of maximum tolerable g-limits.

Consequently, injury criteria based upon acceleration or acceleration-based indices must be viewed in proper context. People in rail crash accidents simply do not get decelerated to death. That is, fatalities and injuries are not caused by excessive whole-body or component accelerations, but by localized impact. Only in the very limited case of total body restraint (approached by, for example, an automotive-type air bag) do acceleration limits have meaning. They enjoy widespread use, primarily because they are measurable; instrumentation is available to record these data. In fact, it is our feeling that the automobile crashworthiness standards injury criteria in FMVSS 208[2] have been selected not so much because they are the most important injury indicators, but because they are data which can be obtained using dummies within the present state-of-the-art. For our study, we are not limited to these values but are free to consider all injury data which may assist us.

The occurrence of impact in the "second collision" resulting from rail-car deceleration can be discussed in terms of injury which occurs as a result of some part of the body being excessively strained (meaning that it has received excessive stress). This stress is caused by local forces or moments exerted on parts of the body. The criteria for injury in this case are (1) the amount of applied force acting on a given area (pressure) and (2) the duration of the force with respect to the response time of the body component upon which it acts. If the duration of the applied load is long compared to the response time of the body component, we have a static case. If the applied load duration is short, however, this is the case of dynamic load, and the ratio of the time of load application to the body-system response time is important since it determines the magnitude of the load that is actually felt. Time of application of load is important, not only because of response effects (that is, the ratio of applied load to felt load), but also to a lesser degree because certain investigators (e.g., Samarco, Burstein, et al.[13]) have reported that bone stress/strain itself is time-dependent.

The correct evaluation of human injury must be based upon strain. Injury severity presented in terms of acceleration, applied load, time duration, or total kinetic energy dissipated represents attempts to recognize (to a varying degree) this criterion. Gadd's Head Severity Index, HSI,[1] for example, correctly recognizes the time dependency of g-loads. Although in part based upon head impact data, it is directed toward the cases of internal stress for restrained-occupant acceleration loads, a condition which may be approximated in the case of impacts applied over very large body surface areas. Certainly, HSI $\leqslant 1000$ is not applicable to accelerations caused by impact upon small surface areas (for example, support posts, or sharp corners of seats).

It is useful to consider a simple quantitative analysis of some of the points discussed. Consider that a train can be designed such that, upon impact into a rigid barrier at velocity, V_c, it will decelerate at a constant rate, a_c, within a crush distance (deflection), δ , during a time interval, t. Then, these values are related through

$$\delta = 1/2\ a_c t^2$$

[13] Samarco, G. J., Burstein, A. H., Davis, W. Q., and Frankel, V. H., "The Biomechanics of Torsional Fractures: The Effect of Loading on Ultimate Properties," Journal of Biomechanics, 4, pp. 113-450, 1971.

and the total energy of the train must equal the work done,

$$F_c \times \delta = \frac{mV_c^2}{2}$$

(where m is the train's mass).

Values of a_c (in g's) versus t (in seconds) for constant values of δ (in inches or feet) are presented in Figure 3-1 to illustrate the magnitudes of deceleration to which a fully restrained occupant could be subjected. If a rail car could be designed to crush a given distance δ independent of impact velocity, the curves of constant δ would be representative of given cars, and the plot would tell us the number of g's which the restrained passenger must accept in the "first collision" to avoid being crushed. Finally, we can graphically present lines of constant initial impact velocity. Now, for varying crush distances, we have a very simple but useful picture of the magnitude of impact velocity that an adequately restrained occupant could accept without exceeding g-tolerance. Note, for example, that a train car designed to produce a constant step acceleration, a_c, which could be crushed 4 feet would allow a restrained occupant to survive impact at velocities greater than 70 mph. The point is that the potential for survivability of high-velocity crashes is large.

This same figure can also be used for "second-collision" analysis. In this case, assume that the passenger is completely unrestrained and that he impacts an object which can be crushed δ feet at an initial velocity of V_c. This allows us to see immediately the accelerations and enables us to approximate the body forces which result for deceleration over impact-surface crush distances, δ.

Because of the predominance of impact-type injury, it is in this second manner that this type of figure, along with the source-of-injury criteria in Table 3-1, can be used to study rail-car crashworthiness. By knowing the velocity at which an occupant impacts a given contact surface which can be crushed a given distance, we obtain a matrix of conditions to which given levels of injury severity can be assigned. Then, by entering this matrix for a given set of rail crash conditions (i.e., crash velocity, car

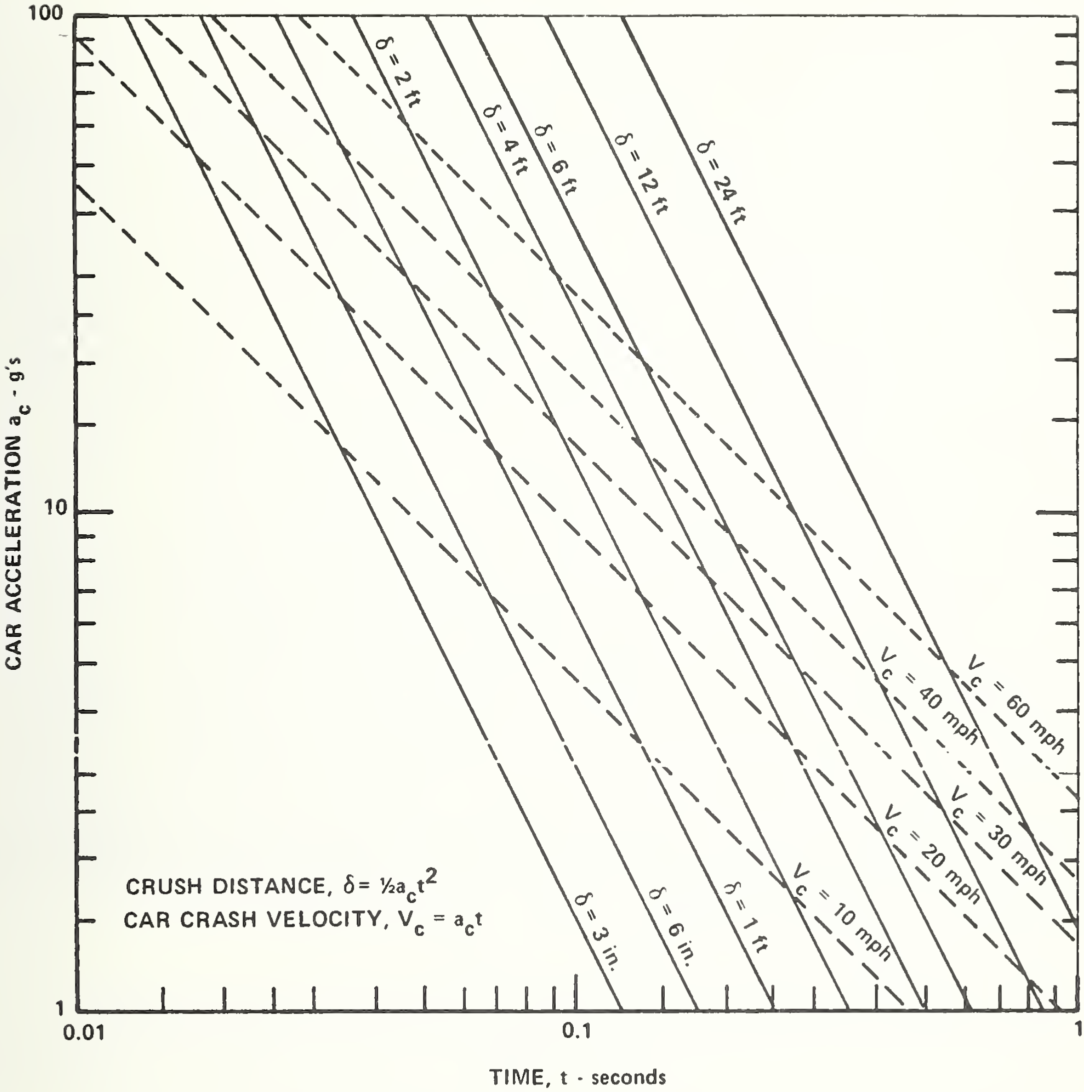


Figure 3-1. Train Crash Dynamics

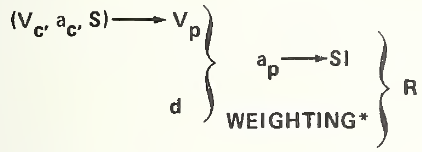
position, occupant position in car, car deceleration profile, etc.), we assess the degree of seriousness of crash conditions for contemporary and proposed rail cars.

The injury criteria defined in the literature and presented in Table 3-1 were reviewed to determine their applicability to rail crash safety. This review is presented as Appendix A.

3.3 PREDICTION OF IMPACT INJURIES

The injury-criteria review presented in Appendix A shows that available injury criteria are reduced for the case of rail crash studies to values of impact forces to the head, chest, and femur areas and to acceleration limits which can be applied to the impact force estimates. Acceleration values can be used where they are properly interpreted as arising from passenger impact upon relatively large-area contact surfaces. From this review, then, it is seen that the head and chest criteria can be incorporated into acceleration/time plots to provide levels of injury as a function of the crash dynamics (i.e., velocity, acceleration, crush distance, surface area, and so on). This approach is feasible when the gross dynamics of the train accident can be assessed with reasonable accuracy (as in straight, longitudinal collisions, where effective train crush force can be predicted) and when the occupant's location in the train and the appropriate interior characteristics can be specified. Examples of the latter situation include the case of a passenger standing in a car area in which the probability of his impacting each of several objects whose force/deflection characteristics are known can be expressed, or -- a situation even more readily mathematically modeled -- the case of a seated occupant having a predictable impact into a seat with known force/deflection characteristics. Other train accidents, not as amenable to computer modeling, are discussed in subsection 3.4.

Table 3-1 and Figure 3-1 and their discussions provide methods of defining crash severity and injury tolerance. To this point, it has become clear that there is a need to couple these results to provide a method for determining the probability of injury from the assumed crash profile. A flow chart of the method used, along with a definition of symbols, is presented as Figure 3-2. Basically, the train structural properties and occupant loading situation are used as inputs to the train crash profile to obtain the relative impact velocity of the passenger. The impact velocity is then used, along with the crush properties of interior components of the rail car, to define a deceleration time history of the occupant. From this, a severity index is assigned based on a cumulative usage of injury criteria available from Table 3-1 -- i.e., Head Injury Criteria, HIC; Chest Severity Index, CSI; and others. Finally, these indices are interpreted in terms of injury severity using the rating scale earlier developed at Calspan.



WHERE

V_c	=	TRAIN CRASH VELOCITY
a_c	=	CAR DECELERATION
S	=	OCCUPANT SPACING WITH RESPECT TO INTERIOR CONFIGURATION
V_p	=	PASSENGER IMPACT VELOCITY
d	=	IMPACTED-OBJECT CRUSH DISTANCE
a_p	=	PASSENGER DECELERATION
SI	=	SEVERITY INDEX (BASED ON HSI, HIC, CSI *et al.*)
R	=	ABBREVIATED INJURY SCALE

*WEIGHTING TO INCLUDE SUBJECTIVE, OR QUALITATIVE, EVALUATION OF INJURY COMPONENTS SUCH AS WINDOW GLASS, SHARP-CORNERED SEATS, ETC.

Figure 3-2. Flow Chart, Crash to Injury

At this time, it is instructive to discuss the injury-severity scale being used in the analysis.

Classification of injury severity is one of the requirements for evaluation of rail crash safety. Fortunately, injury-severity scales developed over the years can be applied directly to the present study. Of the several scales of this type available, the one selected for this study is the American Medical Association's Abbreviated Injury Scale (AIS), shown -- with added severity indices (discussed below) -- in Table 3-2.

The AIS has been adopted by the Department of Transportation and is essentially the worldwide injury-severity research standard used by government,

TABLE 3-2. ABBREVIATED INJURY SCALE

SEVERITY CODE	SEVERITY CATEGORY/INJURY DESCRIPTION	POLICE CODE	CALSPAN SEVERITY INDEX (SI)
0 (Zero)	NO INJURY	0 or D	LESS THAN 250
1	MINOR	C	250 TO 500
	GENERAL ---Aches all over. ---Minor lacerations, contusions, and abrasions (first aid--simple closure). ---All 1° or small 2° or small 3° burns. HEAD AND NECK ---Cerebral injury with headache, dizziness; no loss of consciousness. ---"Whiplash" complaint with no anatomical or radiological evidence. ---Abrasions and contusions of ocular apparatus (lids, conjunctiva, cornea, uveal injuries); vitreous or retinal hemorrhage. ---Fracture and/or dislocations of teeth. CHEST ---Muscle ache or chest wall stiffness. ABDOMINAL ---Muscle ache, seat belt abrasion; etc. EXTREMITIES ---Minor sprains and fractures and/or dislocation of digits.		
2	MODERATE	B	500 TO 1000
	GENERAL ---Extensive contusions, abrasions; large lacerations, avulsions (less than 3" wide). ---10-20% body surface 2° or 3° burns. HEAD AND NECK ---Cerebral injury with or without skull fracture, less than 15 minutes unconsciousness; no post-traumatic amnesia. ---Undisplaced skull or facial bone fractures or compound fracture of nose. ---Lacerations of the eye and appendages, retinal detachment. ---Disfiguring lacerations. ---"Whiplash" - severe complaints with anatomical or radiological evidence. CHEST ---Simple rib or sternal fractures. ---Major contusions of chest wall without hemothorax or pneumothorax or respiratory embarrassment. ABDOMINAL ---Major contusion of abdominal wall. EXTREMITIES AND/OR PELVIC GIRDLE ---Compound fractures of digits. ---Undisplaced long bone or pelvic fractures. ---Major sprains of major joints.		

SEVERITY CODE	SEVERITY CATEGORY/INJURY DESCRIPTION	POLICE CODE	CALSPAN SEVERITY INDEX (SI)
3	SEVERE (Not Life-Threatening)	B	1000 TO 1500
	GENERAL ---Extensive contusions, abrasions; large lacerations involving more than two extremities, or large avulsions (greater than 3" wide). ---20-30% body surface 2° or 3° burns. HEAD AND NECK ---Cerebral injury with or without skull fracture, with unconsciousness more than 15 minutes; without severe neurological signs; brief post-traumatic amnesia (less than 3 hours). ---Displaced closed skull fractures without unconsciousness or other signs of intracranial injury. ---Loss of eye, or avulsion of optic nerve. ---Displaced facial bone fractures or those with antral or orbital involvement. ---Cervical spine fractures without cord damage. CHEST ---Multiple rib fractures without respiratory embarrassment. ---Hemothorax or pneumothorax. ---Rupture of diaphragm. ---Lung contusion. ABDOMINAL ---Contusion of abdominal organs ---Extraperitoneal bladder rupture ---Retroperitoneal hemorrhage ---Avulsion of ureter ---Laceration of urethra ---Thoracic or lumbar spine fractures without neurological involvement EXTREMITIES AND OR PELVIC GIRDLE ---Displaced simple long-bone fractures, and or multiple hand and foot fractures ---Single open long-bone fractures ---Pelvic fracture with displacement ---Dislocation of major joints ---Multiple amputations of digits ---Lacerations of the major nerves or vessels of extremities		

TABLE 3-2. ABBREVIATED INJURY SCALE (Cont.)

SEVERITY CODE	SEVERITY CATEGORY/INJURY DESCRIPTION	POLICE CODE	CALSPAN SEVERITY INDEX (SI)
4	SERIOUS (Life-Threatening, Survival Probable)	B	1500 TO 2000
	GENERAL ---Severe lacerations and/or avulsions with dangerous hemorrhage ---30-50% surface 2° or 3° burns. HEAD AND NECK ---Cerebral injury with or without skull fracture, with unconsciousness of more than 15 minutes, with definite abnormal neurological signs, post-traumatic amnesia 3-12 hours. ---Compound skull fracture CHEST ---Open chest wounds, flail chest; pneumomediastinum; myocardial contusion without circulatory embarrassment; pericardial injuries ABDOMINAL ---Minor laceration of intra-abdominal contents (to include ruptured spleen, kidney, and injuries to tail of pancreas). ---Intraperitoneal bladder rupture ---Avulsion of the genitals ---Thoracic and or lumbar spine fractures with paraplegia EXTREMITIES ---Multiple closed long-bone fractures ---Amputation of limbs		
5	CRITICAL (Survival Uncertain)	A	OVER 2000
	GENERAL ---Over 50% body surface 2° or 3° burns. HEAD AND NECK ---Cerebral injury with or without skull fracture with unconsciousness of more than 24 hours; post-traumatic amnesia more than 12 hours, intracranial hemorrhage, signs of increased intracranical pressure (decreasing state of consciousness, brady-cardia under 60, progressive rise in blood pressure or progressive pupil inequality). ---Cervical spine injury with quadriplegia. ---Major airway obstruction. CHEST ---Chest injuries with major respiratory embarrassment (laceration of trachea, hemomediastinum, etc.) ---Aortic laceration. ---Myocardial rupture or contusion with circulatory embarrassment. ABDOMINAL ---Rupture, avulsion or severe laceration of intra-abdominal vessels or organs, except kidney, spleen or ureter. EXTREMITIES ---Multiple open limb fractures.		
6	FATAL (Within 24 Hours)	K	OVER 2000
	---Fatal lesions of single region of body, plus injuries of other body regions of Severity Code 3 or less. ---Fatal from burns regardless of degree.		
7	FATAL (Within 24 Hours)	K	OVER 2000
	---Fatal lesions of single region of body, plus injuries of other body regions of Severity Code 4 or 5.		
8	FATAL	K	OVER 2000
	---2 fatal lesions in 2 regions of body.		
9	FATAL	K	OVER 2000
	---3 or more fatal injuries. ---Incineration by fire.		
99 X	SEVERITY UNKNOWN		
	---Injured, but severity not known.		
98 Z	PRESENCE UNKNOWN		
	---Presence of injury not known.		

academic, and industrial research teams investigating automobile accidents. This scale originated as an injury classification scheme formulated in 1943 by DeHaven and others at Cornell University Medical College's Crash Injury Research group -- Calspan's crash-injury predecessors -- for evaluation of injuries resulting from light-aircraft accidents.[14] Over the succeeding decades, the approach was developed into a detailed degree-of-injury-severity scale by Calspan's automotive crash-injury researchers, with the assistance of medical specialists and members of the staff of the College and New York Hospital, based on investigation of injuries resulting from thousands of car accidents.[15] That scale has been used, in either its original form or with modifications to amalgamate one or more injury classes or to lengthen the 24-hour accident-fatality criterion, by Calspan and other domestic automotive-accident investigators, and by researchers in England[16] and Australia[17]. A similar but greatly simplified scale using only three injury categories and a 7-day accident-fatality criterion was also employed by the Civil Aeronautics Board.[18]

Although many other approaches to and variations of injury-severity scaling have been developed, the largely universal AIS is based upon a scale formulated by General Motors Corporation which, in turn, was a variant of the

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[14] DeHaven, H., "The Site, Frequency and Dangerousness of Injury Sustained by 800 Survivors of Light Plane Accidents," Unnumbered document, Crash Injury Research, Department of Public Health and Preventive Medicine, Cornell University Medical College, Ithaca, N. Y., July 1952.

[15] Ryan, G. Anthony and Garrett, John W., "A Quantitative Scale of Impact Injury," Report VJ-1823-R34, Calspan Corporation, Buffalo, N. Y., October 1968.

[16] Mackay, G. M., Road Accident Research Report No. 4, Human Engineering Section, Dept. of Transportation and Environmental Planning, University of Birmingham (England), December 1966.

[17] Robertson, J. S., McLean, A. J., and Ryan, G. A., "Traffic Accidents in Adelaide, South Australia," Special Report No. 1, Australian Road Research Board, Melbourne (Australia), 1966.

[18] Safety Investigation Regulations Part 320, Civil Aeronautics Board, U.S. Dept. of Transportation, Washington, D. C., 18 May 1966.

Calspan degree-of-injury-severity scale. The AIS was developed in 1968 and 1969 by an Ad Hoc Committee on Vehicle and Injury Scaling which represented all domestic automobile manufacturers, most U.S. university-based car accident investigators, and several European research teams; its development was supported and encouraged by the American Medical Association, the Automobile Manufacturers Association, and the Society of Automotive Engineers.[19] Thus, the AIS represents the collective efforts of vehicle crash investigators, medical specialists treating crash injuries, and automotive engineers and manufacturers over a period of 30 years.

Like its precursors, the AIS is based on previously normal life expectancy of the victim, and on assessment of his injuries within 48 hours of the accident. In use, the injury encountered in each body area is assigned to one of nine injury-severity categories that have been established on the bases of the energy absorbed by the victim and the threat to his life. (Refer to Table 3-2.) Then, the most-severe (highest-numbered) injury in any body area is used as the overall degree of injury (whole-body injury) for the victim. As earlier indicated, an injury is not classified as fatal unless the victim dies within 24 hours following the accident. The "police code" column in the table permits approximate correlation of injury-severity ratings with the cruder and broader injury ratings commonly assigned by police accident investigators (as contrasted with research accident investigators).

Although this injury-severity scale has been used extensively in automobile accident investigation, a coupling of the train crash to this scale through acceleration/time-based severity indices represents a move to obtain a closed-form representation of the crash-injury prediction scheme. In effect, the progressive stages of injury in the scale are assigned severity indices of 250 to over 2,000.

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[19] States, John D., M.D., "The Abbreviated and the Comprehensive Research Injury Scales," Paper published in Proceedings of Thirteenth Stapp Car Crash Conference, Society of Automotive Engineers, Inc., New York, N.Y., 1969.

The severity indices of 250 to 2,000 were matched to the injury-severity scale (Table 3-2) through consideration of the head and chest injuries described under each injury category and experiential judgment of these injuries in terms of the index numbers and injury data upon which the indices were formulated.

The injury severity indices are presented in the right column of Table 3-2. As stated earlier, they are not a part of the basic table but represent an interpretation of this table in terms of total body-impact velocity and contact-surface crush.

The net result of the previous assumptions regarding crash severity and injury severity can be depicted on a single carpet plot, Figure 3-3, once the passenger impact velocity and deceleration (crush) distance are known. In addition, these relationships have been used as inputs to the rail crash model to enable computer determination of the degree of injury of any given occupant based upon car number, position in car, etc., in any given crash.

3.4 PREDICTION OF INJURIES IN GENERAL COLLISION ENVIRONMENT

Areas of injury and fatality due to body impact which are difficult to address occur when the train dynamics during collision are not predictable (as in derailments involving additional car collisions or car rollovers resulting in ejection of passengers through windows and consequent passenger lacerations or crushing) or when the occupants' positions in the train and the surrounding interior characteristics are such that the nature of impacts is not predictable or involves small, sharp, or irregular objects. Such impact may cause immediate death (e.g., by crushing) or may result in sprains, dislocations, contusions, abrasions, and lacerations where the degree of seriousness is dependent on many factors, including the body component affected. Or, trapping of passengers in the wreckage of overturned cars may cause their death by asphyxiation, drowning, or fire, or by lack of immediate medical attention for injuries. A review of actual train crashes[20] shows that,

[20] Reed, Robert C., Train Wrecks, Superior Publishing Company, Seattle, Wash., 1968.

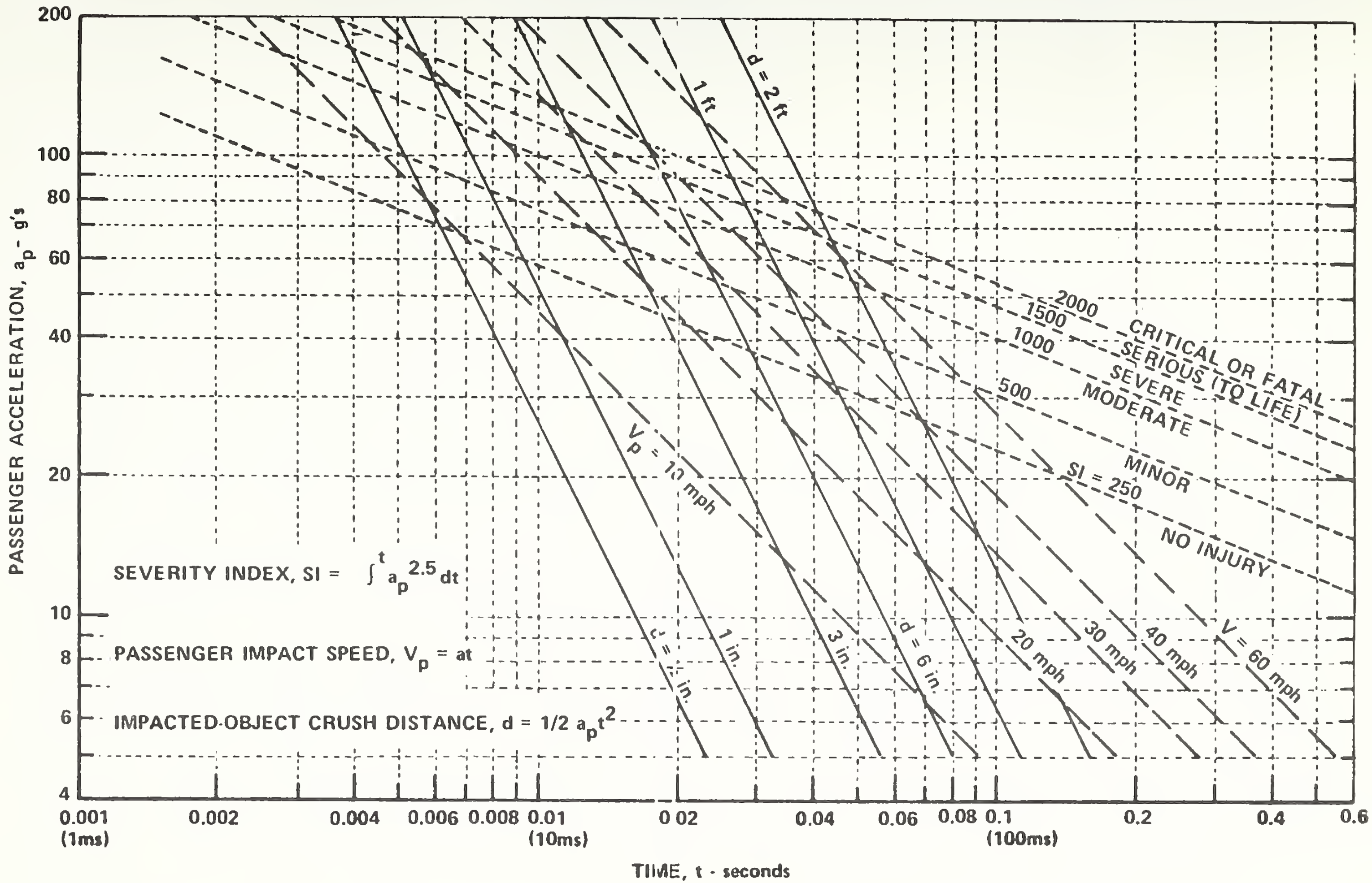

Figure 3-3. Degree of Injury Severity

in fact, many primary injury mechanisms occur which do not involve impact. These include injuries and fatalities caused by fires, drownings, and electrical and other hazards. The thrust of this investigation, however, is directed at the determination of passenger injuries and fatalities due to car penetration and passenger impact in severe frontal collisions and front-to-rear collisions. A review of accident records for this type of collision shows that when it does occur the results, in terms of fatalities and injuries, are frequently catastrophic. (See Section 8.)

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†REFERENCE COLUMN (TABLE 3-1)

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4. INTEGRATED TRAIN/OCCUPANT CRASH MODELING

4.1 INTRODUCTION

The integrated train/occupant model consists of a train collision model and an occupant model which incorporates the bodily injury criteria discussed in Chapter 3. The occupant model and its coupling to the train collision model are described in this section, together with a gross description of the train collision model. The train collision model is based on the structural and dynamic characteristics of the coupled cars; hence it is a series of car structural models coupled together. Characteristics of existing cars are discussed in Chapter 5, followed by a more detailed discussion of the car structural model, and then by a first order evaluation of the performance of existing generic types of constructions in a collision. With this as a background, the actual definition and selection of car structural and interior inputs for the train collision model is made in Chapter 6.

4.2 MODEL DESCRIPTION

4.2.1 Purpose and Overall Operation

The integrated train/occupant (analytical) model was developed for this program to determine the effects of parametric variation of rail-car number/location (in a train), weight, strength, and impact velocity on passenger injury severity resulting from a train collision for assumed occupant spacings (distances from objects they could impact) and impacted surfaces. Although this model can analyze collisions of trains containing as many as 20 cars, the present study is limited to trains consisting of one to ten cars. All cars except the first to crash are assumed to maintain constant mass during deceleration. The mass of the first car decelerated is assumed to decrease linearly with its crushing. Cars are represented as connected by nonlinear, inelastic springs. Each car is modeled as containing a single mass representing a passenger who may be restraining himself (or may be restrained by, for example, sliding friction) or who is free to move until impacting an interior surface.

The train-collision model accepts inputs defining the collision (impact velocity, number and type of cars in each train, and design data for each type of car) and predicts the accelerations and deformations of each car. These data are the input to the occupant model, which determines the magnitudes and durations of the resultant passenger accelerations and compares these values with stored bodily-injury criteria to predict probable extent of injuries and fatalities among the passengers as functions of the types and locations of cars in which they are riding, their locations within those cars, and the crash conditions.

4.2.2 Functioning

The approach taken to determine passenger injury severity for a given crash situation is as follows:

1) For a given train configuration and total velocity change during impact, the model is run to determine the velocity of the car occupant relative to the train after the occupant has moved each of a number of specified spacings (distances from objects he could impact) relative to the train. The spacings used are 2, 4, 6, 9, 12 and 24 feet.

2) Given these relative velocities, the car occupant is assumed to undergo a constant deceleration such that he stops in one of a number of specified (impacted-object) crush distances. Crush distances used are 1/4, 1, 2, 4, and 12 inches.

3) From the occupant deceleration and time, the occupant severity index (discussed in Chapter 3) is computed for each rail car for each of the specified occupant spacings and crush distances.

A weighting can then be assigned to each condition to approximate each rail-car interior (that is, a distribution of occupant spacings and impacted-surface penetrations or stiffnesses is established for that rail car), and an overall severity index for an occupant of that car can in theory be determined.

A simplified schematic diagram of a typical train configuration simulated is provided in Figure 4-1. As shown, the model consists of representations of an optionally moving barrier, a number of rail cars, and a passenger in each rail car who is associated with a variable occupant spacing and a variable crush distance. Forces acting on the rail cars are interpolated from an input tabulation of car structural characteristics. The computational sequence is as follows:

1) Given the positions and velocities of each car relative to a coordinate system fixed at the car position at the moment of impact, calculate the car deflection (crush distance). Note that, with the exception of the deflection calculated between the first car and the barrier, the deflection is taken to be one-half the distance between car displacements since it is assumed that the crush is shared equally among adjacent cars:

$$\delta_i = \frac{1}{2} [X_c (i) - X_c (i-1)]$$

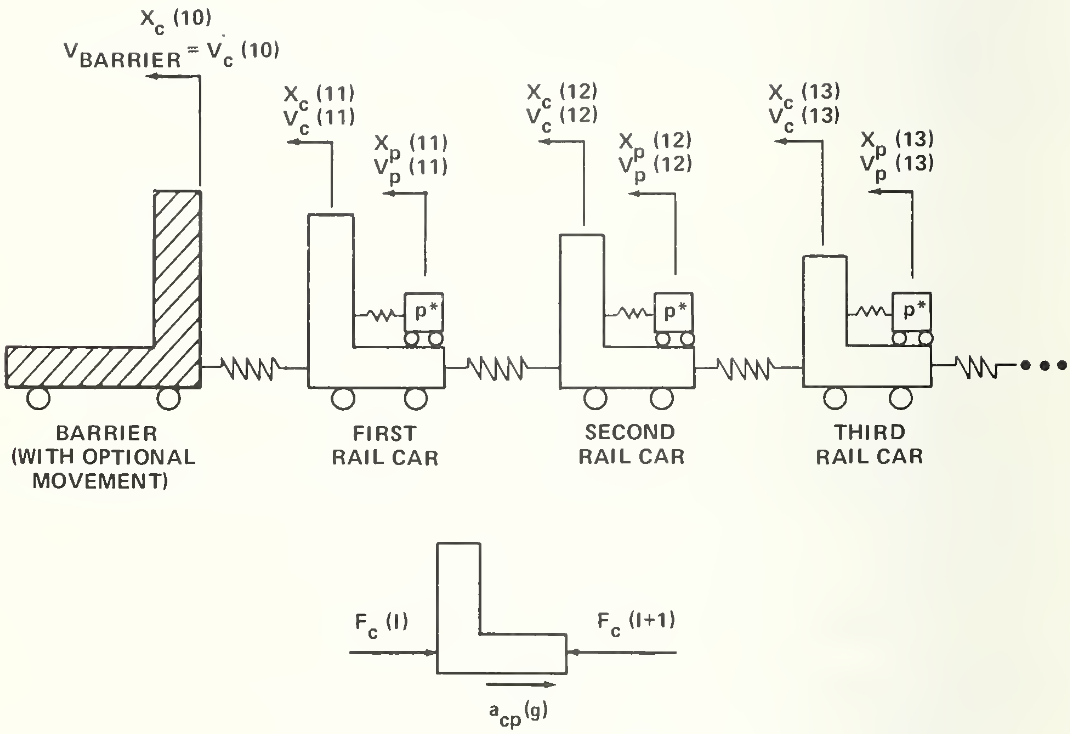
The deflection of the first car is simply:

$$\delta_{11} = X_c (11) - X_c (10)$$

2) Knowing the deflections, the crush forces are interpolated from the input force/deflection characteristic of the car, and the deceleration of the car is computed:

$$\ddot{X}_{ci} = (F_{i+1} - F_i) \, g/WGT_i - (ACO) \, g$$

where F_i is the crush force of spring i,
g is the acceleration due to gravity,
WGT_i is the weight of car i, and
ACO is the train braking deceleration.



*p = PASSENGER (OCCUPANT)

Figure 4-1. Simplified Schematic Diagram of Typical Train Configuration Modeled

3) The car acceleration is then integrated over a time increment to obtain the updated position and velocity.

4) The passenger deceleration is similarly integrated to obtain velocity and displacement.

After the updated positions and velocities have been obtained, the relative velocity and displacement of the passenger with respect to the car are computed. When the passenger reaches each of the specified spacing values (i.e., travels a given distance relative to the car), a severity index is computed for each of the specified crush distances, assuming a constant deceleration over the crush distance to a zero relative velocity, as follows:

$$SI = \int^{t} a_p^{2.5} dt$$

where $a_p = \frac{V_r^2}{2\ dg}$, a constant over distance d

$$SI = a_p^{2.5} \int dt = a_p^{2.5} \frac{V_r}{a_p} = a_p^{1.5} V_r$$

where V_r is the relative velocity between the passenger and the car,

d is the crush distance, and

a_p is the passenger deceleration.

The computed severity indices are then tabulated as a function of spacing and crush distance for each car of the train. Note that the model does not continue to compute the severity index once the occupant impacts and crushes a given object. Actually, some small increase in severity index would occur during "ridedown," being dependent on the car deceleration. Since, however, the train's decelerations are very small compared to the impact decelerations, they have been ignored in the analysis.

4.3 APPLICATION OF MODEL

Application of the integrated train occupant model requires the inputs defined in Subsection 4.2 for the occupant model, together with specific inputs for the train collision model. In Chapter 5, in order to define the exact nature of the train collision model and its inputs, we first review and categorize the characteristics of existing cars (Subsections 5.1 and 5.2) and then proceed to a definition of car structural inputs and their relationship to generic car construction types (Subsection 5.3 through 5.5). Car structural inputs representing existing car construction practice are selected in Chapter 6 (Subsection 6.1) and finally car structural inputs are selected for the purpose of investigating possible improvements to existing construction practice (Subsection 6.2).

5. CHARACTERISTICS OF EXISTING RAILCARS

5.1 SELECTION OF REPRESENTATIVE CARS

In order to determine a realistic range of car characteristics to be used as inputs for the car model, five cars were selected as being representative of transit cars now in operation in the U.S. The chief criterion for selection of the five cars was that they provide a representative cross section of existing cars in terms of:

Type of construction and materials used

Level of specification buff load (longitudinal load applied at coupler pocket)

Dates entering service

Builders and users

Additional criteria to be considered were that the five study cars represent a relatively large number of cars in service, and that they represent a significant range in terms of car weight and car length.

A summary of 12 cars which generally represent these variables is shown in Table 5.1. After further consideration of this information, the following cars were selected to be the study cars.

BART Car

The BART Car, built by Rohr, represents modern lightweight aluminum extruded construction is now in service in the Bay Area Rapid Transit (BART) in San Francisco. The specification buff strength is relatively low (200,000 pounds with no permanent set). Rohr is now building aluminum cars having similar construction features for the Washington Metropolitan Area Transit Authority (WMATA).

TABLE 5-1. CHARACTERISTICS OF REPRESENTATIVE CARS

Car or Agency	Builder	Service Date	Quantity (Approx)	Buff Load (K)	Weight (K)	Length (Feet)	Weight Per Ft. (K per ft)	Material	Const.	Comments
Bart	Rohr	'72	147+	200	70	70	1.0	Alum. Ext.	Side Sill	Modern Alum. Extrusion Design
Path	St.Louis Car	'66	220	400	58.4	51	1.14	Alum.		
Del. River Port Auth.	Budd	'68	75	200	75	67	1.11	Stainless Corrugated		Lightweight
Cleveland Airporter	Pullman	'68	20	200	65	70	0.93	Stainless		Lightweight Modern
NYCTA R-33	St.Louis Car	'62	540	200 (50% yield)	73	51	1.42	Cor Ten Hi Tensile	Side	Old Style Heavyweight
R40/42	St.Louis Car	'67	-	200	68	60	1.14	Cor Ten Hi Tensile	Ctr Sill	
R-44	St.Louis Car	'72	350	250 (50% yield)	82	75	1.10	Stainless Steel	Side	Like SOAC
R-46	Pullman	Under construction	800	400	-	75	-	Stainless Steel		Similar to R-44
MBTA	Pullman	'70	76	200	64	70	0.92	Steel and Alum.	Side	Lightweight alum. sheet metal
CTA (old)	Pullman	pre '62	-	100	-	48		Alloy steel		Older type construction
CTA (new)	Budd	'70	-	200	45	48	0.94	Stainless Steel		Lightweight
Silverliner " "	Budd St.Louis Car G.E.	'59	250	800	101	85	1.19	Stainless Corrugated	Ctr Sill	800 K Buff

R-33 Car

The R-33 car was built by the St. Louis Car Co. for the New York City Transit Authority (NYCTA). This car is more representative of old style heavyweight steel design than the R-40 series, also shown in Table 5.1. The design employs high tensile steel. Specification buff strength is 200,000 pounds at 50% of the yield strength of the material. The R-33 has been in service since 1962 and should see at least ten more years of service. Its significance is increased by the fact that there are over 500 cars believed to be existing.

R-44 Car

The R-44 car represents a contemporary approach to medium weight steel design. High strength, stainless low alloy steel is employed. Specification buff strength is 250,000 pounds at 50% of material yield strength. The construction is similar to the experimental state-of-the-art car (SOAC) with some differences in the superstructure and in construction details. Approximately 350 R-44 cars were delivered by St. Louis Car to NYCTA in 1972.

MBTA Car

The MBTA car was built by Pullman Standard for the Massachusetts Bay Transportation Authority and entered service after 1970. The car employs aluminum exterior construction, with a low alloy steel end underframe. This car has the lightest weight per unit length of any reviewed (.92 Kips per foot). Design buff load is 200,000 pounds at 90 percent yield stress.

Silverliner

The name Silverliner has been applied to commuter cars built by Budd Co., St. Louis Car and G.E. essentially to the same specifications. The car is in use on the Penn Central and the Reading and is generally categorized as a commuter car rather than a transit car.* The car was selected primarily because the 800,000 pound buff load specification appears to represent a buff load at least as high as any buff load which has been specified for transit cars; hence it is used to represent an upper limit of buff load for existing urban rail cars. The Silverliner is self powered, employs stainless steel construction, and employs a "buffing beam" at the front end, instead of the "anti-climber" traditionally employed by transit cars.

A number of other cars were eliminated in the process of this selection. Noteworthy cars which were considered but not selected were:

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* There appears to be no clear technical basis on which to differentiate a commuter car from a transit car. The same lack of clarity exists in the operating systems; the BART system, for example, is as much a commuter system as it is a rapid transit system, and has maximum speeds (80 mph) higher than the speed limit (79 mph) on large portions of commuter railroad lines which do not employ automatic signalling. The accepted means of categorization appears to be that commuter cars operate on railroad lines whereas transit cars operate on particular properties such as NYCTA or BARTD. Platform height on railroad lines is generally below car floor height. Consequently commuter cars employ steps from car floor to platform which prevent the use of continuous side sills. For this reason, commuter cars and inter-city cars have traditionally employed center sill construction (buff loads carried primarily by longitudinal beams below floor level along the car center line) rather than the side sill construction almost always employed by transit cars. Commuter cars may or may not be specified for 800,000 pound buff loads, which is an FRA requirement for all inter-city equipment not classified as "lightweight" (train, including locomotive, less than 600,000 pounds). Most commuter cars are built to the 800,000 buff load requirement; hence they are generally compatible in strength with the mainline inter-city cars which operate on the same lines.

Path Car

This car was built by St. Louis Car for the Port Authority, Trans Hudson (PATH) and entered service in 1966. The car employs relatively heavy aluminum sheet metal-stiffener construction (compared to the BART car) and was not chosen because this type of construction appears less likely to be repeated than the BART aluminum construction. The construction of the PATH car is also similar to the MBTA Silverbird construction.

DRPA Car

This is a corrugated stainless steel car built by Budd for the Delaware River Port Authority (DRPA) and introduced to service in 1968. The car employs corrugated stainless steel construction, as does the Silverliner. Specification buff load is 200,000 pounds. The car was not chosen because it does not represent a clear cut generic alternative to the cars which were selected.

R-46

The R-46 car is now being built by Pullman Standard for NYCTA, and will be placed in service shortly. The general approach to construction of the superstructure is believed to be similar to the approach used on the R-44. Specification buff load is 250,000 pounds at 50 percent of material yield strength. Significantly, specification requirements for front end construction are more severe than for any of the cars reviewed.* Required collision post base shear strength is 300,000 pounds per post and required corner post base shear strength is 200,000 pounds per post. The R-46 was not selected as one of the five study cars because it is not yet in service and because it is believed that its force-deflection characteristics will fall within the range covered by the other cars.

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* The significance of the R-46 specification requirements for front end construction is that they relate more strongly to the problem of override during crashes than do specifications for the other cars reviewed. The override problem is defined and discussed in Chapter 8.

CTA Car (Old)

This car represents older type low alloy steel construction. It was built by Pullman for the Chicago Transit Authority (CTA) and introduced to service well before 1962. This car has a lower design buff load than any car selected (only 100,000 pounds versus 200,000 pounds minimum for those selected) but has not been duplicated in recent years.

CTA Car (New)

This is a lightweight stainless steel car built by Budd and introduced to service in the CTA in 1970. The car was not chosen because the construction similarities with the Silverliner, also built by Budd, is an example of lightweight stainless steel construction. The Silverliner has a higher strength level than the CTA car because it is built to higher mainline buff load requirements.

Cleveland Airport Car

This is a lightweight stainless steel car built by Pullman Standard. It has been in service since 1968 but only about 20 cars have been delivered. It was not chosen as a lightweight representative because the MBTA car is slightly lighter in weight per unit length and has been produced in larger numbers.

Additional descriptive material on the five cars which were selected is included in the following sub-section.

5.2 CAR DESCRIPTIONS

5.2.1 Silverliner Car

Silverliner is the popular name given to the Budd-built commuter coach equipped for self-propelled operation on the Philadelphia commuter lines operated by the Penn Central Railroad and the Reading Company. The cars were dubbed Silverliners because of their longitudinally ribbed, shiny stainless steel exterior. (See Figure 5-1) The cars were derived from the Pioneer III which was a new generation, lightweight, stainless steel coach, built by the Budd Comany in the

Figure 5-1. Exterior of Silverliner Car

mid-1950's for high-density passenger services and first tested on the Pennsylvania Railroad. Six prototype cars, equipped with an electric propulsion system that could be operated over the Pennsylvania Railroad's 11,000-volt AC catenary, were built in the late 1950's and ran for 2 years to evaluate their performance. In the early 1960's the City of Philadelphia and the State of Pennsylvania purchased 55 of these cars equipped with Budd lightweight welded trucks. Thirty-eight of these cars were assigned to the Pennsylvania Railroad's commuter lines in and around Philadelphia as well as to their off-peak-hour, high-speed main-line service between Philadelphia and Harrisburg. The remaining 17 cars were assigned to the Reading Company for their Philadelphia-area commuter services. Because of the similarity between the Pennsylvania and Reading power-distribution systems, the cars were basically identical. During normal operation, the railroads operate Silverliners in train lengths of one to four cars, even though five- or six-car trains have been noted. During off-peak hours, one or two-car trains are common.

The Silverliner measures 85 ft. across the coupler faces and has 59 ft., 6 in. truck centers. The car weights vary from a ready-to-run weight of 101,380 lb. to a maximum loaded weight of 121,070 lb. The loaded weight is based on 127 seated passengers and no standees. The car can accommodate standing passengers even though the original intent was not to carry any. Operating experience has shown that the standing passenger is generally the rule rather than the exception during rush-hour operation. A weight of 155 lb. per passenger can be used to determine additional live load if desired. Some of the cars were also equipped with a toilet; the seating capacity of each of these cars was reduced to 125 to accommodate the toilet.

The cars were built almost entirely of high-strength stainless steel. Most exposed surfaces are made of type 301 stainless steel, and most of the remaining structure is type 201 stainless steel. Basically, the car consists of an underframe and floor structure, a side frame structure, and a roof structure. The underfloor structure is a center-sill/side-sill type construction. The center sill transitions into a substantial end underframe structure which houses the coupler draft gear. Anti-climbing features are typical of Main Line passenger cars, consisting of tight lock coupler, buffer beam, and coupler carrier and truck attachments to car body designed to AAR strength requirements. A pair of collision (antitelescoping) posts forms the end door frame. These posts are designed for an ultimate shear load of 300,000 lb each, as specified in AAR Passenger Car Construction Requirements. The car structure as a whole is designed to withstand an 800,000-lb load applied at the coupler draft gear with no permanent set of the car structure. This, too, is specified in the AAR requirements.

The car interior is relatively simple (Figure 5-2). The seats are the walk-over type, where their facing direction can be changed by simply rotating the seat back. (See Figure 5-3.) The seats are arranged in a three/two configuration and are generally all fore- and aft-facing. There are some

Figure 5-2. Interior of Silverliner Car

Figure 5-3. Changing Facing Direction of Silverliner Seats

center-facing seats at the ends of the car, as shown in the foreground of Figure 5-2. Baggage racks are provided on the two-seat side of the car (Figure 5-2). The doors are located at the ends of the cars, and passengers are protected from the elements by a vestibule partition and vestibule doors. The side and end walls are faced with melamine plastic, and the floor is tile. An operator's cab is located in each vestibule, so the cars can be operated from each end -- a necessity for single-car operations.

5.2.2 R-33 Car

The R-33 (Figure 5-4) is a subway car built by the St. Louis Car Division of General Steel Industries, Inc., for the New York City Transit Authority. The cars were ordered in 1962 and were delivered from November 1962 to October 1963. A total of 540 cars was built, and they were intended for use on NYCTA's IRT lines. Forty of the cars were built to operate as single cars and have motorman's cabs at each end. Although these cars are not operated singly, they retain that capability. The remaining 500 cars must be operated as 250 married pairs because the propulsion, control, and electrical equipment is common to both cars in a pair. The cars used in

Figure 5-4. Exterior of R-33 Car

married pairs have cabs at either end but not on the coupled ends. The cars are designed to operate in trains of up to 12 cars as required by the purchase specification; however, eight- or ten-car operation seems to be normal operating procedure. The 12-car upper limit is based on station platform length. Most NYCTA platforms are 600 ft long. Each R-33 car measures 51 ft, 4 in. over its coupler faces, so a 12-car train is approximately 600 ft long. Because of the tight clearances of the IRT lines, the R-33 is only 8 ft, 9-1/2 in. wide in comparison with the 10-ft-wide cars used elsewhere on the NYCTA. The truck centers on the R-33 are spaced at 36 ft. They are designed to operate on a 90-foot-radius curve -- which, again, is a requirement of the IRT lines.

The construction of the R-33 follows standard practice. The underfloor consists of side sills and center sills. The sills are attached to the body bolster, and the underfloor overhang is a strong, stiff framework which accommodates the coupler draft gear. The end underframe also contains an end sill, to which is attached an anticlimber. The anticlimber runs the full width of the car and is made up of a pair of channels, welded flange-to-flange to form an E-shaped section. The sills are reinforced in the areas where doors are placed in the side frame. The side frame consists of longitudinal members forming the upper and lower frames of the windows. The vertical members (carlines) are used to form window and door frames. There are three sets of side doors per side. The side and roof are sheathed with flat material. On the side frame, thin-gage corrugated steel sheet is used to reinforce the side sheathing. The construction material is low alloy steel.

The R-33 cars are equipped with 44 seating positions. The seats are of the bench type and are all center-facing. (See Figure 5-5.) The seat construction is a basic tubular framework with a molded-fiberglass contoured seat. There is no padding on the seats. The car is primarily intended for use by standing passengers. The intent is to accommodate 136 passengers over and above the 44 seated passengers. In the so-called crush condition, 156 standing passengers can be accommodated. For standing passengers, the car is equipped with swing-type handholds, hung from the roof. Stanchions are also

Figure 5-5. Interior of R-33 Car

provided in the door areas. Also, low railings provided at the end of each bench seat serve as grab handles for standing passengers. The weight of the R-33 varies from a ready-to-run weight of 72,368 lb to a weight with crush load of 100,938 lb. With a normal (180-passenger) load, the weight is 98,138 lb. The passenger loads are based on 140 lb per passenger. These weights are for an "A" (self-propelled) car. The weight of a "B" (unpowered) car is 570 lb greater.

5.2.3 R-44 Car

The R-44 (Figure 5-6) is the latest car to be put in service on the New York City subway system. The cars were ordered in 1970 from the St. Louis Car Division of General Steel Industries, Inc. Deliveries were made in 1970 through 1972. The R-44 is unique in New York City Transit Authority service in that it is 75 ft long. Until introduction of the R-44 car, the longest New York City subway car was 60 ft long. The R-44 is also unique in that it is designed for speeds of up to 70 mph, while most NYCTA cars were designed for maximum speeds of only 45 mph. There were a total of 352 R-44's delivered by the manufacturer.

Figure 5-6. Exterior of R-44 Car

The R-44's are operated in married pairs, which is necessitated by shared traction, braking, and electrical equipment. NYCTA maintains the cars in sets of four (two coupled pairs), which are usually coupled to form an eight-car train. There is no plan to run cars in trains greater than eight cars, since the 600-ft station-platform limitation prevents more than eight 75-ft cars from being used. Of the 352 cars delivered, 300 are being used on NYCTA's "B" Division. The remaining 52 are operated on the Staten Island Rapid Transit Line.

The construction of the R-44 is similar to that of many rapid-transit cars, having side sills but no center sill. The side frames accommodate four side doors, which eliminates any type of continuous longitudinal member; however, there is a substantial longitudinal member at the roof-to-side-frame transition (roof rail). The construction material is basically all low-alloy steel with a small amount of stainless steel sheathing (but it is rather insignificant). There are no collision posts in the R-44. The sheet-metal and fiberglass end-frame structure is to prevent intrusion of another car into the passenger compartment in the event of a train collision. The car has an anticlimber, which is welded to the end underframe structure. The anticlimber is made up of a pair of channels, welded back-to-back. The car is also equipped with a pneumatic coupler centering device which is to ensure coupler contact in a car-to-car impact.

The R-44 interior is a departure from the standard New York City subway car. Whereas most NYCTA cars have center-facing seats, the R-44 has a mixture of fore- and aft-facing and center-facing seats. (See Figure 5-7.)

Figure 5-7. Interior of R-44 Car

The "A" (control) cars have 72 seats, and the "B" (mating) cars have 76 seats. In an A car, there are 48 center-facing seats and 24 fore- and aft-facing seats. A B car has 28 fore- and aft-facing seats. The seats themselves are molded fiberglass with tubular steel frames. There is no padding on the seats, and the fore- and aft-facing seats are fixed, with one half facing one direction and the other half facing the opposite direction. For the 200+ standing passengers, a number of stanchions are provided. Eight floor-to-ceiling stanchions are located slightly off the car centerline between the center-facing seats, and six stanchions run between the fore- and aft-facing seat backs and the ceiling. There are also a series of fixed handgrabs which extend from the car ceiling; these are a departure from the swing type used on previous cars. At each door opening, there is a windscreen which forms a barrier around the door. The windscreen has a tubular framework with a plymetal lower panel and a glass upper panel. The floor is tile.

5.2.4 BART Car

In 1969, the Bay Area Rapid Transit District (BART) awarded a contract to Rohr Industries, Chula Vista, California, to build 250 rapid-transit cars for the new Bay Area Rapid Transit system. These cars were to advance the state-of-the-art in the development of rapid-transit cars.

The car order was split between 150 "A" cars and 100 "B" cars. The A cars are 75 ft. long and have a control cab at one end. (See Figure 5-8) The B cars are 70 ft. long and do not have a control cab. The B cars cannot be operated as an end car on a train. The normal operating procedure is to run trains of two to ten cars that include an A car at either end and B cars in between. (See Figure 5-9) A two-car train consists of two A cars, coupled back to back; a ten-car train consists of two A cars (one at each end) with eight B cars in between. At this time, four- or five-car trains are normal. (A four-car train consists of an A-B-B-A combination, and a five-car train consists of an A-B-B-B-A combination.)

Empty car weights vary from 55,000 lb. for a B car to 56,500 lb. for an A car. Fully loaded weights approach 90,000 lb. for either car.

Figure 5-8. Front End of a BART Car

Figure 5-9. Typical BART Train (Six Cars Shown)

The construction of the BART car is somewhat of a departure from standard practice in rail-car construction. The cars are made primarily of riveted, bonded, and welded aluminum. The only steel used is in the bolster and end underframe assemblies. Low-alloy steel is used for these assemblies, and it is riveted to the aluminum underframe structure. The underframe between bolsters consists simply of aluminum side sills (in actuality, the side sill extrusions are an integral part of the car side frame), with no center sill. There are evenly spaced transverse floor beams, along with intermittent intercostals which act as underfloor equipment supports. The steel end underframe and bolster includes the buffer sill which on an A car includes an anticlimber at the cab end. The coupler draft gear hangs from the end underframe, and a leaf-spring-type coupler centering device is used. A unique feature of the steel underframe is the bolted connection between the bolster and end underframe. The bolts are designed to fail at approximately 180,000 lb. When this occurs, the bolster end of the end underframe would crash against the bolster structure and absorb energy. This, of course, would only take place in a severe impact condition, such as a collision at speeds greater than yard movement speed. The side frame structure consists of a series of six extrusions which are riveted together. The longitudinal stiffening elements are an integral part of these extrusions. They are not continuous members because of the two-door cutout per side; however, the lower and upper extrusions which form the side sill and roof rail are continuous from end frame to end frame. There are also a number of carlines which form the door and window mullions. These are riveted to the side frame. The roof structure is a bonded aluminum-sandwich construction consisting of face sheets with a core consisting of foam and transverse Z-extrusions. The car end frames form the interior end bulk-heads and serve as end-door pockets. There is no specific collision-post structure; however, some minimal resistance to intrusion would be provided by the end frame.

The car interior (Figure 5-10) is designed to provide as much passenger comfort and convenience as possible. The seats are foam-padded, vinyl-covered, contoured, two-passenger seats that are cantilevered from the side frame. They are fixed-direction seats and are designed for loads which are based on durability requirements. Handgrabs for standing passengers are provided on the aisleway corner of each seat. There are 72 seating positions in each A and B car; however, each car is designed to carry a number of standees. (Normal passenger loads are 120 total for an A car and 132 total for a B car; crush loads are 216 passengers for an A car and 228 passengers for a B car.) Windscreens are provided at each door.

Figure 5-10. Interior of BART Car

The cars are carpeted, providing a quieter ride and some degree of passenger protection because of the soft surface. Another passenger-oriented feature provided is pneumatically extended diaphragms between cars which provide a safe, protective passageway between cars.

5.2.5 Silverbird Car

Silverbird (Figure 5-11) is the popular name given to the buffed (shiny)-aluminum-side rail cars used by the Massachusetts Bay Transportation Authority's (MBTA's) Red Line. Seventy-six of these cars were built by the Pullman-Standard Division of Pullman Incorporated in 1968 and 1969. Of these cars, 24 are equipped for single-unit operation, having a control cab at either end. The remaining cars include 26 "A" cars and 26 "B" cars; each of these cars has a control cab at one end and must operate as an A-B married pair. This is necessary because of shared car propulsion, braking, and electrical equipment. The cars can be coupled to form trains of up to eight cars, and such trains predominate in normal daily service. During off-peak hours and weekends, two-, four-, or six-car trains are operated depending upon the service required. Single-unit cars are never operated alone even though they retain that capability.

The single-unit cars are equipped with 60 seating positions. Of the 60 seats, 12 are center-facing, 24 are forward-facing, and 24 are rear-facing. (See Figure 5-12.) Each A or B car has 64 seats. Single-unit cars are designed for a crush load of 228 passengers, and the A and B cars each have a crush load of 239 passengers.

Figure 5-11. Exterior of Silverbird Car

Figure 5-12. Interior of Silverbird Car

The car structure is aluminum except for the end underframe and buffer sill, which are made of low-alloy steel. The car roof is made of corrugated aluminum sheet. The structure is very similar to that which is more or less standard for existing rail cars except for the aluminum. The cars are equipped with full-width anticlimbers at either end. Each anticlimber is simply a pair of channels, welded flange-to-flange in the form of an E-shaped section. Each car measures 69 ft, 9-3/4 in. over the pulling faces and has 51 ft, 0 in. truck centers. Car weights vary from a light weight of 60,048 lb for a B car to a fully loaded weight of 96,382 lb for an A car.

The seats are wall- and floor-mounted and consist of vinyl-covered foam padding on a tubular framework. The aisleway corner of each seat provides a protruding handgrab for standing passengers. The back face of each seat is an aluminum sheet. There are no roof-mounted handgrabs for standing passengers, but 12 stanchions are provided at the doorways. (There are three side doors, each having two windscreens and two stanchions, on each side of the car.) Each stanchion runs from floor to ceiling and forms the inside edge of a windscreen. The windscreens are thin-gage metal panels which extend from the floor to approximately the height of the seat back. As in most rapid-transit cars, the Silverbird's floor is tile.

5.3 GENERAL CRASHWORTHINESS DATA

Tables 5-2, 5-3, 5-4, 5-5 and 5-6 present crashworthiness data obtained or calculated for the Silverliner car, the R-33 car, the R-44 car, the BARTD car, and the Silverbird car, respectively. Three sections within each table, numbered I through III, summarize general crashworthiness data in the following form:

I. General Information: Name, builder, average age, numbers in service, size and weight.

II. Structural Crashworthiness: Strength characteristics and brief qualitative comments on general running stability and override tendency.

III. Interior Configuration: General information on windows, seats, stanchions, degree of interior hostility, subjective evaluation of interior layout and degree of compartmentalization.

The generation of the car structural model and the means of determining appropriate structural and interior inputs are described in the following sections - 5.4 through 5.7.

TABLE 5-2. CRASHWORTHINESS DATA FOR SILVERLINER CAR

I. GENERAL INFORMATION

1. CAR NAME/TYPE Penn Central / Reading Silverliner car (Figures 5-1 and 5-2)	2. BUILDER'S NAME AND ADDRESS The Budd Company, Philadelphia, Pa.	
3. AVERAGE AGE 12 years	4. YEAR(S) OF CONSTRUCTION 1962	5. NUMBER IN SERVICE 208: 6 (Penn Central Railroad) 280: 55 (38, Penn Central Railroad; 17, Reading Co.)
6. CAPACITY: *(a) SEATED* 127	*(b) STANDING* None scheduled	*(c) TOTAL* 127
7. SIZE: *(a) HEIGHT* 12 ft, 6-15/32 in.	*(b) WIDTH* 9 ft, 11-3/4 in.	*(c) LENGTH* 85 ft, 0 in. over pulling faces
8. WEIGHT: *(a) BARE STRUCTURE* 22,000 lb.	*(b) DRY BODY* (without trucks) 73,400 lb	
9. WEIGHT SERVICE: *(a) SEATED ONLY* (BASED ON 155 lb PER PASSENGER) 121,070 lb	*(b) STANDING* (Not applicable)	*(c) CRUSH* (Not applicable)
10. TRACK 4 ft, 8-1/2 in.*	11. WHEELBASE TO ℄ BOLSTER 59 ft, 6 in.	

II. STRUCTURAL CRASHWORTHINESS

1. FLAT-FACE FORCE/DEFLECTION See Figure 5-13	2. OVERRIDE-TELESCOPE FORCE/DEFLECTION See Figures 5-14 and 5-15	
3. TRUCK: *(a) SHEAR STRENGTH* 250,000 lb.	*(b) VERTICAL AFFIXATION* Attached only by bolster anchor rods and safety straps	
4. BUFF LOAD (spec.) 800,000 lb at $\sigma \leq F_y$	5. PROPENSITY TO DERAIL Derailment and rollover have never been a serious problem with any rail car as long as the track is reasonably well-maintained.	6. PROPENSITY TO ROLLOVER
7. PROPENSITY TO OVERRIDE UNDER: *(a) LIKE CARS – COUPLED* *(b) LIKE CARS – UNCOUPLED (COLLIDING)* *(c) UNLIKE CARS – COUPLED* *(d) UNLIKE CARS – UNCOUPLED (COLLIDING)*	Silverliner cars have no anticlimbers. There is a buffer sill which is intended to function as an anticlimber.	

*Standard gauge

TABLE 5-2. CRASHWORTHINESS DATA FOR SILVERLINER CAR (Cont.)

III. INTERIOR CONFIGURATION

1. WINDOWS: *(a) OPENING SIZE*

1 ft, 10 in. x 4 ft, 2-1/2 in. (12 windows per side)

(b) GLAZING MATERIAL	*(c) REMOVAL FOR EMERGENCY EXIT (NUMBER, LOCATION)*
1/4-in. laminated safety plate glass	None removable

2. SEATS: *(a) SEAT-TO-SEAT SPACING, DIRECTION*

2 ft, 1-3/4 in. Most seat backs rotatable to face either end of car (Figure 5-3)

(b) STATIC LONGITUDINAL STRENGTH -- LOAD APPLIED AT HIP LOCATION

Unavailable

(c) SEAT BACK STRENGTH -- LOAD APPLIED AT TOP OF SEAT

Unavailable

(d) PADDING OF REAR OF SEAT BACK, FORCE/DEFLECTION

Unavailable

(e) EXISTENCE OF PROTRUSIONS, SHARP EDGES -- SUBJECTIVE EVALUATION

The seat backs and, especially, the seat corners are hard-faced (aluminum) and could cause injury.

3. STANCHIONS:

(a) POLES: NUMBER	*DIAMETER*	*SHEAR STRENGTH*	*BENDING STRENGTH*
None used	(Not applicable)	(Not applicable)	(Not applicable)

(b) HAND GRIPS: AXIAL STRENGTH, LOCATION

None used

(c) PANELS: SIZE, STRENGTH

None used

4. HOSTILITY: *(a) PRE-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES WITH REGARD TO FLUSHNESS, SHARPNESS, etc.*

Because the seats are of the walk-over type, their backs offer very little resistance to movement until rotated into the reversed position; strength at the limit of travel is unknown. Baggage racks have sharp protrusions.

(b) POST-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES AFTER SLIGHT CAR DEFORMATION -- e.g., EXPOSURE OF SHARP PANEL EDGES

The interior of the car should not change significantly after a minor collision. Broken glass would probably constitute the greatest hazard.

5. FLAMMABILITY OF INTERIOR COMPONENTS -- e.g., SEATS, FLOOR COVERING

Seats are made of nonflammable material. Plywood and tile flooring claimed to be self extinguishing by test.

6. END PANEL, WALL, CEILING, AND FLOOR FLAT SURFACE HARDNESS

The end panels are melamine-plastic-faced with the exception of a circular door window.

7. IMPACT OF ONE OCCUPANT INTO ANOTHER -- COMPARTMENTALIZATION -- SUBJECTIVE EVALUATION FROM LAYOUT OF SEATS AND STANCHIONS

These cars were not designed for use by standing passengers, although such passengers are fairly common during rush hours. Seats, assuming they remain intact, will prevent seated passengers from impacting one another. A standing passenger will be able to move until impacting another passenger, a seat, or an end door.

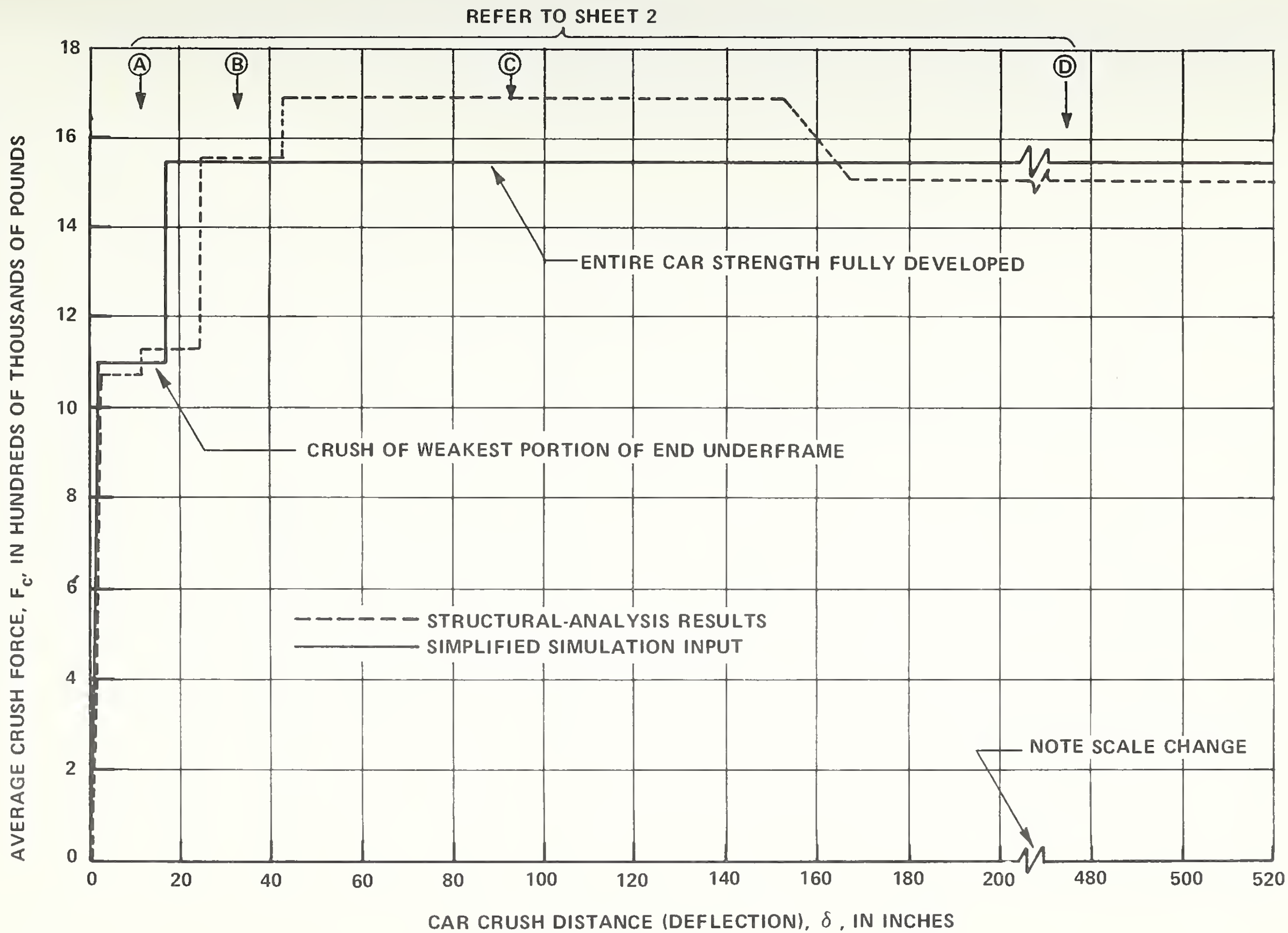

Figure 5-13. Crush Force vs Deflection for Silverliner Car -- No Override (Sheet 1 of 2)

REGION Ⓐ : Weakest portion of end underframe forward of vestibule partitions. (After coupler contact and deflection, buffer sills contact and remain engaged throughout the collision.) Crush of vestibule ceiling, car roof, and rool purlins.

REGION Ⓑ : Forward, stronger portion of end underframe. After complete crushing of vestibule, crush of end frame and vestibule partitions occurs. Then, resistances of side sills, roof rails, belt rails, floor, and sideframes come into play.

REGION Ⓒ : Greatest amount of structural crushing. Crush of end underframe, car roof, roof purlins, side sills, roof rails, belt rails, floor, and sideframes.

REGION Ⓓ : Resistance of area behind body bolster. Center sill offers less resistance than end underframe, to which it is attached. Lower sideframe is stronger than sideframe forward of body bolster. Crushing of center sill is added.

NOTES:

1. End underframe, side sills, roof rails, and belt rails do not locally crumple prior to reaching yield strengths of their materials, and remainder of car framing is sufficient to prevent column failures of these members.
2. Lower sideframe does not locally crumple prior to reaching yield strength of its material, and adjacent car framing is sufficient to prevent column failure of this member.
3. Car roof crumples locally when stressed to only 49% of yield strength of its material, which is reflected by crush strength of the roof.
4. Although its crush force is somewhat higher, REGION Ⓒ crushes before REGION Ⓓ , as indicated by the dashed-line plot. The reason is that the largest contributor to crush resistance is the end underframe, which is crushed in REGIONS Ⓐ, Ⓑ , and Ⓒ . Tests by The Budd Company have shown that, once rail-car crushing has been initiated, a theoretically stronger area may be crushed before a weaker area if crushing of the stronger area is triggered by that of the weaker area.

Figure 5-13. Crush Force vs Deflection for Silverliner Car -- No Override (Sheet 2 of 2)

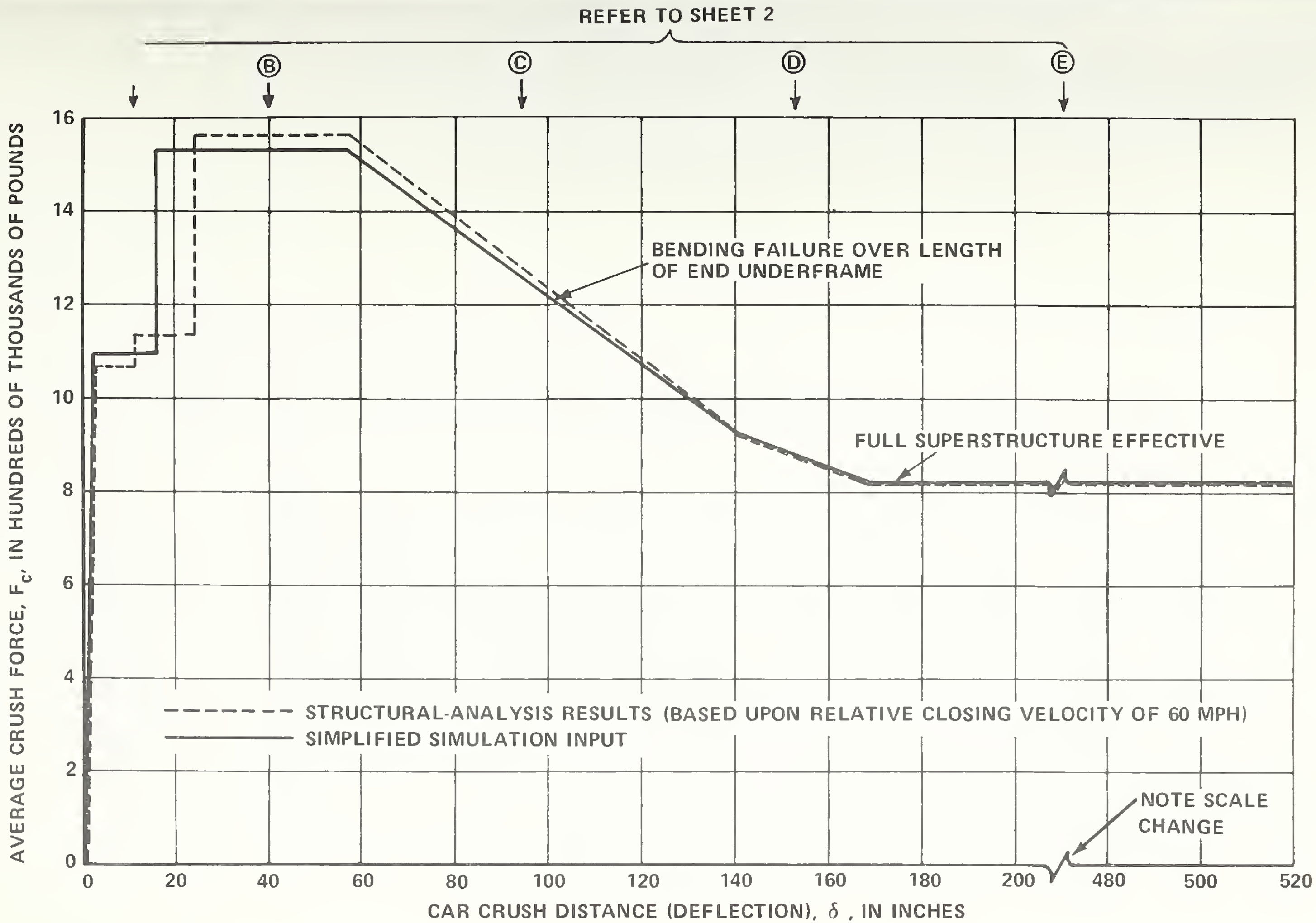

Figure 5-14. Crush Force vs Deflection for Silverliner Car -- Override Due to Structural Failure (Sheet 1 of 2)

REGION Ⓐ : Weakest portion of end underframe forward of vestibule partitions. (After coupler contact and deflection, buffer sills contact and remain engaged throughout the collision.) Crush of vestibule ceiling, car roof, and roof purlins.

REGION Ⓑ : Forward, stronger portion of end underframe. After complete crushing of vestibule, crush of end frame and vestibule partitions occurs. Then, resistances of side sills, roof rails, belt rails, floor, and sideframes come into play. However, due to its eccentric loading, end underframe begins to bend.

REGION Ⓒ : Bending of end underframe becomes quite significant, and catastrophic bending failure takes place just forward of body bolster. Crush of car roof, roof purlins, side sills, roof rails, belt rails, floor, and sideframes. Bending of side sills and floor results from bending of end underframe.

REGION Ⓓ : After end underframe failure, side sills fail behind body bolster. Then, resistance of entire floor and underframe structure is no longer effective, and override occurs. As the result, only the portion of car structure above floor level offers resistance.

REGION Ⓔ : Once overriding has occurred, additional crushing of car roof, roof purlins, roof rails, belt rails, and lower sideframes takes place. Interior appointments offer some resistance, but this is quite minimal.

NOTES:

1. End underframe, side sills, roof rails, and belt rails do not locally crumple prior to reaching yield strengths of their materials, and remainder of car framing is sufficient to prevent column failures of these members.
2. Lower sideframe does not locally crumple prior to reaching yield strength of its material, and adjacent car framing is sufficient to prevent column failure of this member.
3. Car roof crumples locally when stressed to only 49% of yield strength of its material, which is reflected by crush strength of the roof.

Figure 5-14. Crush Force vs Deflection for Silverliner Car -- Override Due to Structural Failure (Sheet 2 of 2)

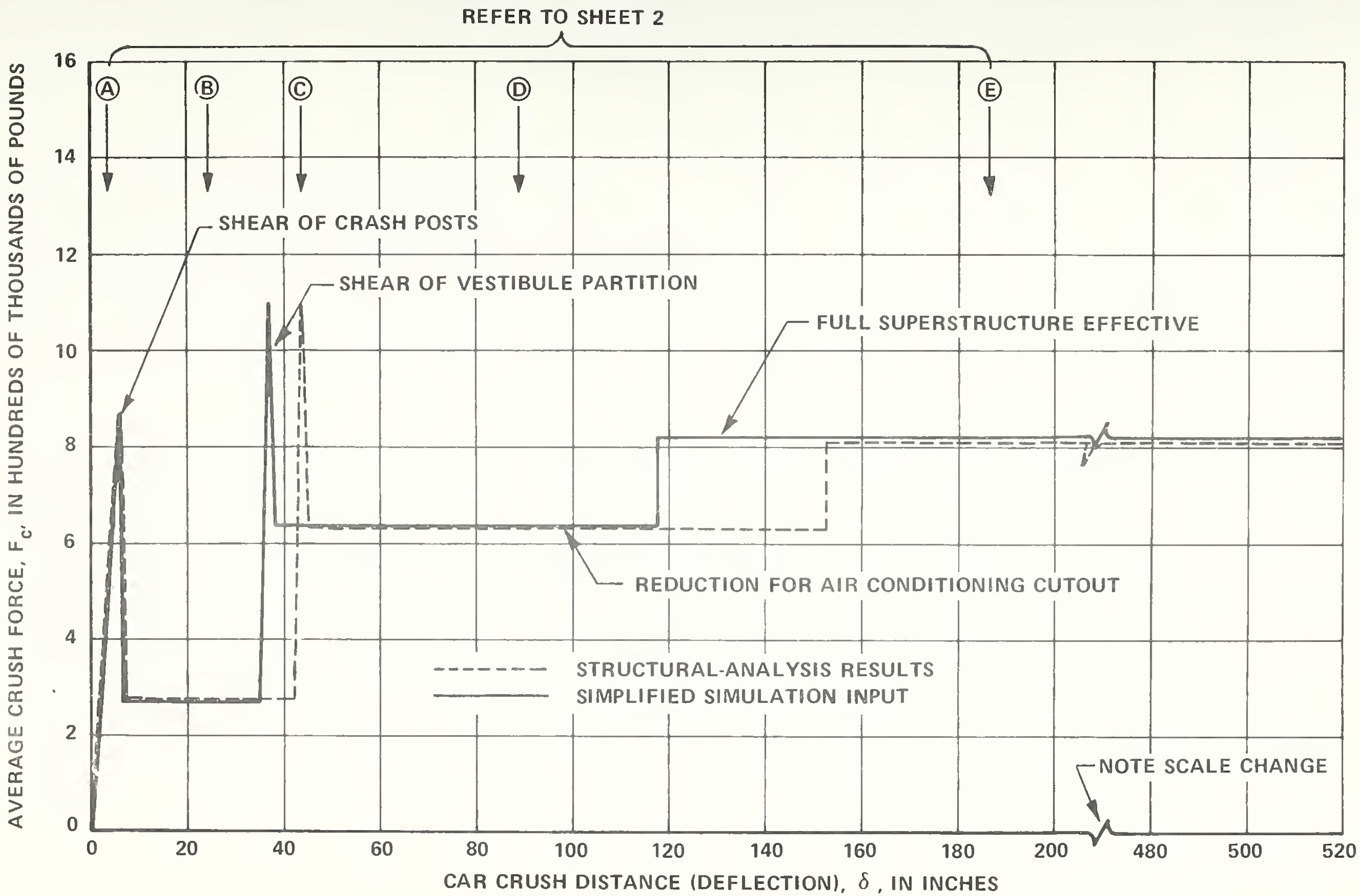

Figure 5-15. Crush Force vs Deflection for Silverliner Car -- Initial Override (Sheet 1 of 2)

REGION Ⓐ : Overriding takes place at the moment of initial impact. Lower end frame of overriding car impacts end frame and buffer sill of car being overridden. Buffer sill fails in shear, causing crush of roof structure, vestibule roof, and side door reinforcements.

REGION Ⓑ : Only areas now resisting intrusion of overriding car include roof structure, vestibule roof, side door reinforcements, and roof purlins. This is reflected by the great reduction of crush force.

REGION Ⓒ : After complete crushing of vestibule, vestibule partition is wiped off the floor/underframe structure. The force required to cause shear failure of the vestibule partition is reflected by this region. Next, resistances of roof rails, belt rails, and side frames begin to have an effect.

REGION Ⓓ : Crush of roof, roof purlins, roof rails, belt rails, and side frames. Side frames offer little resistance because they are cut out to permit installation and operation of air conditioning equipment.

REGION Ⓔ : Crush of structures named for REGION Ⓓ continues. Increase in crush force results because lower sideframes offer significantly greater resistance than cutout sideframes cited for REGION Ⓓ .

NOTES:

1. End underframe, center sill, side sills, and floor offer no resistance to crush because of the nature of the overriding collision.
2. Underfloor equipment of overriding car has no effect on force/deflection characteristics of overridden car.
3. Roof rails and belt rails do not locally crumple prior to reaching yield strengths of their materials, and remainder of car framing is sufficient to prevent column failures of these members.
4. Lower sideframe does not locally crumple prior to reaching yield strength of its material, and adjacent car framing is sufficient to prevent column failure of this member.
5. Car roof crumples locally when stressed to only 49% of yield strength of its material, which is reflected by crush strength of the roof.

Figure 5-15. Crush Force vs Deflection for Silverliner Car -- Initial Override (Sheet 2 of 2)

TABLE 5-3. CRASHWORTHINESS DATA FOR R-33 CAR

I. GENERAL INFORMATION

1. CAR NAME/TYPE: NYCTA R-33 car (A and B cars, essentially the same) (Figures 5-4 and 5-5)

2. BUILDER'S NAME AND ADDRESS: St. Louis Car Division of General Steel Industries, Inc., St. Louis, Mo.

3. AVERAGE AGE: 12 years

4. YEAR(S) OF CONSTRUCTION: 1962

5. NUMBER IN SERVICE: 540 (New York City Transit Authority, MTA)

6. CAPACITY: *(a) SEATED* 44 | *(b) STANDING* 136 (normal), 156 (crush) | *(c) TOTAL* 180 (normal), 200 (crush)

7. SIZE: *(a) HEIGHT* 11 ft, 10-7/8 in. | *(b) WIDTH* 8 ft, 9-1/2 in. | *(c) LENGTH* 51 ft, 4 in. over pulling faces

8. WEIGHT: *(a) BARE STRUCTURE* Unknown | *(b) DRY BODY* (without trucks) 34,412 lb

9. WEIGHT SERVICE: (BASED ON 140 lb PER PASSENGER) *(a) SEATED ONLY* 79,098 lb | *(b) STANDING* 98,138 lb | *(c) CRUSH* 100,938 lb

10. TRACK: 4 ft, 8-1/2 in.*

11. WHEELBASE TO ℄ BOLSTER: 36 ft, 0 in.

II. STRUCTURAL CRASHWORTHINESS

1. FLAT-FACE FORCE/DEFLECTION: See Figure 5-16

2. OVERRIDE-TELESCOPE FORCE/DEFLECTION: See Figure 5-17

3. TRUCK: *(a) SHEAR STRENGTH* 607,500 lb | *(b) VERTICAL AFFIXATION* None; male/female socket arrangement

4. BUFF LOAD: 200,000 lb at $\sigma \leq 1/2F_y$

5. PROPENSITY TO DERAIL / 6. PROPENSITY TO ROLLOVER:

Derailment and rollover have never been a serious problem with any rail car as long as the track is reasonably well-maintained.

7. PROPENSITY TO OVERRIDE UNDER:

(a) LIKE CARS – COUPLED

(b) LIKE CARS – UNCOUPLED (COLLIDING)

(c) UNLIKE CARS – COUPLED

(d) UNLIKE CARS – UNCOUPLED (COLLIDING)

R-33 cars are equipped with anticlimbers and coupler centering devices. The heights of these features are identical from car to car.

*Standard gauge

TABLE 5-3. CRASHWORTHINESS DATA FOR R-33 CAR (CONT.)

III. INTERIOR CONFIGURATION

1. WINDOWS: *(a) OPENING SIZE* 2 ft, 3-9/16 in. x 2 ft, 6-13/16 in. (5 windows per side) and 1 ft, 8-7/8 in. x 3 ft, 1-7/16 in. (1 window per side)

(b) GLAZING MATERIAL

1/4-in. laminated, polished plate glass

(c) REMOVAL FOR EMERGENCY EXIT (NUMBER, LOCATION)

None removable; however, movable sashes are provided for all side windows

2. SEATS: *(a) SEAT-TO-SEAT SPACING, DIRECTION* All seats are center-facing and are separated by the aisle, which has a width of approximately 4 ft, 5 in. (Figure 5-5)

(b) STATIC LONGITUDINAL STRENGTH -- LOAD APPLIED AT HIP LOCATION

(Not applicable to center-facing seats)

(c) SEAT BACK STRENGTH -- LOAD APPLIED AT TOP OF SEAT

(Not applicable to center-facing seats)

(d) PADDING OF REAR OF SEAT BACK, FORCE/DEFLECTION

Unpadded; seats are molded fiberglass units; force/deflection data unavailable

(e) EXISTENCE OF PROTRUSIONS, SHARP EDGES -- SUBJECTIVE EVALUATION

Although the seats have no sharp edges, they do have metal handbars at each end

3. STANCHIONS: *(a) POLES:*

NUMBER	*DIAMETER*	*SHEAR STRENGTH*	*BENDING STRENGTH*
4 per car (steel tubes)	1-1/4 in.	8,800 lb	216 lb applied at the center

(b) HAND GRIPS: AXIAL STRENGTH, LOCATION

Swing-type units suspended from the car ceiling; axial strength unknown

(c) PANELS: SIZE, STRENGTH

None used

4. HOSTILITY: *(a) PRE-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES WITH REGARD TO FLUSHNESS, SHARPNESS, etc.*

No sharp edges are present. Stanchions, seat handbars, and hand grips are the principal potentially injurious objects which passengers could impact.

(b) POST-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES AFTER SLIGHT CAR DEFORMATION -- e.g., EXPOSURE OF SHARP PANEL EDGES

Broken glass would be the most critical passenger hazard resulting from a slight collision.

5. FLAMMABILITY OF INTERIOR COMPONENTS -- e.g., SEATS, FLOOR COVERING

Although the fiberglass seats are flame-retardant, there is no requirement for flame-retardant floor materials or other interior appointments.

6. END PANEL, WALL, CEILING, AND FLOOR FLAT SURFACE HARDNESS

Unknown

7. IMPACT OF ONE OCCUPANT INTO ANOTHER -- COMPARTMENTALIZATION -- SUBJECTIVE EVALUATION FROM LAYOUT OF SEATS AND STANCHIONS

With the use of center-facing bench-type seats, little compartmentalization is provided in these cars; however, because of stanchion locations, passengers tend to congregate at the car doors.

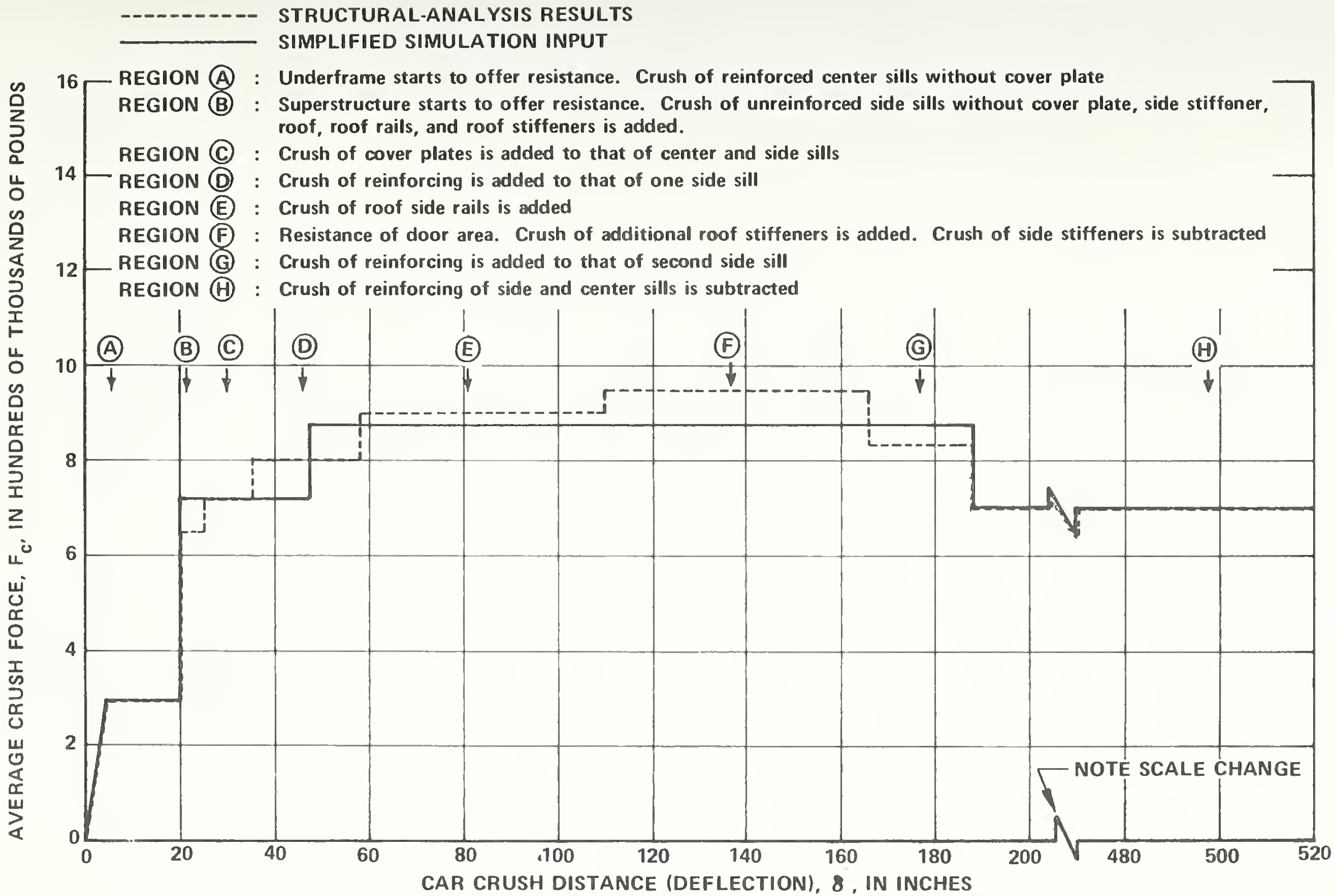

Figure 5-16. Crush Force vs Deflection for R-33 Car -- No Override

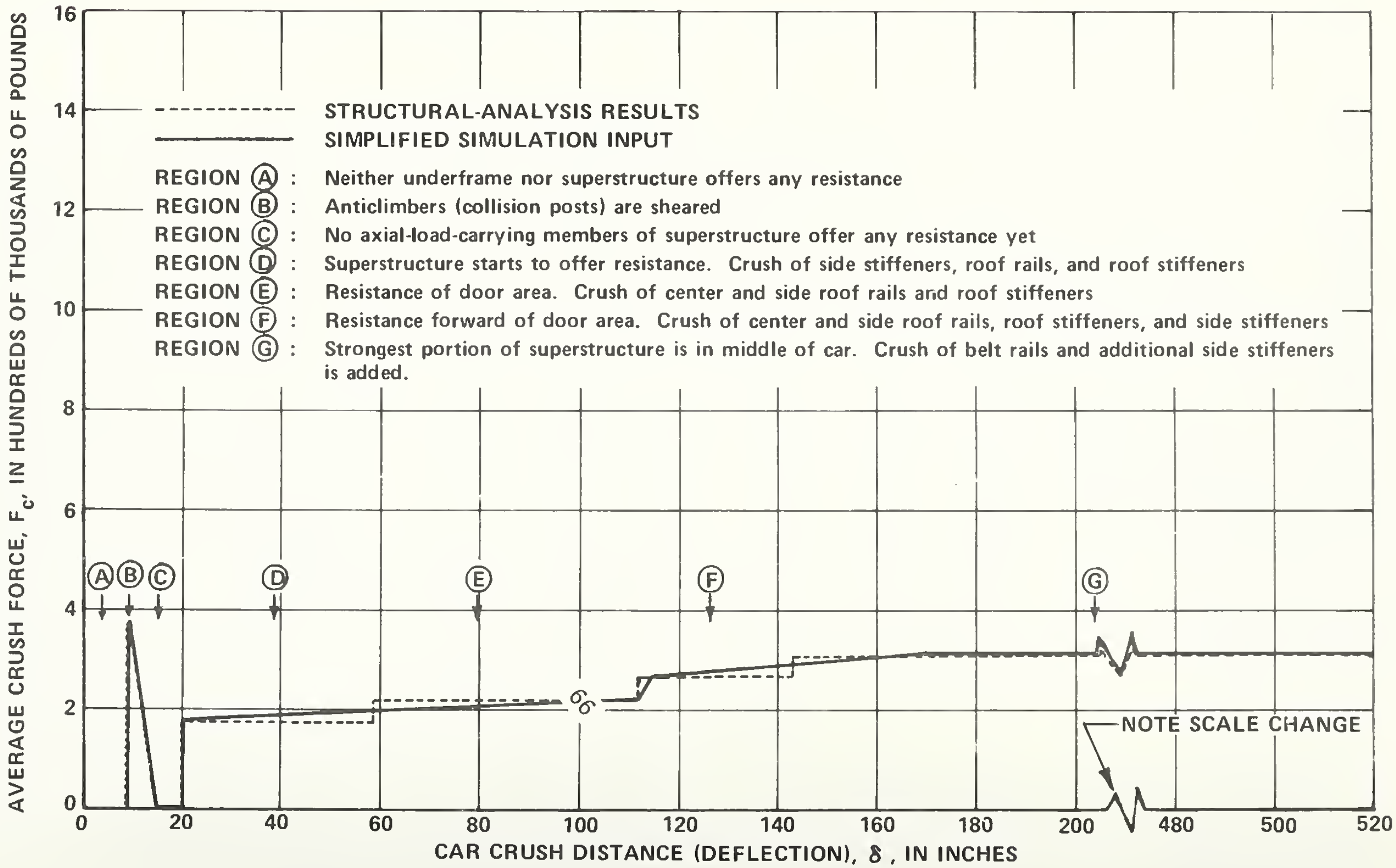

Figure 5-17. Crush Force vs Deflection for R-33 Car -- Override

TABLE 5-4. CRASHWORTHINESS DATA FOR R-44 CAR

I. GENERAL INFORMATION

1. CAR NAME/TYPE NYCTA R-44 car (A and B cars) (Figures 5-6 and 5-7)	2. BUILDER'S NAME AND ADDRESS St. Louis Car Division of General Steel Industries, Inc., St. Louis, Mo.	
3. AVERAGE AGE 2 years	4. YEAR(S) OF CONSTRUCTION 1971 and 1972	5. NUMBER IN SERVICE 240 (New York City Transit Authority, MTA)
6. CAPACITY: *(a) SEATED* 72 (A car) 76 (B car)	*(b) STANDING* 200(normal) or 278(crush)(A) 204(normal) or 274(crush)(B)	*(c) TOTAL* 272 (normal, A car) 280 (normal, B car) 350 (crush, either car)
7. SIZE: *(a) HEIGHT* 12 ft, 1-1/2 in.	*(b) WIDTH* 10 ft, 0 in.	*(c) LENGTH* 75 ft, 0 in. over couplers
8. WEIGHT: *(a) BARE STRUCTURE* Unknown	*(b) DRY BODY* (without trucks) 46,342 lb (A car) 42,766 lb (B car)	
9. WEIGHT SERVICE: (BASED ON 140 lb PER PASSENGER) *(a) SEATED ONLY* 92,868 lb (A car) 89,852 lb (B car)	*(b) STANDING* 120,868 lb (A car) 118,412 lb (B car)	*(c) CRUSH* 131,788 lb (A car) 128,212 lb (B car)
10. TRACK 4 ft, 8-1/2 in.*	11. WHEELBASE TO ℄ BOLSTER 54 ft, 0 in.	

II. STRUCTURAL CRASHWORTHINESS

1. FLAT-FACE FORCE/DEFLECTION See Figure 5-18	2. OVERRIDE-TELESCOPE FORCE/DEFLECTION See Figure 5-19	
3. TRUCK: *(a) SHEAR STRENGTH* 607,500 lb	*(b) VERTICAL AFFIXATION* None; male/female socket arrangement	
4 BUFF LOAD (spec.) 250,000 lb at $\sigma \leq 1/2\ F_y$	5. PROPENSITY TO DERAIL	6. PROPENSITY TO ROLLOVER
	Derailment and rollover have never been a serious problem with any rail car as long as the track is reasonably well-maintained.	

7. PROPENSITY TO OVERRIDE UNDER:

(a) LIKE CARS – COUPLED

(b) LIKE CARS – UNCOUPLED (COLLIDING)

(c) UNLIKE CARS – COUPLED

(d) UNLIKE CARS – UNCOUPLED (COLLIDING)

R-44 cars are equipped with anticlimbers and coupler centering devices. The heights of these features are identical from car to car.

*Standard gauge

TABLE 5-4. CRASHWORTHINESS DATA FOR R-44 CAR (Cont.)

III. INTERIOR CONFIGURATION

1. WINDOWS: *(a) OPENING SIZE* Approximately 3 ft x 5 ft (3 windows per side) and Two 1 ft, 6 in. x 3 ft windows in each of 4 doors on each side

(b) GLAZING MATERIAL	*(c) REMOVAL FOR EMERGENCY EXIT (NUMBER, LOCATION)*
1/5-in. laminated safety windshield glass	None removable

2. SEATS: *(a) SEAT-TO-SEAT SPACING, DIRECTION* Mixed fore- and aft-facing and center-facing seats. Spacing between seats varies from approx.10 in. to 5 ft, 8 in.(Fig. 5-7)

(b) STATIC LONGITUDINAL STRENGTH -- LOAD APPLIED AT HIP LOCATION

Unknown

(c) SEAT BACK STRENGTH -- LOAD APPLIED AT TOP OF SEAT

Unknown

(d) PADDING OF REAR OF SEAT BACK, FORCE/DEFLECTION

Unpadded; seats are molded fiberglass units; force/deflection data unavailable

(e) EXISTENCE OF PROTRUSIONS, SHARP EDGES -- SUBJECTIVE EVALUATION

The seats have no sharp edges.

3. STANCHIONS:

(a) POLES: NUMBER	*DIAMETER*	*SHEAR STRENGTH*	*BENDING STRENGTH*
8 floor-to-ceiling units and 4 seat-back-to-ceiling units	1-1/4 in.	8,800 lb	216 lb applied at the center

(b) HAND GRIPS: AXIAL STRENGTH, LOCATION

1-in. L-shaped steel tubes extending from windscreen end posts to ceiling. (See Figure 5-7.) Axial strength unknown

(c) PANELS: SIZE, STRENGTH 1 ft, 8 in. x 5 ft, 1 in. panels, extending upward from 8 in. above the floor on either side of each side door; lower half is plastic-faced 1-in. plywood, upper half is 1/5-in. laminated safety glass; strength unknown.

4. HOSTILITY: *(a) PRE-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES WITH REGARD TO FLUSHNESS, SHARPNESS, etc.*

There are no sharp edges protruding inside the car. However, fore- and aft-facing seats do protrude into the area accommodating standing passengers.

(b) POST-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES AFTER SLIGHT CAR DEFORMATION -- e.g., EXPOSURE OF SHARP PANEL EDGES

Broken glass would be the most critical passenger hazard resulting from a slight collision.

5. FLAMMABILITY OF INTERIOR COMPONENTS -- e.g., SEATS, FLOOR COVERING

As required by the purchase specification, all interior materials (especially, the seats and flooring) are fireproof.

6. END PANEL, WALL, CEILING, AND FLOOR FLAT SURFACE HARDNESS

Unknown

7. IMPACT OF ONE OCCUPANT INTO ANOTHER -- COMPARTMENTALIZATION -- SUBJECTIVE EVALUATION FROM LAYOUT OF SEATS AND STANCHIONS Fore- and aft-facing seats tend to compartmentalize the interior, but the wide aisle between these seats would enable standing passengers to move the length of the car with little restriction in a crash. (Few floor-to-ceiling stanchions are used.)

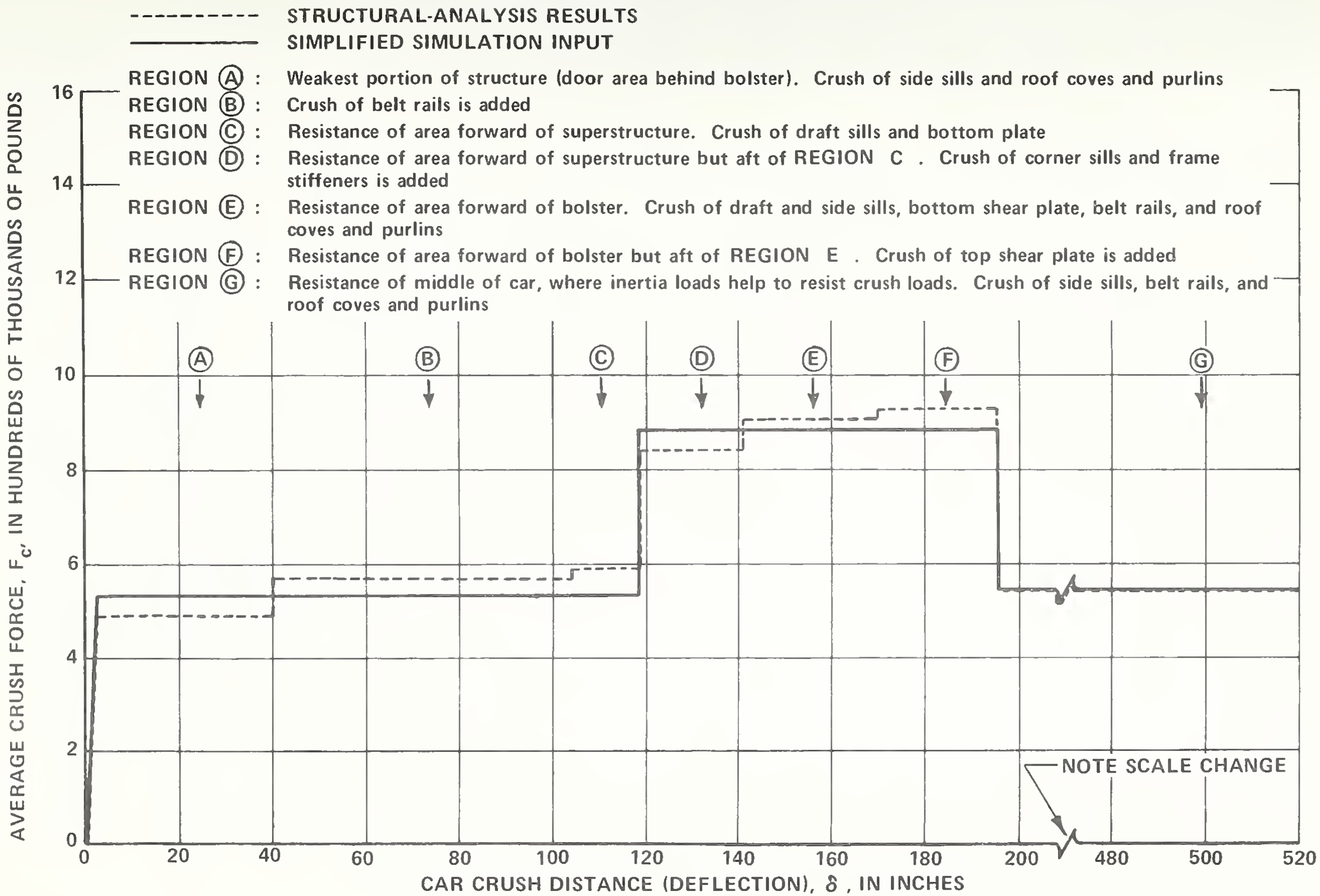

Figure 5-18. Crush Force vs Deflection for R-44 Car -- No Override

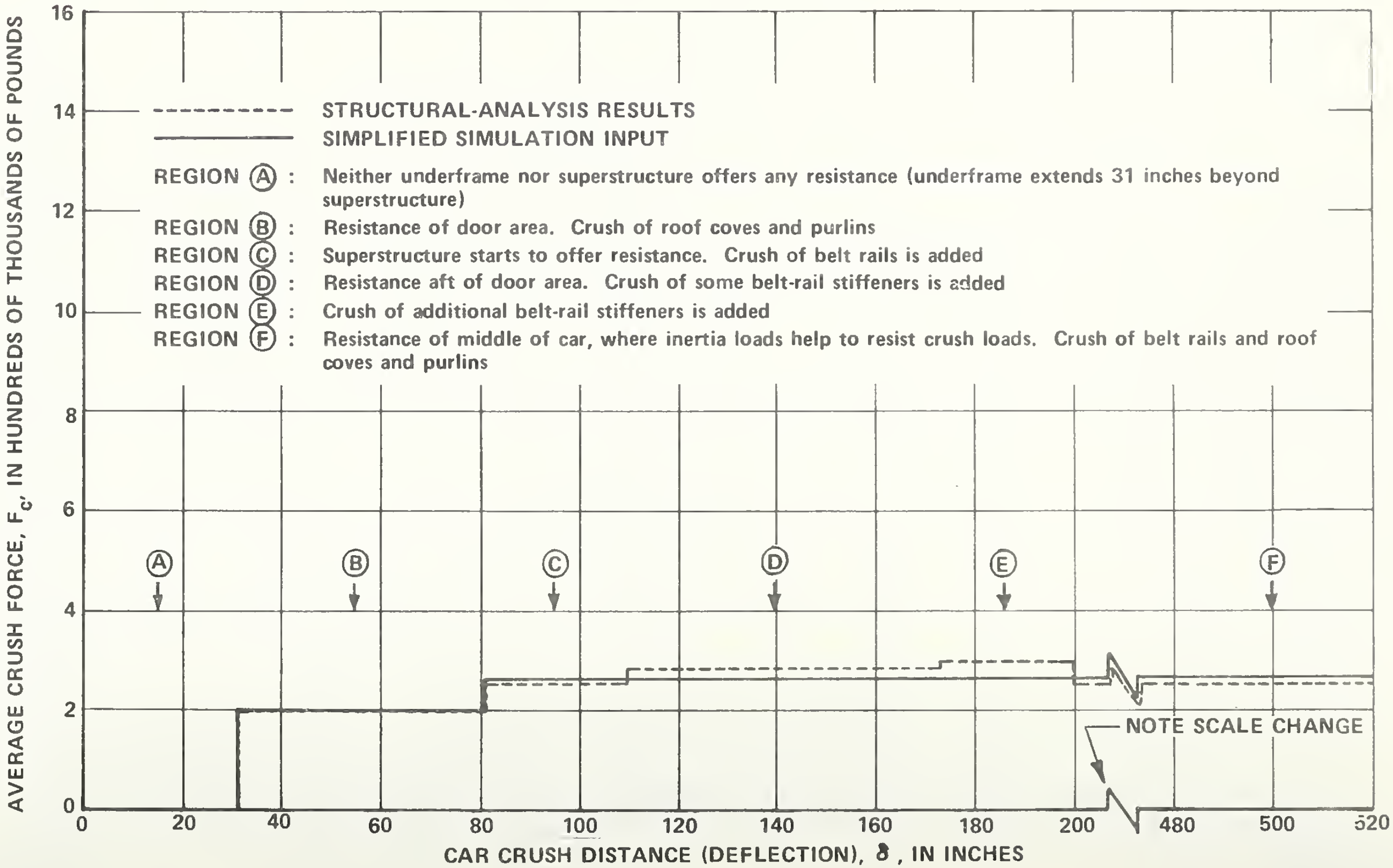

Figure 5-19. Crush Force vs Deflection for R-44 Car -- Override

TABLE 5-5. CRASHWORTHINESS DATA FOR BART CAR

I. GENERAL INFORMATION

1. CAR NAME/TYPE	2. BUILDER'S NAME AND ADDRESS
BARTD (A and B cars) (Figures 5-8 through 5-10)	Rohr Industries, Chula Vista, California

3. AVERAGE AGE	4. YEAR(S) OF CONSTRUCTION	5. NUMBER IN SERVICE
2 years	1972	250 (150 A and 100 B) ([San Francisco] Bay Area Rapid Transit District)

6. CAPACITY: *(a) SEATED*	*(b) STANDING*	*(c) TOTAL*
72 (A car) 72 (B car)	48(normal) or 72(crush) (A) 60(normal) or 156(crush) (B)	120(normal) or 216(crush)(A) 132(normal) or 228(crush)(B)

7. SIZE: *(a) HEIGHT*	*(b) WIDTH*	*(c) LENGTH*
10 ft, 6 in. (A or B car)	10 ft, 6 in. (A or B car)	75 ft, 0 in. (A) 70 ft, 0 in. (B)

8. WEIGHT: *(a) BARE STRUCTURE*	*(b) DRY BODY* (including trucks)
Unknown	60,000 lb (A or B car)

9. WEIGHT SERVICE: (BASED ON 140 lb PER PASSENGER) *(a) SEATED ONLY*	*(b) STANDING*	*(c) CRUSH*
66,580 lb (A car) 65,080 lb (B car)	73,300 lb (A car) 73,480 lb (B car)	86,740 lb (A car)

10. TRACK	11. WHEELBASE TO ℄ BOLSTER
5 ft, 6 in. (A or B car)*	50 ft, 0 in. (A or B car)

II. STRUCTURAL CRASHWORTHINESS

1. FLAT-FACE FORCE/DEFLECTION	2. OVERRIDE-TELESCOPE FORCE/DEFLECTION
See Figure 5-20	See Figure 5-21

3. TRUCK: *(a) SHEAR STRENGTH*	*(b) VERTICAL AFFIXATION*
Unknown (?)	Unknown (?)

4. BUFF LOAD	5. PROPENSITY TO DERAIL	6. PROPENSITY TO ROLLOVER
200,000 lb at $\sigma \leq F_y$	Derailment has never been a serious problem with any rail car as long as the track is reasonably well-maintained.	Low (has wide-track design -- 5 ft, 6 in. compared to standard 4 ft, 8-1/2 in.)

7. PROPENSITY TO OVERRIDE UNDER:

(a) LIKE CARS – COUPLED

(b) LIKE CARS – UNCOUPLED (COLLIDING)

Only the control-cab end of an A car has an anticlimber. However, every car has a buffer sill which is intended to function as an anticlimber provided that it mates with an equal buffer sill.

(c) UNLIKE CARS – COUPLED

(Not applicable)

(d) UNLIKE CARS – UNCOUPLED (COLLIDING)

(Not applicable)

*Not standard gauge (which is 4 ft, 8-1/2 in.)

TABLE 5-5. CRASHWORTHINESS DATA FOR BART CAR (CONT.)

III. INTERIOR CONFIGURATION

1. WINDOWS: *(a) OPENING SIZE* 3 ft,3 in.x 4 ft,10 in.(4/side-between doors); 3 ft,3 in. x 3 ft,11 in.(4/side-at car ends); 1 ft,7 in.x 3 ft, 3 in.(ea. of 4 doors/side).

(b) GLAZING MATERIAL	*(c) REMOVAL FOR EMERGENCY EXIT (NUMBER, LOCATION)*
Laminated safety glass having tempered inside layer and annealed outside layer	None removable

2. SEATS: *(a) SEAT-TO-SEAT SPACING, DIRECTION* Fore- and aft-facing seats have a spacing of 34 in. or more; center-facing seats have a spacing (aisle) of about 51 in.

(b) STATIC LONGITUDINAL STRENGTH -- LOAD APPLIED AT HIP LOCATION
Unavailable

(c) SEAT BACK STRENGTH -- LOAD APPLIED AT TOP OF SEAT
800 lb minimum for load applied at centerline of seat

(d) PADDING OF REAR OF SEAT BACK, FORCE/DEFLECTION
Cloth- & vinyl-covered foam on steel framework;force/deflection data unavailable

(e) EXISTENCE OF PROTRUSIONS, SHARP EDGES -- SUBJECTIVE EVALUATION
Generally clean design

3. STANCHIONS:

(a) POLES: NUMBER	*DIAMETER*	*SHEAR STRENGTH*	*BENDING STRENGTH*
8 windscreen-to-ceiling units, one on each side of 4 paired side doors	1-1/4 in.-square	(Not applicable)	340 lb applied at the center

(b) HAND GRIPS: AXIAL STRENGTH, LOCATION
1-1/4-in. square tubes installed on outside corners of fore- and aft-facing seats only; axial strength 400 lb minimum

(c) PANELS: SIZE, STRENGTH
Approximately 2 ft x 2 ft on either side of paired side doors; strength unknown

4. HOSTILITY: *(a) PRE-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES WITH REGARD TO FLUSHNESS, SHARPNESS, etc.*
Interior is generally free of sharp protrusions except for the square-cross-section design of the hand grips and windscreen-panel posts.

(b) POST-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES AFTER SLIGHT CAR DEFORMATION -- e.g., EXPOSURE OF SHARP PANEL EDGES
Broken glass resulting from possible fracture of the large side windows and, especially, the end-door glass would be the most critical passenger hazard resulting from a slight collision. The steel framing for the padded seats also constitutes an undesirable potential impact hazard.

5. FLAMMABILITY OF INTERIOR COMPONENTS -- e.g., SEATS, FLOOR COVERING
As required by the purchase specification, all interior materials are fireproof.

6. END PANEL, WALL, CEILING, AND FLOOR FLAT SURFACE HARDNESS Panels at ends of aisles are large laminated-safety-glass doors (rated at 15 lb/ft^2), which constitute perhaps the greatest obvious danger to standing passengers in a crash. Ceilings are crashworthy foam-core aluminum sheets. Floors are carpeted with sufficient underpadding to protect passengers from falling-type impacts.

7. IMPACT OF ONE OCCUPANT INTO ANOTHER -- COMPARTMENTALIZATION -- SUBJECTIVE EVALUATION FROM LAYOUT OF SEATS AND STANCHIONS
Fore- and aft-facing seats tend to compartmentalize the interior, but the wide aisle between these seats would enable standing passengers to move the length of the car with little restriction in a crash.

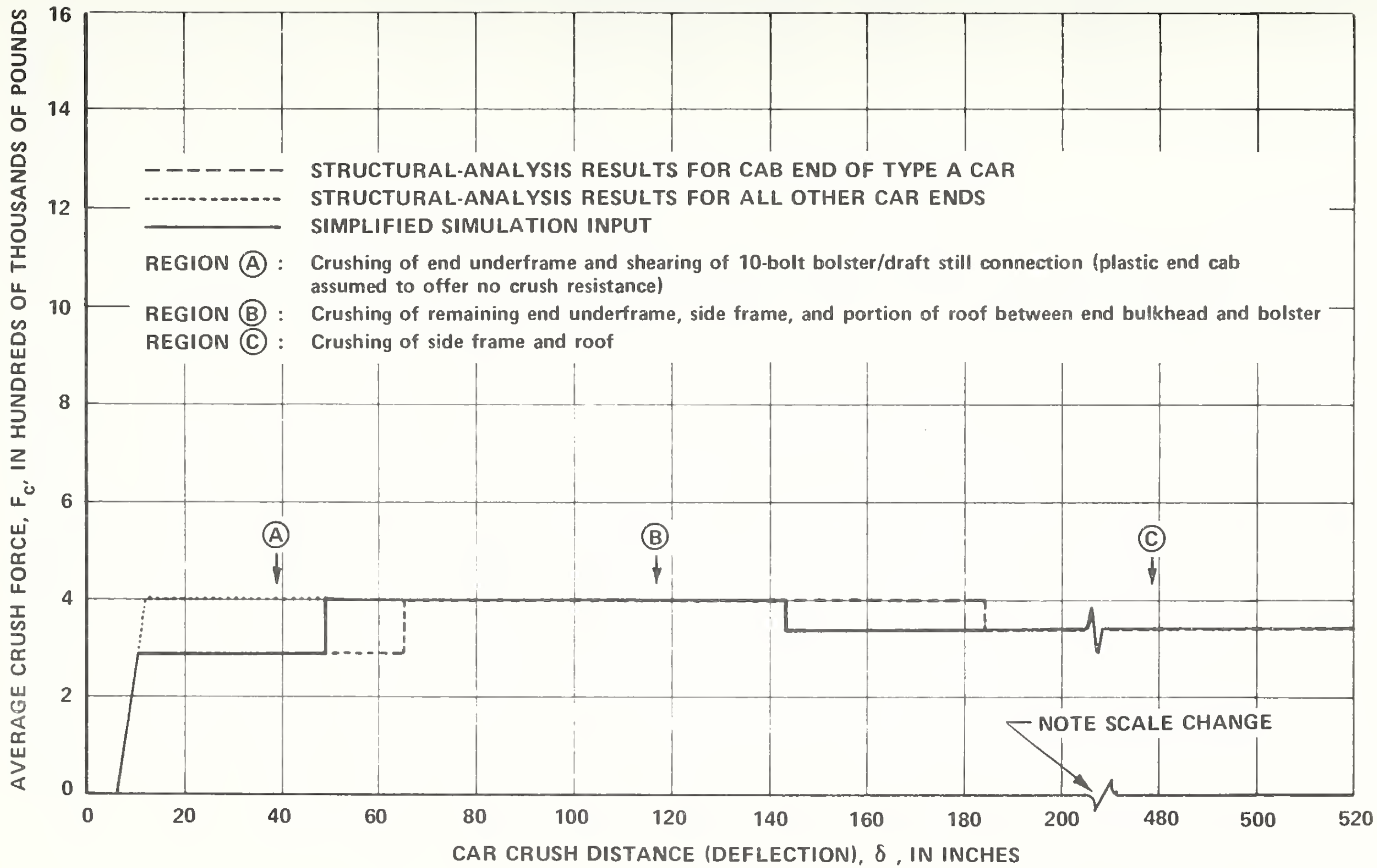

Figure 5-20. Crush Force vs Deflection for BART Car -- No Override

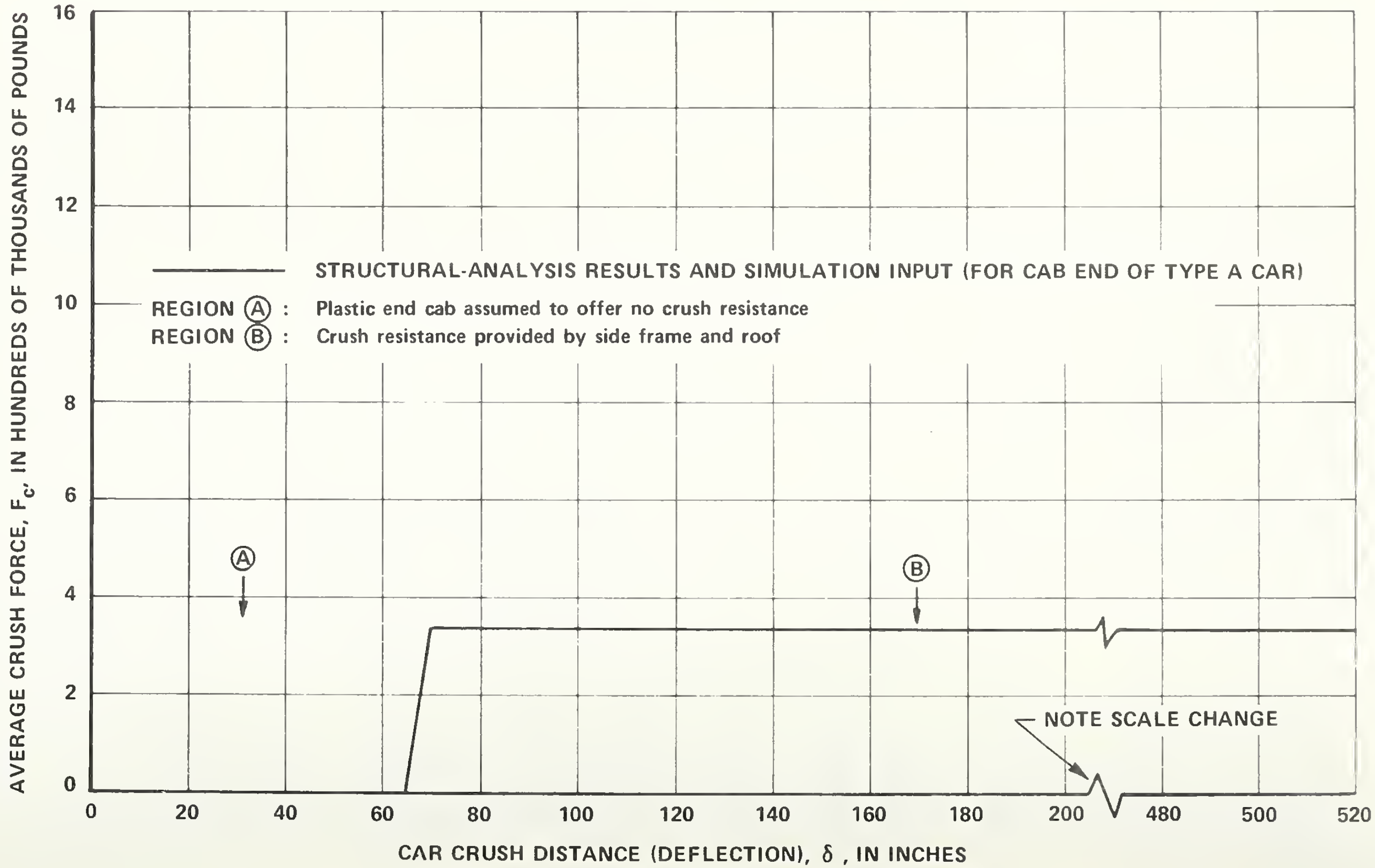

Figure 5-21. Crush Force vs Deflection for BART Car -- Override

TABLE 5-6. CRASHWORTHINESS DATA FOR SILVERBIRD CAR

I. GENERAL INFORMATION

1. CAR NAME/TYPE MBTA Silverbird car (single and A and B cars) (Figures 5-11 and 5-12)	2. BUILDER'S NAME AND ADDRESS Pullman-Standard Div., Pullman Incorporated Chicago, Ill.

3. AVERAGE AGE 6 years	4. YEAR(S) OF CONSTRUCTION 1968	5. NUMBER IN SERVICE 76 (Massachusetts Bay Transit Authority South Shore Rapid Transit line)
6. CAPACITY: *(a) SEATED* 60 (single car) 64 (A or B car)	*(b) STANDING* 168 (single car) (crush) 175 (A or B car) (crush)	*(c) TOTAL* 228 (single car) (crush) 239 (A or B car) (crush)
7. SIZE: *(a) HEIGHT* 12 ft, 4-5/16 in.	*(b) WIDTH* 10 ft, 0 in.	*(c) LENGTH* 69 ft, 9-3/4 in. over pulling faces

8. WEIGHT: *(a) BARE STRUCTURE* Unknown	*(b) DRY BODY* (without trucks) 38,502 lb (single car); 36,348 lb (A car); 35,028 lb (B car)

9. WEIGHT SERVICE: *(a) SEATED ONLY* (BASED ON 140 lb PER PASSENGER) 72,862 lb (single car); 70,688 lb (A car); 69,368 lb (B car)	*(b) STANDING* Unknown	*(c) CRUSH* 96,382 lb (single);95,188 lb (A car);93,868 lb (B car)

10. TRACK 4 ft, 8-1/2 in.*	11. WHEELBASE TO ℄ BOLSTER 51 ft, 0 in.

II. STRUCTURAL CRASHWORTHINESS

1. FLAT-FACE FORCE/DEFLECTION Figure 5-22	2. OVERRIDE-TELESCOPE FORCE/DEFLECTION Figure 5-23
3. TRUCK: *(a) SHEAR STRENGTH* Unknown	*(b) VERTICAL AFFIXATION* Bolted kingpins

4. BUFF LOAD (spec.) 200,000 lb at $\sigma \leq F_y$	5. PROPENSITY TO DERAIL	6. PROPENSITY TO ROLLOVER
	Derailment and rollover have never been a serious problem with any rail car as long as the track is reasonably well-maintained.	

7. PROPENSITY TO OVERRIDE UNDER:

(a) LIKE CARS – COUPLED

(b) LIKE CARS – UNCOUPLED (COLLIDING)

(c) UNLIKE CARS – COUPLED

(d) UNLIKE CARS – UNCOUPLED (COLLIDING)

Silverbird cars are equipped with anti-climbers and coupler centering devices. The heights of these features are identical from car to car.

*Standard gauge

TABLE 5-6. CRASHWORTHINESS DATA FOR SILVERBIRD CAR (CONT.)

III. INTERIOR CONFIGURATION

1. WINDOWS: *(a) OPENING SIZE*

3 ft, 3/8 in. x 4 ft, 1-3/8 in.

(b) GLAZING MATERIAL

1/4-in. laminated safety sheet glass

(c) REMOVAL FOR EMERGENCY EXIT (NUMBER, LOCATION)

None removable

2. SEATS: *(a) SEAT-TO-SEAT SPACING, DIRECTION* 2 ft, 8 in. between most (fore- and aft-facing) seats; 5 ft between each of 6 pairs of center-facing seats.

(b) STATIC LONGITUDINAL STRENGTH -- LOAD APPLIED AT HIP LOCATION

Unknown

(c) SEAT BACK STRENGTH -- LOAD APPLIED AT TOP OF SEAT

Unknown

(d) PADDING OF REAR OF SEAT BACK, FORCE/DEFLECTION

Unknown

(e) EXISTENCE OF PROTRUSIONS, SHARP EDGES -- SUBJECTIVE EVALUATION

Seats have aluminum facings on their backs and protruding steel hand grabs at their corners and, therefore, could cause injury.

3. STANCHIONS: *(a) POLES:*

NUMBER	*DIAMETER*	*SHEAR STRENGTH*	*BENDING STRENGTH*
12 per car (steel tubes)	1-1/4 in.		

(b) HAND GRIPS: AXIAL STRENGTH, LOCATION

One mounted on aisleway corner of each seat; axial strength unknown.

(c) PANELS: SIZE, STRENGTH

28 in. x 30 in. sheet-metal unit on either side of each door.

4. HOSTILITY: *(a) PRE-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES WITH REGARD TO FLUSHNESS, SHARPNESS, etc.*

Stanchions, seat backs, and seat hand grips are the principal potentially injurious objects which passengers could impact.

(b) POST-CRASH SUBJECTIVE EVALUATION OF GENERAL CONDITION OF INTERIOR SURFACES AFTER SLIGHT CAR DEFORMATION -- e.g., EXPOSURE OF SHARP PANEL EDGES

Broken glass would be the most critical passenger hazard resulting from a slight collision. The steel framing for the padded seats also constitutes an undesirable potential impact hazard.

5. FLAMMABILITY OF INTERIOR COMPONENTS -- e.g., SEATS, FLOOR COVERING Although the seat cushions are flame-retardant, there is no requirement for fireproofing of the seat covers, plastic wall coverings, or tile and plywood flooring.

6. END PANEL, WALL, CEILING, AND FLOOR FLAT SURFACE HARDNESS

End panels include three large glass windows, approximately 4 feet in height, across the car width which would constitute unnecessary hazards in crash.

7. IMPACT OF ONE OCCUPANT INTO ANOTHER -- COMPARTMENTALIZATION -- SUBJECTIVE EVALUATION FROM LAYOUT OF SEATS AND STANCHIONS

There is no compartmentalization in these cars; however, because of stanchion locations, passengers tend to congregate at the car doors.

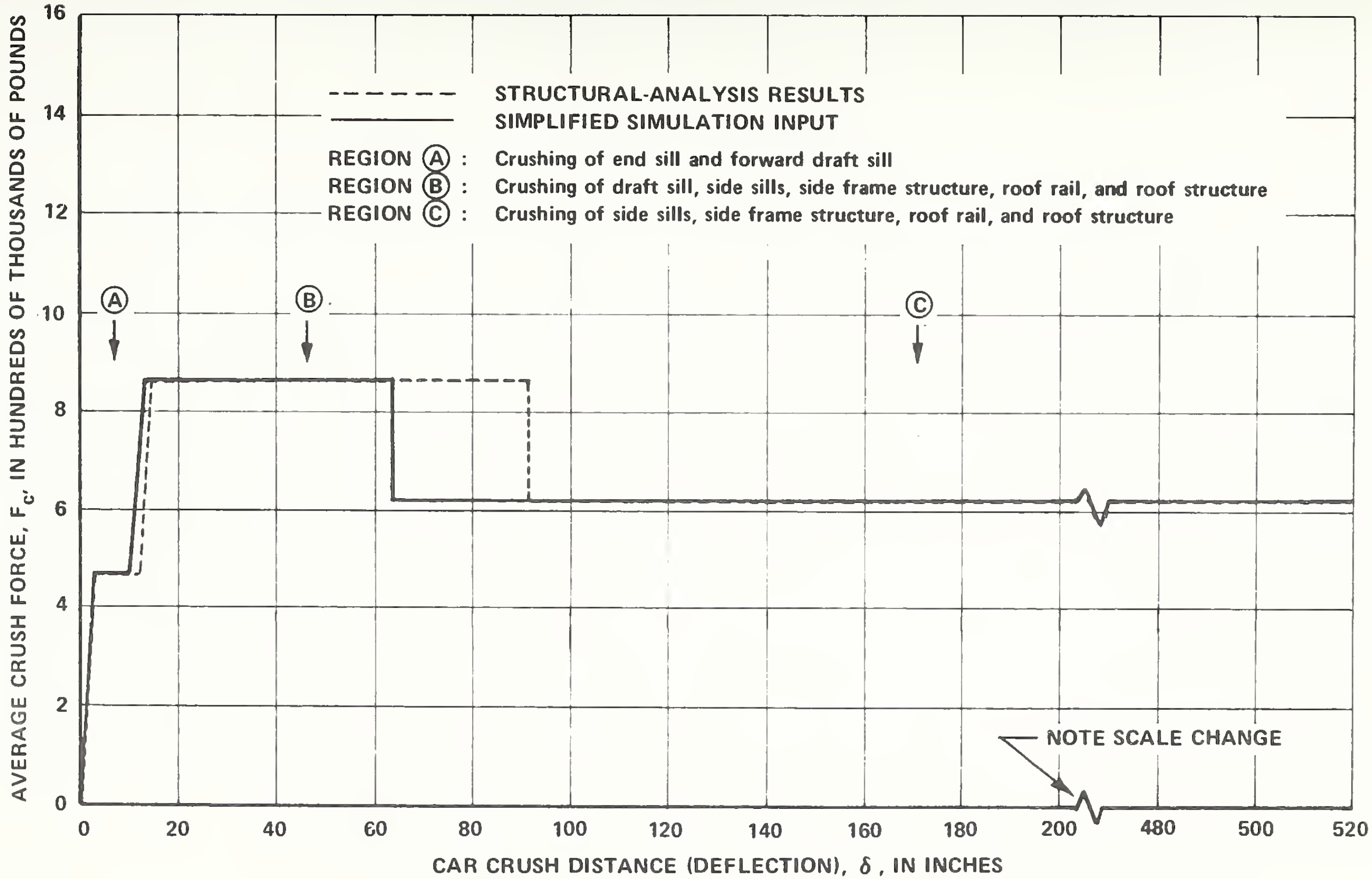

Figure 5-22. Crush Force vs Deflection for Silverbird Car -- No Override

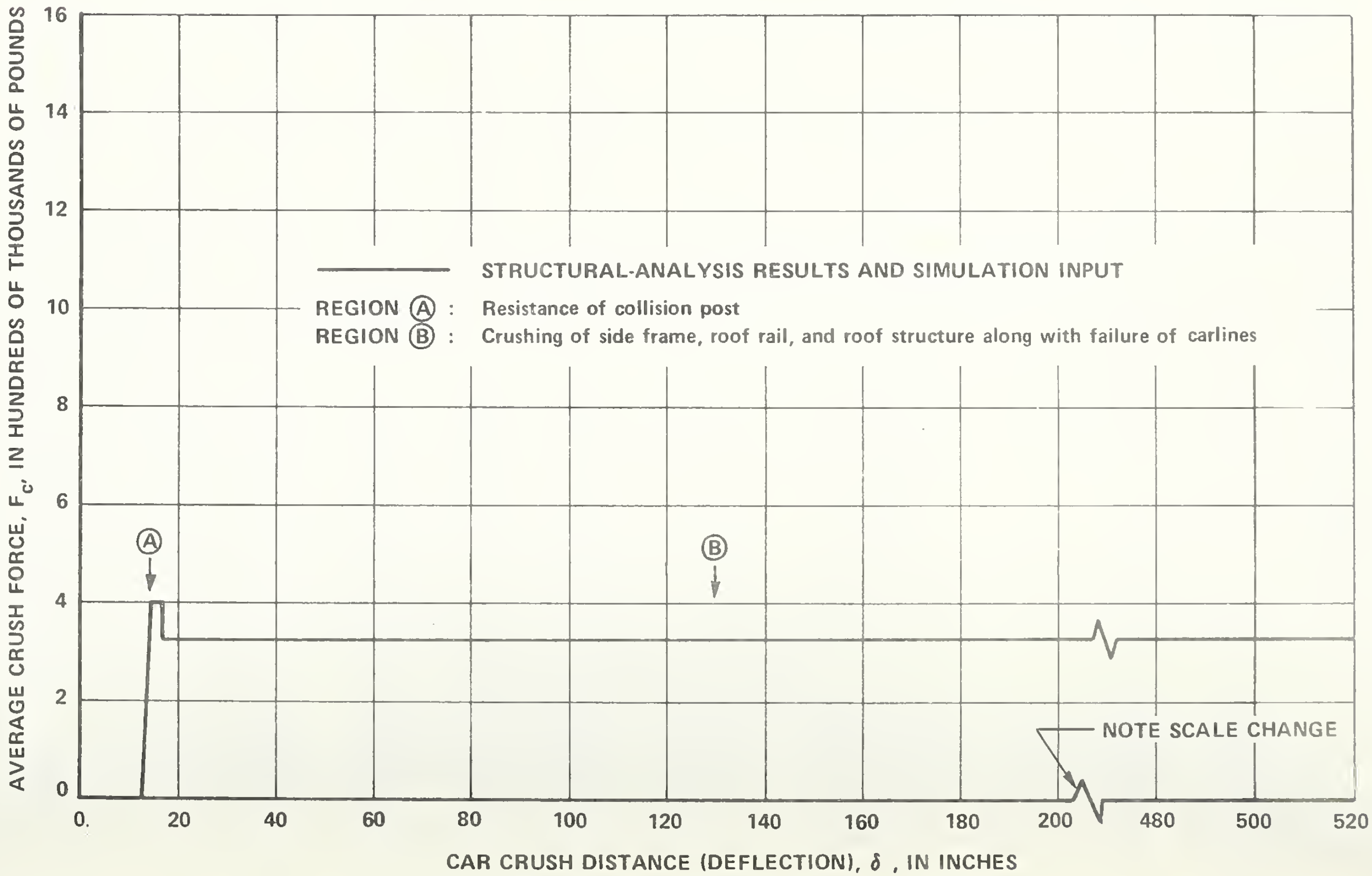

Figure 5-23. Crush Force vs Deflection for Silverbird Car -- Override

5.4 GENERATION OF CAR STRUCTURAL MODEL

A car structural model is required to obtain an elementary description of train behavior in a frontal or front-to-rear accident. Train behavior is defined in terms of (1) the approximate amount of penetration or crush occurring in each car in the train and (2) the approximate velocity - time history for the undeformed portion of each car. In this section, the approach used in generating the required car model is described.

Because car structural failure in the region characterized by the large deflections which are of interest is a multi stage and inherently complex process, it is necessary, within the present state-of-the-art, to make a number of simplifications and assumptions in order to obtain a car model. In this section we describe the basic approach to the simulation of car inertia and strength, and in the following section, 5.5, we discuss in more detail the generation of force versus deflection relationships for the cars.

The car model consists essentially of a one-dimensional representation of car mass and crush strength characteristics, and inter-car elements (coupler draft gear and free play at car ends). The fact that actual car crush can be a complex three dimensional process is acknowledged; nonetheless it is believed that the gross train behavior in a frontal crash can be described by such a model, provided that the model represents the effective longitudinal crush characteristics of the cars. In terms of developing predictive capability for crush characteristics of a given car, the inadequacy of the one dimensional model must be acknowledged. We will re-emphasize this important point a number of times as we develop and apply the model and interpret the results.

It is anticipated that the model described in the following paragraphs can be expanded so that predictive capability can eventually be obtained. This expansion would first take the form of a more rigorous one dimensional treatment (e.g., more degrees of freedom per car) and would then proceed to account for car deformation in the second and third dimensions. Validation of the model by physical tests at each stage of development would be required.

In the present car model, all cars in the train, with the exception of the first car (described as trailing cars) are represented by a force versus deflection input acting on a single fixed mass, (mass does not vary with time) shown schematically in Figure 5-24. The force deflection input for a given trailing car is based on the force deflection characteristics of the aft end of the preceeding car, the inter-car force deflection characteristics, and the force deflection characteristics of the forward half of the car being described. Thus, the mass can be considered as concentrated at the middle of the car. The fixed mass assumption for the trailing cars is believed to be justified by accident experience, which has shown that structural deflection of trailing cars is small compared to car length, even in high speed crashes.

The first car in the train is represented by a force versus deflection input acting on a variable mass, as shown in Figure 5-25. The value of the mass at any instant of time is determined from the condition that the effective mass of the car is proportional to the length of the undeformed portion of the car.

While it is believed that the approach of using a single but variable magnitude mass at the lead car (in lieu of a finer model representing the lead car by a number of masses, as shown in Figure 5-26) will provide a reasonable representation of gross train behavior, possible inaccuracies in the shape of the force-deflection curve for the first car are acknowledged. This effect is discussed in more detail in the following section, where we described the method used for estimating the effective force versus deflection curve for particular cars.

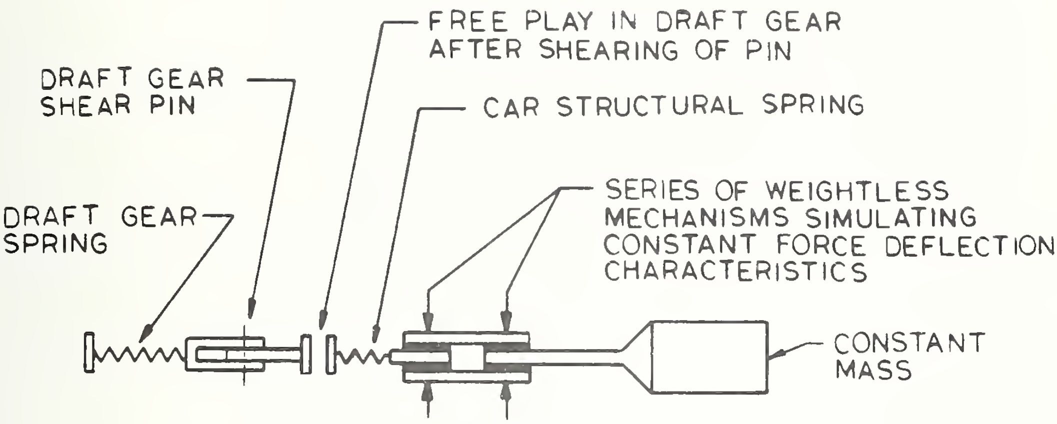

Figure 5-24. Form of Model for Trailing Cars

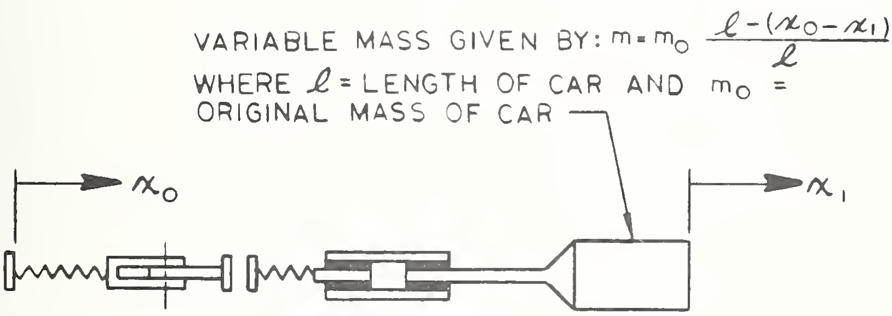

Figure 5-25. Form of Model for Lead Car Same as for Trailing Car Except for Variable Mass

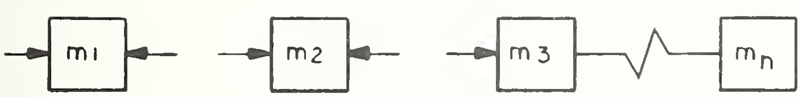

Figure 5-26. Finer Simulation of Lead Car Structure by n Masses with Appropriate Force Inputs

(This Method Not Used in Model)

5.5 FORCE VERSUS DEFLECTION CHARACTERISTICS

The initial approach in generating force-deflection characteristics is that the colliding cars meet in such a way and behave in such a manner that override of one car by another does not occur and that the load carrying elements in the car develop their full compressive capability (whether this be based on column failure or crippling failure, as appropriate for the particular element). It is emphasized that force-deflection characteristics calculated on this basis result in the development of maximum possible force levels, and that the resulting degree of car penetration is the least which can occur. A review of actual train collisions shows that some degree of override occurs in many collisions, and that significant override is most likely to occur in collisions where the closure velocity is high.

The problem of override is dealt with in considerable detail in Chapter 8. Specific accidents are reviewed, possible mechanisms of override are identified, and approximate bounding calculations are shown as a preliminary design guide for providing insight as to the role of particular structural features in the climbing process. It is appropriate to note at this point that the mechanisms causing override are complex, and that a reasonable predictive capability for override will require a significant amount of closely coordinated test and analysis.

The simplified approach taken in the present one-dimensional model is that the "no override" case is represented by the "flat face" or maximum force-deflection curve, and that degrees of override severity are assigned on the basis of the effective mean load developed in an override collision, expressed as a percentage of the predicted mean flat face force level. Thus, if a collision occurs in which the override is such that a given percentage of flat face force level is developed, this input provided to the train model can result in the determination of reasonably accurate car decelerations and car penetration. Again, the use of the train model in this manner should not imply that the degree of override for particular collision conditions and car constructions can be predicted. However, the model at this stage of development is believed to be a useful comparison tool, in that the relationship between passenger safety in a collision and car structural and interior descriptors can be investigated.

The simplified method used in this study for estimating car force versus deflection characteristics is described in the following paragraphs. More refined methods for predicting these characteristics should be developed in subsequent investigations. Finite element analysis (or the approximate equivalent), scale model testing and full scale testing should be investigated.

The simplified method is best described by referring to a particular car. A cross section of the R-44 car at a point in the door area behind the bolster is shown in Figure 5-27. Since the side frame is interrupted by door and window cutouts, members located in the main portion of the car body (between truck bolsters) which are capable of developing longitudinal force are limited to the continuous side sill members located below floor level, and the continuous longitudinal roofing members. The total effective compression area just aft of the bolster in the door area (the section represented by Figure 5-27, which occurs at station 125 in the car) is 15 square inches, as shown in Figure 5-28, where effective cross section area versus car station is plotted. The plot shows that this section in the car has the least area, with the stronger sections occurring in the end underframe area forward of station 125. In this region the area includes the relatively large area of the draft sill (center sill) which extends from the anti-climber to the truck bolster.

A simplified force-deflection curve based on Figure 5-28 can be described in terms of two force plateaus, one plateau representing approximately 100 inches of structure forward of station 125, and the other plateau representing approximately 700 inches of structure aft of station 125. The shape of the actual force-deflection curve depends on the failure sequence (i.e., whether initial failure takes place on the low or the high plateau, and whether full crush takes place on one plateau before crushing is initiated on the other plateau.) The failure sequence, in turn, depends on the manner in which the load is applied and on physical characteristics of the structure other than the cross section area plotted in Figure 5-28.

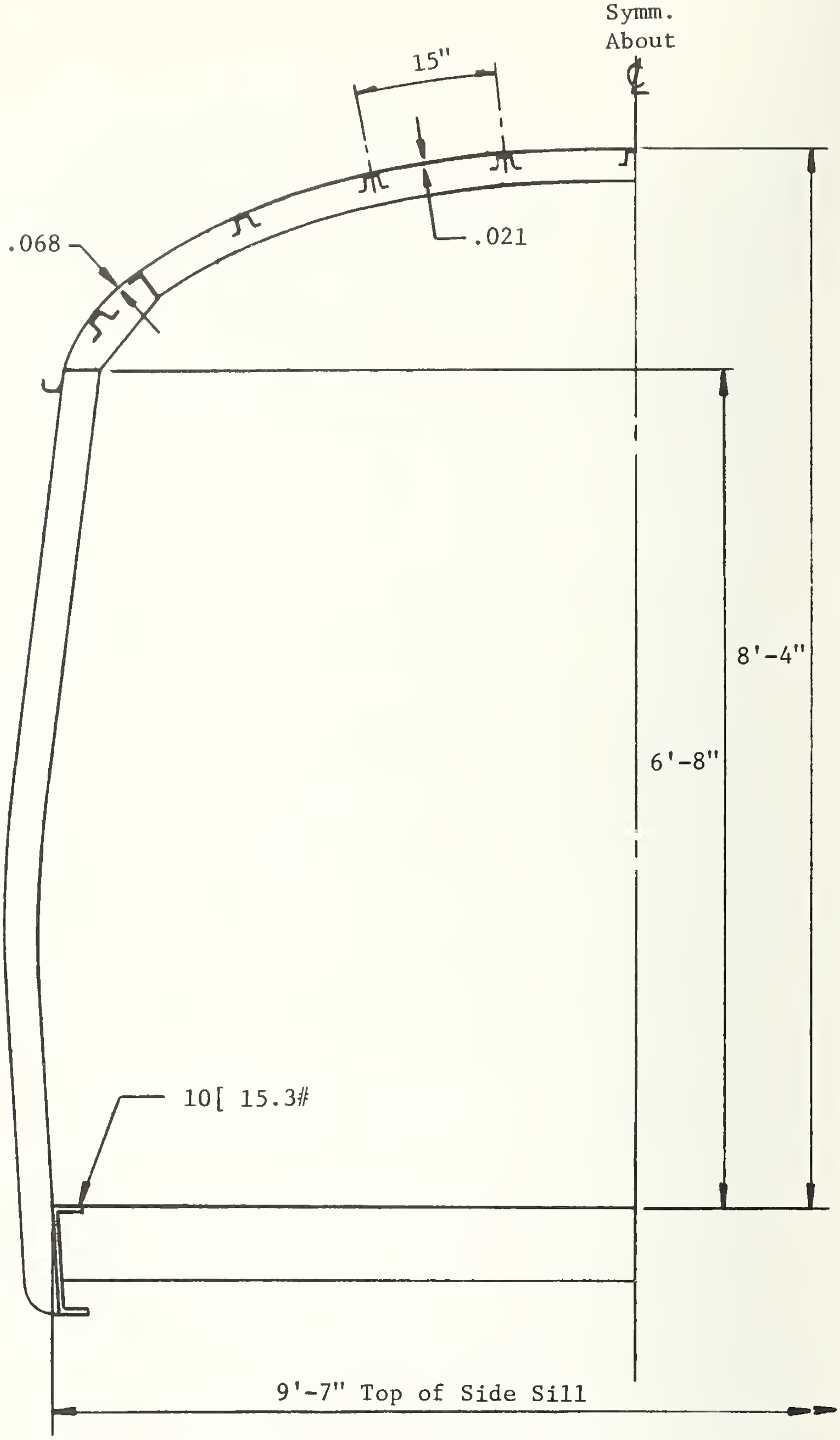

Figure 5-27. Structural Cross Section of R-44 Car Between Stations 125 and 16(

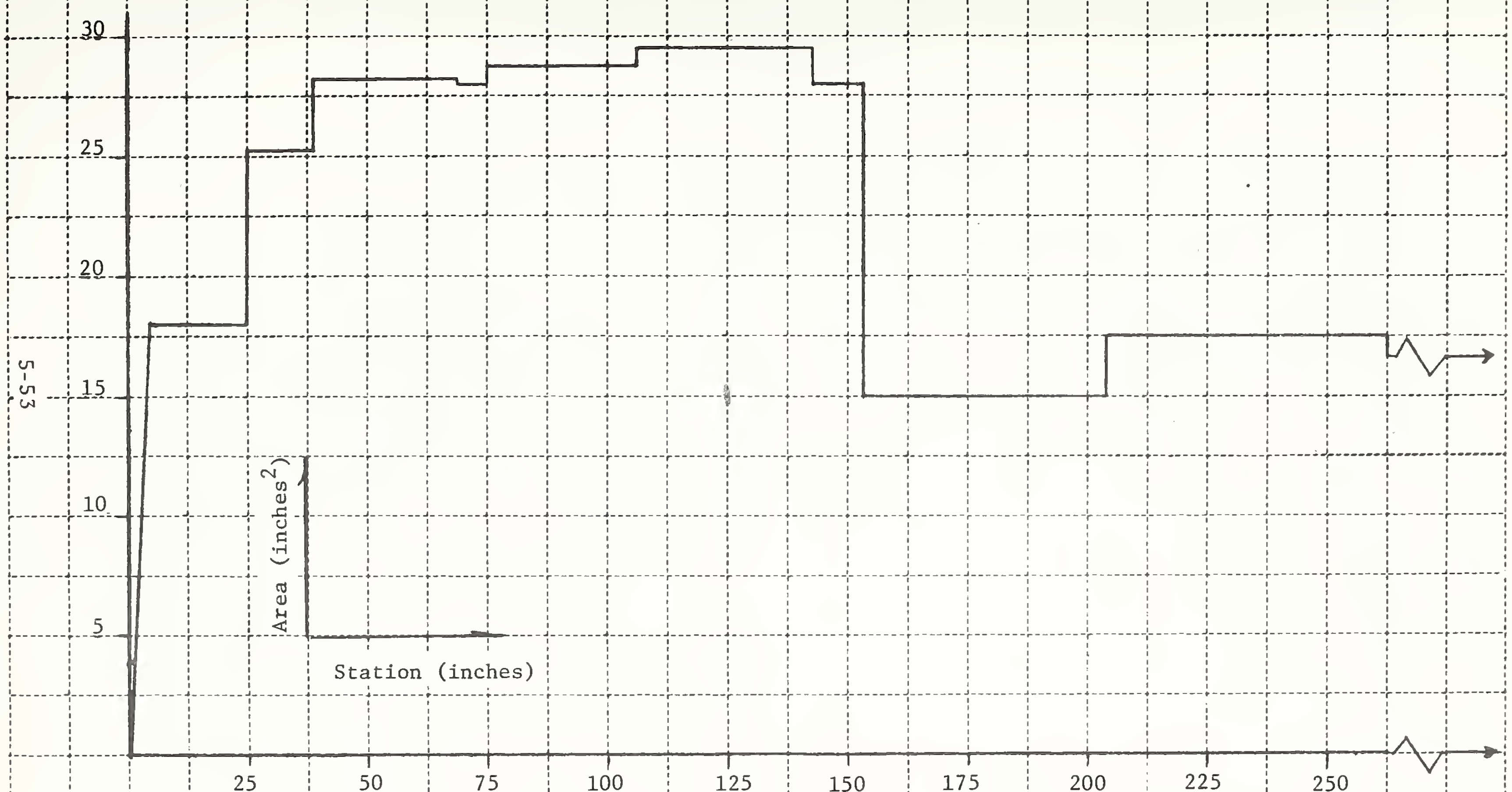

Figure 5-28. Estimated Effective Cross Section Area Versus Car Station for R-44 Car

For a slowly applied longitudinal force the section having the least effective area* would fail first, producing the force-deflection curve shown in Figure 5-29a, provided that (1) internal load paths are such that the effective area is fully utilized and (2) individual elements which are initially stable remain adequately stabilized during the collision.

The provision in regard to internal load paths is illustrated by Figure 5-30, which shows load paths existing between stations 20 and 125. For a flat face load (e.g., applied by rigid end blocks contacting the draft sill and side sills at station 20 and the side sills at station 125), the load path is redundant, with some of the load (P_{c1}) entering the structure at the draft sill. Since the draft sill does not exist aft of the bolster, the shear webs transfer load from the draft sill to the side sills, resulting in decreased center sill load P_{c2} and increased side sill load P_{s2} just forward of the bolster. The bolster serves to distribute the remaining center sill load (P_{c2}) to the side sills, producing the total side sill load ($P_{s2} + \frac{P_{c2}}{2}$ just aft of the bolster. Thus, the structure is redundant with the level of load carried by the center sill evidently depending on relative stiffness and strength of the longitudinal members, shear web rigidity and stability, and the strength and rigidity of the bolster.

If the first failure point in the structure is the connection of the bolster to the side sill, or if the bolster has negligible bending rigidity, then the draft sill is completely ineffective in the post elastic regime, regardless of shear web rigidity. Crushing will be initiated in the side sill at the bolster (the point of maximum side sill load) and will proceed forward to station 20, with the undeformed draft sill moving aft as a rigid body. For this extreme case, load capacity of the structure is limited by the side sill strength, as indicated in Figure 5-31.

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* Effective area as used in this context refers to the maximum amount of area which could be utilized at a particular car section to develop full material crippling or yield stress for large deflections (given the two provisions stated above).

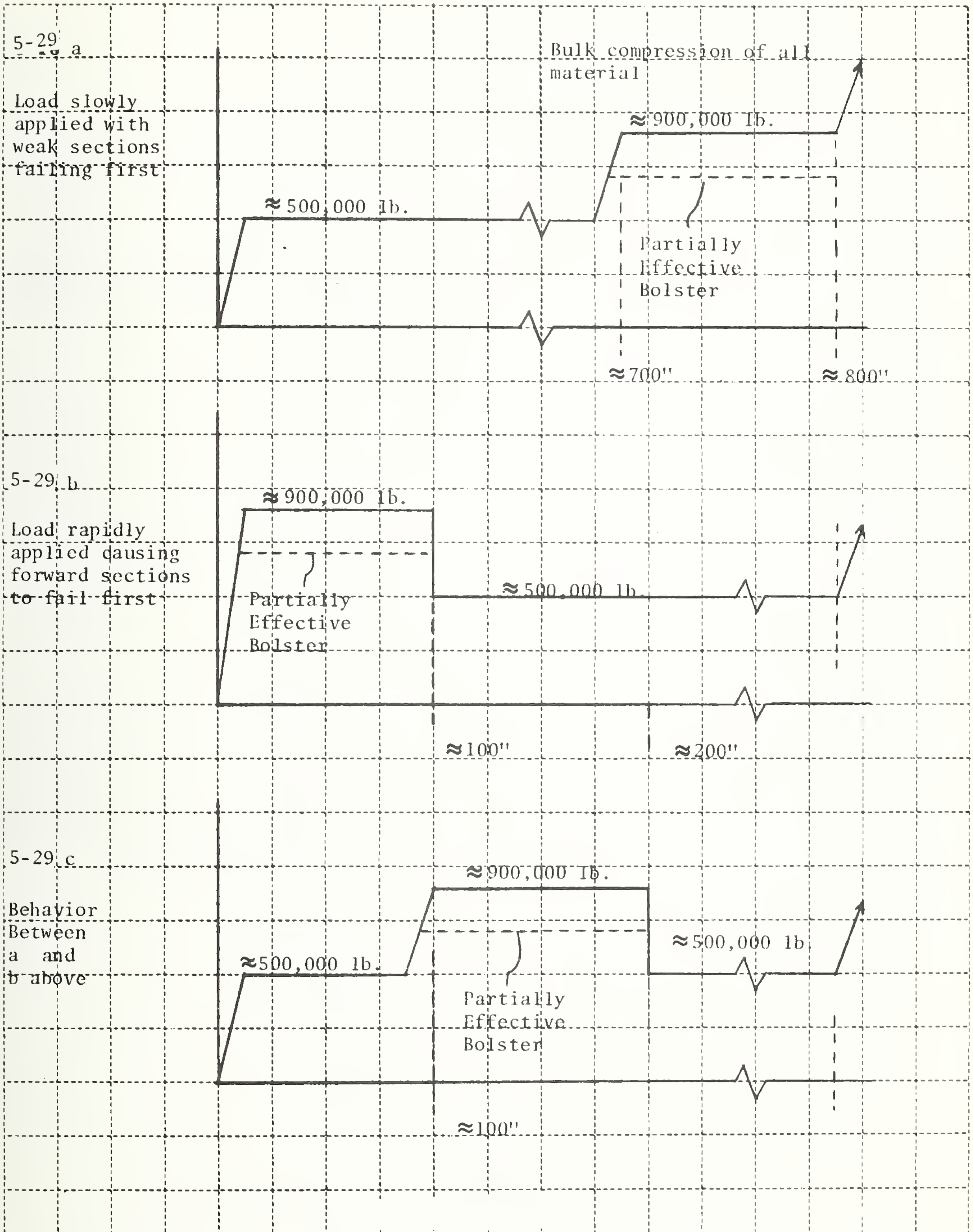

Figure 5-29. Possible Force-Deflection Curves for R-44 (Draft Gear and Free Play Not Included)

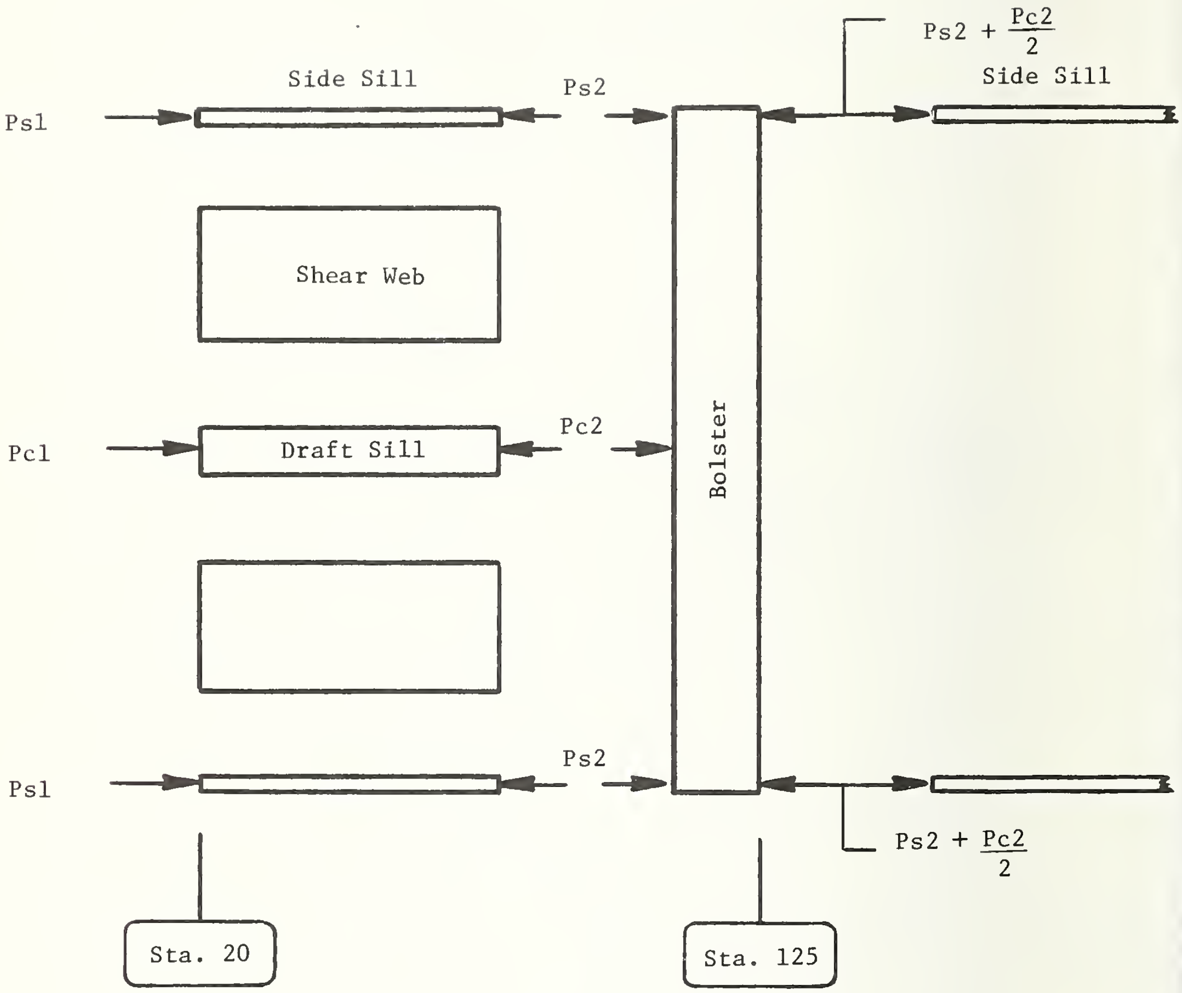

Figure 5-30. Redundant Load Path Thru Bolster

The other extreme (maximum load capability) is represented by the case of a rigid bolster in which failure does not occur in the attachment of the bolster to the side sill. In this case, the draft sill is fully effective, regardless of shear web strength or stiffness, and total section strength is equal to the crushing of the center sills added to the crushing of the side sills.

An intermediate case exists when the bolster has a finite degree of rigidity, but develops less crushing strength than the center sill. The load path through the center sill and bolster is in parallel with the direct load path through the side sills, and the load capacity of the total section is determined by side sill crush plus bolster yield load. This situation is represented by the intermediate dotted line in Figure 5-31. The load is shown decreasing with deflection, as the bending failure of the bolster proceeds.

It is evident that the problem of predicting total crush load in a given structure can be more complex than the elastic redundant problem for the same structure; in this case the total failure load depends on the failure sequence, which in turn depends on the elastic load distribution.

We have also noted that the accuracy of the force-deflection curve for the slowly applied load (Figure 5-29a) is dependent not only on the internal load distribution and the failure sequence resulting from it, but is also dependent on the degree of compressive stability which is maintained for the individual elements during the process of the large post-elastic structural deformations. This can also be illustrated by referring to Figure 5-30. The compressive stability of the side sill is dependent to at least some extent on the lateral and torsional support provided by the shear web and its stiffeners. While this support may initially be adequate to permit the development of maximum crippling stresses in the side sill, large deformations of the shear web during the general crushing process can lead to failure of the connection between the shear web and side sill, with resulting reduction of side sill compressive stability.

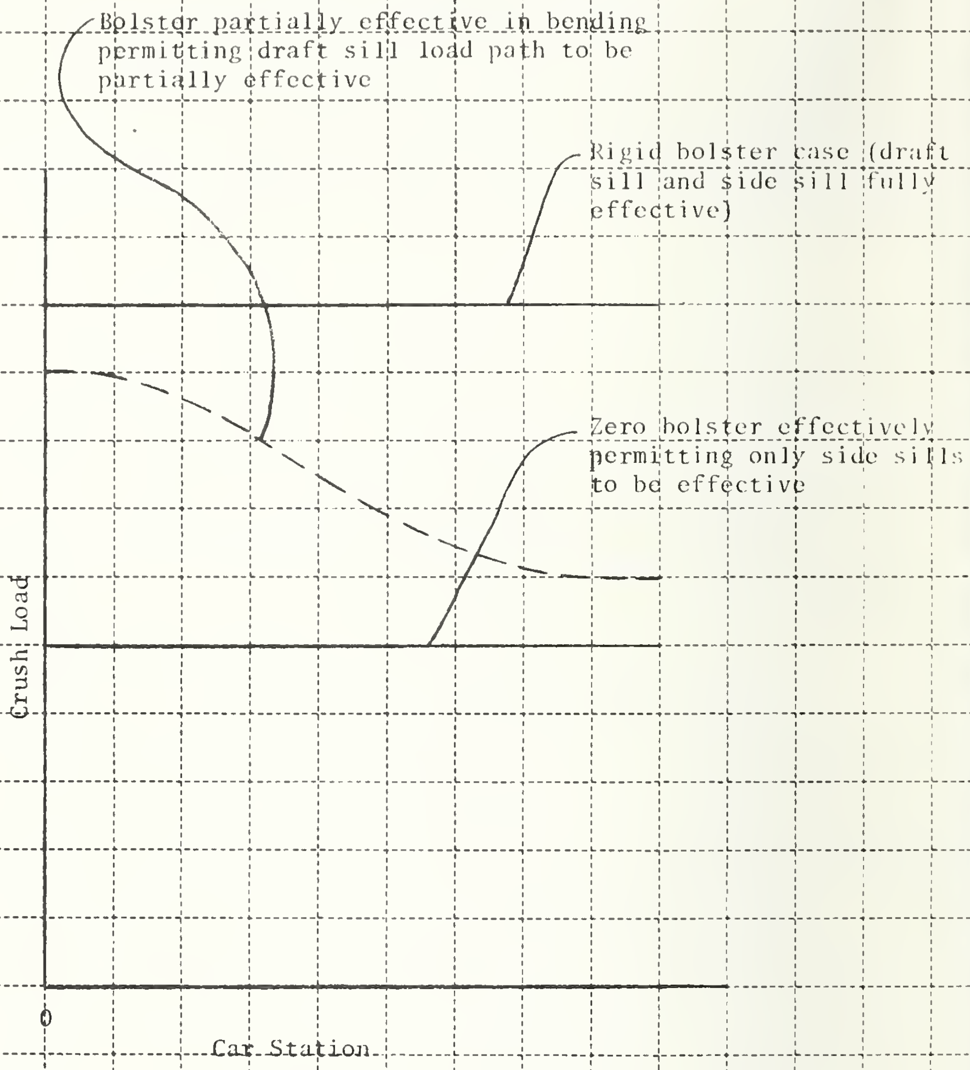

Figure 5-31. Range of Possible Crush Load Levels in End Underframe Area

It is evident that the estimation of the effective force-deflection curve is very approximate, even with the simplifying assumption of a slowly applied load. For the R-44, our estimate for the slowly applied load is represented by Figure 5-29a.

The problem of estimating force-deflection characteristics is further complicated by the fact that the collision loads are rapidly applied. Because the inertia of the car is actually distributed (not concentrated at the center of the car, as in the idealized model) the net compressive load is not constant along car length at any instant in time, as in the case of the slowly applied load. Instead, the load tends to be higher at the forward end of the car in the early stages of the collision.* This can cause strong sections to fail before weaker sections, if the stronger sections are located toward the front end of the car. For a very rapidly applied load, the force-deflection curve shown in Figure 5-29b might approximate the actual case more closely than that shown in Figure 5-29a.

The final force-deflection curve we have estimated for the R-44 is approximated by the plot in Figure 5-29c. (The actual force deflection curve selected, along with explanatory notes, is shown in Figure 5-18.) In this scenario, the weakest portion of the structure immediately aft of the side doors and the relatively weak structure in the forward 20 inches of the car fail almost simultaneously, followed by failure of the stronger sections between stations 20 and 125, and finally by failure of the remainder of the car mid section. It is emphasized that the procedure is subjective in regard to the shape of the force-deflection curve, as well as in regard to the force level in each plateau. The tendency is for railcar structures to fail from the front end in actual collisions, though this may be a result of partial climbing, or failure of the longitudinal elements in the colliding cars to

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* These initially high loads at the front end are important in considering the initiation of climbing deformations and forces. The causes and effects of initial deformations of anti-climber and local back up structure are discussed in more detail in Chapter 8.

develop their full strength potential at the front end, whether due to factors such as those discussed in regard to Figure 5-31, or due to local instability of longitudinal members caused by failure of transverse members at the front end or other failures associated with front end damage incurred in the collision.

Figures 5-13 through 5-23 show estimated flat face ("no override") force-deflection curves and override force-deflection curves for the five study cars. The subjective approach to the determination of the "no override" curves should be emphasized. The override curves are even more subjective, in that they merely represent conceivable scenarios.

In the following section, we review the information obtained for the five generic car types, including the force deflection curves, with the objective of identifying and comparing significant structural parameters for the five methods of construction.

5.6 RELATIONSHIP BETWEEN STRUCTURAL CRASHWORTHINESS AND GENERIC CONSTRUCTION TYPES

In the preceding sections the strength and weight characteristics of five generic car construction types have been obtained. The five study cars range in length from a minimum of 51.3 feet for the R-33 car to a maximum of 85 feet for the Silverliner. Weight, length and strength of each of the five cars are listed in columns 3, 4 and 5, respectively, of Table 5-7. The strength shown in Table 5-7 represents the average car strength over the first ten feet of crush, obtained from the force-deflection curves in Figures 5-13 through 5-23. (Excluding override curves).

At this point, we seek to find if there is any meaningful relationship between type of car construction and structural crashworthiness. In this context we define structural crashworthiness in terms of car crush length and car deceleration in a given collision. These two "outputs" - crush length and car deceleration- can be taken as measures of safety relating to penetration fatalities and second collision injuries, respectively.

TABLE 5-7. STRUCTURAL CHARACTERISTICS OF GENERIC CONSTRUCTION TYPES

1 Type of Construction	2 Car	3 Weight (Pounds)	4 Length (feet)	5 Strength (pounds	6 S/W Pounds Per Pound	7 S/W Normalized	8 Spec. Buff Load
Old medium weight steel	R-33	72,400	51.3	750,000	10.3	7.1	400,000
Contemporary Medium Weight Steel	R-44	82,700	75	550,000	6.7	6.7	500,000
Lightweight Stainless Steel	Sil-ver-liner	101,400	85	1,450,000	14.3	16.2	800,000
Aluminum Extrusion	BART	56,000	75	350,000	6.3	6.3	200,000
Aluminum Sheet Metal	Sil-ver-bird	60,000	69.8	675,000	11.3	10.5	200,000

NOTES:

Column 5 - Strength shown is average strength over first 10 feet of crush, calculated from "no override" force - deflection curves in Section 5.4

Column 6 - S/W is strength to weight ratio of one car, based on strengths in Column 5.

Column 7 - The normalized S/W includes correction for car length, per equation 5-8, Section 5.6.

Column 8 - Buff load corresponds to full yield strength of material.

As such, these measures are meant to be independent of car interior characteristics arising from the car's general interior layout and its degree of "hostility". Specifically, in comparing generic types of car construction, we are interested in the structural performance of the car in a frontal collision, with interior characteristics held constant.

In order to evaluate and compare the structural crashworthiness of the five car types studied it is necessary to determine, in a first order analysis, the manner in which the three structural parameters - weight, strength and length - affect the structural performance of the car in a frontal collision.

Consider a barrier collision in which a train having n cars strikes the barrier at velocity V. Each car has weight W, strength level S and length ℓ. From conservation of energy

$$\frac{1}{2} \, n \, \frac{W}{g} \, V^2 = S \, x_c \tag{5-1}$$

where

n	=	number of cars in train
W	=	weight of each car
g	=	gravity constant
V	=	barrier striking velocity
S	=	strength of each car
x_c	=	total crush distance of all cars in train

Rewriting equation 5-1

$$x_c = \frac{\frac{1}{2} \, n \, \frac{V^2}{g}}{S/W} \tag{5-2}$$

If all deformation takes place at the lead car, train acceleration is given by

$$\ddot{x} = \frac{g}{n} \, (S/W) \tag{5-3}$$

From the equations 5-2 and 5-3 it is evident that the strength to weight ratio of the car is a significant parameter. Car crush distance (which leads to "first collision" or penetration fatalities) is inversely proportional to the strength-weight ratio ($\frac{S}{W}$) and car acceleration (which leads to "second collision" injuries) is directly proportional to S/W.

A more precise parameter relating to penetration fatalities is obtained when car length (ℓ) and "passenger density" ρ_p (number of passengers per foot of car length) are considered. If it is assumed that all passengers within the crush portions of the train become penetration fatalities and that passengers are uniformly distributed along the entire car length, the number of first collision fatalities (N_p) can be found by multiplying both sides of equation 5-2 by ρ_p

$$N_p = \rho_p x_c = \frac{\frac{1}{2} \rho_p n \frac{V^2}{g}}{S/W} \qquad (5\text{-}4)$$

The total number of passengers in the train (N_T) is given by

$$N_T = \rho_p n \ell \qquad (5\text{-}5)$$

The ratio of first collision fatalities to total number of passengers is obtained by dividing 5-4 by 5-5

$$R = \frac{N_P}{N_T} = \frac{\frac{1}{2} \frac{V^2}{g}}{\frac{S}{W} (\ell)} \qquad (5\text{-}6)$$

When first collision fatalities are considered, equation 5-6 shows that longer cars are safer than shorter cars, if other variables are held equal. However, this conclusion is not too meaningful, since weight (W) will tend to increase as length increases. If it is assumed that car weight for a given generic construction is directly proportional to car length,* and that strength is independent of car length

$$\frac{S}{W} \doteq \frac{k}{\ell} \qquad (5\text{-}7)$$

Inspection of 5-6 and 5-7 shows that safety would be independent of length, for these assumptions. Using equation 5-7, strength to weight ratios in column 6 of Table 5-7 can be normalized to a standard car length as follows:

$$\left[\frac{S}{W}\right]_n = \frac{S}{W} \frac{\ell}{\ell_n} \qquad (5\text{-}8)$$

From equation 5-8 the normalized strength to weight ratio for a given car can be obtained by multiplying the calculated strength to weight ratio by the ratio of the actual car length to the normalized length. Applying equation 5-8 to the R-33 car in Table 5-7, the normalized strength weight ratio based on normalized car length of 75 feet is given by

$$\left[\frac{S}{W}\right]_n = 10.3 \frac{51.3}{75} = 7.05$$

The normalized strength-weight ratios calculated in this manner are summarized for the five generic cars in column 7 of Table 5-7.

In comparing strength and weight values of cars having different lengths, designers have noted that car weight should not be directly proportional to car length because total car weight includes some elements whose weights are not proportional to car length, such as end bulkheads, collision posts, couplers, trucks, propulsion system, etc. Thus, a more accurate value for normalized strength to weight ratio would be somewhere between the actual car strength to weight ratio shown in column 6 and the ratio shown in column 7, which is based on direct proportionality between weight and length.

* Inaccuracies resulting from this assumption are discussed shortly.

We are now interested in reviewing the strength to weight ratios in columns 6 and 7 to see if there is any recognizable or predictable pattern relating strength to weight ratio with generic construction type. Initially, we choose to disregard the Silverliner, which is the only non-transit car in the group, and is designed to significantly higher buff loads than are the transit cars. Considering only the transit cars, we note that the older R-33 car, normally considered to have relatively heavy construction, has a higher strength to weight ratio than either the "contemporary medium weight" steel car (R-44) or the "modern lightweight aluminum extrusion" car (BART). This observation holds true for column 7 (normalized strength-weight ratio) as well as for column 6 (actual strength-weight ratio). This appears to conflict with the generally held view that the old methods of construction are structually less efficient than the newer medium weight and light weight constructions.

A possible explanation of this apparent conflict is that the newer cars carry relatively more weight in completely non-structural elements such as air conditioning, propulsion, etc., with the result that the higher efficiency of the modern structures is obscurred.

Though the non-structural aspects of car design tend to obscure the effect of particular structural parameters, it can be seen from Table 5-7 that the strength to weight ratio appears to bear some relationship with specification buff strength, shown in column 8. When all five cars are compared, the Silverliner, which has the highest buff strength requirement (800,000 pounds), also has the highest strength to weight ratio (14.3 to 16.2). Correspondingly, the BART car, which shares the lowest buff strength requirement (200,000 pounds) with the Silverbird, also has the lowest strength to weight ratio (6.25). The relatively high strength to weight ratio of the Silverbird (10.5 to 11.3) can be explained by the fact that the actual calculated car strength of 675,000 pounds is far in excess of the 200,000 pound specification requirement.

The fact that strength to weight ratio tends to increase with increasing car strength suggests that total car weight is relatively insensitive to car strength, regardless of the type of construction. More important, the emperical data implies that strength to weight ratio can be controlled, with small effect on total car weight, by controlling the specification buff strength.

A review of typical car cross section geometry shows that this is, in fact, the case. If it is assumed that the compressive failure mode of the car does not involve major transverse failures, overall instability of the entire car cross section or its individual members, (i.e. large vertical or lateral deformations do not take place) the crush load of the car is at least equal to the load obtained by applying the effective compressive yield stress of the material to the main longitudinal members. In the following example, a car which weighs 70,000 pounds has a crush strength of 420,000 pounds, and a resulting strength to weight ratio of 6. The crush load can be developed by the following typical baseline design.

Structure	Effective Area	Crush Load Based on Compressive Yield Stress of 30,000 psi
Sill Structure Below Flow	$A_s = 10\ in^2$	300,000 lbs.
Effective Roof Structure	$A_R = 4\ in^2$	120,000 lbs.
Total Structure	$14\ in^2$	420,000 lbs.

If additional structure develops the full compressive yield stress (in this case, 30,000 psi) the strength of the car would be doubled if another 14 square inches of structural area were added. For an aluminum car 70 feet in length, the added weight is 1180 pounds, or 1.7 percent of the original weight, and the corresponding increase in strength is 100 percent.

The conclusion that large increases in compressive failure load can be obtained with very small increases in car weight is apparently not correct if failure does occur due to overall instability of the car cross section or its main longitudinal members. However, the examples below show that baseline structures which do not fail due to instability will tend to behave in the same manner when strengthened.

First, basic instability of the entire car section is considered. Provided that the structure behaves as a monocoque or semi-monocoque structure (i.e., the sides, roof and sub floor structure serve to maintain the full strength potential of the entire section), the minimum* effective moment of inertia of the entire section is given by

$$I = A_s Y_s^2 + A_R Y_R^2 \qquad (5\text{-}9)$$

where

Y_s = distance from centroid of A_s to neutral axis of car cross section

Y_R = distance from centroid of A_R to neutral axis of car cross section.

For a typical car cross section,

Y_s = 30 inches

Y_R = 70 inches.

From equation 5-9, the minimum moment of inertia of the entire section is

$$I \approx 10\ (30)^2 + 4\ (70)^2 \approx 28{,}600\ \text{in}^4$$

* Some additional moment of inertia is provided by skin elements connecting the primary longitudinal members.

In the elastic stress regime, the Euler long column buckling load is given by

$$P_{CR} = \frac{\pi^2 E I}{\ell^2} \quad \text{(pin ended)} \tag{5-10}$$

where E is modulus of elasticity, ($\approx 10^7$ psi for steel) and ℓ is column length (typically, about 900 inches). The minimum buckling allowable* is therefore given by:

$$P_{CR} = \frac{(3.13)^2 \ (10)^7 \ (28,000)}{(840)^2} = 4,000,000 \text{ lbs.}$$

Thus the baseline car body, with no material added, has a minimum elastic buckling allowable about 10 times as high as the plastic failure load of 420,000 pounds. When material is added to double the plastic failure load, the corresponding section moment of inertia is also doubled, and the ratio of the elastic buckling allowable to the plastic crush load remains about 10.

If the car section does <u>not</u> behave like a monocoque or semi-monocoque structure, it is possible for the individual longitudinal members to buckle between transverse support points. However, in the typical example given above, doubling of the thickness of all elements in these members will also result in doubling of the section moment of inertia. Therefore, a baseline longitudinal sill or purlin member which has sufficiently close spacing of transverse supports to prevent a buckling failure will tend to retain its original stability margin provided that its area is increased approximately in proportion to the increase in design load.

Regardless of the type of construction employed, a baseline structure which crushes in a "well behaved" manner (no instability of major elements)

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* The assumption of a pin ended column in equation 5-9 leads to a minimum buckling allowable.

will tend to retain this behavior when the primary longitudinal members are strengthened in proportion to the increased design loads. Similarly, if the attachment of transverse members to longitudinal members is destroyed when the car deforms, both the baseline structure and the strengthened structure are likely to fail due to instability. (In Chapter 9, means of presenting such failures are discussed.) It is concluded that use of the compressive yield stress is appropriate when calculating increases in longitudinal strength due to increases in the area of the longitudinal members. Hence, the previous conclusion relating to all generic construction types -- that large strength increases can be obtained with very small percentage increases in weight -- appears to be justified.

It is appropriate to summarize the findings in this-sub section, since they have a significant influence on the direction of the remaining investigation.

1) The effective strength to weight ratio S/W appears to be the most significant gross car parameter influencing car structural performance in frontal collisions.

2) Total amount of car crush in a given collision can be expected to be about inversely proportional to the effective S/W. Hence penetration or first collision fatalities tend to decrease with increasing S/W.

3) The type of car construction (e.g., as in the five generic construction types which have been selected for study) does not determine S/W.

4) For all construction types, there is a very large range of possible S/W because of the fact that total car weight is relatively insensitive to large relative changes in effective compressive areas.

In the following sub-section, the interior characteristics of the five study cars are reviewed.

5.7 INTERIOR CHARACTERISTICS

Interior characteristics of the car affect the severity of the "second collision" injury, in which the unrestrained occupant strikes an interior object or another occupant during collision. The technology for predicting injury severity, and the inherent limitations of this technology, are described in Chapter 3.

Since all occupants in crushed portions of the car are assumed to receive fatal "first collision" injuries, the additional assumption is made that meaningful second collision injuries are confined to uncrushed portions of the car. It is acknowledged that there is an intermediate area between the fully crushed and uncrushed portions of the car where second collision injuries are a factor. Nonetheless, it is believed that a reasonable first approach is to base second collision injury analysis entirely on the environment within that portion of the car shell which is not deformed as a result of the collision.

It is noted in the Introduction (Chapter 1) and in Chapter 3 that injury severity can be predicted with reasonable accuracy only for certain specifically defined situations in which, at a minimum, the following critical interior parameters are known.

S, The occupant spacing with respect to the object which he impacts.

d, The effective impacted object crush distance.

These parameters will vary considerably for different passengers within a single car, depending on the passengers' location within the car, the initial orientation of his body, the location and orientation of other passengers, and the location and nature of any unrestrained objects within the car.

Even when this information is available, meaningful predictions of the effective values for S and d are possible only in particular situations. An example is the forward facing seated passenger in a frontal or front-to-rear accident. In this situation, the probability is relatively high that a particular portion of the passenger's body will impact a particular portion of a seatback for which the compliance is known.

Injury severity predictions are not normally feasible for standing passengers, even in hypothetical situations where the location and posture of all passengers are known, and the location and compliance of all interior objects are known. The motion of the standing passenger must be known with sufficient precision to predict the following events in the second collision and possible subsequent collisions.

> Whether the passenger initially contacts a fixed interior object or another passenger.
>
> Which portion of his body makes first contact, and which portion of the contacted object or body is struck.
>
> How the first contact alters the passenger's motion with respect to the contacted surface (e.g., whether it is fully arrested, changed in direction, etc.).
>
> In cases where the passenger's motion is not fully arrested by the first contact (probably most cases) the specific description of subsequent contacts and motions.

Analysis of sufficient complexity to predict these events is considerably beyond the scope of the present study. Therefore, though injury <u>predictions</u> in the strict sense do not appear to be feasible, <u>design guidelines</u> which can be applied to the safety of the standing passenger can be obtained from a parametric study of the effect of various combinations of S and d on injury severity. For example, if it is assumed that the standing passenger moves directly forward without contacting any obstructions or other passengers for a distance of S feet, and that his head strikes a relatively smooth object which undergoes an effective crush of d inches, a corresponding injury severity can be calculated. This injury severity can generally be taken as an upper limit for all cases in which the passenger is initially S feet from the object in question (i.e., he may contact other passengers in the vicinity, which would usually reduce the injury severity). For a particular design criterion (i.e., elimination of severe or fatal injuries within certain closure speed limits) the injury severities calculated in this manner can be employed to establish required combinations of S and d which can be used as guidelines for the design of the interior layout and the equipment within it. This approach is taken in Chapter 7, where the results of the collision simulations are presented and discussed.

Representative values of S and d for use in the collision simulations are selected in Chapter 6. To provide a background for establishing reasonable ranges for these parameters, the general interior characteristics of the five study cars are reviewed in the remaining portion of this section.

5.7.1 Silverliner

From the matrix of free-space distances (passenger spacings), S, and crush distances, d, the conditions for a typical Silverliner passenger could be estimated based upon interior seating arrangement and interior component construction of the car. Because all passengers are normally seated, a spacing of 2 to 4 feet would be representative of the distance an occupant might move before being provided ridedown. A crush distance of 1 to 2 inches also might be selected as typical of a Silverliner passenger impacting the seat in front of him. This 1- to 2-inch effective crush distance which is based on constraint crush force versus deflection would be equivalent to higher actual deformation if the crush force were not constant.

5.7.2 R-33 Car

Consider train passengers standing in a crowded R-33 car -- perhaps, the third or fourth car of a four-car train. Since the R-33 is designed primarily for standing passengers, having only 44 seated passengers out of a total capacity of 200, over three-fourths of the passengers will satisfy this condition. Now, consider a frontal impact of this train into another four-car train, both trains traveling at 30 or 40 mph. What happens? Within one-quarter of a second, the car being considered is decelerating at over 1g. We can assume that an average passenger could hold onto a handgrip at such decelerations. Not all the force resulting from the deceleration will have to be withstood at the passenger's handgrip; some floor frictional forces will be present; nevertheless, it appears that each standing passenger, for all practical purposes, will be unrestrained.

It is extremely difficult to hypothesize the trajectories the passengers will experience. There are few car interior components to impact, other than four vertical poles (stanchions) and the end doors and wall. Most standing-passenger impacts will be thrown into other passengers -- probably, under a condition where standing capability has already been lost. Most of the passengers will be off their feet, tumbling over, around, and into other passengers. Free-space distances might range from as little as 1 to 2 feet to perhaps half the 50-foot length of the car. Clearly, the passenger-spacing situation is much more difficult to envision here than in the case of the Silverliner car in which it was assumed that the majority of passengers were in equally spaced bench-type seats.

Impacted-object crush distances are equally difficult to determine. In a frontal crash, the window and side-facing seats would probably not play a major role. There are four 1-1/4 inch diameter poles (stanchions) per car which could be impacted and would possibly fail by bending and being torn loose. Other passengers probably would constitute the primary "objects" impacted. From contact sports, we can estimate that 5- to 20-mph impacts into other passengers probably scale the injury-severity range from minor to moderate. From Table 3-2 and Figure 3-3, this would translate into effective deceleration distances of 1 to 3 inches. Consequently, it might be reasonable to consider these values of d to extrapolate to other impact conditions.

5.7.3 R-44 Car

The R-44 is approximately 50% longer than the R-33 and incorporates approximately the same number of side-facing seats. However, forward- and rear-facing seats are also provided which seat an additional two dozen passengers. The greater length increases the total capacity of the car by approximately the same percentage as the increase in car length -- i.e., 50%. More important than the capacity change, however, is the change in passenger compartmentalization obtained in the newer car. Side-facing seats each accommodate only three passengers, with a two-passenger transverse seat adjacent to each side-facing one, the set occupying the spacing between door openings. The additional doors used in the R-44 car (compared to the R-33 car) increase the number of associated floor-to-ceiling poles (stanchions) used, thereby increasing the compartmentalization of the car. In a crash scenario similar to the one described for the R-33 car, free-flight spacings of S = 2 and 4 feet and S = 12 feet might represent a likely range. Crush distances, again might fall into the one to three inch range.

5.7.4 BART Car

The seating and interior design of the BART car appear more closely associated with the layout of a commuter car than with that of an urban rapid-transit car as, indeed, operation does include substantial suburban transportation. These cars seat over half of their normal rated passenger-carrying capacity. (Over 75% of their seats are transverse, with side-facing seats located only adjacent to the door areas.) At each side seat/door junction, windscreens are used, which would restrict side-seated-passenger longitudinal travel during a crash.

The relatively high seat-back strength of the BART cars suggests less chance of seat failure than in the case of the other cars being studied. This, along with the fact that half of the transverse seats are rear-facing, suggests that we can assume even shorter average free-space distances for this car than for the Silverliner.

The construction of seats in the cars under study varies considerably. Although the Silverliner seats are upholstered, they have metal seat-back surfaces. Seats of the NYCTA (R-33 and R-44) cars are made of fiberglass, and BART -car seats consist of metal frames with padding. The stiffness of the upholstery or padding is designed for nominal 1g loads and could not be expected to provide significant crash attenuation in the case of high-speed impacts. Consequently, the inner structure of the upholstered seats must be considered to provide the primary impact surfaces. In this respect, molded fiberglass seats, assuming that they are generally free of sharp edges (as is usually the case), appear preferable to upholstered seats from the point of view of safety. Ideally, seats should have a controlled-crush primary under-structure with some type of fireproof load-distributing foam padding, covered with fireproof material.

5.7.5 Silverbird Car

Of the Silverbird's 239 maximum (crush) passengers, 64 (approximately 27%) are seated. Of those seated, 52 face the front or the rear of the car. Car length is 70 feet. These characteristics define the interior of this car as being quite similar to that of the BART car. This can be more readily seen from Table 5-8, which presents the nominal seated and standing passenger accommodations for the five rail cars studied. Because of this similarity, free-space distances for the Silverbird car might be equivalent to those for the BART car.

TABLE 5-8. PASSENGER ACCOMMODATIONS FOR RAIL CARS STUDIED

CAR	LENGTH IN FEET	NO. OF PASSENGERS			
		SEATED			
		FORE- OR AFT-FACING	SIDE-FACING	STANDING (MAXIMUM)	TOTAL (MAXIMUM)
R-33	51	0	44	156	200
R-44	75	26	48	275	350
SILVERBIRD	70	52	12	175	239
BART	70	56	16	156	228
SILVERLINER	85	127	0	0	127

6. STRUCTURAL AND INTERIOR INPUTS FOR COLLISION MODEL

6.1 INTRODUCTION

At this stage in the study program, it is necessary to review the data obtained on the structural and interior characteristics of the five study cars in order to form a basis for selection of specific inputs for the train-occupant collision model.

In Chapter 5, strength calculations for the five study cars have indicated that a large variation in longitudinal strength exists within the total car population. On the basis of elementary force and energy considerations, it is evident that the effective longitudinal strength to weight ratio is a significant design parameter for railcars. The conclusion is also reached in Chapter 5 that there is no particular correlation between strength to weight ratio and generic construction type, and that a very large range of strength to weight ratios can be obtained on any one of the basic construction types with relatively small impact on total car weight.

We have noted that the effective force-deflection characteristic that occurs in a given condition is dependent on the degree of override, and that a sufficient analytical and test base does not exist to support reasonably accurate predictions of override.

The situation in regard to the significant interior parameters which affect total car crashworthiness is very similar. Large variations exist in interior layouts. The ratio of maximum passenger capacity (standees plus seated passengers) to seated passenger capacity varies significantly from one interior layout to another, as do the locations and amount of unoccupied passenger space at car ends. Any of the interior layouts could be obtained in any of the basic structural configurations, and particular car shells do in fact accommodate a large variation in interior configurations.

The calculations in Section 5.5 show that the number of first collision fatalities in a given collision decreases with increasing S/W. However, car deceleration in a collision increases with increasing S/W. If the passenger experiences "ridedown" in a collision (i.e., if he impacts the interior object before the car has come to rest) higher car decelerations can lead to increases in second collision injury severity. If the pertinent descriptors of a hypothetical car are defined, the collision model can be employed to determine a desirable range of S/W, considering both the first collision and the second collision. It is apparent that a change in the interior descriptors could result in a different desirable range of S/W. With a representative range of interior inputs, the collision simulations can be used to define this aspect of the design problem more clearly.

It is clear that we must select from an infinite combination of structural and interior inputs. In selecting a reasonable number of inputs for the present study, two sets of collision simulations are planned.

The first set of simulations is intended to show the effect of S/W variation and interior descriptor variation on the performance of cars having force-deflection curves which are generally representative of those for existing cars shown in Section 5.5. In this set of simulations, a range of interior descriptors is used at each S/W level. The method of determining the specific inputs is described in Section 6.2 below.

The second set of simulations is intended to show the effect of some significant deviations to the generalized or baseline set of force-deflection curves. It is anticipated that these simulations will provide some indication of desirable force-deflection characteristics other than S/W ratio. The determination of inputs for this second set of simulations is described in Section 6.3.

6.2 GENERALIZED INPUTS REPRESENTING EXISTING CAR CONSTRUCTION

The four generalized force-deflection curves shown in Figure 6.1 represent a range of S/W levels slightly larger than the range for the five study cars (Reference Table 5-7). The curves include the effect of the elastic draft gear and shear pin, as noted in the figure. The generalized curve shape is defined by the following parameters:

$\frac{A_2}{A_1}$ Force level of second plateau divided by force level of first plateau.

x_1 Length of first plateau.

a Slope to first plateau and second plateau.

The first two shape parameters are tailored to represent the average of the corresponding parameters for the five cars studied, when the force deflection curve for each car is approximated by a curve shape having two plateaus. The averages are computed as shown below:

Car	Reference Figure	x_1 inches	$\frac{A_2}{A_1}$
R-44	5-18	120	1.7
Silverliner	5-13	18	1.4
R-33	5-16	45	1.7
BARTD	5-20	50	1.3
Silverbird	5-22	12	1.9
Average		50	1.6

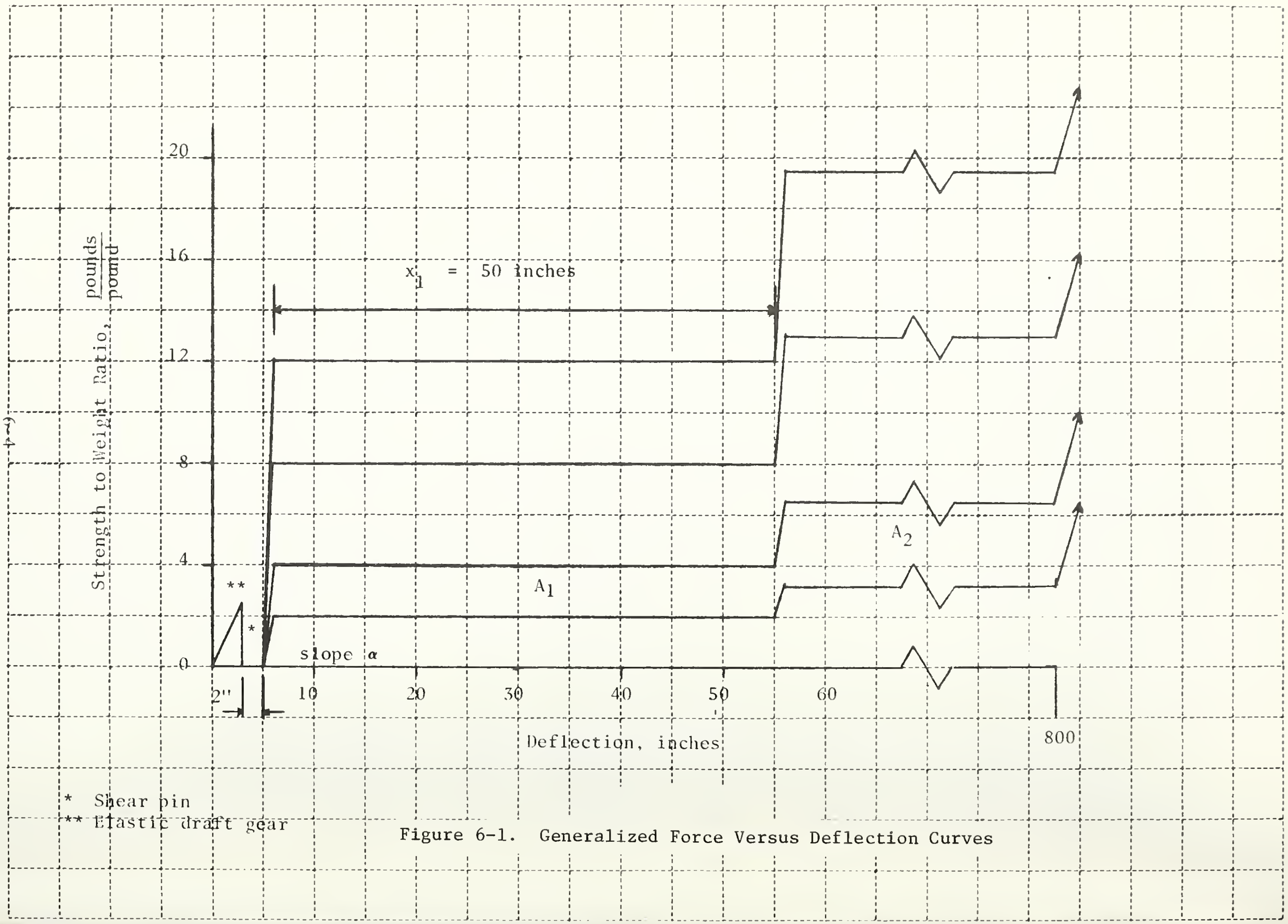

Figure 6-1. Generalized Force Versus Deflection Curves

It should be noted again that crush force versus deflection characteristics of actual cars have not been obtained under controlled conditions. The validity of the second force plateau being higher than the first can be questioned. Structural elements in the superstructure may be less effective than calculations for existing cars indicate, particularly if longitudinal load elements do not line up and are pushed in a horizontal or vertical direction during the collision.

The elastic portions of the force-deflection curves in Figure 6.1, represented by slope α, are determined on the basis of the elastic stiffness of half the car length. This is obtained as follows:

$$\Delta x = \frac{1}{2} \frac{P \ell}{AE}$$

and

$$\alpha = \frac{P}{\Delta x} = \frac{2\,AE}{\ell}$$

where,

P = axial load

Δx = elastic deformation under load P

ℓ = length of car

A = effective area of car cross section

E = modulus of elasticity.

In computing these slopes, the area used is proportional to car strength. Therefore, the stronger cars have proportionately larger slopes, with the result that the intersection of the elastic and plastic portions of all three curves occurs at the same deflection x, as shown in the figure. Each force-deflection curve is run for closure speeds of 20 mph, 40 mph, 60 mph, and 80 mph. For each speed a train consisting of 2, 4, 6 and 8 cars is investigated. From this data, results for longer trains can be extrapolated. Specific occupant spacings (distances from objects he could impact) are 2, 4, 6, 9 and 24 feet. Crush distances used for the impacted object are 1/4, 1, 2, 4, and 12 inches.

All of the curves in Figure 6.1 represent draft gear characteristics typical of those now in use. For approximately the first 2 inches of stroke, the draft gear has an elastic force-deflection characteristic, with force at maximum deflection (2 inches) equal to about 250,000 pounds. At this point, the draft gear shear pin fails, permitting about 2 inches of free play before the car body structure is again loaded.

6.3 INPUTS REPRESENTING DEVIATIONS FROM EXISTING CAR CONSTRUCTION

The curves in Figure 6.2 are intended to provide a preliminary indication of the effect of variation in force-deflection characteristics other than S/W.

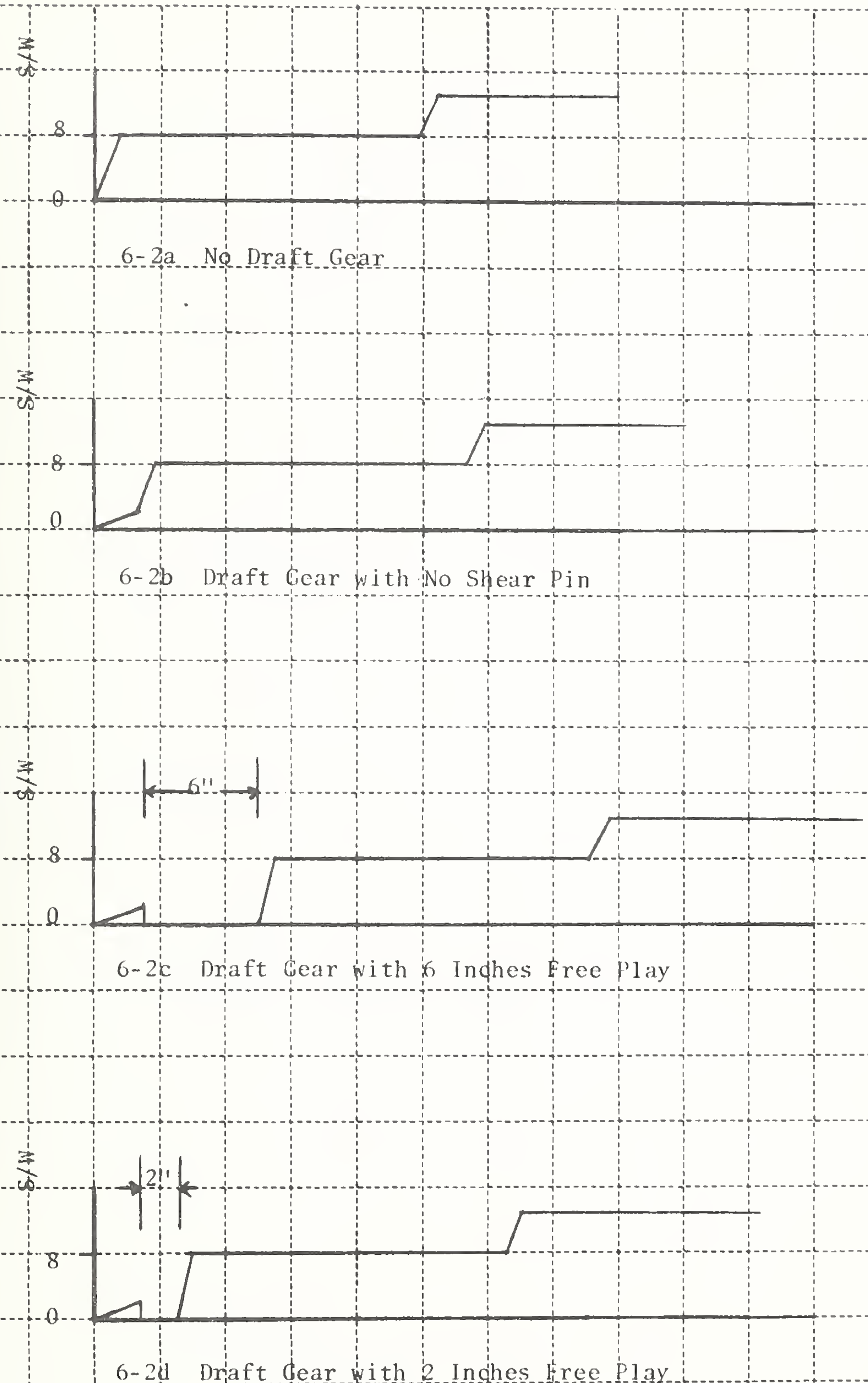

Figure 6-2. Draft Gear Characteristics

The force-deflection curve in Figure 6.2 a represents a structure in which the conventional draft gear is eliminated. In this case, the anti climbers or buffing beams of the colliding structures contact directly. The curve in Figure 6.2 b represents a structure in which the conventional draft gear is employed, but the shear pin is not included. The structure represented by Figure 6.2 c employs a conventional draft gear and a shear pin, with a large amount of "free play" occurring after shearing of the pin (6 inches of free play, versus 2 inches, or less, normally). Finally, for comparison purposes, Figure 6.2 d represents a structure with a conventional draft gear and shear pin, with 2 inches of free play occurring after pin failure.

The general shape of the force-deflection curve should have an effect on the degree to which crush is shared between cars in a train. For example, if there is a significant difference between the force magnitudes in the first and second plateaus in Figure 6.1, some sharing of crush between cars in the train can be achieved when the lower plateau is fully crushed on the first car. A characteristic of the force-deflection curve which can transfer a significant portion of the train crush away from the first car appears to be desirable because:

(1) Several feet at each end of existing cars represent passenger-free crush space. If, for example, 30 feet of total train crush is required to absorb collision energy, and 5 feet at the car ends represents passenger-free crush space, first collision fatalities could be eliminated by designing each train to crush as follows:

Forward end of first car	5 ft.
Aft end of first car	5 ft.
Forward end of second car	5 ft.

It is evident that penetration fatalities are always reduced when crush space is effectively shared by the car ends.

(2) Significant crush between cars means that deceleration levels for cars aft of the first car will be significantly less than for the first car. If sufficient passenger-free crush space for energy absorption is provided in the first car to keep second collision injury levels from becoming excessive, a large benefit is produced because injury severity in cars aft of the first car drop off sharply.

A net benefit (reduction in both penetration fatalities and second collision injuries) can evidently be obtained by proper distribution of train crush. Table 6.1, based only on elementary kinematics, shows how this is possible.

In configuration 1, Table 6.1, the train is designed such that the front end crushes 10.8 feet at a closure speed of 40 mph, with negligible crush at all other points. Passenger impact velocities (for a passenger travel of 6 ft) are only 15 mph (no injuries at about 1 inch crushing of impacted surface - see Figure 3.3). However, the 10.8 feet of lead end crush means that 5.8 feet of passenger occupied space will be crushed, assuming 5 feet of passenger-free crush space. This 5.8 feet is called "X_{fatal}" and is reflected in the last column in the table. If the cars are increased in strength (configuration 1), such that only 5 feet of crush occurs at the front end, X_{fatal} becomes zero. However, all passengers located 5 feet or more from the impacted object have a relative impact velocity equal to the change in train velocity during the collision. For collisions of equal weight trains, this is 20 mph. This impact velocity is much more severe, requiring about 3 inches crushing of the impacted surface to keep injuries negligible, and causing life threatening injuries when only 1 inch of crushing is provided at the impact surface. However, if the train is designed to distribute the crush as shown in configuration 2, penetration fatalities are eliminated, and only the passengers in the first car are subjected to 20 mph impact speed at s = 5 ft or more with all other passengers feeling only 15 mph impact speed at these spacings.

TABLE 6.1 BENEFITS OF TRANSFERRING IMPACT ABSORPTION AWAY FROM FRONT OF TRAIN

(5 feet of passenger free crush space at end of each car)

Config-* uration	Closure Velocity (mph)	Crush at Front of Train	Crush at Aft End of First Car	Crush at Forward End of Second Car	Passenger Impact Velocity at s = 6 ft (mph)		X_{fatal}
					First Car	All Other Cars	
1	40	10.8	0	0	15	15	5.8
1	40	5	0	0	20**	20*	0
2	40	5	2.9	2.9	20**	15	0
1	60	24.2	0	0	15	15	19.2
1	60	14.1	0	0	19.7	19.7	9.1
2	60	11.1	6.5	6.5	22	15	9.1
1	60	5	0	0	30*	30*	0
2	60	5	2.9	2.9	30*	20.2	0

* Configuration 1 - All crush occurs at front end of first car.
Configuration 2 - Crush occurs at front of first and second cars.

** Cut off point at which no passenger "ride down" takes place.

The benefits derived from crush distribution are even more significant at closure speeds of 60 mph, as shown in the table. Note here that a 30 mph passenger impact speed is extremely severe, (again see Figure 3.3) with "critical to fatal" injuries occurring even when the impacted object crushes 3 inches.

The structural and interior inputs which have been selected in this section were systematically varied in the collision model in order to study their effect on car crashworthiness. The results are examined in the next chapter.

7. RESULTS OF CRASH SIMULATIONS

In this chapter, results of collision simulations for the inputs defined in Chapter 6 are presented and discussed. The simulations were obtained with the use of the integrated train/occupant crash model described in Sections 4 and 5. As noted in Chapter 6, the general force-deflection characteristics selected as inputs to the crash model are based on information gained from the simplified analysis of the five study cars described in Chapter 5. Direct correlation between these inputs and actual characteristics of the individual study cars is beyond the scope of the present study, and will require the orderly development of multi-dimensional models with more degrees of freedom, properly validated by experiment at each development phase.

The results which are reviewed in this section deal primarily with 1) length of car crush in frontal collision, and the effect of the collision descriptors and design variables on predicted first collision or penetration fatalities, 2) injury severity indices in the second collision between passenger and interior objects and the effect of the collision descriptors and design variables on them, and finally 3) the combined effect of the design variables on first and second collision fatalities and injuries.

Figures 7-1 through 7-4 deal with the first area of interest - length of car crush and first collision fatalities. The figures show, for collision closure speeds of 20 mph, 40 mph, 60 mph and 80 mph, the crush on each car in the train and the percentage of fatalities for passenger-free crush space of 2 feet, 5 feet and 10 feet - each percentage calculated at car strength to weight ratios of 2, 4, 8 and 12 and for 2, 4, and 8 cars in the train.

The crush on each car (identified as "distance crush" in the figures) is defined for a particular car as the length of crush which takes place at the forward end. The crush at the aft end is equal to the crush at the forward end of the car behind it. Thus in Figure 7-2, for a strength to weight ratio of 4 and an 8 car

No. of Cars in Train (n)	Car #	S/W = 2 Dist. Crush x Feet	S/W = 2 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 4 Dist. Crush x Feet	S/W = 4 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 8 Dist. Crush x Feet	S/W = 8 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 12 Dist. Crush x Feet	S/W = 12 Percentage of Fatalities for End Free Space of* 2'	5'	10'
	1	5.62				1.61				1.00				0.83			
	2	3.41				0.90				0.62				0.53			
	3	0.21				0.91				0.61				0.54			
8	4	0.20	1.14	0.11	0	0.88	0	0	0	0.61	0	0	0	0.54	0	0	0
	5	0.20				0.87				0.62				0.55			
	6	0.20				0.74				0.61				0.55			
	7	0.18				0.56				0.59				0.53			
	8	0.11				0.20				0.47				0.51			
	1	5.64				1.53				0.96				0.73			
4	2	0.24	1.28	0.23	0	0.90	0	0	0	0.61	0	0	0	0.54	0	0	0
	3	0.20				0.85				0.60				0.54			
	4	0.15				0.24				0.55				0.52			
2	1	3.45	1.02	0	0	0.46	0	0	0	0.88	0	0	0	0.72	0	0	0
	2	0.18				0.66				0.58				0.53			

* Percentages are based on assumption of uniform passenger distribution in all areas except for passenger unoccupied space at ends of car.

Figure 7-1. First Collision Fatalities Expressed as Percentage of Total Train Occupants 20 MPH Closure Speed

No. of Cars in Train (n)	Car #	S/W = 2 Dist. Crush x Feet	Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 4 Dist. Crush x Feet	Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 8 Dist. Crush x Feet	Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 12 Dist. Crush x Feet	Percentage of Fatalities for End Free Space of* 2'	5'	10'
8	1	10.95	5.50	2.18	0.17	5.91	2.54	0.17	0	4.81	0.57	0	0	3.12	0.20	0	0
	2	7.30				4.95				2.21				0.91			
	3	5.86				4.26				0.87				0.87			
	4	3.92				0.66				0.97				0.94			
	5	0.92				0.66				0.85				0.85			
	6	0.24				0.76				0.91				0.90			
	7	0.22				0.78				0.79				0.83			
	8	0.16				0.73				0.85				0.87			
4	1	10.97	5.65	2.48	0.34	5.86	2.06	0.31	0	4.47	0.92	0	0	2.25	0.09	0	0
	2	5.51				2.98				0.90				0.90			
	3	0.21				1.21				0.85				0.85			
	4	0.23				0.55				0.84				0.87			
2	1	10.06	5.68	3.55	0.04	5.64	2.56	0.45	0	0.82	0.66	0	0	0.84	0	0	0
	2	0.18				0.75				0.82				0.84			

* Percentages are based on assumption of uniform passenger distribution in all areas except for passenger unoccupied space at ends of car.

Figure 7-2. First Collision Fatalities Expressed as Percentage of Total Train Occupants
40 MPH Closure Speed

No. of Cars in Train (n)	Car #	S/W = 2 Dist. Crush x Feet	S/W = 2 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 4 Dist. Crush x Feet	S/W = 4 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 8 Dist. Crush x Feet	S/W = 8 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 12 Dist. Crush x Feet	S/W = 12 Percentage of Fatalities for End Free Space of* 2'	5'	10'
8	1	32.64				10.38				6.40				5.35			
	2	14.53				7.06				5.28				4.70			
	3	5.35				6.95				4.44				1.29			
	4	5.33	12.70	8.50	5.60	5.00	6.10	2.37	0.06	0.87	2.80	0.35	0	0.87	1.55	0.06	0
	5	3.24				1.64				0.94				0.92			
	6	0.75				0.70				0.79				0.83			
	7	1.01				0.88				0.91				0.90			
	8	0.16				0.65				0.78				0.82			
4	1	36.08				10.15				6.18				5.26			
	2	0.25	12.70	11.60	9.80	6.39	6.00	2.80	0.11	3.69	2.68	0.42	0	1.96	1.15	0.09	0
	3	0.44				1.48				0.94				0.93			
	4	0.15				0.67				0.79				0.82			
2	1	20.25	12.90	10.80	7.20	9.86	5.50	3.34	0	6.09	2,88	0.77	0	4.59	1.82	0	0
	2	0.23				1.51				0.90				0.85			

*Percentages are based on assumption of uniform passenger distribution in all areas except for passenger unoccupied space at ends of car.

Figure 7-3. First Collision Fatalities Expressed as Percentage of Total Train Occupants
60 MPH Closure Speed

No. of Cars in Train (n)	Car #	S/W = 2 Dist. Crush x Feet	S/W = 2 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 4 Dist. Crush x Feet	S/W = 4 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 8 Dist. Crush x Feet	S/W = 8 Percentage of Fatalities for End Free Space of* 2'	5'	10'	S/W = 12 Dist. Crush x Feet	S/W = 12 Percentage of Fatalities for End Free Space of* 2'	5'	10'
8	1	92.34				26.87				9.40				7.16			
	2	8.56				8.78				6.64				5.59			
	3	7.07				8.23				6.30				4.93			
	4	6.07	22.60	17.80	14.50	6.24	17.90	7.10	2.98	4.75	5.45	1.81	0	1.95	3.22	0.59	0
	5	5.02				4.65				1.14				0.85			
	6	1.12				0.73				0.80				0.91			
	7	0.14				0.82				0.88				0.83			
	8	0.08				0.82				0.87				0.86			
4	1	53.86				20.73				9.19				6.77			
	2	7.83	22.50	19.20	15.50	7.86	10.90	7.60	4.00	5.83	5.25	2.07	0	4.65	3.58	0.63	0
	3	2.08				2.16				1.47				0.86			
	4	0.18				0.68				0.79				0.87			
2	1	33.45	22.00	20.00	16.50	16.81	10.40	8.30	4.80	8.89	4.85	2.74	0	6.74	3.32	1.63	0
	2	1.36				1.69				1.52				1.08			

* Percentages are based on assumption of uniform passenger distribution in all areas except for passenger unoccupied space at ends of car.

Figure 7-4. First Collision Fatalities Expressed as Percentage of Total Train Occupants
80 MPH Closure Speed

eight car train, the crush at the forward end of the lead car is 5.91 feet. The crush at the aft end of the lead car is equal to the crush at the forward end of the second car, since the structures are identical. This is 4.95 feet, as shown in Figure 7-2.

The first collision fatalities are shown in Figure 7-1 through 7-4 as a percentage of total train occupants. The percentages are calculated on the assumption that there is uniform passenger distribution in the car, except for space which is unoccupied by passengers at the ends of the car. This is called "end free space" in the figures. For each car end

$$\text{Percentage} = 100\,\frac{[x - y]}{[75 - 2\,y]\,n} \qquad (7\text{-}1)$$

where,

x = crush distance at car end

y = end free space

n = number of cars in train

The numerator of the fraction in equation 7.1 (x-y) is the length of crush which results in fatalities, and the denominator is the train length which is available for passengers. Note that the length of each car is assumed to be 75 feet, which is a transit car length frequently used.

Taking the same example as before (Figure 7-2, strength to weight ratio of four and an eight car train) and using end free space of 2 feet, the percentage* for the forward end of the first car is given by

---

* Expressed as percentage of occupants in the entire train.

$$\text{Percentage} = 100 \frac{5.91 - 2}{[75 - 2x2]\ 8} = 0.70$$

Similarly the percentage for the aft end of the first car, which is equal to the percentage for the forward end of the second car, is given by

$$\text{Percentage} = 100 \frac{4.95-2}{[75 - 2x2]\ 8} = 0.52^{*}$$

The percentage for the aft end of the second car, which is equal to the percentage for the forward end of the third car, is given by

$$\text{Percentage} = 100 \frac{4.26-2}{[75 - 2x2]\ 8} = 0.40^{*}$$

We note from Figure 7-2 that crush distances aft of the third car are less than 2 feet, and therefore do not cause fatalities. The percentage for the entire train is obtained by summing the percentages for the individual car ends, as follows:

Lead Car, Forward End	0.70
Lead Car, Aft End	0.52
Second Car, Forward End	0.52
Second Car, Aft End	0.40
Third Car, Forward End	0.40
Total	2.54

Thus, for the case taken, 2.54 percent of the passengers in the train become first collision fatalities. For full crush loading (about 200 passengers per car) the number of fatalities in this case would be

$$(.0254)\ (8)\ (200) \approx 42 \text{ passengers}$$

---

* In the computer program, significant crush occurred on trailing cars. This has not been generally true in actual accidents. The reason for this difference, and the implications of it, are discussed subsequently in this section.

Figure 7-5 shows percentage of fatalities versus closure velocity for symmetrical collisions of eight car trains, with each car end having free space of 2 feet. The four curves in the figure are for strength to weight ratios of 2, 4, 8 and 12. The benefits of high strength to weight ratio can be seen by looking at fatalities for a 40 mph collision. Based on a crush load of 200 passengers per car, Figure 7-5 shows

Strength/Weight Ratio	Percentage Fatalities	Number of Passengers
2	5.5	88
4	2.5	40
8	0.6	10
12	0.2	3

Note that the car with the highest strength to weight ratio (12) still produces some first collision fatalities when only 2 feet of free space is provided. Review of Figure 7-2 for the 40 mph case shows that 3.12 feet of crush occurs in the first car. It is evident from Figure 7-2 that the amount of end free space is extremely important in this speed range.

The combined effect of strength to weight ratio and end free space on first collision passenger fatalities is shown in Figure 7-6, which plots first collision fatalities versus strength-weight ratio for an eight car train at closure speed of 40 mph, and for end free spaces of 2 feet, 5 feet and 10 feet. We note that if end free space is increased to 5 feet, a strength-weight ratio of 8 is required to eliminate first collision passenger fatalities at 40 mph closure speed. Referring back to Figure 7-2, we see that car crush distances for this case are:

Forward end, first car		4.81 feet
Aft end, first car		2.21 feet
Forward end, second car		2.21 feet
Remaining 12 car ends	≈	0.88 feet

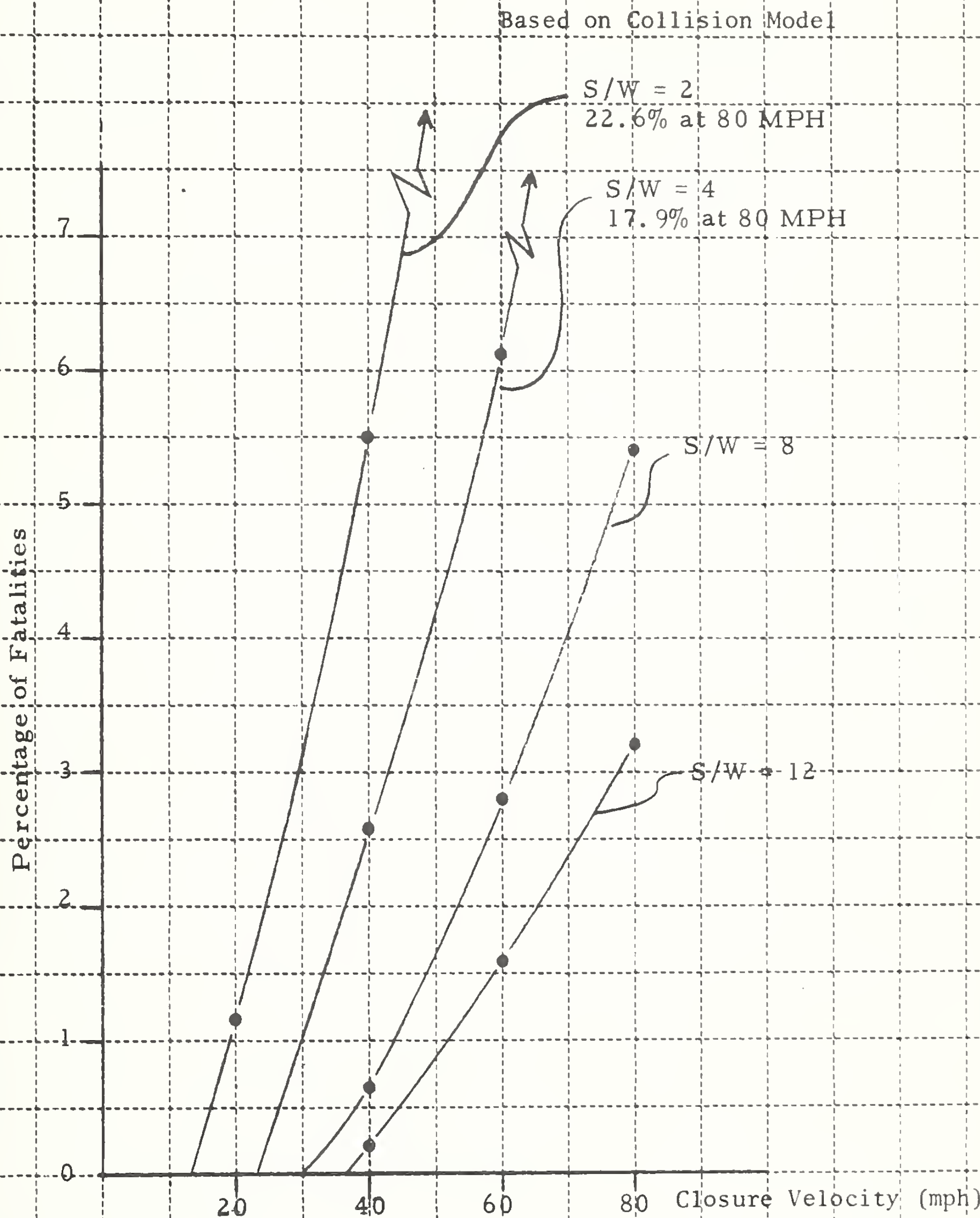

Figure 7-5. Percentage of Fatalities Versus Closure Velocity
End Free Space = 2 Feet
8 Car Train

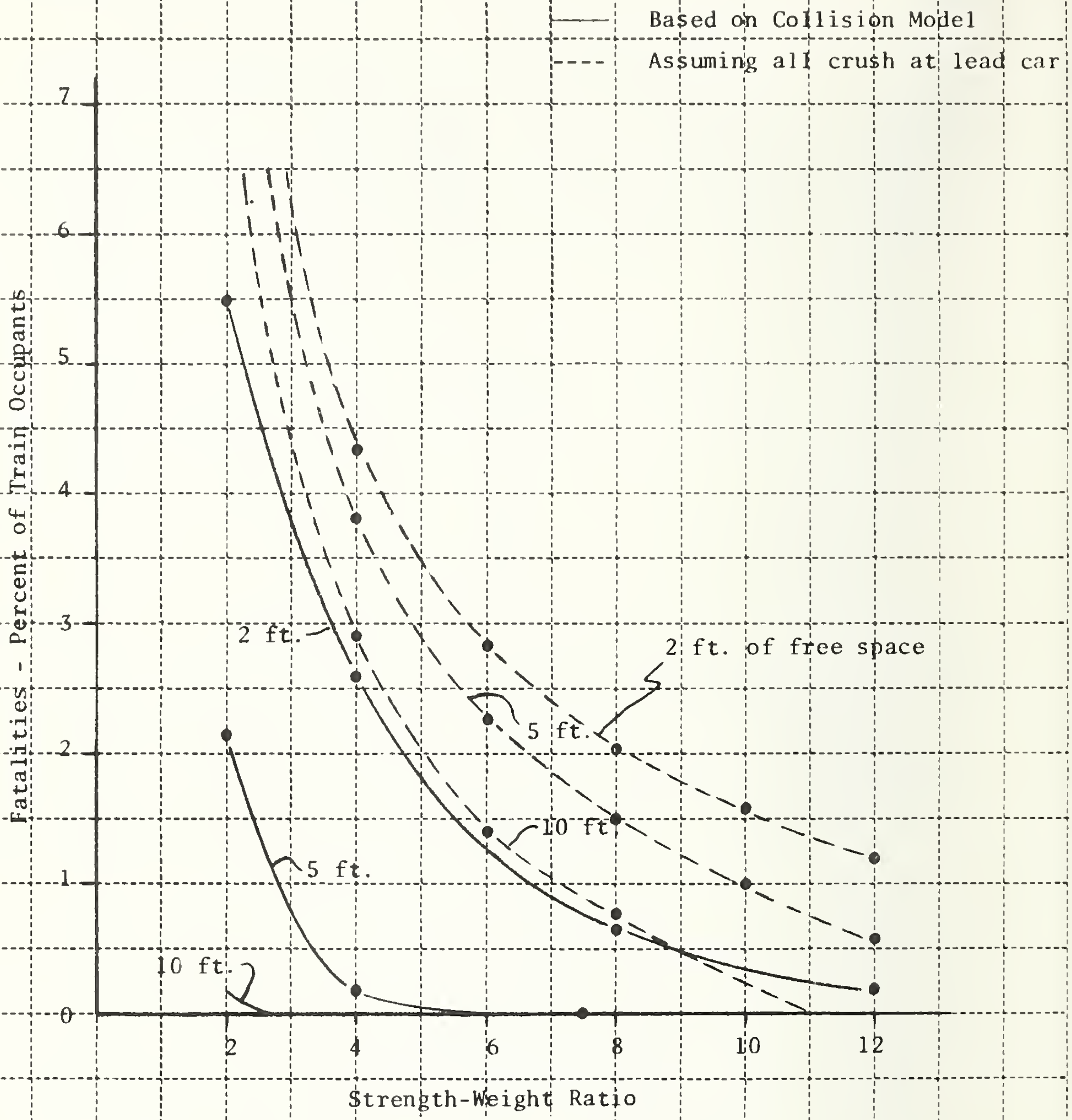

Figure 7-6. Effect of Strength to Weight Ratio on First Collision Fatalities
8 Car Train - 40 mph Closure Speed

The total crush to all the cars in the train is approximately 19.7 feet. A significant amount of this crush, however, occurs at the relatively small average force level required to compress each of the eight draft gears in the train, and to take up the slack remaining after shearing of the draft gear pin. The total crush which occurs on the car structures (i.e., at force level equal to eight times car weight) in the train can be calculated fairly accurately by equating kinetic energy of the collision to car crush energy, as follows

$$\frac{1}{2} (8) \frac{W}{g} V^2 = 8 W x \qquad (7\text{-}2)$$

Note that the factor of 8 on the left hand side reflects eight cars in the train, and the factor of 8 on the right hand side reflects the fact that crush force level is eight times car weight. Solving equation 7-2 for x:

$$x = \frac{1}{2} \frac{V^2}{g} \qquad (7\text{-}3)$$

The appropriate velocity for the 40 mph closure speed case is the equivalent barrier velocity of 20 mph (29.3 feet per second). Inserting this in equation 7-3, the effective length of crush of actual car structures is given by

$$x = 13.3 \text{ feet}$$

Thus, if all crush occurs at the lead car, about 13.3 feet of end free space would be required instead of the 5 feet indicated by the computer analysis. The large difference is accounted for by the fact that train behavior on the computer model was such that significant crushing was shared by the cars. In actual crashes, this sharing of crush by the cars does not generally happen to a significant extent. A strong factor in many actual crashes may be the over-riding (climbing) tendency on the lead car - initial structural deformations causing this car to fail at a strength level less than would be predicted by application of a flat-face, slowly applied load. This would result in all or almost all of the crush occurring at the lead car. This situation is reflected by the dotted lines in Figure 7-6.

The curve in Figure 7-7 is also obtained from the data in Figure 7-2. The information shown is the same as that shown in Figure 7-6, except that it applies to a four car train in a 40 mph collision, instead of an eight car train in a 40 mph collision. We note in comparing the two figures that first collision fatalities comprise a larger percentage of train occupants for the short train than for the long train. In the elementary example where all crush occurs in the lead car, and no crush free space exists, the four car train would have half as much crush as the eight car train, and fatalities would comprise the same percentage of total occupants for each train. Inspection of Figure 7-2 (S/W=8) shows that the four car train experiences almost as much crush in the first car as in the eight car train (4.47 feet versus 4.81 feet). Since most fatalities occur in the first car in both trains, the shorter train therefor has a larger percentage of fatalities. The relatively large crush in the first car of the short train is evidently due to the step in the force versus deflection curve (reference Figure 6-1) for the car, which has the effect of limiting the deflection of the first car in the eight car train at the step point, while additional crush proceeds at the lower force level in the trailing cars.

It is clear from Figures 7-5 through 7-7 that higher strength to weight ratios provide very large reductions in first collision fatalities. However, we have noted in Section 6 that higher strength to weight ratio also causes higher car deceleration in a collision, with the result that second collision injuries may be more numerous and more severe.

Information on second collision injuries is provided in Figures 7-8 through 7-15. Figures 7-8 through 7-11 apply to an eight car train collision at speeds of 20 mph, 40 mph, 60 mph and 80 mph, respectively. Figures 7-12 through 7-15 apply to collisions between four car trains. For each strength to weight ratio shown, percentage of severity indices exceeding 2000, 1500 and 1000 are listed separately for combinations of three object crush distances (d equal to one fourth inch, one inch and two inches) and three distances to the impacted object (S equal to 2 feet, 6 feet and 12 feet).

We note from Chapter 3 that the three severity indices used as reference indices correspond to the following injury severity:

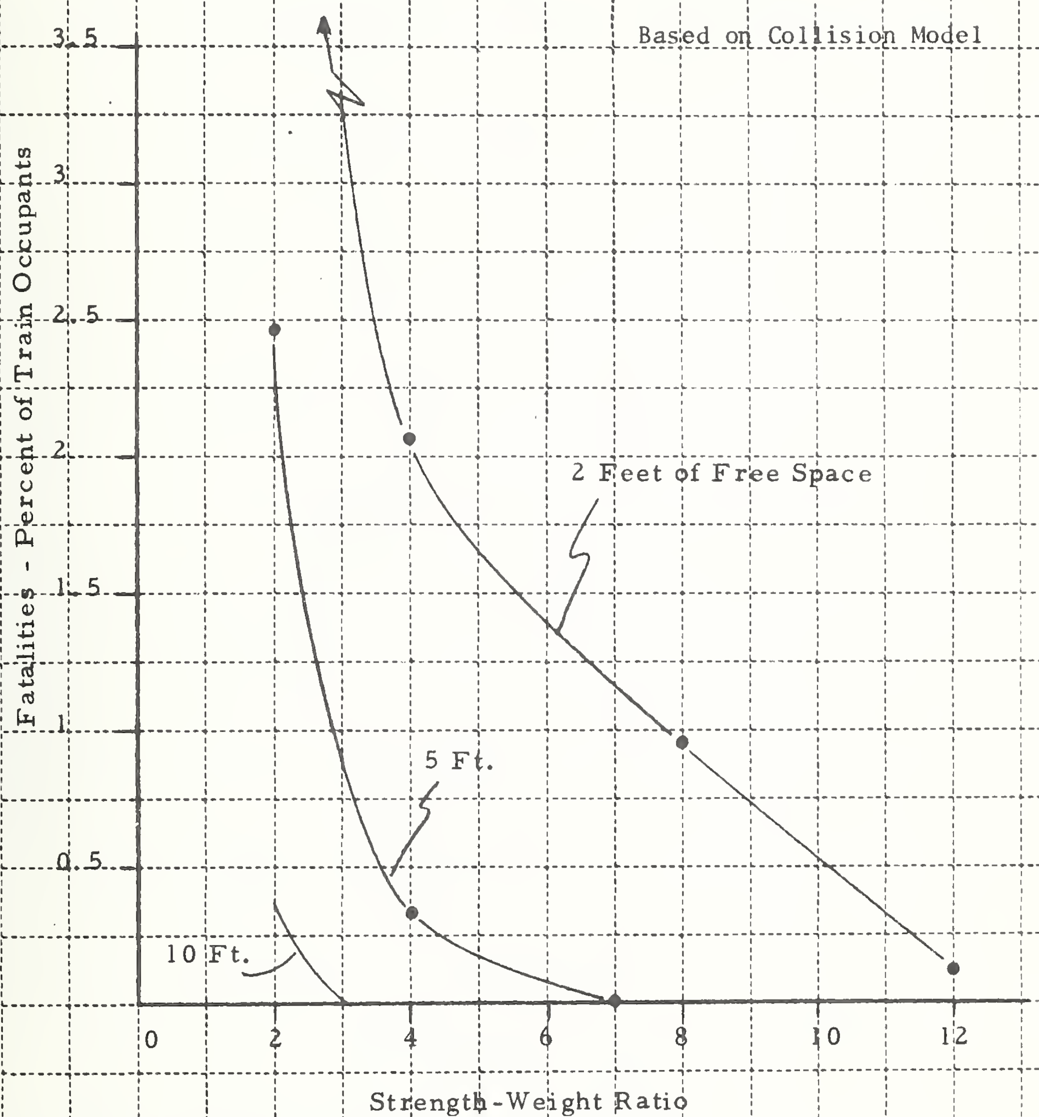

Figure 7-7. Effect of Strength to Weight Ratio on First Collision Fatalities 4 Car Train, 40 MPH Closure Speed

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s=2'	s=6'	s=12'	s=2'	s=6'	s=12'	s=2'	s=6'	s=12'
1/4"	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	12.5	50	50
	1,000	0	50	87.5	25	50	100	100	75	100
1 "	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0
2 "	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0

Figure 7-8. 20 MPH Closure Speed - 8 Car Trains

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s=2'	s=6'	s=12'	s=2'	s=6'	s=12'	s=2'	s=6'	s=12'
1/4"	2,000	12.5	50	100	100	100	100	100	100	100
	1,500	12.5	62.5	100	100	100	100	100	100	100
	1,000	37.5	62.5	100	100	100	100	100	100	100
1 "	2,000	0	0	0	0	0	37.5	0	25	37.5
	1,500	0	12.5	12.5	0	12.5	62.5	12.5	37.5	75
	1,000	0	12.5	25	0	25	87.5	100	100	100
2"	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0

**Figure 7-9. 40 MPH Closure Speed - 8 Car Trains
Percentage* of Severity Indices Exceeding
1,000, 1,500 and 2,000**

* Refers to percentage of total train passengers. The percentages shown in Figures 7-8 through 7-15 represent upper limits based on the assumption that the passenger travels unimpeded the full distance s to the impacted object. For standing passengers the percentages are therefore larger than would be expected to occur in actual accidents. See discussion on accompanying pages explaining the significance of these percentages.

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s=2'	s=6'	s=12'	s=2'	s=6'	s=12'	s=2'	s=6'	s=12'
1/4"	2,000	12.5	37.5	100	100	100	100	100	100	100
	1,500	12.5	62.5	100	100	100	100	100	100	100
	1,000	25	87.5	100	100	100	100	100	100	100
1"	2,000	0	12.5	25	0	12.5	75.0	0	37.5	87.5
	1,500	0	12.5	25	0	25	87.5	12.5	50	87.5
	1,000	0	12.5	50	0	37.5	100	100	100	100
2"	2,000	0	0	12.5	0	12.5	12.5	0	12.5	50
	1,500	0	0	12.5	0	12.5	37.5	0	12.5	62.5
	1,000	0	12.5	25	0	12.5	62.5	0	25	75

Figure 7-10. 60 MPH Closure Speed - 8 Car Trains

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s=2'	s=6'	s=12'	s=2'	s=6'	s=12'	s=2'	s=6'	s=12'
1/4"	2,000	12.5	50	100	100	100	100	100	100	100
	1,500	12.5	62.5	100	100	100	100	100	100	100
	1,000	25	87.5	100	100	100	100	100	100	100
1"	2,000	0	12.5	25	0	25	87.5	0	37.5	100
	1,500	0	12.5	37.5	12.5	25	100	25	50	100
	1,000	0	12.5	50	12.5	37.5	100	100	100	100
2"	2,000	0	0	12.5	0	12.5	37.5	0	12.5	62.5
	1,500	0	0	12.5	0	12.5	50	0	12.5	75
	1,000	0	12.5	25	0	12.5	62.5	0	37.5	87.5

Figure 7-11. 80 MPH Closure Speed - 8 Car Trains
Percentage* of Severity Indices Exceeding
1,000, 1,500 and 2,000

* Refers to percentage of total train passengers. The percentages shown in Figures 7-8 through 7-15 represent upper limits based on the assumption that the passenger travels unimpeded the full distance s to the impacted object. For standing passengers the percentages are therefore larger than would be expected to occur in actual accidents. See discussion on accompanying pages explaining the significance of these percentages.

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s =2'	s =6'	s =12'	s =2'	s =6'	s =12'	s =2'	s =6'	s =12'
1/4"	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	25	100	100	75	100	100	100	100	100
1 "	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0
2 "	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0

Figure 7-12. 20 MPH Closure Speed - 4 Car Trains

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s =2'	s =6'	s =12'	s =2'	s =6'	s =12'	s =2'	s =6'	s =12'
1/4"	2,000	25	100	100	100	100	100	100	100	100
	1,500	50	100	100	100	100	100	100	100	100
	1,000	75	100	100	100	100	100	100	100	100
1 "	2,000	0	0	50	0	50	75	0	50	75
	1,500	0	25	100	0	50	100	25	75	100
	1,000	0	50	100	0	75	100	100	100	100
2 "	2,000	0	0	0	0	0	0	0	0	0
	1,500	0	0	0	0	0	0	0	0	0
	1,000	0	0	0	0	0	0	0	0	0

Figure 7-13. 40 MPH Closure Speed - 4 Car Trains
Percentage of Severity Indices Exceeding
1,000, 1,500 and 2,000

* Refers to percentage of total train passengers. The percentages shown in Figures 7-8 through 7-15 represent upper limits based on the assumption that the passenger travels unimpeded the full distance s to the impacted object. For standing passengers the percentages are therefore larger than would be expected to occur in actual accidents. See discusson on accompanying pages explaining the significance of these percentages.

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s =2'	s =6'	s =12'	s =2'	s =6'	s =12'	s =2'	s =6'	s =12'
1/4"	2,000	25	100	100	100	100	100	100	100	100
	1,500	50	100	100	100	100	100	100	100	100
	1,000	50	100	100	100	100	100	100	100	100
1 "	2,000	0	25	100	0	75	100	25	100	100
	1,500	0	50	100	0	75	100	25	100	100
	1,000	0	50	100	0	100	100	100	100	100
2"	2,000	0	0	50	0	25	100	0	75	100
	1,500	0	0	100	0	50	100	0	75	100
	1,000	0	25	100	0	50	100	0	100	100

Figure 7-14. 60 MPH Closure Speed - 4 Car Trains

Crush Distance	S.I. Exceeding	S/W = 4			S/W = 8			S/W = 12		
		s =2'	s =6'	s =12'	s =2'	s =6'	s =12'	s =2'	s =6'	s =12'
1/4"	2,000	25	100	100	100	100	100	100	100	100
	1,500	50	100	100	100	100	100	100	100	100
	1,000	50	100	100	100	100	100	100	100	100
1 "	2,000	0	25	100	0	75	100	0	100	100
	1,500	0	50	100	25	75	100	50	100	100
	1,000	0	75	100	25	100	100	100	100	100
2 "	2,000	0	0	50	0	50	100	0	75	100
	1,500	0	0	100	0	50	100	0	75	100
	1,000	0	25	100	0	75	100	0	100	100

Figure 7-15. 80 MPH Closure Speed - 4 Car Trains
Percentage* of Severity Indices Exceeding
1,000, 1,500 and 2,000

* Refers to percentage of total train passengers. The percentages shown in Figures 7-8 through 7-15 represent upper limits based on the assumption that the passenger travels unimpeded the full distance s to the impacted object. For standing passengers the percentages are therefore larger than would be expected to occur in actual accidents. See discussion on accompanying pages explaining the significance of these percentages.

Severity Index	Injury Description
2000	Lower limit of "critical or fatal" and upper limit of "serious to life".
1500	Lower limit of "serious to life" and upper limit of "severe".
1000	Lower limit of "severe" and upper limit of "moderate".

The percentages in Figures 7-8 through 7-15 are based on the assumption that each passenger travels unimpeded the specified distance of s feet and is fully stopped by impacting an object with the specified crush distance d inches. Note that this is a hypothetical condition, since standing passengers will tend to contact other standing passengers and glance off fixed objects before coming to a stop. Each percentage applies to all those passengers on the train who satisfy the specified hypothetical condition. (i.e., a specified s and d.)

It has been noted previously that the forward facing seated passenger most closely approaches the hypothetical situation since the distance to the impacted seatback and its characteristics are reasonably predictable. The seated passenger is represented by the d = 2 foot column in Figures 7-8 through 7-15. If the very severe 1/4 inch compliance is excluded,* Figure 7-9 shows that for S/W of 8 and less the seated passenger does not receive severe injuries at speeds up to 40 mph (i.e., severity index is less than 1000). For a very rigid car

* A 1/4 inch compliance provides for bone deformation and this case is felt to be roughly equivalent to impacting an object with infinite rigidity.

(S/W = 12), no passengers receive fatal second collision injuries at a crush distance of 1 inch, but 100% of the passengers in this hypothetical condition receive severe injuries. When crush distance is increased to 2 inches, this is reduced to zero percent. Existing seatbacks are believed to be, very approximately, in this range (d = 1 inch to 2 inches). Accident experience at closure speeds of about 40 mph* appears to generally correspond with the data in Figure 7-9. In accidents at these speeds, fatal second collision injuries to seated passengers are not known to have occurred, though some seated passengers do receive severe injuries.

It has been stressed previously in this report that the actual prediction of injury severity for most situations other than those involving forward or rear facing seated passengers is far less feasible (see Section 1.2.1, 3.3 and 5.6). However, it is noted in Section 5.6 that when a particular s and d are assumed for a standing passenger, the resulting severity index can generally be taken as an upper limit for all cases in which the passenger is initially s feet from the object in question (i.e., he may contact other passengers in the vicinity, which would usually reduce the injury severity). Therefore, the percentages shown for the standing passenger (the columns labeled d = 6 feet and d = 12 feet in Figures 7-8 through 7-15) represent only upper limits for the specified s and d, and should not be taken as predictions applying to actual accidents. Figure 7-8 (for closure speed of 20 mph) shows that no severe or fatal second collision injuries should be sustained by standing passengers at closure speeds of 20 mph, for all car strength to weight ratios up to 12, all passenger spacings up to 12 feet and all crush distances of 1 inch and higher. When closure speed is increased to 40 mph, (Figure 7-9) second collision injuries and fatalities can occur when relatively high strength to weight ratios and passenger spacings are combined with an object crush distance of 1 inch. However, when object crush distance is increased to 2 inches, second collision injuries and fatalities are shown to be eliminated.

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* Significant accidents are reviewed in Chapter 8.

The following factors prevent quantitative comparison of the percentages shown in Figure 7-8 through 7-15 for standing passengers with corresponding percentages in actual accidents.

1) The hypothetical nature of the condition (i.e., assumption of "free flight" into impacted object, with no intermediate contacts).

2) The relatively few accidents at 40 mph closure speed and higher.

3) The fact that most accidents at speeds of 40 mph and higher have been on inter-city and commuter lines where standing passengers are relatively rare.

4) The very high sensitivity of second collision injury severity to object crush distance (i.e., note from Figure 7-9 that by increasing d from 1 inch to 2 inches, the percentage figure associated with severe injuries is reduced from 100 percent to zero), and the lack of information relating to the degree of object compliance for existing interior equipment.

Consider only the last point (i.e., assume a hypothetical accident in which sufficient information is available to eliminate unknowns associated with (1), (2) and (3), above) and consider the specific percentage figure in Figure 7-9 associated with:

$$d = 1 \text{ inch}$$
$$s = 12 \text{ feet}$$
$$S/W = 8$$

The percentage shown in Figure 7-9 for these variables is 87.5 percent. The percentage can be interpreted as meaning that a standing passenger satisfying assumption (1) above, as well as the s, d and S/W prescribed above, has an 87.5 percent chance of sustaining a severe injury. However, as previously noted, this figure is reduced to zero when d is increased from 1 inch to 2 inches. Hence, if one is to evaluate the accuracy of the 87.5 percent figure he must have accurate information on the effective object compliance. For example, if the percentage figure varies linearly from d = 1 inch to d = 2 inches, a 20 percent error in the percentage figure would correspond to a difference of only 0.2 inches in the effective compliance. Hence, because severity index is very sensitive to crush distance, meaningful predictions would require very accurate information on object compliance.

Precisely the same sensitivity factor which prevents meaningful prediction makes the data in Figures 7-8 through 7-15 very significant when viewed in terms of a design guideline or specification guideline. It is extremely important for the interior layout designer and the specifier of interior equipment to know (1) the approximate degree of compliance required to satisfy a particular safety criterion (e.g., zero second collision severe injuries at closure speeds of up to ___ mph and spacings of s ___ feet) and (2) the approximate sensitivity of this compliance to safety performance. If, for example, it can be established that 2 inches of interior object compliance is required to eliminate severe injuries at closure speeds less than 40 mph, the specification could be written in such a way that this compliance is obtained.

Figures 7-16 and 7-17 show severity indices for collisions of an eight car train, with cars having strength to weight ratio of eight, and an interior object crush distance of 1 inch. In Figure 7-16, percentage of severity indices exceeding 1000 (lower limit of severe injury) are plotted versus closure speed for three passenger distances (s) to the impacted object (2 feet, 6 feet, and 12 feet). Inspection of Figure 7-16 shows that, for s = 2 feet (generally representative of a seated passenger impacting the seat in front of him) the vehicle with strength to weight ratio of 8 can sustain a 60 mph closure speed collision with no severe injuries (i.e., zero percentage of severity indices

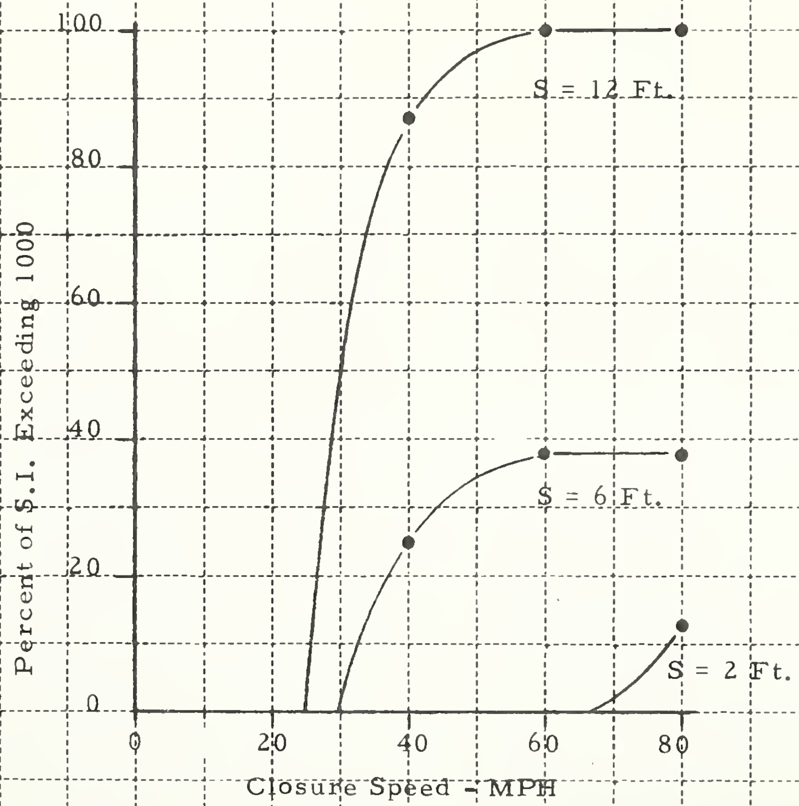

Figure 7-16. Percent of S.I. Exceeding 1000 (8 Car Train, Object Crush Distance = 1 inch Strength to Weight Ratio = 8)

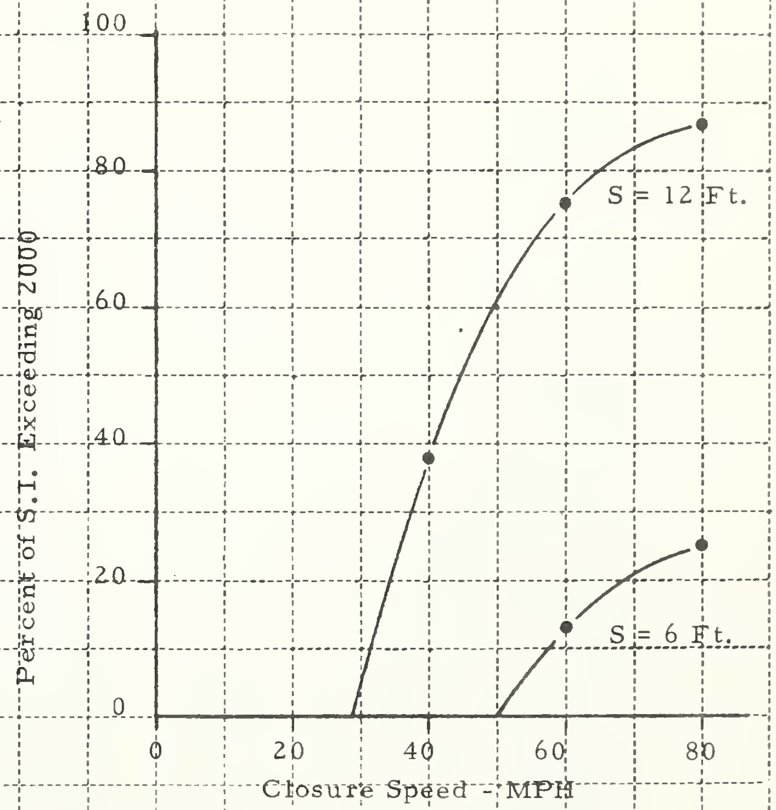

Figure 7-17. Percent of S.I. Exceeding 2000 (8 Car Train, Object Crush Distance = 1 inch, Strength to Weight Ratio = 8

exceeding 1000). However, when the distance to the impacted object is increased to 6 feet, (more likely to occur in the case of a standing passenger hitting a stanchion or seatback) 25 percent of such passengers in the train receive injuries exceeding the lower limit of severity at a closure speed of 40 mph.

Inspection of Figure 7-17, which shows incidence of critical or fatal injuries for the same collision descriptors (strength to weight ratio of 8, eight car train, object crush distance equal to 1 inch) shows that the train can sustain a collision at 50 mph closure speed with no fatal injuries occurring to passengers located up to 6 feet from the impacted object. However, 60 percent of standing passengers located 12 feet from the point of impact receive fatal injuries at a closure speed of 50 mph, and slightly less than 40 percent of standing passengers located 12 feet from the point of impact receive fatal injuries at a closure speed of 40 mph.

Figures 7-16 and 7-17 provide design insight into the effect of distance between passenger and impacted object on injury severity. However, key design characteristics are fixed (e.g., S/W=8 and d = 1 inch), and no direct information is obtained relating to a trade-off between car strength (reflected by strength to weight ratio) and the compliance of the interior object (reflected by d).

Figure 7-18 is identical to Figure 7-6 (previously discussed in regard to first collision only) except that two curves are added to show incidence of second collision fatalities, which are identified by severity indices exceeding 2000. The second collision curve on the left in Figure 7-18 is for a distance (S) from passenger to impacted object of 2 feet and for an extremely low object crush distance d of only 1/4 inch. This is generally equivalent to impacting a completely rigid object, since deflection of the passenger's bone structure in a severe collision is generally at least this much. For such a rigid object, the curve shows that fatal second collision injuries can occur at 40 mph closure speeds even when relatively low strength cars (S/W = 4) are involved.

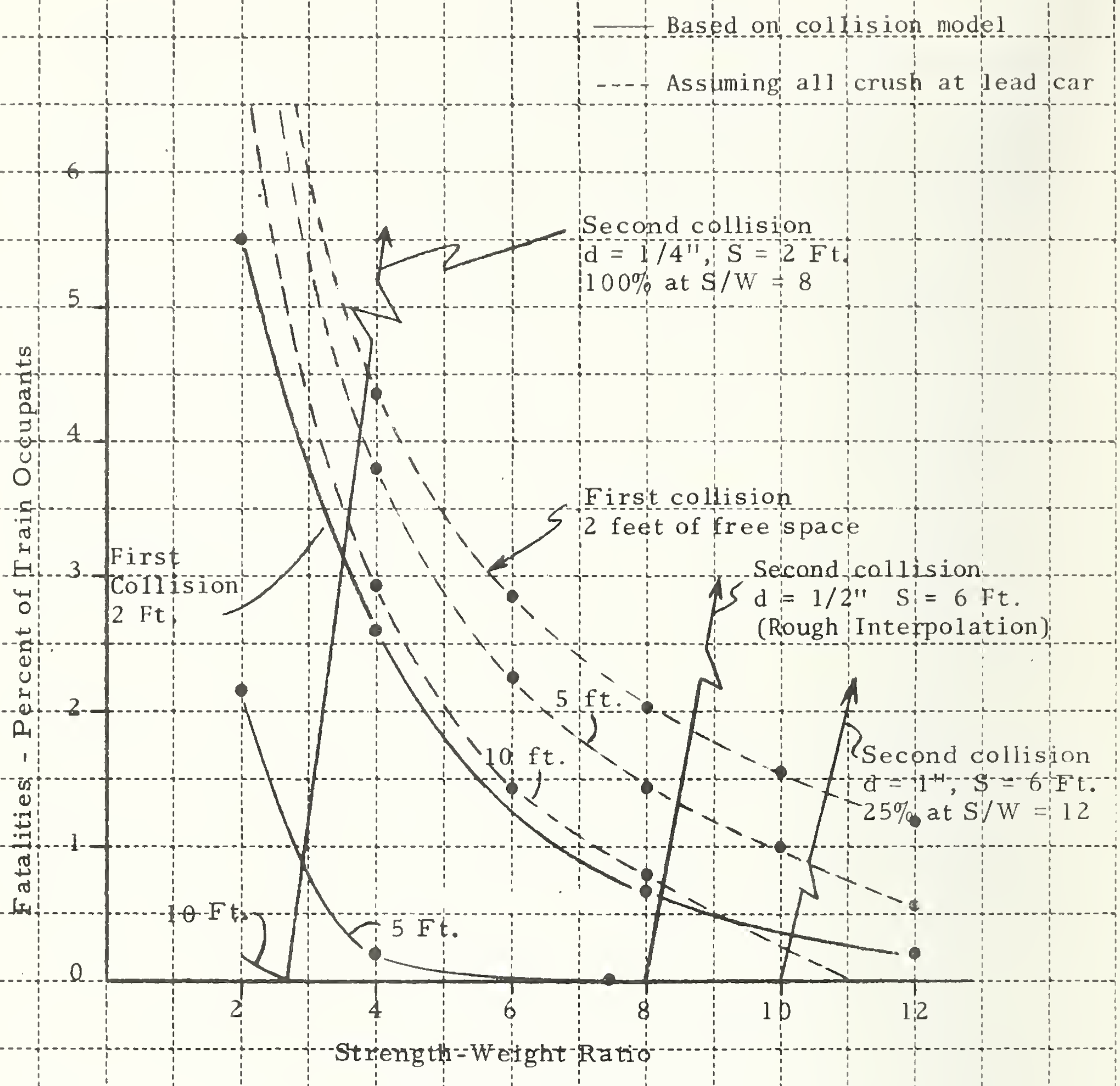

Figure 7-18. Effect of Strength to Weight Ratio on First and Second Collision Fatalities
8 Car Train, 40 MPH Closure Speed for Second Collision
Collision Fatalities, S/I > 2000

The second collision curve on the right in Figure 7-18 is for a distance (S) from passenger to impacted object of 6 feet, and an object crush distance d of 1 inch. It is evident from this curve that object crush distance has an extremely large effect on second collision fatalities. The curve shows that passengers located up to 6 feet from the impacted object will not receive fatal injuries in a 40 mph closure speed collision when relatively high strength cars (S/W = 10) are involved.

Direct comparison of the two second collision curves in Figure 7-18 provides the designer with a strong insight into the design relationship between car strength and interior object compliance. When the interior object is rigid - reflected by the second collision curve on the left - even very weak cars (S/W of 4 and less) can produce second collision fatalities in 40 mph closure speed collisions to passengers located only 2 feet from the impacted object. However, when 1 inch of object crush is provided, relatively strong cars (S/W = 10) result in zero second collision fatalities for all passengers located up to 6 feet from the impacted object.

Figure 7-19 provides similar information for a four car train in a 40 mph closure speed collision. In this situation the incidence of second collision fatalities is higher than for the heavier eight car train, because the same lead car crush forces produce higher decelerations on the lighter train. Even in this case, however, when considering both first and second collision fatalities, it is very interesting to note that the following design configuration eliminates both types of passenger fatalities in a 40 mph closure speed collision:

End free space of approximately 5 feet

Strength to weight ratio of approximately 6

Effective interior object compliance of approximately 1 inch

Maximum passenger travel of 6 feet to impacted object

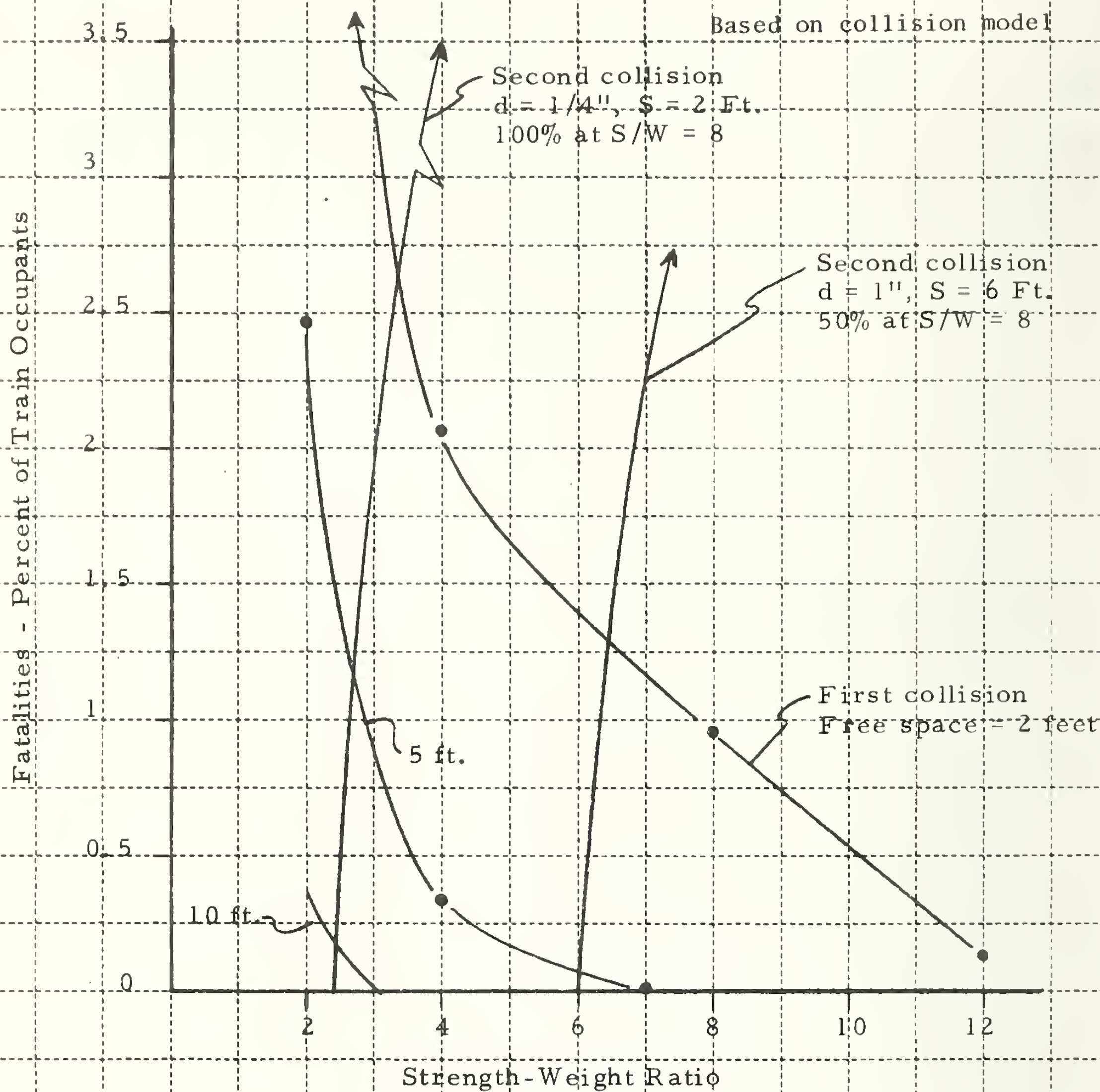

Figure 7-19. Effect of Strength to Weight Ratio on First and Second Collision Fatalities
4 Car Train, 40 MPH Closure Speed for Second Collision Fatalities, S/I > 2000

By counting total number of fatalities (first collision plus second collision fatalities) in Figures 7-18 and 7-19, quantitative relationships between structural and interior parameters can be obtained. Consider the two sets of parameters below:

	Set a	Set b
End free space	2 feet	2 feet
Passenger-object spacing (s)	6 feet	6 feet
Object crush distance (d)	1 inch	1/2 inch

If a design criterion is established that first collision plus second collision fatalities do not exceed a given percentage of train occupants, the following combinations of parameters are required for set (a) and set (b), based on summing first and second collision fatalities in Figure 7-18.*

Percentage Fatalities in Train	Set a		Set b	
	d (inches)	S/W	d (inches)	S/W
2	1	4.8	1/2	4.8
1	1	6.7	1/2	6.7
0.5	1	9	1/2	Not possible

Similar results can be obtained for other parameter sets. Note that for set b, no S/W exists which will meet the 0.5 percent fatality criterion. In this case, the lowest possible percentage figure occurs at S/W = 8. At this S/W, approximately 0.65 percent fatalities occur, all first collision fatalities. If S/W is increased very slightly (from 8 to 9), first collision fatalities are reduced from 0.65 percent to 0.5 percent. However, second collision fatalities increase rapidly, from 0 percent to almost 3 percent. In cases such as this, because of the steep slope of the second collision fatality curve, the optimum S/W for a particular design criterion tends to be very close to the highest S/W which results in zero second collision fatalities.

* This example is based on the first collision fatality curves obtained from the collision model (the solid first collision curves in Figure 7-18).

Figures 7-18 and 7-19 do not provide complete design information, since non-fatal injuries to the passenger in the second collision are not considered. Pertinent design information relating to prevention of "severe" injuries (S.I $<$ 1000) in a 40 mph closure speed collision of an eight car train is shown in Figure 7-20, which plots incidence of severe injuries versus strength to weight ratio. The three curves shown in Figure 7-20 represent three different passenger travel distances (S = 2 feet, 6 feet, and 12 feet) and the same interior object crush distance (d = 1 inch) previously studied for second collision passenger fatalities.

We note from the right hand curve in Figure 7-20 that no severe injuries occur to passengers located only 2 feet from the impacted object, (again, this is generally descriptive of seated passengers) for collisions involving cars with strength to weight ratio as high as 10. However the two remaining curves show that when passenger travel distance is increased to 6 feet and 12 feet (generally descriptive of standing passengers) the incidence of severe injuries rises very sharply. For a car with strength to weight ratio of 8, 25 percent of the passengers in the train who are located 6 feet from the impacted object receive severe injuries, and 100 percent of the passengers located 12 feet from the impacted object receive severe injuries.

For vehicles within the strength to weight ratio regimes which have been studied (from S/W = 4 to S/W = 12) it is evident that effective interior object crush distances larger than 1 inch are required to prevent severe injuries to standing passengers in collisions with closure speeds up to 40 mph. The next largest interior object crush distance used as an input to the dynamic model was 2 inches. For this crush distance, it is quite significant that no severe injuries occur to passengers in 40 mph closure speed conditions, for all passengers located up to <u>24</u> feet from the impacted object. Hence, no curves for d = 2 inches are shown in Figures 7-18 through 7-20.

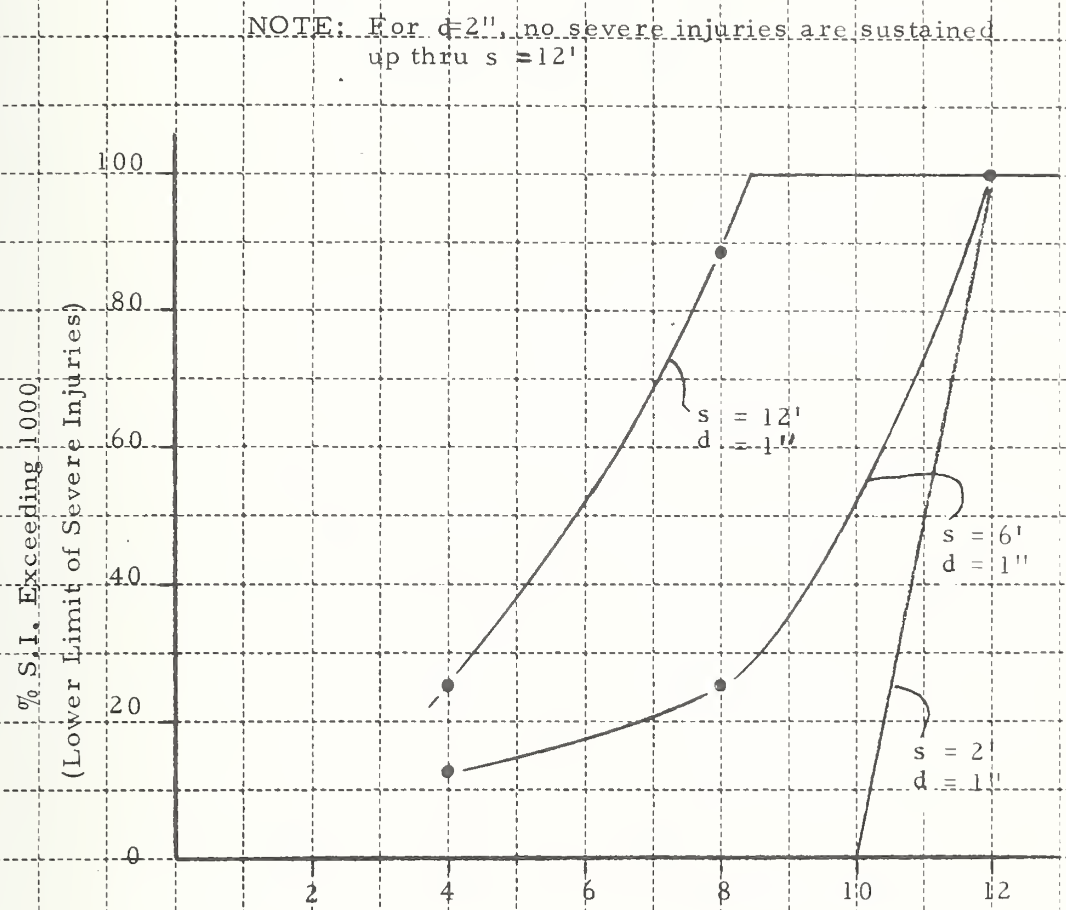

Figure 7-20. Effect of Strength to Weight Ratio on Second Collision Injuries 8 Car Train, 40 MPH Closure Speed

In Figure 7-21, severity indices along train length are shown for strength to weight ratios of 12 and 4, and for interior object crush distances of 1 inch and 2 inches. For the information shown in the figure, closure speed is 40 mph, and the passenger is located 2 feet from the impacted object. For the relatively short passenger travel, it is evident that strength to weight ratio and object crush distance both have extremely strong effect on severity index. It is significant that an increase in object crush distance from 1 inch to 2 inches reduces severity index from the maximum case (S/W = 12, d = 1 inch) almost as much as a decrease in strength-weight ratio from 12 to 4.

The increase in severity index toward the rear of the train which is shown in Figure 7-21 is an interesting phenomenon which occurs fairly consistently in the computer runs. We discuss this peculiarity and its causes in more detail later in this section. However, in considering this tendency and possible means of reducing it, it should be emphasized that for given strength to weight ratio and passenger travel, by far the strongest means for reducing injury severity is the crush distance or compliance which is provided in the impacted object.

Figure 7-22 shows information similar to that shown in Figure 7-21, except that the passenger is located 12 feet from the impacted object, instead of 2 feet. For larger passenger travels, the very strong effect of object crush distance on injury severity is even more striking. We note that the two top curves in Figure 7-22 are both for object crush distances of one inch. The upper curve, for strength to weight ratio of 12, is only slightly higher than the curve for strength to weight ratio of 4. This is because the passenger is located sufficiently far from the impacted object that the velocity of impact is very close to the total change in velocity of the car. (That is, almost no "ride down" occurs). Though the beneficial effect of reduced strength to weight ratio is almost eliminated for the relatively high passenger travel of 12 feet, the beneficial effect of increased object crush distance is in no way diminished. This is clearly shown by the two lower curves in Figure 7-22, both representing an object crush distance of 2 inches.

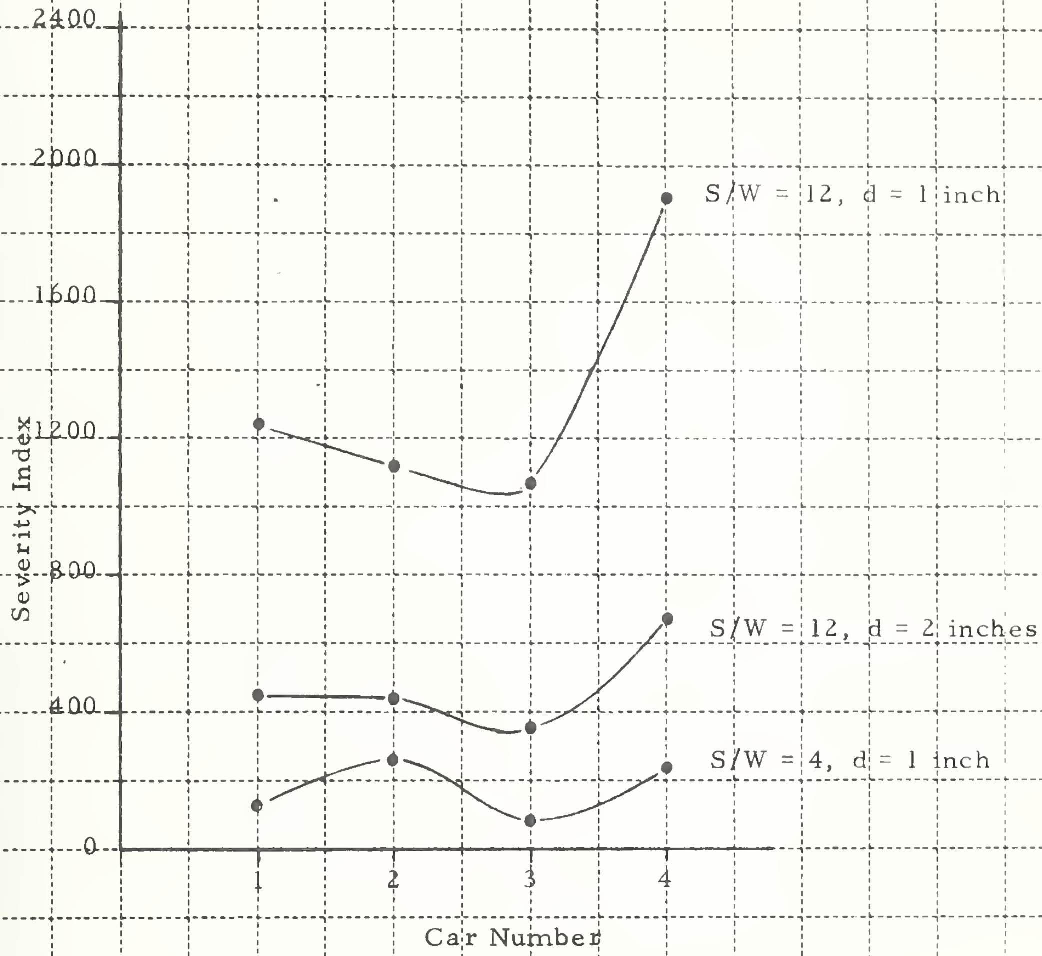

Figure 7-21. Severity Index Along Train Length (Passenger Located 2 feet from Impacted Object, Closure Speed = 40 mph)

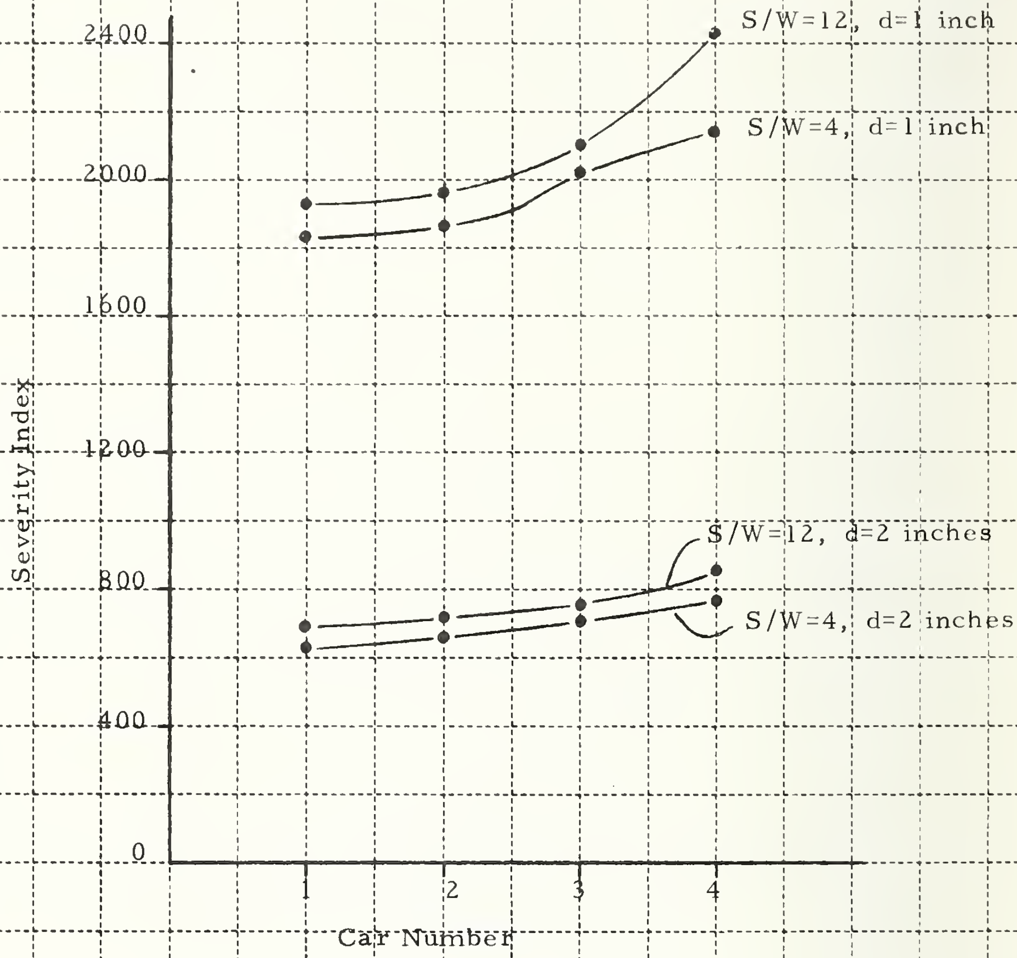

Figure 7-22. Severity Index Along Train Length (Passenger Located 12 Feet from Impacted Object, Closure Speed = 40 mph)

Though no computer program inputs for object crush distances between 1 inch and 2 inches were made, considerable insight into the effect of object crush distances between 1 inch and 2 inches can be obtained by plotting severity indices versus object crush distance for those object crush distances which were used as inputs* (d = 1/4 inch, 1 inch, 2 inches, 4 inches and 6 inches). This is done in Figures 7-23 through 7-25.

Severity indices in Figure 7-23 are plotted for a four car train collision, with cars having strength to weight ratio of 4, and closure speed of 40 mph. An envelope of worst possible severity indices is shown by curve 1, which reflects severity indices at passenger travels of 9 feet and higher. At approximately this point, as has been previously noted, no ride down occurs and higher passenger travels do not result in higher severity index. Curves 2, 3 and 4 show reduced severity indices at 6 feet, 4 feet and 2 feet, respectively.

Severity indices in Figure 7-24 are plotted for a four car train, with cars having strength to weight ratio of 12, and closure speed of 40 mph. Note that the envelope for worst possible injury severity is not significantly higher than for the train with cars having strength to weight ratio of only 4 - again because the no ride down situation has been reached.

The most significant information developed by Figures 7-23 and 7-24 is that, for 40 mph closure speed collisions, the object crush distance required to eliminate all severe second collision injuries is about 1.8 inches, occurring at car strength to weight ratio of 12, (Reference Figure 7-24) and is not significantly more than that for cars having strength to weight ratio of 4 (about 1.6 inches, from Figure 7-23).

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* The higher inputs were used to study the effect of crashes with closure speeds significantly higher than 40 mph.

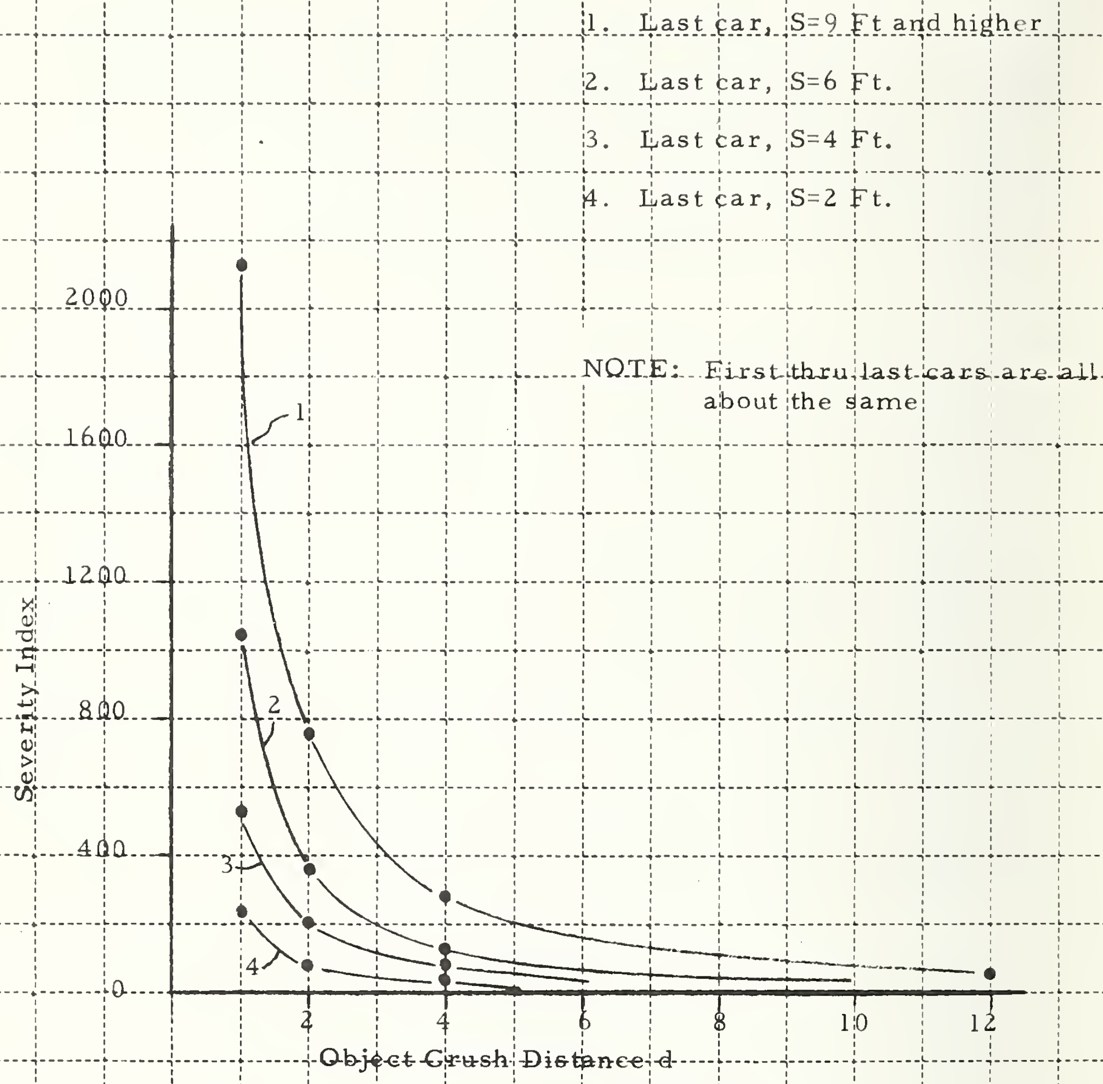

Figure 7-23. Severity Index Versus Object Crush Distance
4 Car Train 40 MPH, S/W = 4

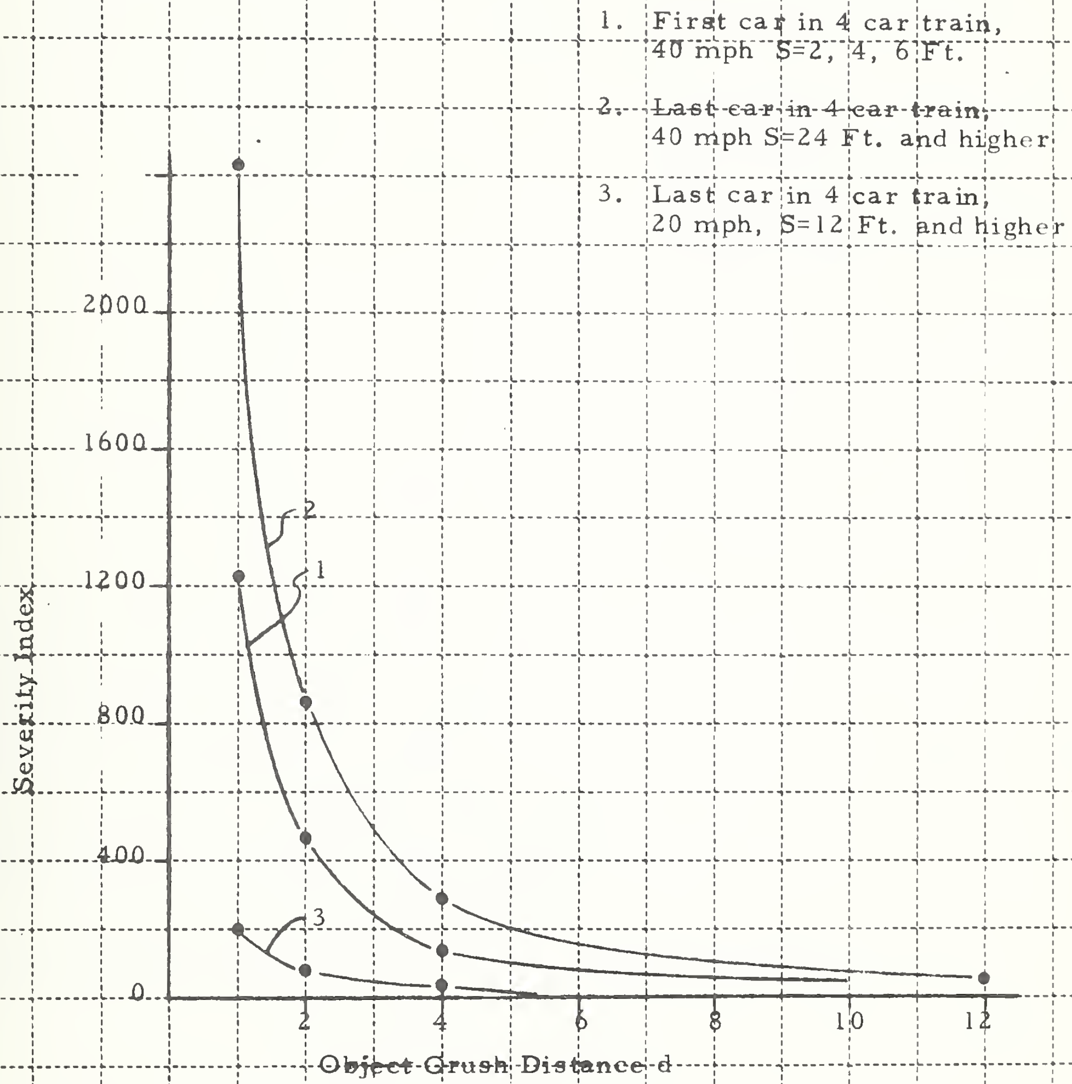

Figure 7-24. Severity Index Versus Object Crush Distance 4 Car Train, 40 MPH and 20 MPH, S/W=12

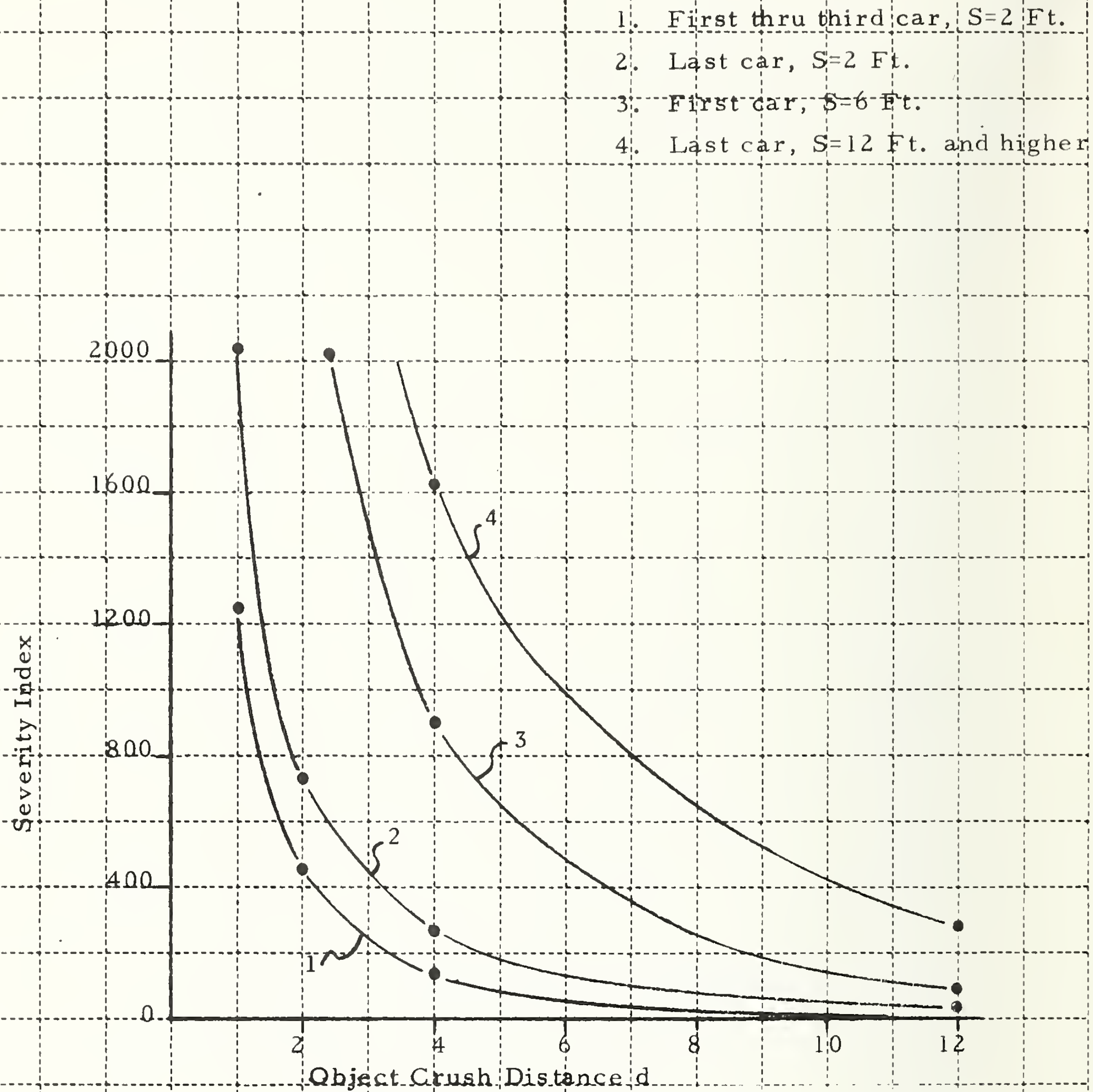

Figure 7-25. Severity Index Versus Object Crush Distance
4 Car Train, 60 MPH, S/W=12

In Figure 7-25, severity indices are plotted for a four car train collision, with cars having strength to weight ratio of 12, and closure speed of 60 mph. These conditions are similar to those represented by the previous Figure 7-24, except that maximum closure speed is increased from 40 mph to 60 mph. The envelope of worst injury severities, given by curve 4, shows severity indices considerably higher than for the 40 mph collisions. This is because of the higher cut off point for the zero ride down passenger impact speed, which is increased from 20 mph for the symmetrical 40 mph closure speed collisions to 30 mph for the symmetrical 60 mph closure speed collisions. Required object crush distances to maintain all injury severity levels below the severe injury level of 1000 are increased very significantly from the 40 mph case, from 1.8 inches to 6 inches.

In all cases, the envelope for maximum severity index is determined by the maximum change in vehicle speed during the crash. For passengers sufficiently far from the impacted interior object that no ride down occurs, the passenger impact speed is equal to the maximum change in vehicle speed. Collisions considered so far (e.g.; represented by Figures 7-1 through 7-25) are for trains having equal masses. When trains with unequal masses collide at closure velocity V_1, the final velocity V_2 is given by

$$m_1 V_1 = (m_1 + m_2) V_2 \qquad (7\text{-}4)$$

If m_1 is the larger mass, the maximum change in speed is for the lighter train, and, from equation 7-4, is given by

$$V_2 = \frac{m_1}{m_1 + m_2} V_1 \qquad (7\text{-}5)$$

If a six car train strikes a standing two car train at closure velocity of 40 mph, the increase in velocity for the two car train is, from equation 7-5

$$\cdot V_2 = \frac{6}{6 + 2} (40) = 30 \text{ mph}$$

This is the same as the change in train velocity for symmetrical collisions between identical trains at closure speed of 60 mph, represented by Figure 7-25. Therefor, the maximum severity indices for passengers in a two car train struck by a six car train at closure speed of 40 mph are approximately equal to the maximum indices shown in Figure 7-25.

Seated passengers in the two car train will not receive maximum severity indices, because the short travel to the forward seat (2 feet or less) permits significant ride down to take place. We may conclude that the most difficult situation to design against is the second collision injury to the standing passenger in a short train in a collision with a significantly longer train. Because of the large object crush distances required to keep injuries below the severe level (e.g.; 4 to 6 inches for the case of a six car train hitting a two car train, from Figure 7-25 for the equivalent four car train symmetrical collision) an operational policy that might be considered would be the elimination of standees in very short trains which must operate on the same tracks with longer trains. Since short trains tend to be used in off hour situations when traffic is relatively low, such a policy might not be unreasonable. Also consideration should be given to running trains of equal consist.

A very good insight into the effect of strength to weight ratio on second collision injury severity is provided by Figures 7-26 through 7-28. In these figures, the required object crush distance to prevent severe injuries (SI $<$ 1000) is plotted versus closure velocity for strength to weight ratios of 4, 8, and 12. The figures represent collisions between identical 4 car trains.* The data points in these figures (connected by solid lines) represent

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* Short trains produce high second collision injury severity than longer trains. Note previous discussion on collision of 2 car train and 6 car train.

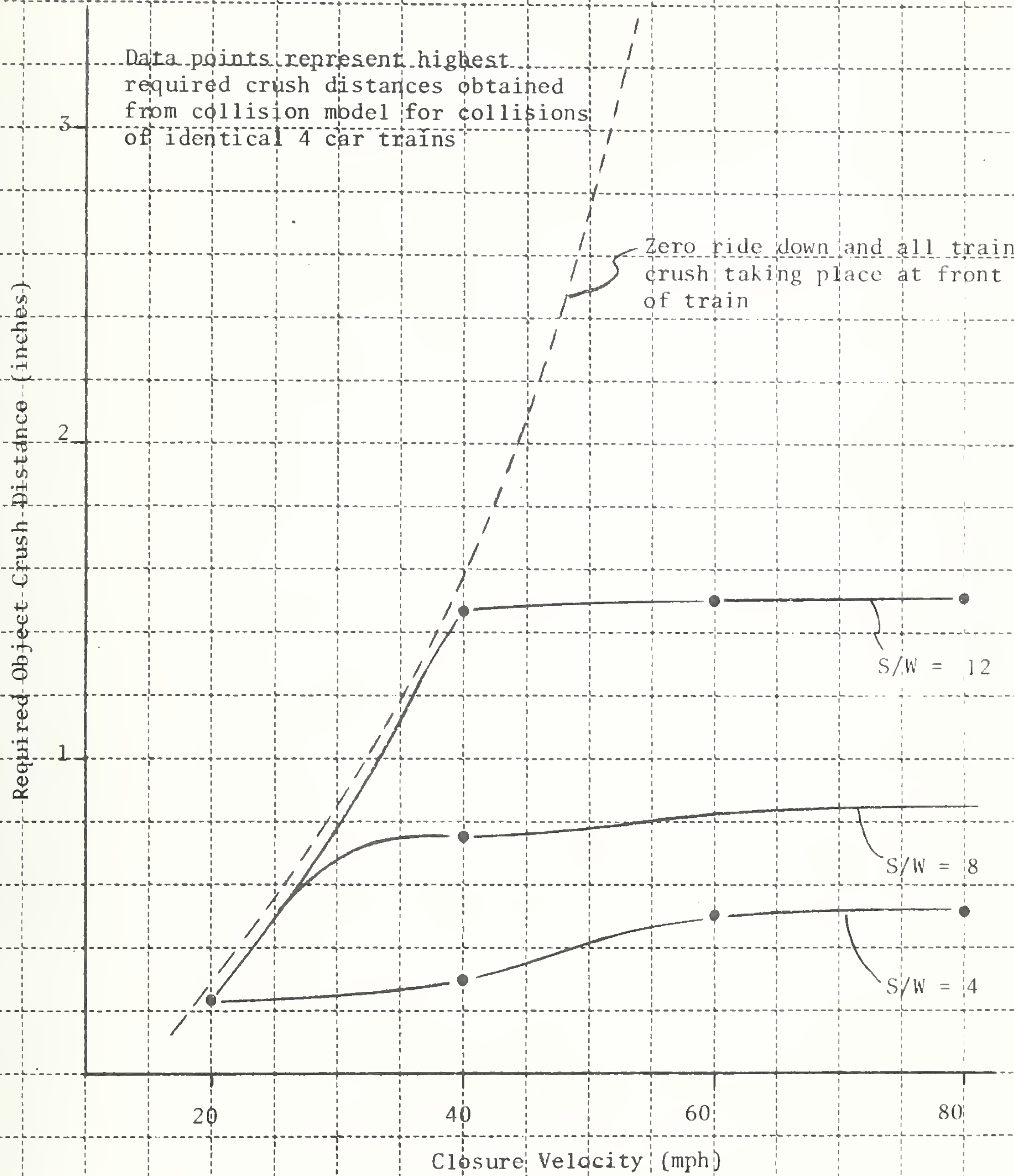


Figure 7-26. Required Object Crush Distance to Prevent Severe Injuries Versus Closure Velocity (Passenger Spacing = 2 Feet)

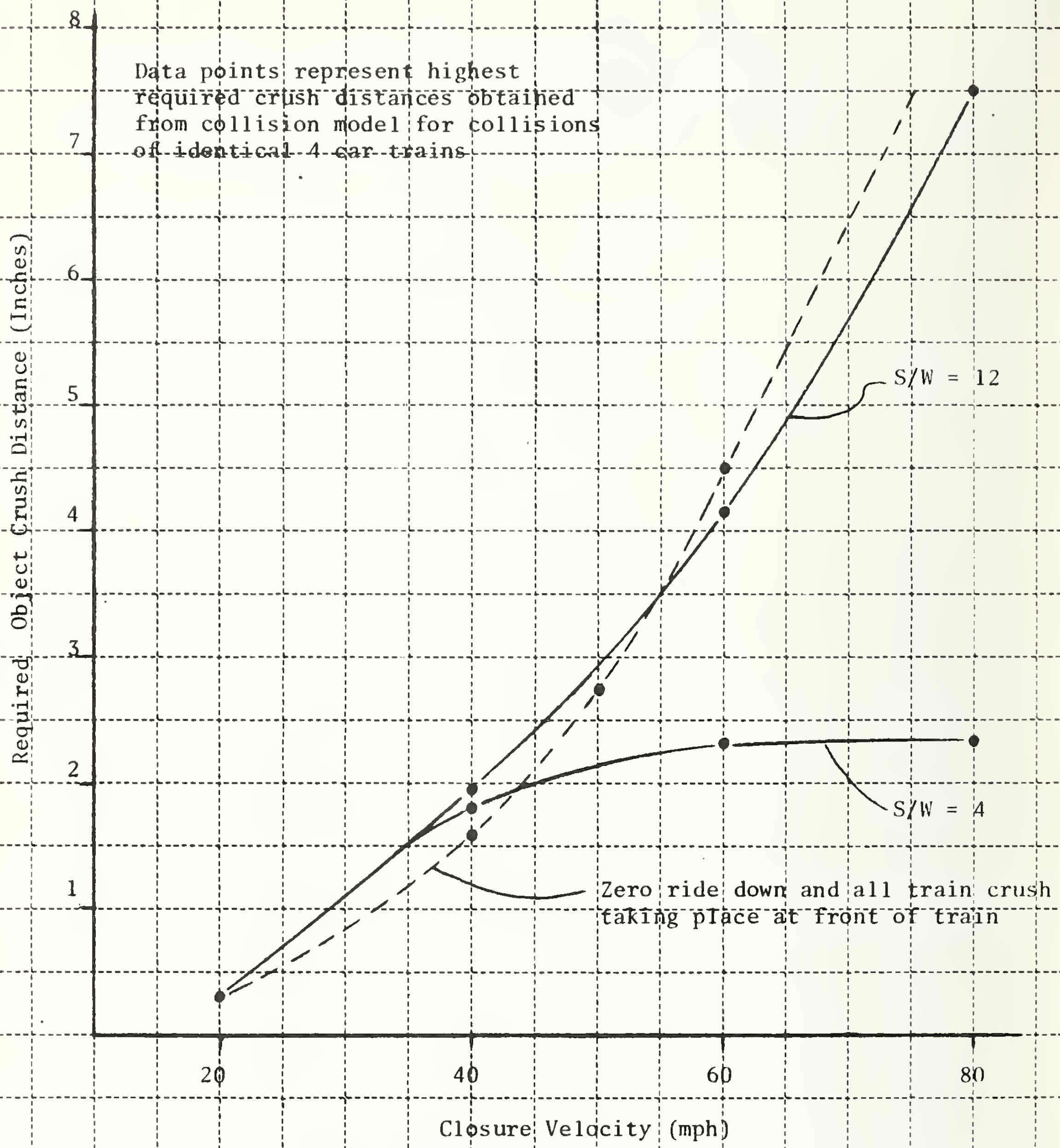


Figure 7-27. Required Object Crush Distance to Prevent Severe Injuries Versus Closure Velocity (Passenger Spacing = 6 Feet)

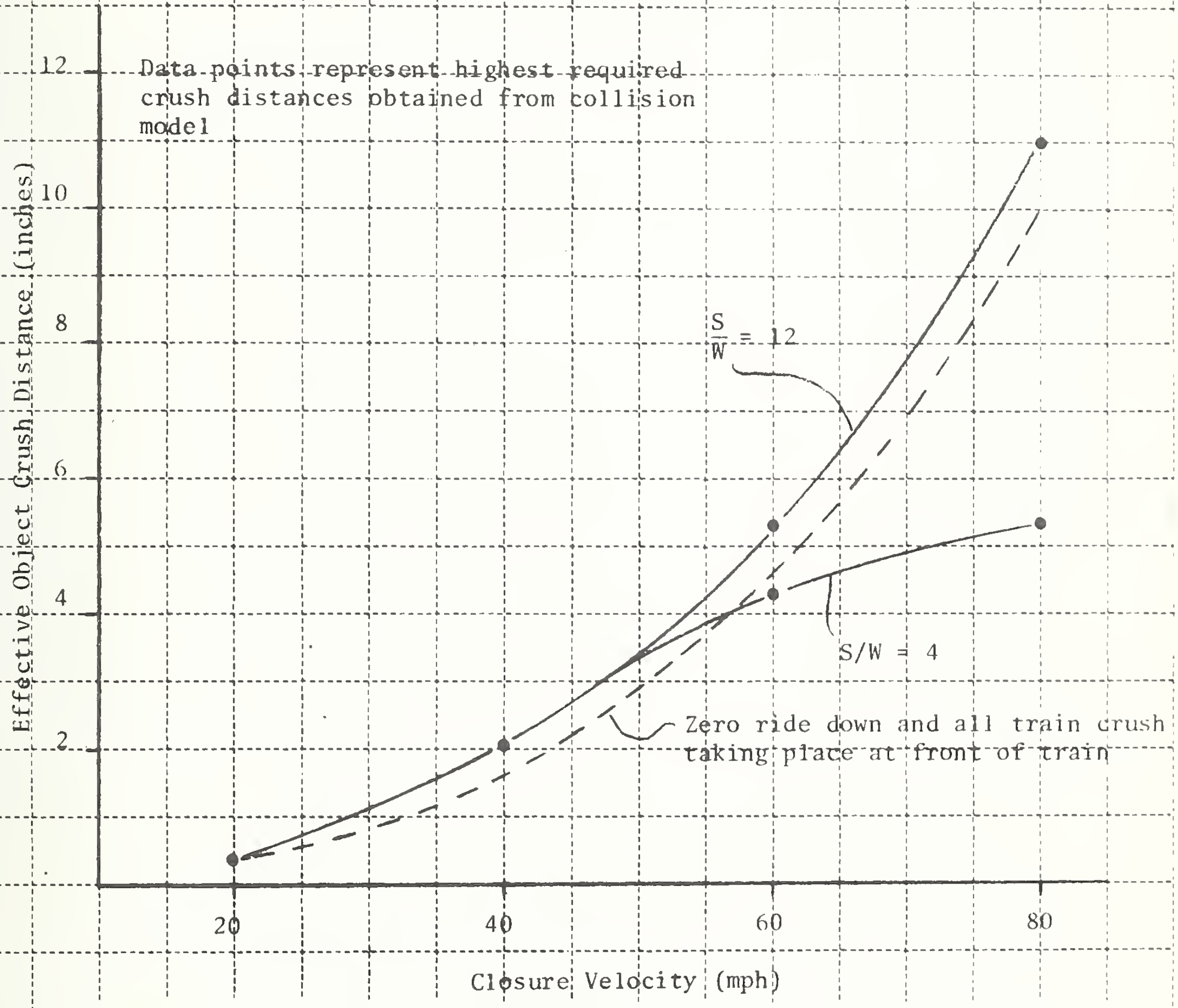


Figure 7-28. Required Object Crush Distance to Prevent Severe Injuries Versus Closure Velocity (Passenger Spacing = 12 Feet)

the highest required object crush distances (to prevent severe injuries in any car in the train) obtained from the collision model. The dashed lines represent the corresponding object crush distances which would be required if (1) the passenger is sufficiently far from the impacted object that no ride down occurs, and (2) all train deformation takes place at the lead car. The passenger impact velocity for the dashed curves is the total change in train velocity during the collision, obtained directly from equating total momentum of both trains at the instant of striking to total momentum at the instant when full crush has taken place. Using this impact velocity, the required object crush distances represented by the dashed lines are obtained from Figure 3-3 (Degree of Injury Severity).

Figure 7-26, for a passenger spacing of s = 2 feet, is generally representative of a forward facing seated passenger. The figure shows that a ride down "cutoff point" exists for each strength to weight ratio. At all closure speeds less than 20 mph, the required object crush distance is independent of strength to weight ratio because no ride down occurs (i.e., for the range of strength to weight ratios shown, passenger impact velocity is equal to the total change in car velocity during the collision). Similarly, at all closure speeds less than 30 mph, the required object crush distance for all cars with strength to weight ratio greater than 8 is independent of strength to weight ratio. It is evident from the figure that existing transit cars with relatively low strength to weight ratios (about 4) provide a less severe second collision environment for seated passengers than existing inter city and commuter cars designed to FRA standards. However, the figure also confirms the obvious point that transit cars with strength to weight ratios increased to levels for cars falling under FRA standards (such as the Silverliner, which has a strength to weight ratio of 12 to 14) would provide the same second collision environment for forward facing seated passengers as cars built to FRA standards, provided that the seatback for the transit car is no more hostile than existing seatbacks for the FRA cars.

A particularly interesting point shown by Figure 7-26 is that the envelope of maximum required crush distances corresponds very closely to the zero ride down line in which, as we have noted, passenger impact velocity is independent of S/W.

Figures 7-27 and 7-28 (for passenger spacing of 6 feet and 12 feet, respectively) show that the zero ride down effect for standing passengers is even more significant than it is for seated passengers. At 12 feet of effective passenger spacing, the required object compliance for the prevention of severe injuries at speeds up to 60 mph is approximated by the zero ride down line; hence it is not affected strongly by strength to weight ratio.

Required object crush distances (for prevention of severe injuries) which are plotted in Figures 7-26 through 7-28 are summarized below:

	Required crush distance at 40 mph for S/W of:			Required crush distance at 60 mph for S/W of:		
Object Location	4	8	12	4	8	12
2 feet	0.3"	0.75"	1.5"	0.3"	0.75"	1.5"
6 feet	1.5"	1.5"	1.5"	1.5"	2.6"	4.5"
12 feet	1.5"	1.5"	1.5"	4"	4.5"	5"

At car strength to weight ratio of 12, the required crush distance at closure speeds up to 40 mph is about 1.5 inches, regardless of spacing between passenger and impacted object. Thus, at this level of strength to weight ratio, ride down is not a factor in reducing maximum injury severities. Experience in inter-city rail-car accidents in the 40 mph to 60 mph range (see discussion in Chapter 8) indicates that passengers do not receive severe second collision injuries. Since inter-city cars generally have a strength to weight ratio of 12 or more, the 1.5 inch effective crush distance is taken as a very approximate baseline which is representative of relatively well designed existing interiors. Since this amount of interior object compliance is adequate to prevent severe injuries to standing passengers as well as seated passengers at closure speeds up to 40 mph, it is concluded that severe injuries to standing passengers in transit cars can be prevented at closure speeds up to 40 mph, provided that interior objects in the cars have compliance characteristics equivalent to those of relatively well designed existing equipment.

At 60 mph, for low strength to weight ratios (e.g., S/W = 4) the required object crush distance at 6 foot passenger spacing can be reduced significantly from that at 12 foot spacing (1.5 inches versus 4 inches). Hence, for combinations of very low strength to weight ratios and high closure speeds, compartmentalization can be effectively utilized to significantly reduce required interior object compliance. However, at strength to weight ratios at the high end of the present transit car range (e.g., 10 to 12), reduction in passenger space has relatively little effect in reducing required compliance (4.5 inches at 6 foot spacing, versus 5 inches at 12 foot spacing). Because of the large car penetration at low strength levels, it is concluded that more benefits can be obtained from the development of interior equipment with sufficient compliance to prevent severe second collision injuries at closure speeds in excess of 40 mph and at strength to weight ratios representing the high end of the present transit car range. If this is achieved, even higher strength to weight ratios can be employed without further increase in interior compliance, since passenger impact speed at these strength levels is again limited by maximum change in car speed during the collision. However, to prevent severe injuries at 60 mph closure speeds, note that 4 to 5 inches of effective compliance is required; hence compliance would have to be increased by a factor of 2 or 3 times that required to prevent severe injuries at 40 mph closure speed.

In the discussion of Figure 7-21 and 7-22, it has been noted that there is a general tendency for the severity index to increase toward the rear of the train. This is evidently due to the fact that different cars in a train have slightly different deceleration versus time characteristics in a collision. In all cases, the force deflection curves used in the collision simulations have a general shape shown in Figure 6-1. The curves consist primarily of two constant force plateaus, with the first force plateau preceded by a draft gear force - deflection characteristic which includes free play (zero force versus deflection) after shearing of the draft gear pin. In order to determine the effect of draft gear characteristics on differential car decelerations, and resulting differences in severity indices, draft gear characteristics were systematically varied as shown in Figure 7-29, a through d. The characteristics shown are:

a) no draft gear

b) draft gear consisting of elastic spring, with no shear pin

c) draft gear with elastic spring, shear pin, and 6 inches of free play after shearing of pin and before contacting of structure

d) draft gear with elastic spring, shear pin, and 2 inches of free play after shearing of pin and before contacting of structure

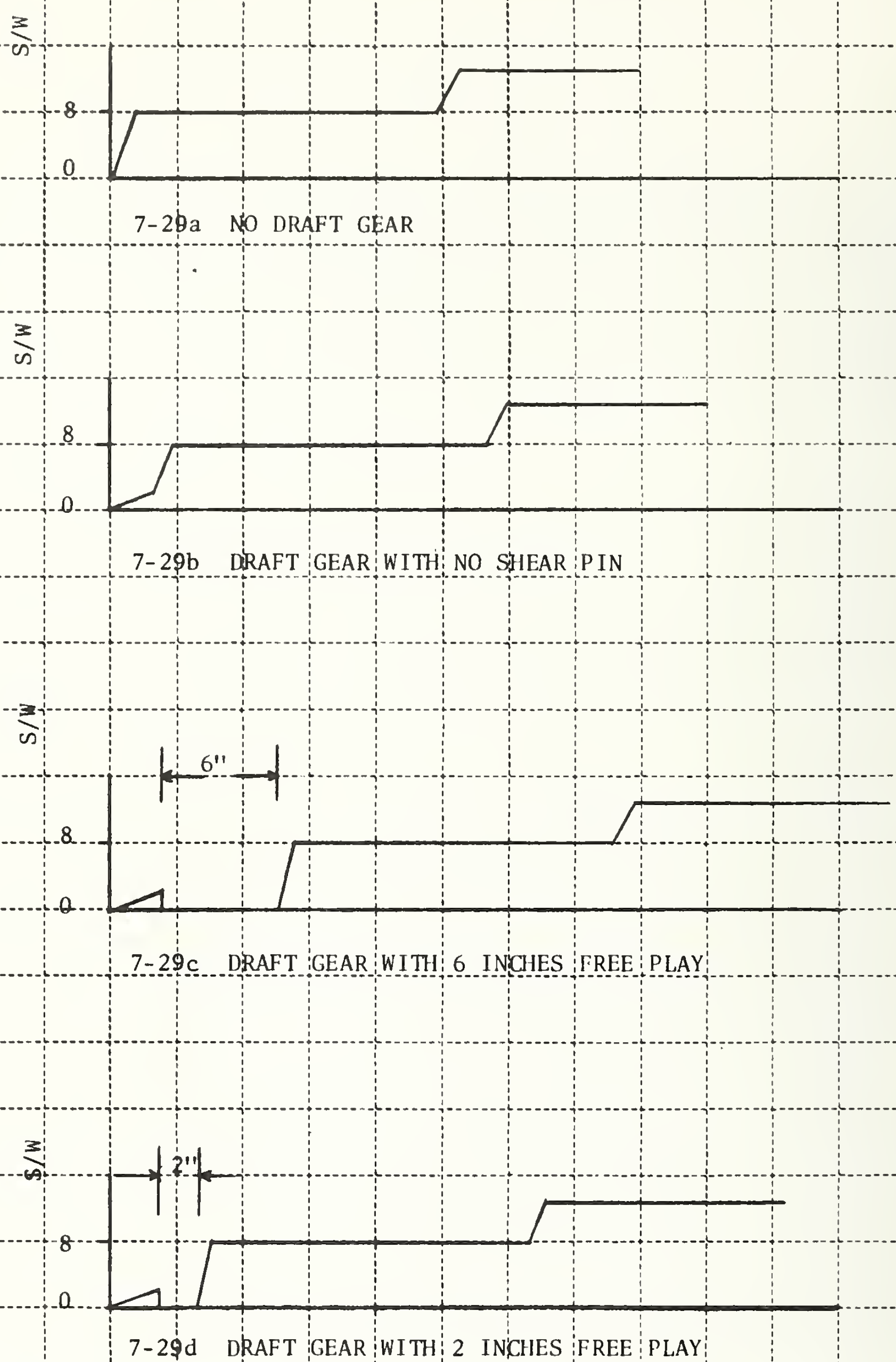


Figure 7-29. Draft Gear Characteristics

Configuration (d) is identical to the basic configurations which were run throughout the study, and represents characteristics of existing draft gears. Configurations (a) and (b) provide less draft gear effect than (d), and configuration (c) provides considerably more draft gear effect than (d), with free play increased from 2 to 6 inches. Thus, configurations (a), (b) and (c) bracket the standard configuration (d).

Each of the four draft gear characteristics were used as inputs to a symmetrical 40 mph closure speed collision, with trains of eight cars having a strength to weight ratio of 8. Figure 7-30 shows severity indices along the train for a passenger travel (s) of 2 feet and object crush distance (d) of 1 inch. It is evident from Figure 7-30 that draft gear free play increases severity index considerably for this condition, which is generally representative of a seated passenger. Configuration (c) (maximum draft gear free play) produces by far the highest severity indices, and configuration (a) (no draft gear) produces the lowest indices. Configuration (b) (draft gear with no free play) produces slightly lower indices then the standard configuration (d), which has 2 inches of free play.

Figure 7-31 shows severity indices along the train for conditions identical to those shown by Figure 7-30, except that passenger travel to the impacted object is increased from 2 feet to 9 feet. Figure 7-31 is therefor representative of a standing passenger located at a relatively long distance from the impacted object. The results for the standing passenger appear to follow generally the same trend as for the seated passenger, with increasing draft gear free play causing increasing severity indices. The trend is particularly clear for the last two cars in the train. By eliminating free play from the standard draft gear after shearing of the pin the following reductions in severity indices in cars 7 and 8 are achieved:

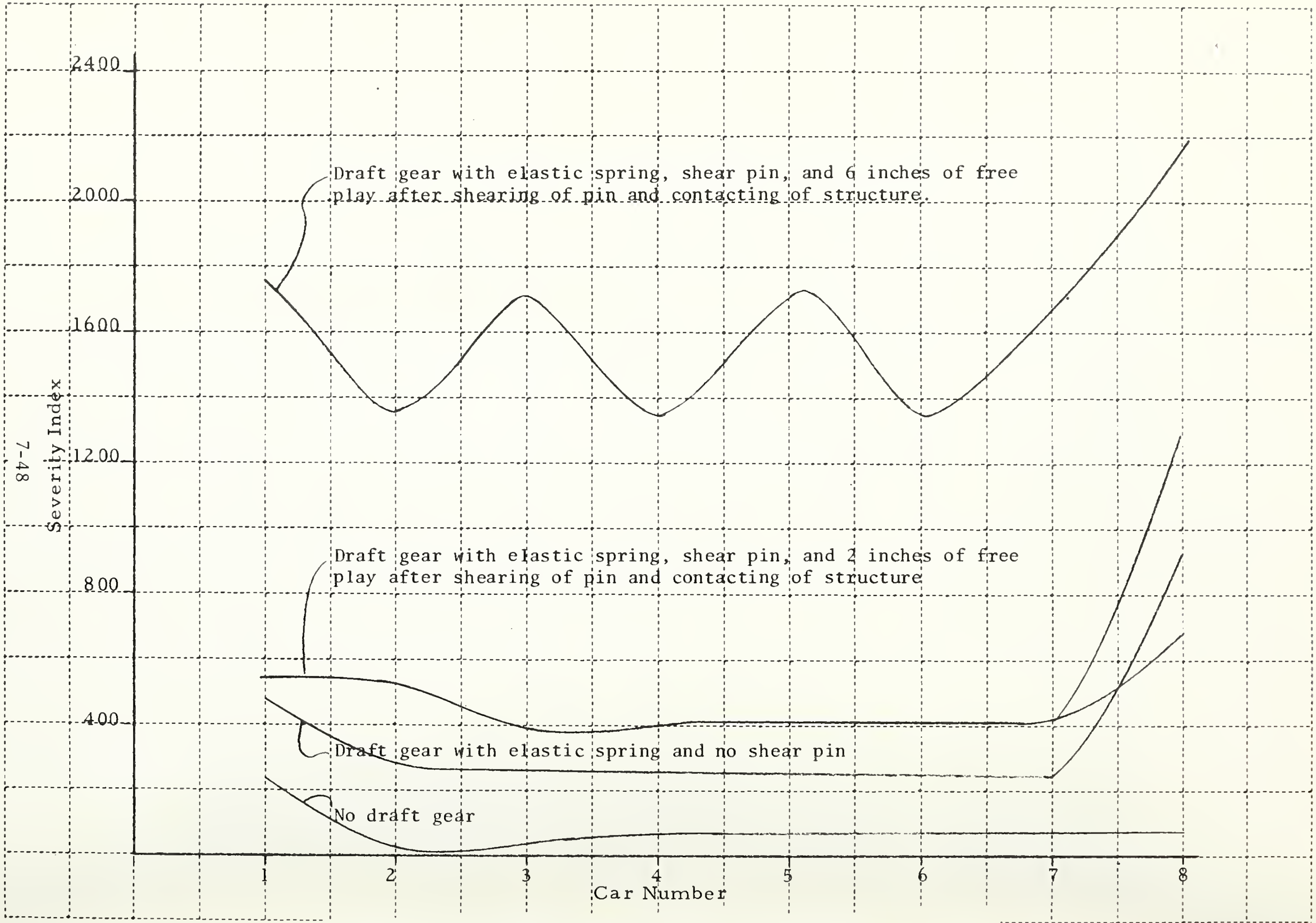


Figure 7-30. Severity Index Versus Train Length
40 MPH Closure Speed, S.W=8, S=2 Ft., d=1 Inch

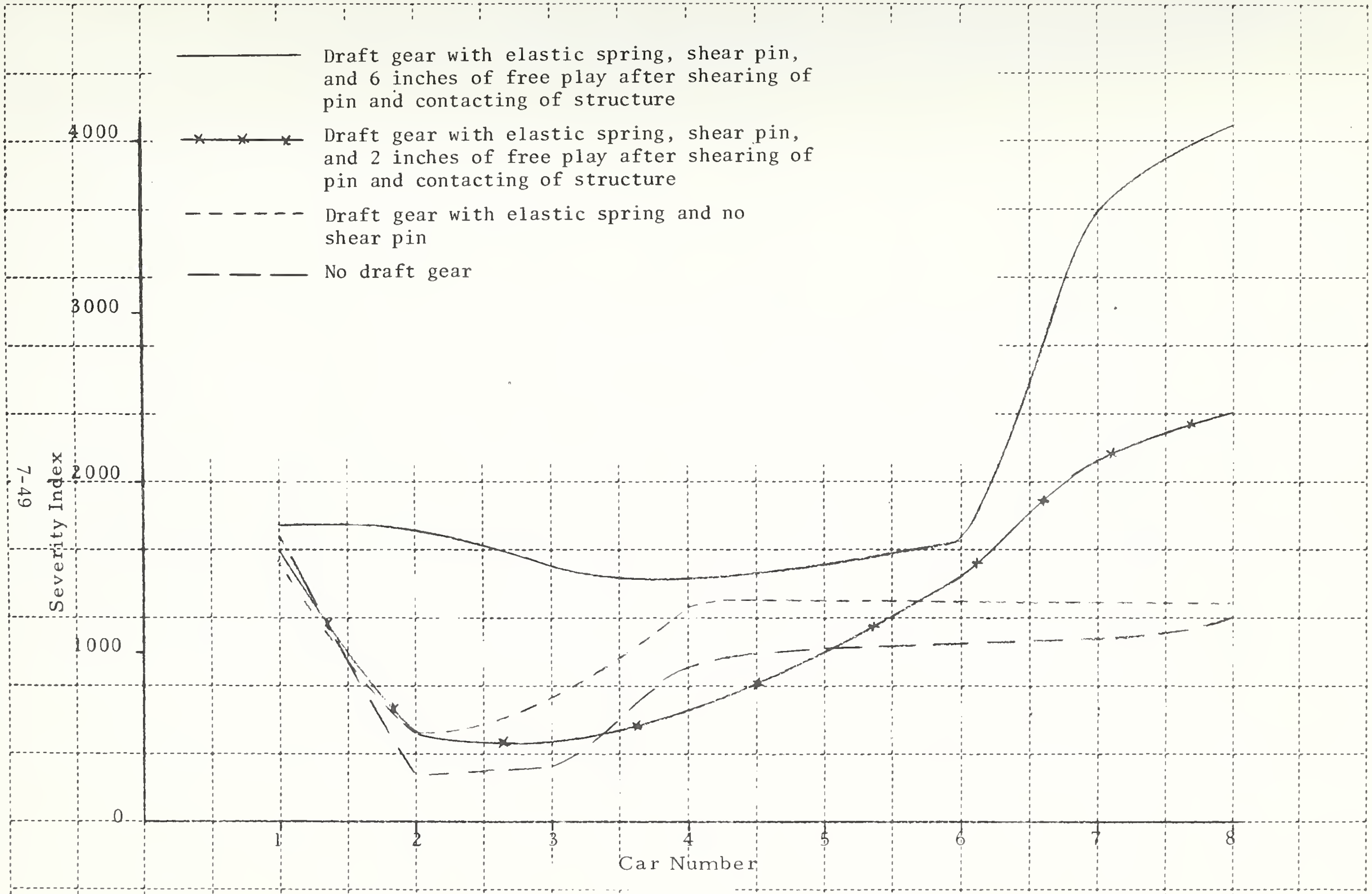


Figure 7-31. Severity Index Versus Train Length
40 MPH Closure Speed, S .W=8, S=9 Ft., d=1 Inch)

	Standard draft gear configuration	Standard configuration with free play eliminated
Car 7	2200	1100
Car 8	2420	1200

These, of course, are extremely large reductions, indicating that fatal second collision injuries in the last 2 cars can be reduced to levels which are at the low end of the severe category by elimination of draft gear free play.

It should be emphasized that no information has yet been found to confirm from the results of actual accidents this tendency of increasing severity index at the rear of colliding trains. We have noted that very significant or partial override generally occurs in severe frontal accidents, with the result that the lead car has a significantly lower effective strength to weight than the trailing cars, leading to high incidence of first collision fatalities in the lead car, and low incidence of second collision injuries in the trailing cars. However, if car construction can be improved to eliminate or minimize override, the predictions of increasing severity index toward the rear of the train may be meaningful, and should require further investigation. A preliminary understanding of this peculiarity can be obtained by investigating velocity/time histories of adjacent cars in a collision. In Figure 7-32, such information, obtained using the computer program, is shown for the second and third cars of a four-car Silverliner train in a crash with an identical Silverliner train at a closing velocity of 40 mph. Note from the figure that the second car is decelerating rapidly for the first 0.10 second of the crash. During this period, the force just forward of the second car is significantly higher than the force just aft of the second car, causing the high deceleration. For example, at t = 0.05 second, the two forces are 816,000 pounds and 122,000 pounds, respectively. At this time, both of these force points are on the first portion of the Silverliner force/deflection curve, shown in Chapter 5. However, at a time of 0.12 second, both force points have moved onto the 1,100,000-pound

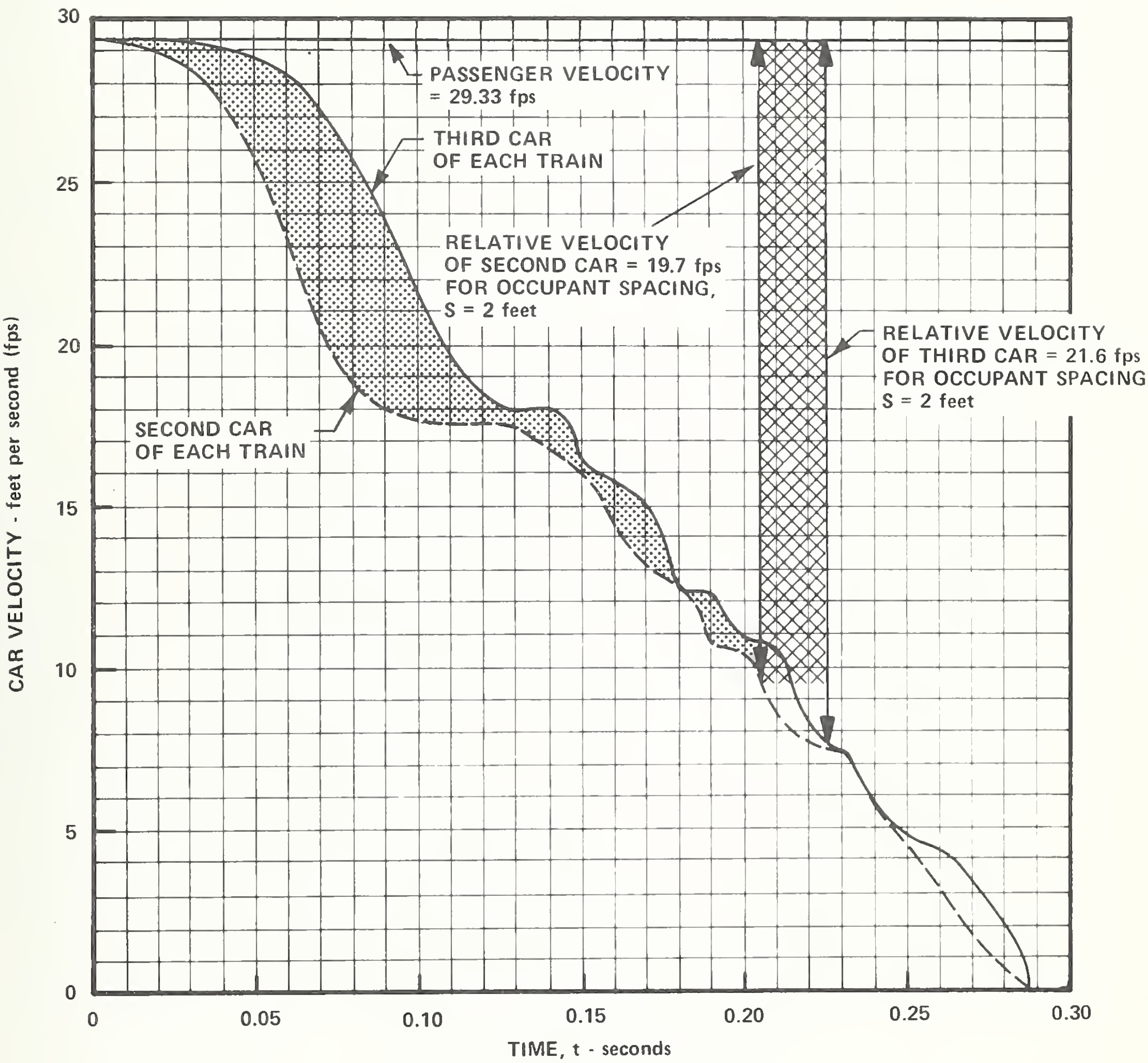


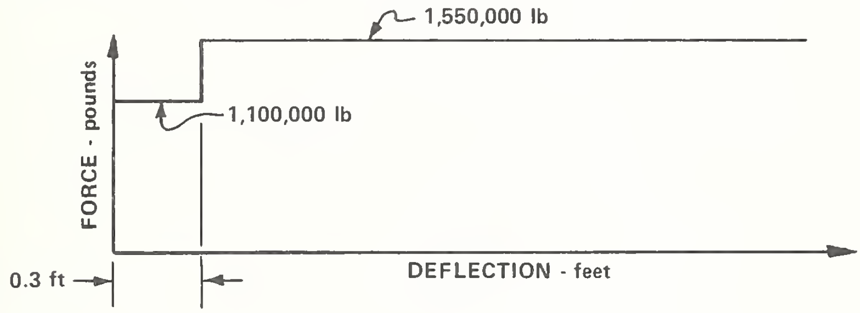
Figure 7-32. Car Velocity vs Time for Second and Third Cars of Each Train in a Collision of Two Four-Car Silverliner Trains at a Relative Closing Velocity of 40 MPH

plateau causing the deceleration of the second car (slope of the velocity curve in Figure 7-32) to be zero. The third car, meanwhile, undergoes more uniform and generally lower deceleration in the first 0.15 second, with both cars converging to about the same velocity/time curve at about 0.15 second.

For any time t, the relative travel (distance) of a passenger with respect to the car can be obtained by integrating, between time limits of zero and t, the area between the car velocity curve and the passenger velocity curve. The integrated areas corresponding to a free-space distance (occupant spacing), S, of 2 feet for each car can be compared in Figure 7-32. An understanding of the increasing severity index is obtained by looking at the differences in these areas, shown by the shaded regions of Figure 7-32. In the first 0.10 second, relative travel between passenger and car is greater for the second car because of its relatively high deceleration; the measure of this greater travel is the shaded area between the two velocity curves. A value of 2 feet is reached for the second car at 0.205 second, as shown in the figure. At this instant, the relative displacement for the third car is less than 2 feet by an amount equal to the shaded area between the velocity curves. A displacement of 2 feet for the third car is not reached until an elapsed time of 0.225 second, approximately 0.02 second after this level is reached for the second car. This final portion of the travel in the third car is given by the shaded area between t = 0.205 second and t = 0.225 second, which is equal to the shaded area between the velocity curves. It can be seen from Figure 7-32 that the relative velocity between passenger and car at a free-space (occupant-spacing) distance of 2 feet is greater for the third car than for the second car, causing a higher passenger severity index to exist in the third car.

It is evident that the characteristic of increasing passenger severity index from one car to a following car is associated with an early high deceleration of the forward car, followed by a period of relatively low or zero deceleration of the forward car. This change in the rate of car deceleration appears to arise fundamentally from the shape of the force/deflection curve, and does not necessarily require a linear (elastic) ramp in the force/deflection curve, or free play in the draft gear. The numerical example which follows illustrates this.

Consider a four-car train in a collision at a 40-mph closing velocity, with each car having a force/deflection curve as shown in the graph sketched below.



No linear ramps or free play exist in the curve, which steps directly from a force plateau of 1,100,000 lb to a force plateau of 1,550,000 lb at a deflection of 0.3 feet. Car weights are assumed to be the same as that of the Silverliner (101,000 lb). Velocity-versus-time curves for the first and second cars of the train are plotted in Figure 7-33.

In the initial time regime ($0 < t < 0.01$ second), the entire train decelerates as a rigid body under a front-end force level of 1,100,00 lb. At $t = 0.01$ second, the force level at the front end of the train increases instantly to 1,550,000 lb, marking the start of the second time regime. At this time, the train attempts to decelerate as a rigid body at a higher rate corresponding to the increased force. However, this would require that the force level between the first and second cars be

$$F_{12} = 3/4\ (1,550,000) = 1,160,000 \text{ lb}$$

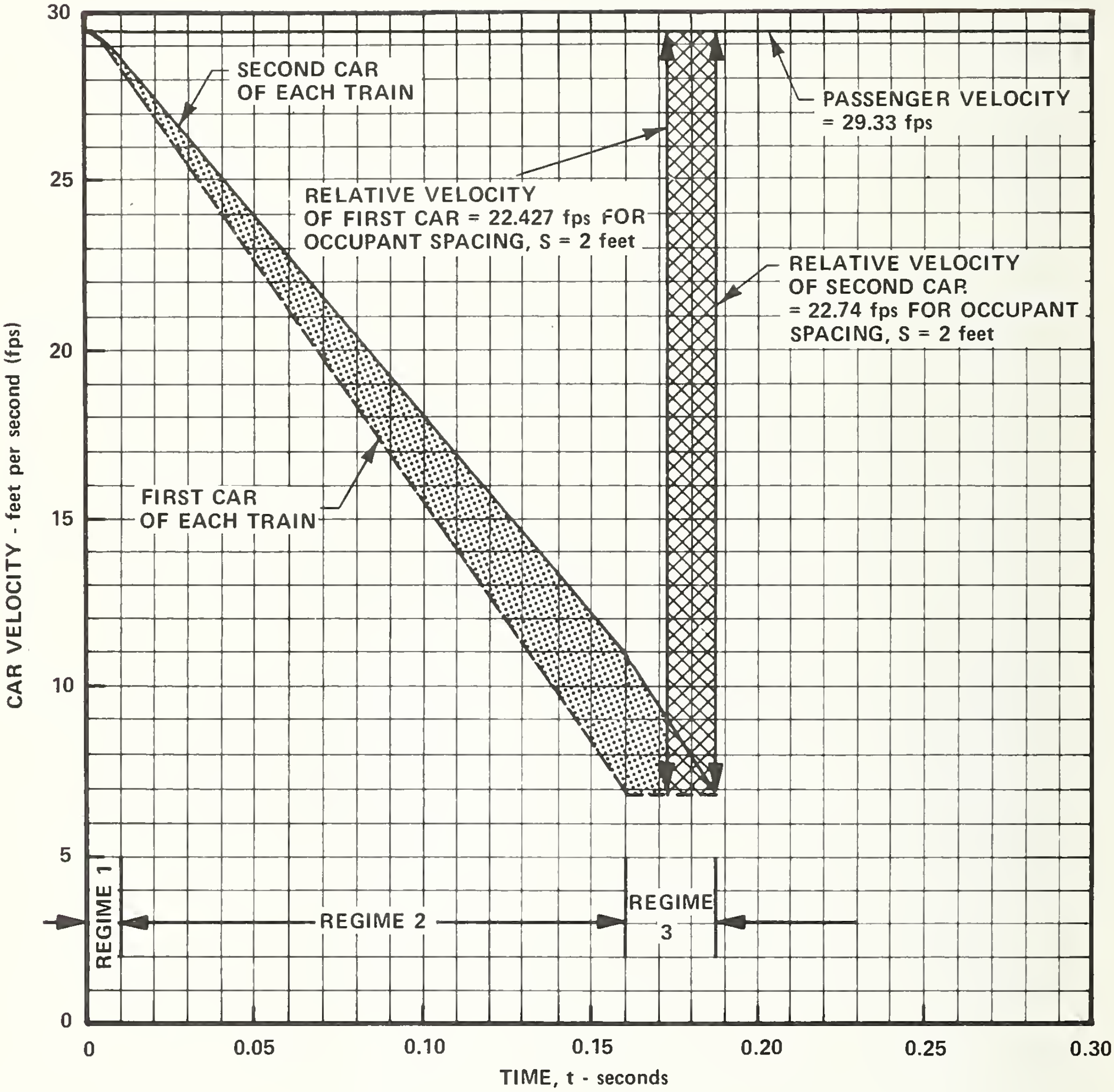


Figure 7-33. Minimum Passenger Severity Indices for First and Second Cars of Each Train in a Collision of Two Four-Car Silverliner Trains at a Relative Closing Velocity of 40 MPH

But, this force level exceeds the force level in the first plateau; hence, the first plateau between cars 1 and 2 starts crushing simultaneously with the second plateau forward of car 1. Thus, during time regime 2 ($0.01 < t < 0.16$ second), the first car decelerates under a force level given by

$$F_{01} = 1{,}550{,}000 - 1{,}100{,}000 = 450{,}000 \text{ lb}$$

and the second, third, and fourth cars each decelerate as a rigid body under a force level of 1,100,000 lb. During this time regime, the deceleration of the first car is greater than that of the following cars, as shown in the figure.

The next (third) time regime of interest starts when the first plateau between cars 1 and 2 has crushed fully. During this time regime, the full force of 1,550,000 lb exists forward and aft of the first car, resulting in zero deceleration of the first car. Now, the remaining cars each decelerate as a rigid body at an increased rate corresponding to a force of 1,550,000 lb, as shown in the figure. This regime continues until the remaining cars have decelerated to a velocity equal to that of the first car, which occurs at approximately 0.186 second. A relative passenger displacement of 2 feet occurs in the first car at approximately 0.172 second and corresponds to a relative velocity of 22.427 fps, as shown in Figure 7-33. A 2-foot displacement occurs in the second car at approximately 0.188 second, slightly into the fourth time regime. The corresponding relative velocity in the second car is 22.74 fps, causing higher severity index in the second car than in the first car. Note that the difference in the severity indices would be greater at free-space distances slightly less than or slightly greater than 2 feet.

The example given above shows again that increasing severity index (between two given cars) is caused by a leveling off in the deceleration rate of the forward of the two cars, which, in turn, is caused by the gross shape of the force/deflection curve. Since this effect is not specifically dependent on a linear ramp or free play in the force/deflection curve, it does not require the generation of a pressure wave (which is associated with finite, non-zero slopes in the force/deflection curve). Moreover, it appears to be possible for the increase in severity index to occur anywhere in the train, depending on the particular force/deflection characteristics; in this case, it occurs between the first and second cars of the four-car train.

For existing transit cars, the studies in this section confirm accident experience - major losses in frontal and front to rear accidents are first collision fatalities due to car penetration (crush). In Figure 7-34, crush distance is shown as a function of closure speed, strength to weight ratio, and number of cars in the train. The crush distances shown are based on collisions of identical trains. No confirmation of crush distance can be obtained from existing static test data, which is limited to buff (longitudinal load) tests in the elastic range. Controlled dynamic tests in which large post elastic deflection behavior can be determined have not been performed. In the following section which deals primarily with the problem of override, actual collisions are reviewed, including one oblique collision which occurred in a cross over. Collision velocities in actual accidents cannot be independently determined with sufficient accuracy to verify estimates of car behavior made in this section. However, qualitative observations are made in the following section which relate to gross car behavior in frontal and oblique collisions. In particular, the review of previous collisions provides an initial insight into the nature of the override mechanism.

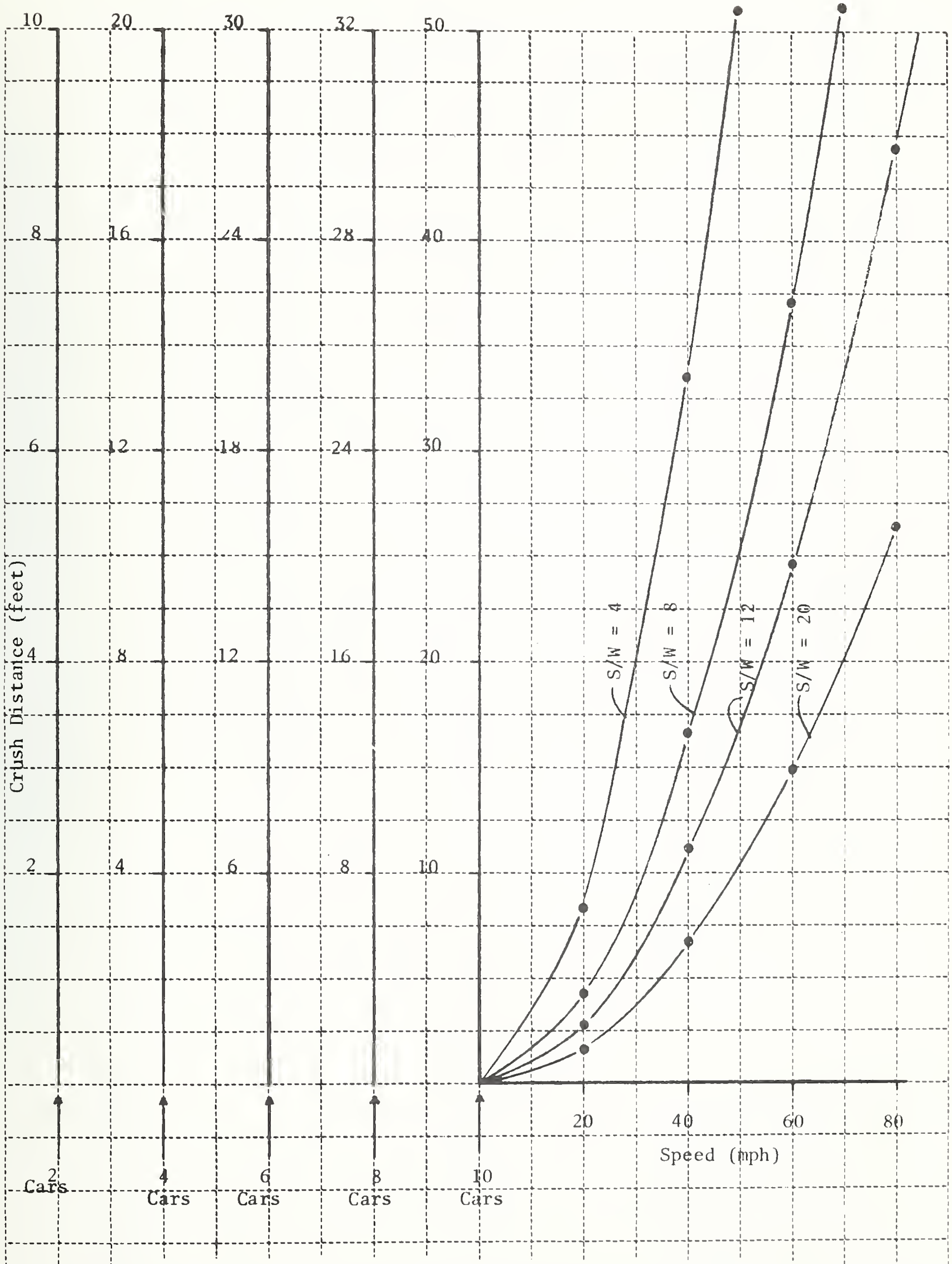


Figure 7-34. Train Crush Distance Versus Closure Speed