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GRADE CROSSING ACCIDENT INJURY MINIMIZATION STUDY

PB81-155236

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16. Abstract

The purpose of this study was to identify and evaluate potential concepts for reducing injuries to highway occupants and train occupants in rail-highway grade crossing collisions. A review of railroad, highway vehicle, and aviation sources was made. The identified concepts were principally those from railroad crashworthiness and collision attenuation studies, plus some collision attenuation concepts from highway safety work. A list of concepts was developed and each approach evaluated for effectiveness according to a set of criteria based primarily on performance in normal operations and in accidents. Several concepts were rejected on this basis. Certain concepts were effective but applied to situations of very low statistical importance where preventive measures are more effective. Some numerical simulation of accidents was done in the evaluation. The more effective concepts consisted of a hard-faced deflector covering the locomotive coupler to remove the highway vehicle from the tracks, a soft crushable collision attenuator to reduce impact accelerations and forces, and increased use of rail brakes in passenger cars. Estimates of fatality reduction from various measures and of costs are made. It is concluded that testing of the more promising concepts is warranted.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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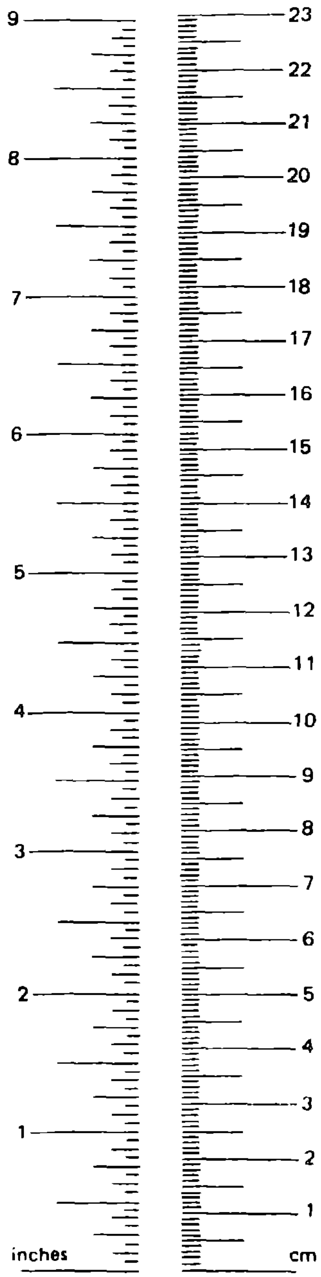
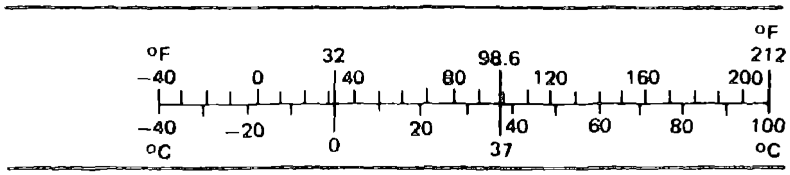
*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

GRADE CROSSING ACCIDENT INJURY MINIMIZATION STUDY

1. Purpose of Study

The goal of this study was investigation and evaluation of concepts for the reduction of injuries to occupants of highway vehicles and of trains in rail-highway grade crossing accidents. For each concept identified, the study was to determine the conditions in which it would be applicable, its effectiveness in reducing injuries, and estimates of potential reductions in injuries achieved, and of costs of implementation.

2. Study Procedure

Consideration of certain accident situations and certain injury reduction concepts was specifically required by the contract. A review of rail literature on injury reduction methods was followed by a review of the highway transport and aviation fields. Some highway work suggested alternative implementation methods, but no new concepts were identified.

Evaluation criteria were developed involving feasibility, performance in routine operations and in emergency situations, acceptability and convenience to the personnel involved, costs, and logistic and indirect effects. Estimates of injury reductions and of costs were developed only for concepts meeting the criteria for feasibility and satisfactory performance. Estimates were based on existing accident statistics, obtained from FRA data files, and from injury models which were related to the statistics to the extent possible. Whenever possible, results of previous crashworthiness studies were used in cost estimates.

3. Conclusions

A list of the primary conclusions appears below, and is followed by estimates of benefits and costs of certain concepts, and a brief discussion of the background of some of the conclusions.

(1) Of approximately 1,150 fatalities from grade crossing accidents in a typical recent year, about 200 occur in cases where the highway vehicle strikes the train. For such accidents, which constitute about 30 percent of all accidents, there is no practical train-mounted palliative measure. Of the 860 fatalities occurring annually when trains strike motor vehicles, about two thirds occur when the train speed is between 20 and 50 miles per hour; it is these fatalities which offer the greatest potential for reduction.

Collisions of trains with buses are so uncommon that the most effective approach to injury reduction is preventive, rather than palliative. Collisions of MU cars with fuel trucks are even more uncommon, and although there are potential design countermeasures for injury reduction, the most effective procedures are essentially preventive, for example, improved braking.

(2) Three concepts for injury reduction met performance criteria sufficiently well and offered enough potential to warrant further study. The concepts are:

- a rigid hard faced deflector at the front of a locomotive, covering the coupler to prevent impalement and retention of highway vehicles in a collision. Simulations indicate the device removes the highway vehicle from the train's path with lower accelerations than those imparted by conventional flat-front locomotives. When the coupler is to be used, the device hinges back and is stowed on the locomotive front. The deflector could also be covered with a soft layer for further reduction of impact forces.

- a soft faced crushable attenuator at the front of a locomotive, which significantly reduces the forces between train and highway vehicle in a collision, and helps remove the highway vehicle from the path of the train. When the locomotive is not at the front of a train, the device, about eight feet long, is folded back into a stowed position on the locomotive front. The added length presents a problem, because it may convert into actual collisions incidents which might otherwise have been near misses.

- addition of rail brakes to MU cars, and possibly to other passenger cars, to improve braking capability and reduce both incidence and severity of collisions.

(3) Certain essentially negative conclusions were reached about various other concepts for injury reduction and about certain accident situations.

- existing locomotive construction generally protects locomotive occupants adequately in collisions not involving hazardous materials or very heavy trucks. Recent changes in FRA standards on glazing and locomotives address some of the problems which may occur in collisions involving combustible fuels. Individual protective equipment and clothing for train crews for use in collisions involving hazardous materials do not appear to be practical.

- none of the proposed collision attenuation systems depending upon automatic actuation of a mechanism immediately before a potential collision is practical.

- very long crushable attenuators, equipped with their own wheels and articulated to the locomotive front, do not appear to be practical, although they offer the possibility of the greatest reduction in forces and accelerations of the highway vehicle.

(4) Collection of more detailed accident records, reflecting medical examiners' or coroners' reports and providing further detail on automobile location and condition after the accident, might make it more possible to predict the effects on injuries of changes in automotive and railroad design. Such data might also help establish clearer relationships between train speed and injury.

The concepts considered worthy of future consideration were chosen on the basis of the feasibility of implementation, compatibility with normal railroad operations and equipment, convenience of use and freedom from trouble or malfunction, long life and reasonable cost, and, of course, effectiveness in reducing injuries in accident situations. The same criteria served for rejection of other concepts, for example, the complexity of automatically actuated systems, the possibility of inadvertent actuation, the need for frequent maintenance, and the cost were all reasons for rejection. None of the acceptable concepts involves new technology, but materials behavior of the honeycomb proposed for the crushable attenuator may require some significant development and test efforts.

The effectiveness of the concepts in reducing injury is expressed in terms of the estimated savings in lives of the approximately 860 annual fatalities occurring when trains strike highway vehicles. The estimated savings in lives due to use of the deflector depends on the deflector design, and ranges from about 120 for a short coupler cover to about 240 for a longer rounded design. The estimated savings for the soft-faced crushable attenuator were about 390 lives annually. The estimates are not adjusted for the possibility of additional accidents caused by the length of the attenuator. No estimates were made for the addition of rail brakes to MU cars, since the statistics are too sparse and the benefits may occur in accidents other than rail-highway collisions.

The major problem anticipated with both attenuators and deflectors is achievement of relatively uniform and effective designs which are compatible with the varying geometry of locomotive fronts, and with current operating procedures. The construction materials and methods are conventional.

The principal problem of addition of rail brakes to MU cars would be the complexity and cost of an additional system. Such devices are already in use on various urban transit and light rail vehicles , but development is required to adapt them to new cars.

Cost estimates can vary by a factor of three or even more, depending on the specific design characteristics. The estimates shown in the table below reflect middle of the range values for the attenuator and the deflector. Such costs may be partially offset by reduction in damages to rail property occurring in rail-highway collisions. The current annual amount of such damages is more than $10,000,000. No estimate of the potential reduction has been made, but any reduction in derailments could have a significant effect. No costs are shown in the table for rail brakes; in recent years the cost of the rail brakes for a light rail vehicle has been approximately $7,000.

ESTIMATED COSTS - ATTENUATOR AND DEFLECTOR

ITEM	ATTENUATOR		DEFLECTOR	
Initial Costs	Number of Units	Cost (Millions of $)	Number of Units	Cost (Millions of $)
(1) Development, Test, and Evaluation		1.0		1.0
(2) Retrofit, Both Ends of 10,000 Line Haul Locomotives	20,000	60.0	20,000	30.0
Annual Recurring Costs				
(3) Installation on 1,000 new locomotives	2,000	5.0	2,000	2.0
(4) Replacement, units destroyed in accidents	1,800	5.4	900	1.35
(5) Repairs to damaged units	3,200	1.0	2,000	0.5
(6) Operating costs (deployment, Storage, Lubrication)	—	4.5	—	2.5
Total annual cost:		15.9		6.35

Chapter 1 Introduction and Summary

1.1 Background Information

For many years the leading cause of death in railroad operations has been grade crossing accidents. In 1977, of the 1,530 deaths in railroad operations, 944 occurred as a result of the 12,299 such accidents.* These accidents, together with the 390 non-railroad and non-passenger personnel killed by being struck or run over, form 87 percent of all fatalities. The preventive measures of recent years, along with a number of other factors, have succeeded in reducing the grade crossing deaths significantly from earlier years, e.g. from the 1,780 recorded in 1966.** However, they remain the dominant cause, and have received attention from the Federal Railroad Administration (FRA), the National Transportation Safety Board (NTSB), and various other organizations. This is indicated by publications of various personnel describing some of the problems and possible approaches to dealing with them. (1-1), (1-2)

This report presents the results of a study, performed for the FRA, aimed at reducing injuries and fatalities from grade crossing collision. Although earlier studies tend to concentrate only on protecting the motorist, the FRA directed that this study consider measures aimed at protecting rail passengers and crew members as well. The study was to consider certain specific accident situations and certain proposed measures described in this report. Figure 1-1 illustrates some of the situations to be considered.

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* Figures from Accident/Incident Bulletin No. 146, Calendar Year 1977, Federal Railroad Administration.

** Figures from Rail-Highway Grade-Crossing Accidents/Incidents Bulletin, Calendar Year 1976, Federal Railroad Administration.

(1-1) "Crash Safety for Railroad Passengers, Train Crews, and Grade Crossing Crash Victims", Wakeland, Hentry H., SAE Congress, Feb 27-March 3, 1978, Paper 0148-7191/78/0022.

(1-2) "An Array of Social Values for Use in Analyzing The Need for Safety Regulations", Wakeland, Henry H., Fourth Intl. Cong. on Automobile Safety, San Francisco, July 14-16, 1975.

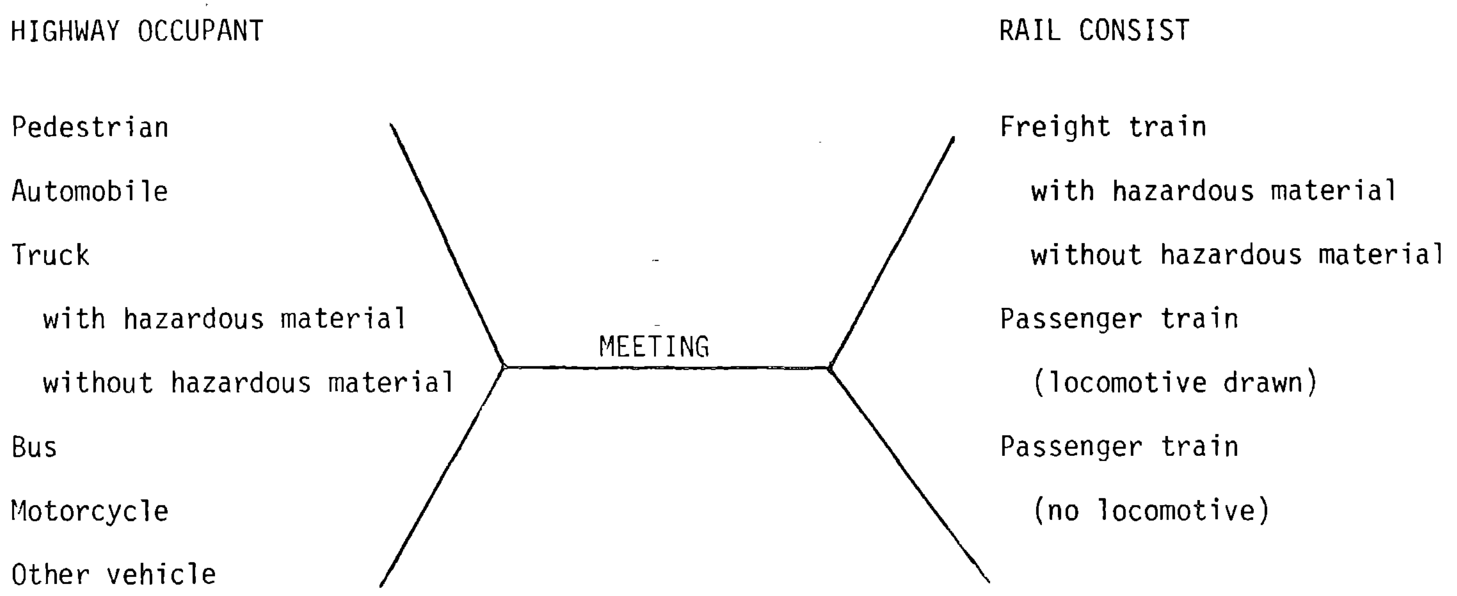


Fig. 1-1 RAIL-HIGHWAY COLLISIONS, POSSIBLE EVENTS

1.2 Organization of Report

Chapter 1 of this report provides introducing information and a brief outline of the study organization. Chapter 2 starts by classifying the possible methods of achieving injury reduction, describes the literature search aimed at identifying possible injury reduction measures, and then provides a list of the possibilities found. Chapter 3 considers first the criteria of judgment to be applied to evaluation of the various injury reduction concepts, and then proceeds to evaluate the effectiveness and acceptability of each of the concepts listed in the preceding chapter. Some of the concepts are rejected. Chapter 4 proceeds to an estimation of the benefits to be derived from some of the acceptable concepts, and Chapter 5 contains a brief estimation of costs of a few of the measures. Chapter 6 contains the conclusions, and chapter 7 the recommendations. Two appendices contain the equations and the program used in the numerical simulations conducted and the numerical results. The final appendix is an analysis of expected accident increases which could occur with certain types of injury reduction systems.

1.3 Study Organization

The statement of work defined the following five tasks to be accomplished in the study:

(1) Review of past work in grade crossing injury minimization and identification of possible concepts.

(2) Review of injury minimization concepts from other fields of transportation and identification of those appropriate to rail-highway grade crossing accidents.

(3) Classification of concepts by type of accident involved and type of personnel protected, and evaluation of effectiveness of each concept.

(4) Estimation of benefits derived from each concept, including certain specified individual accident situations.

(5) Estimation of costs of development and implementation of each concept, and of potential benefits of lives saved and injuries prevented or or reduced.

2. Collection of Injury Reduction Concepts

2.1 Classification of Concepts by Type

Logical classification of injury reduction concepts starts with the nature of the injuries themselves, which generally involve mechanical injury, fire, asphyxiation, or chemical toxicity. Mechanical injury occurs when the human body meets another object at a force level sufficient to damage the tissue; the sharper the object and the smaller the contact surface, the less the force required to produce injury. For occupants of moving vehicles, such injury is frequently labelled as due to primary or to secondary impact, depending on whether it occurs at the time of the initial collision, or after a period of "free flight" during which the motion of the occupant is substantially independent of the motion of the vehicle.

Reduction of accident injuries by appropriate design of the vehicle or its environment is the goal of crashworthiness, a topic which has been the subject of effort in all fields of transportation. Structural crashworthiness addresses mechanical injury from primary or secondary impact; fire crashworthiness is concerned with fire and its potential results of asphyxia or poisoning,with escape from vehicles after accidents, and with fire-fighting measures.

Injury reduction concepts are usually directed at specific occurrences which produce injury; consequently the nature of the injury provides a convenient means of classification of concepts, which will be used in succeeding sections where concepts are listed. In certain cases the concepts may be identical or closely related to those applying to other types of accidents; in other cases the concept may apply only to rail-highway collisions.

Classification is also possible according to the group of victims protected; for example, measures which protect highway vehicle occupants in a collision need not offer protection to the rail vehicle occupants, and conversely. Crashworthy design of passenger trains is concerned with the occupants of the train, and while it may protect them during a rail-highway collisions as well as during a train-to-train collision, it will generally do nothing for the highway vehicle occupants. Fire crashworthiness for rail vehicles may also have a special connotation for rail-highway collisions, where the danger of fire, asphyxiation, or toxic material release is generally related to the presence of a hazardous cargo on the train or the highway vehicle.

2.2 Concept Search

Task 1 of the contract statement of work requires a review of past work on grade crossing injury minimization, and Task 2 requires review of work in other fields of transportation, such as automotive or aerospace, which may be applicable to grade crossing collisions. The results of these reviews are then to be included in a list of all potentially applicable concepts. This section discusses briefly the material surveyed and summarizes the results. Reference lists are included in tables in the text of this section when they involve bibliographies; otherwise, references appear in Appendix A. The section concludes with a tabulation of concepts suitable for injury minimization which were identified in the study.

2.2.1 Railroad Sources

The statement of work lists several possible approaches to injury minimization and specifies certain accident situations which must be considered. The major injury reduction approaches involve reducing highway vehicle accelerations in collisions, i.e., collision attenuation, and providing structural and fire protection to rail vehicle occupants, i.e., crashworthiness. Not all of the work done in these areas has resulted in publications. FRA provided references to its principal efforts in these areas, including the locomotive-automobile crash tests conducted at the Transportation Test Center in 1974. (2-1) A workshop on crashworthiness sponsored by the Urban Mass Transportation Administration (UMTA) in 1978 will result in a publication which should appear at about the time of completion of work on the present study. (2-2)

(2-1) Locomotive to Automobile Baseline Crash Tests, Report No. FRA-OR&D-76-03, R.L. Anderson, Dynamic Science Division of Ultrasystems, Aug. 1975

(2-2) Proceedings of the Urban Rail Vehicle Crashworthiness Workshop, April 1978, Report DOT-TSC-UMTA-79-34, to appear November 1979

The principal sources used for the survey were the Railroad Information Service (RRIS) bibliographies and abstracts, National Technical Information Service (NTIS), and various domestic and international railroad journals. A number of safety recommendations from the National Transportation Safety Board (NTSB) also referred to the grade crossing accident area. Although the crashworthiness literature available includes many specific techniques for protection of personnel in crew and passenger compartments, in general the literature seemed to be almost totally devoid of concepts for collision attenuation beyond those already suggested by FRA. As anticipated, grade crossing accident literature dealt almost exlusively with prevention. However, one paper (2-3) suggested broader application of electromagnetic rail brakes for emergency use on rail passenger cars as a means of reducing crash severity or completely avoiding some collisions.

Table 2-1 lists the major pertinent RRIS publications, all of which were reviewed for appropriate references. These publications are listed in a table rather than cited in the appendix of references, since they consist of bibliographies and abstracts, i.e., indexes to the subject material rather than subject matter itself. The Railroad Research Bulletin list and very briefly describe United States and Canadian research programs, as well as publications. Unfortunately, no new leads were derived from this source, since the cited programs were in general already known to the investigators from other sources, such as publications.

Table 2-1 also lists major pertinent NTIS bibliographies from the transportation field; review of this material indicated that in general it had already been included in the RRIS indexes. Computer searches of some of the automated files, such as NTIS (1964-1978), Engineering Index (Compendex, 1970-1978), SSIE Current Research (1975-1978), Predicasts' PROMT (1972-1978), and ABI/INFORM (1971-1978) revealed no new material. Consequently no further computer searches were conducted in this area.

(2-3) "American Railcars - A Study in Safety", Prosser, R.S., Rail International, Vol. 5, No. 2, Feb. 1974, 143-153

TABLE 2-1

List of RRIS and NTIS Bibliographies

1. Special Bibliography: Safety-Related Technology, RRIS, Publication No. 73 S1, March 1973

2. Special Bibliography: Railroad Safety Research, RRIS, Report FRA OR8D 76-280, October 1976

3. Railroad Research Bulletin, RRIS

No. 7601 - Spring 1976	No. 7602 - Fall 1976
No. 7701 - Spring 1977	No. 7702 - Fall 1977
No. 7801 - Spring 1978	No. 7802 - Fall 1978
No. 7901 - Spring 1979	

4. NTIS Annual Index, Transportation

1976 - NTISUB/B/085-76/052
1977 - NTISUB/C/085-052
1978 - NTISUB/D/085-053

5. NTIS Weekly Index, Transportation, 1979, NTISUB/E/085-001 to 035 inclusive

Table 2-2 presents a list of railroad periodicals which were reviewed individually, and a separate list which were not reviewed individually because they had been covered in one of the bibliographies listed in Table 2-1, or by the Engineering Index which had been covered by a computer search. Table 2-3 presents a list of journals, primarily foreign, which were not reviewed, and which were not necessarily included in the bibliographies of Table 2-1, nor in the computer files which had been searched. However, a large part of the content of these journals had presumably been covered by RRIS, especially in its first safety survey (item 1 of Table 2-1), which included a very large percentage of foreign publications. The later RRIS bibliography also included a significant amount of foreign material. Reference 2-3, the railcar safety study, was located in this process.

References 2-4, 2-5, and 2-6 are reports on three of the crashworthiness studies sponsored by FRA and UMTA. Since the primary concerns are train-to-train collisions and derailments, rather than grade crossing collisions or hazardous material accidents, the studies emphasize primary and secondary collision injury considerations. Reference 2-7 reports on a more general study. Naturally, measures to reduce collision injuries to personnel in the rail vehicles during the more serious accelerations encountered in train-to-train collisions will be effective in the less violent accelerations generally prevailing in rail highway grade crossing collisions.

(2-4) Rail Safety/Equipment Crashworthiness (4 volumes), Reilly, MH, Jines RH, Tanner, AE (Boeing Vertol Co.), Report FRA/ORD-77/73, July 1978

(2-5) An Assessment of the Crashworthiness of Existing Urban Rail Vehicles, (3 volumes) Cassidy, R.J., Romeo, D.J. (Calspan Corp.), Report UMTA-MA-06-0075-16, Jan 1977

(2-6) Crashworthiness Analysis of the UMTA State-of-the-Art Cars, Widmayer E, Tanner, AE, Klump R. (Boeing Vertol Co.), Report UMTA-MA-06-0025-7515, Oct 1975

(2-7) Human Factors and Hardware Design Considerations for Passenger Protection in High Speed Crashes", Wilkins, L.O., Hullender, D.A., High Speed Ground Transportation Journal, Vol. 9 No. 1, 1975, 425-433

TABLE 2-2

Railway Periodicals Reviewed

Direct Review

- High Speed Ground Transportation Journal (1970-1979)
- International Railway Congress Association Monthly Bulletin (to 1970, replaced by Rail International)
- International Railway Journal (1975 -) (U.K.)
- Japanese Railway Engineering
- Progressive Railroading (1960 -)
- Rail International (1971 -)
- Railway Age (1970 -)
- Railway Engineer (1976 -) (U.K.)
- Railway Division Journal (to 1971, replaced by Railway Engineering Journal) (U.K.)
- Railway Engineering Journal (1972-1976, replaced by Railway Engineer) (U.K.)
- Railway Gazette (1970 -) (U.K.)
- Railway Locomotive and Cars (1971 -)

Covered by RRIS, Engineering Index, or NTIS Bibliographies

- ASCE Transportation Engineering Journal
- AREA Bulletin
- Modern Railroads - Rail Transit
- Railway Technical Research Institute, Quarterly Reports (Japan)

TABLE 2-3

Railway Periodicals Not Reviewed Individually

DET Eisenbahntechnik (German Dem. Rep.)

Eisenbahningenieur (Fed. Rep. of Germany)

Eisenbahntechnische Rundschau (German Fed. Rep.)

Elektrische Bahnen (Switz)

French Rail News (Fr.)

French Railway Technology (Fr.)

Glasers Annalen ZEV (German Fed. Rep.)

Ingegneria Ferroviaria (It)

Institution of Locomotive Engineers Journal (U.K.)

International Railway Documentation (U.K.)

Revue Generale des Chemins de Fer (Fr.)

Vestnik Vniizt (USSR)

Reference 2-8 reports on a fire hazard study of an urban transit railcar, and references 2-9 to 2-11 also refer to fire hazard studies.

2.2.2 Other Transportation Industry Sources

The principal non-railroad areas in which appropriate concepts can be anticipated to exist are the automobile and aerospace fields. Much recent work in automobile collision attenuation, structural crashworthiness, and personnel restraint has contributed both published material and systems in actual use, often with sponsorship by the Federal Highway Administration (FHWA) or the National Highway Traffic Safety Administration (NHTSA). Impact attenuation features are provided by both the automobile bumper and by various devices designed to reduce the effects of collisions of automobiles with highway abutments, pillars, etc.

A variety of impact attenuation systems were tested for FHWA by the Texas Transportation Institute(2-12), and some of the mechanisms appeared to be applicable to the rail-highway collision situation, and had been the subject of significant study and test, as described in references (2-13) to (2-16.) (See footnotes on next page).

(2-8) A Fire Hazard Evaluation of the Interior of WMATA Metrorial Cars, Braun, E., (Natl. Bur. of Stds), Report NBSIR-75-971, Dec. 1975 (NBS-4927371, NTIS PB-249776/6 ST, DOTL)

(2-9) Transit Flammability Requirements, Schafran E., (Transit Development Corp.), Report TDC/500-74/3, June 1974 (NTIS PB-241851/5ST, DOTL)

(2-10) Safety Priorities in Rail Rapid Transit, Connell, W.M. (Transit Development Corp.), Report UMTA-DC-06-0091-75-1, March 1975 (NTIS PB-242953, DOTL)

(2-11) "Fire Experiments of Coach", Oikawa, I., Railway Technical Research Institute, Quarterly Report, Vol. 15, No. 3, Sept 1974, 131-132.

(2-12) Test and Evaluation of Vehicle Arresting, Energy Absorbing, and Impact Attenuation Systems, Texas Transportation Institute, November 1971. (Final Report on FHWA Contract No. CPR-11-5851)

Searches of aerospace literature revealed no collision attenuation methods suited for rail application which had not already appeared in the ground transportation literature. The extensive work on aircraft windshield safety was also reflected in the ground transportation literature, inparticular the rail literature.

Thus the appropriate concepts derived from these fields came exclusively from the automobile and highway safety sources.

2.3 Concept List

The potentially applicable concepts identified in the search process are listed in this section, grouped into the following four categories:

(1) Collision attenuation - reduction of impact forces between rail vehicle and highway vehicles, and removal of object struck by rail vehicle from the rail right of way.

(2) Structural crashworthiness - rail personnel compartment design measures to reduce injury from primary and secondary collision, flying objects, and derailments.

(3) Fire crashworthiness - rail personnel compartment design measures to reduce hazard from fire and toxic materials

(4) Individual protective clothing and equipment.

(2-13) Development of a Hydraulic-Plastic Barrier for Impact Energy Absorption, Warner, C.Y. and Free, J.C. Brigham Young Univ., April 1970 (Final Report on FHWA Contract No. FH-11-6909)

(2-14) "Vehicle Impact Attenuation by Modular Crash Cushion," Texas Transportation Inst. Research Report No. 146-1, June 1969

(2-15) A Reusable Energy Absorbing Highway Protective System for Median Areas, Aerospace Research Associates Inc., Report No. 96, June 1968

(2-16) TOR-Shok Energy Absorbing Protective Barrier, Texas Transp. Inst., Technical Memo 505-2, July 1968

The first of these four categories is the only one which applies exclusively to rail-highway collisions; a system which reduces forces between a train and a highway vehicle may have very little or no effect on a train-to-train collision. The benefits of crashworthy design apply more to derailments or train-to-train collisions than to rail-highway collisions which usually involve lower levels of acceleration. An exception is the case of collision of a rail vehicle with a hazardous materials truck, where fire crashworthiness becomes extremely important.

2.3.1 Concepts for Rail Highway Collision Attenuation

The concepts all involve modifications of the front end of the locomotive or railcar to achieve the desired result, except for one concept involving improved braking for passenger cars. In most cases, the modication involves addition of some energy-absorbing structure which reduces force levels between the vehicles, in which case the structure may be permanently mounted in place or mounted with degrees of freedom which permit it to be deployed into position of use. For "passive" systems, the deployment occurs before use of the rail vehicle, and during use the structure is always in functional position. For "active" systems, deployment occurs immediately before collision. Several passive attenuation mechanisms were studied and tested by FHWA as means of reducing automobile injuries in collisions with massive stationary objects (references 2-12 to 2-16). These mechanisms constitute the only concepts identified which were not already suggested by FRA or by rail literature.

Table 2-4 lists the passive systems, table 2-5 the active systems. Some of the individual concepts are capable of being combined with others; for example, various crushable or rigid attenuator structures may be mounted to a locomotive through a hydraulic piston damper. The inclusion of a concept does not automatically imply its acceptability and effectiveness; it implies only that the concept has been suggested and is therefore being considered. Many of the concepts will indeed be excluded as unacceptable or ineffective in the analysis.

Table 2-4

Passive Collision Attenuation Systems
(No action required upon collision)

1. Flat front locomotive with coupler covered by blunt protrusion or recessed by folding (deflector).

2. Rigid deflector covering coupler, designed to remove encountered objects from the right of way. High yield level.

3. Crushable attenuator structure with low yield point, covering coupler. Structure may consist of any of the following:

    i Honeycomb
    ii Plastic foam
    iii Light weight cellular concrete

4. Composite attenuator structure of cylindrical steel structural elements interconnected by panels, cables, welding, etc. to provide desired collision properties. Individual elements may range in size from diameters of a few inches to the size of 55 gallon drums.

5. Hydraulic Cushion- composite of multiple polyvinyl chloride cylindrical cells containing inert liquid which is expelled under load. Cylinders connected by cables and reinforced by structural panels or diaphragms.

6. Toroidal shock cushion of cylindrical steel tubing supported by energy - absorbing steel structural elements.

7. Hydraulic piston or dashpot similar to hydraulic buffer arrangements.

8. Pneumatic pressurized gas bag system.

Table 2-5

Potential Active Collision Attenuation Systems
(Actuation required immediately before collision)

1. Pneumatic gas-bag system deployed immediately before collision.

2. Water-jet system energized immediately before impact; high speed spray of water used to reduce relative velocity at collision, and to remove highway vehicle from right of way.

3. Spray of slippery liquid before impact to reduce coefficient of friction between highway vehicle and grade crossing surface to help remove highway vehicle from right of way more rapidly.

4. Electromagnetic rail brakes for emergency use on all passenger cars.

Table 2-6 presents both structural and fire crashworthiness concepts in the form of design principles or functional requirements, rather than as specific design concepts. This table is partially drawn from a crashworthiness study performed by FRA by Boeing-Vertol (2-4), and is presented in the form of principles rather than specific mechanisms because most of the specific design measures relate more to train-to-train collisions than to rail-highway collisions. Specific measures which are appropriate to rail-highway collisions, such as sealing of locomotive cabs against entry burning fuel in a collision with a fuel truck, are discussed in more detail than the less important factors such as secondary collision.

The final group of concepts for individual protective clothing and equipment, applies only to train crews. The list is brief, and the equipment is essentially similar to fire-fighting protective gear. The list is brief, and the equipment is essentially similar to fire-fighting protective gear. The list follows:

(1) Fire protective clothing for locomotive crew, either as regular wear or for emergency use

(2) Emergency breathing apparatus for locomotive and caboose crews

(3) Clothing and helmets for impact protection against flying objects, sharp surfaces, etc.

TABLE 2-6 DESIGN PRINCIPLES FOR CRASHWORTHINESS

PRIMARY IMPACT PROTECTION	SECONDARY IMPACT PROTECTION	POST CRASH PROTECTION AND ESCAPE
. Keep areas subject to collapse unoccupied; avoid structural collapse or vehicle ingress in occupied areas	. Design geometry to minimize force and trajectory distances and reduce probability of dangerous impact	. Emergency exit design-structural integrity to prevent jamming; location and access to permit rapid egress with vehicle in any position
. Design seats to restrain occupants without injury (whiplash, leg entrapment, etc.)	. Surface passivation of areas potentially struck by occupants to reduce g loads; elimination of protrusions, etc.	. Interior design to facilitate rapid removal of injured
		. Emergency lighting
. Seal front surface structures against massive entry of combustible or toxic liquids (glazing and door design)	. Retention or restraint of personnel, cargo, baggage, interior equipment and fittings (including seat anchoring)	. Availability and accessibility of emergency and fire-fighting equipment
		. Materials selection to reduce post-crash fire, smoke, and toxic fumes generation

3. Concept Applicability and Effectiveness

This section is concerned with analysis of the various injury reduction concepts listed in section 2.3, first to determine the type of occurrences in which a particular concept is useful, and then to determine how effective the concept is. Applicability of various groups of concepts is discussed first, followed by evolution of some criteria for judging effectiveness, and finally by analysis of individual concepts. When concepts are judged unsuitable for use, several concepts may be grouped together in one subsection for discussion of the reasons for elimination.

For certain collision attenuation devices, numerical simulations of collisions were conducted. In these cases, results and conclusions are discussed in this section, and details of the simulation are presented in Appendix A and Appendix B.

3.1 Concept Applicability

Performance of an injury reduction concept depends on the relationship of the protective measure to the group of people protected, to the people's location at the time of the accident, and to the events which occur during and after the collision. Those relationships suggest grouping people, vehicles, protective measures, and events according to the nature of what happens in rail-highway collisions. The consideration of each case also involves the frequency of occurrence of the event, and the severity of the consequences. For example, consideration of train-motorcycle collisions has already been eliminated on the basis of infrequency of occurrence and low number of fatalities in cases where injury reduction is possible.

The concepts for injury reduction can be tabulated in a slightly different version from the list of Sec. 2.3, as follows:

1. Collision attenuation (front of train)
2. Derailment prevention (front of train)
3. Structural crashworthiness
4. Fire crashworthiness
5. On-board fire fighting equipment
6. Individual protective gear
7. Improved emergency braking for passenger cars

The first two items on the list are functions potentially performed by a device or system at the front of the train which may serve both goals. However, the collision attenuation function attempts in general to protect the highway vehicle occupant, since in most collisions with automobiles, buses, and light trucks (at least), the occupants of the train are quite safe. The prevention of derailment attempts to protect train occupants and bystanders who might be injured by a derailment. The remaining items on the list also refer to measures designed to protect train occupants.

The victim groups can be categorized by location:

V1 Pedestrians and highway vehicle occupants
V2 Locomotive occupants
V3 Passenger railcar occupants
V4 Caboose occupants
V5 Bystanders

Thus the collision attenuator concept attempts primarily to protect the group of highway occupants, since in a collision with an automobile, train occupants are rarely at risk. Derailment prevention aims at protecting all the other groups. Relationships may be complex; for example collision attenuation could serve to protect railcar occupants in a collision with a heavy highway vehicle.

This introduces the subject of vehicle characteristics, and suggests some revision of the list of highway occupants which appears in Figure 1-1, to reflect differences in behavior in an accident. A revised list follows:

H1 Passenger automobile and light truck or van
H2 Bus
H3 Heavy truck, no hazardous cargo
H4 Truck with hazardous chemical cargo
H5 Truck with mechanically hazardous cargo

Combining light trucks with passenger automobiles is logical because both the hazard for the occupants and the potential for causing derailments are similar. Buses are grouped separately because of the concern for the passengers at risk. Separation of trucks with hazardous cargo reflects the risk for train occupants posed by such cargo.

The list of rail consists which appears in Figure 1-1 already reflects the possible differences in behavior during a collision, distinguishing the presence of passengers or of hazardous cargo, and the presence or absence of a locomotive which protects rail passenger cars in a collision.

In the event of a collision, the hazards depend on the ensuing events, notably whether or not a derailment occurs, and whether or not hazardous material is released from either the train or the highway vehicle.

The importance of various types of protection depends on the statistical incidence of the hazardous events involved and on the number of endangered persons. Figures 3-1 to 3-7 inclusive show the potential applicability of different injury reduction concepts to various events and victim groups. In general, cases of negligible statistical occurrence are omitted, except where very severe consequences ensue, such as occurs when a passenger car is filled with burning fuel from a truck. These figures summarize, in very brief form, the cases or circumstances when injury reduction concepts can apply.

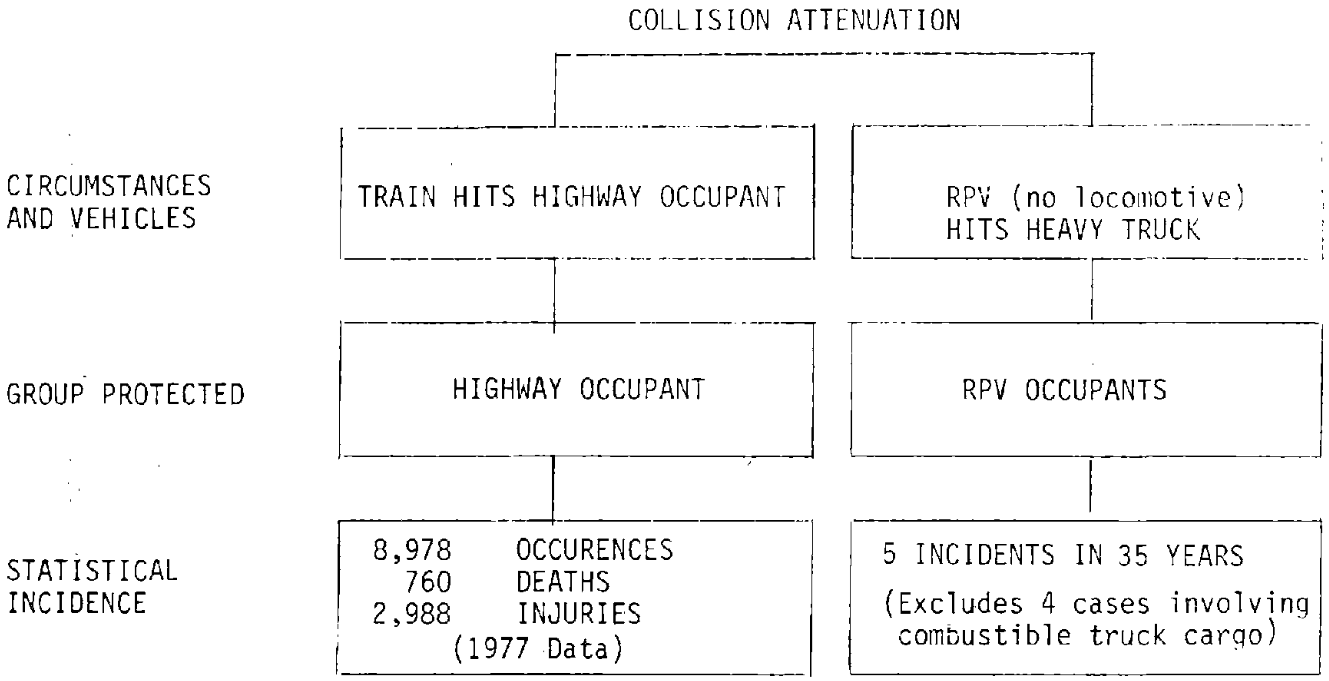


FIG. 3-1 APPLICABILITY OF COLLISION ATTENUATORS AT FRONT OF TRAIN

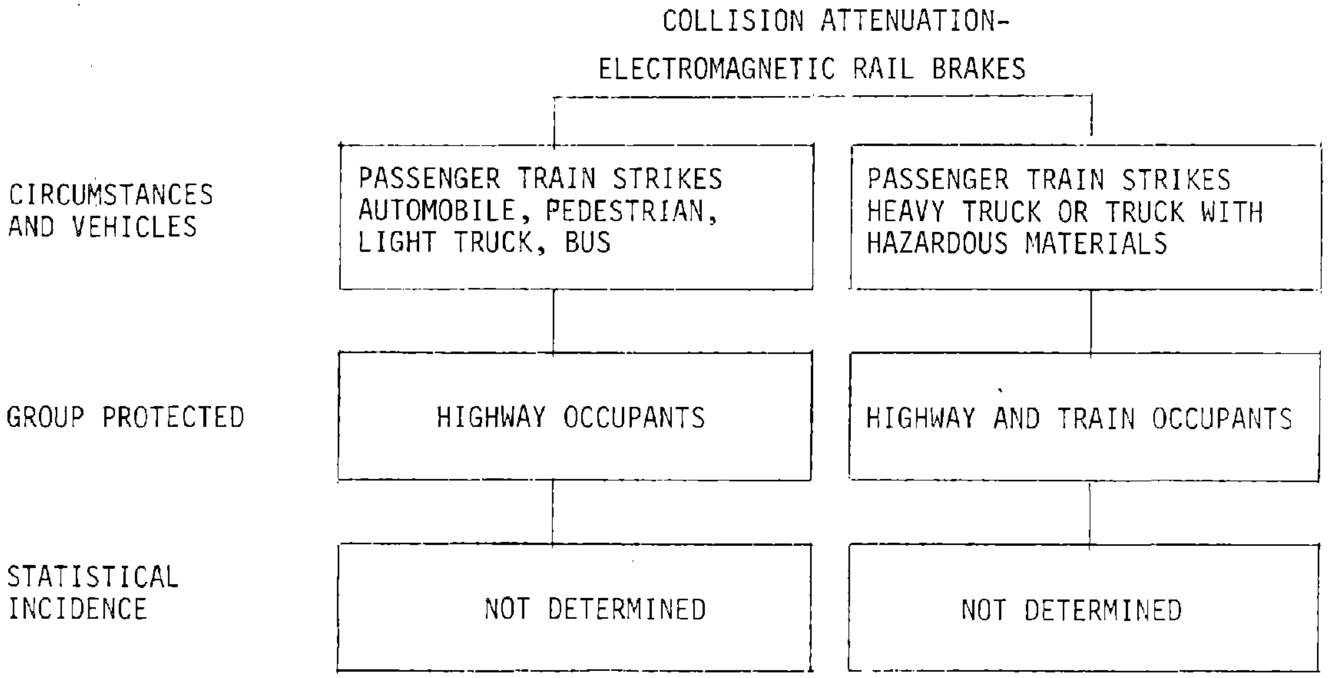


FIG. 3-2 APPLICABILITY OF RAIL BRAKES FOR PASSENGER CARS

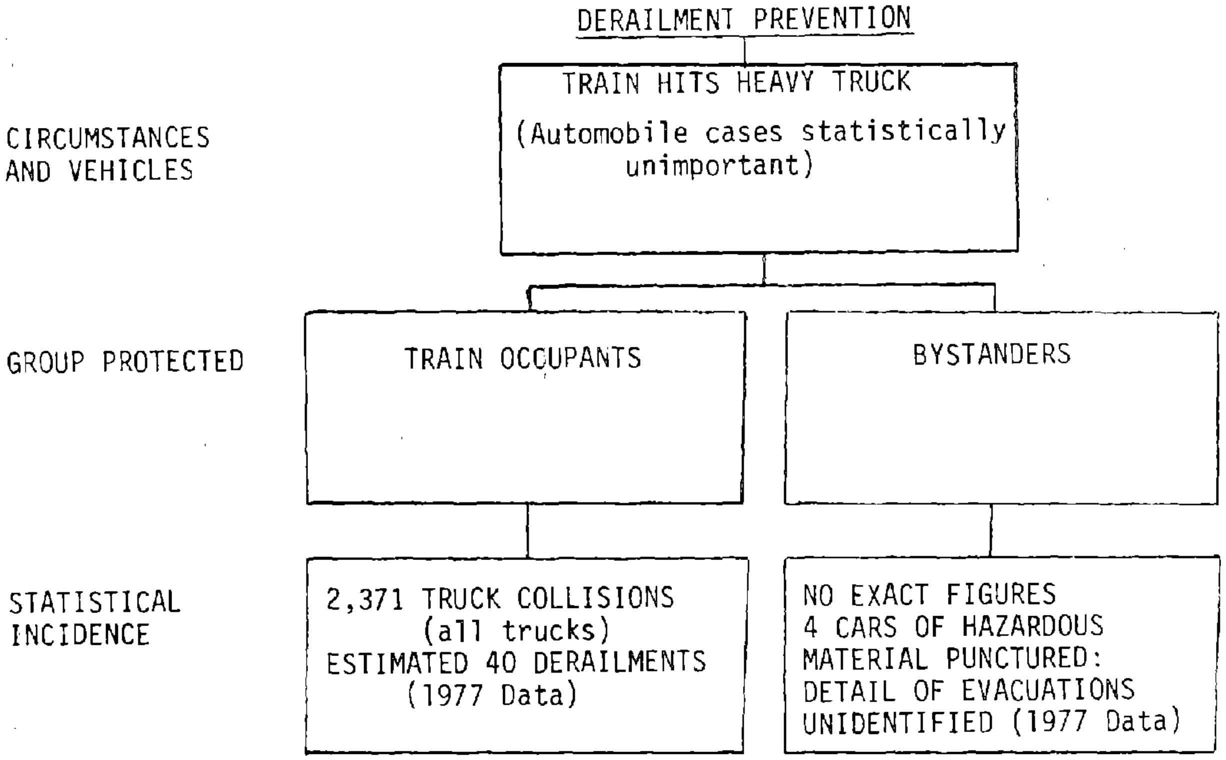


FIG. 3-3 APPLICABILITY OF DERAILMENT PREVENTION DEVICE

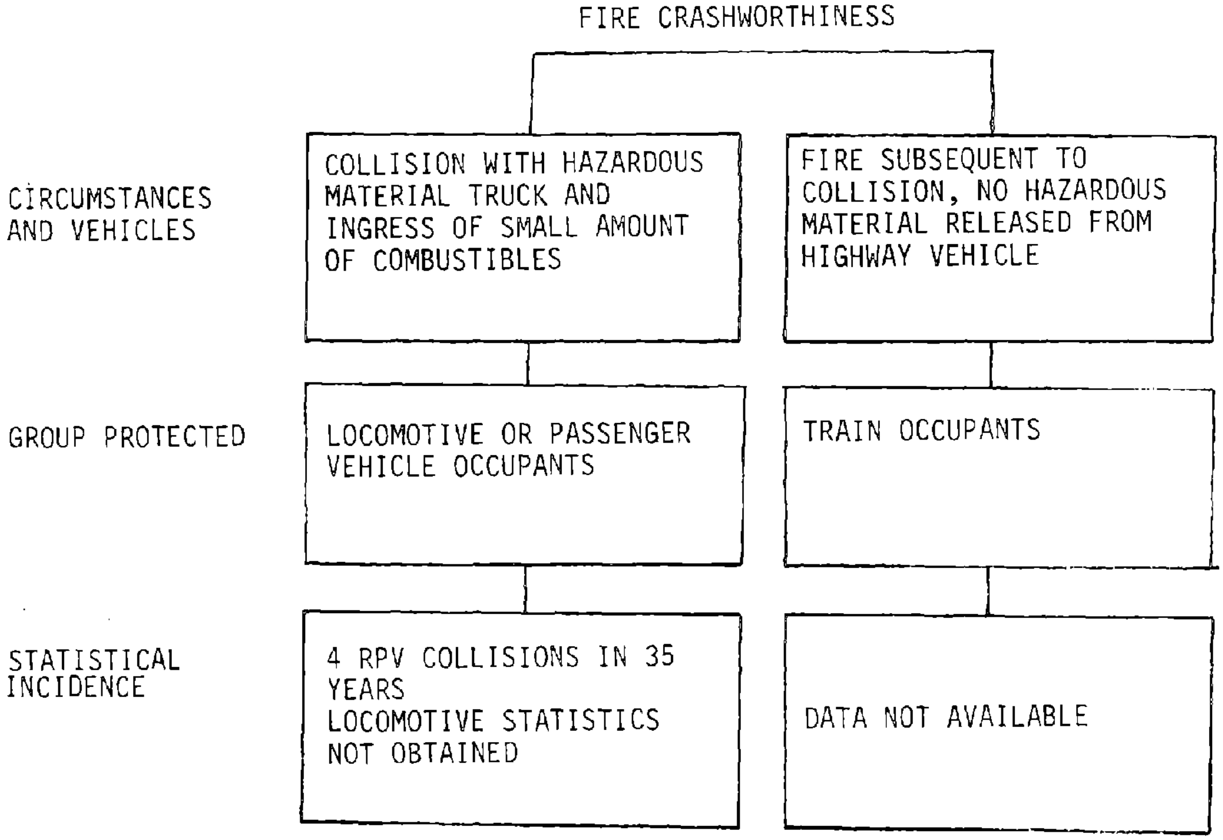


FIG. 3-4 APPLICABILITY OF FIRE CRASHWORTHINESS

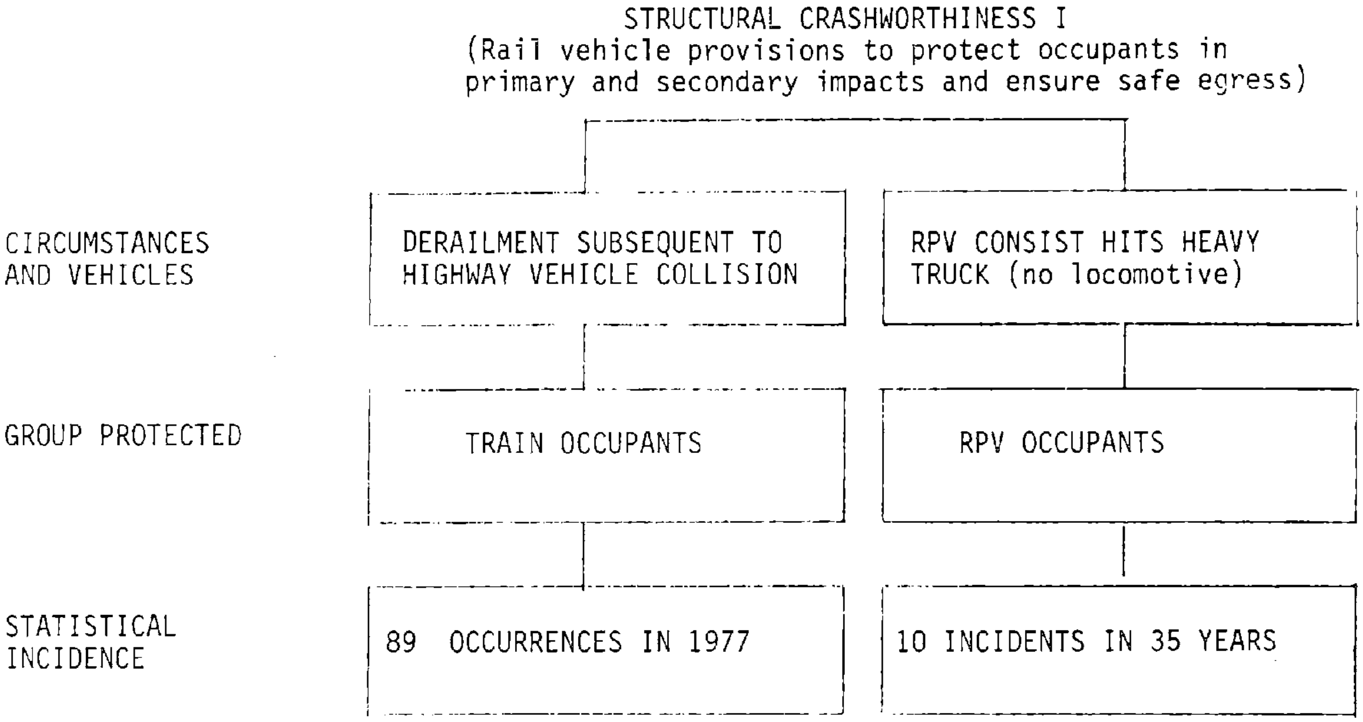


FIG. 3-5 APPLICABILITY OF STRUCTURAL CRASHWORTHINESS (I)

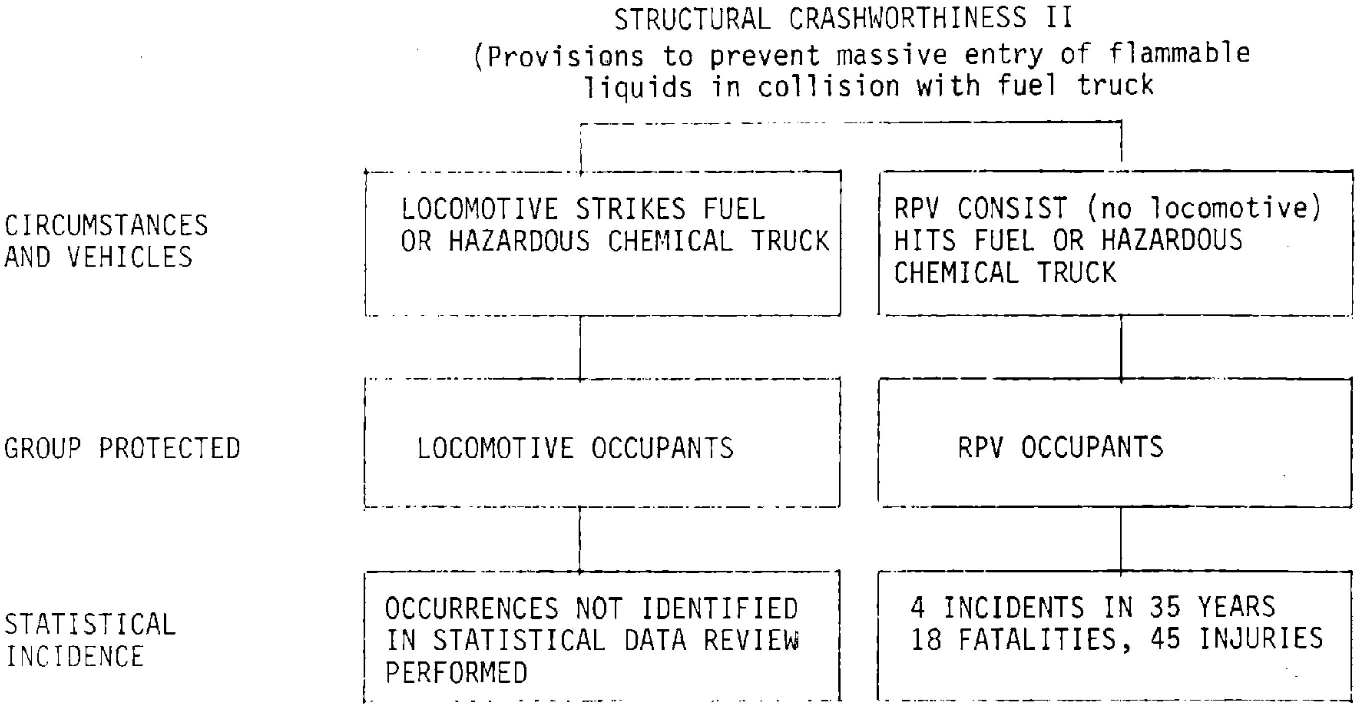
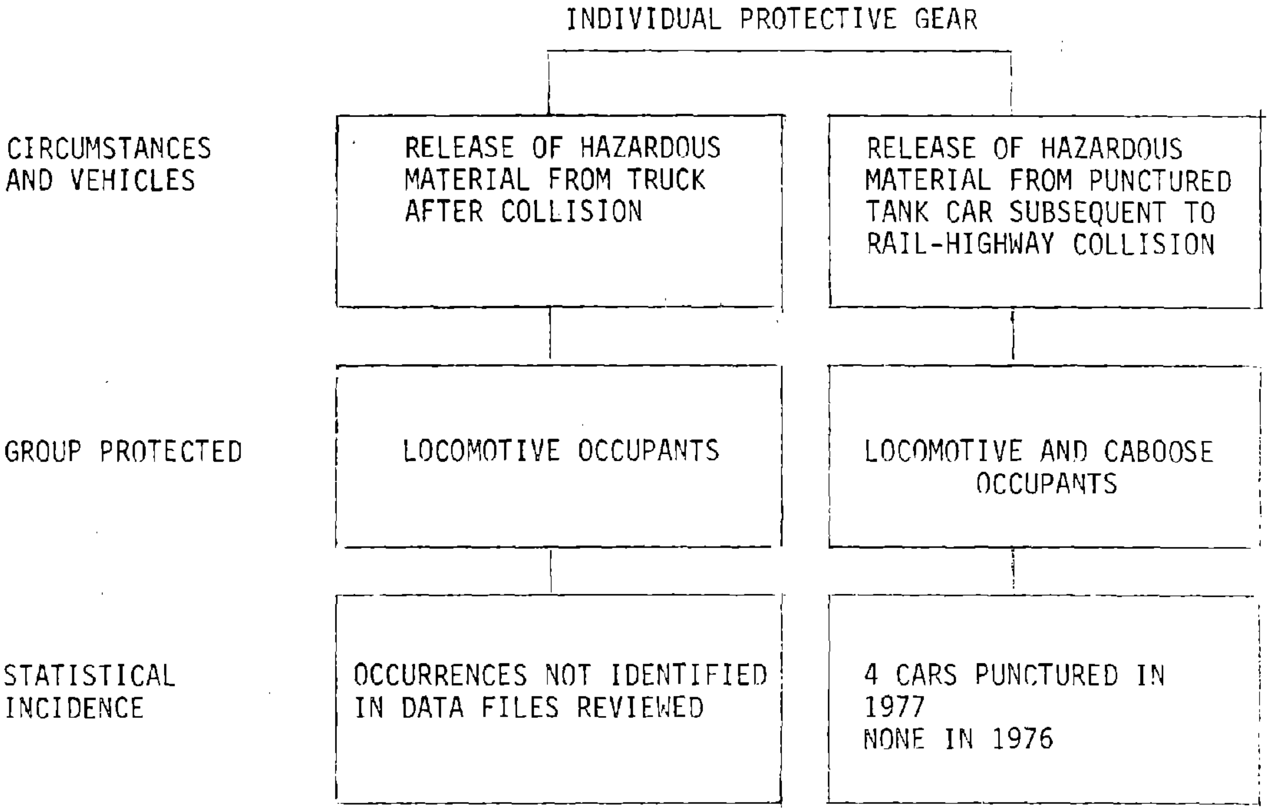


FIG. 3-6 APPLICABILITY OF STRUCTURAL CRASHWORTHINESS (II)



INDIVIDUAL PROTECTIVE GEAR		
CIRCUMSTANCES AND VEHICLES	RELEASE OF HAZARDOUS MATERIAL FROM TRUCK AFTER COLLISION	RELEASE OF HAZARDOUS MATERIAL FROM PUNCTURED TANK CAR SUBSEQUENT TO RAIL-HIGHWAY COLLISION
GROUP PROTECTED	LOCOMOTIVE OCCUPANTS	LOCOMOTIVE AND CABOOSE OCCUPANTS
STATISTICAL INCIDENCE	OCCURRENCES NOT IDENTIFIED IN DATA FILES REVIEWED	4 CARS PUNCTURED IN 1977 NONE IN 1976

FIG. 3-7 APPLICABILITY OF INDIVIDUAL PROTECTIVE GEAR

3.2 Evaluation Criteria

To evaluate and to establish requirements for injury reduction measures, one must review several aspects of the acquisition and the operation of the system. These can be summarized as follows:

- Performance in emergency situations (including conditions other than those for which the systems was intended)
- Performance in and effects on normal operations
- Economic and logistical effects (acquisition and operation costs, facility requirements, materials availability)
- Indirect effects (personnel, environmental, marketing, legal, etc.)

Since these considerations may depend on the intended function, separate analysis of some groups of measures may be necessary.

Consider first the crashworthiness measures. With one exception, none of the events against which these measures offer protection differs in a rail-highway collision from the occurrences in any other derailment or crash. The exception is structural design aimed at preventing entry into the rail vehicle of large amounts of flammable or toxic liquids during a collision with a fuel or hazardous material truck (see fig. 3-6). For all the other cases, the work already performed for FRA and UMTA (references 2-2, 2-4, 2-5, 2-6, and 3-1*) has produced a set of criteria and of design measures which apply to the rail-highway collision events without change. (See table 3-1) This work need not be duplicated, and the design measures of these studies are therefore implicitly included as part of the concepts listed under crashworthiness, with no change and with no need for further evaluation. The statistical surveys in reference 3-1 also indicate that the incidence of appropriate rail-highway collisions and their casualty importance are significantly below those of train-train events and derailments.

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*3-1 A Structural Survey of Classes of Vehicles for Crashworthiness", Report No. FRA/ORD-79-13, Widmayer, E., Boeing Vertol Co., Sept 1979.

TABLE 3-1*

DESIGN CRITERIA FOR RAIL VEHICLE CRASHWORTHINESS

1. Restrain seated rail vehicle occupants from being thrown forward into an unyielding or hazardous surface.
2. Minimize the distance an unrestrained occupant can travel from their seated position to a non hazardous surface or object in front of them.
3. Assure that the object impacted in front of an unrestrained seated position presents a smooth surface free of protrusions and is sufficiently deformable or padded to absorb the impact energy, to reduce the forces below the injury threshold.
4. Provide sufficient seat beack surface and strength to support the upper torso and head to prevent back and neck injury (whip-lash) due to rearward accelerations.
5. Eliminate the capability for passenger seats to be rotated to a face-to-face position or to become unlocked during a collision. (Seat rotation should be limited to train personnel using a special tool or key.)
6. Eliminate the capability for seated occupants' legs to become wedged under a seat or equipment in front of them.
7. Eliminate or minimize hazardous furnishings such as window shades, unpadded or nonyielding sunvisors, flammable materials or materials which give off toxic fumes.
8. Equipment which is irregularly shaped or has a high temperature and which can be struck by standing rail vehicle occupants should be covered with shrouds, shields or flush panels.
9. Remove small irregularly surfaced objects mounted on bulkheads and stow in flush surface compartments.
10. Eliminate protective railings, grab rails and stanchions and replace with recessed hand grabs in flush panels.
11. Flush or recess all knobs, handles, latches, lighting fixtures etc.
12. Secure all portable and fixed equipment to withstand collision forces without tearing loose.
13. Provide closed compartments for passenger luggage.
14. Pad or design for deformation all surfaces subject to impact by rail vehicle occupants.

*Extracted from reference 2-4.

On-board fire fighting equipment is concerned primarily with fires which may occur in derailments due to arbitrary causes, or in train-train collisions. Thus similar remarks apply to requirements and criteria for this purpose, i.e. there is nothing special in the rail-highway collision. For individual protective gear in cabooses, the same comments apply; however, individual protective gear for locomotive occupants tends to be a measure aimed particularly at collisions with hazardous material trucks.

Thus the list requiring study is reduced to the collision attenuation and derailment prevention measures, and the protective measures for collisions with hazardous materials trucks. For this more restricted group, a set of criteria may be stated. The topics of primary and secondary impact for train occupants are no longer involved; in fact with the exception of protection in collision with hazardous materials trucks, all of the considerations of Table 2-6 have been covered.

The possibility of establishing numerical evaluation criteria was considered, but rejected on the basis of the diversity of the measures and the difficulty of establishing valid criteria for a study of limited scope. No numerical criteria were found in the earlier studies, such as the collision attenuation study by Minicars Inc. done for FRA, the FRA crashworthiness studies (2-4, 3-1), the UMTA crashworthiness studies (2-5, 2-6), and the FHWA impact attenuation study (2-12). Therefore the criteria remain qualitative, and follow the functional and logical outline set forth above.

1. Emergency situation performance.

Criteria for behavior in collisions and derailments involve physical behavior of the system in these situations, and thus may depend on the function the system is designed to perform. The goal in all cases is reduction of injury severity and fatality rates, but the measures may be aimed at protecting different groups in vehicles of different sizes.

A brief restatement of goals is desirable here. The purposes of improved braking and of structural design of the rail vehicle front to prevent entry of burning fuel in collisions with tank trucks are obvious. For collision attenuation and for derailment prevention, rapid removal of the highway vehicle from the right of way, as gently as possible, and the avoidance of entrapment of the highway vehicle between train and roadbed, are the goals. In collision attenuation, reduction of forces between train and highway vehicle, and between highway vehicle and its environment, are the means of injury reduction.

For each of the primary goals, the purpose must be served as effectively as possible in the occurrence of the primary event for which protection is intended. An additional criterion is that injury severity should not be increased by the measure in other collision or derailment events. Thus a collision attenuator designed to protect automobile occupants should not increase risk for bus or truck occupants, nor increase risk for train occupants in a train-to-train collision, e.g., by interfering with the functioning of other safety of protective systems, such as anti-climbing devices. In summary, there must be functional compatability with other safety measures and other accident situations, as well as effective performance in one particular situation. Finally, in the event of a minor collision involving either no injury or minor injuries, any damage to the collision attenuator or derailment prevention device alone should not prevent continued operation of the consist.

2. Performance in normal operations.

For each system, there are three aspects of normal operations to consider: safety, compatibility, and reliability.

For safety, the system should not increase the chances of an accident or injury of any type in normal operations, nor, for deployable devices or devices which require some preparatory operations, should these operations be hazardous. The possible malfunctions of the system should not lead to hazards in normal consist preparation or operation.

Compatability with other elements of the railroad system implies that the measures require no changes to the right-of-way or track, that any changes to normal operations be minimal in extent and simple in nature, and that they impose no inconveniences to the execution of normal operations and normal schedules. This requirement is particularly important for systems requiring either test or deployment before use in a consist.

Reliability of a system in use implies long life and low maintenance, with little mechanical or structural deterioration in the normal range of environment and operating conditions. Changes which interfere either with the collision functions of the safety system, or with normal operations, require replacement. For collision attenuation devices, for example, this implies resistance to vibration, temperature and humidity changes, impacts from small debris encountered along the right-of-way, hard coupling shocks. etc. Ease of repair of damage from normal operations would come under the same heading.

3. Economic and logistic effects.

Economic factors include costs of acquisition, including development and test, retrofit installation if applicable, maintenance and replacement costs, and those operating costs traceable to the system, such as time spent in deploying, testing, or vertifying devices. Replacement rate and repair rate caused by accidents as well as by normal wearout must be considered.

Logistic factors involve time spent in repair or replacement after accidents, and possible effects of regulations on operations. For example, in the proposed new standards for locomotive cab glazing, it is specified that in a multiple-locomotive consist, if one of the locomotives meets the new glazing standard, then such a locomotive shall be used as control unit.

Similar standards could conceivably be applied in this case; however, since it is not known whether such regulations will apply, the question is not considered here. The question of facilities required arises only in the case of complex systems such as some of the "active" radar actuated systems, and is otherwise unimportant. Materials availability should be no problem if reasonable design choices are made. Thus in general, logistic considerations should be minor.

Economic factors and logistic factors are to be examined only for systems which meet the performance criteria in both normal use and emergency situations.

4. Indirect effects

This classification includes any influence the system may have on the railroad system and on the public through other than operational and direct economic costs. A possible example would be adverse environmental effects; actually none are anticipated to exist. Another example is effects on railroad personnel; it is conceivable that measures which reduce injury and fatality rates among highway victims, and (perhaps more important) among rail personnel could improve personnel morale. A further possible effect would occur if reduction in injury levels also was accompanied by reduction in operating delays and in railroads rolling stock damage; for example, if schedule improvements resulted, there could be a favorable influence on marketing. All of the preceding involve rather tenuous relationships which would be hard to relate to valid estimates of results, so none have actually been considered in the evaluation process.

However, one category of possible results does deserve mention; this is the potential legal results of the measure. Grade crossing accidents can result in insurance claims and lawsuits against the railroad, and any measure which increases the responsibility or liability of the railroad in an accident is undesirable to that extent. In particular, with systems which are actuated automatically immediately before collision, the question can be raised as to what would have happended if the system had not been actuated, and as to whether the system should have been actuated or was properly actuated (e.g. at the right time). Conversely, if in an accident the system was not actuated, additional liability may accrue to the railroad. Since suits against railroads are not uncommon, the subject is of some concern, and has been investigated by the Department of Transportation.(3-2)

3-2 "Legal Effects of Use of Innovative Equipment at Railroad-Highway Grade Crossings on Railroads' Accident Liability," Glater, David S. and Terry K. Mond, DOT Report No. FRA-RRS-80-01, Oct. 1979.

3.3 Individual Concept Evaluations

3.3.1 General

In the evaluation process, some of the concepts are judged unacceptable and excluded from further analysis. Several of the crash attenuation systems tested by FHWA are discussed in one section because of their functional similarity. For one of the active devices, the water-jet system, simulations of the performance were considered worthwhile because the results could serve as limits or bounds on the performance of other systems. For general structural and fire crashworthiness measures aimed at all collisions or derailment situations, the evaluations performed in completed FRA and UMTA studies are accepted without modification as applicable also to rail-highway collisions. The evaluation follow

3.3.2 Conventional Structural and Fire Crashworthiness Measures

Volume I of reference 2-4, the report by Boeing-Vertol for FRA, lists a number of specific crashworthiness measures for locomotives, passenger cars, and cabooses, and estimates costs of implementation. Volume III suggests standards which could be used to require the appropriate performance characteristics. The report mentions the paucity of information on specific injury mechanisms in current accident reports, but does indicate that injury severity in existing passenger railcar accidents is less than in locomotives and cabooses, except for override situations. Since accelerations of passenger cars are more severe in train-to-train collisions than in rail-highway collisions, it appears that the subject may not be too important for the latter case, where override is not a problem.

The Calspan Corp. crashworthiness studies for UMTA (ref 2-5, 2-6) concern urban rail transportation, which often has no highway grade crossings. Consequently the situations addressed are train-to-train collisions. The several collision attenuators considered are too stiff to protect highway vehicle occupants in anything except very heavy trucks. Therefore the Calspan study has more limited application to rail-highway collisions than the Boeing-Vertol study, and the conclusions of the latter can be accepted as appropriate for this study.

Both studies emphasize the importance of anti-climbing provisions in rail passenger cars; there is consequently a need for compatibility with the anti-climbing system in any front end rail-highway collision attenuator for such cars. This requirement is of major importance for MU cars, and will be considered in the sections on collison attenuators.

The standards section of the Boeing study lists major headings of occupant containment, impact protection, seating systems, windows, and materials flammability (including smoke and toxicity). For the design modification section, the list was restricted to seating, partition and bulkhead padding, and luggage retention. Since improved glazing has already been proposed for revised FRA standards, this measure does not appear appropriate to include in a rail-highway collision study. The remainder of the measures are accepted as valid for inclusion, i.e. seats, padding, luggage retention, and materials choice.

3.3.3 Front End Structural Crashworthiness (Collisions with Hazardous Materials Trucks)

This section deals with protective procedures for collisions with trucks carrying hazardous or flammable chemicals or mechanically hazardous cargo. The study contract specifically requires examination of collisions involving mechanically hazardous cargo, perhaps as a result of a collision between an electric rail passenger car and a truck-trailer carrying three heavy coils of steel, (3-3) or of other accidents involving heavy truck cargo.

In the accident cited, an 8 ton coil of steel plate sheared off one of the collision posts of the lead car and traveled approximately 66 feet through the 85 foot car, and a 5-ton coil traveled a shorter distance through the car. The three occupants of the car were killed. The train had been traveling at 60 mph. Although the mechanical potential energy stored in tightly wound steel coils makes them qualify as hazardous cargo if they are released, any equally heavy and dense cargo of similar structural integrity could have done equal damage. In fact, in this accident, at least one of the coils did not unwind. Although heavy pieces of steel do occur as truck cargo, the shapes vary and the occurrence is not very common.

The comment of the NTSB follows: "It is not feasible to design commuter trains to protect passengers against forces such as those experienced by the train in this accident". Accordingly, the NTSB recommendations referred to preventive measures rather than structural redesign, e.g. elimination of grade crossings in the relatively modest amount of track then used by commuter transport (about 3,000 miles). Although design against such events may indeed be feasible, it does not appear to be very practical or economical, in large part because protection against all possible heavy masses, struck at arbitrary locations, imposes extremely severe structural design limits. Hence this problem is not addressed here, for no reasonable injury reduction concept is available.

3-3 "Collision of Reading Company Commuter Train and Tractor-Semitrailer Near Yardley, Pennsylvania, June 5, 1975" National Transportation Safety Board Railroad Accident Report No. NTSB-RAR-76-4, March 3, 1976

The locomotive is generally better protected in similar accidents by a sturdier front structure, and frequently by the presence of some sand to help absorb the impact. Consequently additional protective measures seem to be impractical for locomotives as well as for MU cars.

Protection against flammable truck cargo is important since fuel trucks are relatively numerous. The functional requirement is to prevent entry into occupied areas of the train of any large quantity of combustible or toxic liquids. This means that some front structure must remain substantially intact in the collision to protect the occupied section to the rear (locomotive cab or passenger section of an MU car).

The height of current locomotive cabs places them above the bulk of the fuel in a tank truck, but fuel can splash upward and enter through shattered cab windows, or directly through a break in a locomotive front structure, such as a nose door. Structures meeting the new glazing standard(3-4) are probably adequate to keep windows substantially intact during a collision, so that this problem seems to be addressed adequately. While the presence of a nose door is not required in the new locomotive standard (3-4), there is no requirement for the front structure to be strong and staunch enough to prevent fuel entry in a collision. Since the revisions in the standards and the work on such topics as collision override indicate that similiar problems are being given some consideration, no further detailed attention is devoted to the subject here.

For MU cars, the situation is different, since the cab is closer to the ground and the front surface is neither as rugged nor as easily strengthened as that of a locomotive. The usual flat front offers a fairly large surface to be sealed against entry of liquids. The relatively low mass of a one of two car consist, compared to that of a locomotive and its consist, also presents a problem. In a collision, the locomotive momentum carries it away from the fuel spill and it stops at some distance from the fire. A single MU car, with a smaller mass and momemtum, may be stopped close to the burning fuel. The only counter of this problem consists of conventional fire suppression techniques.

3-4 Federal Register, Vol. 44, 77348 et seq., Dec. 31, 1979, Docket No. RSGM-1, Notice 3; also 45FR 21092 et seq., March 31, 1980

The logical place for sealing the front of a MU car against the entry of liquids from a tank truck would be in the plane of the collision posts located at or near the end of the car. The 200,000 pound yield of each post specified in current crash post standards should be adequate to keep the posts intact as they contact the sides of a fuel tank. The typical large fuel tank truck has the tank bottom at approximately the same height above the ground as the passenger car floor. Thus, with a tank five feet high, the contact between tank and post would occur approximately 30 inches above the attachment of the crash posts to the underframe. The contact height will change very little if the posts are moved back from the end of the car, since the sill and underframe now underride the truck tank in a collision, and present underframe and tank bottom heights are not expected to change.

If the posts remain at present locations next to the diaphragm, the area between can be effectively closed to entry of liquid by a sliding door of suitable strength, placed at the rear of the posts so that it will not have to sustain the load of the initial contact. Once the tank has yielded at the crash post locations, the portion between will present a much lower load per unit of area to the door, since the tank section will already have been accelerated by the posts, and the rupture of the tank permits the fluid behind the tank wall to flow freely. The design load could be determined by experiment using a simple model.

However, the remaining section of the plane through the posts, i.e., the section outboard of the posts, will still require strengthening. Corner posts of suitable strength could extend the section, but the intervening area still presents a problem. On one side a metal structural surface can provide the needed integrity, but in front of the motorman, a transparent surface is needed. The materials for front glazing referenced in the newly proposed FRA glazing standards appear to be inadequate to survive a truck collision intact.(3-5) Metallic structural grillwork in front of the glazing could ensure that the glazing remains intact; however such grillwork must not seriously interfere with the motorman's forward vision and thereby

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3-5 "The Design and Development of Heated, Impact Resistant Windshields for Locomotives", Wright, R.W., ASME paper 78-RT-5, IEEE-ASME Joint Railroad Conference, St. Paul, Minn. April 11-13, 1978.

introduce a different hazard. A visibility study is beyond the scope of this effort, and is therefore pursued no further here.

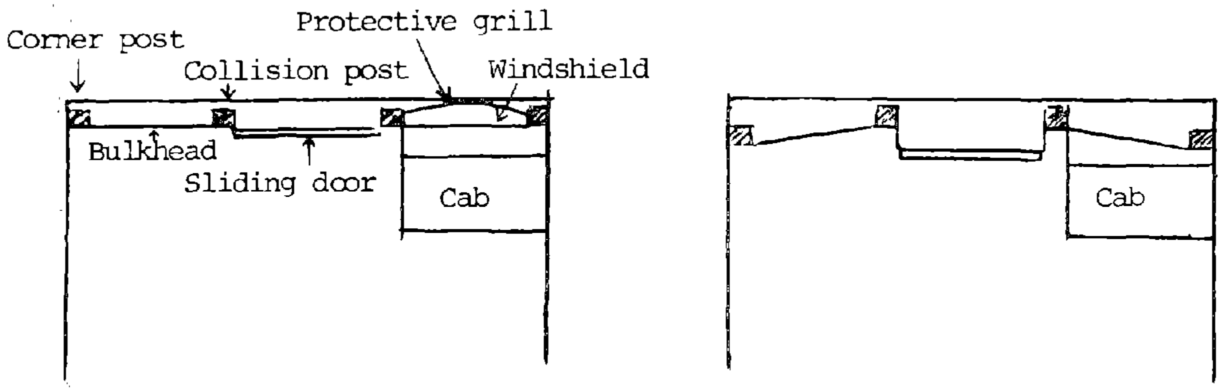
When the tank truck is angled across the rails, and the corner posts are in the same plane as the collision posts, as shown in figure 3-8 (a), the corner post strikes the tank first and sustains the maximum force. This increases the needed strength for corner posts. Alternatively, the corner posts may be moved back as shown in figure 3-8 (b), and bulkhead and windshield slanted between posts. This may introduce design problems in sealing the center opening, and may also cause the loss of usable space.

Another possibility is that the rear of the motorman's cab constitute part of the barrier, and the cab door, running aft from the collision post to the back of the cab, constitute the other part. In this case, shown in figure 3-8 (c), the front collision post sustains the load, and the cab door is only under such side load as is transmitted through the post. This arrangement appears feasible but presents difficulties in execution.(3-6)

The final possibility occurs if the collision posts are located behind the motorman's cab, as shown in figure 3-8 (d), thus permitting a single plane cross-section of the car to constitute the sealing surface. In all cases the crash posts must be braced sufficiently in the upper sections to withstand anticipated crash loads without rupture or major inelastic distortion. The entry of a modest amount of liquid through small interstices might be considered acceptable.

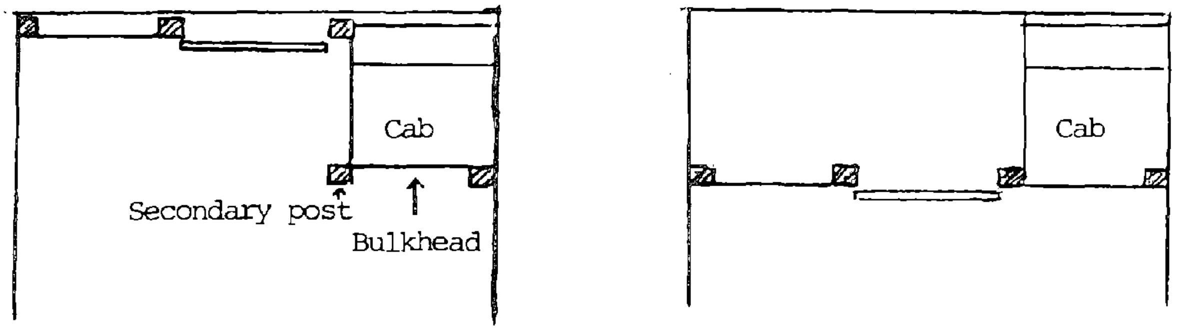
Aside from the problems of visibility through a protective grill or a slanted windshield, the major effects of these changes on rail operations arise from use of end vestibules for exits. Some of the arrangements shown may cost additional space lost if side doors are included at the ends, as is common in many MU cars. Sliding doors might serve to seal the center opening, but sticking problems could occur, especially under loads that distort them, such as occur in train-to-train accidents. The only other known effect of these measures is the minor weight addition they cause, which is unimportant compared to the operational problems.

(3-6) "The Design of Drivers' Cabs", Powell A.D., Cartwright, A., Proc Inst Mech Eng. Vol 191-33/77, 1977



(a) Corner Posts Even With Collision Posts

(b) Corner Posts Moved Back From Collision Posts



(c) Corner Post And Bulkhead At Rear Of Cab

(d) Crush Zone Forward Of Collision Posts

FIGURE 3-8 POSSIBLE SEALING OF MU CAR FRONT AGAINST ENTRY OF FLAMMABLE FLUIDS

3.3.4 Individual Protective Equipment

Three types of individual protective gear mentioned in Sec. Sec. 2.3 were respirators, fire protective clothing, and impact protection items such as helmets and resistant clothing or body armor. All of the items are relatively conventional, normally used either by firefighters or other security personnel.

Each of the items involves a certain amount of discomfort, inconvenience, or other difficulty, and presents some uncertainties in its acceptability for use and effectiveness.

Consider first the fireman's respirator, which typically provides a 15 minute or 30 minute oxygen supply. This is a conceivable item for locomotive cab emergency use, to protect the lungs against high temperatures or toxic matter in the cab. However, personnel must be trained in its use, and the equipment requires periodic inspection and recharging if necessary. In recent fires, firefighters have perished because of defects in their breathing apparatus (3-7); it should not be assumed that railroad crews will exercise greater care then professional firefighters for whom such gear is normal equipment. The regular training exercises and equipment maintenance checks needed for proper use of respirators would be inconvenient and costly, and might not be effective unless personnel were highly motivated. Hence the respirator is dismissed as impractical for those not daily engaged in hazardous occupations.

There are similar objections to body armor, helmets, and impact resistant clothing. All of these tend to be heavy and uncomfortable, enough so that their use (except for helmets) by professional security personnel, other than firefighters, is extremely rare. Crashworthy design of crew compartments would generally eliminate the needs. Unless specific cases arise where helmets appear to offer some protection, there does not appear to be any benefit from use of such items equivalent to the negative effects on comfort, freedom of motion, etc.

(3-7) "The Lubbock Fatalities", Fire Command, V46 No. 11, Nov. 1979, pp 20-23

Most fire protective clothing has similar drawbacks, and is unacceptable for regular wear. Although improved fabrics such as novoloid have high fire resistance and reasonable weight, their durability and comfort are not equal to those of conventional fabrics. A throw-on poncho for emergency use, such as is used occasionally in the chemical industry, is a conceivable alternative. Even this has its limits, for while it may protect the body in a fire in the locomotive cab, the lungs are unprotected. In a collision with a gasoline truck, (3-8) of the three occupants of the locomotive cab, two were killed by injuries as they jumped from the locomotive at high speed. The third, who left the cab last, succumbed three days later - timing which is consistent with lung injury from high temperatures, although the NTSB report did not identify the actual cause of death.

Thus individual protective equipment does not appear to be the best answer to collisions with hazardous materials trucks, for reasons of inconvenience of use, ineffectiveness in many accident circumstances, and the operational inconveniences of necessary training and equipment care. The structural measures discussed in Section 3.3.3, which would keep most of the flammable or toxic liquids outside of the locomotive cab, appear to be preferable. If only small amounts of flammable liquids enter the cab, conventional dry chemical fire extinguishants, such as were available in the locomotive in the incident cited, would probably suffice for momentary protection until it is safe to leave the cab.

Consequently no individual protective gear is recommended as an injury reduction measure.

(3-8) Railroad/Highway Accident Report, Illinois Central Railroad Co. Train No. 1 Collision with Gasoline Tank Truck at South Second Street Grade Crossing, Loda, Illinois, Jan. 24, 1979; NTSB Report No. NTSB-RHR-71-1, July 8, 1971.

3.3.5 Electromagnetic Rail Brakes

The small contact surface between wheels and rail and the low coefficient of friction provide rail transport its high energy effectiveness, but make braking relatively ineffective. Sanding increases the coefficient of friction, but not the contact surface. The rail brake is one means of increasing the braking surface.

Rail brakes are common in electrically powered urban rail transport, where the power is readily available to supply the electromagnetic actuators. The Boeing-Vertol light rail vehicle is a modern example of such vehicles. Since freight cars are not electrically powered, the electromagnetic rail brake is impractical for freight use. It does not seem to have been used on MU cars in the United States, perhaps for reasons of tradition, additional weight, or cost. The principal difficulty appears to be rail condition. With continuous welded rail, use of rail brakes on new MU cars, with the possibility of reducing accident severity by reducing impact speed or even avoiding collision, is worth considering.

In addition, since passenger cars are all provided with electric power when drawn by locomotives, the use of rail brakes on these cars is also possible. In this case, however, the dynamics of relative braking action of passenger cars and of locomotives must be studied to determine whether the system can be truly effective.

Thus electromagnetic rail brakes appear to offer distinct injury reduction possibilities to MU cars, and may offer advantages to coaches as well. The technology is known, reliable, and tested by years of use; it is effective for the intended purpose of braking. Normal railroad operations are relatively unaffected by the addition of rail brakes. Maximum acceleration and deceleration achievable in normal starts and stops are decreased by the amount of relative increase in the loaded vehicle weight; this is a relatively unimportant effect. The initial checkout routime at the start of a day's operation should be changed to include a test of the rail brakes. Otherwise operations are unchanged. For any powered device, the possibility of inadvertent actuation should be considered; since this has not been a problem with existing rail brake systems, no difficulties need be anticipated here.

For emergency situations other than rail-highway collisions, the additional braking capability is a distinct advantage. A known disadvantage is that every car in a consist must be equipped with the brakes. No indirect effects are known, and none are anticipated. Thus, the rail brake system meets all the criteria listed in Sec. 3.2 for normal operations, emergency situations, and indirect effects.

Tests with the UMTA Boeing-Vertol light rail vehicle gave decelerations using the rail brakes at a level ranging from two to three times the maximum braking level of the wheel brakes, i.e. up to 9 mph per second with the rail brakes versus about 3 mph per second with the wheel brakes.

In summary, the concept suggested in reference 2-3 appears to be worthy of further consideration on a feasibility and effectiveness basis.

3.3.6 Gas Bag Collision Attenuator Systems

An unpublished study performed by Minicars Inc. for FRA considered two concepts for gas bag collision attenuators. One involved a device similar to an automotive gas bag, normally carried stowed, and released automatically upon command of a radar detection system. The other system was to be inflated by locomotive air before travel, to remain permanently inflated during travel, and to be collapsed into storage configuration upon completion of the route. Minicars found neither system competitive with other collision attenuators, primarily on the basis of benefits. Although this study evaluates one system as unacceptable and the other as noncompetitive, the reasons differ to some extent from those of Minicars. Therefore a short description of the systems and a brief discussion of the problems follow.

Figures 3-9 and 3-10, extracted from the Minicars study, illustrate the concept for a gas bag deployed upon radar signal. Inflation requires one second. During impact, total force level is controlled by successive release valves which provide increasing pressure, ranging from 6 psi inflation pressure, to 10 psi and then 18 psi, as the bag is crushed. However, bag length must be limited compared to bag width, or buckling occurs; this limits the effective attenuator length to 5 or 6 feet at most. In the automotive application of gas bags, the well controlled geometry, with a short distance between driver and windshield and steering wheel, avoids such problems. The length may be less important than the fact that the attenuator has no controlled mechanism for application of forces normal to the track direction, i.e. forces tending to move the highway vehicle off the tracks. As the bag conforms to the shape of the side of the automobile, it will provide a force normal to the automobile axis, which may have a small cross-track component working either with or against the automobile velocity. This is a fairly common problem with "soft" crash attenuators, but for the gas bag, the authors know of no solutions.

There is also the problem of possible inadvertent deployments, with resultant costs and delays. To ensure that the system is actually

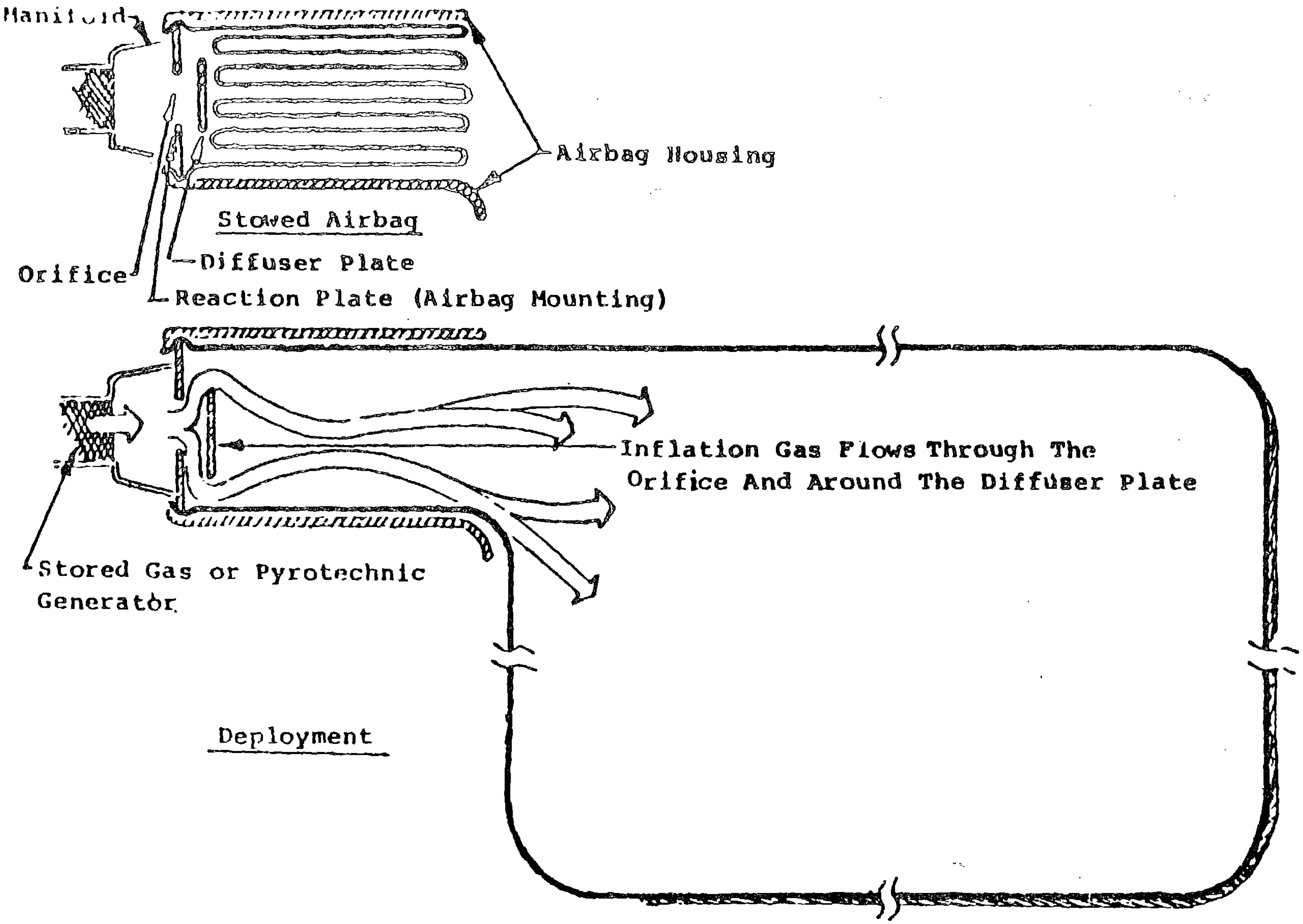


Figure 3-9 LOCOMOTIVE AIRBAG ATTENUATOR SCHEMATIC
(Extracted from Minicars Inc. document)

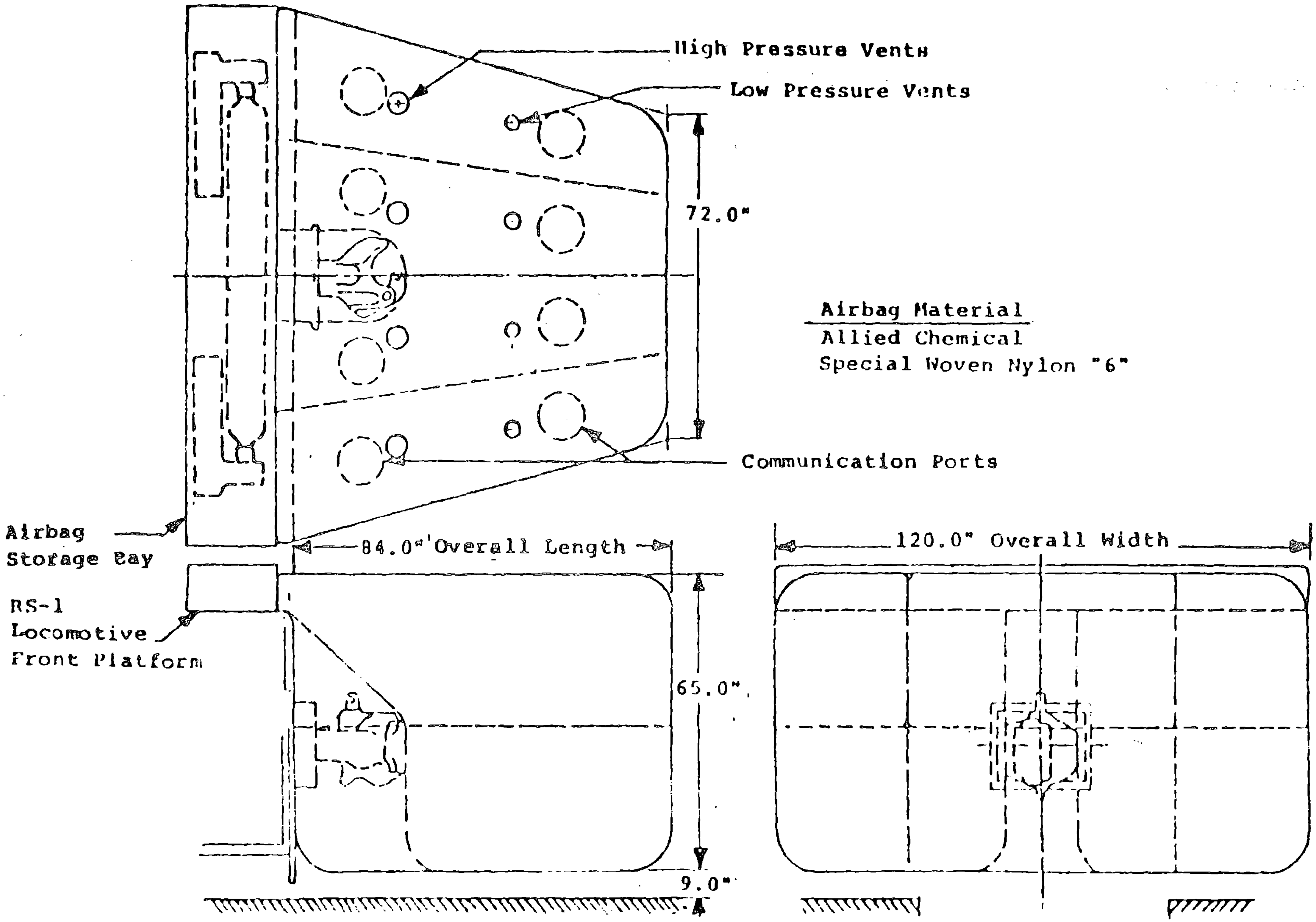


Figure 3-10 SENSOR-DEPLOYED AIRBAG ATTENUATOR (Pueblo Test Configuration)
(Extracted from Minicars Inc. document)

functional would require regular checks of at least the radar system, up to the deployment command signal. Such checks might be necessary before each trip, if current experience with police radar is used as a guide, and could be both inconvenient and time-consuming. Finally, there are also the potential indirect effects mentioned in Sec. 3.2, specifically the increased probability of legal controversy and potentially increased liability of the railroad in any collision involving an automatically deployed device. On the basis of these considerations, this gas-bag concept is considered unacceptable.

Figures 3-11 and 3-12, also extracted from the Minicars study, illustrate the concept for a gas bag which is permanently inflated during locomotive operation. In a collision, its effectiveness has the same limitations of length and lateral force capability as the other gas bag system. The system proposed was self-stowing, automatically, when its air supply stopped, and was to be inflated upon push-button command, at the beginning of consist operation. Thus there is general compatibility with normal operations, and relatively little requirement for checkout, since the normal deployment is at least a partial checkout.

One potential problem with this system is the durability of the gas bags, both through repeated foldings and deployments, and through damage from debris encountered on the track, and from thrown objects and other forms of vandalism. The proposed material for the two 36-inch diameter tubes was polyurethane; presumably other materials of suitable characteristics could also be chosen. In recent years there has been an increasing incidence of railroad vandalism (ref. 3-5, e.q.), one of the types of occurrences which have led to the newly proposed glazing standards. A continuously deployed airbag might be an attractive target for vandalism. On the other hand, an airbag deployment is estimated to require only ten seconds, so that when the engineer is aware of the possibility of collision early enough to deploy the device, a mode of use is possible for the collision attenuator which can avoid vandalism and much of the potential damage from debris along the tracks. This advantage is obtained at the cost of the attenuator being inoperable for unexpected collisions, and of potential litigation problems. The remaining problem is to ensure that

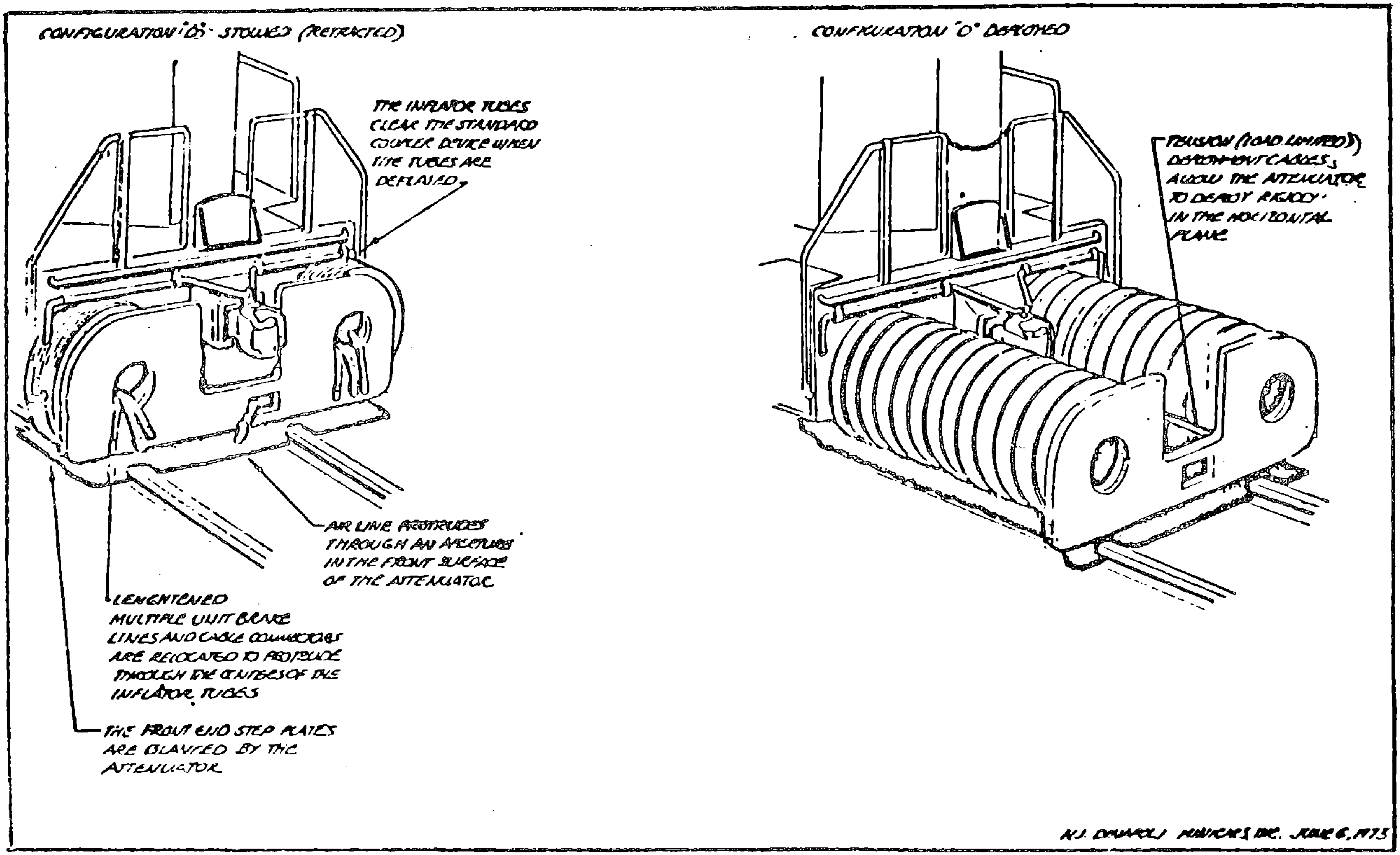


Figure 3-11 CONTINUOUSLY OR ENGINEER-DEPLOYED AIRBAG (Stowed and Deployed)

(Extracted from Minicars Inc. document)

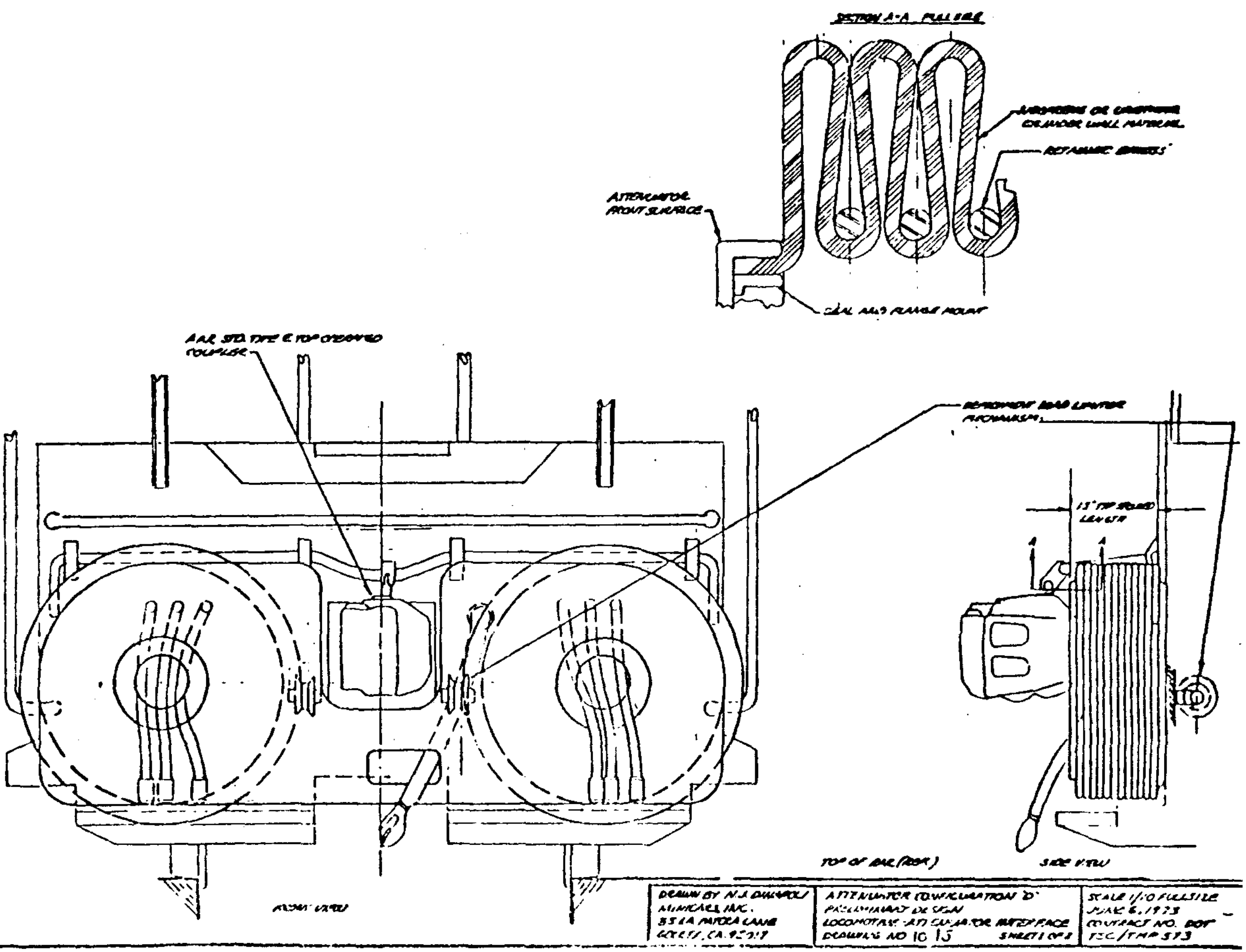


Figure 3-12 CONTINUOUSLY OR ENGINEER DEPLOYED AIRBAG (Interior Views)
(Extracted from Minicars Inc. document)

the attenuator does not interfere with any anticlimbing provisions on the train, an essential compatibility requirement for all front-end collision attenuators.

No computer simulation of this type of airbag system was attempted since the Minicars study provided no guide to the crash dynamics of the device.

3.3.7 Spray to Reduce Surface Coefficient of Friction

This concept was an outgrowth of the water jet concept, based on the thought that the water spray reduced the coefficient of friction between the ground and the highway vehicle, and thereby could reduce the net force on the highway vehicle. Only a brief consideration was needed to find the concept unacceptable.

The first problem is that the concept relies only on the coefficient of friction of the surface, and on no other collision attenuation mechanism. Thus,its potential for injury reduction is quite limited, since the force reduction due to this cause alone is very modest. The second objection arises from the fact that only on a relatively smooth grade crossing surface will the friction coefficient be seriously reduced; once the vehicle is off the surfaced grade crossing, there is little effective reduction in friction. Finally, the effects on pedestrians in the area may be diastrous if it causes them to lose their footing in front of the train.

These considerations are adequate to dismiss further examination of this concept.

3.3.8 Piston Collision Attenuators

The contract statement of work lists piston devices as one of the collision attenuation concepts to be studied. Hydraulic devices have long been used to reduce coupling shocks.(3-9) Such devices can absorb a large amount of energy in a relatively short stroke, which is important in coupling, which joins large masses with potentially high shock levels resulting from the closing speed at contact. In grade crossing accidents a heavy locomotive meets a light highway vehicle, and different characteristics are desired.

A piston device alone, supporting a relatively rigid front surface, will produce peak force at impact, and decreasing force thereafter, if it meets a completely rigid body. Of course this does not actually happen in a collision, because the highway vehicle structure starts to yield. However, in order to delay the deformation of the highway vehicle, it is usually desired that the collision attenuator provide a small force initially, which subsequently increases to a maximum value. This is the force profile sought by Minicars Inc. in their work for FRA. A variable damping coefficient piston which provides a force increasing with piston displacement is feasible and has been used (3-10), but may add some mechanical complexity, although it need not reduce reliability.

The potential reliability of simple hydraulic devices and the fairly extensive experience with them make them attractive as engineering devices with well known characteristics. If, however, a fairly soft initial contact is desired for a rail highway vehicle collision attenuator, it is probably necessary to combine a hydraulic device with some other type of energy absorber, such as a frangible structure. Such a combination may be more versatile in what it can achieve then either element alone.

(3-9) "Advantages of Hydraulic Buffers," Railway Gazette, V106, Feb 1957, pp 180-181

(3-10) "The Hydracushion Car," MacCurdy, W.K., and Hermes, R.M., in "Anthology of Rail Vehicle Dynamics, Vol. 1, Freight Car Impact," (S. Guins, Ed.) ASME, New York, 1971, pp 9-14.

Hence all that can be said at this point is that the hydraulic piston is a candidate for use, in combination with another attenuation device. Deployment and retraction of the hydraulic device appear to present no serious problems or inconvenience. If the hydraulic device has a long stroke, it can be subject to sufficient damage from transverse forces in accidents to incapacitate the system and require its replacement. This may be a limiting factor on stroke length. No other problems which exclude the hydraulic system have been identified. To the extent that hydraulic devices may help solve problems in other collision attenuation systems, they should be considered.

3.3.9 Collision Attenuators Based on Highway Abutment Collision Devices

FHWA sponsored the test of a variety of fixed systems designed to protect automobile occupants in collisions with piers, abutments, dividing structures, bridges, etc (ref. 2-12 to 2-16 inclusive). Tests by the Texas Transportation Institute indicated that several systems were very effective in reducing automobile damage and occupant accelerations, and thus in reducing occupant injury. Therefore these systems were listed in Table 2-4 as potential rail-highway collision attenuation concepts:

(1) Crushable attenuator structure of light weight cellular concrete

(2) Composite structure of vertical cylindrical steel structural elements, interconnected by cables, panels, welding, etc. Typical element diameters from several inches to two feet, several configurations tested.

(3) Toroidal shock cushion of cylindrical steel tubing mounted on energy-absorbing steel elements.

(4) Hydraulic cushion composite of polyvinyl chloride vertical cylindrical cells containing inert liquid which is expelled under load. Cells interconnected by cables and reinforced by structural panels or diaphragms.

In addition to the preceding, a plastic foam crushable attenuator was tested; however, a similar arrangement had already been studied by Minicars Inc. for rail-highway use.

The effectiveness of a fairly wide variety of devices gave hope that some of the techniques might be adaptable to rail-highway collisions. Unfortunately, most of the methods appear not to be effective in the new application. The following list identifies some of the most important differences between the two uses, which affect the desired attenuator characteristics.

(1) In the highway application, the direction of the impact on the automobile

is longitudinal; in the rail-highway collision the direction is transverse. The automobile structure by design is suited to withstanding longitudinal impacts better than transverse, for that is the direction of motion.

(2) The dynamic environment of a railroad collision attenuator imposes more severe structural demands and limitations due to vibration, acceleration, and increased probability of contact with debris in motion.

(3) The railroad use imposes more stringent limits on dimensions, especially length.

(4) The railroad use may impose greater climatic variations, i.e. temperature and humidity, than the fixed highway application.

(5) For attenuators made of multiple separate elements, in the highway application the earth can serve as a compression member against which tension members used to hold the elements together can be stressed. In the railroad application, a sturdy compression member would act in similar fashion to the locomotive coupler, which serves essentially as a battering ram in a rail-highway collision.

Note that all of the concepts listed, except for the light weight cellular concrete attenuator, are composite structures assembled out of multiple elements. This is characteristic of many approaches to shock attenuation, for it makes it possible to choose desired behavior characteristics in modest size units where behavior can be controlled. Even the cellular concrete structure was cast around cylindrical voids to give it the desired structural softness properties; thus it too is a non-uniform, if not a composite, structure.

The problems with the various concepts are now discussed and in some cases brief description of the concepts are included. Drawings and photographs of the systems are contained in reference 2-12.

3.3.9.1 Lightweight Cellular Concrete Cushion

This attenuator is made of concrete mixed with vermiculite (expanded mica) to make it extremely light, and cast with welded wire fabric reinforcement in a three foot height, around an array of empty vertical cardboard tubes of 23 inch diameter. A typical cushion was 24 feet long and somewhat over 6 feet wide (three tubes). The light material and the large voids make for a soft structure which performed well in the crash tests. However, the structure is inadequate to withstand the rail vibration environment without rapid deterioration. It is also subject to moisture absorption and subsequent degradation, especially in freezing cycles. The latter problem has been solved in fixed locations by coatings or covers, which are probably not effective in the rail conditions. Thus this concept is excluded as not effective in the rail environment.

3.3.9.2 Hydraulic Cushion

This device consists of an array of vertical tubes typically 6 inches in diameter and 42 inches long, filled with water, and with openings at the top covered by flexible flaps so that the liquid can exit if the tube is squeezed. The dynamic behavior under load provides a viscous hydraulic effect; the coefficients are adjusted by choice of the size of the openings. The tubes were made either of polyvinyl chloride or of vinyl-impregnated nylon fabric. The array is held together by longitudinal cables anchored to the ground at both ends and arranged to give the desired structural properties. Directional properties are provided by plywood panels along the sides and longitudinal diaphragms between the tubes. For freezing climates, calcium chloride solutions are used instead of water.

Performance in the TTI crash tests, and in experimental installations in southern states, was good. The basic problem is holding the assembly together with no longitudinal compression member other than the plywood diaphragms and the water cylinders themselves. Although this could conceivably be done by using the diaphragms as compression members, the need to support the considerable weight of the liquid imposes a relatively heavy structure which would not have the desired property of yielding at low force levels. With a lighter structure the attenuator is likely to fly apart upon impact. The large weight needed to implement the concept suggests that any attenuator of this type would have to ride on its own supporting wheels, rather than be contilevered from a locomotive, this would further increase the cost. Thus this concept was reluctantly discarded, in the absence of an effective and economical structural design.

3.3.9.3 Toroidal Shock Cushion

This device is of interest primarily because its construction is sufficiently rugged to perform in the railroad environment. It is composed of a number of lengths of high-strength steel tubing with an elliptical cross section 4 inches by 7 inches, and thickness of .065 inch. The tubing is shaped to surround a concrete pier, for example, in approximately a rounded V or U shape, whose total length may be 20 feet. One typical installation contained five tubes arranged one above the other in a vertical tier. The tubes are mounted to fixed piers by arms which provide friction forces; the arms consist of concentric steel tubes with steel tori between the tubes, and the rolling of the tori provides the friction. When the device is struck by an automobile, the cushion effect is provided by the combination of plastic deformation of the ellipsoidal cylinders and the frictional forces of the arms.

In the TTI tests, the toroidal shock system behaved well in head-on direct collisions, especially with heavy cars. It performed less well with the one light car (2520 pounds), which sustained fairly severe damage and fairly high accelerations of the dummy occupant (33g longitudinal peak). In side impacts it did not perform well until a revised mounting arm design embodying rotary action energy absorption was used; however the side impact performance is not of interest in the railroad application.

Although the cushioning effect of the system was not generally superior to that of other successful systems tested by TTI, the system has interest because the type of construction is compatible with railroad rolling stock, the materials are commonly used and relatively cheap, and there appear to be no particular maintenance problems. The structure is also integrally self-supporting. The combination makes it worth further consideration in comparison with other collision attenuation devices.

For railroad use, it would be necessary to reduce the yield point of the elliptical tubes, probably by reducing the thickness of the tube walls. This would undoubtedly be required to reduce the intrusion of the tubes into the automobile, because of the transverse direction in which the train strikes the automobile. The .065 inch thickness can undoubtedly be reduced while still maintaining a structure which will survive normal rail travel. The arms could also be modified to achieve desired friction characteristics; hydraulic substitutes may also be possible replacements for the present arm design.

In summary, the toroidal shock system, suitably redesigned, can provide some collision attenuation, and has few drawbacks in normal railroad operations. To achieve the length needed to provide a reasonable amount of attenuation would require a deployable device which is lowered into position on the locomotive before use. This is not a major interference with normal operations. Since the metal structure in a collision between trains could interfere with anticlimbing devices, such a system should probably not be used on an MU car. For locomotives, it may be possible to retain compatibility with devices aimed at preventing caboose override. No indirect effects which create problems are known to exist.

3.3.9.4 Cylindrical Steel Composite Structures

Composite structures consisting of assemblies of 55 gallon drums, or of corrugated steel pipes in diameters ranging from 8 inches to 36 inches, were studied by TTI and a number of crash tests were conducted, especially with the drums. These structures, like the toroidal shock cushion, are suitable for use in the motion and vibration environment of the railroad, and therefore are of interest. Various configurations of steel drums were tested, and some gave excellent crash test results.

The composite structures of vertical cylinders were held together by various means, including tension cables and welded steel crossmembers, or were welded to each other. Fiberglass coated plywood panels were also used to provide directional properties and to bounce off automobiles impacting the structure at an angle. In some initial tests, the drums were filled with empty metal beverage containers; this configuration proved to be too stiff and was discarded. The empty 16 gage barrels first tested were also too stiff, and holes had to be cut in the top and bottom to reduce their yield point. 20-gage barrels were used in later tests, and smaller holes were cut. Finally, in some tests, the hole sizes were varied, with the softest structures used in front, and with stiffness increasing toward the rear. Since barrels are manufactured in gages down to 24, use of lighter weight barrels may be considered.

Only limited tests were conducted on the corrugated steel tubes, and the results were not satisfactory. Although the problems appeared to be solvable by suitable redesign, the later tests concentrated on the steel drum approach, because of the ready availability and low cost of the drums. However, there is nothing which inherently rules out the tubes, and tubes in suitable smaller diameters can be interspersed with 55 gallon drums to fill the voids and thus adjust structural stiffness.

In all of the crash tests, the drums tended only to crush, and not to tear apart nor fly apart. This is important because individual pieces of sheet metal flying loose can cause severe injuries if they strike an occupant of a highway vehicle, who might otherwise be protected by the vehicle structure.

None of the tests, however, involved an impact which was transverse to the automobile. Presumably a much softer structure would be needed to protect automobile occupants in this case, where little deformation of the automobile structure can be allowed. Use of a fairly long crash attenuator and the lightest gage of metal readily available is indicated as a first approach. A shorter stiffer structure could still reduce occupant accelerations and injuries, but to a lesser extent.

As with the toroidal shock cushion, effects on normal operations are limited to a possible need for deployment. Interference with anti-climbers is still a problem with the MU car, but probably not with the locomotive. No indirect problems have been determined to exist.

3.3.10 Rigid Flat-Front and Rounded-Front Locomotives (Deflectors)

3.3.10.1 Description and General Discussion

One concept for injury reduction involves covering the locomotive coupler to prevent it from impaling the highway vehicle and retaining it on the locomotive front. Such retention increases the probable injuries because the vehicle is battered against the ground until the locomotive comes to a stop. This occurred in the two FRA crash tests(2-1) where the automobile was centered on the track and the coupler entered the body through the front door. The occurrence is avoided if a rigid metal cover conceals the coupler; the cover can be moved into place from a storage position for a locomotive in leading position. Similar covers were used on some locomotive designs in the past, especially with folding couplers. To minimize injury the leading surface should be flat or rounded, rather than pointed, as it was in some of the old cowcatchers.

This system constitutes one extreme of a possible range of attenuators, with the other extreme being a very long and very "soft" easily crushable structure, which would significantly reduce the highway vehicle acceleration. The flat-front locomotive used in the FRA crash tests was fairly representative of the hard-front case for the tests where the automobile was not centered on the tracks and thus not impaled.

The crash test data provide a standard to which numerical simulation results can be compared. Therefore crash simulation was attempted for the flat and rounded front locomotives, and also for the soft honeycomb attenuator and the water-jet attenuator. For the two latter systems there are no corresponding crash test data.

The efficacy of the hard front system in reducing injury is discussed below in the summarization of simulation results. The one certain capability is a substantial reduction of impalement and retention of highway vehicles in a collision. The compatibility with other safety measures, primarily with anti-climbing devices, for train-to-train collisions is still necessary, despite the relatively sturdy structure in front. The anti-climb provisions vary with the rail vehicle and the type of situation addressed, and it may not be possible to design a compatible cover for every existing anticlimbing design. In normal operations the short hard front coupler has no known disadvantages, other than the need to close or move it in front of the coupler on the locomotive which is in lead position. The various types of designs used in the past (largely with steam locomotives) have appeared to be unobjectionable. No other operational or indirect drawbacks are known nor anticipated.

3.3.10.2 Crash Simulation

It was hoped that a crash simulation using a fairly simple model of automobile and structural behavior could reproduce the results of the FAA crash tests. Reasonable reproduction of the crash test results would provide confidence that the model can also represent the physical behavior of the system in somewhat different circumstances.

Two earlier crash simulations had been conducted, one by Minicars, Inc. in its study of collision attenuation for FRA, the other (3-11) by Control Systems Research, Inc. (CSR), as an outgrowth of work on automobile stiffness under side loading. The Minicars simulation covered a two-dimensional horizontal plane encounter between an automobile and a soft attenuator, in which both bodies yielded. The automobile forces were represented by springs at various locations, with each spring having a stiffness curve composed of several linear force-deflection segments, and with each spring accompanied by a parallel viscous damping element. An occupant was attached to the automobile through a set of four springs. The attenuator was described by two springs, with its contact surface and deflections represented by forward linear motion and rotation in the plane. The train had constant velocity corresponding to infinite momentum. The Minicars report summarized the results of a number of computer runs covering different train and highway vehicle speeds and relative positions.

[3-11] "A Fortran Program for Grade Crossing Collision Studies Using Computer Graphics," Report No. 351-001-01, 27 July 1973, J. Taylor, Control Systems Research, Inc., and P. Spencer, FRA.

The CSR simulation was designed for rapid CRT screen display of the geometric situation and vehicle configuration. No attenuator was involved. The force model used simple linear springs, so that force depended only on crush distance until the vehicles started to move apart, when forces were set to zero. No simulation results were available to the authors.

The first goal of simulation in this study was to determine whether the gross behavior of the highway vehicles in the FRA crash tests could be duplicated by a relatively simple model of a flat front locomotive striking an automobile, at least for the period when the motion was substantially planar, i.e. with essentially no sustained vertical acceleration and with rotational motion about a vertical axis only. In the crash tests, this behavior was typical of the body of the impaled automobile throughout the encounter, and in the case where the vehicle was not impaled, it lasted for at least 0.3 second, and generally until contact between locomotive and automobile ceased. Thus a two dimensional model should adequately describe the automobile behavior during the period of maximum forces and accelerations in the collision with a hard-front locomotive, which is the period of initial contact.

In the instrumented crash tests, accelerometer signal recordings, from several clusters of threee accelerometers each, mounted at various locations on the automobile (and also on the locomotive front), provided information on the linear accelerations of the vehicle. Information on angular motion came only from the high speed cameras and from what could be be deduced from the accelerometer data. For the case where the automobile was off-center and ultimately cleared the tracks, several events gave some information on the rotation, up to 180 degrees of motion, after which significant rotation about horizontal axes occurred.

The sequence, starting from time zero at initial contact of coupler with automobile, appears in Table 3-2, reprinted from reference 2-1. The automobile is perpendicular to the locomotive when struck by the coupler above the left front wheel. At 269 milliseconds the left rear of the automobile strikes the side of the locomotive, indicating angular motion of approximately 90 degrees, perhaps a bit more. At 285 milliseconds the table indicates the automobile approximately parallel to the locomotive,

Table 3-2 SEQUENCE OF EVENTS DURING TEST TGB-4

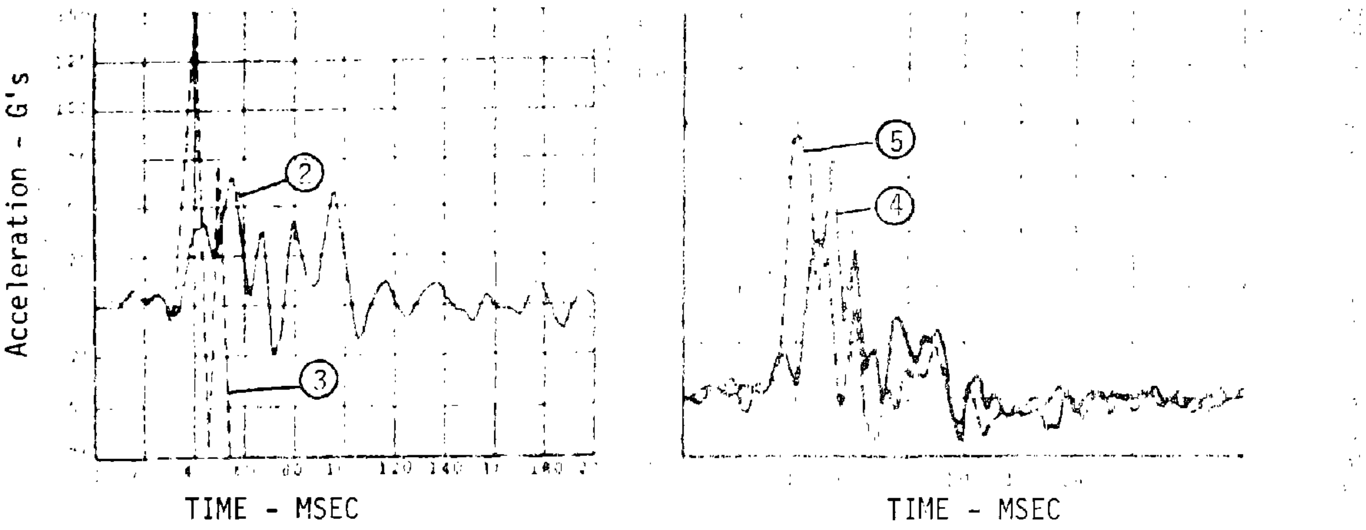
Time (msec)	Event
14	Coupler contacts hood
27	Driver's window breaks
28	Dummy right arm begins to rotate upward and rearward
30	Locomotive front plate contacts left front door
31	Locomotive front plate contacts front bumper
31	Panel under dash comes loose
35	Left lower corner of front windshield breaks
38	Left front door begins to open
40	Left rear door buckles open at top
44	Dash begins to crush
54	A post contacts steering wheel
57	Front seat begins rearward rotation as dummy torso moves back toward rear window
82	Dummy head passes through rear door window
148	Right front wheel dips between rails
162	Automobile is free of coupler
162	Left front fender and left side of hood begin to rotate away from firewall
189	Right front wheel is on top of north rail
234	Automobile is free of front plate of locomotive
269	Rear of automobile impacts side of locomotive
285	Automobile is approximately parallel to track
775	Automobile is approximately perpendicular to track and facing away from track
1558	Automobile is facing up the track on left (driver's side)
1900	Automobile is on roof, facing up track
2600	Automobile on right (passenger) side, facing up track
3875	Automobile is on wheels, facing up track

Test conditions: Automobile at rest perpendicular to tracks, weight 4693 pounds. Locomotive coupler strikes left front fender at wheel, at 50 miles per hour.

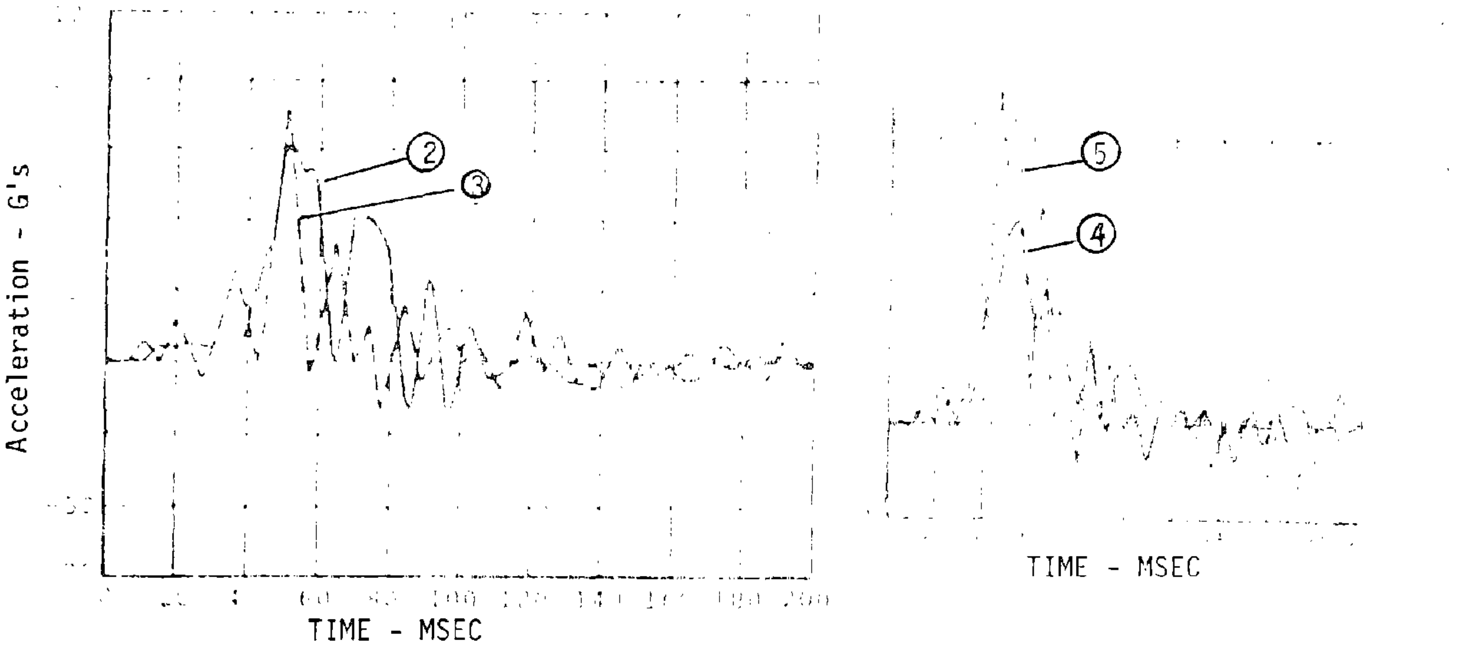
i.e. 90 degrees of rotation. At 775 milliseconds, the automobile is perpendicular to the track and facing away, i.e. 180 degrees of motion. In the first test (TGB-2), without instrumentation, the times are fairly similar: 250 and 824 milliseconds for 90 and 180 degrees respectively. Since the major linear accelerations occur during the first 200 milliseconds, the 90 degree point is of major interest in the simulation, the 180 degree point is not.

Linear motions of the automobiles in the crash tests are described by the accelerometer recordings. Figure 3-13 shows plots of the output of the lateral accelerometers in four locations on the automobiles in the two instrumented test crashes. In test TGB-3 the automobile is centered on the track and the coupler enters the front door and retains the automobile on the locomotive front. In test TGB-4 the automobile is offset and bounced off the track after the coupler strikes the left front fender above the wheel. The recordings all show an initial period of low acceleration while the coupler penetrates sheet metal only, followed by high acceleration once the locomotive front plate engages the side of the vehicle. At the locomotive speed of 50 mph, the approximately 35 milliseconds of low acceleration correspond to about 30 inches of locomotive motion, somewhat more than the coupler length. This allows for the crush of a few inches of relatively fragile sheet metal.

Besides the accelerometers in the four locations shown in Figure 3-13, several other locations were equipped with either a single lateral accelerometer or a cluster of three orthogonal accelerometers. All except for those mounted at the point actually struck by the coupler, indicated similar delays in the onset of high acceleration.



(a) Test TGB-3 Automobile centered on tracks



(b) Test TGB-4 Automobile offset on tracks

————	Location 2 Right Front	————	Location 4 Right Rear
– – – –	Location 3 Left Front	– – – –	Location 5 Left Rear

Figure 3-13 Locomotive-Automobile Crash Test, Lateral Accelerations in Occupant Compartment

3.3.10.3 Crash Model

For the hard front locomotive, the crash model assumes infinite rigidity and strength for the locomotive front. All deflection is assumed to occur in the automobile, which instantaneously conforms to the locomotive shape at the contact points. For computational uniformity, the hard fronts were chosen to be parabolic in shape, with the nominally "flat" front represented by a one-foot protrusion of the center of the parabola from the ten foot wide segment which joins the two front corners. This shape kept the contact surface relatively flat during the collision, yet permitted the same formulae to be used when a more rounded shape, i.e. a longer parabolic protrusion, represented the locomotive front.

Originally it was hoped that a continuous, homogeneous body representation of the automobile could be used. To match the FRA tests, the automobile was assumed to weigh 4700 pounds, with 55 percent of the weight on the front wheels, and to be a rectangle 18.6 feet long and 6.6 feet wide. The intersection of the car side and locomotive front determines the depth of penetration of the automobile.

An initial attempt to model the forces on a simple spring basis, as in the CSR model, was unsuccessful, as an inspection of Figure 3-13 would indicate. As soon as the major structure of the automobile is engaged, a maximum acceleration is reached for the entire vehicle, while the deformation is still minimal, except for the coupler passing through thin sheet metal. As the deformation increases, the acceleration and force are decreasing. Thus a spring would have to have negative force coefficients against displacement in order to describe the actual behavior recorded. A standard curve of force as a function of deflection alone would be unrealistic, for clearly the force is a dynamic quantity depending on relative speed, rather than exclusively on static deflection. In fact, after inelastic distortion, there may be no force once the deflection has been produced. Thus a viscous force proportional to deflection rate similar to that used by Minicars in its model, was introduced. Such a force is relatively realistic because the force can now be proportional to the rate at which structural volume is crushed, which is an energy rate, dimensionally equivalent to force when one realizes that the rate is a displacement or distance rate rather than a time rate.

With these assumptions for the model it became possible to duplicate the accelerations recorded in the test where the automobile was centered on the tracks. However, this was essentially a one-dimensional trajectory with the automobile impaled on the coupler. Attempts to duplicate both the linear and angular motions that occurred in test TGB-4, with the automobile offset on the tracks, were unsuccessful , even when different force coefficients were allowed for along-track and normal-to-track motion. Coefficients that produced reasonable duplication of the linear accelerations would not produce the proper angular motion, and conversely. The quickest solution was modifying the automobile model by replacing the homogeneous body with a structure with four tranverse elements which received all the load. This resembles the Minicars approach. The transverse elements were located at each end and at locations equivalent to the A and C posts at the front and rear of the passenger compartment. With these modifications it became possible to reproduce the behavior of the automobiles in the test crashes, but only after applying drastically different coefficients to along-track and cross-track forces.

The forces needed to match the test data were reassuring in that practically all of the force applied came from the viscous, or crushed volume rate, force, with only a few percent (typically 2 or 3) originating in the spring forces. This would be expected from the shape of the curves in Figure 3-13. There were some problems in choosing the direction of the forces, which is difficult to identify in a rigid metal to metal contact. The very small spring forces, proportional to penetration depth, were simply assumed to point straight ahead along the tracks. The first approach was to make the crush rate forces normal to the nominal undistorted automobile side, for want of any better model. This approach was unsuccessful and the cross-track components were simply increased by use of a larger coefficient. The forces were assumed to apply equally to each of the transverse elements encountered by the locomotive front (typically two in an off-center crash); and the moments determing automobile rotation were thereby fixed as well.

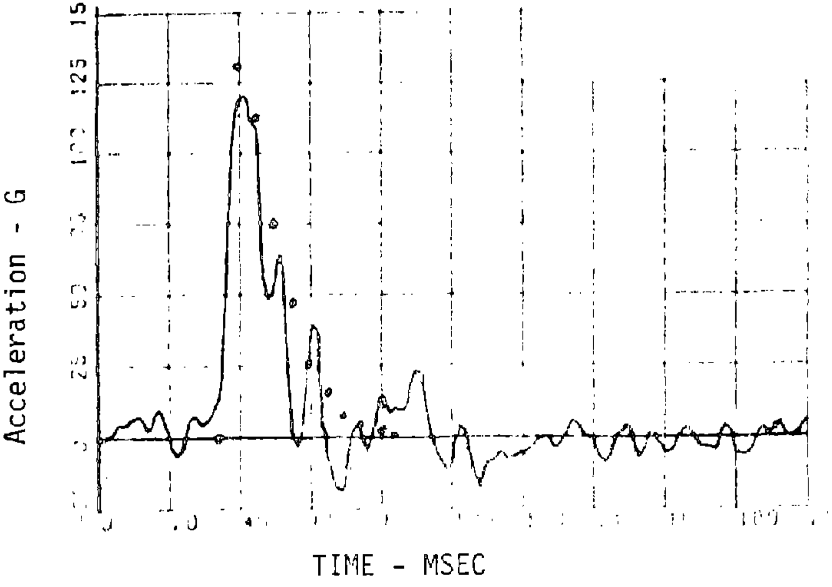
Simulations were then conducted with this model for parabolic fronts which protruded either one foot (flat front) or ten feet (rounded front), with the automobile center of gravity midway between the tracks as in test TGB-3, or in front of the left side of the locomotive as in test TGB-4. Time zero for the simulation runs represented the start of the period of high acceleration, and therefore corresponded to time .035 seconds of the tests.

Further details on the simulation equations are presented in Appendix A, and numerical results appear in runs N1 to N5 inclusive of Appendix B. For one run with the rounded front, the center of gravity of the automobile was moved two feet in from the left side of the locomotive.

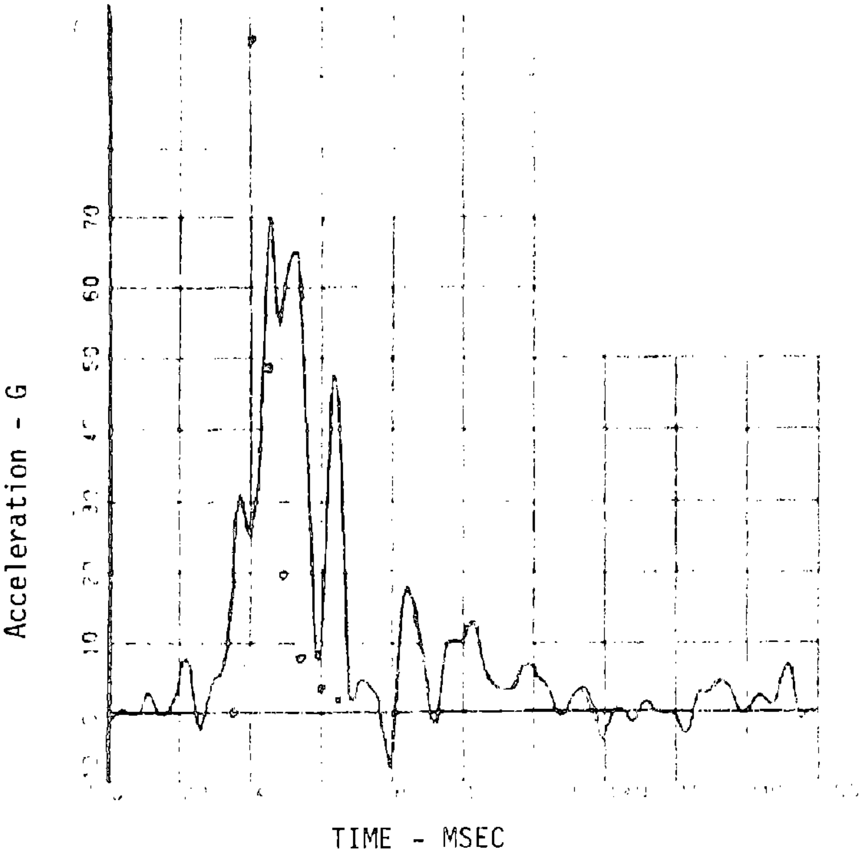
3.3.10.4 Simulation Results

With the automobile initially centered on the tracks, it remains on the tracks. With the automobile initally offset, it clears the tracks in about 225 milliseconds. With two feet less offset, the automobile clears the tracks at 300 milliseconds. This agrees in general with the tests, since 225 milliseconds for the simulation corresponds to 260 milliseconds for the crash test, with the 35 millisecond delay in starting time of the simulation runs.

Figure 3-14 shows plots of the automobile lateral acceleration, as recorded in the tests, and points from the corresponding simulation runs, where the along-track acceleration is recorded. For the first 100 milliseconds, the lateral automobile accelerations are essentially along the track direction. Figure 3-14 (a) shows very good agreement between the test and the corresponding simulation; figure 3-14 (b) shows less agreement. Actually, in the test accelerometers located at various parts of the automobile show distinctly different traces. The simulation is



(a) Test TGB-3 (curve) and Run N-2 (points)



(b) Test TGB-4 (curve) and Run N-1 (points)

Figure 3-14

Comparison of Lateral Accelerations in Tests (Left Rear Occupant Compartment) and Along-Track Acceleration in Simulation intended to represent the motion of the center of gravity, which would be a weighted average of the motions of individual parts of the automobile. The plotted points of figure 3-14 (b) show a peak acceleration of 96.5 g; points of the automobile body in the test showed acceleration peaks ranging generally from 70 to 117 g, with values from 80 g to 100 g fairly common. The time of occurrence of the peak acceleration varies with the location, being a function of how the locomotive plate and the coupler strike the automobile and how it responds.

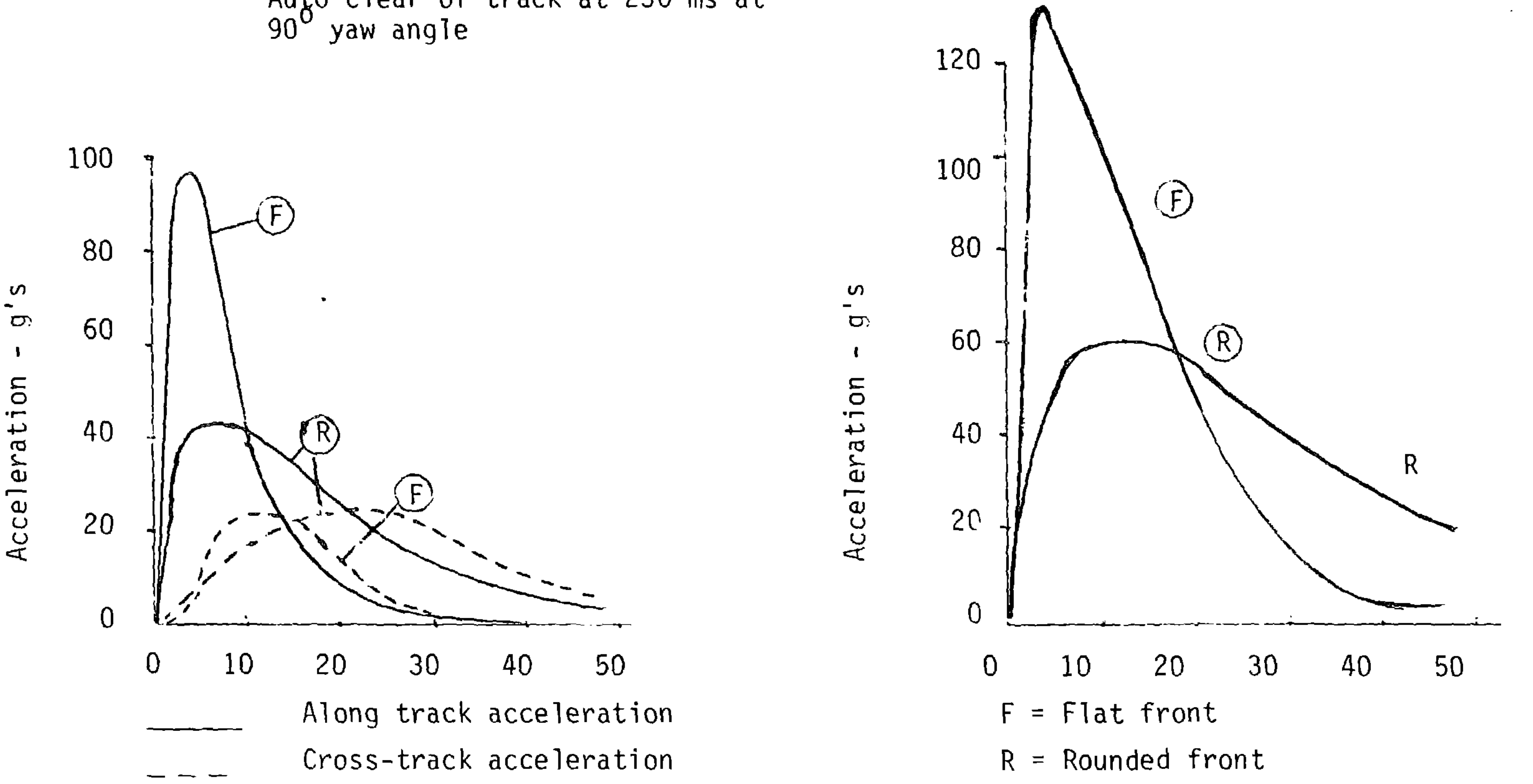
Comparison of cross-track accelerations in the simulation with the longitudinal automobile accelerations in test TGB-4 was difficult because the curves presented in reference 2-1 are not easily read since the longitudinal accelerations appear only as part of a triplet of accelerometer curves which cannot readily be distinguished from one another. However, the cross-track accelerations in run N-1 were matched to the one readable curve from test TGB-4, which showed longitudinal acceleration at the engine.

In summary, runs N-2 and N-1 provide reasonable, but not precise, representations of the along-track motion of the automobile center of gravity in conditions corresponding to those of tests TGB-3 and TGB-4 respectively. The cross-track linear motion and the angular motion in run N-1 are also reasonable representation of the corresponding quantities in test TGB-4, to the limited extent that the test observations of these quantities were available and readable.

Test TBG-4, with the automobile offset, shows significantly lower automobile accelerations than test TGB-3, where the automobile is centered. The simulator runs showed similar behavior.

The behavior of the flat front in simulations can be compared to that of the rounded front, represented by Tables N-3, N-4, and N-5 of Appendix B. Figure 3-15 presents plots of the linear accelerations for the two shapes and for the two different automobile locations. As with the flat front, the rounded front shows lower accelerations for the offset automobile.

Conditions: Train Speed = 50 MPH
Vehicle Weight = 4693 lbs
Initial Velocity = 0 MPH
Initial Yaw Angle = 0°



(b) Auto offset on track

Auto clear of track at 230 ms at 90° yaw angle

(b) Auto centered on tracks

Figure 3-15 Simulation of Hard Front Crashes

For each automobile position, the rounded front shows a much lower acceleration peak, and a longer duration of the period of acceleration. The centered automobile reaches a forward speed of 45 mph at time 25 milliseconds with the flat front, and at about 53 milliseconds with the rounded front (see runs N-2 and N-5). The 45 mph speed is nine tenths of the locomotive speed and thus represents the end of the major along-track acclerations. However, the reduced acceleration with the rounded front is accompanied by a greater penetration depth of 1.37 feet at 25 milliseconds, versus 0.88 feet for the flat front, and 1.84 feet at 50 milliseconds versus 0.94 feet. Primary impact injury increases with penetration depth secondary impact injury grows with acceleration.

The lower acceleration with the rounded front is the result of the model used which makes the force between the vehicles proportional to the rate of crush of volume, which is in turn the product of the cross-section of the contact area, and the relative speed. The flat front almost immediately engages a large area of the automobile side, producing a large force and acceleration. The rounded front has the same relative speed at first contact, but engages a much smaller area. For an encounter with a homogeneous body, this model is probably relatively realistic, but in a crash with a rigid locomotive front the yielding automobile body is far from homogeneous. In fact, a sheet metal skin covers a structure of distinct members, with separated lateral stiffening structures, and these structures determine how the vehicle yields.

In light of the difficulties encountered in modeling cross-track acceleration, and of the drastically different coefficients of force used for the along-track and cross-track components, there is little to be gained by drawing conclusions from the cross-track motion in the simulation. An additional problem came from the fact that the longitudinal automobile accelerations in the crash tests were frequently not easily readable from the figures of reference 2-1. The simulation coefficients were chosen to match the one curve that was most easily readable, which may not have been typical, and also to match approximately the behavior described from the photographic record. Consequently, it appears that any conclusions should be based on the along-track motions only, for these appear relatively consistent and are satisfied by simple and relatively realistic equations.

3.3.10.5 Summarization

A rounded front appears to offer some significant reductions in automobile accelerations in a hard front collision. The rounded front requires deployment with a larger and probably more complex mechanism than the simple flat front, and has the probable drawbacks of increasing the number of accidents. Compatibility with anti-climbing mechanisms is necessary for both flat and rounded fronts, and may present more problems with the rounded front, simply because it involves more material. The materials and techniques involved are conventional and familiar to the railroad industry. Both devices should prevent impalement of a struck automobile on the coupler.

A serious problem may appear with long deflectors. This is the probability, discussed in Appendix C, that increasing the length of the locomotive by extending the front forward, will cause an increase in the number of accidents. A particular class of accidents, where drivers attempt to cross in front of a consist they know is moving, is affected, and can be affected quite seriously. The increase in accidents is approximately proportional to the deflector length.

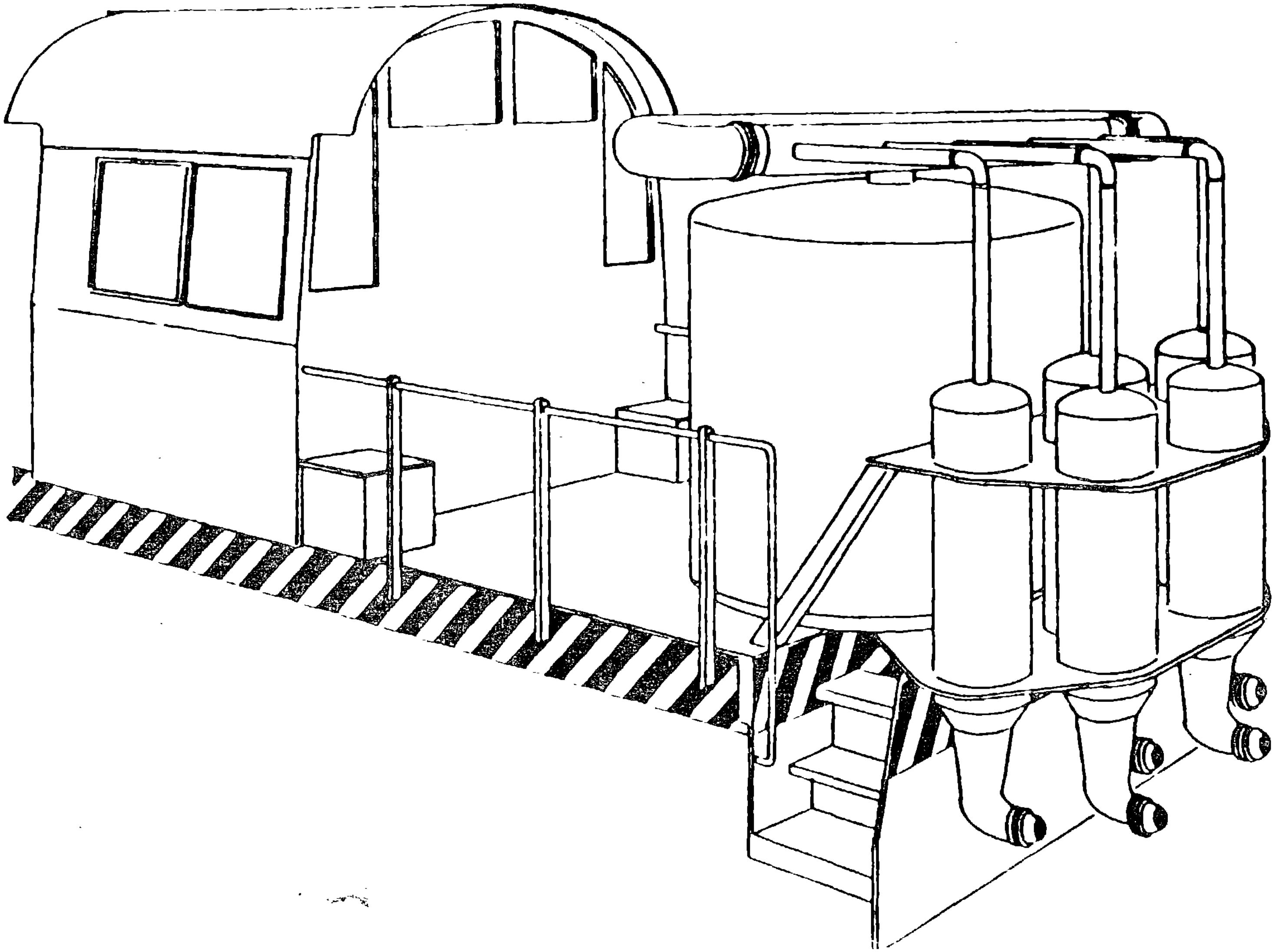
3.3.11 The Water-Jet Collision Attenuator

3.3.11.1 Description and General Discussion

This collision attenuator was considered in an unpublished study by Minicars, Inc., and a preliminary design was presented. Figure 3-16, extracted from this study, illustrates the concept. A supply of water is carried on board the locomotive for use, in water-cannon fashion to accelerate a highway vehicle which is in the locomotive's path. The goal is either removing the highway vehicle from the right of way before the locomotive arrives, or accelerating the vehicle to make the collision with the locomotive less violent.

The system is "active", i.e. it requires automatic actuation when a collision is imminent, by a signal from a radar detection subsystem which senses the presence of the highway vehicle on the right of way. In the design illustrated, the water is stored in five tanks of 15 cubic feet each, and released through five nozzles which point forward. Energy to drive the water is provided by a 200 cubic foot tank of compressed air to 250 psi. Actuation is accomplish by explosive rupture of a diaphragm by means of a pyrotechnic device (blasting cap). If the locomotive is to operate in a freezing climate, presumably a calcium chloride solution or other non-freezing solution would be used. Water exit velocities of up to 150 feet per second are achievable with such pressures if the cross section of each nozzle is about 0.5 square foot. With five nozzles, the release rate of 375 cubic feet per second corresponding to a 150 feet per second nozzle velocity would provide a spray of 0.2 second duration. Presumably the spray would be released at an initial distance of between 20 and 50 feet from the automobile; the range could be adjusted to depend on train speed.

The concept is of interest since in effect it constitutes a very long and very soft attenuator. The momentum of the water is transferred to the automobile while the automobile is still at a considerable distance from the locomotive. This allows time for removing the automobile from the



· Figure 3-16 PROTOTYPE WATER JET ATTENUATOR SYSTEM INSTALLED ON LOCOMOTIVE
(Reprinted from study for FRA by Minicars, Inc.)

tracks or bringing it up to a speed along the tracks which minimizes the effects of the actual collision. Because of the system's implicit position as the "gentlest" of possible attenuators, it was decided to simulate it, so that the results could be compared to those of other simulations. The simulation is discussed before the system characteristics are evaluated.

3.3.11.2 Simulation Model

The water is assumed to be emitted in a stream spread uniformly across the locomotive front's ten foot width. The stream retains its original nozzle velocity and remains in a ten foot width without spreading out. Two nozzle velocities, 150 fps and 110 fps, were used; the actual water velocity is the sum of the locomotive velocity and the relative nozzle velocity. Two locomotive speeds, 40 mph and 80 mph, were used. The height of the stream is assumed to be such that an automobile intercepting any horizontal segment of the stream receives all of water passing through that segment. This corresponds to the water stream remaining at a height which meets the automobile sides, e.g. between about 10 and 36 inches. These assumptions give the system maximum effectiveness in accelerating the automobile.

Upon contact with the side of the automobile , the water transfers to the car all the momentum due to its velocity component normal to the side. The velocity component parallel to the automobile side is presumed not to affect the automobile, i.e. the water simply rolls along the side. The automobile is modeled as a homogeneous body with no width, a center of gravity 40 percent from the front end, and uniform densities in front of and behind the center of gravity. The length is 15 feet and the weight 3200 pounds, except for one run in which a weight of 5000 pounds was used. The automobile is initially either at rest or moving at 25 mph to the right; its longitudinal axis makes an angle θ with the x axis (perpendicular to the tracks), of either 0° or 30°, positive θ being a counterclockwise measurement from the x axis to the automobile axis. Two of the runs included a simple model of friction between automobile and ground.

The automobile center of gravity was located in either of three positions, in front of either the left side, the center, or the right side of the locomotive. Time t=o occurs when the water first contacts the automobile, at which time it is 40 feet from the locomotive. This means that the water was initially released between .267 and .364 second earlier, depending on the water nozzle speed. At that time, depending on its speed, the locomotive is between 55.6 and 82.7 feet from the automobile.

Equations of the simulation are presented in Appendix A, and results in Appendix B.

3.3.11.3 Attenuator Performance

Table 3-3 summarizes results of 14 simulation runs. In most cases where the automobile was not centered on the tracks, it clears the track before the arrival of the locomotive. The acceleration levels are modest and survivable; the highest acceleration of 19.2 g occurring in one case where the automobile is centered on the tracks and the train is moving at 80 mph. Collisions occur in both runs where the locomotive speed is 80 mph, and also in the cases where a friction coefficient between ground and automobile was used. Otherwise, the automobile was clear of the tracks before the arrival of the train.

The apparent good performance in the simulation runs should be subject to some words of caution. First, as indicated earlier, the model favored the system performance by assuming that the water stream neither diverged nor slowed down; both assumptions are not very realistic at release distances of between 55 and 80 feet. In addition, it was assumed that the automobile received the full stream of water it intercepted, and all the momentum in the water at a direction normal to the side of the car. In fact, much of the water is likely to pass under or over a typical automobile, and the momentum transfer may not be total. However, other considerations applying to the water jet system will determine whether or not it is acceptable. For the moment, the runs provide boundaries on a attenuator performance in the sense of attenuator "length" (range at water release), and acceleration levels.

TABLE 3-3 SIMULATION RESULTS, WATER-JET ATTENUATOR

RUN	DURATION OF WATER FLOW (seconds)	MAX, AUTO, ACCELERATION ALONG TRACK (g's)	INITIAL AUTO LOCATION (ft)**	INITIAL AUTO SPEED (mph)	INITIAL AUTO DIRECTION ( )	TIME WHEN AUTO CLEARS TRACK (seconds)	LOCOMOTIVE SPEED (mph)
W-1	.2	10.9	+10	0	0	8 sec	40
▲W-1F	.2	10.6	+10	0	0	may not clear	40
W-2	.2	7.6	+10	0	30°	1.7 sec	40
W-3	.2	9.8	+10	25	0	.2 sec	40
W-4	.2	8.5	0	25	0	.45 sec	40
*W-5	.2	5.6	0	25	0	.5 sec	40
W-6	.27	5.6	0	25	0	.6 sec	40
W-7	.2	11.4	0	25	30°	1.25 sec	
▲W-7F	.2	11.4	0	25	30°	collision at 1.58 sec	40
W-8	.2	4.8	0	0	30°	.3 sec	40
W-9	.2	9.2	+5	0	30°	.45 sec	40
W-10	.2	12.0	+5	25	0	.25 sec	40
W-11	.2	19.2	+5	0	0	collision at 1.261 sec	80
W-12	.27	14.1	+5	0	0	collision at .32 sec	80

▲ A crude friction model was used in these runs

* Auto weight. 5000 lbs. For all other runs, weight is 3200 pounds

** Distance from locomotive left side to automobile center of gravity

Consider first the performance in the emergency pre-collision situation. The water jet may indeed remove an automobile from the locomotive path or reduce the collision severity in the simulation conditions, but there are several additional factors to consider. First is that the water stream may actually trap pedestrians or persons escaping from the automobile in the locomotive path. A person between the automobile and locomotive would be driven into the automobile by the water. A person on the other side of the automobile would probably lose his footing, and then be swept down track, ultimately to be struck by the locomotive. If automobile windows are open, persons in the automobile may be injured by the water, or may claim to be injured.

If the automobile is ultimately struck by the train, it can be claimed that it would have escaped without collision had not the water jet been actuated. If there is no collision, the same claim may be made for any property and personal damages, including psychological trauma. The operation of any remote acting system always opens the question of what might have happened had the device not been actuated, and invites litigation. This is one of the indirect effects listed among the evaluation criteria in Section 3.2; the occurrences described in reference 3-2 indicate that such litigation does actually occur. Finally, there may also be cases where no collision would have occurred had the water jet not been actuated, in other words, where the collision is actually caused by the system, even though the simulations do not identify any such cases.

With an active system, there is also always the possibility that the system does not function when it should, or malfunctions in some way. For example, the radar may malfunction and not provide the actuation signal at the proper time, or at all. Actuation at the wrong time could indeed create a collision when none would have occurred. There is also the possibility of the blasting caps failing to explode to release the water, and possibility of blockage of or damage of the nozzles by debris encountered during travel or by vandalism. Finally, the influence of the water jet on the vehicle also depends on the shape of the vehicle; a jet that is effective against an automobile may be ineffective against a van, and conversely.

The preceding problems are enough to create serious doubt about the overall system effectiveness. To these must be added the problem of inadvertent actuation of the system (either unintentially or by intent, through vandalism) and the potential damages and injuries created by such actuation. The radar system must also be protected against actuation by the transmitter on another locomotive approaching on double track system, and against the reflections from a passing train. Such protection is possible, but increases system complexity and cost. Finally, attempts to actuate the system would be attractive to juveniles interested in the display and in vandalism.

Consider next the problems of maintenance and inspection during routine operations. Police radars, which are admittedly different since they are doppler devices, are normally calibrated daily before use. A similar checkout before each trip is probably required for the complex water jet system, to determine that an actuation signal will be emitted in the proper circumstances, and at the proper range. Note that such checkout would only check subsystems up to the point of firing the blasting caps, and that a separate inspection of the nozzles would be needed. A significant amount of time would be required for checkout, with corresponding costs. In addition, the blasting caps would require periodic replacement as they age.

The Minicars study also mentioned the possibility of a system which could detect automobile velocity and which could swivel the nozzles to direct the water stream so as to move the vehicle off the track. Such a system would require a complex and expensive scanning radar, and a computer and servo system for the nozzles. To keep such a system working would require a very high level of maintenance and would be extremely expensive, as would be the initial cost. Such a system is totally out of the range of practicality for any sort of economic railroad operation.

In addition, the cost estimates for the water jet system included a figure of $15 per year for total maintenance and operating expenses of either the water jet system or the more complicated "steered water jet" system just mentioned. This estimate is probably low by several orders of magnitude.

Consequently, the water jet system is dismissed from further consideration as impractical.

3.3.12 Crushable Collision Attenuators

3.3.12.1 Description and General Discussion

In the unpublished study done for FRA, Minicars Inc. examined the concept of a crushable attenuator aimed at controlling impact forces on the automobile. Attenuators of lengths up to ten feet, capable of being stowed permanently on locomotives and deployed into position of use when the locomotive was used in lead position, were given some preliminary design studies. Longer separate attenuators with their own wheels, capable of being articulated or coupled to the locomotive, were also considered. The studies included examination of choice of materials, and two kinds of honeycomb were selected for the initial design concept, paper for a very soft easily crushable front section, backed up by a firmer aluminum honeycomb. The design goals were to hold the initial contact forces with the automobile to a level of 10,000 pounds, to be followed by forces rising to a peak of 110,000 pounds. The rising force curve was obtained by varying the cross-section of the aluminum honeycomb along the length of the attenuator. Figures 3-17 and 3-18, reprinted from the Minicars study, illustrate the deployable attenuator concept.

In its crashworthiness study performed for UMTA (2-5), Calspan Corp examined similar crushable attenuators to reduce injuries in collisions between passenger cars. Various lengths between 8 feet and 50 feet were considered, with the shortest version being cantilevered to the car, the intermediate lengths articulated through the coupler, with one truck on the attenuator, and the longest version an attenuator with two trucks that couples to the car. Since the design goal was to absorb the energy of an eight car train at speeds in the twenty to thirty mph range, the materials proposed had much higher yield points than the automobile collision attenuator. Although, the concepts were similar, the train-to-train collision attenuator concept emphasized the anti-climbing problem.

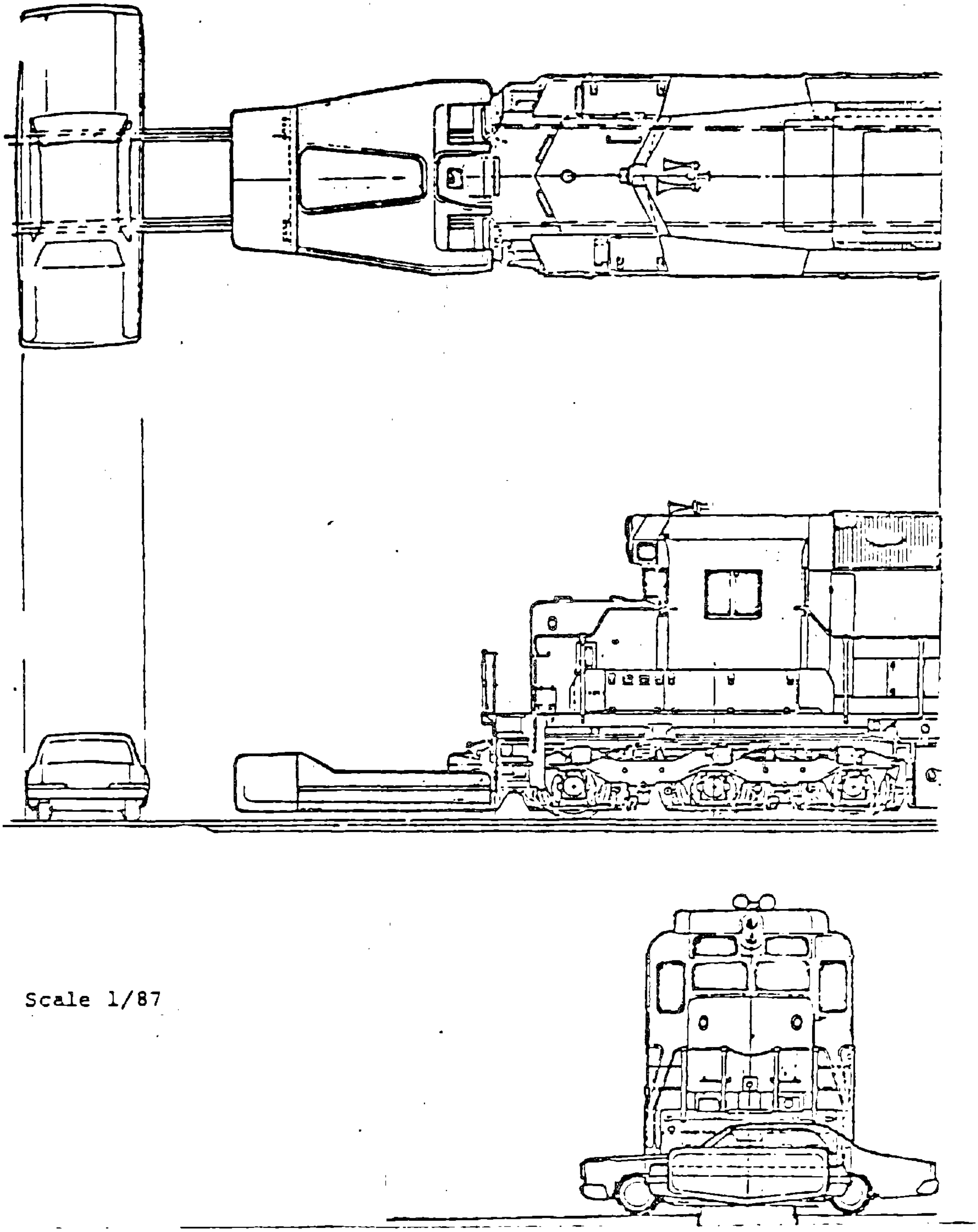


Figure 3-17 LOCOMOTIVE-TO-AUTOMOBILE RELATIONSHIP--DEPLOYED CAD (Crushable Attenuator)

Reprinted from study for FRA by Minicars, Inc.

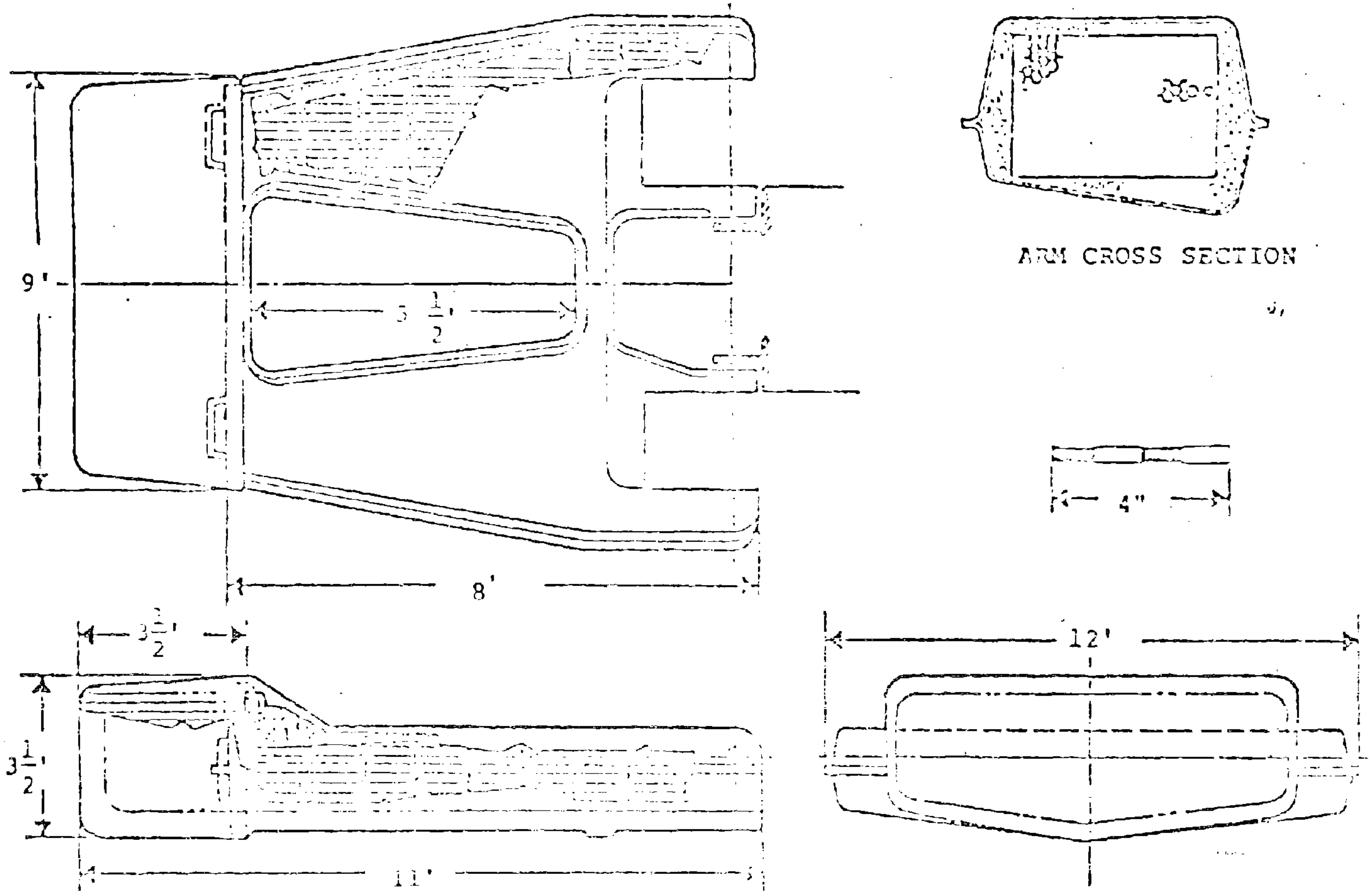


Figure 3-18 BASIC DIMENSIONS OF CAD DESIGN CONCEPT
(Reprinted from study for FRA by Minicars, Inc.)

Minicars in its study chose the illustrated design for their most detailed effort. The deployable device, shown in stowed position in figure 3-19, is shaped to permit access from one locomotive to another despite the presence of stowed attenuators on both locomotives. (Such access will not be available if proposed new standards require closing and considerable strengthening of the access doors at the end, to prevent flammable fluid entry.) The materials used were selected for structural suitability, cost, and availability, and consideration was given to proper weatherproofing and protection from collisions with small pieces of debris along the right of way. The arguments are not repeated here, rather the concept is accepted as reasonably effective and some simulation runs are made. Minicars also reported on the results of somewhat similar simulations accomplished in its study. The simulation results would provide interesting comparisons with those for the extremely "soft" water-jet attenuator.

The effectiveness of a soft collision attenuator in reducing injuries will be discussed after the simulation procedure is outlined. Clearly the soft attenuator can potentially provide a milder collision environment than a hard face deflector. There may be questions of effectiveness and of potential problems in collisions, depending on the design.

In addition to behavior in collisions, the requirement and performance of the attenuators in normal operations must be considered. The cantilevered honeycomb attenuator is stowed in vertical position on the locomotive front. A horizontal cross section of the stowed configuration is shown in figure 3-19; the attenuator must be lowered into the operating position (fig. 3-17) on the lead locomotive before each trip. After the trip it must be stowed back in the vertical position. The durability of the device is presumably achieved by suitable design procedures, some of which were discussed by Minicars. Thus the operational characteristics are accepted as satisfactory. No other operational problems are known at present.

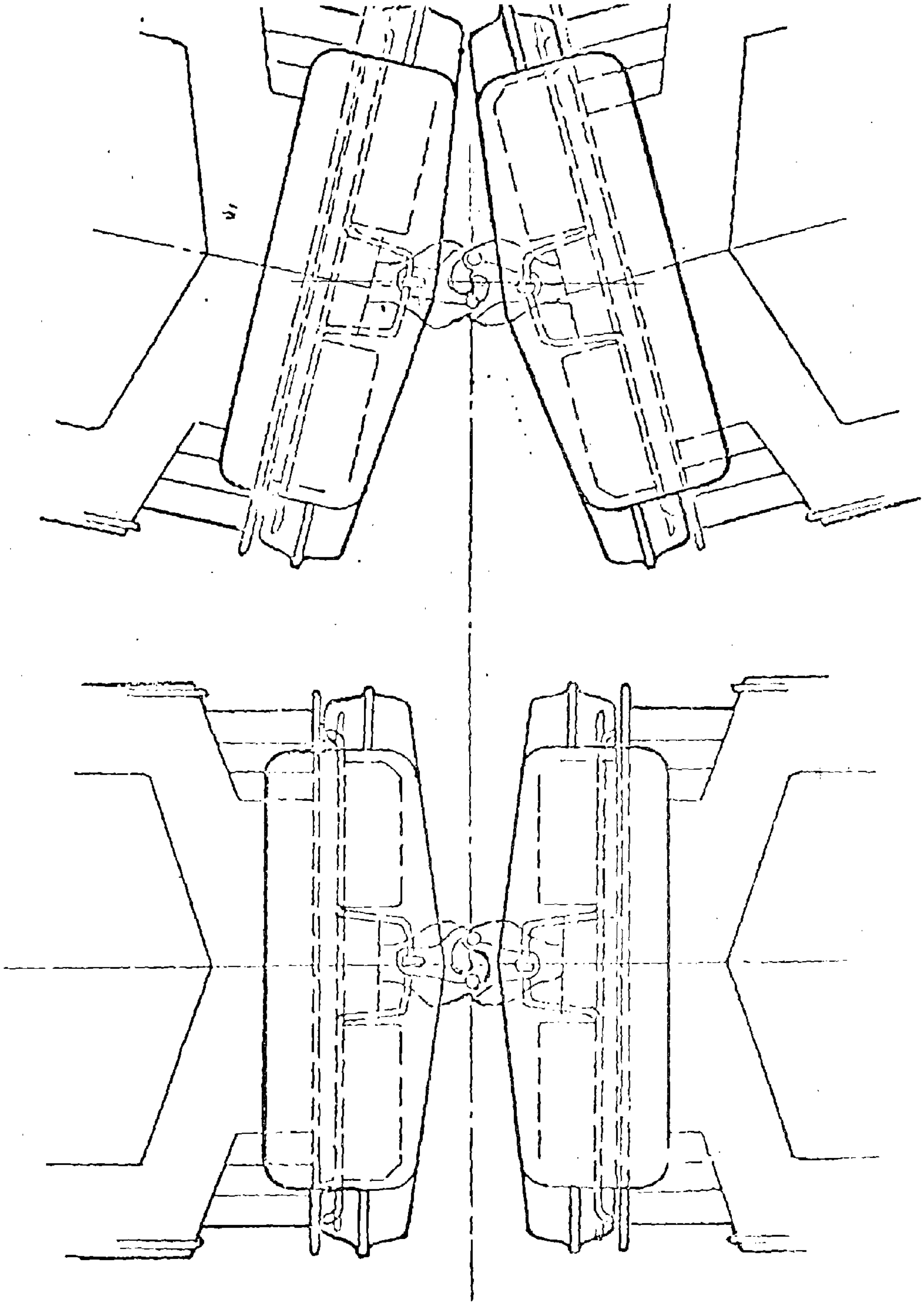


Figure 3-19 CAD in Stowed Position, Plan View
(Extracted from Minicars, Inc. study)

The long attenuator with wheels must be attached to the locomotive front, either through the coupler or other attachment points, before each trip, and detached and stored afterwards. The same methods used to ensure durability of the deployable attenuator can be applied to this version. However, another problem appears for the wheeled attenuator, which must be light in weight if it is to serve effectively to reduce injuries. The light weight may make the attenuator very subject to derailment, particularly since the articulation to the locomotive may supply additional vibratory excitations beyond those imposed by rail irregularities. Attenuator derailments imply stops and delays for the consist, and may also frequently imply destruction of the attenuator. Thus this attenuator would be acceptable only if relatively free from derailment problems, but no information on behavior of such a device has been located in this study.

Aside from the problems in normal operations mentioned above, there is a question of behavior in other emergency situations, notably train-to-train collisions. Compatibility with anticlimbing measures is the principal requirement and should be achievable by suitable design measures, but could conceivably require modification of the anticlimbing system in some cases. Since there are now no standard, universal, anticlimbing systems on locomotive fronts, this does not appear to present a problem.

3.3.12.2 Crash Force Models

With the crushable attenuator, the automobile is assumed to be infinitely rigid for simulation purposes, and the attenuator instantaneously conforms to the automobile shape. In interpreting results, the automobile could be assumed to have yielded also, perhaps in proportion to the attenuator yield, with the relationship established by some sort of yield level or stiffness factor.

In its simulation work, Minicars was able to express force exerted by the crushable attenuator solely in terms of the crush distance, because the materials and cross section had been chosen to produce selected force values. The choice of materials fixed the yield pressure, and the cross section, which was varied, determined the area and total force. The first three feet of crush material was paper honeycomb with a yield pressure of 5 psi and a total cross section that could produce a 10,000 pound force at the yield point. The next five feet involved aluminum honeycomb of 50 psi yield strength, but with cross section increasing from front to rear, so that force exerted increases from 10,000 to 110,000 as the attenuator is crushed. The final foot of crush remained at 110,000 pounds yield force.

The simulation in this study was simplified by assuming a constant cross section of uniform material, and the results were supplemented by an analytic study which allowed variable cross section and determined relationships between some of the variables involved. The analytic study assumed the attenuatorto be shaped like a horizontal truncated pyramid with square cross-section and straight line taper from front to rear. In both simulation and analytic study, the material yield point is assumed to be exceeded immediately upon contact, and the forces are assumed to remain at the yield point level until the vehicles have the same forward velocity or start to move apart, at which point contact forces drop to zero. Equations for both the analytic model and the simulation are presented in Appendix A; the simulation program and tabulations of runs appear in Appendix B.

The analytic study covered only the case of an automobile which remains centered on the tracks without rotation or cross-track motion. In this case the automobile remains in contact with the full cross-section of the attenuator throughout the collision, and the force is the product of the contact area and the yield pressure of the material, until the final moment $t = t_f$ when the automobile reaches the same speed as the locomotive and force ceases. (No friction with the ground is assumed.) The same force model is used in the simulation, except that the contact area varies with the automobile angular position, and the force is presumed normal to the automobile side. In the few simulation cases where the complete length of the attenuator is crushed, the force on the automobile is assumed to be a linear combination of the crushable attenuator force model and the hard front locomotive force model.

3.3.12.3 Analytic Study and Simulation Results

The analytic study expressed maximum depth of crush (d_f) of the attenuator in terms of three quantities - locomotive speed (v_L) and initial and final accelerations (g_I, g_F). Final acceleration occurs at the time t_f when the automobile reaches the same speed as the locomotive, initial acceleration at time of first contact. Relating the two accelerations to attenuator characteristics and automobile mass permits interpreting the initial results in terms of performance goals or guidelines for the attenuator. The formula expressing the relationship is:

$$d_F = \frac{1.5V_L{}^2}{32.17} \cdot \frac{1}{g_F + \sqrt{g_f g_i} + g_i} \qquad (3\text{-}1)$$

where d_f is expressed in feet, V_L in feet/second , and g_f and g_i in g's, with g = 32.17 feet/second ^{2}. Figure 3-20 shows plots of this relationship, in the form of a set of curves, with the initial and final accelerations as the abscissa and ordinate, where each curve represents some combination of values for d_f and V_L. Each curve begins where initial acceleration g_I is zero (corresponding to a pointed pyramid attenuator) and ends where initial and final acceleration are equal (corresponding to a constant attenuator cross section). For example, one curve represents a penetration depth of d_f of 8 feet and a locomotive speed V_L of 50 mph. At one end of the curve a final acceleration of 32 g is required, at the other end

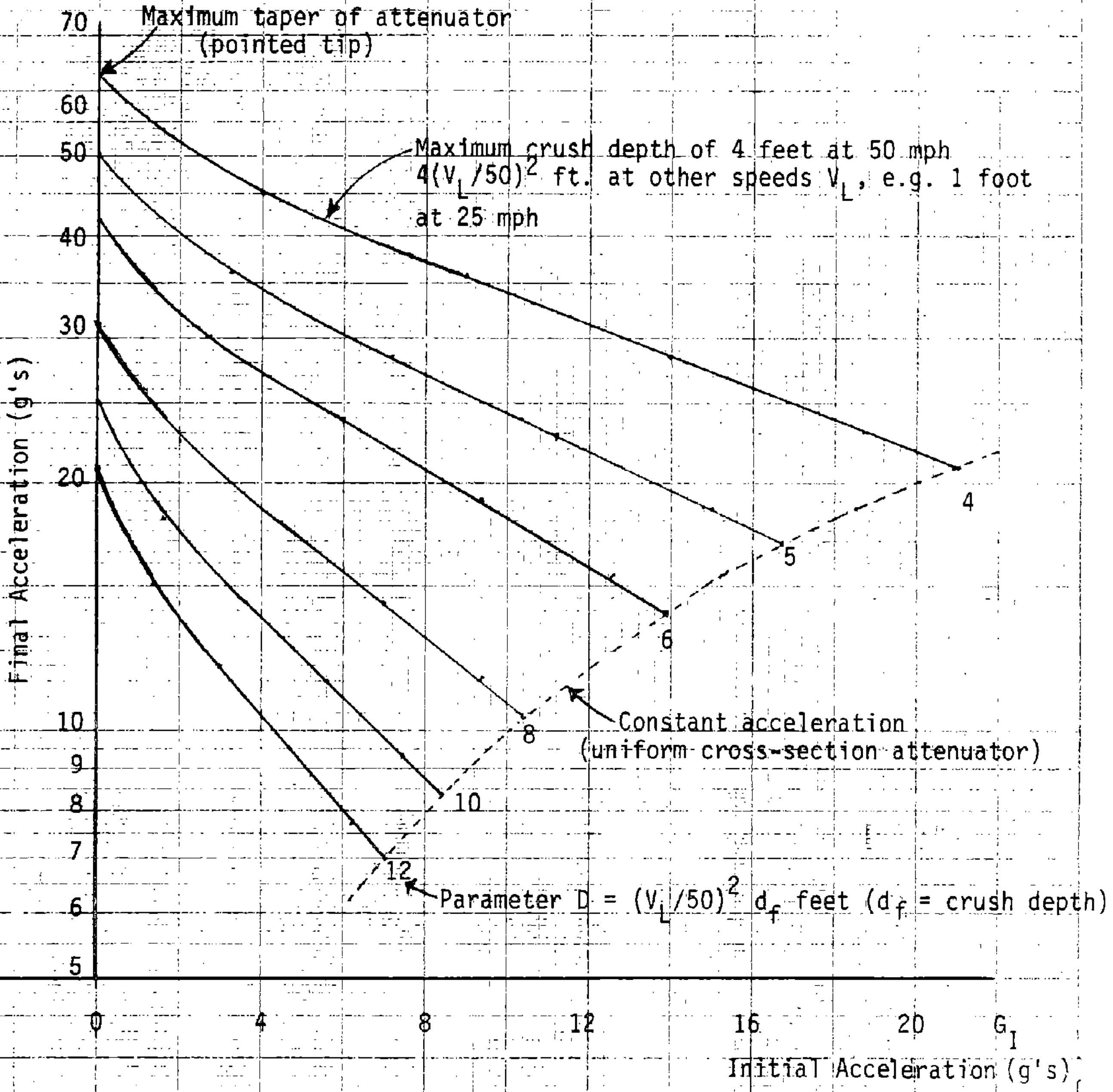


FIGURE 3-20 RELATIONSHIP OF DEPTH OF CRUSH OF ATTENUATOR TO LOCOMOTIVE SPEED AND AUTOMOBILE INITIAL AND FINAL ACCELERATION

a uniform acceleration of 10.5 g keeps the total crush depth to 8 feet. The same curve could equally represent behavior with a 25 mph locomotive and two foot crush depth, or 35 mph speed and 3.92 foot depth.

The parameters considered thus far, acceleration and attenuator crush depth, are important to injury rates in accidents, and to the attenuator geometry. The relationship above (3-1) admittedly is derived for only the case of an automobile centered on the track, and does not cover the collision with an offset automobile, but it is still useful as a guide. The simulation can help explore the behavior for the offset case. However, formula 3-1 permits selecting a range of survivable accelerations and relating it to an attenuator length for a range of speeds. Attenuator length is a factor influencing acceptability of the system to the railroads. The speed ranges of importance will be considered later under the subject of benefits and injury models; what is important is to influence a statistically important part of the total number of accidents involving casualties.

Note that the parameter d_f represents a maximum crush depth in certain speed and acceleration conditions, but is used also as the total attenuator length, if one assumes the postulated conditions to be the maximum the attenuator will withstand. Note also the assumption that until the final time t_f, the attenuator is always yielding at its crush yield point.

When turning to the question of automobile and attenuator characteristics, the desired goals in acceleration and crush distance must be translated into feasible and practical attenuator materials, sizes, and construction practices, and into a design that satisfies the goals for a satisfactory statistical part of the automobiles and other vehicles which will be encountered. The criteria now are forces, which for the attenuator involves material yield point and cross section, and which relate back to the accelerations through the highway vehicle mass.

The relationship can be illustrated by an example. For instance, suppose it was decided that acceptable acceleration levels were 6 g initial and 24 g final acceleration, and that the attenuator should be completely used up, or crushed, by a 4,000 pound automobile in a 50 mph collision. The curves of figure 3-20 imply a 6 foot attenutor length, and the attenuator yield point and cross section can be matched to these requirements.

Obviously, at 50 mph a 5,000 pound vehicle will completely crush this attenuator and will sustain higher accelerations when it meets the rigid attenuator backing. On the other hand, a 3,000 pound vehicle will be accelerated to locomotive speed before the material is crushed to a depth of 6 feet; in this case initial acceleration will be higher because of the lower mass of the automobile. The crush depth for this case can be computed using the formula given in Appendix A. For the case cited, a 40 psi crush point material would require a pyramid 2.04 feet on the side at its tip and 4.08 feet at the base; the 3000 pound automobile would have a crush depth of 5.04 feet. The initial acceleration y_I varies inversely with the automobile mass, it will therefore be 8 g. The final acceleration can be read from figure 3-20 by interpolating to a curve where d_f is 5.04; it is 27.1 g.

Note that the pyramidal attenutor shape was chosen only for computional convenience, and is not a recommended design shape; the Minicars study presented arguments in favor of an increasing acceleration level, and this shape is adaptable either to a uniform or an increasing cross section.

The analytic results discussed so far pertain only to the collision where the automobile is centered on the tracks and does not rotate; they also do not cover the cases where the full length of the attenuator is crushed, either on one side or along its full cross section. The simulation addresses these situation, although it is limited to a uniform attenuator cross-section, assumed to be ten foot wide and three feet high, with three possible yield levels of 5.0, 7.5, and 10.0 psi. These yield levels are not practical for aluminum honeycomb, although they might be achievable with paper honeycomb. One could think of the 30 square foot cross section as a broad front which contacts the automobile, backed up by a much smaller cross section of material with a higher yield point, such as aluminum honeycomb. Paper honeycomb is structurally suitable for only a modest depth and load.

As indicated earlier, the automobile is assumed to be infinitely rigid, and the attenuator instantaneously conforms to its shape. The force is proportional to the contact area between the two bodies, and perpendicular to the side of the automobile. If only part of the automobile is in contact with the attenuator, the equations reflect the area engaged. The locomotive and attenuator move at constant speed with infinite momentum; when the automobile reaches the locomotive speed, force ceases.

When the automobile penetrates the full depth of the attenuator, the force formula becomes a linear combination of the hard-front contact formulae of Section 3.3.10 and the crushable attenuator formula, with a weighting factor depending on the relative areas engaged.

Tables A-1 to A-11 of Appendix B present the results of eleven simulator runs; with material yield points of 5.0, 7.5, and 10.0 psi, train speeds of 30 and 50 mph, mostly with a 3000 pound vehicle 16 feet long and 5 feet wide, and initially at rest perpendicular to the tracks. The vehicle center of gravity is either in front of the left edge of the attenuator, or three feet to either side of that location. For three runs a larger vehicle matching the crash test sizes was postulated - 4693 pounds and 18.6 by 6.6 feet. Table 3-4 and Figure 3-21 summarize some features of the simulation results, the table showing all the runs and the figure showing accelerations for a few runs, all with the same vehicle weight and initial location.

The modest acceleration levels reflect the relatively low yield points postulated for the material, and are generally comparable with the accelerations shown in the water-jet simulations. With the low yield point used, for all but one run involving a 50 mph train speed, the attenuator was crushed through its complete 10 foot depth. The exception was one run with a 10 psi yield point material. At 30 mph in general the attenuator did not crush through its complete depth. Complete crushing led in some cases

TABLE 3-4 SUMMARY OF SIMULATIONS OF CRUSHABLE ATTENUATOR COLLISIONS

RUN	MATERIAL YIELD (PSI)	MAXIMUM FORCE** (POUNDS)	INITIAL AUTO C.G. LOCATION (FT)	LOCOMOTIVE SPEED (MPH)	MAX. ACCELERATION (G) ALONG TRACK	MAX. ACCELERATION (G) CROSS-TRACK	ATTENUATOR CRUSHED TO END	AUTO CLEAR OF TRACK AT 90° ROTATION
A-1	10	31,100	0	50	10.8	-13.9	No	No
A-2	7.5	23,300	0	50	8.2	-9.5	Yes	No
A-3	7.5	32,400	+3	50	10.8	-7.3	Yes	No
A-4	5.0	15,600	0	50	5.4 (21.1)▲	-5.2	Yes	No
A-5	5.0	15,600	0	30	5.4	-7.9	Yes (Corner only)	Almost
A-6*	7.5	27,100	0	50	6.1	-8.3	Yes	Almost
A-7*	10.0	36,200	0	50	8.2	-12.1	Yes (Corner Only)	Almost
A-8*	5.0	9,100	-3	50	3.3 (43.5)▲	-1.8	Yes	Yes
A-9	7.5	23,300	0	30	8.2	-5.0	No	No
A-10	7.5	13,600	-3	30	4.9	-3.1	No	Yes
A-11	7.5	32,400	+3	30	10.8	-2.0	No	No

Automobile - 3000 pounds, 16 feet long, 5 feet wide, except a noted

* Runs A-6, A-7, A-8 - 5,000 pounds, 18.6 feet long, 6.6 feet wide.

Automobile initially at rest, perpendicular to tracks, center of gravity location measured from left edge of train, positive to right (into train path), negative to left.

Attenuator 10 feet wide by 3 feet high, 10 feet long.

** Based on actual area in contact with automobile , before bottoming out.

▲ Observed after bottoming out.

Conditions:

AUTOMOBILE INITIALLY AT REST, PERPENDICULAR TO TRACKS, C.G. IN FRONT OF LEFT EDGE OF LOCOMOTIVE. WEIGHT 3000 LBS.

TRAIN SPEEDS 50 MPH AND 30 MPH. ATTENUATOR YIELD LEVELS: 5.0, 7.5, 10.0 PSI

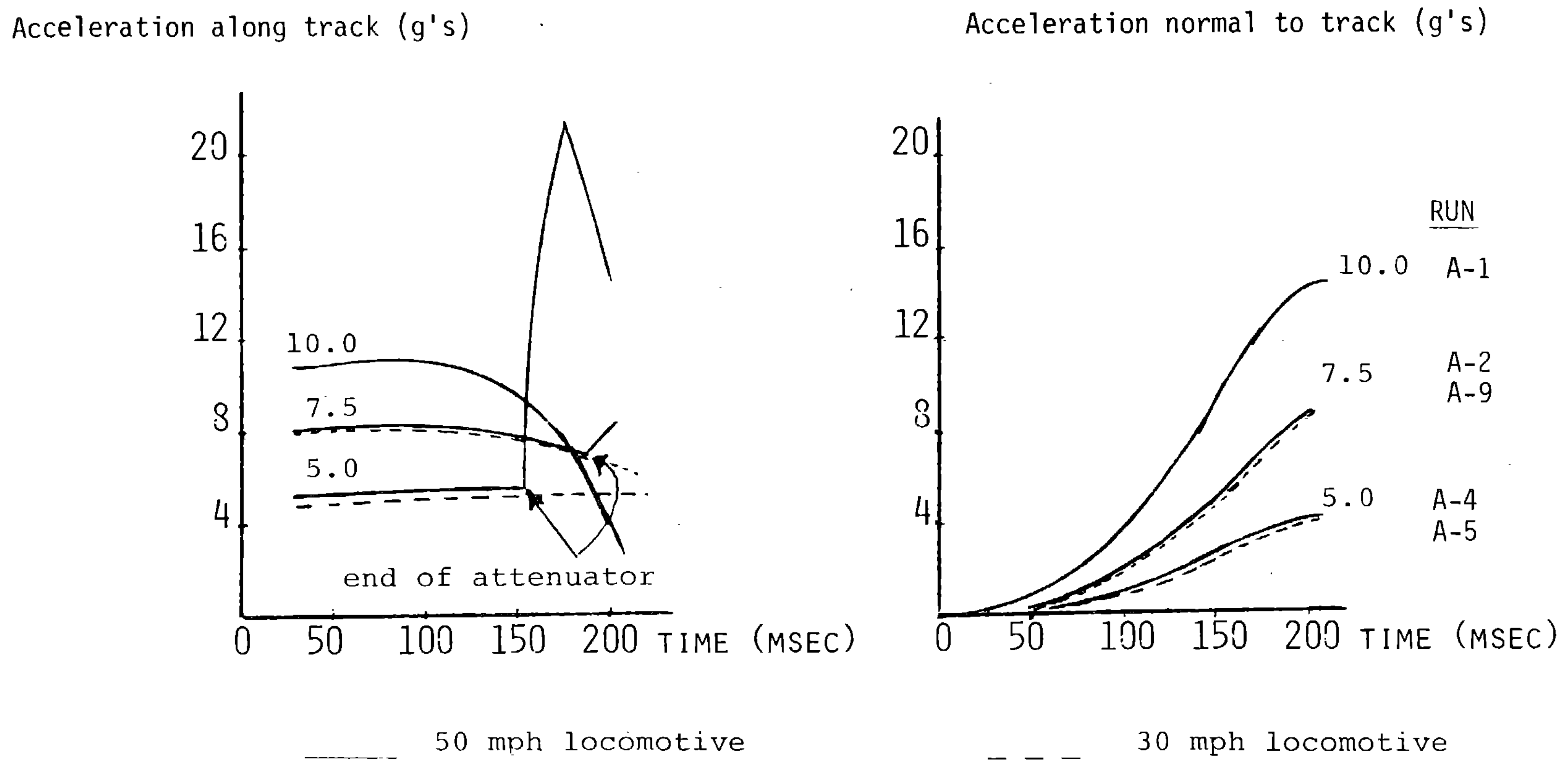


FIGURE 3-21 SIMULATION RESULTS - CRUSHABLE ATTENUATOR

to a much higher acceleration when the automobile met the rigid plate behind the attenuator. Naturally, increasing the yield force raises the acceleration and reduces the depth of penetration.

In an effort to provide a comparison with the crash tests, where the off center automobile cleared the locomotive path at about the time it had rotated through 90°, the table provides for each run information as to whether or not the automobile was clear of the right of way at that time. In general, it is not, unless the automobile was offset to the left initially, in which case only 4.2 feet of the car extend into the locomotive's path. However, these results should be viewed with caution, since they depend completely on the cross track acceleration of the automobile. This in turn depends on the assumption that the force exerted by the attenuator is normal to the side of the automobile. Such an assumption appears to be more reasonable for a crushable attenuator than for a collision of hard surfaces, but it is still unverified by experiment or detailed analysis. Consequently, the results on lateral motion are considered to be very tentative.

The simulator results overall indicate that the crushable attenuator can significantly reduce the automobile acceleration levels in a collision, even with use of a design much stiffer than those postulated in the simulator runs.

3.3.12.4 Summary of Attenuator Effectiveness

If one accepts the results of the Minicars study, adequate and effective materials are available and designs which are potentially effective in reducing injury at various speeds are also available. These designs are those which involve an attenuator which is cantilevered in front of the locomotive. The acceptability of a design may depend on its size and on the inconvenience of deploying the attenuator into position of use, and on any perceived inconveniences or defects of the device in normal operations. Generally, the smaller and simpler the device, the more reliable and acceptable it should be. Such a device should also be able to be made compatible with other safety devices (such as anticlimbers) on locomotives, with little or no difficulty. Simulation results indicate that a variety of devices, aimed at different speed ranges, are feasible and can be effective at injury reduction.

On the other hand, for the MU car, where anticlimber provisions are extremely important, the cantilevered attenuator which reduces injury for highway vehicle occupants will do nothing to protect rail passengers in collisions with heavy trucks, other consists, or fuel trucks. The relative importance of train-to-train collisions suggests that any attenuators used for MU car should be aimed at this situation. In particular, an attenuator aimed at highway collisions, which interferes with anticlimbers in train-to-train collisions, must be avoided at all costs. Hence the device seems to be at best dubious for application to MU cars, and is not recommended. The devices studied by Calspan Corp. for UMTA seem more appropriate.

There is finally the long crushable attenuator equipped with its own wheels, which can be articulated to the locomotive. The serious problem of keeping such a long and light device from derailing must be studied or tested carefully before such a device can be considered effective. The acceptability of the need to articulate the attenuator to the lead locomotive before each trip, and detach it afterward, must also be investigated. Although the individual accident can probably be significantly reduced in severity by such a device, the increase in accidents which would probably occur because of its great length must be taken into account. This increase, discussed in Appendix C, occurs because drivers who attempt to cross in front of a moving train frequently misjudge the situation and are hit by the train or hit the lead locomotive or car. The increase in such accidents varies with the length of the extensions, in the model created in Appendix C, and would be very serious with an attenuator which is twenty feet long. This same increase must also be taken into account with the shorter collision attenuator, and the eight foot length used for the calculations of Appendix C indicates potentially serious problems.

4. Benefit Estimation

4.1 Statistical Basis and Injury Models

4.1.1 Injury Statistics

Any estimation of benefits of a procedure must be based on historical or present damages or costs, and must proceed from that information to the estimates of the anticipated reductions due to the measures considered. The injury information is contained in the FRA accident record files, and an annual summary is published in the Rail-Highway Grade-Crossing Accidents/ Incidents Bulletin. As indicated earlier, there has been a quite steady decline in fatalities from 1966 to 1977. Fatalities, injuries, and number of reported accidents all decreased rather uniformly from 1966 to 1974. However, in 1975 there was a change in the reporting procedures, so that all grade crossing occurrences were reported, rather than only those meeting the earlier reporting criteria. While fatalities continued to decline, on the new reporting basis the number of occurrences was tripled in 1975, and increased by about ten percent from 1975 to 1977. The number of injured also increased by 28% from 1974 to 1975, and by another 11.5% from 1975 to 1977. Thus total number of casulties actually increased from 1966 to 1977, (which may partly be due to the reporting method change), and seems also to have risen since 1975. Of course the number of highway vehicles registered and miles driven also increased, by more than 80%, during this period, while the number of train miles decreased by 16.2%.

Table 4-1, presenting the casualty figures for 1977, is derived from the FRA bulletin for that year, and can form one of the starting points for the study. The table separates the occurrences where the highway vehicle struck the train, for no practical means of protection of highway vehicle occupants in such circumstances was identified. The question of train occupants in such collisions is examined separately below, and also turns out to be neither statistically important nor affected by the devices considered in this study. For the moment, it is ignored here.

TABLE 4-1

CASUALTY IMPORTANCE OF VARIOUS EVENTS
1977 Statistics

HIGHWAY OCCUPANT	TRAIN STRIKES HIGHWAY OCCUPANT			HIGHWAY VEHICLE STRIKES TRAIN*		
	Occurences	Fatalities	Injuries	Occurences	Fatalities	Injuries
PEDESTRIAN	114	70	44	--	---	--
AUTOMOBILE	6,102	477	2,234	2,433	100	1,031
BUS	31	6	56	1	0	0
TRUCK	2,371	185	766	818	54	330
MOTORCYCLE	24	6	1	69	18	37
MISCELLANEOUS**	336	28	150	--	---	--
TOTAL	8,978	772	3,251	3,321	172	1,398

* No practical countermeasures identified

** Not classified as to train or highway vehicle striking

This means that of the 12,299 accidents, only 8,978, or 73.0%, are subject to proposed injury reduction methods, and only 81.8% of the fatalities and 69.9% of the injuries. These figures define the current statistical incidence of the problems addressed, an incidence which can vary independently of the injury minimization methods, because of variations in highway and rail traffic, in number and protection of grade crossings, and in other preventive measures. In the absence of other information, it will be assumed that the current incidence will remain unchanged. Thus the figures on the left side of Table 4-1 can be considered as the target number of injuries which are potentially subject to reduction.

Two items in Table 4-1 lead to some immediate conclusions. The first concerns motorcycles, where the number of fatalities caused by motorcycles striking trains is thrice the number due to trains striking motorcycles. Over the last five years of data, exactly 75% of the motorcycle fatalities were due to cases where the motorcycle struck the train. The small number of the remaining cases, averaging 7.4 per year, makes it unreasonable to attempt to do anything to reduce motorcycle fatalities, and therefore the subject is henceforward ignored.

The bus accidents are also worthy of comment; once again the statistical incidence is small, with a five year average of 21 incidents of train hitting a bus, 8.6 fatalities, and 55.8 injuries. In recent years the bus incidents constitute about 0.3% of the total occurrences of train striking highway vehicle, and about 1.0% of fatalities and 1.7% of injuries. Since the bus casualties represent only a very small portion of the total, to minimize total casulties the automobile should be given priority over the bus in any measure which might protect occupants of either highway vehicle. A typical example occurs in selection of stiffness for a crushable attenuator; different values are desired for the different masses involved. The small number of train-bus accidents suggests that emphasis on preventive, rather than palliative, measures might be more effective. Preventive measures are not the subject of this study, but examples include selection of bus routes to avoid unprotected crossings, as well as the more conventional warning systems, visibility improvements, and driver training.

The hazards to occupants of a train struck by a highway vehicle can arise either in direct injury by the striking vehicle, or from injury in a derailment caused by the collision. Table 4-2 presents some statistics on derailments subsequent to rail-highway collisions, derived partly from earlier FRA annual Accident/Incident Bulletins and partly from more recent automated FRA Equipment Accident file records.* Such derailments amount to just above one percent of the total number of derailments, i.e. a very unimportant fraction. Protection of occupants involves conventional crashworthiness measures which have no special relationship to rail-highway collisions, and benefits and costs would be counted only in proportion to the incidence of casualties involved. (The annual bulletin provided only number of accidents in this category, not the number of casulties.) In view of the small statistical importance of these events, no further consideration is given.

Consider next injuries caused directly by the striking highway vehicle. In two thirds of the cases of a highway vehicle striking a consist, it is a locomotive that is struck. A locomotive structure provides its occupants enough protection from direct impact by a highway vehicle, and cabooses rarely seem to be struck. Since passenger train derailments, or heavy vehicles striking passenger trains, place a larger number of personnel at risk, they might warrant some special attention. Less than four percent of rail-highway collisions involve passenger trains; if the same percentage figures hold for the cases where the highway vehicle hits the train, of the 3,321 such collisions occurring in 1977, 127 might have involved passenger trains, or 3 or 4 of the resulting derailments could have involved passenger

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* The DOT Transportation Systems Center derived the data presented in this and in subsequent tables, and also provided advice and suggestions on the selection of data and on specific questions to be explored.

TABLE 4-2

RAIL-HIGHWAY GRADE CROSSING ACCIDENTS* RESULTING IN DERAILMENTS

TYPE OF ACCIDENT	NUMBER OF DERAILMENTS			BREAKDOWN BY PERCENT	
	1977**	1976**	1971	Accident Type	Vehicle Type
Truck struck train	32	34	26	35.6%	Truck 78.1%
Train struck truck	38	41	31	42.5	
Auto struck train	11	12	9	12.3	Auto 13.7%
Train struck auto	1	1	1	1.4	
Sudden brake application to avoid collisions	2	3	2	2.7	Other 8.2%
Other	5	5	4	5.5	
Total derailments	89	96	73	100%	100%
Total number of accidents	321	339	311		
Derailments as percent of accidents	27.7%	28.3%	23.5%		

* All figures based on annual equipment accident reports

** Percent breakdown by type not available for these years; 1971 breakdown assumed.

trains. Such occurrences are thus infrequent, although they have indeed occurred, for example, in 1975, when a truck struck a passenger train and caused a derailment. (4-1) The particular incident caused no fatalities but 41 injuries resulted primarily from derailment rather than truck impact. The French-built turbotain involved was not equipped with AAR couplers, the presence of which might have reduced the number of cars derailed. The point is that the injuries were derailment injuries, except for two caused by the glass windows broken at impact. In other words, injuries from direct impact seem to be unimportant even in the few cases where this occurs.

Tables 4-3 and 4-4, covering the years 1977 and 1976 summarize the statistics readily available on derailments caused by rail-highway grade crossing accidents. The annual FRA Accident/Incident Bulletins used to provide a count of derailments by type of highway vehicle and by whether the train or the highway vehicle was struck, but by 1975 this information had been eliminated. The 1977 and 1976 data were obtained from the automated FRA Equipment Accident/Incident Reports, by identifying all reports with a rail-highway crossing accident type code or collision cause code. Presumably the count includes all such occurrences; the numbers are consistent with those from the earlier bulletins. These are the numbers which were used as the basis for Table 4-1, by assuming that the 1976 and 1977 events followed the same ratios of automobiles versus trucks and of highway vehicle striking versus being struck.

These tables presumably cover all, or almost all, cases of derailments caused by rail-highway accidents. They indicate that the number of such occurrences is quite limited, currently running somewhat below one hundred per year, and that about six percent of these accidents involve consists carrying hazardous materials, and 1.4 per cent involve derailment or damage to a hazardous material car. For hazardous material accidents, the concern

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(4-1) National Transportation Safety Board Report NTSB-RHR-76-2, "Collision of a Crown-Trygg Construction Truck with an Amtrak Passenger Train, Elwood, Illinois, Nov. 19, 1975".

TABLE 4-3

GRADE CROSSING ACCIDENT DATA FROM FRA RAIL EQUIPMENT ACCIDENT/INCIDENT REPORTS, 1977

Group 1: Accident Type = 7, Cause Code = 700.

(1)	(a)	Total Reports	341*
	(b)	Total Accidents	321
	(c)	Derailments	89
(2)	(a)	Events involving HM**	22
	(b)	Trains not carrying HM	299
(3)		Trains carrying HM, with no HM cars damaged or derailed	14
(4)		Trains carrying HM, with no HM released	19
(5)		Events requiring evacuation	6
(6)		HM cars	98
(7)		HM cars damaged or derailed	25
(8)		Cars releasing HM	4
(9)		Persons evacuated	2288
(10)	(a)	Total locomotives	830
	(b)	Locomotives derailed	113
(11)	(a)	Total cars	16,216
	(b)	Cars derailed	489
(12)	(a)	Total injuries (accident report)	159
	(b)	Total injuries (injury report)	290
(13)	(a)	Total fatalities (accident report)	25
	(b)	Total fatalities (injury report)	93

Group 2: Accident type = 7; Cause code ≠ 700; Number of reports = 2

Group 3: Accident type ≠ 7; Cause code = 700; Number of reports = 0

Accident Type 7 - Rail Highway Crossing
Cause Code 700 - Collision with Highway User at Grade Crossing

* Two reports are possible for one accident

** HM = hazardous material

TABLE 4-4

GRADE CROSSING ACCIDENT DATA FROM FRA RAIL EQUIPMENT ACCIDENT/INCIDENT REPORTS, 1976

Group 1: Accident Type = 7, Cause Code = 700

(1)	(a)	Total reports	367*
	(b)	Total accidents	339
	(c)	Derailments	96
(2)	(a)	Events involving HM**	17
	(b)	Trains not carrying HM	322
(3)		Trains carrying HM, with no HM cars damaged or derailed	13
(4)		Trains carrying HM, with no HM released	17
(5)		Events requiring evacuation	0
(6)		Total HM cars	114
(7)		HM cars damaged or derailed	4
(8)		Cars releasing HM	0
(9)		Persons evacuated	0
(10)	(a)	Total locomotives	869
	(b)	Locomotives derailed	113
(11)	(a)	Total cars	14,606
	(b)	Cars derailed	471
(12)	(a)	Total injuries (accident report)	190
	(b)	Total injuries (injury report)	291
(13)	(a)	Total fatalities (accident report)	36
	(b)	Total fatalities (injury report)	115

Group 2: Accident type = 7; Cause code ≠ 700; Number of reports = 14

Group 3: Accident type ≠ 7; Cause code = 700; Number of reports = 0

Accident type 7 - Rail Highway Crossing
* Two reports are possible for one accident
** HM = hazardous material
Cause code 700 - Collision with Highway User at Grade Crossing

is as much with other personnel in the area as with train or highway vehicle occupants. (For example, in a recent collision between a freight train and an anhydrous ammonia tank truck, two bystanders were killed, while both the truck driver and the locomotive crew survived.) The only countermeasures within the scope of this study involve avoidance of derailment, and benefits accrue only to the extent that casualties due to these derailments are reduced. Since at present this classs of casualties is negligible, no benefits can be expected in this area.

In summary, one reaches the conclusion that, with negligible exceptions, the casualties which can be reduced by measures within the scope of this study are limited to those resulting from a rail consist striking a pedestrian, an automobile, or a truck. The statistics of these casualties are examined as a function of train speed, which clearly affects the results. Tables 4-5, 4-6, 4-7, and 4-8 present incident and casualty figures for collisions involving automobiles, trucks, buses, and pedestrians respectively. Each table separates the incidents into ten mile per hour groups of train speed, and groups those incidents where the train strikes the highway user separately from the events where the highway user strikes the train. At this point there is no longer any benefit interest in the latter group, which appears as a separate unit in the lower half of each table.

Tables 4-5 and 4-6 present the most interest, since they show that the greatest number of casualties occur in collisions which involve train speeds between twenty and fifty miles per hour. 417 automobile collision fatalities and 152 truck collision fatalities occurred when trains struck vehicles at speeds within this range (out of 561 and 286 respectively for all speeds). There is also a sizable number of injuries occurring at lower speeds, which might be reduced, although the number of fatalities is modest (46 for automobiles, 74 for trucks). Thus it is in this group of 569 fatalities, and similar injuries, that one can look for the greatest possibility of injury reduction or benefit.

The fatality figures of Tables 4-5 and 4-6, derived from the FRA accident files, show a significantly greater number of fatalities from trains striking automobiles and trucks, than does Table 4-1, derived from the annual summary bulletin. Since the files have been updated to reflect injuries which become deaths, Tables 4-5 and 4-6 should be used rather than 4-1 in estimating total fatalities. The net effect is to increase the total fatalities in instances where the train hits the highway occupant from 772 to 964, with negligible change in injuries. Since injury reduction methods do not apply to cases where a highway occupant strikes a train, the fatality increase and injury decrease observed in the FRA files have no effect on estimated benefits.

The next step is to attempt to derive some model or statistical basis for the actual injury as a function of accident conditions.

TABLE 4-5 AUTOMOBILE-TRAIN COLLISION BY TRAIN SPEED

SOURCE: RAIL-HIGHWAY GRADE CROSSING ACCIDENT/INCIDENT REPORTS - 1977

GROUP 1: ITEM 12 = 1; ITEM 18 = 1; NUMBER OF EVENTS = 6519 (Train Strikes Auto)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	2495	22	2124	15	463	3376
11 - 20	1176	6	791	31	505	1541
21 - 30	1250	14	754	140	602	1562
31 - 40	792	15	451	126	384	964
41 - 50	530	8	285	151	247	699
51 - 60	142	9	77	60	53	192
61 - 70	69	0	46	27	13	83
71 - 80	32	1	10	13	21	65
81 - 90	6	0	2	8	0	10
91 -999	1	0	1	0	0	0

GROUP 2: ITEM 12 = 1; ITEM 18 = 2; NUMBER OF EVENTS = 2456 (Auto Strikes Train)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	1185	16	887	20	371	1635
11 - 20	353	1	220	15	161	484
21 - 30	300	7	183	12	153	447
31 - 40	218	4	114	30	116	323
41 - 50	80	2	39	10	40	114
51 - 60	26	0	10	12	13	35
61 - 70	4	0	0	0	4	8
71 - 80	11	0	7	1	7	17
81 - 90	2	0	0	2	0	2
91 -999	0	0	0	0	0	0

TABLE 4-6 TRUCK-TRAIN COLLISIONS BY TRAIN SPEED

SOURCE: RAIL-HIGHWAY GRADE CROSSING ACCIDENT/INCIDENT REPORTS - 1977

GROUP 3: ITEM 12 = 2,3; ITEM 18 = 1; NUMBER OF EVENTS = 2751 (Train Strikes Truck)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	1067	20	941	65	133	1194
11 - 20	389	29	274	9	129	421
21 - 30	542	56	348	35	186	559
31 - 40	344	32	194	67	144	367
41 - 50	244	34	129	50	98	263
51 - 60	99	14	61	18	23	93
61 - 70	26	6	12	27	9	44
71 - 80	31	11	16	15	9	50
81 - 90	0	0	0	0	0	0
91 -999	0	0	0	0	0	0

GROUP 4: ITEM 12 = 2,3; ITEM 18 = 2; NUMBER OF EVENTS = 856 (Truck Strikes Train)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	378	17	284	43	99	465
11 - 20	126	8	78	5	49	145
21 - 30	134	11	70	13	72	183
31 - 40	96	12	50	16	37	120
41 - 50	37	4	22	5	13	45
51 - 60	12	2	8	1	6	16
61 - 70	5	1	4	1	0	5
71 - 80	3	1	0	3	4	7
81 - 90	2	0	0	0	2	4
91 -999	0	0	0	0	0	0

TABLE 4-7 BUS-TRAIN COLLISIONS BY TRAIN SPEED

SOURCE: RAIL-HIGHWAY GRADE CROSSING ACCIDENT/INCIDENT REPORTS - 1977

GROUP 5: ITEM 12 = 4,5; ITEM 18 = 1; NUMBER OF EVENTS = 31 (Train Strikes Bus)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	17	0	11	0	15	93
11 - 20	8	0	5	0	16	34
21 - 30	4	1	1	1	13	20
31 - 40	1	0	0	4	4	8
41 - 50	1	0	0	0	2	3
51 - 60	0	0	0	0	0	0
61 - 70	0	0	0	0	0	0
71 - 80	0	0	0	0	0	0
81 - 90	0	0	0	0	0	0
91 -999	0	0	0	0	0	0

GROUP 6: ITEM 12 = 4,5; ITEM 18 = 2; NUMBER OF EVENTS = 1 (Bus Strikes Train)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	0	0	0	0	0	0
11 - 20	0	0	0	0	0	0
21 - 30	1	0	1	0	0	1
31 - 40	0	0	0	0	0	0
41 - 50	0	0	0	0	0	0
51 - 60	0	0	0	0	0	0
61 - 70	0	0	0	0	0	0
71 - 80	0	0	0	0	0	0
81 - 90	0	0	0	0	0	0
91 -999	0	0	0	0	0	0

TABLE 4-8 PEDESTRIAN-TRAIN COLLISIONS BY TRAIN SPEED

SOURCE: RAIL-HIGHWAY GRADE CROSSING ACCIDENT/INCIDENT REPORTS - 1977

GROUP 7: ITEM 12 = 7; ITEM 18 = 1; NUMBER OF EVENTS = 114 (Train Strikes Pedestrian)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	25	0	0	10	17	6
11 - 20	21	0	5	6	10	5
21 - 30	21	0	1	15	6	4
31 - 40	23	0	1	20	2	5
41 - 50	11	0	0	11	2	2
51 - 60	6	0	0	4	2	0
61 - 70	3	0	0	1	2	0
71 - 80	3	0	2	1	0	0
81 - 90	0	0	0	0	0	0
91 -999	0	0	0	0	0	0

GROUP 8: ITEM 12 = 7; ITEM 18 = 2; NUMBER OF EVENTS = 7 (Pedestrian Strikes Train)

SPEED CATEGORY (MPH)	NO. OF EVENTS	EVENTS WITH FORM F6180.54 ALSO FILED	EVENTS WITH NO CASUALTIES	FATALITIES	INJURIES	OCCUPANTS
1 - 10	3	0	0	0	3	1
11 - 20	3	0	1	1	1	0
21 - 30	1	0	0	1	0	0
31 - 40	0	0	0	0	0	0
41 - 50	0	0	0	0	0	0
51 - 60	0	0	0	0	0	0
61 - 70	0	0	0	0	0	0
71 - 80	0	0	0	0	0	0
81 - 90	0	0	0	0	0	0
91 -999	0	0	0	0	0	0

4.1.2 Injury Models

The modeling of injuries attempts to establish statistical or mathematical formulae relating the physical accident situation to the resulting injuries. The large number of automobile casualties had led to extensive work in this field, establishing numerical values for injury severity and to criteria and indices relating velocity and acceleration to injury severity. How well and how easily this work can be applied to rail-highway accidents?

In the analysis of the FRAlocomotive-automobile crash tests (2-1), Dynamic Science applied one of the commonly used formulae which relate acceleration to injury, the Gadd severity index. This index is the integral of the 2.5 power of the acceleration; if the index exceeds a certain value the occurrence is considered to be fatal. A related unit is the head injury criterion, which consists of an averaged acceleration raised to the power 2.5 and multiplied by the averaging time; this measure, applied to either head or thorax, is considered to define a fatal situation if it exceeds certain limits for any period of time. Note that these indices require knowledge of the acceleration, which was measured in the test crashes. Since the simulated accelerations in this study are dubious in comparison with the measured accelerations in the test crashes, it did not appear worthwhile to carry the computations to the extent of a severity index. In addition, the simulation included only mean vehicle acceleration and not occupant acceleration. The exponent of 2.5 which is common to both the severity index and the injury criterion indicate that the relationship between acceleration and injury is far from linear. In the unpublished study of collision attenuation for FRA, Minicars Inc. set up a model relating train speed in the collision to fatality and injury distribution, using formulae for train speed distribution, collision probability, and injury severity distribution.

Unfortunately the statistics used were derived from the 1971 annual rail-highway accident bulletin, which included only those collisions causing either personal injuries or railroad damages exceeding a certain monetary limit. Most collisions did not meet this criterion and were classified as "incidents" and excluded from the report. In later years, when incidents were also reported, the number of occurrences in the annual bulletin quadrupled. Thus, since the study was based on the 1971 data, almost all the collisions not resulting in injuries were ignored in the model; in particular, most of the low speed accidents were excluded and the train speed distribution was thus heavily biased toward higher speeds.

Admittedly the statistics used did cover the cases where injuries occurred, and could therefore conceivably provide a valid basis of prediction. Nevertheless, the exclusion of the large part of the sample space where injury could occur, and the inclusion of another portion where the injuries which occur are not subject to collision attenuation methods (highway vehicle strikes train cases), raise questions as to the applicability of the models. A further drawback is that the benefit estimates were made on the basis of the total number of casualties, rather than on the basis of only those casulties occurring when a train strikes a highway vehicle.

The Minicars study related injury, expressed in dollar value, to both train speed and the location of the automobile with respect to the track at collision time. Although injuries are not translated into dollar values in this study, clearly the train speed and automobile location are primary factors in determining injury severity. The difficulties encountered with the earlier model suggested using the simplest possible model based on these two factors, with the two parameters related in some simple way to acceleration of the highway vehicle. When the basic physical relationships are as complex and as imprecisely understood as those of crash injuries, sophisticated mathematical models cannot be verified and therefore cannot replace extensive statistics in making predictions. Thus only a simple model is used, coupled with the statistics of Tables 4-5 and 4-6, i.e. current statistics of accidents where trains strike automobiles and trucks.

Two convenient assumptions may be made in the absence of contraindicating data: first, that automobile speed may be ignored, and next, that the effects of train speed and automobile location are independent. Clearly automobile speed does affect the outcome of a collision, but available data include only very imprecise speed estimates and very incomplete accident descriptions, providing no basis for a mathematical model of speed effects.

In considering the effects of automobile location on the tracks, one would expect maximum injury and fatalities when the automobile is centered on the tracks, a condition in which retention on the coupler is very probable and casualties should be highest. The Minicars study included curves of expected injury (dollar value) as a function of automobile location, which showed this effect; at each train speed, the injury value increased toward the central location. For this study a fatality probability is probably an adequate measure, and it should be maximal when the coupler can entrap the vehicle. Measurements of the distance between the A and C pillars of a number of recent domestic and imported automobiles of all sizes gave an average slightly less than 6 feet, a figure which could therefore be used in the model. Making the questionable assumption that automobile position is uniformly distributed over all possible collision locations, a high probability of the vehicle being entrapped occurs over a range of six feet, between the automobile A and C pillars, out of a total range equal to the sum of the automobile length, taken to be 16 feet, and the width of the train, assumed to be 10 feet. Thus the high probability of entrapment occurs with frequency 6/26 = 0.23, and the fatality probability should drop fairly steeply at a distance of 3 feet from the center of the automobile. A typical fatality probability distribution might then have the appearance shown in figure 4-1. Naturally a separate curve would apply at each speed.

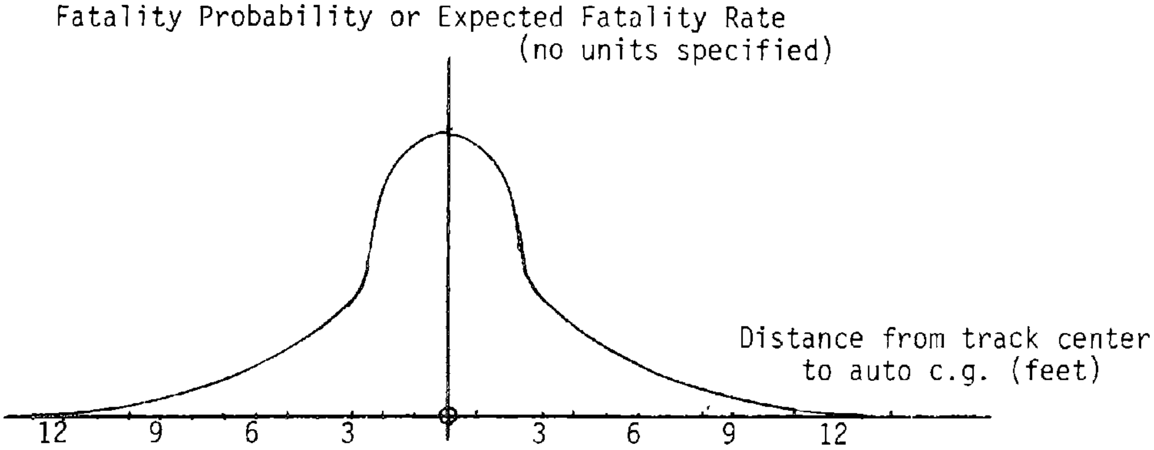


Figure 4-1 Typical Shape of Fatality Probability Curve As A Function Of Automobile Location

Curves such as the one in the figure could also represent the expected number of fatalities per accident, as a function of automobile location. The fatality figures of Tables 4-5 and 4-6 could be used for this purpose. Note that with collision attenuation or deflection, separate curves must be used for automobiles and trucks, since the countermeasure will apply differently to the different vehicles, depending on their mass, geometry, and average number of occupants. The curves of the figure could be integrated over all possible positions and matched to the fatality rates of the tables, for each speed group of the tables. The effects of attenuators could then be expressed as equivalent to moving from one train speed to a lower speed, which is the general approach used by NHTSA in automobile accidents. A deflector would tend to flatten the curves by avoiding entrapment.

In this connection, some comments on vehicle occupancy rates are appropriate. From Table 4-6, the average number of occupants of a truck which strikes a train is 990/793 = 1.248, while the average when the train hits the truck is 2991/2742 = 1.091. The lower occupancy rate is expected, because occupants may have fled from some of the trucks before they were struck. From the FRA accident files it was determined that 309 of the trucks had no occupants when struck, which would make the average occupancy of the remaining trucks 2991/2433 = 1.229, a figure close to that prevailing for trucks which strike trains. For automobiles the figures are somewhat different. The average automobile striking a train has 1.407 occupants, and the average automobile being struck by a train has 1.308 occupants. However, of the 6493 automobiles which were struck, 861 were not occupied, leaving an occupancy rate of 1.508 persons for the remaining automobiles, a figure significantly higher than that of the automobile which strike trains. These figures could be affected by time of occurrence of the accidents, e.g. night versus day, or by the possibility of occupants having jumped from automobiles before they struck the train, which would raise the occupancy rate of the remaining automobiles striking trains. They could also be affected by the possibility of entering injury claims against railroad or insurance companies, something which could affect the supposed number of automobile occupants at the moment of impact.

A separate model for injuries and fatalities is not warranted by the quality of information available; in the circumstances the simplest approach is to assume that there would be a proportional decline in both fatalities and severity of injuries.

The statistical information of importance to simple models of benefits can be derived from Tables 4-5 and 4-6, and is summarized in Table 4-9. This table presents the percent of accidents in each ten mile per hour speed range, the percent of fatalities, and the fatalities per accident. Figures for automobiles and trucks are tabulated separately; since there are some differences. For both automobiles and trucks, the percentage of accidents decreases with increasing train speed, with no important difference between the two, almost 40 percent of the accidents occurring at ten miles per hour of less. There is a difference in fatalities, since for automobiles very few fatalities occur at collision speeds of 20 mph or less, while for trucks fully 22.7 percent of the fatalities occur at 10 mph or less.

Table 4-9

Distribution of Accidents and Fatalities by Train Speed (Train Strikes Highway Vehicle, 1977)

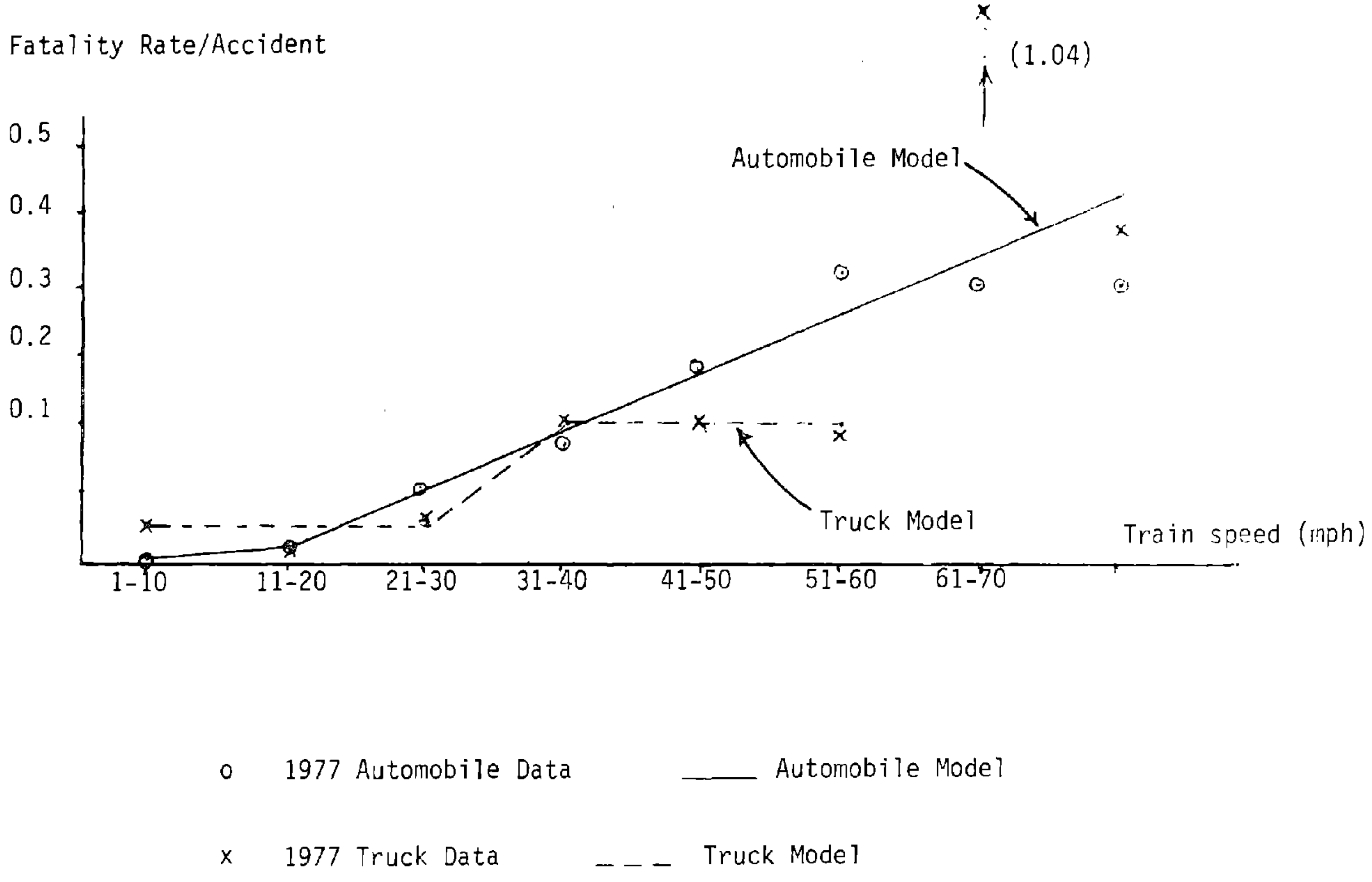
Train Speed (mph)	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81+
Percent of Accidents									
Automobiles	38.4	18.1	19.2	12.2	8.2	2.2	1.1	0.5	0.1
Trucks	38.9	14.2	19.8	12.5	8.9	3.6	0.9	1.1	0
Percent of Fatalities									
Automobiles	2.6	5.4	24.5	22.1	26.4	10.5	4.7	2.3	1.4
Trucks	22.7	3.1	12.2	23.4	17.5	6.3	9.4	5.2	0
Fatalities per Accident									
Automobiles	.0060	.026	.112	.159	.285	.423	.391	.406	1.14
Trucks	.0609	.023	.065	.195	.205	.182	1.04	.484	-

Fatality Count; Automobiles-571, Trucks-286, Total-857

Evidently there is something in the nature of truck operations which creates this very significantly higher fatality rate at low train speeds. The table shows that at 10 mph or less, there are 6 fatalities per thousand automobile-train collisions, and 6 fatalities per hundred truck-train collisions. At other speed ranges there are far lower differences in fatality rates for automobiles and trucks.

The fatality rate per accident can be used in estimating benefits if the effect of an attenuator or deflector is made equivalent to a reduction in train speed. For automobiles, this rate can be expressed as an increasing function of train speed, as shown in Figure 4-2. For trucks, assuming a rate of .055 up to 30 mph, and a rate of .20 up to 50mph, and .50 thereafter, would agree fairly well with the 1977 data. The accuracy of the postulated rates at high and very low speeds is unimportant, because the range of importance is the speed range from 21 to 50 mph, which includes 73 percent of the automobile fatalities and 53 percent of the truck fatalities.

This speed range includes 569 fatalities out of a total of 857 fatalities from trains striking automobiles or trucks, i.e. 65.6 percent of the fatalities which are potentially subject to injury reduction. To be successful, injury reduction approaches should focus on this speed range.



Speed Range (mph)	1-10	11-20	21-30	31-40	41-50	51-60
Model-Automobile Rate	.006	.023	.105	.188	.271	.353
Truck Rate	.055	.055	.055	.20	.20	.20

Fig. 4-2 FATALITY RATE PER ACCIDENT - DATA AND MODEL

4.2 Individual Concept Estimates

Three concepts examined in this study are worthy of estimates of anticipated benefits. Short comings in both supporting data and models imply that no estimate can be considered to be of high reliability. The three concepts consist of the soft collision attenuator, studied in some detail by Minicars, the hard-front deflector, and the sealing of the front of MU cars against the entry of flammable liquids in collisions with tank trucks.

(1) The MU car is considered first. Four instances of railcar-fuel truck collisions have been identified (2-3) as occurring over the past 50 years, with the last two being the most serious in terms of casualties. In the most serious accident (4-2), several normal crashworthiness measures would have reduced the toll of 13 deaths. The accident itself, and the fatalities, were partly due to inadequate or malfunctioning safety provisions on both train and truck. The design of the truck'smalfunctioning brake system and its safety features left the truck immovable across the right of way; the condition of the crossing, with numerous potholes,probably contributed to the failure's occurring at that point. Improved braking in the MU car could have reduced the accident severity or possibly avoided collision entirely; emergency lighting and emergency egress methods would probably have drastically reduced the number of fatalities. Thus benefits may be derived from a variety of different measures.

However, the probability of such collisions, which have averaged approximately one per decade, is difficult to estimate for the future. The probability depends not only on the incidence of fuel trucks at grade crossings used by MU cars, but also on the condition of the crossings and on the design and condition of the trucks.

(4-2) NTSB Railroad Highway Accident Report, "Boston and Maine Single Diesel-Powered Passenger Car 563 Collision with Oxbow Transport Company Tank Truck at Second Street Railroad-Highway Grade Crossing, Everett, Massachusetts, Dec 28, 1966", Report dated Mar 7, 1968

Assuming the historic fatality rate, there are approximately five lives to be saved per decade from protective measures designed to prevent ingress of burning fuel into an MU car. If the same measures also serve other safety purposes, the benefits would be increased, but no such advantages are known to the authors. The low fatality benefit suggests that such features as improved braking, which serve in many different situations, may have higher benefits.

(2) The hard faced deflector is considered next. The benefit estimate requires predicting the reduction in entrapment and its effect on casualties, and also any reduction in highway vehicle acceleration and its effect. The reduction in entrapment would be the only benefit of a flat front locomotive without a projecting coupler. The simulation described in Section 3.3.10 indicates that a rounded front deflector will also produce lower accelerations, but the accuracy of the model is sufficiently in question to suggest a conservative approach to benefits arisng thereby.

For a uniform distribution of automobile locations across the track at time of collision, and a typical selection of sub-compact, compact, and full-size automobiles, the coupler would strike between the A and C pillars of the automobile with probability 0.23, according to the discussion presented in Sec. 4.12. The "high" probability of entrapment in such a case was not given any numerical value. In the FRA crash tests, both automobiles tested in this way were retained. However, these automobiles were stationary, and forward automobile velocity at impact may reduce the probability of retention. If 50% of these cases are retained on the coupler, than 11.5 percent of all automobiles in collisions are retained. In the absence of other information, a similar figure will be used for trucks. In the tests, with a locomotive speed of 50 mph, the accidents were judged to be fatal to the automobile occupants. If these figures are applied to the collisions of Table 4-5, it implies that 80 out of 151 fatalities in the 41-50 mph range and 22 out of 60 fatalities in the 51-60 mph range occurred when automobiles were trapped. In the 31-40 mph range, 111 out of 964 automobile occupants would be in retained cars, but the fatality rate might be decreased to 0.7 because of the lower speed, producing 78 fatalities out of a total of 126. At 21-30 mph, 180 occupants out of 1562 would be on impaled cars, and assuming a fatality rate of 0.4 would attribute 72 fatalities out of 140 to this source. Not all of the fatalites would be avoided if the automobiles were not retained, but some percentage which decreases with speed. Table 4-10 suggests the possible savings.

Table 4-10 Possible Fatality Reduction Due To Flat Front Locomotive

Speed Range (MPH)	Total Fatalities	Estimated Fatalities In Impaled Cars	Estimated Fatalities With No Impalement	Benefit
21-30	140	72	36	36 (0.5)
31-40	126	78	47	31 (0.4)
41-50	151	80	64	16 (0.2)
51-60	60	22	20	2 (0.1)
TOTAL	477	252	167	85

This table was constructed on the assumption of savings in fatalities because of avoidance of impalement ranging from 0.5 in the 21-30 mph speed range down to 0.1 in the 51-60 mph range. The table assumes that 252 of the 477 fatalities, i.e. 53 percent, occurred in cases where the automobile was impaled. Since there are no collected data on the actual percentage of impalements and of fatalities occurring in these cases, there is no basis for better estimates than these. Applying similar ratios to the 172 truck collision fatalities occurring in the same range produces an estimated reduction of 32 fatalities, for an overall total of 117.

The importance of more detailed accident records in providing a better statistical basis for estimates of this type cannot be overemphasized.

For the rounded frontdeflector, additional benefits would presumably apply due to reduced accelerations. The simulation results briefly summarized in Figure 3-15 show that a ten-foot long rounded front reduced peak accelerations by approximately one half, composed to the crash test data. Assuming a more modest, and more manageable, deflector length of five feet might reduce the peak accelerations to an intermediate level, say 0.8. Then the reduction in acceleration can be considered equivalent to a reduction in fatality rate, equivalent to the fatality rate of a lower speed. This is NHTSA's approach to using barrier equivalent velocity as the criterion.

Unfortunately there is no firm basis for establishing this equivalence. A crude approach would be to assume that the momentum involved, which is proportional to the train speed, is roughly linear with the accelerations over the limited speed range of 20 to 50 mph which is of primary interest. In this case, using the factor of 0.8 would approximately change the 40-50 mph range to 33-40 mph, and the 31-40 mph range to 25-32 mph, and the 21-30 mph to 17-24 mph. The fatality rates can then be read from the model curve of Figure 4-2, and the associated fatality reductions computed from the differences in fatality rates multiplied by the number of accidents in the group. Since the curve is linear over the range covered, the same reduction rate of .074 applies to each group from 21 to 50 mph, and the total of 2572 accidents in this range gives a benefit of 191 fewer fatalities in automobile accidents, compared to the 417 actual fatalities. If the same technique were applied to trucks, the results would be considerably different, for the corresponding truck curves would consist of two flat segments, and the only savings would occur in the 31-40 mph range, where the 0.14 fatality per accident difference, over 344 accidents, would correspond to a 48 reduction in fatalities. (No claim is made for the realism of this estimate.) Thus the total estimated reduction for automobiles and trucks is 239 fatalities, compared to 117 for the flat faced deflector.

These benefits could be further increased if the rounded attenuator were covered with even a shallow layer of crushable material such as honeycomb, with a stiffness chosen to provide the maximum acceptable initial acceleration to automobiles, thereby reducing the severity of the final contact with the hard deflector surface.

The benefits should probably be reduced to account for a probable increase in the number of accidents due to the deflector length, as discussed in Appendix C. The calculations of Appendix C are based on an eight foot long deflector, but are easily convertible to the five foot length used as the basis of estimating benefits. The estimated benefits could then easily decrease by ten percent from 239 fatalities to about 210. The effect of a ten foot long attenuator would be twice as serious.

(3) To estimate the benefits from a soft-face attenuator, the 10 foot long version designed by Minicars Inc in its study is used, and the simulations from that study are applied in preference to those described in Sec. 3.3.12 and Appendices A and B. The technique of calculating reduction in fatality rate per accident, which was employed with the rounded front deflector, could be used with the attenuator. However, with the soft attenuator, as long as the attenuator has not completely crushed through, the acceleration is primarily established by the attenuator design rather than the train speed, which predominates for the deflector. Therefore the simplest procedure is to adopt the overall result from the earlier study of a fatality saving of .45 for a feasible design, and couple this with the 857 fatalities from Tables 4-5 and 4-6 to obtain a fatality reduction of 386 for automobile and truck collisions. This figure is adequate to express the total savings, since bus and motorcylce fatalities are not major items, and the behavior in pedestrian collisions is not known.

These fatality reductions should also be adjusted to account for the probable increase in accidents discussed in Appendix C. A ten foot attenuator extension could decrease the benefits by twenty percent or more, from 386 fatalities to about 300.

5. Cost Estimates

5.1 General Cost Considerations

Among the earlier studies on crashworthiness and collision attenuation which developed cost estimates were the work by Boeing-Vertol (ref. 2-4) and Calspan (ref. 2-5), and the unpublished work by Minicars Inc. Some of the techniques and results are directly applicable to this work, and will be used as appropriate.

Since the benefit estimates are fairly crudely computed, the cost estimates do not warrant a very complex and detailed procedure, especially since this study included no detailed design efforts, which are needed to provide the basis of accurate estimates. Therefore results of the earlier efforts are used wherever possible. All estimates are made in terms of 1979 dollars; once again the quality of the information does not warrant a more complex approach.

The study must generate preliminary estimates of the cost of research to develop each suitable concept, and the cost per year of implementing the concept. Th cost per year may be expressed in terms of an initial cost, with separate values for new equipment installations and for retrofits on existing rolling stock, and in terms of expected life and maintenance and operating costs. The Minicars study produced such estimates for several collision attenuation devices, which will be used in updated form. The Calspan estimates also included costs of train-to-train collision attenuators, and the methods used are appropriate here.

Operating costs may be derived from extra time required to operate the new feature, and from maintenance costs. Replacements and repairs due to accidents constitute another category of costs, which can be estimated from the number of collisions.

In certain cases, the injury reduction devices may also cause reductions in damage to rolling stock, and the savings constitute an offset to the gross costs of the device.

In 1976 and 1977, there were respectively 352 and 322 accidents exceeding the monetary thesholds of $1750 and $2300, with total damages of $8,394,168 and $10,482,498 respectively. The average damage per accident was thus $23,840 in 1976 and $32,548 in 1977. These costs are potentially reducible by deflectors and collision attenuators, especially if derailments are prevented. The data of Table 4-2 indicate that there are approximately 40 derailments per year due to trains striking highway vehicles.

Another potential saving could occur if the injury reduction system reduces the time loss attendant upon the accident, or if it prevents a derailment which might otherwise occur. These savings would be much more difficult to estimate, since there are no collected statistics to form a basis.

5.2 Individual Concept Cost Estimates

Cost estimates are developed only for the concepts of statistical importance, i.e., the soft collision attenuator and the hard-front deflector, and the use of rail brakes for passenger cars.

(1) The Minicars studies of the soft collision attenuator produced several estimates of initial cost, including one of $1,400 and others ranging from $2,000 to $6,000 per unit, for a deployable honeycomb device approximately ten feet long. An inflation factor computed from the cost price index, for the period from 1974 to 1979 would increase these figures significantly. A figure of $2,500 is used here for installations on new rolling stock covering both the attenuator and the push-button deployment mechanism, and a figure of $3,000 for retrofits on existing equipment and replacements of destroyed units.

At this cost, installation of attenuators at both ends of line haul locomotives would cost $180,000,000 for a fleet of 30,000 locomotives. It is assumed that switchers would not be equipped. Power units without cabs would not need the equipment, but the total number of such units is now so low that it can be ignored here. If retrofits were limited only to a part of the fleet, and only fitted units were used in lead position, the initial requirement could be reduced to 10,000 units, with a cost of $60,000,000, after which new units could all be equipped. At a delivery rate of 1000 line haul units per year, the annual cost would be $5,000,000 for continuing years. (In actual practice, initial retrofitting would probably be accomplished at time of major locomotive rebuilding or maintenance.)

The Minicars estimate of the cost of deployments and storage during operations for the total fleet was $5,600,000, per year (1977 for this estimate). Reassessment of the cost basis led to an estimate of $4,500,000 annually, due to a reduction in the number of deployments and unit costs. Note that this amount does not differ very significantly from the continued procurement rate.

To these costs must be added the replacement and repair rate due to accidents and wear and tear from objects encountered along the right of way. The best source for repair and replacement estimates is the automobile and truck collision data tabulated for various train speeds in Tables 4-5 and 4-6. The 6500 automobile collisions and 2740 truck collisions must be reduced to account for the 3080 yard collisions where no attenuators are involved. Assuming 2220 of the yard collisions were cases where train strikes vehicle, with 1500 automobiles and 720 trucks, leaves approximately 5,000 automobile collisions and 2000 truck collisions as occurrences in which attenuators are involved. Then assume the attenuator is totally destroyed in 550 automobile collisions and 750 truck collisions, for a total of 1,800 replacements costing $5,400,000. The remaining cases are assumed to be repairable, at an average cost depending on the train speed, or not to require repair. For automobiles, using a sliding repair cost ranging from $100 to $500 for 2,000 accidents, and no repair for the rest, leads to a total annual repair cost of $350,000. For trucks, using a cost between $200 and $600 for 1200 accidents leads to a repair cost of $350,000. Thus the total annual replacement rate due to accidents is 1800 units at $5,400,000, and the annual repair cost due to accidents is $700,000. To this must be added repair and replacement costs due to striking other objects on the right of way, and to losses in derailments and other accidents. It is difficult to estimate these from existing data, so the above figures are increased by about 40 percent to allow for these factors.

Thus the attenuator costs may be summarized as follows:

(i)	Initial development, test, and evaluation	$1,000,000
(ii)	Initial retrofit at both ends of 10,000 line haul locomotives	$60,000,000
(iii)	Annual installation on 1,000 new line haul locomotives	$5,000,000/year
(iv)	Annual replacement of 1,800 destroyed units	$5,400,000/year
(v)	Annual repairs to damaged units	$1,000,000/year
(vi)	Annual operating costs	$4,500,000/year

(2) A similar approach can be used to develop costs for the hard-faced deflector. In this case, the Calspan Corp. study (2-5) provides estimates for cost per pound of essentially structural items. This category includes the rigid deflector, and the cost per pound varied from one dollar for heavy simple structures to three dollars for complex structures. Estimates for a ten foot wide and four foot deep deflector, of one fourth inch steel, with strengthening truss work, gave a weight of about 400 pounds. Allowing for additional costs for the hydraulic deployment system, and using an intermediate figure of two dollars per pound for the basic structure, produces an estimate of about $1000 for a new installation and $1500 for a retrofit.

Destruction and damage of hard faced deflectors are considerably reduced compared to soft-faced attenuators. Assuming that the destroyed units are reduced to 900 per year, compared to the 1,800 attenuators, and reducingrepair costs to allow for lower damage of the simple sturdy structure,produces the following estimates.

(i)	Initial development, test, and evaluation	$1,000,000
(ii)	Initial retrofit at both ends of 10,000 line haul locomotives	$30,000,000
(iii)	Annual installation on 1,000 new line haul locomotives	$2,000,000/year
(iv)	Annual replacement of 900 destroyed units	$1,350,000/year
(v)	Annual repairs to 2,000 damaged units	$ 500,000/year
(vi)	Annual operating costs	$2,500,000/year

The annual operating cost reflects time spent in deploying the deflector in preparation for a trip and stowing it afterwards, and in lubrication. The figure was derived from the Minicars study and corrected for the differences and simplifications in procedure, and for some reduction is deployments per year. Obviously this figure, which is the major annual cost for the deflector, and the next to largest annual cost for the attenuator, is strongly affected by operating procedures. For this reason, the importance assigned to the item should not be overemphasized; a more careful study might identify changes in the item.

(3) The costs of braking systems in rail passenger cars were identified by Calspan Corp. in its UMTA study(2-5). The costs cited there applied to urban transit cars of the Light Rail Vehicle Type. A current figure of $15,000 for the complete braking system applies; this can be divided more or less equally between the wheel brakes and rail brakes at $7,000 each, with $1,000 allowed for emergency hand brakes and emergency air supply system. Allowing $7,000 per car for addition of a rail brake system appears to be reasonable.

The number of passenger cars and MU cars ordered per year is variable. Assuming 1,000 per year would imply a cost of $7,000,000 per year. The benefits of such devices, however, would be largely derived from accidents other than rail-highway collisions.

6. Conclusions

(1) The present form of grade crossing accident data, as collected on a national basis, does not permit injury modeling of the accuracy which is possible for automotive accident data. This is due in part to the much smaller annual set of accidents, and in part to the fact that the collected data include very little physical detail of the accident and injuries. The closest approach to prediction of injury severity, or of the effects of various safety measures, is to attempt to use the train speed in the same way as NHTSA uses "barrier equivalent velocity" as a criterion for automotive accidents and standards.

Collection of more detailed accident records, reflecting medical examiners' or coroners' reports and further detail on automobile location and condition after the accident, might make it more possible to predict the effects on injuries of changes in automotive and railroad design. Such data might also help establish clearer relationships between train speed and injury.

(2) Several specific approaches to injury reduction in grade crossing accidents appear to be feasible, reasonably effective, and reasonably economical. The concepts involve:

(a) prevention of highway vehicle impalement on the locomotive coupler
(b) reduction of collision intensity by use of a yielding attenuator or shape which tends to remove the highway vehicle from the tracks
(c) prevention of entry of flammable fuels into an MU car in collision with a fuel truck
(d) improvement of passenger car braking capability.

There may be problems of performance, operational characteristics, acceptability, or cost associated with some or all of the concepts. Solution of these problems will usually involve analysis, design and test.

(3) The specific methods for achieving the goals listed above follow. Potential problems which may exist are stated with the method.

(a) A hard faced coupler cover, either short and relatively flat or longer and rounded, designed for the front of a locomotive to prevent the coupler from striking and impaling the highway vehicle. The device may be folded back to uncover the coupler when the locomotive is not in lead position. Several materials and methods of construction, some of which have been tested by FHWA with favorable results in longitudinal automobile collisions, are possible.

Associated problems: (i) the effectiveness is limited by the small size and low strength of the automobile in the laternal direction (ii) compatibility with different locomotive geometries and with anticlimbing features may require individual designs for each unit, which is expensive, (iii) the rounded deflector will probably cause an increase in the number of accidents, depending on its length.

(b) A crushable collision attenuator of intermediate length, e.g. ten feet, to be deployed in cantilever fashion in front of a locomotive. Low yield strength of the attenuator is achieved by choice of suitable materials such as honeycomb.

Associated problems: (i) possible significant increase in number of accidents, caused by the length of the attenuator, (ii) possibility of buckling or tearing of the material, especially under transverse loads, (iii) material stability, strength, and durability in a high vibration operating environment.

(c) A long crushable attenuator, e.g. twenty or more feet long, equipped with wheels, to be articulated to locomotive through coupler or other attachment method, and to be made of materials similar to those of the intermediate length attenuator.

Associated problems: (i) possibility of derailment of attenuator in normal train operation, (ii) possible very serious increase in number of accidents, (iii) structural and material problems similiar to those of the intermediate length attenuator, but increased by greater length (especially buckling and tearing)

(d) Hybrid attenuators consisting of a firm deflector with a crushable covering layer of modest depth, to be folded back on the locomotive front when the coupler is in use. There are essentially hybrids of (a) and (b) above, and have similar associated problems.

(e) Increased use of electromagnetic rail brakes on rail passenger cars, to reduce collision speeds or avoid collisions,

Associated problems: (i) possible train dynamics problems for locomotive-drawn consist, (ii) cost and weight.

(f) Sealing of MU car fronts against entry of flammable fluids during collision with tank trucks.

Associated problems: (i) cost; (ii) operational acceptability to passengers and crew; (iii) limited number of occurrences where system is useful.

(4) Several negative conclusions were also reached.

(a) There is no practical system depending on automatic actuation of a device immediately before an anticipated collision.

(b) Collision attenuators for grade crossing collisions do not appear to be suitable for MU cars.

(c) Protective clothing and equipment for train crews does not appear to be as effective as other procedures.

7. Recommendations

(1) Several of the injury minimization concepts described appear to be worth continued effort. In particular, further effort might be directed at answering the basic questions concerning the hard and soft faced deflectors, indicated by the anticipated problems associated with each concept. Initial efforts could be aimed at:

(a) Scale model experiments aimed at determing automobile behavior in collisions with hard front locomotives.
(b) Design studies of different structural approaches to hard front collision deflectors. Geometric compatibility studies.
(c) Identification of operational problems with deflectors and collision attenuators. Further study of the question of possible increase in number of accidents due to additional length of protective device.
(d) Identification of railroad industry and highway user attitudes on deflectors and collision attenuators.
(e) Tests of performance of honeycomb under transverse loads. Buckling problems.
(f) Design efforts at providing desired directional properties and transverse strength to honeycomb assemblies.

Ultimately, these efforts should lead to experimental test of one or more suitable collision injury reduction devices.

(2) The possibility of increased use of electromagnetic brakes on rail passenger cars should be investigated further. Information exchange with UMTA and with European railroads may be useful. If potential dynamics problems are determined to exist, analytic studies of these problems should be initiated.

(3) Modification of FRA accident data collection procedure should be considered, so that the files could provide more useful data. Some of these data may now be available in state or local government files, and if so, how to organize and use the results should be studied. In particular, information on accident associated derailments, nature of injuries, and summarizes of medical examiner reports, blood alcohol or drug counts, and location and condition of highway vehicle wreckage, would be useful.

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APPENDIX A

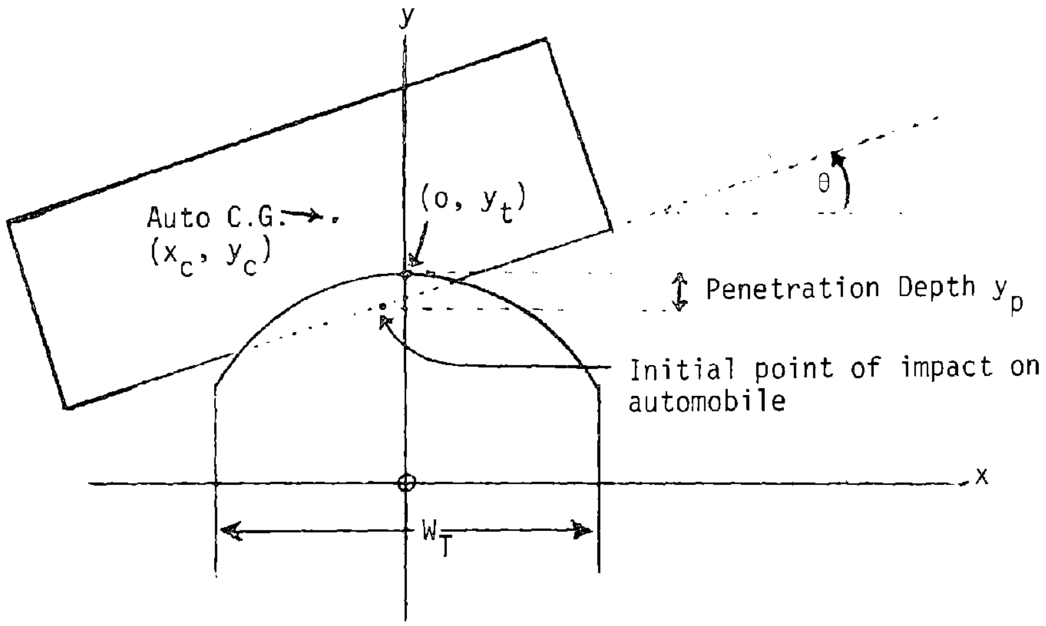
SIMULATION EQUATIONS

A.1 Hard-Front Locomotive

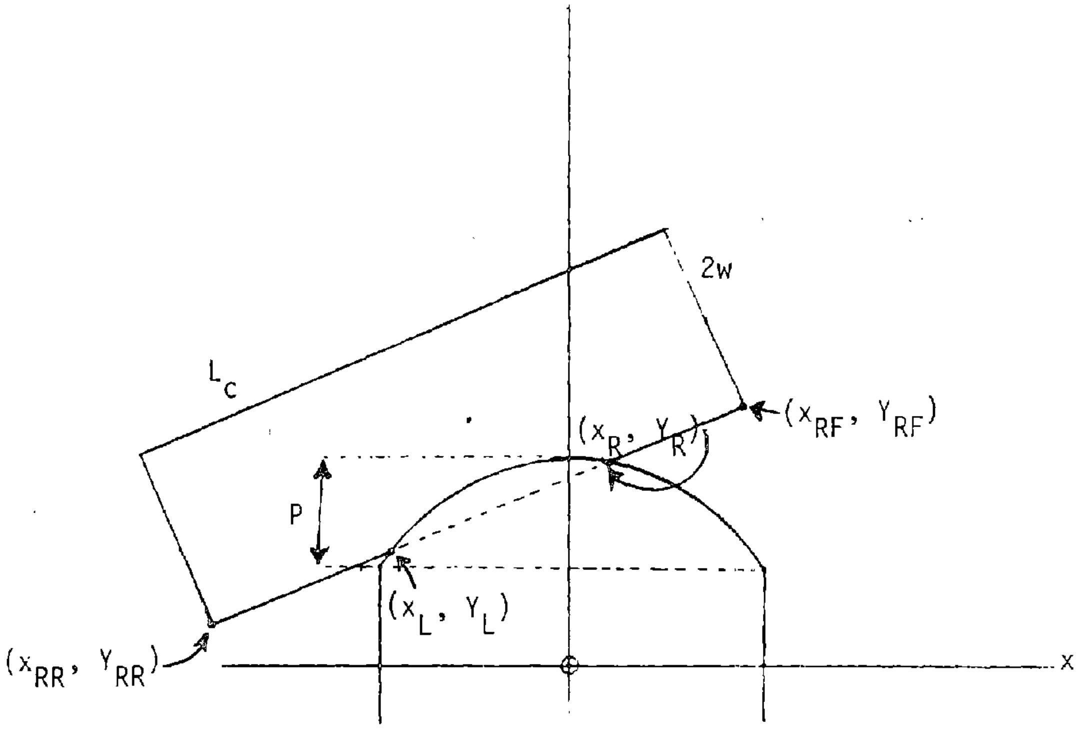
The locomotive is ten feet wide and has two front shapes. The "flat" front is a parabola extending one foot forward from the two sides; the rounded front is also parabolic, but extends ten feet forward. The locomotive speed V_L is 50 miles per hour throughout the encounter, corresponding to infinite momentum. The parabolic front surface is assumed to be infinitely rigid and the automobile surface conforms instantaneously to the locomotive shape. Horizontal plane cross sections are used to represent both locomotive and automobile, and all motion takes place in the plane. Locomotive motion is in the positive y direction at constant speed. The automobile, initially at rest in all runs, translates and rotates under the influence of forces applied by the locomotive.

The automobile is a rectangle with its longitudinal axis originally parallel to the x axis, facing forward toward positive x. Automobile length is 18.6 feet, width is 6.6 feet, and weight 4693 pounds, 55 percent on the front wheels. The center of gravity is 8.37 feet from the front of the car. These values are chosen to match conditions in the FRA crash tests. (The same coordinate system and automobile shape are used in all simulations, but different automobile weights are used is some of the simulations not involving hard-front locomotives.) The locomotives strikesthe automobile on its right side, although it hit the left side in the crash tests.

Two sets of forces act between the locomotive front and the automobile. Figure A-1 illustrates the geometry for both forces. The first force is a "spring" force proportional to the depth of penetration of the automobile by the locomotive. This force acts only in the positive y direction and only when the penetration distance is increasing; it represents



(a) GEOMETRY AND PENETRATION DEPTH FOR ELASTIC FORCES



(b) GEOMETRY AND VARIABLES FOR CRUSH RATE FORCES

FIGURE A-1 GEOMETRY FOR HARD-FRONT COLLISION SIMULATION elastic properties of the automobile in a lateral direction, and forms only a very small, almost negligible, part of the total body forces. However, the calculation of the penetration distance and rate was necessary to determine when the contact forces stop, and the spring force was associated with this calculation. It was also needed in the modeling of the other forces.

Let x_C, y_C be the coordinates of the automobile center of gravity, and y_T the y coordinate of the tip of the locomotive. Let θ be the angle from the x axis to the longitudinal axis of the automobile, let 2w be the car width, and L_0 the x distance from the automobile center of gravity to the locomotive tip at time (t=o) of initial contact, i.e.

$$L_0 = x_T(o) - x_C(o) \qquad (A.1\text{-}1)$$

The penetration depth Y_p is then defined as:

$$y_p = y_T - (y_c + L_0 \sin\theta - w\cos\theta) \qquad (A.1\text{-}2)$$

which is the difference in y coordinates of the locomotive tip and the point on the automobile side first struck by the locomotive tip, assuming that this point moves uniformly with the undistorted portion of the automobile. The automobile center of gravity and the moments of inertia both remain fixed with respect to the original undistorted geometry, so that simple rigid body dynamics are used to describe the automobile motion.

The spring force F_{1y} is then defined to be:

$$\left.\begin{aligned} F_{1y} &= K_y\, y_p, \text{ when } y_p > o \\ &= o \quad \text{otherwise} \end{aligned}\right\} \qquad (A.1\text{-}3)$$

Thus no force is applied if the automobile starts to move away from the locomotive.

The second, and by far the largest, force is assumed to be proportional to the volume of material crushed per unit interval of time. This assumption is realistic for "soft" attenuators or homogeneous crushable structures, and was convenient for use in the hard-front case, where the forces are less easily defined, especially in direction. If h is the height of the section being crushed, x_R and x_L the x coordinates of the right and left edges of the contact zone, the increase ΔV in volume crushed over time Δt will be:

$$\Delta V = \quad h\ (x_R - x_L)\ V_r\, \Delta t \qquad \text{(A.1-4)}$$

where V_r is the average relative y velocity of the two vehicles over the impact zone, defined by the relationship:

$$V_R = V_L - (\dot{y}_c + \dot{M}\theta) \qquad \text{(A.1-5)}$$

M is a particular moment arm described below.

The use of θ is an approximation which is adequate for the important period of contact forces, which occur when Θ is small.

The moment arm M is related to the four load point structure assumed for the lateral loads on the automobile. This structure, similar to one used by Minicars, was postulated when it was difficult to obtain angular motions matching the crash tests with a continuous structure. The model assumes that the load is applied exclusively to four points on the automobile side, which represent the ends of transverse structural members. These points are located at the two ends of the automobile, and at distance .242 L_A forward and aft of the center of gravity, where L_A is the automobile length. The center of gravity is at distance .45 L_A from the front, corresponding to approximately 55 per cent of the weight on the front wheels. The force is then assumed to be applied equally to all the load points engaged, and the moment arm M is the average for the points engaged. These points are those lying between the x_L and x_R limits of the contact area, which are determined by the intersection of the parabolic locomotive front and the near side of the car. The equation of the near side of the car is:

$$y - y_C + w \sec\theta = (x - x_c)\ \tan\theta \qquad \text{(A.1-6)}$$

and of the parabolic front is:

$$y - y_T = -P\ \left(1 - \frac{2x}{w_T}\right)^2 \qquad \text{(A.1-7)}$$

where P is the protrusion distance of the locomotive tip and W_T the locomotive width, and the y axis lies midway between the tracks. The solution of the two equations provide x_L' and x_R', except for the cases where these are beyond the car limits, e.g. when the front corner of the car is to the left of the solution giving x_R. Let X_{RF} be the coordinate of the front right corner; it satisfies:

$$x_{RF} = x_c + .45\ L_c \cos\theta - w \sin\theta \qquad \text{(A.1-8)}$$

In that case, the value used for x_R is

$$x_R = \min [\ x_R', x_{RF}\ ] \qquad \text{(A.1-9)}$$

Similarly, for the right rear corner, with coordinate x_{RR} satisfying

$$x_{RR} = x_c - .55\ L_c \cos\theta - w \sin\theta \qquad \text{(A.1-10)}$$

the corresponding choice for X_L is:

$$x_L = \max [\ x_L', x_{rr}]. \qquad \text{(A.1-11)}$$

It was first attempted, for simplicity, to make the viscous force normal to the side of the car, with x and y components varying with -sinθ and cosθ respectively. However, in this case the cross-track motions were well below those observed in test TGB-4. Since the direction of the forces in a plastic deformation crash involving a complex structure is highly uncertain, the simplest solution was to allow different coefficients in the two directions, and use whatever values gave reasonable results. The coefficients turned out to be drastically different, the x coefficient being about twenty times the size of the y coefficient. The actual forces F_{2x} and F_{2y} had the form:

$$\left.\begin{aligned} F_{2x} &= C_x h\ (x_R - x_L)\ V_r \sin\theta \\ F_{2y} &= C_y h\ (x_R - x_L)\ V_r \cos\theta \end{aligned}\right\} \qquad \text{(A.1-12)}$$

The final force components acting on the automobile are then:

$$F_x = F_{2x}\ ;\ F_y = F_{1y} + F_{2y} \qquad \text{(A.1-13)}$$

i.e., the sum of the spring and the viscous forces. The normal equations of rigid body motion then relate the automobile position and attitude to these forces:

$$M\ddot{x}_c = F_x, \qquad M\ddot{y}_c = F_y, \qquad I\ddot{\theta} = M_xF_x + M_yF_y \qquad \text{(A.1-14)}$$

where M is the automobile mass and M_x and M_y appropriate resolved moment arms. In the tables N1 through N5, the spring force coefficient K_y is expressed in terms of the damping coefficient c_y through a damping factor zeta (ζ):

$$K_y = c_y^2/4M\zeta^2 \qquad \text{(A.1-15)}$$

The unusual cross-track coefficient C_x should be recognized only as a means of matching the cross-track motion in the test crash, which would be very difficult to model with simple equations.

The results presented in Tables N-1 to N-5 inclusive in Appendix B summarize the numerical results. Runs N-1 and N-2 correspond to tests TGB-4 and TGB-3 respectively; runs N-5 and N-4 correspond to the same initial conditions, but with the rounded front. Run N-3 corresponds to a situation where the automobile offset is only three feet, rather than five feet as in run N-4.

A.2 Water Jet System

The x, y coordinate system is similar to that used in the simulation of the hard-front collision, and is shown in Figure A-2. The train moves in the positive y direction with its left side on the y axis. The automobile is modeled as a thin body, or line of length L_C = 15 feet, facing toward positive x, with its center of gravity on the x axis at time t=o. The automobile makes an angle θ with the x axis, with θ measured from the axis to the automobile. The center of gravity is located at distance 0.4 L_C (6 feet) from the forward end of the automobile, and separate uniform densities in ratios 0.6 to 0.4 apply in front of and behind the center of gravity. Moment of inertia ($0.0876\ m\ L_C^{\ 2}$) is calculated from these densities. Time t = o is when the stream of water first reaches the x axis and meets the automobile.

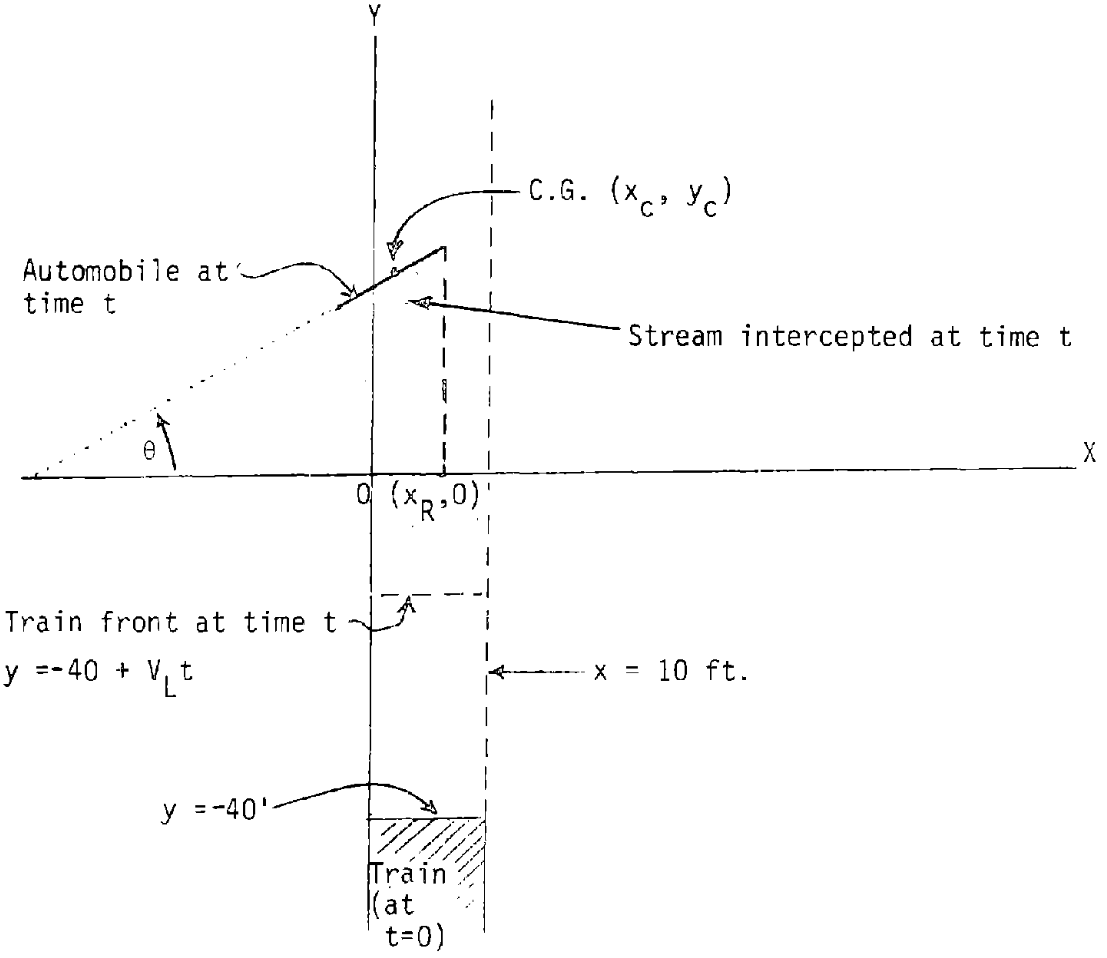


Figure A-2 Geometry for Water Jet Attenuator Simulation

At time t=0, the locomotive front is located along $y = 40$ feet. The locomotive speed is V_L, the nozzle exit speed of the water is V_e, and the water covers the ten foot wide path in front of the locomotive uniformly, without spreading out or slowing down. The water speed is thus $V_L + V_e$. The simplifying assumption is made that the water stream contacts all parts of the automobile lying between $x = o$ and $x = 10$ feet, from time $t = o$ until the time $t=75/A_e V_e$ where A_e is the nozzle exit area and $A_e V_e$ is therefore the total rate of water flow from the nozzles. Actually this time represents the period of water flow at the nozzles, but the automobile will be in the water stream longer than this time if it moves in the positive y direction, for at time t, the water stream will still cover the strip between $y = t\ (V_L + V_e)$ and $y = o$, and will continue to move forward past that time under the assumptions of no loss of speed. Another small effect which has been ignored is that of the water reaching one end of the car first when the angle θ is not zero; it is simply assumed that water arrives over the whole surface once it meets the center of gravity. The same simplification applies at water cutoff.

Total water force per unit length along the car is derived from the difference between the water velocity, parallel to the y axis, and the automobile speed with components $\dot{x}_c$, $\dot{y}_c$ along both axes. With $\bar{i}$ and $\bar{j}$ representing unit vectors in the x and y directions, the relative water velocity is:

$$\bar{V}_R = (V_L + Ve - \dot{y}_c)\ \bar{j} - x_c\ \bar{i} \qquad \text{(A.2-1)}$$

The component of relative velocity normal to the automobile side is therefore $(V_L + V_e - \dot{y}_c) \cos \theta + \dot{x}_c \sin \theta$, and the rate at which water impinges on the side is proportional to this component. Thus the momentum transfer follows the usual pressure relationship, in being proportional to the square of this velocity component. Designating the normal force F_n, one has:

$$\bar{F}_n = \rho\ A\ [(V_L + V_e - \dot{y}_c)\cos\theta + x_c \sin\theta]^2\ (\bar{j}\cos\theta - \bar{i}\sin\theta) \qquad \text{(A.2-2)}$$

where ρ is the water density and A the area of the cross-section being struck by the water. These can be expressed in terms of the total water release rate $\rho A_e V_e$ over the ten foot width, and the coordinates x_R and x_L of the right and left extremes of the automobile which are in the stream. The quantities x_R and x_L are defined as in section A.1, x_R as: the minimum of the right edge of the car and of the stream, and x_L as the maximum of the left edges:

$$x_R = \min (x_c + 0.4\ L\cos\theta\ ,\ 10);\ y_R = \max (0,\ x_c - 0.6\ L\cos\theta) \quad (A.2\text{-}3)$$

The automobile x velocity $\dot{x}_c$ is relatively small compared to the water velocity, so equation A.2-2 is simplified, and the magnitude of the force is simply represented as proportional to $(V_L + V_e - \dot{Y}_c)^2$. The x and y components are then suitably resolved from the direction normal to the automobile side, and applied to the usual equations of motion.

In some of the runs, a friction force was added to represent friction between automobile and ground. The force is proportional to automobile weight, but not to speed. A higher starting friction coefficient of 0.9, compared to the moving friction coefficient of 0.3, is used. For computational ease the two coefficients are approximated by a single exponential function:

$$9.66 + e^{-115.72\ V_A} \quad (7111.035\ V_A - 9.66) \qquad (A.2\text{-}4)$$

which provides a coefficient which reaches 0.9 at .01 fps and reduces to 0.3 at .07 fps.

Twelve runs with varying initial conditions are presented in Tables W-1 to W-12 of Appendix B; with no friction. Two of the runs are then repeated with friction.

A.3 Crushable Attenuator

A.3.1 Analytic Model Equations

The automobile is centered on the tracks and does not rotate; it remains in contact with the attenuator steadily. Force starts instantaneously at contact and ceases when the automobile velocity equals the locomotive velocity;force equals the contact area of the attenuator times the constant yield pressure P_y of the material. The attenuator crushes to adapt to the shape of the automobile, which does not yield.

The attenuator is a horizontal truncated pyramid with square cross-section of area $(a_0 + a_1 d)^2$ at distance d from the tip. The side of the square increases from tip to rear of the attenuator, with slope a_1. A relationship is derived for the depth of crush d_f at the time t_f when automobile speed $\dot{y}$ equals locomotive speed V_L. Figure A-3 illustrates the geometry at an arbitrary time t; t = o corresponds to initial contact. Attenuator initial length is L_0, automobile mass is m and half width C. The automobile center of gravity at time t is at y; the train coordinate is $Y_T = V_L t$, with the train moving at constant speed V_L.

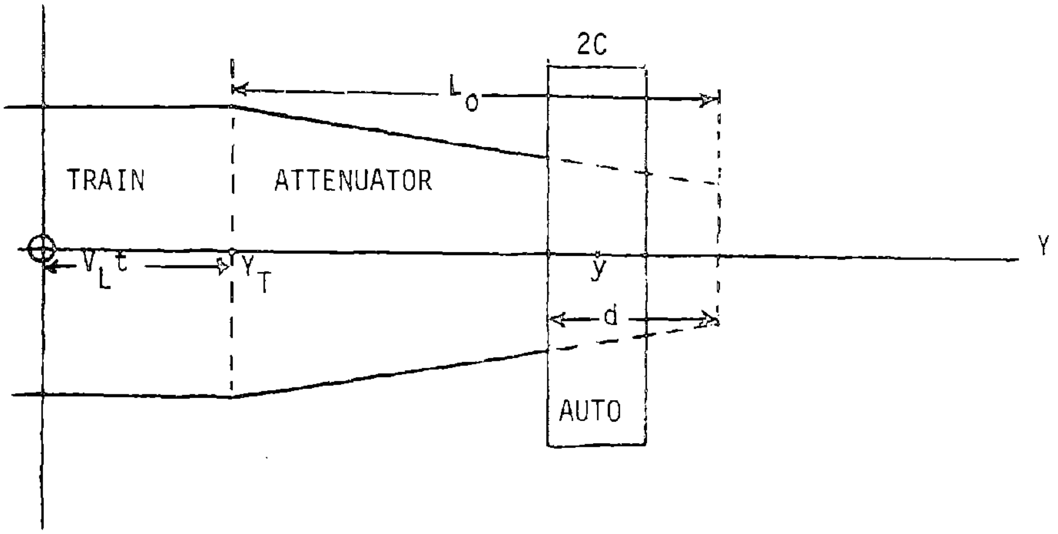


Figure A-3 ATTENUATOR GEOMETRY

Thus attenuator crush depth d equals the difference in current position of locomotive and automobile:

$$d = L_o + C + V_L t - y \qquad \text{(A.3-1)}$$

Since L_o and V_L are constants:

$$\dot{d} = V_L - \dot{y}$$

$$\ddot{d} = \ddot{y} = F/m = -(P_y/m)(a_o + a_1 d)^2 \qquad \text{(A.3-2)}$$

Integration gives:

$$\tfrac{1}{2} m\dot{d}^2 + (P_y/3a_1)(a_o + a_1 d)^3 = k \qquad \text{(A.3-3)}$$

where K is a constant of integration which is evaluated at time t = o, when d = o and $\dot{d} = V_L$ because $\dot{y}(o) = o$. Thus the last equation becomes:

$$\tfrac{1}{2} m \dot{d}^2 + (P_y/3a_1)(a_o + a_1 d)^3 = \tfrac{1}{2} m V_L^2 + (P_y/3a_1) a_o^3 \qquad \text{(A.3-4)}$$

At time t_f when $\dot{d} = o$, the corresponding value of d_f satisfies:

$$(P_y/3a_1)(a_o + a_1 d_f)^3 = (m/2) V_L^2 + (P_y/3a_1) a_o^3 \qquad \text{(A.3-5)}$$

or: $$a_o + a_1 d_f = (1.5a_1 m V_L^2/P_y + a_o^3)^{1/3} \qquad \text{(A.3-6)}$$

from which d_f may be determined.

It is convenient to express the relationship for d_f in a different form involving the initial and final accelerations $\ddot{Y}_I$ and $\ddot{Y}_F$. These are determined from the initial and final cross sections:

$$\ddot{Y}_I = P_y a_o^2/m, \ \ddot{Y}_F = P_y (a_o + a_1 d_f)^2/m \qquad \text{(A.3-7)}$$

Equation A.3-5 may first be simplified to the form:

$$d_f \left[(a_o + a_1 d_f)^2 + a_o (a_o + a_1 d_f) + a_o^2\right] = 1.5\, m V_L^2/P_y \qquad \text{(A.3-8)}$$

which combines with A.3-7 to provide the result:

$$d_f = \frac{1.5\ V_L^2}{\ddot{Y}_F + \sqrt{\ddot{Y}_F \ddot{Y}_I} + \ddot{Y}_I} \qquad (A.3\text{-}9)$$

where the units are normal accelerations in feet per second squared. Expressed in units of g, this becomes:

$$d_f = \frac{1.5\ V_L^2}{32.17} \cdot \frac{1}{G_F + \sqrt{G_F G_I} + G_I} \qquad (A.3\text{-}10)$$

Note that if units of feet, pounds, and slugs are used, the yield pressure P_y must be expressed in pounds per square foot, rather than per square inch. For the examples cited in the text, the 5 psi and 40 psi become 720 and 5760 psf.

A.3.2 Simulation Equations

The equations of motion are essentially the same as those for the hard-front deflector simulation, presented in section A.1. The differences are noted below.

The highway vehicle is now assumed to be infinitely rigid, and the attenuator conforms instanteneously to the highway vehicle shape, which retains its flat side undistorted. The attenuator width is 10 feet and height 3 feet, which approximate the dimensions used in the Minicars study of a crushable attenuator.

The force between attenuator and automobile equals the yield pressure P_y of the material times the area of the contact surface. The contact surface area is defined, as in the preceding sections, by a left and right limit x_L and x_R determined by the automobile and attenuator geometry:

$$A = 3\ (X_R - X_L) \sec \theta \qquad (A.3\text{-}11)$$

$$F = 3\ P_y\ (X_R - X_L) \sec \theta \qquad (A.3\text{-}12)$$

Since the force is normal to the side of the vehicle:

$$F_x = 3\ P_y\ (X_R - X_L)\ \tan\theta$$

$$F_y = 3\ P_y\ (X_R - X_L) \qquad \text{(A.3-13)}$$

Three values of P_y are used, 720, 1080, and 1440 pounds per square foot (i.e. 5, 7.5, 10 psi). These equations and the corresponding moment equations based on assuming uniform force over the contact area, thus determine the equations of linear and angular motion of the automobile. The automobile position and attitude in turn determines the amount of crush of the attenuator.

If the attenuator has been crushed completely through its ten foot depth, the preceding force is combined linearly with a force calculated as for the hard front locomotive given in section A.1.

Appendix B presents the results for eleven runs, A-1 through A-11, covering two locomotive speeds, 30 and 50 mph, and three initial automobile locations. The automobile is always initially at rest, perpendicular to the track direction, with its center of gravity either directly in front of the left edge of the attenuator, or 3 feet to the left or right of that location. The automobile weight is 3,000 pounds, length 16 feet and width 5 feet, except for three runs where an automobile of the size used in the crush tests is postulated, i.e. 4,693 pounds, 18.6 feet long and 6.6. feet wide.

Appendix B also includes a print of the FORTRAN program used for both the water jet and the crushable attenuator simulations.

APPENDIX B

Simulation Run Printouts

B.1	Hard Front Locomotive, Runs N1 to N5 inclusive
B.2	Crushable Attenuator, Runs A1 to A11 inclusive
B.3	Water Jet Attenuator, Runs W1 to W12 inclusive, W1F and W7F
B.4	Listing of Program for Crushable and Water Jet Attenuators

B.1 Hard Front Locomotive

RUN N-1

```
LOCO FRONT:   Y-DAMPING    X-DAMPING   WIDTH/FT   ATTEN.LNGTH/FT    V-LOCO/MPH
AHEAD  1.FT     1750.00     38000.00      10.00             0.00         50.00

ZETA                                                 CAR SPR.         SIDE CRUSH,FT
1.050                                                  4760.              0.500

VEH:WDTH   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
    6.60    4693.     18.60       0.0         55.0          OF TRACK 13.37 FT

 TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD     Y-DD   TH-DD    YTR  VEH
 MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S      G/S  RAD/S2    FT.  CLR
   0.    5.00    0.00    0.00    0.00    0.00    0.00    0.00     0.00    0.00  -2.80  NO
   5.    5.00    0.02    0.00    0.00    9.19    0.00    0.00   130.97    0.00  -2.43  NO
  10.    5.00    0.14    0.00    0.00   23.17    0.00    0.00   113.26    0.00  -2.07  NO
  15.    5.00    0.36    0.00    0.00   33.98    0.00    0.00    76.37    0.00  -1.70  NO
  20.    5.00    0.63    0.00    0.00   40.93    0.00    0.00    46.15    0.00  -1.33  NO
  25.    5.00    0.95    0.00    0.00   45.04    0.00    0.00    26.40    0.00  -0.97  NO
  30.    5.00    1.29    0.00    0.00   47.37    0.00    0.00    14.68    0.00  -0.60  NO
  35.    5.00    1.64    0.00    0.00   48.65    0.00    0.00     8.04    0.00  -0.23  NO
  40.    5.00    2.00    0.00    0.00   49.35    0.00    0.00     4.37    0.00   0.13  NO
  45.    5.00    2.36    0.00    0.00   49.73    0.00    0.00     2.36    0.00   0.50  NO
  50.    5.00    2.73    0.00    0.00   49.94    0.00    0.00     1.28    0.00   0.87  NO
  75.    5.00    4.56    0.00    0.00   50.01    0.00    0.00     0.00    0.00   2.70  NO
 100.    5.00    6.40    0.00    0.00   50.01    0.00    0.00     0.00    0.00   4.53  NO
```

RUN N-2

```
LOCO FRONT:   Y-DAMPING    X-DAMPING   WIDTH/FT   ATTEN.LNGTH/FT    V-LOCO/MPH
AHEAD  1.FT     1750.00     38000.00      10.00             0.00         50.00

ZETA                                                 CAR SPR.         SIDE CRUSH,FT
1.050                                                  4760.              0.500

VEH:WDTH   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
    6.60    4693.     18.60       0.0         55.0          OF TRACK  8.37 FT

 TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD     Y-DD   TH-DD    YTR  VEH
 MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S      G/S  RAD/S2    FT.  CLR
   0.    0.00    0.00    0.00    0.00    0.00    0.00    0.00     0.00    0.00  -2.80  NO
   5.    0.00    0.02    0.26   -0.18    8.27  139.70   -9.59    96.49  605.68  -2.43  NO
  10.   -0.01    0.12    1.33   -2.05   16.72  272.31  -24.38    48.71  263.72  -2.07  NO
  15.   -0.03    0.26    2.85   -4.69   20.62  324.00  -21.23    20.26   89.92  -1.70  NO
  20.   -0.07    0.41    4.52   -6.67   22.22  341.51  -13.05     8.27   30.64  -1.33  NO
  25.   -0.13    0.58    6.24   -7.79   22.88  347.68   -6.75     3.54   12.40  -0.97  NO
  30.   -0.19    0.75    7.99   -8.36   23.18  350.48   -3.14     1.77    7.14  -0.60  NO
  35.   -0.25    0.92    9.75   -8.60   23.34  352.31   -1.12     1.07    5.58  -0.23  NO
  40.   -0.31    1.09   11.51   -8.67   23.44  353.84   -0.10     0.82    5.16   0.13  NO
  45.   -0.38    1.26   13.28   -8.67   23.53  355.32    0.00     0.82    5.23   0.50  NO
  50.   -0.44    1.44   15.07   -8.67   23.62  356.84    0.00     0.85    5.33   0.87  NO
  75.   -0.77    2.31   24.10   -9.67   24.22  366.76   -4.38     1.37    9.85   2.70  NO
 100.   -1.16    3.21   33.44  -10.95   24.99  380.12    0.00     1.94   10.55   4.53  NO
 125.   -1.56    4.15   43.16  -10.95   26.31  397.78    0.00     2.87   13.64   6.37  NO
 150.   -1.96    5.15   53.35  -10.95   28.06  417.69    0.00     3.48   13.56   8.20  NO
 175.   -2.36    6.22   64.02  -10.95   30.60  436.30    0.00     5.89   10.95  10.03  NO
 200.   -2.77    7.38   75.06  -10.95   32.89  443.62    0.00     2.83    0.00  11.87  NO
 225.   -3.17    8.61   86.15  -10.95   33.47  443.62    0.00     0.05    0.00  13.70  NO
 230.   -3.25    8.85   88.37  -10.95   33.47  443.62    0.00     0.00    0.00  14.07  YES
```

RUN N-3

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD 10.FT    1750.00    38000.00     10.00            0.00        50.00

ZETA                                                 CAR SPR.        SIDE CRUSH,FT
1.050                                                 4760.            0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   6.60    4693.    18.60      0.0        55.0        OF TRACK 11.37 FT

TIME   X-VEH   Y-VEH  THETA   X-DOT   Y-DOT   TH-DT     X-DD     Y-DD    TH-DD   YTR   VEH
MSEC    FEET    FEET    DEG   MI/HR   MI/HR   DEG/S      G/S      G/S   RAD/S2   FT.   CLR
  0.    3.00    0.00   0.00    0.00    0.00    0.00     0.00     0.00     0.00 -2.80   NO
  5.    3.00    0.01   0.03   -0.01    3.08   18.28    -0.58    48.39   108.97 -2.43   NO
 10.    3.00    0.05   0.21   -0.21    8.89   51.77    -4.39    57.12   120.91 -2.07   NO
 15.    3.00    0.14   0.55   -0.98   15.15   85.03   -11.37    55.61   105.68 -1.70   NO
 20.    2.98    0.27   1.05   -2.57   21.01  112.62   -19.16    49.52    81.76 -1.33   NO
 25.    2.96    0.45   1.66   -4.97   26.11  133.34   -25.55    41.87    58.90 -0.97   NO
 30.    2.91    0.65   2.37   -7.97   30.36  148.01   -29.45    34.26    40.70 -0.60   NO
 35.    2.84    0.89   3.14  -11.27   33.81  158.05   -30.75    27.44    27.52 -0.23   NO
 40.    2.74    1.15   3.94  -14.63   36.56  164.82   -29.91    21.64    18.52  0.13   NO
 45.    2.62    1.42   4.78  -17.81   38.71  169.39   -27.55    16.90    12.62  0.50   NO
 50.    2.48    1.71   5.64  -20.70   40.39  172.54   -24.27    13.09     8.89  0.87   NO
 75.    1.54    3.29  10.06  -28.42   44.30  182.17     0.00     1.85    11.87  2.70   NO
100.    0.50    4.92  14.71  -28.42   44.55  186.25     0.00     0.00     0.00  4.53   NO
125.   -0.54    6.55  19.36  -28.42   44.55  186.25     0.00     0.00     0.00  6.37   NO
150.   -1.59    8.18  24.02  -28.42   44.55  186.25     0.00     0.00     0.00  8.20   NO
175.   -2.63    9.82  28.68  -28.42   44.55  186.25     0.00     0.00     0.00 10.03   NO
200.   -3.67   11.45  33.33  -28.42   44.55  186.25     0.00     0.00     0.00 11.87   NO
225.   -4.71   13.09  37.99  -28.42   44.55  186.25     0.00     0.00     0.00 13.70   NO
250.   -5.75   14.72  42.65  -28.42   44.55  186.25     0.00     0.00     0.00 15.53   NO
275.   -6.80   16.35  47.30  -28.42   44.55  186.25     0.00     0.00     0.00 17.37   NO
300.   -7.84   17.99  51.96  -28.42   44.55  186.25     0.00     0.00     0.00 19.20  YES
```

RUN N-4

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD 10.FT    1750.00    38000.00     10.00            0.00        50.00

ZETA                                                 CAR SPR.        SIDE CRUSH,FT
1.050                                                 4760.            0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   6.60    4693.    18.60      0.0        55.0        OF TRACK  8.37 FT

TIME   X-VEH   Y-VEH  THETA   X-DOT   Y-DOT   TH-DT     X-DD     Y-DD    TH-DD   YTR   VEH
MSEC    FEET    FEET    DEG   MI/HR   MI/HR   DEG/S      G/S      G/S   RAD/S2   FT.   CLR
  0.    0.00    0.00   0.00    0.00    0.00    0.00     0.00     0.00     0.00 -2.80   NO
  5.    0.00    0.01   0.09   -0.02    2.99   50.74    -1.51    44.55   286.92 -2.43   NO
 10.    0.00    0.05   0.55   -0.48    8.01  133.56    -9.17    44.51   270.70 -2.07   NO
 15.   -0.01    0.12   1.40   -1.91   12.54  203.25   -18.60    35.88   199.60 -1.70   NO
 20.   -0.03    0.23   2.55   -4.26   16.05  252.49   -24.65    26.52   133.84 -1.33   NO
 25.   -0.07    0.36   3.90   -7.07   18.61  285.09   -26.20    18.85    87.57 -0.97   NO
 30.   -0.14    0.50   5.38   -9.88   20.41  306.49   -24.35    13.14    58.20 -0.60   NO
 35.   -0.23    0.65   6.95  -12.40   21.66  320.89   -20.51     9.05    40.16 -0.23   NO
 40.   -0.32    0.82   8.55  -14.44   22.51  330.99   -15.82     6.19    28.94  0.13   NO
 45.   -0.41    0.98  10.26  -15.97   23.10  338.38   -11.07     4.22    21.65  0.50   NO
 50.   -0.55    1.16  11.96  -16.99   23.50  343.96    -6.79     2.91    16.58  0.87   NO
 75.   -1.20    2.04  20.78  -17.83   24.48  359.73     0.00     1.53     9.32  2.70   NO
100.   -1.85    2.95  29.92  -17.83   25.07  368.82     0.00     0.70     3.98  4.53   NO
125.   -2.51    3.88  39.25  -17.83   25.77  378.67     0.00     1.48     7.46  6.37   NO
150.   -3.16    4.83  48.78  -17.83   26.02  381.84     0.00     0.00     0.00  8.20   NO
175.   -3.81    5.79  58.33  -17.83   26.02  381.84     0.00     0.00     0.00 10.03   NO
200.   -4.47    6.74  67.88  -17.83   26.02  381.84     0.00     0.00     0.00 11.87   NO
225.   -5.12    7.69  77.42  -17.83   26.02  381.84     0.00     0.00     0.00 13.70  YES
250.   -5.78    6.65  86.97  -17.83   26.02  381.84     0.00     0.00     0.00 15.53  YES
255.   -5.91    8.84  88.88  -17.83   26.02  381.84     0.00     0.00     0.00 15.90  YES
```

RUN N-5

```
 LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT    V-LOCO/MPH
 AHEAD 10.FT    1750.00    38000.00    10.00              0.00         50.00

 ZETA                                           CAR SPR.          SIDE CRUSH.FT
 1.050                                           4760.              0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    6.60   4693.   18.60       0.0        55.0          OF TRACK 13.37 FT

TIME  X-VEH  Y-VEH  THETA  X-DOT  Y-DOT  TH-DT   X-DD     Y-DD   TH-DD  YTR   VEH
MSEC   FEET   FEET    DEG  MI/HR  MI/HR  DEG/S    G/S      G/S  RAD/S2  FT.   CLR
  0.   5.00   0.00   0.00   0.00   0.00   0.00   0.00     0.00    0.00 -2.80  NO
  5.   5.00   0.01   0.00   0.00   3.09   0.00   0.00    48.96    0.00 -2.43  NO
 10.   5.00   0.05   0.00   0.00   9.03   0.00   0.00    59.19    0.00 -2.07  NO
 15.   5.00   0.14   0.00   0.00  15.59   0.00   0.00    59.23    0.00 -1.70  NO
 20.   5.00   0.28   0.00   0.00  21.89   0.00   0.00    54.17    0.00 -1.33  NO
 25.   5.00   0.46   0.00   0.00  27.52   0.00   0.00    46.93    0.00 -0.97  NO
 30.   5.00   0.68   0.00   0.00  32.33   0.00   0.00    39.20    0.00 -0.60  NO
 35.   5.00   0.93   0.00   0.00  36.30   0.00   0.00    31.93    0.00 -0.23  NO
 40.   5.00   1.21   0.00   0.00  39.52   0.00   0.00    25.54    0.00  0.13  NO
 45.   5.00   1.51   0.00   0.00  42.07   0.00   0.00    20.15    0.00  0.50  NO
 50.   5.00   1.83   0.00   0.00  44.08   0.00   0.00    15.75    0.00  0.87  NO
 75.   5.00   3.55   0.00   0.00  49.06   0.00   0.00     4.25    0.00  2.70  NO
100.   5.00   5.38   0.00   0.00  50.04   0.00   0.00     0.00    0.00  4.53  NO
125.   5.00   7.21   0.00   0.00  50.04   0.00   0.00     0.00    0.00  6.37  NO
150.   5.00   9.05   0.00   0.00  50.04   0.00   0
```

B.2 Crushable Attenuator

RUN A-1

```
 LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT    V-LOCO/MPH
 AHEAD  1.FT    1750.00    38000.00    10.00             10.00         50.00

 ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.        SIDE CRUSH,FT
 1.050    4320.         4320.         10.0       7447.            0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00   3000.   16.00       0.0        55.0          OF TRACK  7.20 FT

TIME  X-VEH  Y-VEH  THETA  X-DOT  Y-DOT  TH-DT   X-DD     Y-DD   TH-DD  YTR   VEH
MSEC   FEET   FEET    DEG  MI/HR  MI/HR  DEG/S    G/S      G/S  RAD/S2  FT.   CLR
  0.   0.00   0.00   0.00   0.00   0.00   0.00   0.00     0.00    0.00-12.50  NO
 25.   0.00   0.08   1.02  -0.03   4.78  93.79  -0.18    10.43   77.98-10.67  NO
 50.   0.00   0.36   4.75  -0.29  10.54 205.03  -0.88    10.62   77.14 -8.83  NO
 75.  -0.03   0.55  11.25  -1.08  16.43 314.17  -2.15    10.83   74.80 -7.00  NO
100.  -0.09   1.56  20.42  -2.73  22.38 418.24  -4.03    10.84   69.77 -5.17  NO
125.  -0.24   2.49  32.08  -5.56  28.23 512.75  -6.49    10.35   61.25 -3.33  NO
150.  -0.52   3.63  45.94  -9.86  33.60 592.86  -9.35     9.05   49.83 -1.50  NO
175.  -0.99   4.94  61.58 -15.78  37.99 656.10 -12.35     6.68   36.34  0.33  NO
200.  -1.69   6.39  78.56 -23.01  40.68 694.81 -13.87     2.81   11.06  2.17  NO
```

RUN A-2

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT    V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00    10.00             10.00         50.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    3240.        3240.          7.5          7447.            0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00   3000.   16.00      0.0         55.0           OF TRACK  7.20 FT

TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT     X-DD      Y-DD   TH-DD   YTP   VEH
MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S      G/S       G/S  RAD/SS   FT.   CLR
  0.    0.00    0.00    0.00    0.00    0.00    0.00     0.00      0.00    0.00-12.50  NO
 25.    0.00    0.06    0.76   -0.02    3.58   70.38    -0.10      7.81   58.52-10.67  NO
 50.    0.00    0.27    3.57   -0.16    7.89  153.96    -0.49      7.93   58.09 -8.83  NO
 75.   -0.02    0.64    8.45   -0.60   12.28  236.50    -1.20      8.07   56.96 -7.00  NO
100.   -0.05    1.17   15.37   -1.52   16.73  316.63    -2.24      8.16   54.57 -5.17  NO
125.   -0.14    1.86   24.25   -3.10   21.19  392.17    -3.63      8.05   50.39 -3.33  NO
150.   -0.29    2.72   34.92   -5.52   25.51  460.32    -5.31      7.61   44.21 -1.50  NO
175.   -0.55    3.73   47.18   -8.92   29.46  518.53    -7.20      6.67   36.61  0.33  NO
200    -0.96    4.88   60.80  -13.24   33.44  573.00    -8.39      8.03   38.99  2.17  NC
205    -1.06    5.12   63.70  -14.17   34.31  583.88    -8.57      7.63   36.28  2.54  NC
210    -1.17    5.38   66.64  -15.12   35.12  593.91    -8.74      7.02   32.99  2.90  NC
215    -1.28    5.64   69.63  -16.08   35.86  602.96    -8.91      6.27   29.50  3.27  NC
220    -1.40    5.90   72.67  -17.07   36.51  611.01    -9.07      5.41   25.97  3.64  NC
225    -1.53    6.17   75.74  -18.07   37.06  618.04    -9.22      4.48   22.42  4.00  NC
230    -1.67    6.45   78.85  -19.08   37.51  624.04    -9.35      3.50   18.63  4.37  NC
235    -1.81    6.72   81.98  -20.12   37.85  628.87    -9.47      2.49   13.79  4.74  NC
```

RUN A-3

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT    V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00    10.00             10.00         50.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    3240.        3240.          7.5          7447.            0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00   3000.   16.00      0.0         55.0           OF TRACK 10.20 FT

TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT     X-DD      Y-DD   TH-DD   YTP   VEH
MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S      G/S       G/S  RAD/SS   FT.   CLR
  0.    3.00    0.00    0.00    0.00    0.00    0.00     0.00      0.00    0.00-12.50  NO
 25.    3.00    0.07    0.33   -0.01    4.70   32.31    -0.06     10.80   28.25-10.67  NO
 50.    3.00    0.35    1.64   -0.10   10.63   72.28    -0.31     10.80   27.42 -8.83  NO
 75.    2.99    0.85    3.94   -0.38   16.55  110.65    -0.74     10.80   26.00 -7.00  NO
100.    2.97    1.57    7.16   -0.94   22.47  146.62    -1.36     10.80   24.06 -5.17  NO
125.    2.92    2.50   11.25   -1.88   28.39  188.43    -2.15     10.80   73.59 -3.33  NO
150.    2.82    3.65   17.26   -3.35   34.32  290.87    -3.36     10.80   68.66 -1.50  NO
175.    2.66    5.02   25.73   -5.64   40.24  384.85    -5.20     10.80   61.65  0.33  NO
200     2.38    6.64   36.87   -9.33   46.57  474.35    -7.33      9.78   46.00  2.17  N(
205     2.31    6.98   39.27  -10.15   47.62  487.01    -7.63      9.34   41.49  2.54  N(
210     2.24    7.34   41.74  -11.00   48.63  498.39    -7.95      8.91   37.04  2.90  N(
215     2.15    7.70   44.25  -11.88   49.59  508.49    -8.27      8.49   32.59  3.27  N(
220     2.06    8.06   46.82  -12.80   50.50  517.31    -8.60      8.07   28.11  3.64  N(
225     1.96    8.44   49.42  -13.76   51.37  524.84    -8.94      7.65   23.57  4.00  N(
250     1.36   10.39   62.83  -19.11   54.99  541.83   -10.60      5.44   -1.99  5.34  N(
275     0.55   12.45   76.15  -25.32   57.34  513.16   -12.07      2.98  -46.30  7.67  N(
310     0.87   14.15   89.05   -9.33   46.57  474.35        0         0       0 10.22  N(
```

RUN A-4

```
 LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
 AHEAD  1.FT    1750.00    38000.00     10.00           10.00        50.00

 ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
 1.050    2160.         2160.          5.0         7447.           0.500

 VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00    3000.   16.00      0.0        55.0         OF TRACK  7.20 FT

TIME   X-VEH   Y-VEH  THETA  X-DOT  Y-DOT  TH-DT    X-DD     Y-DD   TH-DD  YTP  VEH
MSEC   FEET    FEET    DEG  MI/HR  MI/HR  DEG/S     G/S      G/S  RAD/S2  FT.  CLR
  0.   0.00    0.00   0.00   0.00   0.00   0.00    0.00     0.00    0.00-12.50  NO
 25.   0.00    0.04   0.51  -0.01   2.39  46.95   -0.05     5.20   39.03-10.67  NO
 50.   0.00    0.18   2.38  -0.07   5.25 102.76   -0.22     5.25   38.86 -8.83  NO
 75.  -0.01    0.42   5.64  -0.27   8.15 158.17   -0.53     5.33   38.44 -7.00  NO
100.  -0.02    0.78  10.28  -0.67  11.10 212.73   -0.98     5.41   37.61 -5.17  NO
125.  -0.06    1.24  16.27  -1.36  14.07 265.67   -1.59     5.44   36.14 -3.33  NO
150.  -0.13    1.81  23.54  -2.42  17.04 315.96   -2.34     5.38   33.84 -1.50  NO

175    -0.30    2.51  32.14   -9.91   22.62  392.97   -2.80    21.09   132.58   0.34   NO*
180    -0.38    2.68  34.20  -10.22   24.97  431.22   -2.85    21.44   132.13   0.70   NO*
185    -0.45    2.87  36.45  -10.54   27.27  467.99   -2.93    20.18   121.35   1.07   NO*
190    -0.53    3.08  38.87  -10.86   29.40  501.08   -3.04    18.20   106.39   1.44   NO*
195    -0.61    3.30  41.45  -11.20   31.31  529.79   -3.16    16.10    91.16   1.80   NO*
200    -0.70    3.54  44.16  -11.55   32.98  554.30   -3.31    14.17    77.55   2.17   NO*
205    -0.78    3.79  46.99  -11.92   34.46  575.15   -3.46    12.53    66.13   2.54   NO*
210    -0.87    4.04  49.91  -12.31   35.78  592.98   -3.63    11.16    56.76   2.90   NO*
235    -1.36    5.45  65.56  -14.53   40.57  651.90   -4.49     6.46    27.70   4.74   NO*
260    -1.94    6.99  82.25  -17.19   42.92  679.30   -5.20     1.83    10.83   6.57   NO*
```

RUN A-5

```
 LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
 AHEAD  1.FT    1750.00    38000.00     10.00           10.00        30.00

 ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
 1.050    2160.         2160.          5.0         7447.           0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   5.00    3000.   16.00      0.0        55.0         OF TRACK  7.20 FT

TIME   X-VEH   Y-VEH  THETA  X-DOT  Y-DOT  TH-DT    X-DD     Y-DD   TH-DD  YTP  VEH
MSEC   FEET    FEET    DEG  MI/HR  MI/HR  DEG/S     G/S      G/S  RAD/S2  FT.  CLR
  0.   0.00    0.00   0.00   0.00   0.00   0.00    0.00     0.00    0.00-12.50  NO
 25.   0.00    0.03   0.44  -0.01   2.12  41.73   -0.04     5.20   39.04-11.40  NO
 50.   0.00    0.16   2.18  -0.06   4.98  97.56   -0.20     5.25   38.88-10.30  NO
 75.  -0.01    0.40   5.31  -0.24   7.88 153.02   -0.49     5.32   38.49 -9.20  NO
100.  -0.02    0.74   9.82  -0.62  10.82 207.67   -0.92     5.40   37.70 -8.10  NO
125.  -0.06    1.19  15.68  -1.29  13.79 260.79   -1.53     5.44   36.30 -7.00  NO
150.  -0.12    1.75  22.84  -2.21  16.77 311.36   -2.27     5.39   34.08 -5.90  NO
175.  -0.23    2.42  31.22  -3.78  19.68 358.15   -3.15     5.20   30.97 -4.80  NO
200.  -0.40    3.19  40.70  -5.77  22.44 399.90   -4.14     4.81   27.08 -3.70  NO
225.  -0.66    4.06  51.15  -8.21  24.84 433.39   -4.68     3.77   18.36 -2.60  NO
250.  -1.01    5.01  62.26 -10.86  26.60 453.12   -4.95     2.60    9.00 -1.50  NO
275.  -1.46    6.01  73.70 -13.62  27.73 459.73   -5.17     1.51   -0.27 -0.40  NO
300.  -2.01    7.03  85.14 -16.64  28.30 452.85   -6.34     0.54  -12.62  0.70  NO
305.  -2.13    7.24  87.39 -17.38  28.35 446.00   -7.88     0.36  -27.92  0.92  NO
310.  -2.27    7.45  89.60 -18.11  28.37 438.51    0.00     0.00    0.00  1.14  NO
```

RUN A-6

```
  LOCO FRONT:  Y-DAMPING    X-DAMPING   WIDTH/FT   ATTEN.LNGTH/FT    V-LOCO/MPH
  AHEAD  1.FT     1750.00     38000.00     10.00              10.00        50.00

  ZETA   YATTEN.DAMP   XATTEN.DAMP   ATT.YLD,PSI    CAR SPR.          SIDE CRUSH,FT
  1.050     3240.         3240.            7.5         4760.             0.500

 VEH:WDTH   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
     6.60     4693.    18.60       0.0         55.0            OF TRACK  8.37 FT

TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD       Y-DD    TH-DD   YTR   VEH
MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S        G/S   RAD/S2   FT.   CLR
  0.    0.00    0.00    0.00    0.00    0.00    0.00    0.00       0.00     0.00-13.30   NO
 25.    0.00    0.04    0.47   -0.01    2.65   43.67   -0.05       5.80    36.49-11.47   NO
 50.    0.00    0.20    2.21   -0.07    5.84   95.85   -0.23       5.86    36.33 -9.63   NO
 75.   -0.01    0.47    5.26   -0.28    9.08  147.65   -0.55       5.96    35.94 -7.80   NO
100.   -0.02    0.86    9.59   -0.69   12.37  198.65   -1.02       6.06    35.16 -5.97   NO
125.   -0.06    1.38   15.18   -1.42   15.72  248.17   -1.66       6.13    33.82 -4.13   NO
150.   -0.13    2.02   21.98   -2.53   19.08  295.26   -2.47       6.12    31.71 -2.30   NO
175.   -0.25    2.78   29.91   -4.13   22.41  338.75   -3.43       5.97    28.75 -0.47   NO
200.   -0.44    3.66   38.88   -6.30   25.60  377.44   -4.53       5.62    25.01  1.37   NO
225.   -0.72    4.65   48.74   -9.10   28.54  410.38   -5.73       5.02    20.77  3.20   NO
250.   -1.12    5.75   59.34  -12.57   31.07  437.18   -6.97       4.13    16.52  5.03   NO
275.   -1.65    6.92   70.55  -16.73   33.04  457.84   -8.30       2.93    10.39  6.87   NO
299.   -2.32    8.11   81.69  -21.51   34.23  469.04    0.00       2.68     0.00  8.63   NO←
300.   -2.36    8.16   82.15  -21.51   34.29  469.04    0.00       2.41     0.00  8.70   NO←
305.   -2.51    8.41   84.50  -21.51   34.50  469.04    0.00       1.28     0.00  9.07   NO←
310.   -2.67    8.67   86.84  -21.51   34.60  469.04    0.00       0.47     0.00  9.43   NO←
315.   -2.83    8.92   89.19  -21.51   34.63  469.04    0.00       0.03     0.00  9.80   NO←
```

RUN A-7

```
  LOCO FRONT:  Y-DAMPING    X-DAMPING   WIDTH/FT   ATTEN.LNGTH/FT    V-LOCO/MPH
  AHEAD  1.FT     1750.00     38000.00     10.00              10.00        50.00

  ZETA   YATTEN.DAMP   XATTEN.DAMP   ATT.YLD,PSI    CAR SPR.          SIDE CRUSH,FT
  1.050     4320.         4320.           10.0         4760.             0.500

 VEH:WDTH   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
     6.60     4693.    18.60       0.0         55.0            OF TRACK  8.37 FT

TIME   X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD       Y-DD    TH-DD   YTR   VEH
MSEC    FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S        G/S   RAD/S2   FT.   CLR
  0.    0.00    0.00    0.00    0.00    0.00    0.00    0.00       0.00     0.00-13.30   NO
 25.    0.00    0.06    0.62   -0.01    3.53   58.20   -0.08       7.74    48.64-11.47   NO
 50.    0.00    0.26    2.95   -0.13    7.80  127.70   -0.40       7.85    48.33 -9.63   NO
 75.   -0.01    0.63    7.00   -0.49   12.14  196.46   -0.98       8.01    47.54 -7.80   NO
100.   -0.04    1.15   12.76   -1.25   16.57  263.57   -1.84       8.15    45.93 -5.97   NO
125.   -0.11    1.84   20.16   -2.55   21.06  327.57   -3.00       8.18    43.09 -4.13   NO
150.   -0.24    2.70   29.10   -4.56   25.50  386.51   -4.45       7.99    38.77 -2.30   NO
175.   -0.46    3.71   39.42   -7.44   29.76  438.24   -6.13       7.46    33.03 -0.47   NO
200.   -0.80    4.88   50.93  -11.28   33.62  481.08   -7.99       6.48    26.46  1.37   NO
225.   -1.30    6.17   63.40  -16.17   36.80  514.51   -9.93       4.97    20.05  3.20   NO
250.   -2.00    7.56   76.57  -22.17   39.01  537.21  -12.14       2.90     8.82  5.03   NO
275.   -2.93    9.01   90.03  -28.09   39.86  534.90    0.00       0.00     0.00  6.87   NO←
```

RUN A-8

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00     10.00            10.00        50.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    2160.        2160.          5.0       7447.             0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   5.00    3000.   16.00      0.0        55.0             OF TRACK  4.20 FT

TIME  X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD      Y-DD    TH-DD  YTR   VEH
MSEC   FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S       G/S   RAD/S2  FT.   CLR
  0.  -3.00    0.00    0.00    0.00    0.00    0.00    0.00      0.00     0.00-12.47  NO
  5.  -3.00    0.00    0.00    0.00    0.09    1.79    0.00      1.68    12.64-12.11  NO
 10.  -3.00    0.00    0.02    0.00    0.32    6.22    0.00      2.55    19.25-11.74  NO
 15.  -3.00    0.01    0.07    0.00    0.63   12.30    0.00      3.03    22.79-11.37  NO
 20.  -3.00    0.01    0.15    0.00    0.96   18.83   -0.01      3.03    22.80-11.01  NO
 25.  -3.00    0.02    0.26    0.00    1.29   25.37   -0.01      3.03    22.81-10.64  NO
 30.  -3.00    0.03    0.40    0.00    1.62   31.90   -0.02      3.04    22.81-10.27  NO
 35.  -3.00    0.04    0.58   -0.01    1.96   38.44   -0.03      3.04    22.82 -9.91  NO
 40.  -3.00    0.06    0.78   -0.01    2.29   44.98   -0.04      3.05    22.83 -9.54  NO
 45.  -3.00    0.08    1.03   -0.02    2.62   51.52   -0.05      3.06    22.84 -9.17  NO
 50.  -3.00    0.10    1.30   -0.02    2.96   58.06   -0.07      3.06    22.86 -8.81  NO
 75.  -3.00    0.24    3.16   -0.08    4.65   90.84   -0.17      3.11    22.91 -6.97  NO
100.  -3.01    0.44    5.84   -0.22    6.37  123.68   -0.32      3.17    22.93 -5.14  NO
125.  -3.02    0.70    9.34   -0.45    8.13  156.48   -0.53      3.23    22.84 -3.31  NO
150.  -3.04    1.04   13.66   -0.81    9.92  189.04   -0.80      3.27    22.58 -1.47  NO
175.  -3.20    1.46   18.93  -19.13   17.39  269.72   -0.77     42.66   303.32  0.36  NO*
180.  -3.34    1.60   20.50  -19.21   22.17  358.16   -0.76     43.51   306.47  0.72  NO*
185.  -3.48    1.78   22.51  -19.30   26.78  442.62   -0.82     39.23   272.67  1.09  NO*
190.  -3.62    2.00   24.91  -19.39   30.81  515.30   -0.94     32.69   223.28  1.46  NO*
195.  -3.77    2.23   27.64  -19.50   34.06  572.90   -1.11     24.92   166.58  1.82  NO*
200.  -3.91    2.49   30.61  -19.63   36.41  613.65   -1.31     16.05   104.93  2.19  NO*
205.  -4.05    2.77   33.74  -19.79   37.75  636.38   -1.53      6.27    40.96  2.56  NO*
210.  -4.20    3.04   36.94  -19.96   38.13  643.14   -1.66      2.20    15.92  2.92  NO*
235.  -4.95    4.46   53.28  -20.84   39.04  662.65   -1.31      0.98    10.43  4.76  NO*
260.  -5.72    5.90   69.95  -20.98   39.16  664.84    1.78     -0.65   -19.02  6.59 YES*
```

RUN A-9

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00     10.00            10.00        30.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    3240.        3240.          7.5       7447.             0.500

VEH:WDTH  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   5.00    3000.   16.00      0.0        55.0             OF TRACK  7.20 FT

TIME  X-VEH   Y-VEH   THETA   X-DOT   Y-DOT   TH-DT    X-DD      Y-DD    TH-DD  YTR   VEH
MSEC   FEET    FEET     DEG   MI/HR   MI/HR   DEG/S     G/S       G/S   RAD/S2  FT.   CLR
  0.   0.00    0.00    0.00    0.00    0.00    0.00    0.00      0.00     0.00-12.50  NO
 25.   0.00    0.05    0.65   -0.01    3.18   62.43   -0.09      7.81    58.53-11.40  NO
 50.   0.00    0.24    3.26   -0.14    7.48  146.06   -0.45      7.91    58.14-10.30  NO
 75.  -0.01    0.60    7.95   -0.55   11.86  228.73   -1.13      8.06    57.09 -9.20  NO
100.  -0.05    1.11   14.68   -1.42   16.31  309.14   -2.14      8.15    54.85 -8.10  NO
125.  -0.13    1.79   23.37   -2.93   20.77  385.19   -3.49      8.07    50.85 -7.00  NO
150.  -0.27    2.64   33.86   -5.19   24.98  451.46   -4.56      6.80    38.11 -5.90  NO
175.  -0.51    3.61   45.73   -7.82   28.19  493.83   -5.01      4.88    20.62 -4.80  NO
200.  -0.85    4.69   58.36  -10.63   30.42  512.79   -5.22      3.22     5.81 -3.70  NO
225.  -1.29    5.83   71.21  -13.55   31.81  512.74   -5.52      1.88    -7.65 -2.60  NO
250.  -1.85    7.02   83.83  -16.89   32.55  491.97   -7.49      0.81   -27.61 -1.50  NO
255.  -1.97    7.25   86.26  -17.78   32.63  482.25   -9.53      0.62   -48.41 -1.28  NO
260.  -2.11    7.49   88.66  -17.99   32.64  479.48    0.00      0.00     0.00 -1.06  NO←
265    -1.54    7.33   90.17   -7.82   28.19  493.83    0         0        0      -.84  NO
```

RUN A-10

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00    10.00              10.00       30.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    3240.        3240.           7.5          7447.           0.500

VEH:WDTH   WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00    3000.   16.00      0.0         55.0           OF TRACK  4.20 FT

TIME  X-VEH   Y-VEH   THETA  X-DOT  Y-DOT   TH-DT    X-DD      Y-DD   TH-DD  YTR   VEH
MSEC   FEET    FEET     DEG  MI/HR  MI/HR   DEG/S     G/S       G/S  RAD/S2  FT.   CLR
  0.  -3.00    0.00    0.00   0.00   0.00    0.00    0.00      0.00    0.00-12.47  NO
 25.  -3.00    0.02    0.29   0.00   1.59   31.28   -0.02      4.55   34.21-11.37  NO
 50.  -3.00    0.13    1.69  -0.04   4.10   80.34   -0.14      4.61   34.31-10.27  NO
 75.  -3.00    0.32    4.31  -0.17   6.65  129.55   -0.36      4.71   34.39 -9.17  NO
100.  -3.01    0.61    8.17  -0.45   9.27  178.79   -0.69      4.82   34.32 -8.07  NO
125.  -3.04    1.00   13.25  -0.94  11.94  227.73   -1.15      4.91   33.91 -6.97  NO
150.  -3.09    1.49   19.54  -1.72  14.63  275.74   -1.74      4.90   33.00 -5.87  NO
175.  -3.17    2.08   27.02  -2.85  17.28  322.06   -2.41      4.73   31.52 -4.77  NO
200.  -3.30    2.76   35.61  -4.36  19.78  362.06   -3.10      4.33   20.31 -3.67  NO
225.  -3.49    3.52   45.03  -6.21  21.99  391.36   -3.64      3.63   20.72 -2.57  NO
250.  -3.76    4.36   55.18  -8.16  23.64  419.44   -2.98      2.07   15.55 -1.47  NO
275.  -4.08    5.24   65.86  -9.22  24.28  431.46   -0.51      0.23    2.25 -0.37  NO
300.  -4.43    6.14   76.72  -9.76  24.46  439.50    0.00      0.00    0.00  0.73 YES
325.  -4.79    7.03   87.71  -9.76  24.46  439.50    0.00      0.00    0.00  1.83 YES
330.  -4.86    7.21   89.91  -9.76  24.46  439.50    0.00      0.00    0.00  2.05 YES
```

RUN A-11

```
LOCO FRONT:  Y-DAMPING   X-DAMPING  WIDTH/FT  ATTEN.LNGTH/FT   V-LOCO/MPH
AHEAD  1.FT    1750.00    38000.00    10.00              10.00       30.00

ZETA  YATTEN.DAMP  XATTEN.DAMP  ATT.YLD,PSI   CAR SPR.          SIDE CRUSH,FT
1.050    3240.        3240.           7.5          7447.           0.500

VEH:WDTH   WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
    5.00    3000.   16.00      0.0         55.0           OF TRACK 10.20 FT

TIME  X-VEH   Y-VEH   THETA  X-DOT  Y-DOT   TH-DT    X-DD      Y-DD   TH-DD  YTR   VEH
MSEC   FEET    FEET     DEG  MI/HP  MI/HR   DEG/S     G/S       G/S  RAD/S2  FT.   CLR
  0.   3.00    0.00    0.00   0.00   0.00    0.00    0.00      0.00    0.00-12.50  NO
 25.   3.00    0.06    0.27  -0.01   3.95   27.13   -0.05     10.80   28.29-11.40  NO
 50.   3.00    0.31    1.45  -0.08   9.87   67.21   -0.27     10.80   27.55-10.30  NO
 75.   2.99    0.78    3.62  -0.33  15.79  105.81   -0.68     10.80   26.20 -9.20  NO
100.   2.97    1.47    6.72  -0.85  21.71  142.11   -1.27     10.80   24.32 -8.10  NO
125.   2.92    2.37   10.70  -1.75  27.64  175.40   -2.04     10.80   74.01 -7.00  NO

355    2.33   11.69   51.04  -1.75  27.64  175.40   0            0    0      +3.12  NO
575    1.76   20.61   89.63  -1.75  27.64  175.40   0            0    0      12.80  NO
```

RUN W-1

```
WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
TCRIT=.200.      102.27         0.50       10.00            15.00         40.00

    VEH:   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
10.9 g's,  max 3200.    15.0       0.0          60.0         OF TRACK 16.00 FT

TIME       X-VEH     Y-VEH     THETA        X-DOT        Y-DOT   THETA-DOT   Y-LOCO   VEH
MSEC.       FEET      FEET       DEG        MI/HR        MI/HR     DEG/SEC     FEET   CLR
   0.      10.00      0.00      0.00         0.00         0.00        0.00   -40.00    NO
  50.      10.01      0.45     -5.95         0.39        11.90     -230.72   -37.07    NO
 100.      10.10      1.68    -22.25         2.49        21.15     -410.91   -34.13    NO
 150.      10.40      3.45    -45.71         5.68        26.25     -512.71   -31.20    NO
 200.      10.89      5.43    -72.22         7.38        27.45     -538.46   -28.27    NO
 250.      11.44      7.45    -99.14         7.38        27.45     -538.46   -25.33   YES
 300.      11.98      9.46   -126.06         7.38        27.45     -538.46   -22.40    NO
 350.      12.52     11.47   -152.98         7.38        27.45     -538.46   -19.47    NO
 400.      13.06     13.49   -179.91         7.38        27.45     -538.46   -16.53    NO
 450.      13.60     15.50   -206.83         7.38        27.45     -538.46   -13.60    NO
 500.      14.14     17.51   -233.75         7.38        27.45     -538.46   -10.67   YES
 550.      14.68     19.53   -260.68         7.38        27.45     -538.46    -7.73   YES
 600.      15.23     21.54   -287.60         7.38        27.45     -538.46    -4.80   YES
 650.      15.77     23.55   -314.52         7.38        27.45     -538.46    -1.87    NO
 700.      16.31     25.56   -341.44         7.38        27.45     -538.46     1.07    NO
 750.      16.85     27.58   -368.37         7.38        27.45     -538.46     4.00    NO
 800.      17.39     29.59   -395.29         7.38        27.45     -538.46     6.93   YES
 850.      17.93     31.60   -422.21         7.38        27.45     -538.46     9.87   YES
 900.      18.47     33.62   -449.14         7.38        27.45     -538.46    12.80   YES
 950.      19.01     35.63   -476.06         7.38        27.45     -538.46    15.73   YES
1000.      19.56     37.64   -502.98         7.38        27.45     -538.46    18.67   YES
```

RUN W-1F

```
WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
TCRIT=.200.      102.27         0.50       10.00            15.00         40.00

    VEH:   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
10.6 g's,  max 3200.    15.0       0.0          60.0         OF TRACK 16.00 FT

TIME       X-VEH     Y-VEH     THETA        X-DOT        Y-DOT   THETA-DOT   Y-LOCO   VEH
MSEC.       FEET      FEET       DEG        MI/HR        MI/HR     DEG/SEC     FEET   CLR
   0.      10.00      0.00      0.00         0.00         0.00        0.00   -40.00    NO
  50.      10.00      0.44     -5.70         0.16        11.60     -220.83   -37.07    NO
 100.      10.06      1.64    -21.29         1.87        20.67     -392.82   -34.13    NO
 150.      10.31      3.37    -43.72         4.77        25.78     -489.75   -31.20    NO
 200.      10.73      5.32    -68.96         6.42        26.94     -510.41   -28.27    NO
 250.      11.19      7.29    -94.21         6.09        26.61     -499.77   -25.33   YES
 300.      11.63      9.23   -118.94         5.76        26.28     -489.12   -22.40    NO
 350.      12.04     11.14   -143.13         5.43        25.95     -478.48   -19.47    NO
 400.      12.42     13.03   -166.78         5.10        25.62     -467.83   -16.53    NO
 450.      12.78     14.90   -189.91         4.77        25.29     -457.19   -13.60    NO
 500.      13.12     16.74   -212.50         4.44        24.96     -446.55   -10.67    NO
 550.      13.44     18.56   -234.56         4.11        24.63     -435.90    -7.73    NO
 600.      13.73     20.35   -256.09         3.79        24.30     -425.26    -4.80   YES
 650.      13.99     22.12   -277.09         3.46        23.97     -414.61    -1.87   YES
 700.      14.23     23.87   -297.55         3.13        23.65     -403.97     1.07   YES
 750.      14.45     25.59   -317.49         2.80        23.32     -393.33     4.00    NO
 800.      14.64     27.29   -336.89         2.47        22.99     -382.68     6.93    NO
 850.      14.81     28.96   -355.75         2.14        22.66     -372.04     9.87    NO
 900.      14.96     30.61   -374.09         1.81        22.33     -361.39    12.80    NO
 950.      15.08     32.24   -391.89         1.48        22.00     -350.75    15.73    NO
1000.      15.17     33.84   -409.16         1.15        21.67     -340.11    18.67    NO
```

RUN W-2

```
   WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
   TCRIT=.200.      102.27         0.50      10.00            15.00         40.00

        VEH:   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
 7.6 g's, max   3200.      15.0       0.0         60.0           OF TRACK 15.20 FT

TIME      X-VEH     Y-VEH      THETA        X-DOT      Y-DOT  THETA-DOT   Y-LOCO   VEH
MSEC.      FEET      FEET        DEG        MI/HR      MI/HR    DEG/SEC     FEET   CLR
   0.     10.00      0.00      30.00         0.00       0.00       0.00   -40.00    NO
  50.      9.83      0.30      25.98        -4.56       8.33    -160.37   -37.07    NO
 100.      9.36      1.24      13.79        -8.01      17.49    -329.98   -34.13    NO
 150.      8.72      2.89      -7.08        -9.78      27.40    -500.63   -31.20    NO
 200.      8.16      5.20     -35.35        -6.12      34.90    -617.54   -28.27    NO
 250.      7.71      7.76     -66.23        -6.12      34.90    -617.54   -25.33    NO
 300.      7.26     10.32     -97.11        -6.12      34.90    -617.54   -22.40    NO
 350.      6.81     12.88    -127.98        -6.12      34.90    -617.54   -19.47    NO
 400.      6.36     15.44    -158.86        -6.12      34.90    -617.54   -16.53    NO
 450.      5.91     18.00    -189.74        -6.12      34.90    -617.54   -13.60    NO
 500.      5.46     20.56    -220.62        -6.12      34.90    -617.54   -10.67    NO
 550.      5.02     23.12    -251.49        -6.12      34.90    -617.54    -7.73    NO
 600.      4.57     25.68    -282.37        -6.12      34.90    -617.54    -4.80    NO
 650.      4.12     28.24    -313.25        -6.12      34.90    -617.54    -1.87    NO
 700.      3.67     30.80    -344.13        -6.12      34.90    -617.54     1.07    NO
 750.      3.22     33.35    -375.00        -6.12      34.90    -617.54     4.00    NO
 800.      2.77     35.91    -405.88        -6.12      34.90    -617.54     6.93    NO
 850.      2.32     38.47    -436.76        -6.12      34.90    -617.54     9.87    NO
 900.      1.87     41.03    -467.64        -6.12      34.90    -617.54    12.80    NO
 950.      1.42     43.59    -498.51        -6.12      34.90    -617.54    15.73    NO
1000.      0.98     46.15    -529.39        -6.12      34.90    -617.54    18.67    NO

1700      -5.30     81.98    -961.67        -6.12      34.90    -617.54    59.74   YES
```

RUN W-3

```
   WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
   TCRIT=.200.      102.27         0.50      10.00            15.00         40.00

        VEH:   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   VEH.FRONT ONTO LEFT SIDE
 9.8 g's max    3200.      15.0      25.0         60.0           OF TRACK 16.00 FT

TIME      X-VEH     Y-VEH      THETA        X-DOT      Y-DOT  THETA-DOT   Y-LOCO   VEH
MSEC.      FEET      FEET        DEG        MI/HR      MI/HR    DEG/SEC     FEET   CLR
   0.     10.00      0.00       0.00        25.00       0.00       0.00   -40.00    NO
  50.     11.84      0.42      -5.93        25.33      10.80    -228.94   -37.07    NO
 100.     13.74      1.48     -21.90        26.78      17.44    -396.92   -34.13    NO
 150.     15.76      2.87     -43.96        28.08      19.74    -467.15   -31.20    NO
 200.     17.83      4.32     -67.38        28.11      19.77    -468.39   -28.27   YES
 250.     19.89      5.77     -90.80        28.11      19.77    -468.39   -25.33   YES
 300.     21.95      7.22    -114.22        28.11      19.77    -468.39   -22.40   YES
 350.     24.01      8.67    -137.64        28.11      19.77    -468.39   -19.47   YES
 400.     26.07     10.12    -161.06        28.11      19.77    -468.39   -16.53   YES
 450.     28.13     11.57    -184.47        28.11      19.77    -468.39   -13.60   YES
 500.     30.19     13.02    -207.89        28.11      19.77    -468.39   -10.67   YES
 550.     32.26     14.47    -231.31        28.11      19.77    -468.39    -7.73   YES
```

RUN W-4

```
   WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
   TCRIT=.20S.     102.27        0.50     10.00           15.00        40.00

      VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 8.5 g's, max. 3200.    15.0     25.0        60.0           OF TRACK  6.00 FT

TIME       X-VEH     Y-VEH     THETA       X-DOT       Y-DOT  THETA-DOT  Y-LOCO  VEH
SEC.       FEET      FEET       DEG        MI/HR       MI/HR   DEG/SEC    FEET   CLR
   0.       0.00      0.00      0.00       25.00        0.00      0.00  -40.00   NO
  50.       1.83      0.33      2.65       24.85        9.32    102.05  -37.07   NO
 100.       3.62      1.38      9.67       23.83       19.34    172.54  -34.13   NO
 150.       5.29      3.15     19.12       21.50       28.63    194.39  -31.20   NO
 200.       6.76      5.53     28.16       18.35       35.87    160.18  -28.27   NO
 250.       8.10      8.16     36.17       18.35       35.87    160.18  -25.33   NO
 300.       9.45     10.79     44.18       18.35       35.87    160.18  -22.40   NO
 350.      10.79     13.42     52.19       18.35       35.87    160.18  -19.47   NO
 400.      12.14     16.05     60.20       18.35       35.87    160.18  -16.53   NO
 450.      13.49     18.68     68.21       18.35       35.87    160.18  -13.60   YES
 500.      14.83     21.31     76.21       18.35       35.87    160.18  -10.67   YES
 550.      16.18     23.94     84.22       18.35       35.87    160.18   -7.73   YES
 600.      17.52     26.57     92.23       18.35       35.87    160.18   -4.80   YES
 650.      18.87     29.20    100.24       18.35       35.87    160.18   -1.87   YES
 700.      20.21     31.84    108.25       18.35       35.87    160.18    1.07   YES
 750.      21.56     34.47    116.26       18.35       35.87    160.18    4.00   YES
 800.      22.91     37.10    124.27       18.35       35.87    160.18    6.93   YES
 850.      24.25     39.73    132.28       18.35       35.87    160.18    9.87   YES
 900.      25.60     42.36    140.29       18.35       35.87    160.18   12.80   YES
 950.      26.94     44.99    148.30       18.35       35.87    160.18   15.73   YES
1000.      28.29     47.62    156.30       18.35       35.87    160.18   18.67   YES
```

RUN W-5

```
   WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
   TCRIT=.20S.     102.27        0.50     10.00           15.00        40.00

      VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
   5.6 g's, max.5000.   15.0     25.0        60.0           OF TRACK  6.00 FT

TIME       X-VEH     Y-VEH     THETA       X-DOT       Y-DOT  THETA-DOT  Y-LOCO  VEH
MSEC.       FEET      FEET       DEG       MI/HR       MI/HR   DEG/SEC    FEET   CLR
   0.       0.00      0.00      0.00       25.00        0.00      0.00  -40.00   NO
  50.       1.83      0.22      1.72       24.94        6.11     66.78  -37.07   NO
 100.       3.65      0.92      6.38       24.47       13.08    115.66  -34.13   NO
 150.       5.40      2.14     12.74       23.32       20.06    130.16  -31.20   NO
 200.       7.05      3.83     18.60       21.63       26.07     97.74  -28.27   NO
 250.       8.64      5.75     23.49       21.63       26.07     97.74  -25.33   NO
 300.      10.23      7.66     28.37       21.63       26.07     97.74  -22.40   NO
 350.      11.81      9.57     33.26       21.63       26.07     97.74  -19.47   NO
 400.      13.40     11.48     38.15       21.63       26.07     97.74  -16.53   NO
 450.      14.98     13.39     43.04       21.63       26.07     97.74  -13.60   NO
 500.      16.57     15.31     47.92       21.63       26.07     97.74  -10.67   YES
 550.      18.16     17.22     52.81       21.63       26.07     97.74   -7.73   YES
 600.      19.74     19.13     57.70       21.63       26.07     97.74   -4.80   YES
 650.      21.33     21.04     62.58       21.63       26.07     97.74   -1.87   YES
 700.      22.92     22.95     67.47       21.63       26.07     97.74    1.07   YES
 750.      24.50     24.87     72.36       21.63       26.07     97.74    4.00   YES
 800.      26.09     26.78     77.24       21.63       26.07     97.74    6.93   YES
 850.      27.67     28.69     82.13       21.63       26.07     97.74    9.87   YES
 900.      29.26     30.60     87.02       21.63       26.07     97.74   12.80   YES
 950.      30.85     32.51     91.90       21.63       26.07     97.74   15.73   YES
1000.      32.43     34.43     96.79       21.63       26.07     97.74   18.67   YES
```

RUN W-6

WATER DATA:	VEL.MI/HR	AREA/SQ.FT	WIDTH/FT	INIT.VOL/CU.FT	V-LOCO/MPH
TCRIT=.27S.	75.00	0.50	10.00	15.00	40.00

VEH:	WT/LBS	LGTH/FT	SPD/MPH	% WT.FT.WH	VEH.FRONT ONTO LEFT SIDE OF TRACK
5.6 g's, max	3200.	15.0	25.0	60.0	6.00 FT

TIME MSEC.	X-VEH FEET	Y-VEH FEET	THETA DEG	X-DOT MI/HR	Y-DOT MI/HR	THETA-DOT DEG/SEC	Y-LOCO FEET	VEH CLR
0.	0.00	0.00	0.00	25.00	0.00	0.00	-40.00	NO
50.	1.83	0.22	1.74	24.94	6.17	67.47	-37.07	NO
100.	3.65	0.92	6.42	24.47	13.04	115.71	-34.13	NO
150.	5.40	2.13	12.77	23.36	19.75	129.74	-31.20	NO
200.	7.06	3.79	18.65	21.77	25.39	99.27	-28.27	NO
250.	8.59	5.83	22.18	19.99	30.14	38.13	-25.33	NO
300.	10.02	8.15	22.88	19.22	32.00	6.84	-22.40	NO
350.	11.43	10.50	23.22	19.22	32.00	6.84	-19.47	NO
400.	12.83	12.84	23.56	19.22	32.00	6.84	-16.53	NO
450.	14.24	15.19	23.91	19.22	32.00	6.84	-13.60	NO
500.	15.65	17.54	24.25	19.22	32.00	6.84	-10.67	NO
550.	17.06	19.88	24.59	19.22	32.00	6.84	-7.73	NO
600.	18.47	22.23	24.93	19.22	32.00	6.84	-4.80	YES
650.	19.88	24.58	25.28	19.22	32.00	6.84	-1.87	YES
700.	21.29	26.92	25.62	19.22	32.00	6.84	1.07	YES
750.	22.70	29.27	25.96	19.22	32.00	6.84	4.00	YES
800.	24.11	31.61	26.30	19.22	32.00	6.84	6.93	YES
850.	25.52	33.96	26.64	19.22	32.00	6.84	9.87	YES
900.	26.93	36.31	26.99	19.22	32.00	6.84	12.80	YES
950.	28.34	38.65	27.33	19.22	32.00	6.84	15.73	YES
1000.	29.75	41.00	27.67	19.22	32.00	6.84	18.67	YES

RUN W-7

WATER DATA:	VEL.MI/HR	AREA/SQ.FT	WIDTH/FT	INIT.VOL/CU.FT	V-LOCO/MPH
TCRIT=.20S.	102.27	0.50	10.00	15.00	40.00

VEH:	WT/LBS	LGTH/FT	SPD/MPH	% WT.FT.WH	VEH.FRONT ONTO LEFT SIDE OF TRACK
11.4 g's, max	3200.	15.0	25.0	60.0	5.20 FT

TIME MSEC.	X-VEH FEET	Y-VEH FEET	THETA DEG	X-DOT MI/HR	Y-DOT MI/HR	THETA-DOT DEG/SEC	Y-LOCO FEET	VEH CLR
0.	0.00	0.00	30.00	21.65	12.50	0.00	-40.00	NO
50.	1.48	1.10	31.45	18.66	17.58	55.94	-37.07	NO
100.	2.73	2.58	35.32	15.19	22.88	95.67	-34.13	NO
150.	3.70	4.44	40.68	11.43	27.72	115.70	-31.20	NO
200.	4.40	6.63	46.61	7.64	31.72	119.14	-28.27	NO
250.	4.96	8.95	52.57	7.64	31.72	119.14	-25.33	NO
300.	5.52	11.28	58.53	7.64	31.72	119.14	-22.40	NO
350.	6.08	13.61	64.48	7.64	31.72	119.14	-19.47	NO
400.	6.64	15.93	70.44	7.64	31.72	119.14	-16.53	NO
450.	7.20	18.26	76.40	7.64	31.72	119.14	-13.60	NO
500.	7.76	20.58	82.35	7.64	31.72	119.14	-10.67	NO
550.	8.32	22.91	88.31	7.64	31.72	119.14	-7.73	NO
600.	8.89	25.23	94.27	7.64	31.72	119.14	-4.80	NO
650.	9.45	27.56	100.23	7.64	31.72	119.14	-1.87	NO
700.	10.01	29.89	106.18	7.64	31.72	119.14	1.07	NO
750.	10.57	32.21	112.14	7.64	31.72	119.14	4.00	NO
800.	11.13	34.54	118.10	7.64	31.72	119.14	6.93	NO
850.	11.69	36.86	124.05	7.64	31.72	119.14	9.87	NO
900.	12.25	39.19	130.01	7.64	31.72	119.14	12.80	NO
950.	12.81	41.52	135.97	7.64	31.72	119.14	15.73	NO
1000.	13.37	43.84	141.93	7.64	31.72	119.14	18.67	NO
1250.	16.17	55.47	171.72	7.64	31.72	119.14	33.34	YES

RUN W-7F

```
WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
TCRIT=.20S.      102.27         0.50      10.00            15.00         40.00

     VEH:   WT/LBS  LGTH/FT   SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 11.4 g's, max.3200.    15.0      25.0        60.0           OF TRACK  5.20 FT

TIME      X-VEH     Y-VEH     THETA       X-DOT      Y-DOT  THETA-DOT   Y-LOCO  VEH
MSEC.      FEET      FEET       DEG       MI/HR      MI/HR    DEG/SEC     FEET  CLR
   0.      0.00      0.00     30.00       21.65      12.50       0.00   -40.00   NO
 100.      2.68      2.54     34.29       14.54      22.36      75.94   -34.13   NO
 200.      4.21      6.51     42.87        6.31      31.27      85.81   -28.27   NO
 300.      5.09     11.04     50.39        5.65      30.61      64.52   -22.40   NO
 400.      5.87     15.48     55.78        4.99      29.95      43.24   -16.53   NO
 500.      6.55     19.83     59.04        4.34      29.29      21.95   -10.67   NO
 600.      7.14     24.08     60.16        3.68      28.63      -0.25    -4.80   NO
 700.      7.63     28.23     60.16        3.02      27.97      -0.25     1.07   NO
 800.      8.02     32.28     60.16        2.36      27.32      -0.25     6.93   NO
 900.      8.32     36.24     60.16        1.70      26.66      -0.25    12.80   NO
1000.      8.52     40.10     60.16        1.04      26.00      -0.25    18.67   NO
1100.      8.63     43.87     60.16        0.38      25.34      -0.25    24.53   NO
1200.      8.64     47.54     60.16        0.00      24.68      -0.25    30.40   NO
1300.      8.64     51.11     60.16        0.01      24.02      -0.25    36.27   NO
1400.      8.64     54.58     60.16        0.00      23.36      -0.25    42.13   NO
1500.      8.64     57.96     60.16        0.01      22.71      -0.25    48.00   NO
1584.      8.64     60.72     60.16        0.01      22.15      -0.25    52.93   NO

          TRAIN COLLIDED WITH VEHICLE AT 1584. MILLISECONDS
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RUN W-8

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WATER DATA:   VEL.MI/HR   AREA/SQ.FT   WIDTH/FT   INIT.VOL/CU.FT    V-LOCO/MPH
TCRIT=.20S.      102.27         0.50      10.00            15.00         40.00

     VEH:   WT/LBS  LGTH/FT   SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 4.8 g's, max 3200.     15.0       0.0        60.0           OF TRACK  5.20 FT

TIME      X-VEH     Y-VEH     THETA       X-DOT      Y-DOT  THETA-DOT   Y-LOCO  VEH
MSEC.      FEET      FEET       DEG       MI/HR      MI/HR    DEG/SEC     FEET  CLR
   0.      0.00      0.00     30.00        0.00       0.00       0.00   -40.00   NO
  50.     -0.12      0.20     31.76       -3.12       5.29      68.89   -37.07   NO
 100.     -0.45      0.75     36.69       -5.95       9.51     126.21   -34.13   NO
 150.     -0.98      1.56     44.12       -8.30      12.32     167.87   -31.20   NO
 200.     -1.65      2.52     53.19       -9.88      13.74     192.08   -28.27   NO
 250.     -2.37      3.53     62.79       -9.88      13.74     192.08   -25.33   NO
 300.     -3.10      4.54     72.40       -9.88      13.74     192.08   -22.40   YES
 350.     -3.82      5.55     82.00       -9.88      13.74     192.08   -19.47   YES
 400.     -4.55      6.55     91.61       -9.88      13.74     192.08   -16.53   YES
 450.     -5.27      7.56    101.21       -9.88      13.74     192.08   -13.60   YES
 500.     -6.00      8.57    110.81       -9.88      13.74     192.08   -10.67   YES
 550.     -6.72      9.58    120.42       -9.89      13.74     192.08    -7.73   YES
 600.     -7.45     10.59    130.02       -9.88      13.74     192.08    -4.80   YES
 650.     -8.17     11.59    139.63       -9.89      13.74     192.08    -1.87   YES
 700.     -8.89     12.60    149.23       -9.89      13.74     192.08     1.07   YES
 750.     -9.62     13.61    158.83       -9.88      13.74     192.08     4.00   YES
 800.    -10.34     14.62    168.44       -9.88      13.74     192.08     6.93   YES
 850.    -11.07     15.62    178.04       -9.88      13.74     192.08     9.87   YES
 900.    -11.79     16.63    187.64       -9.88      13.74     192.08    12.80   YES
 950.    -12.52     17.64    197.25       -9.88      13.74     192.08    15.73   YES
1000.    -13.24     18.65    206.85       -9.89      13.74     192.08    18.67   YES
```

RUN W-9

```
WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
TCRIT=.203.    102.27        0.50     10.00           15.00        40.00

    VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 9.2 g's, max 3200.   15.0      0.0        60.0         OF TRACK 10.20 FT

TIME      X-VEH    Y-VEH    THETA     X-DOT     Y-DOT  THETA-DOT  Y-LOCO  VEH
MSEC.      FEET     FEET      DEG     MI/HR     MI/HR    DEG/SEC    FEET  CLR
   0.      5.00     0.00    30.00      0.00      0.00       0.00  -40.00  NO
  50.      4.78     0.38    30.04     -5.82     10.08       3.45  -37.07  NO
 100.      4.17     1.44    30.53    -10.75     18.54      17.45  -34.13  NO
 150.      3.23     3.06    31.95    -14.80     25.26      40.92  -31.20  NO
 200.      2.02     5.10    34.74    -18.09     30.30      71.25  -28.27  NO
 250.      0.69     7.32    38.30    -18.09     30.30      71.25  -25.33  NO
 300.     -0.64     9.55    41.86    -18.09     30.30      71.25  -22.40  NO
 350.     -1.96    11.77    45.42    -18.09     30.30      71.25  -19.47  NO
 400.     -3.29    13.99    48.99    -18.09     30.30      71.25  -16.53  NO
 450.     -4.62    16.21    52.55    -18.09     30.30      71.25  -13.60  YES
 500.     -5.94    18.43    56.11    -18.09     30.30      71.25  -10.67  YES
 550.     -7.27    20.66    59.67    -18.09     30.30      71.25   -7.73  YES
 600.     -8.60    22.88    63.24    -18.09     30.30      71.25   -4.80  YES
 650.     -9.92    25.10    66.80    -18.09     30.30      71.25   -1.87  YES
 700.    -11.25    27.32    70.36    -18.09     30.30      71.25    1.07  YES
 750.    -12.58    29.54    73.92    -18.09     30.30      71.25    4.00  YES
 800.    -13.90    31.77    77.49    -18.09     30.30      71.25    6.93  YES
 850.    -15.23    33.99    81.05    -18.09     30.30      71.25    9.87  YES
 900.    -16.56    36.21    84.61    -18.09     30.30      71.25   12.80  YES
 950.    -17.88    38.43    88.17    -18.09     30.30      71.25   15.73  YES
1000.    -19.21    40.65    91.74    -18.09     30.30      71.25   18.67  YES
```

RUN W-10

```
WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
TCRIT=.203.    102.27        0.50     10.00           15.00        40.00

    VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 120 g's, max. 3200.   15.0     25.0        60.0         OF TRACK 11.00 FT

TIME      X-VEH    Y-VEH    THETA     X-DOT     Y-DOT  THETA-DOT  Y-LOCO  VEH
MSEC.      FEET     FEET      DEG     MI/HR     MI/HR    DEG/SEC    FEET  CLR
   0.      5.00     0.00     0.00     25.00      0.00       0.00  -40.00  NO
  50.      6.83     0.50    -0.84     25.04     13.14     -49.19  -37.07  NO
 100.      8.69     1.87    -6.21     25.59     24.02    -176.46  -34.13  NO
 150.     10.62     3.96   -18.92     27.22     32.16    -325.92  -31.20  NO
 200.     12.69     6.49   -37.89     29.30     36.31    -421.25  -28.27  NO
 250.     14.84     9.15   -58.95     29.30     36.31    -421.25  -25.33  YES
 300.     16.99    11.82   -80.01     29.30     36.31    -421.25  -22.40  YES
 350.     19.14    14.48  -101.08     29.30     36.31    -421.25  -19.47  YES
 400.     21.28    17.14  -122.14     29.30     36.31    -421.25  -16.53  YES
 450.     23.43    19.80  -143.20     29.30     36.31    -421.25  -13.60  YE
 500.     25.58    22.47  -164.26     29.30     36.31    -421.25  -10.67  YE
 550.     27.73    25.13  -185.33     29.30     36.31    -421.25   -7.73  YE
 600.     29.88    27.79  -206.39     29.30     36.31    -421.25   -4.80  YE
 650.     32.03    30.46  -227.45     29.30     36.31    -421.25   -1.87  YE
 700.     34.17    33.12  -248.51     29.30     36.31    -421.25    1.07  YE
 750.     36.32    35.78  -269.58     29.30     36.31    -421.25    4.00  YE
 800.     38.47    38.44  -290.64     29.30     36.31    -421.25    6.93  YE
 850.     40.62    41.11  -311.70     29.30     36.31    -421.25    9.87  YE
 900.     42.77    43.77  -332.76     29.30     36.31    -421.25   12.80  YE
 950.     44.92    46.43  -353.83     29.30     36.31    -421.25   15.73  YE
1000.     47.07    49.10  -374.89     29.30     36.31    -421.25   18.67  YE
```

RUN W-11

```
 WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
  TCRIT .20S      102.27        0.50     10.00           15.00        80.00

     VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
19.2 g's, max 3200.   15.0      0.0        60.0         OF TRACK 11.00 FT

TIME     X-VEH    Y-VEH    THETA       X-DOT      Y-DOT  THETA-DOT  Y-LOCO  VEH
MSEC.    FEET     FEET      DEG        MI/HR      MI/HR    DEG/SEC    FEET  CLR
   0.    5.00     0.00     0.00         0.00       0.00       0.00  -40.00  NO
  50.    5.00     0.80     0.00         0.00      21.03       0.00  -34.13  NO
 100.    5.00     2.98     0.00         0.00      37.70       0.00  -28.27  NO
 150.    5.00     6.26     0.00         0.00      51.25       0.00  -22.40  NO
 200.    5.00    10.44     0.00         0.00      62.47       0.00  -16.53  NO
 250.    5.00    15.03     0.00         0.00      62.67       0.00  -10.67  NO
 300.    5.00    19.63     0.00         0.00      62.67       0.00   -4.80  NO
 350.    5.00    24.23     0.00         0.00      62.67       0.00    1.07  NO
 400.    5.00    28.82     0.00         0.00      62.67       0.00    6.93  NO
 450.    5.00    33.42     0.00         0.00      62.67       0.00   12.80  NO
 500.    5.00    38.01     0.00         0.00      62.67       0.00   18.67  NO
 550.    5.00    42.61     0.00         0.00      62.67       0.00   24.53  NO
 600.    5.00    47.21     0.00         0.00      62.67       0.00   30.40  NO
 650.    5.00    51.80     0.00         0.00      62.67       0.00   36.27  NO
 700.    5.00    56.40     0.00         0.00      62.67       0.00   42.13  NO
 750.    5.00    60.99     0.00         0.00      62.67       0.00   48.00  NO
 800.    5.00    65.59     0.00         0.00      62.67       0.00   53.87  NO
 850.    5.00    70.18     0.00         0.00      62.67       0.00   59.73  NO
 900.    5.00    74.78     0.00         0.00      62.67       0.00   65.60  NO
 950.    5.00    79.38     0.00         0.00      62.67       0.00   71.47  NO
1000.    5.00    83.97     0.00         0.00      62.67       0.00   77.33  NO

1261.    5.00   107.98     0.00         0.00      62.67       0.00  107.98  NO
        Train collided with vehicle at 1261. milliseconds
```

RUN W-12

```
 WATER DATA:  VEL.MI/HR  AREA/SQ.FT  WIDTH/FT  INIT.VOL/CU.FT   V-LOCO/MPH
   TCRIT .27S      75.00        0.50     10.00           15.00        80.00

     VEH:  WT/LBS  LGTH/FT  SPD/MPH  % WT.FT.WH  VEH.FRONT ONTO LEFT SIDE
 14.1 g's, max 3200.  15.0      0.0        60.0         OF TRACK 11.00 FT

TIME     X-VEH    Y-VEH    THETA       X-DOT      Y-DOT  THETA-DOT  Y-LOCO  VEH
MSEC.    FEET     FEET      DEG        MI/HR      MI/HR    DEG/SEC    FEET  CLR
   0.    5.00     0.00     0.00         0.00       0.00       0.00  -20.00  NO
  50.    5.00     0.59     0.00         0.00      15.47       0.00  -14.13  NO
 100.    5.00     2.20     0.00         0.00      28.13       0.00   -8.27  NO
 150.    5.00     4.66     0.00         0.00      38.68       0.00   -2.40  NO
 200.    5.00     7.83     0.00         0.00      47.61       0.00    3.47  NO
 250.    5.00    11.61     0.00         0.00      55.26       0.00    9.33  NO
 300.    5.00    15.84     0.00         0.00      58.43       0.00   15.20  NO
 321.    5.00    17.64     0.00         0.00      58.43       0.00   17.66  NO

        TRAIN COLLIDED WITH VEHICLE AT  321. MILLISECONDS
```

B.4 Listing of Program for Crushable and Water Jet Attenuators

```
*P1:*
      REAL X(3),XD(3),XDD(3),XN(3),XDN(3),XPD(3),MX,MA,KEQ
      INTEGER IGM(2),IAT(2)
      DATA IAT/' ','*'/
      DATA IGM/' NO','YES'/
      DATA NSTEP,TPR,DELT/600,5.0,1./
      DATA KEQ,BEQ,AL,PA/1750.,38000.,10.,1./
      DATA ZETA,AKATY,AKATX,CRS/1.05,3240.,3240.,.5/
      DATA VE,AE,WR,WCAP/102.273,.5,10.0,15.0/
      DATA VL,VA,THETA,X0,TOFF/50.,0.,0.,0.,40./
      DATA WA,DA,PFW,WDTH/3000.,16.,.55,5.0/
      II=1
      IIL=1
      IBY=0
      NCOL=0
      CX=.5*WDTH
      PSI=AKATY/432.
      IF(AL.EQ.0) CX=CX-CRS
      MA=WA/32.17
      BAX=.25*WR*WR/PA
      CRSPR=KEQ*.5/ZETA
      CRSPR=CRSPR*CRSPR/MA
      JET = 0
      NSTEP=NSTEP + 1
      RHO = 62.285
      DELT=DELT/1000.
      X(3)=THETA/57.295
      TNTH = TAN(X(3))
      PFW1=100.*PFW
      VLF=VL*22./15.
      X(2)=0.
      X(1)=X0
      XD(3)=0.
      XD(2)=VA*SIN(X(3))*22./15.
      XD(1)=VA*COS(X(3))*22./15.
      DR=PFW*DA
      DF=DA-DR
      FTRK=DF*COS(X(3))+X0
      IF(JET.EQ.1) GO TO 2
      RTRK = X0 - DR*COS(X(3))
      XTEST = .5*WR - WR*WR*TNTH/(8.*PA)
      Y1=XTEST
      IF(XTEST.LT.RTRK) Y1=AMAX1(0.,RTRK)
      IF(XTEST.GT.FTRK) Y1 = AMIN1(WR,FTRK)
      PXX=(Y1-X(1))/COS(X(3))-CX*TNTH
      Y2=(Y1-X(1))*TNTH-CX/COS(X(3))-AL
      YTR=Y2 + PA*(1.-2.*Y1/WR)*(1.-2.*Y1/WR)
    2 CONTINUE
      B=(DR*DR+DF*DF)/6.+CX*CX/3.
      V=(VL+VE)*22./15.
      C=RHO*AE/WA
      IF(JET.EQ.1) YTR=-TOFF
      TCRIT=WCAP*15./(AE*VE*22.)
      TNOW=0.
      TSP=1.
      TCYC=0.
```

```
        IF(IBY.EQ.1) GO TO 202
        IF(JET.EQ.0) TYPE 18
18      FORMAT(3X,'LOCO FRONT:',2X,'Y-DAMPING',2X,' X-DAMPING',2X,
        1'WIDTH/FT',2X,'ATTEN.LNGTH/FT',3X,'V-LOCO/MPH')
        IF(JET.EQ.0)TYPE 19,PA,KEQ,BEQ,WR,AL,VL
19      FORMAT(3X,'AHEAD ',F3.0,'FT',2X,F9.2,2X,F10.2,2X,F8.2,8X,F8.2,
        15X,F8.2,/)
        IF(JET.EQ.0)TYPE 21
21      FORMAT(3X,'ZETA',2X,'YATTEN.DAMP',2X,'XATTEN.DAMP',2X,
        1'ATT.YLD,PSI',3X,'CAR SPR.',8X,'SIDE CRUSH,FT')
        IF(JET.EQ.0)TYPE 22,ZETA,AKATY,AKATX,PSI,CRSPR,CRS
22      FORMAT(3X,F5.3,F9.0,F12.0,F13.1,F15.0,10X,F5.3,/)
        IF(JET.EQ.0) GO TO 20
        TYPE 8
        TYPE 9,TCRIT,VE,AE,WR,WCAP,VL
8       FORMAT(3X,'WATER DATA:',2X,'VEL.MI/HR',2X,'AREA/SQ.FT',2X,
        1'WIDTH/FT',2X,'INIT.VOL/CU.FT',3X,'V-LOCO/MPH')
9       FORMAT(3X,'TCRIT=',F3.2,'S.',2X,F9.2,2X,F10.2,2X,F8.2,8X,F8.2,
        15X,F8.2,/)
20      CONTINUE
        TYPE 11
11      FORMAT('  VEH:WDTH   WT/LBS   LGTH/FT   SPD/MPH   % WT.FT.WH   ',
        1'VEH.FRONT ONTO LEFT SIDE')
        TYPE 12,WDTH,WA,DA,VA,PFW1,FTRK
12      FORMAT(4X,F6.2,F9.0,3X,F5.2,5X,F4.1,8X,F4.1,9X,'OF TRACK',
        1F6.2,' FT',/)
202     CONTINUE
        TYPE 13
13      FORMAT(1X,'TIME',2X,'X-VEH',2X,'Y-VEH',2X,'THETA',2X,'X-DOT',
        12X,'Y-DOT',2X,'TH-DT',3X,'X-DD',4X,'Y-DD',3X,'TH-DD  YTR  VEH')
        TYPE 14
14      FORMAT(1X,'MSEC',2(3X,'FEET'),4X,'DEG',2(2X,'MI/HR'),
        12X,'DEG/S',4X,'G/S',5X,'G/S',2X,'RAD/S2  FT.  CLR')
        DO 10  J=1,NSTEP
        MX=0.0
        PX=0.0
        ICLR=1
        UCOL=DR
        ABSN=ABS(SIN(X(3)))
        IF(SIN(X(3)).LT.0.0) UCOL=-DF
        UF=DF*COS(X(3))
        UR=DR*COS(X(3))
        IF(COS(X(3)).LT.0.0) UF=-DR*COS(X(3))
        IF(COS(X(3)).LT.0.0) UR=-DF*COS(X(3))
        UA=UR+UF
        IF(X(1).LE.-(UF+CX*ABSN)) ICLR=2
        IF(X(1).GE.(WR+UR+CX*ABSN)) ICLR=2
        IJSW=ICLR+2*JET
        GO TO (30,40,3,4),IJSW
```

```
01050    3       PX=(X(1)+UF)/WR
01060            MX=PX*(UF-X(1))/2.0
01070            IF(UA.GT.WR.AND.X(1).LE.(WR-UF)) GO TO 4
01080            IF(UA.LE.WR.AND.X(1).LE.UR) GO TO 4
01090            PX=AMIN1(WR,UA)/WR
01100            MX=(X(1)-WR)*(X(1)-WR)  - X(1)*X(1)
01110            IF(UA.LT.WR) MX=UF*UF-UR*UR
01120            MX=MX/(2.0*WR)
01130            IF(UA.GT.WR.AND.X(1).LE.UR) GO TO 4
01140            IF(UA.LE.WR.AND.X(1).LE.(WR-LF)) GO TO 4
01150            PX=(UR+WR-X(1))/WR
01160            MX=-PX*(UR-WR+X(1))/2.0
01170    4       AUX=C*(V-XD(2))*(V-XD(2))*COS(X(3))
01180            IF(TNOW/1000..GE.TCRIT) AUX=0.0
01190            XDD(1)=-AUX*SIN(X(3))*PX-FRC(XD(1))
01200            XDD(2)=AUX*COS(X(3))*PX-FRC(XD(2))
01210            XDD(3)=ABS(AUX)*MX/B-FRC(XD(3))*.5*DA/B
01220            GO TO 35
01230    30      CONTINUE
01240            BQD=(WR-BAX*TAN(X(3)))*.5
01250            CQD=BAX*(PA+X(2)-YTR-AL-CX/COS(X(3))-X(1)*TAN(X(3)))
01260            DISCR=BQD*BQD-CQD
01270            IF(ABS(DISCR).LT..0001) DISCR=0.0
01280            IF(DISCR.LT.0.0) XDISP=0.0
01290            IF(DISCR.LT.0.0) GO TO 25
01300            XLO=BQD-SQRT(DISCR)
01310            XLU=BQD+SQRT(DISCR)
01320            XLO=AMAX1(XLO,(X(1)+CX*SIN(X(3))-UR),0.0)
01330            XLU=AMIN1(XLU,(X(1)+CX*SIN(X(3))+UF),WR)
01340            XDISP=XLU-XLO
01350    25      CONTINUE
01360            YLC=(XLU+XLO)*.5*TAN(X(3))
01370            YDATT=0.0
01380            IF( DISCR.GE.0.)YDATT=X(2)-CX/COS(X(3))-X(1)*TAN(X(3))
01390            1-YTR+AMIN1(XLO*TAN(X(3)),XLU*TAN(X(3)))
01400            YDISP=-PXX*SIN(X(3))+CX*COS(X(3))-X(2)+YTR+AL
01410            AXDS=ABS(XDISP)
01420            IF(AXDS.GT.D6.OR.J.EQ.1) D6=AXDS
01430            IF(AXDS.LT.D6) XDISP=0.0
01440            IF(YDISP.GT.D5.OR.J.EQ.1) D5=YDISP
01450            IF((YDISP-D5).LT.0.0) YDISP=0.0
01460            IF(YDISP.EQ.0.0.AND.TNOW.GT.20.)D55=D5
01470            IF(YDISP.EQ.0.0.AND.TNOW.GT.20.0) D5=1000.
01480            IF(XDISP.EQ.0.0.AND.TNOW.GT.20.)D6=1000.
01490            YDFIX=1.
01500            IF(AL.GT.0.0.AND.YDATT.GT.0.) GO TO 17
01510            IF((XDISP+YDISP).EQ.0.0) YDFIX=0.0
01520    17      CONTINUE
```

```
01530          IF(AL.GT.0.0)AKEQ=AKATY
01540          IF(AL.GT.0.0)ABEQ=AKATX
01550          IF(YDATT.LT.0.0)AKEQ=KEQ
01560          IF(YDATT.LT.0.0)ABEQ=BEQ
01570          SPR=AKEQ◆.5/ZETA
01580          SPR=SPR◆SPR/MA
01590          IF(AL.GT.0.0.AND.YDATT.GE.0.0) SPR=0.0
01600          IF(AL.GT.0.0.AND.YDATT.LE.0.0) II=2
01610          PM1=X(1)-UR
01620          PM2=X(1)-.44◆UR
01630          PM3=X(1)+.53778◆UF
01640          PM4=X(1)+UF
01650          ARM=0.0
01660          IF(PM1.GT.0.0.AND.PM1.LT.WR) ARM=ARM+PM1-X(1)
01670          IF(PM2.GT.0.0.AND.PM2.LT.WR) ARM=ARM+PM2-X(1)
01680          IF(PM3.GT.0.0.AND.PM3.LT.WR) ARM=ARM+PM3-X(1)
01690          IF(PM4.GT.0.0.AND.PM4.LT.WR) ARM=ARM+PM4-X(1)
01700          IF(AL.GT.0.0.AND.YDATT.GE.0.0) GO TO 23
01710          COEF=VLF-ARM◆.5◆XD(3)-XD(2)
01720          GO TO 24
01730    23    COEF=1./COS(X(3))
01740          IF(AXDS.GT.0.0.AND.COEF.GT.DA/AXDS)COEF=DA/AXDS
01750    24    IF(COEF.LT.0.0) COEF=0.0
01760    40    CONTINUE
01770          CON = AXDS
01780          IF(AL.GT.0.0.AND.YDATT.LT.0.0)CON=AMIN1(-YDATT◆TAN(X(3)),AXDS)
01790          XARM=X(2)-YTR
01800          IF(AL.GT.0.0) XARM=CX/COS(X(3))-YLC+X(1)◆TAN(X(3))
01810          XDD(1)=-ABEQ◆SIN(X(3))◆CON◆COEF◆YDFIX/MA
01820          XDD(2)=AKEQ◆COEF◆CON◆COS(X(3))/MA+SPR◆YDISP/MA
01830          XDD(3)=(XDD(1)◆(XARM)-XDD(2)◆-.5◆ARM)/B
01840          NPRT=0
01850          IF(XDD(2).GT.160..AND.II.GT.IIL) NPRT=1
01860          IF(XDD(2).GT.160..AND.II.GT.IIL) IIL=II
01870          DO 111 ITEMP = 1,3
01880          IF(ICLR.EQ.2)XDD(ITEMP) = 0.
01890   111    CONTINUE
```

```
Line 01590:          Delete symbols   .AND.YDATT.GE.0.0
Lines 01710, 01730, 01740, 01750, 01810:  Replace COEF by COEFX
Line 01780:          Replace symbol ◆ by /
Insert following lines in indicated sequence
01802                COEF=VLF-(X(1)+CON) XD(3)-XD(2)
01803                IF(COEF.LT.0.0)COEF=0.0
01805                IF(II.EQ.1)COEF=COEFX
01807                IF(II.EQ.2.AND.COEFX.LE.-XD(1))COEFX=0.0
01823                IF(II.EQ.2)XDD(1)=XDD(1)-(AXDS-CON)◆AKATX TAN(X(3))/MA
01825                IF(II.EQ.2)XDD(2)=XDD(2)+(ASDS-CON)◆AKATY/MA
```

```
35      DO 5 I=1,3
        XDN(I)=XD(I) + XDD(I)*DELT
        XN(I) = X(I) +  XD(I)*DELT + .5*XDD(I)*DELT*DELT
        IF(I.EQ.3) GO TO 5
        XPD(I)=XD(I)*15./22.
5       CONTINUE
        IF(YTR.GE.(X(2)-UCOL*SIN(X(3)))) NCOL  = (2-ICLP)*JET
        X(3) = X(3)*57.295
        XPD(3) = XD(3)*57.295
        IF(TNOW.LT.TCYC.AND.NCOL.EQ.0.AND.NPRT.EQ.0) GO TO 7
        XDD(1)=XDD(1)/32.17
        XDD(2)=XDD(2)/32.17
        TYPE 15,TNOW,(X(LL),LL=1,3),(XPD(LL),LL=1,3),(XDD(LL),LL=1,3)
        1,YTR,IGM(ICLR),IAT(II)
        XDD(2)=XDD(2)*32.17
        XDD(1)=XDD(1)*32.17
7       X(3)=X(3)/57.295
        IF(JET.EQ.0.AND.ABS(X(3)).GT.1.571) STOP
        YTR=YTR+VL*DELT*22./15.
        IF(NCOL.EQ.1) TYPE 16,TNOW
        IF(NCOL.GT.0) STOP
        TNOW = TNOW + DELT*1000.
        TSP=5.0
        IF(TNOW.GT.50.)TSP=5.
        IF(ABS(X(3)).GT.1.4) TSP=1.
        IF(TNOW.GT.TCYC) TCYC=TCYC+TPR*TSP
        DO 10 I=1,3
        X(I) = XN(I)
        XD(I)=XDN(I)
10      CONTINUE
15      FORMAT(F5.0,7(F7.2),2(F8.2),F6.2,1X,A3,A1)
16      FORMAT(/,9X,'TRAIN COLLIDED WITH VEHICLE AT ',F5.0,
        1' MILLISECONDS')
        STOP
        END
        FUNCTION FRC(VIN)
        AA=ABS(VIN)
        F2=9.66+F3*(7111.035*AA - 9.66)
        FRC = SIGN(F2,VIN)*0.0
        RETURN
        END
```

APPENDIX C

POTENTIAL ACCIDENT INCREASE DUE TO ADDED LENGTH OF COLLISION ATTENUATOR

A collision attenuation device by lengthening a locomotive may convert what might otherwise have been a near miss into an actual accident. Review of current accident statistics provides some insight to develop a mathematical model of the rail-highway encounter for use in predicting the incidence of such events. The key statistical data of Table C-1 are extracted from the 1978 FRA Rail-Highway Crossing Accident/Incident and Inventory Bulletin.

These data provide some information on accident circumstances and perhaps on driver behavior. However, before analyzing the figures in the table, one should identify those situations where the chance of accident occurrence is not changed by addition of the attenuator or deflector. Such casescan then be excluded from the statistics in predictions.

Stationary automobiles struck by trains will presumably be struck whether or not the locomotive is preceded by an attenuator, although the severity of the collision will be affected. Presumably the incidence of stationary trains or light locomotives being struck by automobiles might be increased slightly if the train is lengthened by the addition of an attenuator; the increase would probably be proportional to the relative increase in train length, in the absence of any special contrary indications. For a light locomotive, an 8 foot attenuator would cause a significant increase in length, and a corresponding increase in accidents. However, this case is still statistically unimportant, since there are only 26 such accidents per year. In addition, if the part struck is a soft attenuator, the accident would be serious only if the automobile speed were high. For a typical freight consist of perhaps 2,000 foot length, the relative increase in length is only 0.4 percent, and once again the effect is statistically unimportant. Hence it will be assumed that accidents where either the train or the highway vehicle is stationary are unaffected, and attention will be limited to cases where both are in motion.

TABLE C-1 ACCIDENTS/INCIDENTS AT GRADE CROSSINGS INVOLVING MOTOR VEHICLES BY RAILROAD EQUIPMENT INVOLVED, PART OF TRAIN STRUCK, AND CIRCUMSTANCE, 1978 *

	*** CIRCUMSTANCE ***		*********PART OF TRAIN STRUCK ***********					
				- - - QUARTER - - -				
RAILROAD EQUIPMENT INVOLVED	CONSIST STRUCK VEHICLE ACC/INC	VEHICLE STRUCK CONSIST ACC/INC	LOCO(S)#	1	2	3	4	UNKNOWN
TRAIN (UNITS PULLING)	6969	2380	1610	175	184	117	156	138
TRAIN (UNITS PUSHING)	623	289	46	117	48	30	33	15
TRAIN (STANDING)	1	252	61	30	52	41	50	18
LIGHT LOCOS# (MOVING)	731	265	211	0	0	0	0	54**
LIGHT LOCOS# (STANDING)	0	26	20	0	0	0	0	6**
OTHER	235	238	31	2	5	3	38	148
TOTAL	8559	3440	1979	328	289	191	274	379

LOCOMOTIVES

* EXTRACTED FROM FRA RAIL-HIGHWAY CROSSING ACCIDENT/INCIDENT AND INVENTORY BULLETIN NO. 1, CALENDAR YEAR 1978

** OBVIOUSLY LOCOMOTIVES, ACCIDENT FORM PROBABLY INCOMPLETE

The part of Table C-1 dealing with highway vehicles striking consists shows very clearly that the leading part of a moving consist is the one which is most commonly struck. For standing consists, the locomotive is struck 24.2 percent of the time, with the other impacts relatively uniformly distributed along the length of the train. When the consist struck is moving, with a locomotive pushing, the locomotive is struck only 15.9 percent of the time and the first quarter of the train is struck 40.5 percent of the time, with the remaining 44.6 percent evenly distributed over the balance of the train. However, in those cases where a locomotive is pulling, the locomotive is struck 67.6 percent of the time, and the rest of the train shares the remaining 32.4 percent fairly uniformly.

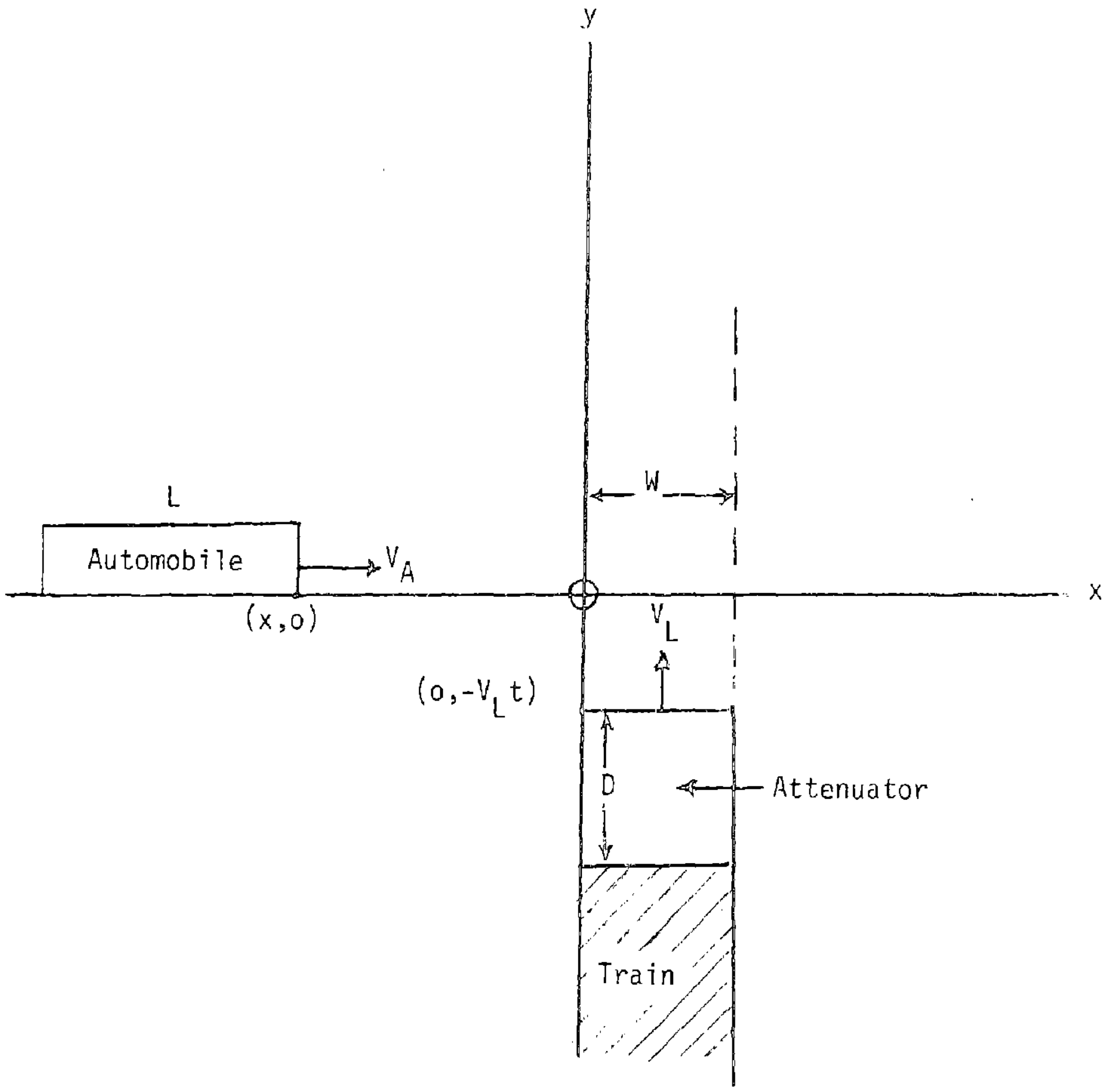
This distribution of accidents, with impacts concentrating heavily on the locomotive or leading part of the consist, suggests that collision probability is not directly proportional to train length, for a long part of the train in the middle and rear receives relatively few hits. It is obvious that in one group of accidents, the driver simply does not see the train until too late, and crashes into it. Such accidents provide most of the impacts which are relatively evenly distributed over the length of the train. The involvement of poor visibility is suggested by separate data which show that 33.0 percent of the train-strikes-highway-vehicle accidents occur at night, while 50.1 percent of the highway-vehicle-strikes-train accidents occur at night. Driver inattention is also probably involved. For some of these accidents the highway vehicles may tend to hit the leading part of the train more frequently than other sections because the drivers' attention was limited to the road before them, which was clear of the arriving train until the last moment. These cases could involve drivers who have not detected the warnings and who do not observe occurrences to the sides, but who might have detected a train crossing the road had it arrived well before the highway vehicle reached the crossing. Such cases would tend to increase the number of impacts on the front of the train.

Other cases may involve drivers who are aware of the train and believe they can cross the intersection first. If they misjudge the situation, they either are struck by the train or strike the leading part, depending on the amount of miscalculation. When they clear the crossing before the arrival of the train, no accident occurs. Such occurrences have been observed and documented.

There are no statistics covering the number of misses which are the situations potentially converted into accidents. The model attempts to estimate the statistics of the near misses in terms of the statistics of the events where the train hits a moving highway vehicle. This is done by postulating a distribution of automobiles moving along a highway toward a grade crossing which is also being approached by a train. The model is not concerned with whether or not the driver observes the train, but only in the driver actions which affect the highway vehicle motions and the resulting position and velocity statistics.

The assumptions involved are discussed at a later point of the development. At this point it is merely pointed out that, if those drivers who are consciously trying to cross before a train are credited with any semblance of competence, probably more of them get across without accident than are hit or hit the train. For those who are unaware of the train, a given time interval before the arrival of the train is likely to witness the arrival of the same number of highway vehicles as the same time interval a moment later. These observations will lead to an assumption of a uniform position distribution of cars along the highway at any given automobile speed.

Consider the situation shown in Figure C-1. A train is moving with its left edge on the y axis at constant speed V_L, in the positive y direction. The train front at time $t = o$ is at $y = D$.



NOTE: Attenuator front arrives at y axis at time t = o. Automobile front at that time is at $x = x_0$.

Figure C-1 GEOMETRY OF ACCIDENT MODEL

When the train is preceded by an attenuator of length D, the front of the attenuator arrives at the x axis at time t = o. At time $t = D/V_L$ the train front arrives at the x axis. The train width is W. An automobile of length L is moving in the positive x direction at constant speed V_A, with its right side on the x axis. At time t = o, the automobile front is at $x = x_o$; thus at time t, the automobile front is at $x = x_o + V_At$ and the rear is at $x = x_o + V_At - L$. Automobile, attenuator, and locomotive are assumed to have rectangular horizontal cross-sections. Trucks are not considered in this model, primarily because the fatality incidence in collisions at low train speeds is drastically different from the automobile pattern.

Examine first the situation when the train is not equipped with an attenuator. When the train front arrives at the x axis, if the automobile has already cleared the crossing there will be no collision. This requires that the rear of the auto be located to the right of x = W, at time $t = D/V_L$, i.e.

$$x_o+V_AD/V_L-L>W$$

or

$$x_o>W+L-V_AD/V_L \qquad (C-1)$$

On the other hand, if when the locomotive arrives at the x axis, the automobile front has not yet arrived at the y axis, the automobile will presumably either hit the train or cross after the train has passed. Neither of these cases will be affected by the attenuator, and both cases are excluded from consideration. This situation arises if:

$$x_o+V_AD/V_L<0, \text{ or; } x_o<-V_AD/V_L \qquad (C-2)$$

Thus if the initial position x_o of the front of the automobile lies in the interval $(-V_AD/V_L,-V_AD/V_L+W+L)$, the automobile will be struck by the train.

The next step is to determine how the interval of automobile initial positions which result in collisions is extended by the addition of the attenuator. The growth of this collision interval, together with an estimate of how many automobiles are found in each interval, will provide a means of estimating the increase in the number of collisions. It will be assumed that there is a uniform distribution of automobiles at all positions along the x axis; the assumption is discussed below. Initial positions to the left of the collision interval already defined are of no interest; they cover the cases of automobiles which strike the train or cross after its passage, and these cases are unaffected by the attenuator. The extension of the collision interval to the right is what affects the number of accidents. Once a formula for the interval growth is obtained in terms of V_A and V_L, the train velocity distributions from table 4-5 and the automobile velocity distributions from table C-2 can be applied to estimate the overall increase in accidents.

The several statistical assumptions inherent in this estimate are discussed briefly. These are the constant automobile and train speeds and the uniform distribution of automobile initial positions along the x axis. Consider the automobile speed first. In fact, an automobile trying to cross in front of a moving train should be accelerating (but is not necessarily doing so). For the brief period of the actual crossing of the right of way, a constant speed assumption is probably not unreasonable. Similarly, for the short distance involved, a constant speed assumption for the train is probably also fairly reasonable, especially in light of the limited acceleration capability of the train.

However, the distribution of automobiles along the x axis is probably not uniform. Attributing some judgment ability to the drivers who consciously try to cross in front of the train suggests that more of them succeed than fail. In that case, one would expect that to the right of the point $x_0 = W+L-V_AD/V_L$, which is the last point of safe crossing, the density of automobiles might increase, reflecting correct judgment on the possibility of crossing without collision. Thus assuming the uniform distribution along the x axis probably underestimates the number of additional accidents of this type caused by extension of the train, unless the decisions of the drivers in evaluating the situation are changed by the addition of the attenuator.

TABLE C-2

DISTRIBUTION OF HIGHWAY VEHICLE SPEEDS FOR VEHICLES STRUCK BY TRAINS, 1978

ESTIMATED SPEED (MPH)	ACCIDENTS		FATALITIES		INJURIES	
	NUMBER	PERCENTAGE*	NUMBER	PERCENTAGE*	NUMBER	PERCENTAGE*
STANDING	2014	-	50	-	340	-
1 - 9	1605	34.8	120	22.9	462	24.7
10 - 19	1363	29.6	158	30.2	603	32.3
20 - 29	897	19.5	107	20.5	394	21.1
30 - 39	453	9.8	67	12.8	254	13.6
40 - 49	186	4.0	36	6.9	109	5.8
50 - 59	85	1.8	28	5.4	43	2.3
60 and over	17	0.4	7	1.3	4	0.2
Unknown	1939	-	133	-	585	-
TOTAL	8559	-	706	-	2794	-
Partial Total*	4606		523		1869	

* EXCLUDES STANDING VEHICLES AND UNKNOWN SPEED CASES.

Assessing the driver response to the introduction of attenuators is extremely difficult. Three factors come into play - frequency of attenuator presence or absence, driver habituation to and anticipation of attenuator presence, and attenuator visibility. None of these can be accurately estimated in advance. If attenuators were universal on line haul locomotives, at crossings traversed principally by such consists experienced drivers might anticipate the presence of attenuators, but those unfamiliar with the crossing might not. At crossings traversed principally for deliveries to sidings, attenuators could be rare and pusher locomotives might be common, in which case the lead car would never carry an attenuator. Thus, attenuator frequency would be a characteristic of the rail traffic at a particular intersection, and driver anticipation would depend on the individual driver, his experience and knowledge of the intersection, and his competence in judgment. The drivers who are involved in these accidents may be assumed to be fairly limited in judgment, which suggests that they may not anticipate the presence of the attenuator in their calculations, and that consequently the attenuator might influence the situation only if it were clearly visible. However, typical attenuator designs are quite low, extending up to a height of about four feet, and therefore are less visible than the much higher locomotive. In these conditions, the assumption that the drivers concerned react primarily to the locomotive and not to the attenuator may be fairly realistic. On this basis, the model proceeds as if the driver actions were unaffected by the attenuator presence. The pessimistic assumption about the driver is offset by the optimistic assumption about uniform position distribution of the automobiles.

Now examine the range of initial positions resulting in collisions when the locomotive is preceded by an attenuator of length D. In order to cross the right of way before arrival of the attenuator front at the x axis at time t = 0, the rear of the car must now be to the right of x = W at this time, i.e.

$$x_0 - L > W, \text{ or } x_0 > W + L \qquad \text{(C-3)}$$

and the interval of accident occurrence is now $-V_A D/V_L < x_0 < W+L$. The cases where the automobile strikes the locomotive ($x_0 < -V_A D/V_L$) are still excluded from consideration. The width of this interval is now extended from a width of W+L to a width of $W+L+V_A D/V_L$. The relative ratio in the interval width is the quotient of these quantities, which is:

$$1 + \frac{V_A}{V_L} \cdot \frac{D}{W+L}$$

The relative increase is simply the right hand term of this expression, and is proportional to the automobile speed and attenuator length, and inversely proportional to the locomotive speed and to the sum of the automobile length and train width. This result may appear less surprising if one expresses it in the form:

$$(D/V_L) \div [(W+L)/V_A]$$

which is the ratio of the time the train spends covering the distance of the attenuator length to the time the automobile spends in the risk zone. The relative increase is then simply a matter of the added risk time due to the presence of the attenuator.

Once this formula is available, the statistical occurrence of the automobile speed ranges shown in Table C-1 and the train speeds of Table 4-5 can be applied, and values of D, W, and L can be chosen to determine the relative increase. In the absence of any information, it is assumed that automobile and train speeds are statistically independent. This is a questionable assumption, since both speeds are limited by the grade crossing characteristics. Therefore, it seems simplest to omit the extremes caused by small values of VL in the denominator and high values of V_A, and to consider the results as approximate lower bonds for the expected increase. The expected increase is calculated by multiplying the fixed ratio D/(W+L) by an expectation reflecting the increase in accidents for all speed ranges. This expectation is the sum of individual elements for each speed range, i.e.

$$\frac{D}{W+L} \Sigma(V_A/V_L)n(V_A,V_L)$$

where $n(V_A,V_L)$ is the number of occurrences in the speed range, determined as the product of the number of occurrences at a train speed V_L, taken from Table 4-5, multiplied by the probability of the speed range V_A taken from Table C-2. Summation may then be done over both automobile and train speed ranges. The omission of any speed range, for example, the lowest train speeds of 1-9 mph, means that the summation is a lower bound for the estimate. If the final result is divided by the original total number of accidents, the result is the expected relative increase in accidents, rather than the expected increase in number of accidents. The overall relative increase is the quantity calculated below.

Using values of D = 8 feet, W = 10 feet, and L = 16 feet, some increases are determined for various speed ranges. First the values of V_A above 40 mph are excluded to reduce the influence of the V_A term in the numerator and make the estimate more conservative. Then the relative increase in accidents for various train speed ranges above 10 mph are compared, with the following results for automobiles struck by trains, based on Table 4-5 data.

Train Speed (mph)	Relative Increase (%)	Increase In Number of Accidents
11-20	28.5	335
21-30	16.6	207
31-40	12.1	96
41-50	9.3	49
51-60	7.5	40
61-70	6.3	4
11-70	18.5	731

This indicates a relatively serious increase in the number of accidents occurring at train speeds above 10 mph, by a factor of 18.5 percent. If automobile speeds above 40 mph were included in the calculation, the relative increase for train speeds from 10 to 70 mph would change from 18.5 to 21.3 percent, i.e. a relative increase of more than one fifth.

At lower train speeds, the factor V_L in the denominator of the formula produces a very striking increase in the number of accidents. For example, at 8 mph, the relative increase is 50 percent, and at 5 mph, it is 80 percent. A longer or shorter attenuator would change the relative increase in proportion to attenuator length, which suggests that for both collision attenuators and deflectors, there are tradeoffs favoring reduced length.

In summary, the present accident statistics indicate that there are a fair number of drivers who attempt to cross in front of a train which they know is approaching a grade crossing, and that a significant number of them miscalculate seriously enough so that they strike the locomotive or lead car. Another percentage of these drivers are caught by the train in the intersection. Logic indicates that such drivers are not very good judges of speeds and crossing times, and are likely to be equally poor judges of the added train length due to the presence of an attenuator or deflector. These drivers are even more likely to be unaware of the presence of an attenuator, which is far less visible than a locomotive. The model is created on a conservative basis which tends to underestimate the number of additional accidents due to the lengthened consist, but it assumes that the driver does not react to the presence of the attenuator. On this basis, there is about a 20 percent increase in the number of automobile accidents which occur at train speeds above 10 mph, due to addition of an 8 foot long attenuator or deflector. This suggests that the potential problem should be carefully investigated before the introduction of long attenuators or deflectors. No estimate of the increase in truck accidents has been made, but presumably there will be some increase there too.