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The Mechanics of Automobile Collisions

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CONTENTS

ABSTRACT

The damage and injury from automobile accidents is treated as a mechanical problem in mitigating the shock from collisions. General principles of energy and momentum are described and applied to the collision problem. Present work in the field of automobile safety during collisions is surveyed and possible mechanisms for dealing with excess kinetic energy during a collision are reviewed. It is recommended that passenger compartments be strong and rigid, that passengers be strapped into their seats at all times, that front bumpers of automobiles be required to interface properly with fronts, sides, and backs of all other vehicles on the road, and that front bumpers be required to absorb energy on a graduated-damage system.

PROBLEM STATUS

This is a final report on a particular phase of a problem.

AUTHORIZATION

The work was authorized by Director of Research, Naval Research Laboratory, and was conducted under General and Administrative Job Order 74011-1507.

THE MECHANICS OF AUTOMIBLE COLLISIONS

I. INTRODUCTION AND SUMMARY

There has been a great deal of concern recently by the Government, the automobile industry and the general public about the large and increasing cost in lives, injury, and property damage of automobile accidents. The Applied Mechanics Branch of the U. S. Naval Research Laboratory, sharing this concern, is pleased to attempt to contribute to an increased understanding of this problem, and to examine in this report possible ways to mitigate this large cost. The qualifications of this Branch to examine this problem stem in large part from a number of years of analytical and experimental experience in understanding and mitigating the effects of underwater explosions on ships and on shipboard equipment. Because of this particular experience in shock dynamics, we are looking at the automobile problem primarily from the point of view of the mechanics of collision forces and motions, with a view to enhancing the safety of a passenger taking part in a high-speed collision, while at the same time minimizing property damage under conditions of low speed impact.

Our main conclusions and recommendations follow in Section II, "Conclusions and Recommendations". This subject of automobile accidents and their effects has received so much attention recently that we do not wish in any way to claim novelty for our suggestions and approaches. At the same time, we have attempted to concentrate our judgment on those aspects of the problem in which the basic mechanics of collision forces and motions and the technology of energy absorbing materials and devices play a substantial role.

Section III, "The Mechanics of Collisions" bearing essentially the same title as the report itself and comprising its main body, begins with a brief section reviewing the most important types of accidents and the statistics of their incidence. The statistical material in this section was in large part made available to us by Mr. Howard P. Gates, also of the Naval Research Laboratory. The main part of Section III reviews the basic mechanics of single-car and two-car collisons in terms of the conservation of momentum, and the conservation of total energy (including kinetic energy and deformation energy), and includes curves depicting required stopping or crush distances as a function of initial velocity and g loading for various types of impact absorbing mechanisms. The basic objective of obtaining maximum safety while minimizing low speed damage leads to a concept of graduated damage, in which collisions up to 10 mph can be mitigated elastically, with higher impact speeds requiring successively costlier energy absorbing devices, up to highway speeds at which the automobile itself is given up in order to save its occupants. Needless to say, this concept of graduated damage and designed energy absorption depends in an essential manner upon appropriate standardization of bumper heights and shapes.

Section III concludes with a more comprehensive analysis of the mechanics of impact of a vehicle impinging on a rigid barrier, and of two impacting vehicles initially traveling at arbitrary relative speeds and directions. The simplifying assumptions made in this analysis are to neglect the effect of vehicle spin induced by non-central impact forces and to assume perfectly plastic impact in which the final velocities of both vehicles are identical. A most interesting result of this investigation is the proportion of the total available kinetic energy which has to be transformed into vehicle deformation work under these conditions.

Section IV, "Review of Proposed Approaches" is a brief review of possible hardware approaches to implement the ideas expressed in Section II and III, with particular reference to presently ongoing programs in the development of safety vehicles. Section V, "Standards and Tests" reviews relevant standards and tests having to do with the mitigation of injury and damage in automobile collisions, and makes some suggestions on how these standards and tests might be modified to reflect any adoption of hardware approaches suggested here. The report concludes with references and a review of the rather extensive bibliography available on this subject.

Appendix A, "The Automobile as a Component of a Transportation System," discusses briefly some matters which are peripheral to the subject of automobile collisions but which must be considered in the overall problem of the future of the automobile in our society.

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II. CONCLUSIONS AND RECOMMENDATIONS

A. General Conclusions

1. The Mechanics of a Collision

A reasonably good description of what happens when two automobiles collide is provided by the model of a perfectly plastic impact of two mass points. While this description omits such considerations as elastic deformation and the production of vehicle rotation as a result of noncentral collision forces, it nonetheless provides some useful insight into the causes and mitigation of injury and damage. A more comprehensive analysis, including the angular momentum effects, as well as arbitrary values of a coefficient of restitution to include elastic as well as plastic effects, was not attempted in detail because of time constraints, but would provide useful additional information. One example of such additional information would be a better analytical understanding of the relative advantages or disadvantages of rear-mounted engines from the point of view of vehicle rotational stability.

The paramount considerations in collisions, as considered here, are the change in momentum induced in each vehicle and the quantity of kinetic energy transformed into deformation of the vehicles. Human beings in the passenger compartment of an automobile are capable of withstanding large changes in momentum provided (1) they are properly restrained, (2) the change in momentum of the passenger compartment does not occur too rapidly, and (3) exterior objects to the passenger compartment do not penetrate to where they could injure the passengers. For these reasons our recommendations include appropriate restraint systems within the passenger compartment, well-designed energy absorption systems exterior to the passenger compartment to decrease the speed of the momentum change, and a passenger compartment configuration of a relatively hard capsule which resists deformation as well as penetration by external objects.

It is important to not that if this passenger capsule is rigid and the passenger is restrained, then the probability of his being injured is not very much affected by whether the collision energy is in fact absorbed by his own vehicle or by the other one. Since most accidents involve the front end of at least one of the participating vehicles, it would seem to pay from the point of view of passenger safety, to place most of the energy absorbing structures in the front of automobiles, provided of course that the passenger capsule is designed to be sufficiently rigid on all sides. These frontal energy absorbing structures would include the bumper system for protecting the vehicle itself, as well as those parts of the vehicle which are intended to become expendable in a high-speed collision. From the point of view of the safety of a passenger enclosed in a hard capsule, it makes relatively little difference, not only whether the required energy was absorbed by his vehicle or by the other vehicle, but indeed on whether it was absorbed in a destructive or non-destructive manner. On the other hand, from the point of view of car damage limitation the latter consideration becomes paramount. The problem of damage limitation is a relatively easy one at low speeds and becomes impossible at open road speeds. For this reason, we wish to consider the possible trade offs in terms of what we have called a concept of "graduated damage" as discussed below.

2. Concept of Graduated Damage

It is easily shown from basic mechanics that an automobile traveling at a given speed, and limited for safety reasons to a given deceleration or force loading, will require a certain minimum stopping or crush distance to come to rest. Given a deformation and penetration-resistant passenger compartment plus adequate passenger restraints, the key to safe car design is to provide, in at least one of the impacting vehicles, this crush distance during which significant decelerating forces are applied. The key to minimizing vehicle damage is to make as much of this crush distance as possible be as lightly destructive as possible. Typical possible arrangements of crush distances and associated energy absorbing methods are discussed below.

We believe that automobiles could reasonably be designed in such a manner that bumper to bumper, or bumper to wall, front-end collision at up to 10 m/h could be sustained without injury or damage, using a front bumper system capable of deflecting elastically or viscoelastically against a damped elastometer material, up to 3 inches. At impact speeds up to 20 m/h, injury should still be preventable, provided that a total controlled stopping distance of 12 inches is made available. An effective way to implement this would be the use of a renewable crushable energy absorber. Alternatively, a self-resetting hydraulic energy absorber could be employed. The incidence of vehicle damage at these speeds would depend upon the ability to have this total 12 inch energy absorbing bumper system protrude in front of the damageable components of the vehicle. If such a protruding bumper can not be made available, then at least the car parts in this 12 inch crush distance should be limited to nonessential and easily replaceable ones, such as removable fender panels.

At speeds up to 30 m/h, injury can in general still be prevented assuming penetration-resistant passenger compartments and adequate restraints. However, the total crush distance should be about 24 inches. This necessitates encroachment of the distance on space needed for other purposes, so that limited car damage must be accepted. The car should, however, remain structurally intact, and in many cases repairable by replacement of such parts as fenders and radiators. So far, average g loadings have been limited to the order of 15, injury should almost always be preventable, and vehicle damage can be substantially limited.

At collision speeds above 30 m/h the chances of serious injury even in a very well designed vehicle would begin to become appreciable. At the same time, structural damage to the vehicle would begin to make attempts at repair less and less attractive. Both these factors strongly suggest that at these higher speeds, passenger safety becomes the only valid consideration and the vehicle should be given up to save its occupants. Between 30 and 50 m/h, one could thus bring into play an additional crush distance of 24 inches with progressively greater damage to the vehicle at the longer penetrations. At the end of this 24 inches, where we have now absorbed a total crush distance of 48 inches including the earlier devices, one could hope to stop a car traveling at speeds up to 50 m/h. It is likely that at the higher end of this spectrum the car would be so severely damaged that it would be no longer practical to attempt to salvage it. At impact speeds in excess of 50 m/h it would make sense to use some kind of hinged mechanism by which the engine is able to slide under the rigid passenger compartment, thus allowing perhaps an additional 24 inches in which the passenger compartment can decelerate. Alternatively, the required frontal crush distance of 24 inches could be obtained by mounting the engine rigidity to the frame behind the passenger compartment. With either type of arrangement there is, of course, no longer any thought of saving the automobile or any of its parts, but one might still hope that the passengers will come out alive even when impacting at turnpike speeds.

3. Both Safety and Mitigation of Damage

With good design, and particularly with arrangements similar to those discussed in (2) above, we have found no overriding conflict between designing a car which both is safe at high speed and sustains minimal damage under low speed collision situations.

4. Matching of Bumpers

In order to permit the above-discussed safety and damage limitation system to operate, it is essential that bumpers be designed in such a way as to match each other. They must be at the same height, they must have shapes which tend to make them stay together rather than override or underride, and they must cover the full width of the front and back of the vehicle. There is no reason for them to contain sharp protrusions or other devices which not only are dangerous to pedestrians and to other vehicles, but also tend to get into each other's way and can be subject to being broken. Bumpers must have sufficient vertical dimension so that they will still meet adequately even when one of the cars dips because of the effect of a braking deceleration on the suspension. In addition, the height of the bumpers must accurately match the height of frames and other parts of the car where the bumper might impact on a vehicle side. Needless to say, the bumper should be well out in front of the damageable parts of a vehicle.

5. Optimum Location of Energy Absorption Capability

Since useable crush space in an automobile is limited, and since maximum total nondestructive energy absorption capability is sought for most types of collisions, the best place to put most of the energy absorbing capability is into the front bumper system. For example, we must consider the possibility of a vehicle being struck in its side by the front of another vehicle. If the side of the struck vehicle is sufficiently rigid, then, as has been stated, it makes relatively little difference to that vehicle's occupant whether the energy absorption device is on his car's side or on the other car's front. However, there is little room on the side of a vehicle to put energy absorbing capability. Therefore, if every potential striking vehicle had such capability in its front bumper system, then the safety of all passengers would be increased significantly.

6. Large Vehicles vs. Small Vehicles

For reasons having no connection with the mechanics of collisions, such as the problems of pollution, energy resource management and traffic congestion, there is a tendency to gradually go to smaller sized cars. The question can be asked whether small cars can be as safe or nearly as safe as large cars under collision conditions. The safety of passengers in these types of vehicles would seem to be affected by the following considerations:

a. The possibilities of adequate restraint of passengers are probably more or less independent of the size of the vehicle.

b. In a collision between a heavy vehicle and a lighter vehicle, the weight factor would favor the occupants of the heavier vehicle because of momentum conservation. Because of its greater mass the heavier vehicle is likely to suffer a smaller change in velocity.

c. If, in addition, the lighter vehicle has considerably shorter length, then the available crush distances would have to be shortened, thus leading to a lessened capability for controlled deceleration, and correspondingly higher g loadings on the passengers.

d. On the other hand, the potential advantage of a smaller vehicle, particularly a smaller passenger compartment, is that such a compartment would be relatively easier to make rigid and penetration proof. Similarly, it would take less to give greater relative rigidity to the frame of a smaller vehicle.

Overall, it is likely that at a given speed greater safety can be made available for the occupants of a large vehicle in a mixed vehicle system. At the same time, a great deal can be done for the safety of a passenger of small cars by providing excellent restraint systems, taking advantage of the greater possibilities of a capsulized, strong passenger compartment, and providing adequate length to include a good energy absorption system. If the passenger of a small vehicle wishes to have his safety equal to that of a large car passenger, it would be advisable to use small vehicles at a somewhat lower maximum speed limit.

C. Specific Recommendations

1. Passenger Capsule and Frame

For the purpose of safety, passenger compartments of vehicles should be designed to be as rigid and penetration proof as possible. This would likely include roll-over bars, rigidity of the frame under the side doors, adequate door latches, etc. The frame under the doors should, of course, be at the same level as the standard bumper height.

2. Passenger Restraints

The operation of a car should be made contingent upon all passengers being strapped in. This would appear to require a relatively minor electrical change from present systems in which failure to fasten a belt activates a warning light.

3. Bumper Matching

Front bumpers must be located and shaped in such a way as to properly interface with the front and rear bumpers of all vehicles as well as with the frame on the side in the vicinity of the passenger compartment.

4. Front Bumper Characteristics and Graduated Damage System

Front bumpers should be required to absorb an appropriate quantity of kinetic energy by stages according to the concept of graduated damage, described under General Conclusions. A possible configuration would be a 3-inch deep elastic structure, a 9-inch distance of self resetting energy absorption, an additional 12 inches of "fuse" or renewable energy absorption material, an added 24-inch vehicle crush distance, and finally a means of having the passenger compartment travel over the engine for perhaps an additional 24 inches. The last requirement might alternatively be met by rear mounting the engine. For the initial 24 inches, including the travel of the renewable energy absorption device, damage to the vehicle should be absolutely minimized. This means that any possible fender or other structures which because of space limitations must get in the way of say, the second half of this 24 inch travel, would be inexpensive, modular, and replaceable.

5. Rear Bumper System

Besides an ability to properly interface with front bumpers, rear bumpers should be sufficiently hard to prevent damage up to approximately 30 mph when struck by the front of a vehicle having appropriate energy absorbing characteristics. To guard against excessive whiplash above these speeds, and to provide additional energy absorption capability, the rear end should begin to collapse when struck by another vehicle at speeds above 30 mph.

6. Overall Vehicle Hardening

In addition, there will need to be added requirements on such items as engine mounts which must be built rugged enough to prevent failure under acceleration conditions corresponding to the use of the above-mentioned energy absorption devices.

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III. THE MECHANICS OF COLLISIONS

A. Types of Collisions

1. Review of Collision Occurrences for 1967

The present section of the report attempts to define the threat and establish a perspective on the problem of automobile accidents. During 1967 (the latest year for which complete results are available) the Department of Transportation reported that there were 13.7 million motor vehicle accidents in the United States, and that 53,100 persons were killed in 44,500 of the accidents. Distributions of the accidents by location and type are shown in Figures 1 through 3, based on figures released by the Department of Transportation.

Urban 9,820,000	Single Vehicle 1,404,000		Pedestrian	216,000
			Fixed Objects	363,000
			Nonmotor Vehicle	128,000
			Noncollision	697,000
	Vehicle-Vehicle 8,416,000	Streets 8,276,000	Opposite Direction	811,000
			Same Direction	5,239,000
			Side Impact	1,804,000
			Other	422,000
		Freeways 140,000	Opposite Direction	8,000
			Same Direction	130,000
			Side Impact	2,000
Rural 3,880,000	Single Vehicle 1,571,000		Pedestrian	35,000
			Fixed Objects	194,000
			Nonmotor Vehicle	109,000
			Noncollision	1,233,000
	Vehicle-Vehicle 2,309,000	Roads 2,253,000	Opposite Direction	426,000
			Same Direction	1,352,000
			Side Impact	385,000
			Other	90,000
		Freeways 56,000	Opposite Direction	1,000
			Same Direction	51,000
			Side Impact	4,000

Fig. 1 - Summary of 13,700,000 motor vehicle accidents for 1967.

Urban 15,300	Single Vehicle 10,200	Pedestrian	6,000
		Fixed Object	900
		Nonmotor Vehicle	700
		Noncollision	2,600
	Vehicle-Vehicle 5,100	Opposite Direction	1,700
		Same Direction	1,400
		Side Impact	2,000
Rural 29,200	Single Vehicle 16,600	Pedestrian	3,200
		Fixed Object	1,100
		Nonmotor Vehicle	1,400
		Noncollision	10,900
	Vehicle-Vehicle 12,600	Opposite Direction	7,000
		Same Direction	2,900
		Side Impact	2,700

Fig. 2 - Summary of 44,500 fatal motor vehicle accidents for 1967.

Urban	16,700	Single Vehicle	11,400	Pedestrians	6,100
				Fixed Objects	1,050
				Nonmotor Vehicles	850
				Noncollision	3,400
		Vehicle-Vehicle	5,300		
Rural	36,400	Single Vehicle	19,700	Pedestrians	3,300
				Fixed Objects	1,350
				Nonmotor Vehicles	1,450
				Noncollision	13,500
		Vehicle-Vehicle	16,700		

Fig. 3 - Summary of 53,100 fatalities from motor-vehicle accidents in 1967. The difference of 100 between the breakdown and the total for fatalities from rural, single-vehicle accidents is as shown in the original data used to prepare this figure.

Figures 4 through 7 are based on unpublished material from a special study of motor-vehicle accidents made at the Naval Research Laboratory by Mr. Howard P. Gates. They represent analyses and estimates based on the preceding figures and on other data, leading to an estimate of the distribution of type of impact for individual vehicles as shown in Figure 7.

The reported distributions by type of accident have been combined for all locations in Figures 4 and 5. Figure 6 shows the cause of fatal injury of occupants of automobiles distributed by type of impact, and is based on a particular small-sample study. The distribution of fatalities by time of impact shown in Figure 4 is taken directly from Figure 6. The distribution of vehicles by type of impact for all accidents shown in Figure 7 represents a conversion of the data in Figure 4 from the types of accidents listed there to probable areas of impact for each of the vehicles involved. Some estimation was involved in this conversion: for example, accidents in which a vehicle leaves the road and collides with an object off the right-of-way, as well as accidents in which a vehicle rolls over on or off the road, are both classified as "noncollision" types of accidents in the original tabulations.

Fig. 4

Distribution of Accidents by Type

Based on 13.7 million accidents which involved 24.4 million motor vehicles during 1967. Totals may not agree with detail because of rounding

Type of Accident	Proportion of Accidents (percent)	Proportion of Vehicles (percent)
Noncollision (ran off road or rolled over)	14	8
Striking a pedestrian	3	2
Collision with a fixed object	4	2
Collision with a nonmotor vehicle	2	1
Total Single-Vehicle Accidents	22	13
Vehicles moving in opposite directions	9	10
Vehicles crossing (side impact)	16	1[illegible]
Vehicles moving in same direction	49	[illegible]
Other collisions between vehicles	4	4
Total Vehicle-to-Vehicle Accidents	78	87

Fig. 5

Distribution of Fatal Accidents by Type

Based on 44,500 fatal accidents which involved 62,200 motor vehicles during 1967. Totals may not agree with detail because of rounding.

Type of Accident	Proportion of Accidents (percent)	Proportion of Vehicles (percent)
Noncollision (ran off road or rolled over)	31	22
Striking a pedestrian	20	14
Collision with a fixed object	4	[illegible]
Collision with a nonmotor vehicle	5	4
Total Single-Vehicle Accidents	60	[illegible]
Vehicles moving in opposite directions	20	28
Vehicles crossing (side impact)	10	14
Vehicles moving in same direction	10	[illegible]
Other collisions between vehicles	0	[illegible]
Total Vehicle-to-Vehicle Accidents	40	[illegible]

Fig. 6

Distribution of Occupant Fatalities by Type of Impact and Cause of Fatal Injury.

Based on a sample reported by CPR National Journal, April 17, 1971. Tabular values are proportions of fatalities in percent. Totals may not agree with detail because of rounding.

Cause of Fatal Injury	Type of Impact				Total for All Impacts
	Front of Vehicle	Side of Vehicle	Rear End of Vehicle	Vehicle Rolled Over	
Struck steering wheel	17	0	0	3	20
Struck instrument panel	8	0	1	0	8
Struck windshield	8	0	0	0	8
Struck top structure	0	0	0	3	3
Struck door structure	0	6	0	0	6
Ejected from vehicle	0	11	1	16	27
Other causes	13	9	1	5	28
Total for All Causes	45	26	2	27	100

Fig. 7

Estimated Distribution of Type of Impact

Based on 23.6 million vehicles involved in accidents and on 42,200 occupants of vehicles who were killed during 1967.

Type of Impact	Proportion of Vehicles (percent)	Proportion of Fatalities (percent)
Front of Vehicle	49	45
Side of Vehicle	17	26
Rear End of Vehicle	29	2
Vehicle Rolled Over	4	27
Other	1	0

The data suggest that it is difficult to classify automobile accidents and assign statistical measures which describe them in meaningful ways. For example, the 44,500 fatal accidents represent only 0.3 percent of the total of all accidents. Can the fatal accidents be ignored as statistically insignificant?

The distribution of fatalities by type of impact is, as shown in Fig. 7 , quite different from the distribution of all vehicles in accidents by type of impact. If saving lives is the object, protection should be applied first for impacts from the front of the vehicle, followed by protection during a rollover accident. These two categories cover 72 percent of the fatalities.

If repair bills are the problem, however, protection should be applied first against impacts from the front and then against impacts from the rear, to cover 78 percent of all vehicles in accidents. Only 4 percent of vehicles roll over in an accident, but these rollovers account for a disproportionate 27 percent of the fatalities. Also, although 29 percent of vehicles in accidents are struck from the rear, this is a relatively safe accident which produces only 2 percent of the fatalities.

Impact from the side occurs for 17 percent of the vehicles in accidents, and accounts for 26 percent of the fatalities. It is third in importance for all accidents and for fatalities.

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2. Review of Statistics on Automobile Crashes Prior to 1967

A summary of various statistical studies of motor-vehicle accidents prepared prior to 1967 is contained in Reference 1. None of these studies were based on large or complete samples. The largest sample discussed in Reference 1, for example, is based on a study of 33,250 automobiles which were involved in accidents. This sample represents less than one-fifth of one percent of one year's accumulation of vehicles involved in accidents in the United States.

Despite the smallness of the samples, none appeared to have been subjected to the usual statistical controls which should be applied in selecting a small sample from a large population. The statistical studies represented data accumulated from many different sources, using different criteria and definitions.

Different samples gave widely divergent results in many cases. For example, a survey of 33,250 automobiles involved in injury-producing accidents showed that fires occurred in 156 of the automobiles, suggesting a rate of fires after accidents of about 0.5 percent. On the other hand, during a chain-reaction collision on the New Jersey Turnpike in November of 1969, eight out of the 29 vehicles involved spilled gasoline and there were multiple fires, as described in Reference 2. If the statistic from the study were applied to the 29-vehicle accident, it would show 7-to-1 odds that there should have been no fire in any vehicle, rather than the multiple fires which actually occurred.

In the previous comparison the bias between the samples (unselected collisions in one case, compared to multiple rear-end collisions on a high-speed turnpike in the other) is obvious. In other important cases, however, the selection bias seems to affect interpretations and comparisons, but the causes are more subtle. In the important matter of rear-end collisions, for example, different samples disagree widely as to whether rear-end collisions are common enough to warrant that rear ends of automobiles be designed with strength commensurate with that of the front end.

One study indicated that the front ends of automobiles were damaged by collisions 2.5 times as frequently as the rear ends. A ratio similar to this is quoted by Perrone in Reference 3, who said that his examination of the statistics shows that the front end of the vehicle is involved in about half of the accidents, that rollovers and side collisions are next in importance with about 20 percent of the total each, and that rear-end collisions are less important. These statistics suggest that rear bumpers are less important than front bumpers and the present Federal Motor Vehicle Standards require, in Reference 4, that rear bumpers only accept one-half of the barrier impact speed as front bumpers.

A different sample reported by Haddon in Reference 5, however, says that the ratio of front-end damage to rear-end damage is 1.26 to 1, indicating that rear bumpers are nearly as important as front bumpers.

A tabulation of 4016 accidents in Texas, Connecticut, and California for the period 1954 to 1960, reported in Reference 1, indicated that rear-end collisions were the most common type of accident (40 percent of the total). And a summary of accidents in New York State for 1964-65, also reported in Reference 1, showed that rear-end collisions represented more than half (5?.3 percent) of the nonfatal accidents reported to the state during that period.

3. Survey of Important Problems in Collisions

The most important accident, both from its frequency and from the proportion of fatalities, is an impact from the front of the vehicle. The analysis of data from 1967 described previously shows that this type of impact occurs to 49 percent of all vehicles in accidents and accounts for 45 percent of the fatalities. Mechanically, the front impact produced by driving an automobile head-on into a rigid post is also the most severe type of collision. This collision can occur at speeds up to the full forward speed which the automobile is capable of making, and requires that the automobile be brought to a full stop by a concentrated force applied to the front end. It is also a collision which occurs frequently as automobiles run into trees, posts, and the corners of abutments. It is likely that the design of the front bumper and front-end structure of an automobile should be determined almost entirely by the requirement that the automobile be capable of accepting a head-on collision into a rigid post.

An automobile capable of accepting head-on collison into a rigid post can also accept a collision with another automobile if driven into it so that its speed relative to the center of gravity of the two automobiles does not exceed its capability for striking a post, provided that the two automobiles interface no less favorably than a single automobile would interface with a post. The vehicle-to-vehicle collision thus reduces to an interfacing problem, in which the mix of vehicles which might be present on the roads must be closely examined to insure that protection designed into the front of an automobile is not bypassed when the automobile collides with some other vehicle.

If the rear bumper of an automobile is designed to be stronger than the front bumper, the damage from a front-to-rear collision can largely be limited to the front of the striking vehicle. The capability for accepting such a collision then reduces to the problem of the head-on collision with a rigid post. The interface problem arises again not only in the requirement that the rear bumper match front bumpers properly, but also with regard to the effect of a mix of different vehicles having different overall weights and different values of strengths of bumpers corresponding to their weights.

An automobile could be protected for collisions from the side by making the sides stronger than the front of the striking vehicle, with the same interfacing problem as for the front-to-rear collision. Protection against side collisions produced by skidding sideways into a rigid obstacle would require extension of a front protection system around both sides of the automobile, and some tradeoff may be necessary if the protection system requires too much weight or space.

The severity of the head-on collision with a rigid post is such that great efforts should be made to render such accidents impossible or highly improbable. Some highway-design work has been done in this direction by installing guard rails, deflectors, breakaway posts, and crash cushions such as described in Reference 6 at selected points on major highways, but many obvious hazards still exist.

The most important problems in collisions, problems considered feasible of solution and deserving first efforts, are thus seen to be the following:

1. Designing the front ends of automobiles to accept head-on collision with a rigid post at the highest practicable speed.

2. Correlating design of the front end with design of the front, sides, and back of other vehicles to assure proper interfacing during collision of the automobile with another vehicle.

3. Correlating design of the sides and back of an automobile with the fronts of other vehicles in an attempt to localize damage as much as possible to the front of a striking vehicle rather than to the sides and back of an automobile being struck.

Many other problems, of course, exist and are deserving of effort. Among them are protection against rollover accidents and sideswipes, and protection of pedestrians. Low-speed accidents caused by backing into a post or another vehicle also deserve consideration. Solutions of some of these problems may be correlated with the three important problems listed above, or may require some compromises in solutions to the important problems.

4. Limitations of the Present Study

The present study examines, in as great depth as possible within the limited time available, the collision resulting when an automobile is driven head-on into a rigid post (Sections III-B and III-C of this report), and when two cars collide at arbitrary relative angle (Section III-D). For such collisions, and especially for front-back accidents, damage to the automobile and injury to occupants are examined and general requirements are developed for minizing damage to the automobile and injury to its occupants. Ranges of practical speed limits for such a collision are developed on the basis of implementation with feasible hardware.

Some attention is given to problems of interfacing among vehicles and to the strengths of the sides and backs of automobiles, in connection with collision of one vehicle with another. The present study does not consider in detail the problems associated with rollover accidents, sideswipe collisions, or protection of pedestrians.

Present and proposed standards and tests for automobiles are considered from the point of view of automobile damage as well as occupant safety. The emphasis is on standards and tests related to simple collisions and no attempt is made to assess overall safety standards or to generate a complete set of proposed standards for automobiles.

B. Review of Mechanical Principles

1. Limitations set by strength and deflection

If the front end of an automobile is designed strongly enough to withstand a maximum force F_p, the acceleration of the center of gravity of the automobile produced by forces transmitted through the front end will be limited in absolute value by the relation

$$A_p = F_p/M . \qquad B(1)$$

If the front end strikes a rigid post while the automobile is moving at a speed V_o, the acceleration will be limited to the range from 0 to $-A_p$ and the time required to bring the center of gravity to a stop then cannot be less than

$$T_n = V_o/A_p . \qquad B(2)$$

During the stopping time the center of gravity must move a distance of at least

$$D_n = (1/2)\ V_o T_n . \qquad B(3)$$

A chart of Equation B(3) is shown as Fig. 8 .

As an example of use of the equations and chart, consider the publicized design for a safety car which has a bumper useful at 50 miles per hour (References 7 and 8). The bumper is a hydraulic system producing a constant force 33 times the weight of the automobile over a stroke of 30 inches. The point appears on the chart to show that the system has minimum possible stroke for its designed strength at rated speed.

Tradeoffs necessary are clear from Figure 8 . Either the front end of an automobile must be designed with great strength to decelerate the automobile severely when it collides with an obstacle, or the front end must be allowed to deflect a distance which becomes very large as speeds increase into the range of highway speeds. Remember that the distances shown in Figure 8 are <u>minimum</u> stopping distances corresponding to simple general principles.

2. Energy criterion

An automobile of mass M moving at uniform speed V_o would have kinetic energy

$$KE = (1/2)\ MV_o^2 . \qquad B(4)$$

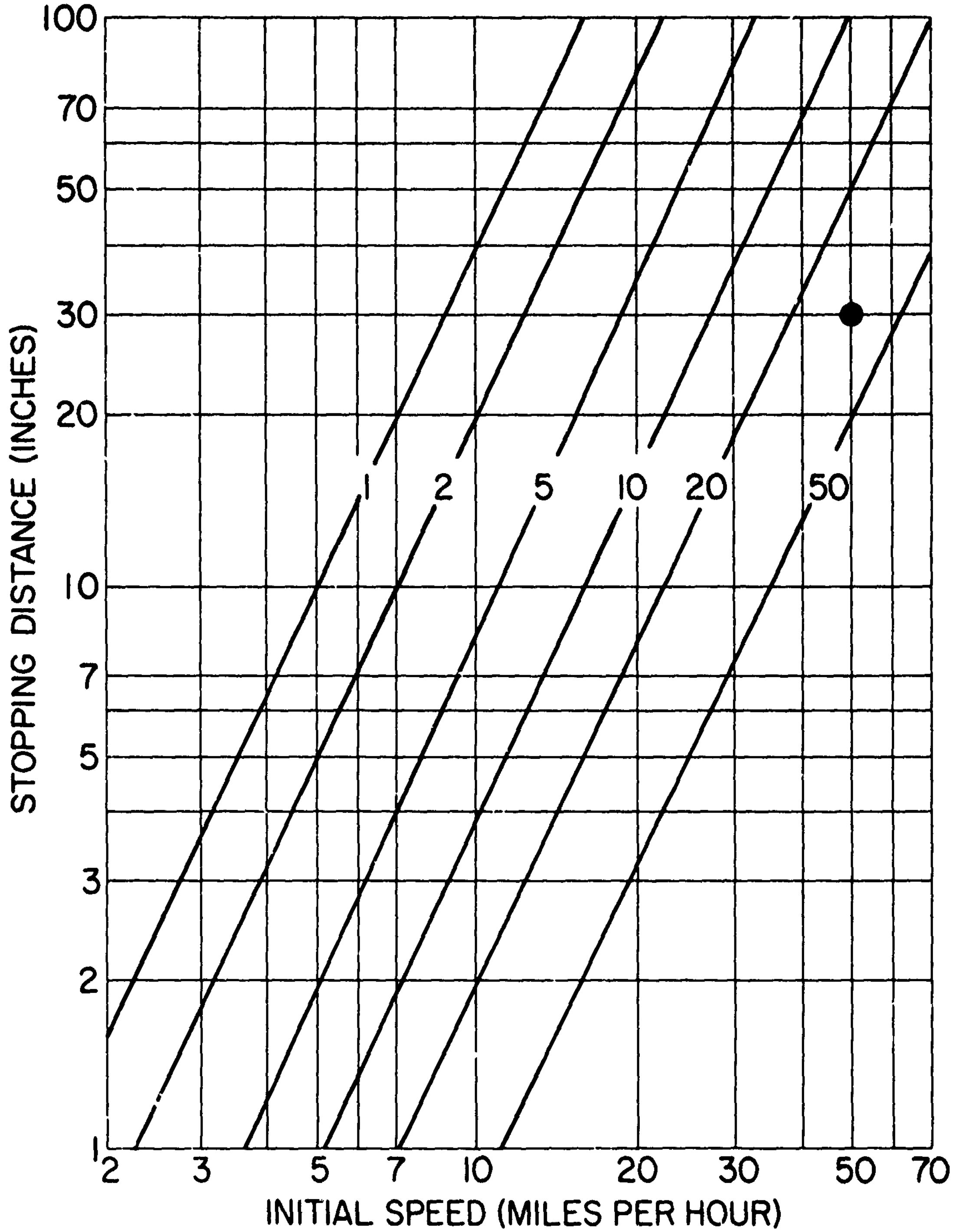


Fig. 8 - Minimum stopping distance from a collision. Sloping lines are labeled with the ratio of the strength of the front end of an automobile to the weight of the automobile. The center of gravity of the automobile cannot be brought to a stop in any distance less than the value shown by forces applied through the front end. The circle represents an example described in the text.

As a conservative design assumption, it can be supposed that all parts of the automobile must be brought to a stop on collision with a post by transforming all of the kinetic energy into the work represented by the product of a force with maximum value F_p acting through some distance. The minimum action distance required can be obtained by equating the work done to the kinetic energy, to obtain the expression

$$D_n = (1/2)\ (M/F_p)V_o^2 \qquad B(5)$$

for the minimum distance.

Equation B(5) is the same equation for minimum distance as can be obtained by combining the previous Equations B(1) through B(3) and shows that the energy criterion is simply an alternate way of representing the strength-deflection relationship stated earlier.

Interpreting strength and deflection as an energy has an advantage, however, in that preliminary design requirements for energy-absorbing structures can be developed using several very powerful methods. One method used for design of foundations on combat ships of the United States Navy is particularly useful (Reference 9), since it allows the weight of a structure to be estimated early in the design stages, before detailed design is undertaken.

The method involves rating materials and mechanical systems in terms of energy per weight, applying an efficiency factor as appropriate, and dividing the energy-per-weight figure into the kinetic energy to obtain an estimate of the required weight of the structure. Detailed design can then be carried out to develop a structure having the required weight. The weight estimates by themselves frequently give an immediate indication of the practicality of some proposed approach.

3. Conservation of momentum

Two vehicles colliding form an isolated system with external forces applied through contact of their tires with the ground. The maximum coefficient of friction between a tire and pavement does not exceed 0.8, decreases to only 0.6 if the tire is sliding, and may be much smaller than these values for road surfaces other than dry concrete (Reference 10). If the weight of the automobile supplies the normal force to the tires, external forces in the horizontal direction thus cannot exceed 0.8 times the weight of the automobile.

Collision-generated forces, on the other hand, are usually larger than 8 times the weight of an automobile. Proposed design strengths for automobiles, some demonstrated by collision tests (Reference 11), are generally in the range from 30 to 40 times the weight of the automobile. The maximum tire forces of 0.8 times the weight of the automobile are small in comparison with these collision forces and it is appropriate to ignore tire forces during the time that the collision forces are acting. An exception may occur, of course, if the automobile is driven downward by the collision so as to increase the normal force on a tire by a great amount, or if some part of the automobile other than a tire digs into the road surface during a collision.

If the external forces are neglected, the center of gravity of a two-automobile system moves uniformly through space with a constant horizontal velocity during a collision. This uniform motion expresses the fact that the momentum of an isolated system is not changed by internal forces acting between its parts. Except for interfacing problems, each automobile involved in the collision will behave as if it were colliding with a post erected at the center of gravity of the system.

Two cars of equal weight approaching each other head-on at equal speeds will have a center of gravity which is stationary midway between the automobiles and the effect of the collision will be as if each struck a stationary object. If one of the automobiles is lighter in weight than the other, the center of gravity will be moving toward the lighter automobile and the effect of the collision will be greater on the lighter-weight automobile. If the automobiles are equal in weight but one is stationary, the center of gravity moves toward the stationary automobile at one-half of the speed of the moving automobile and the effect on each automobile corresponds to collision with a fixed object at half the speed of the moving automobile.

The equation

$$V_c = (M_1V_1 + M_2V_2)/(M_1 + M_2) \qquad B(6)$$

gives the speed of the center of gravity between automobiles of masses M_1 and M_2 traveling at speeds V_1 and V_2. If V_1 and V_2 are taken as vectors giving both speed and direction, the equation can be treated as a vector equation and V_c then represents the velocity (speed and direction) of the center of gravity. Automobile 1 will behave as if it struck a stationary post while traveling at velocity

$$V_o = V_1 - V_c \ , \qquad B(7)$$

and Automobile 2 will have an effective impact velocity

$$V_o = V_2 - V_c \ . \qquad B(8)$$

When tire forces are neglected, angular momentum about the center of gravity of the system is also conserved during a two-automobile collision. The angular momentum just before a collision is given by summing the two products of mass, speed, and the distance by which the direction of motion of the center of gravity of each automobile misses the center of gravity of the system. Just after the collision the same sum applies but with the addition of terms representing the spinning of each automobile about its own axis and the available angular momentum can redistribute itself in different proportions among the different rotational motions.

The conservation laws described here apply regardless of the types of forces occurring between automobiles during a collision whether elastic, inelastic, linear, or nonlinear.

C. Management of Collision Energy

1. Deceleration of center of gravity

If a force F is applied to an automobile of total mass M, the instantaneous acceleration of the center of gravity of the automobile is given by

$$A = F/M \ . \qquad C(1)$$

The instantaneous speed V is the integral of A with respect to time, and the distance D traveled by the center of gravity is the integral of V with respect to time. Both V and D can be evaluated directly if F/M is given.

If F is the collision force occurring when an automobile approaches a rigid post with initial speed V_o (or approaches the center of gravity of a two-automobile system with initial relative speed V_o), then both F and A will be negative (directed oppositely to the initial speed) and the time required to extinguish the initial velocity can be obtained by giving the expression for V an initial value of V_o and a final value of zero. The distance traveled during this time can then be obtained from the expression for D.

Calculations for several different simple forms of F/M are summarized in the following charts. If the retarding force F is constant and equal to $-F_o$, then

$$A = -F_o/M \ , \qquad C(2)$$

$$V = V_o - (F_o/M)T \ , \qquad C(3)$$

where T is time after contacting the post, and

$$D = V_oT - (1/2)(F_o/M)T^2 \ . \qquad C(4)$$

The speed V becomes zero at time

$$T_1 = V_o(M/F_o) \ , \qquad C(5)$$

and the distance traveled by the center of gravity at time T_1 is

$$D_1 = (1/2)(M/F_o)V_o^2 \,. \qquad C(6)$$

This relation is charted in Figure 9. Note that it is the same relation shown earlier (Equation B(5)) for minimum possible stopping distance, showing that a constant retarding force is the force which can, with limited absolute value, stop an automobile in the shortest distance.

If the retarding force is proportional to speed in the form

$$F = -K_1 V \,, \qquad C(7)$$

where K_1 is a constant, then

$$A = -(K_1/M)V \,. \qquad C(8)$$

The speed and distance satisfying this equation and the initial conditions are

$$V = V_o e^{-T(K_1/M)} \,, \qquad C(9)$$

and

$$D = V_o(M/K_1)\left[1 - e^{-T(K_1/M)}\right]. \qquad C(10)$$

The center of gravity oozes to a stop after a very long time and the distance traveled approaches

$$D_1 = V_o(M/K_1) \,. \qquad C(11)$$

This equation was used to prepare the chart of Figure 10.

The initial speed V_o is the largest and produces a force

$$F_o = -K_1 V_o \,. \qquad C(12)$$

In terms of this force and speed, Equation C(11) becomes

$$D_1 = (M/F_o)V_o^2 \,. \qquad C(13)$$

Comparison with Equation C(6) shows that a force proportional to speed requires just twice the stopping distance as would a constant force equal to the initial value of the speed-proportional force.

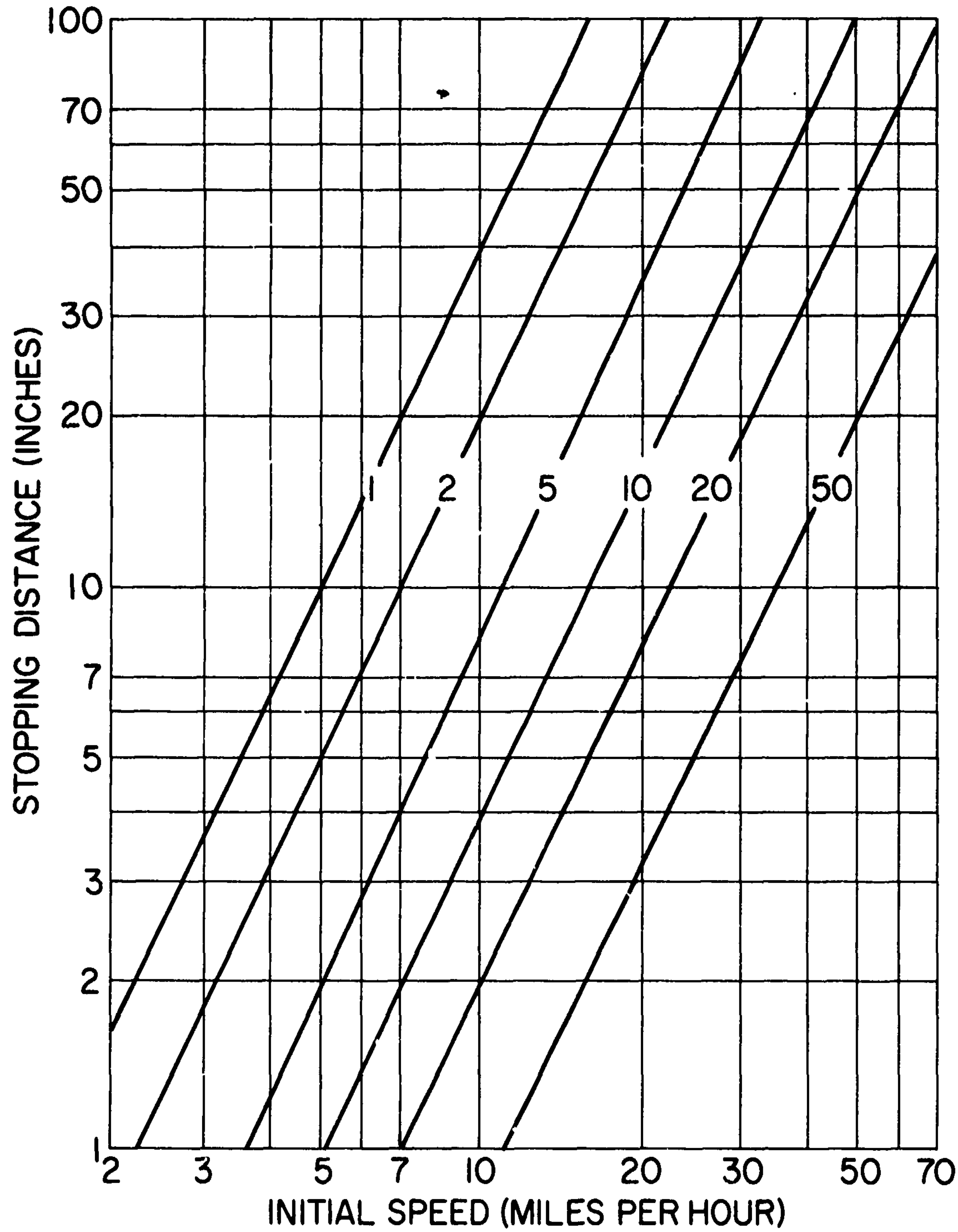


Fig. 9 - Stopping distance under constant force. Sloping lines are labeled with the ratio of the stopping force to the weight of the automobile. Ordinate shows the distance travelled by the center of gravity after the force is applied and before the automobile comes to a stop.

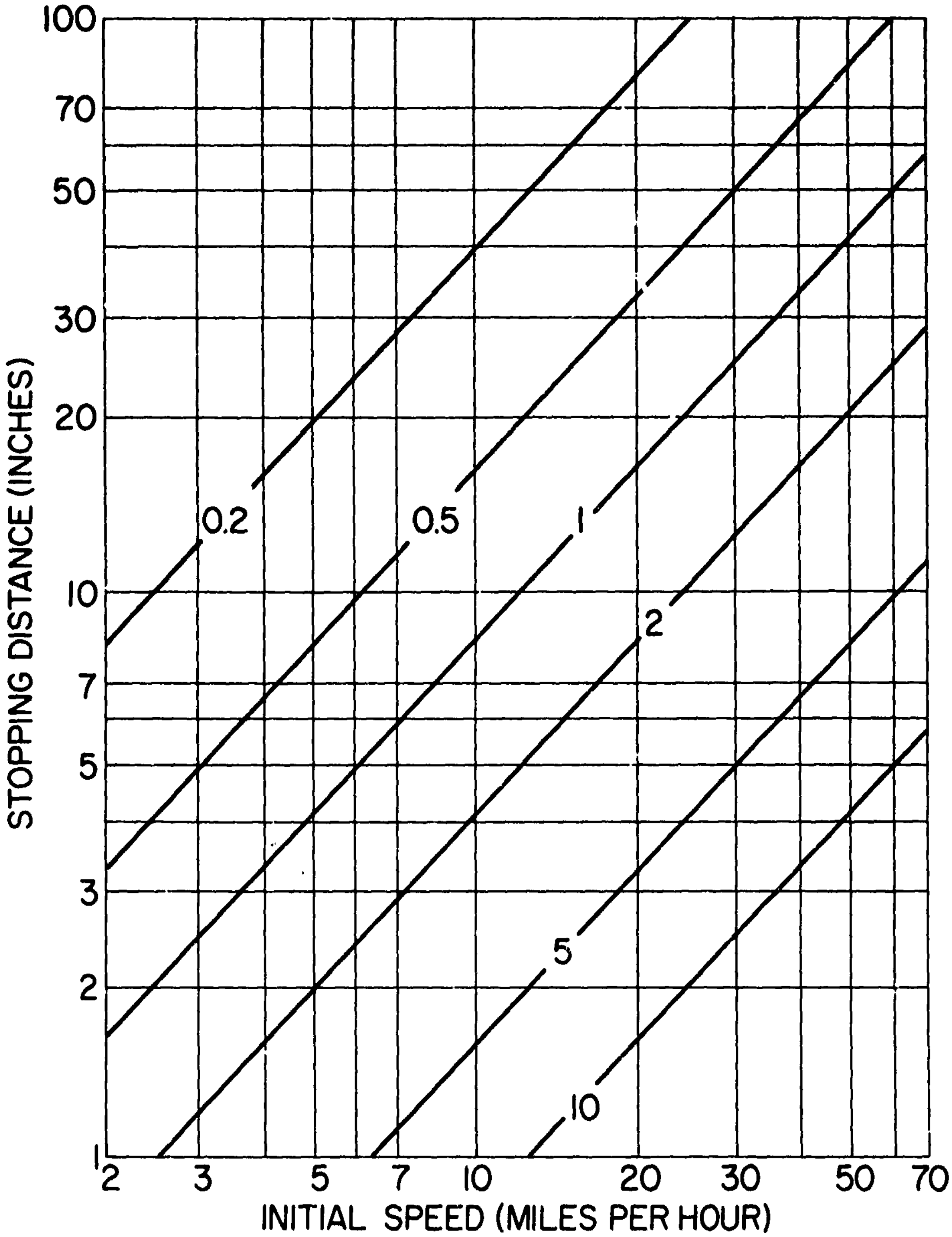


Fig. 10 - Stopping distance for a force proportional to speed. Sloping lines are labeled with values of the proportionality constant giving force per weight of the automobile as proportional to speed in miles per hour. The line labeled "1" for example, corresponds to a force 10 times the weight at a speed of 10 miles per hour, or 50 times the weight at a speed of 50 miles per hour.

If the retarding force is proportional to the square of the speed,

$$F = -K_2V^2 , \qquad C(14)$$

then

$$A = -(K_2/M)V^2 . \qquad C(15)$$

This relation has solutions

$$V = V_o / \left[1 + V_oT(K_2/M)\right] \qquad C(16)$$

and

$$D = (M/K_2) \log \left[1 + V_oT(K_2/M)\right] . \qquad C(17)$$

where log is a logarithm to base e. Note that although the speed decreases, it never reaches zero and the distance traveled continues to increase without any limit. Equation C(17) can be rewritten in the form

$$D = - (M/K_2) \log (V/V_o) , \qquad C(18)$$

to show that the travel distance required to reduce an initial speed V_o to a particular proportion V/V_o of its original value is independent of the initial speed. Equation C(18) was used to prepare the chart of Figure 11 , showing the distance required to reduce an impact speed to one-tenth of its initial value.

The initial retarding force from the speed-squared function is given by

$$F_o = -K_2V_o^2 . \qquad C(19)$$

Comparison with Equations C(6) and C(13) shows that, for the same value of initial force, the speed-squared system still has a residual speed 61 percent of the initial speed as it passes through the stopping point corresponding to the constant-force system (Equation C(6)), and still has a residual speed 37 percent of the initial speed as it passes through the stopping point corresponding to the speed-proportional system (Equation C(13)).

If the retarding force is proportional to distance traveled,

$$F = -K_3D , \qquad C(20)$$

then

$$A = -(K_3/M)D . \qquad C(21)$$

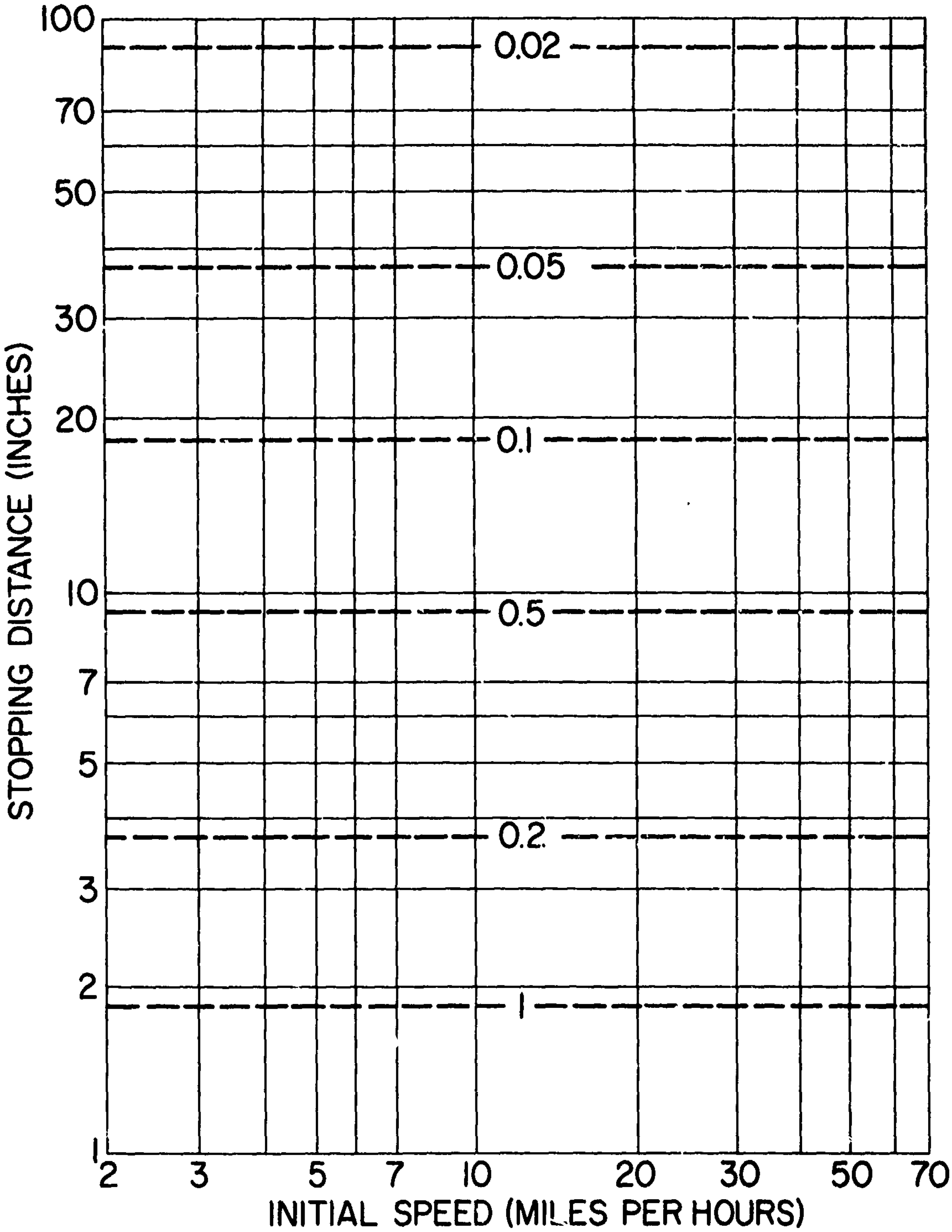


Fig. 11 - Stopping distance for a force proportional to the square of the speed. The speed-squared force does not bring the automobile to a complete stop in any finite distance. Horizontal broken lines show the distances required to reduce the speed of the automobile to one-tenth of its initial value and are labeled by force per weight of automobile, taken as proportional to the square of the speed in miles per hour. The line labeled "1", for example, corresponds to a force 100 times the weight at a speed of 10 miles per hour and to a force 2500 times the weight at a speed of 50 miles per hour.

This relation has solutions

$$V_o = V_o \cos(\sqrt{K_3/M}\,T) \qquad C(22)$$

and

$$D = (V_o/\sqrt{K_3/M}) \sin(\sqrt{K_3/M}\,T) \ . \qquad C(23)$$

The automobile stops after its center of gravity has traveled a distance

$$D_1 = V_o/\sqrt{K_3/M} \ . \qquad C(24)$$

This relation has been used to prepare the chart of Figure 12.

The force just at maximum displacement is given by

$$F_o = -K_3 D_1 \ , \qquad C(25)$$

and a combination of this equation with Equation C(24) gives the equation

$$D_1 = (M/F_o)V_o^2 \qquad C(26)$$

for the stopping distance. Note that this stopping distance is just double the stopping distance for a constant force F_o (Equation C(6)) and just equal to the stopping distance for a speed-proportional force with initial value F_o (Equation C(13)).

2. Human tolerance to deceleration

A survey of some of the data on human tolerance to acceleration pulses is given in Reference 10, together with recommended limiting values. Both the data and the limits are expressed in terms of acceleration, jerk, and duration.

Three curves from charts presented in Reference 10 have been replotted in terms of initial speed and stopping distance in Figure 13. The curves show lower limits for voluntary tolerance to acceleration pulses and are seen to be incomplete and to include significant differences among themselves over the ranges of speeds and stopping distances associated with automobile crashes.

Two upper limits for the deceleration which can be withstood by a seated man without serious injury are stated in Reference 10. It is supposed that the man is in good physical condition and is tightly restrained by an appropriate harness. One limit is an acceleration 40 times the acceleration of gravity (g) sustained for 0.16 second with jerk not exceeding 1500 g

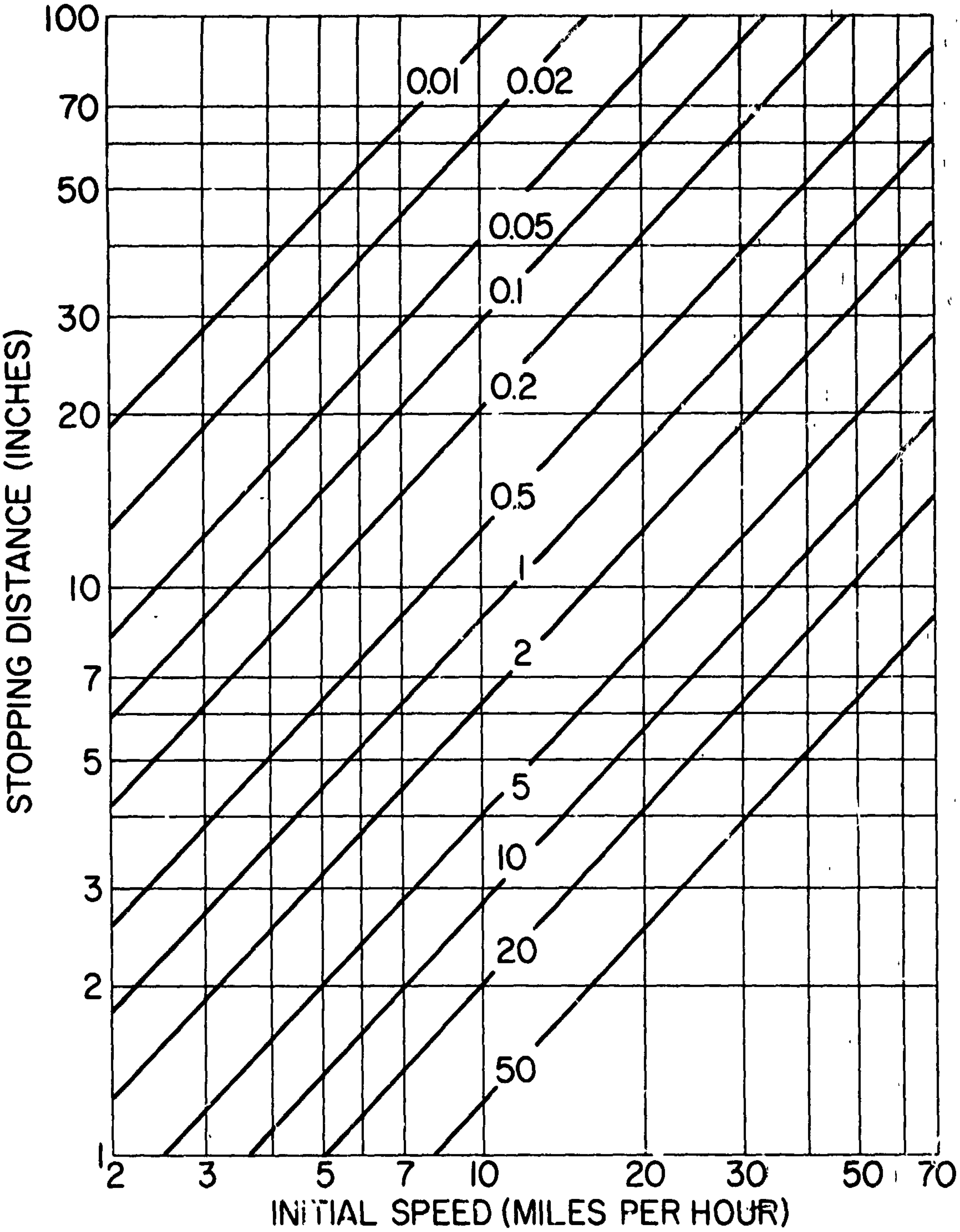


Fig. 12 - Stopping distance for a force proportional to distance. Sloping lines are labeled with values of force per weight of automobile as proportional to distance travelled in inches. The line labeled "1" for example, corresponds to a force 10 times the weight at a deflection of 10 inches, or 50 times the weight at a deflection of 50 inches.

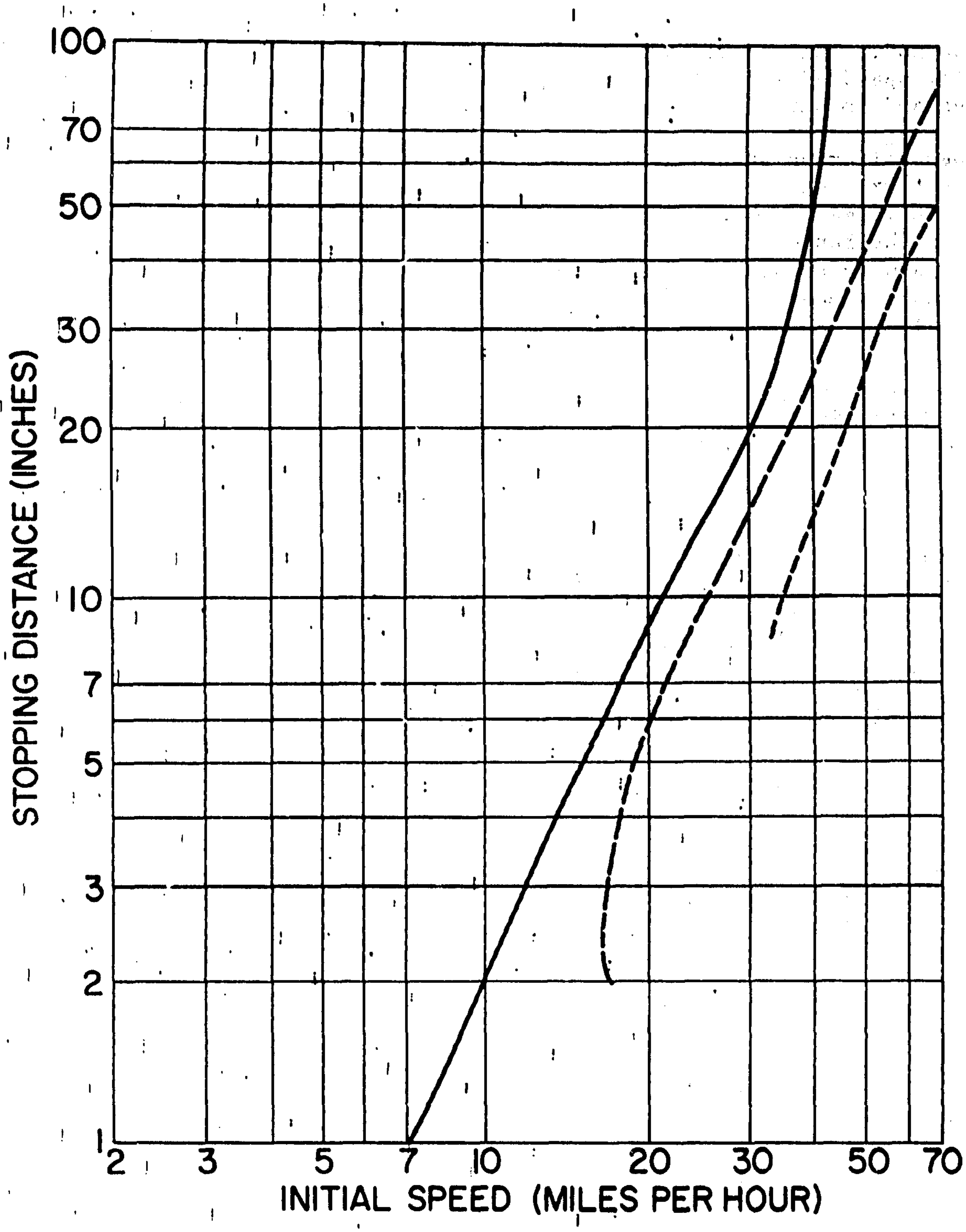


Fig. 13 - Lower limits for voluntary tolerance to acceleration pulses. The three curves represent three different estimates of the same lower limit from three different sources. They have been replotted here in terms of initial speed and stopping distance from their original presentations as duration and magnitude of an acceleration pulse. Two of the lines end on the chart because the original presentation did not extend to pulses of short-enough duration. Each line represents one investigator's assessment of a tolerable situation. As speeds increase from each line, conditions become less tolerable, intolerable, injurious, and finally fatal.

per second. This acceleration pulse corresponds to stopping from an initial speed of 117 miles per hour in a stopping distance of about 160 inches and is out of the range of interest for automobile crashes.

Another criterion stated is an upper limit of 50 g for 0.2 second with jerk not exceeding 500 g per second. This pulse corresponds to stopping from 110 miles per hour in a distance of about 190 inches, and is also outside the range of interest for automobile crashes. Carrying these criteria down toward lower speeds and shorter stopping distances appears to produce somewhat inconsistent results, as suggested by the curves in Figure 13.

An automobile occupant seated on a soft seat and restrained fairly loosely by a simple harness can move forward appreciably relative to the center of gravity of an automobile during a collision. As a limit, it can be supposed that his stopping distance can be increased, relative to the stopping distance of the center of gravity of the automobile, by the amount of clearance which he has available between himself and the nearest solid structure into which he could be thrown. The data in Figure 13 suggest that with a reasonable clearance of 20 inches or so and a fairly effective restraint system, an occupant of an automobile could voluntarily accept collisions at initial speeds up to about 30 miles per hour, nearly independent of the manner in which the automobile itself was brought to a stop.

3. Review of mechanisms to absorb collision energy

a. elastic systems

Steel springs immediately come to mind as a mechanism to mitigate the effects of an automobile crash. Preliminary design requirements for a steel-spring system can be obtained by using the energy criterion described previously. A piece of steel having weight W and density ρ has volume W/ρ. Stressing it uniformly and uniaxially to a stress S requires energy

$$E = (1/2)(W/\rho)(1/Y_m)S^2, \qquad C(27)$$

where Y_m is Young's modulus. Structural steel having a density of 0.285 pounds per cubic inch, Young's modulus 30 million pounds per square inch, and an allowable stress of 40 thousand pounds per square inch can accept an energy per weight of

$$E/W = 8 \text{ foot-pounds per pound of steel.} \qquad C(28)$$

A 3000-pound automobile moving at a speed of 10 miles per hour has kinetic energy 10,021 foot-pounds (Equation B(4)). The weight of a steel structure to absorb this energy can be estimated as

$$W = 10{,}021/8 = 1253 \text{ pounds of steel.} \qquad C(29)$$

Even at the low speed of 10 miles per hour, Equation C(29) indicates that more than one-third of the total weight of the automobile must be devoted to a steel structure which can be uniformly stressed by a collision. At

50 miles per hour the kinetic energy of the 3000-pound automobile would be 250,518 foot-pounds and the required weight of structural steel to absorb the energy is more than ten times the weight of the automobile.

A spring steel capable of accepting a stress of 200 thousand pounds per square inch could absorb 195 foot-pounds of energy per pound of steel if stressed uniformly and uniaxially to its limit. The collision at 10 miles per hour could be handled by 51 pounds of this spring steel used in this way, but 1285 pounds of it would be required for a 50-mile-per-hour collision.

It is difficult to arrange for absolutely uniform stressing of a material in any practical design. If the spring steel, for example, were formed into flat springs which could be bent, the stress from bending in each spring would vary from a maximum at one surface, through zero at a neutral axis, and to a minimum at the opposite surface. The average value of the square of the stress (as required for Equation C(27)) would then be only one-third of the square of the maximum stress, and the bending spring would absorb only one-third as much energy as a piece of steel uniformly stressed to the same maximum stress. Even if the surface stress were uniform from one end of each spring to the other (another difficult design problem), the spring steel used in bending would absorb only 65 foot-pounds per pound of spring steel. Springs required at 10 miles per hour would have to weigh 154 pounds, and those required at 50 miles per hour would have to weigh 3854 pounds, more than the total weight of the automobile.

Other metals, used elastically, have energy-absorbing characteristics which (on a per-pound basis) are generally within the range for steel. Any attempt to use metal springs to mitigate automobile-collision forces and damage for a range of speeds much above those corresponding to minor collisions in a parking lot leads immediately to an estimate of structural weight for the metal which must be devoted to energy absorption which is beyond any practical limit for an operating automobile.

Elastomers, such as rubber, provide a large increase in energy per weight, in part because of their lower density but mostly because they can accept very large strains. A survey of elastomers made for the Navy, Reference 12, lists characteristics for sixteen major categories of elastomers. Natural rubber, for example, has a density of 0.034 pounds per cubic inch, a tensile strength of 1000 pounds per square inch, and an elongation of 100 percent before rupture. Stretched to its limit, such a material would absorb 1225 foot-pounds of energy per pound of material.

Only 8 pounds of natural rubber, installed to be stretched with 100 percent efficiency, could absorb the collision energy from a 3000-pound automobile moving at 10 miles per hour. It would take 205 pounds of rubber to accept the energy from a collision at 50 miles per hour. This latter weight of rubber corresponds to a cube 18 inches on each edge, which must be cut up and distributed around the car with a mechanism which places it all in uniform tension during a collision. The elastomers, as a class, are seen to be much more useful in protecting an automobile from a collision than are the best spring steel or any other kind of metal.

The elastic characteristics of fluids can also be used to store collision energy. Ordinary water, for example, has a bulk modulus of 0.30 million pounds per square inch and a density of 0.036 pounds per cubic inch. Compressing water to a pressure of 20,000 pounds per square inch requires an energy of 1543 foot-pounds per pound of water. The energy from a 3000-pound automobile moving at 10 miles per hour could be transferred to 6 pounds of water (less than a gallon) if the water were compressed to 20,000 pounds per square inch. At 50 miles per hour, using the same pressure, 162 pounds of water would be required (nearly 25 gallons). Other liquids (hydraulic fluid and silicone oil in particular) have bulk moduli appreciably smaller than that of water and can accept correspondingly larger energies at the same working pressures. Gasses, used in pneumatic systems, have the advantage that the working fluid has an extremely low density and its weight may be partially or completely buoyed up by the surrounding air.

Fluid systems require a container and the weight of the container must be included in preliminary design estimates for the system. The container must be large enough to hold the required volume of fluid and must be strong enough to withstand the working pressure developed. A cylindrical container, for example, having radius R and length L can hold a weight W of fluid having density ρ according to the equation

$$W = 2\pi R L \rho \ , \qquad C(30)$$

where π is 3.14159. Stress in the wall of the container from an interior pressure P is given approximately by

$$S = PR/H \ , \qquad C(31)$$

where H is wall thickness. The container, if made of a material having density ρ_c, will have a weight given approximately by

$$W_c = 2\pi RHL \ \rho_c \ . \qquad C(32)$$

The radius and wall thickness can be eliminated among the three equations to give the result

$$W_c = \rho_c \ PW^2/(2\pi SL \ \rho^2) \ . \qquad C(33)$$

The equation indicates that the container should be made of a material with a small ratio of density to allowable stress (ρ_c/S) and that it should have a length L chosen as large as practicable. There is also an advantage in going to smaller volumes W/ρ of fluid even though they must be worked to higher pressures P to absorb a given amount of energy.

A container designed of pipe-grade steel (allowable stress 60 thousand pounds per square inch and density 0.285 pounds per cubic inch) to hold the 162 pounds of water required to absorb the energy from a collision at 50 miles per hour with maximum pressure 20,000 pounds per square inch would have a weight

$$W_c = 765 \text{ pounds of container ,} \qquad C(34)$$

if the length of the container were chosen as 400 inches so that it could be split into two parts, each about as long as could possibly be fitted into the length of an automobile. Radius of the container would be 1.79 inches and its wall thickness would be 0.60 inches. As indicated by Equation C(33), a heavier container would be required if it were made any shorter or if more water were used at a lower working pressure. The container plus water have a weight of 927 pounds, approaching one-third of the total weight of the automobile.

b. energy-dissipating systems

The elastic systems described in the previous section have the disadvantage that the energy which they accept is stored as potential energy to be returned to the system, causing an automobile to rebound from whatever object it strikes with a (theoretical) speed which is equal and opposite to its approach speed. A better system would allow the energy to be dissipated during or after storage so that the automobile would not tend to be pushed back away from the point of collision as violently as it approached. A complete lack of such rebound implies that a system would have to be manually reset in some way after a collision before it would be ready for another collision. Such systems are discussed in the next section. In the present section, attention is directed toward systems which automatically return to their original condition after a collision, but do so with a smaller release of energy than the energy stored during the collision.

All of the elastic systems described in the previous section can be modified to provide for energy dissipation. Providing frictional forces to oppose motion of the system during both the energy-storage and energy-release phases is one way of dissipating energy. It is necessary that the frictional forces never be larger than the elastic forces, or the system will stick and fail properly to reset itself. Three systems which combine elastic and frictional forces are the Belleville spring, the ring spring, and the shim spring.

The Belleville spring consists of a stack of cupped washers arranged with some convex and concave sides facing each other. A force applied along the axis of the stack flattens the washers and the stack operates as an elastic spring. The washers also rub against one another as they flatten, producing frictional forces which vary as the normal forces on the stack vary. In an ideal case the frictional force can be nearly equal to the elastic force, causing the stack to compress with a total force nearly double the elastic force and then return toward its initial length with a very small net force. Stresses through the washers vary in a complicated way as the washers flatten, and the efficiency of the spring is likely to be low even if the extra compressive force from friction is taken into account.

The ring spring is a stack of alternating larger and smaller rings partially overlapping. A force along the axis of the stack pushes the larger rings over the smaller ones along beveled edges. Elastic forces are generated as the larger rings expand and the smaller ones contract, and frictional forces come from the sliding along the bevels. As for the Belleville spring, the frictional forces add to the elastic forces during compression and subtract from them during rebound and vary in proportion to the normal force. The ring spring is likely to be more efficient than the Belleville spring, since each ring has a nearly uniform circumferential stress.

The shim spring is made by stacking up layers of thin sheets and connecting them together at alternate ends to make a zig-zag connection through the stack. When the top sheet is moved in its own plane relative to the bottom sheet, alternate sheets are placed in compression and in tension to generate an elastic force. The sheets also slide on one another to generate a frictional force which increases with increasing stress as normal forces constrain the sheets from curling and buckling. This system, using the material in uniform tension and compression only, has prospects of very high efficiency. Energy storage as high as 208 foot-pounds per pound of shim spring has been claimed for working models with automotive applications (Reference 13).

The preceding designs, for metal springs with some friction, are all limited by the limited energy-absorption capability of metals. It would still take, for example, 1205 pounds of shim springs to accept the energy from a 3000-pound automobile traveling at 50 miles per hour.

Highly-damped elastomers are especially attractive for absorbing and dissipating the energies from collisions. Many damped elastomers have energy-storage capability per pound equal or better than that of the natural rubber discussed earlier. The damped elastomers behave visco-elastically in such a way as to be appreciably stiffer for high-speed loadings than they are for low-speed loadings. They thus can absorb an amount of energy which increases with the speed of the collision. After a collision they return to their original shape more slowly and with smaller forces than the forces generated by the impact. The United States Navy has had much experience with damped elastomers as used for mitigating shock and vibration on ships, and experienced Navy laboratories have found it possible to tailor-make elastomers with specific characteristics for particular applications (Reference 12). A suitable elastomer for automotive application should be resistant to weather, oil, and gasoline, and should be viscoelastically damped to produce forces which increase in a predictable way with speed of deformation.

Hydraulic and pneumatic systems can easily be made to dissipate energy by allowing them to leak. The energy put into them during a collision then can escape in part with the leaking fluid. A relatively weak spring added to the system can reverse the leak after the collision and restore the system slowly to its original condition. Great increases in energy-absorption characteristics of fluid systems can be obtained by allowing the energy to leak off as rapidly as it is delivered to the system. The energy then transfers to kinetic energy of the leaking fluid and energy-absorption characteristics are limited only by the requirement of providing enough fluid, expelled at high enough speed, to account for the energy.

One hydraulic system with an orifice (Reference 14) claims to absorb 28,300 inch-pounds of energy in a complete system weighing about 3 pounds. The ratio of 786 foot-pounds per pound of system suggests that an automobile weighing 3000 pounds could be protected against collisions at 10 miles per hour by a system weighing about 13 pounds, or protected for collisions at 50 miles per hour by a system weighing about 319 pounds, if the ratio of energy to weight could be maintained for larger systems.

The hydraulic buffer proposed for one safety car (References 7 and 8) consists of a pair of pistons with radii 2.25 inches moving in cylinders 30 inches long filled with 43 pounds of glycerine (density 0.045 pounds per cubic inch, bulk modulus 0.67 million pounds per square inch) which is expelled from an orifice at a constant working pressure of 5569 pounds per square inch. The system is designed to absorb 443,062 foot-pounds of energy. Equation C(33) indicates that the cylinders, if constructed of steel with density 0.285 pounds per cubic inch and allowable stress 60,000 pounds per square inch, would weigh 64 pounds, for a total weight (excluding pistons and a container for the expelled fluid) of 107 pounds. The indicated energy capacity of 4141 foot-pounds per pound of system is higher than that of any other system discussed previously. Compressing the glycerine to the working pressure accounts for only 1843 foot-pounds from the total of 443,062 foot-pounds: the remainder of the energy is represented by kinetic energy of the expelled fluid. The compression takes place during the first 0.25 inch of piston motion, as the two pistons move into the fluid with combined elastic stiffness 711 thousand pounds per inch.

c. systems requiring resetting or replacement after collision

The systems described in the previous se tion automatically return to their pre-collision status after a collision. Somewhat more freedom in design can be obtained if this requirement is not maintained, at the expense of having a system which must be worked on, replaced, or at least manually adjusted after a collision. High-friction devices are simple and can produce relatively large values of energy per weight, for example, but remain in a deflected condition after a collision until jacked back into shape.

Energy per weight for a high-friction device can be very high. For example, pulling a steel plate through a pair of brake shoes set to produce a stress of 20,000 pounds per square inch in the plate (density 0.285 pounds per cubic inch) requires an energy of 5848 foot-pounds per pound of plate, independent of the dimensions of the plate. If a cylinder is to be pushed through a set of brake shoes (a more practical arrangement), its total length is limited by the requirement that it not buckle under the applied compressive force along its axis and practical limitations arise. One simple structure developed and tested by the Navy (Reference 15) consists of a piece of thick-walled steel pipe inserted into a larger pipe with an interference fit. In tests, forces up to 23,000 pounds could be developed by pipes having wall thickness 0.25 inch when a pipe with outer diameter 1.4 inches was forced into another with inner diameter 1.4 inches. Energy capability was about 3000 foot-pounds per pound of pipe if the full length of the pipe were available for sliding. Pipes weighing only 3 pounds would be needed to absorb the energy from a 3000-pound automobile moving at 10 miles per hour, or 84 pounds of pipes to absorb the energy at 50 miles per hour. Force required to initiate the sliding motion was about three times the force for continued motion, and the pipes had to be strong enough to resist the initial force.

A more elaborate pipe-in-pipe arrangement has been described for an aerospace requirement (Reference 16). Here deformable rollers are fitted between an inner and an outer pipe and the force resisting the motion of one pipe within the other is from a combination of friction and yielding of the rollers. A strut 3 feet long, weighing 13.6 pounds, can produce a constant force of 9300 pounds over a stroke of 13.5 inches, to absorb 769 foot-pounds of energy per pound of strut.

Although metals are limited in their capability for absorbing energy elastically, they can absorb a much larger amount of energy plastically. The energy absorbed by deforming a weight W of metal having density ρ and yield stress S to an ultimate strain U is given approximately by

$$E = (W/\rho)SU. \qquad C(35)$$

For mild steel, with density 0.285 pounds per cubic inch and yield stress 20,000 pounds per square inch, which is deformed to a strain of 10 percent, energy per weight is

$$E/W = 585 \text{ foot-pounds per pound of steel.} \qquad C(36)$$

The energy from a collision of a 3000-pound automobile at 10 miles per hour could be absorbed by deforming 17 pounds of this low-grade steel. At 50 miles per hour 428 pounds of steel would have to be deformed. The design of an efficient structure to yield uniformly in a collision would be quite difficult. Usual collapsing structures have areas of yield localized near plastic hinges and efficiencies (indicated by how closely the actual yield throughout the structure approaches the presumed strain of 10 percent) are likely to fall below 25 percent even with great attention to design.

Nickel wires were deformed to absorb energy in one study (Reference 17). Annealed nickel wire has density 0.320 pounds per cubic inch and in the referenced study wires were elongated 30 percent at a constant stress (relative to initial area) of 60,000 pounds per square inch. The energy capability is 4687 foot-pounds per pound of wire, so that only 53 pounds of wire, arranged to be properly stretched, could be used to absorb the collision energy for a 3000-pound automobile striking an obstacle at 50 miles per hour.

Two particular designs for simple structures which absorb energy, but must be replaced after a collision, deserve mention. A thin-walled tube can be turned inside-out at one end and attached to a lip. A force applied to the other end of the tube then causes the tube (if made of a ductile metal such as soft aluminum or mild steel) to move through the lip by turning itself completely inside-out. In one experimental study, 3-inch aluminum pipe produced forces up to 4000 pounds and was tested at speeds up to 20 miles per hour. Energy absorptions of 4000 foot-pounds per pound of tube were typical, with some configurations showing energy absorption to 7000 foot-pounds per pound. Tubes weighing 63 pounds would be sufficient for a 50-mile-per-hour collision with a 3000-pound automobile, using the lower of the two energy-absorption figures (Reference 18). Even higher energy absorption capability is provided by a system which forces a blunt die into the open end of a tube to flare the tube out and break it into small fragments (Reference 19). This device (frangible metal tube) is said to accept up to 31,000 foot-pounds per pound of tubing (weight of die not included) and has been tested dynamically at speeds up to 12 miles per hour.

There have been many studies of inexpensive and lightweight crushable materials with semistructural characteristics, which could be used to absorb the energy of an automobile collision and then replaced. Paper honeycomb was tested by impacting it with loads up to 1200 pounds at speeds up to 41 miles per hour in an extensive study reported in Reference 20. Information gained during the earlier study was used to develop paper-honeycomb impact systems which could protect army vehicles from damage during parachute drops in which they impacted the ground at speeds up to 20 miles per hour (Reference 21). The reference emphasizes practical design problems and their solutions.

Other crushable materials are less sensitive to weather and more suitable for structural applications than paper honeycomb. For example, honeycomb panels made of 8-mil steel sheets (Reference 22) were tested in segments 6 inches thick and a foot in diameter which weighed only 4 pounds but could absorb 24,000 foot-pounds of energy statically or 48,000 foot-pounds dynamically, for an energy-per weight ratio of at least 6000 foot-pounds per pound. Only 42 pounds of such honeycomb, properly crushed, could accept the energy from a 3000-pound automobile at 50 miles per hour.

d. systems for minimizing repair costs

In the preceding section it was tacitly assumed that the energy-absorbing systems described could slide, deform, fracture, or crush without any other damage to the automobile and that they could then be reset or replaced by a simple operation. As a practical matter, the deflection required to absorb energy from anything other than a very low-speed collision while keeping forces manageable is large enough (a foot or more even at 30 miles per hour) that it would be inefficient to allocate that space entirely to energy absorption from collisions. A collision is then likely to damage some functionally-useful part of the automobile which originally shared space with the clearance space provided for the energy-absorbing system and the repair after the collision will involve not only resetting or replacing the energy absorber, but repairing a useful part of the automobile as well.

Designing automobiles for minimum cost of repair or replacement of a part damaged by a collision is a matter of design detail, with attention directed especially to those parts within the crush space of an energy absorber. These parts should be light, simple, inexpensive, and easily replaced as modules. The front of an automobile, in particular, should be simple metal panels without expensive ornamentation. Vital and expensive components, such as the motor and cooling system, should not be located within the crush space provided for the front energy-absorbing system.

e. protecting passengers during high-speed collisions

Examples of collisions in the preceding sections were based on automobile speeds of 10 and 50 miles per hour. Automobiles are regularly driven, however, at speeds up to 70 miles per hour and on some interstate highways the posted speed limit is 75 miles per hour. At a speed of 71 miles per hour the kinetic energy available for a collision is double the energy available at 50 miles per hour and any provisions made for collisions at the lower speed are likely to be completely inadequate when the energy which they must deal with is doubled.

In a high-speed collision, any energy-absorbing system is likely to be defeated almost immediately and the automobile is likely to be a total loss. The concern should be to give the occupants as much chance of survival as possible. This would seem to involve restraining them as well as possible within a soft (padded) enclosure which is designed as strongly as practicable to prevent it from being breached by other parts of the automobile or the object being struck. The design problem is a general one, involving many compromises, tradeoffs, and special circumstances, and will not be discussed in detail here.

4. Concept of graduated damage

A feature of systems sometimes referred to as "robustness" or (more cynically) as "graceful degradation" is that the system still has some effectiveness even under conditions which go beyond its original conception.

It gradually loses effectiveness as conditions become more adverse but retains as much capability as possible at each step and does not tend to pass suddenly from full service to a hopeless condition.

It can be supposed that an ideal capability for automobiles would be to accept all collisions under all conditions without damage to the automobile and without injury or discomfort to the occupants. On the concept of graduated damage this capability is lost as gradually and reluctantly as possible as the severity of the collisions increases.

For collisions up to a certain severity, the concept (no damage, no discomfort or injury) can be kept intact. It is believed, on the basis of the preceding discussion, that the concept could be maintained in large part for collisions equivalent to striking a rigid post head-on at 10 miles per hour. This is an appreciable increase over present capabilities for automobiles but would seem to involve an energy-absorbing system of feasible design with reasonable actuation distance, automatically resetting itself after a collision, together with reasonable methods of restraining and protecting occupants.

Beyond 10 miles per hour it seems necessary to abandon the goals of an automatically-resettable energy absorber and of occupant comfort. The decelerations must be more abrupt to prevent too much space from being devoted to an energy-absorbing mechanism and the energy-absorbing system itself could probably be made less expensive and lighter in weight if it were allowed to undergo some controlled permanent deformation or crushing during the collision. It is believed that collisions up to about 20 miles per hour (equivalent, head-on into a post) could be tolerated at the expense of some occupant discomfort from rapid decelerations and with some permanent damage to a structure specifically added to the automobile to mitigate the effects of collisions.

Between 20 and 30 miles per hour it seems necessary to accept some limited amount of damage to the automobile itself, as the deflection space required for energy absorption begins to encroach on space devoted to other purposes. It seems quite feasible that occupants should not be injured by collisions occurring at speeds up to 30 miles per hour.

Beyond 30 miles per hour it seems necessary to accept major damage to the automobile, damage severe enough so that repair of the automobile to place it back in service would not be economically justified. Here the capabilities of the various energy-absorbing systems added to the automobile can be terminated and the frame and structural members of the automobile designed to collapse in a controlled way about the passenger compartment, in an attempt to protect the occupants as much as possible. This design regime should continue up to the range of turnpike speeds.

5. Compromises and tradeoffs

The concept of graduated damage provides smooth roll-offs from one capability to another as the severity of collisions increases. A relatively soft and automatic energy-absorption system for low-speed collisions without damage or discomfort needs to become progressively stiffer as speeds increase until the decelerations become uncomfortable, whereupon the excess energy begins to be absorbed by permanent deformation or crushing of a special structure. At still higher speeds the deformation begins to involve some inexpensive and nonvital parts of the automobile, and eventually the entire automobile outside of the passenger compartment is involved in the damage process.

A major compromise is involved in the intermixing of different types of vehicles on the highways. In order to allow any vehicle to collide with any other vehicle, each protected automobile must consider the prospect of being struck from the side or rear by some vehicle which does not interface properly with it, and of any weight. Complete protection would require energy-absorption capability to be provided around the entire circumference of the automobile. If the fronts of all vehicles, on the other hand, were required to interface properly with the sides and backs of all other vehicles, energy-absorbing structures on the fronts of all vehicles would be effective in mitigating not only head-on crashes for the protected vehicle, but collisions against the sides and backs of other vehicles as well. Neither of the two courses described seems entirely feasible and some tradeoff appears necessary.

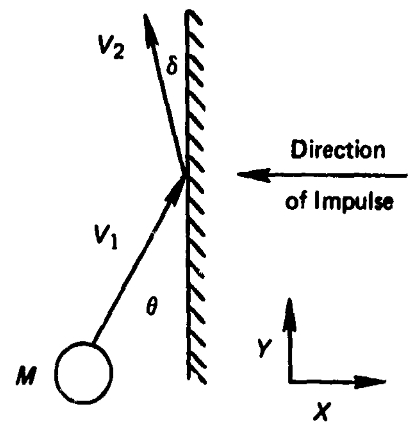
(RLB)

D. A Simple Overview of the Mechanics of Collision

In this section automobiles are imagined as mass points without rotary inertia. It is assumed that a collision occurs and that events as predicted by assumptions on elastic and inelastic properties of these masses are reasonable.

CASE I.

Consider an auto traveling along striking a smooth rigid wall as indicated in Fig. 14. The impact causes a change in direction and final velocity of the car, but because of the assumed smoothness of the wall the component of the velocity along the wall is unaffected. This is the case for no frictional forces.



Momentum Equations:

$$E V_1 \sin\theta = V_2 \sin\delta \ ,$$
$$V_1 \cos\theta = V_2 \cos\delta \ .$$

Energy Loss:

$$E_L = \frac{M}{2}(V_1^2 - V_2^2) \ .$$

Fig. 14. Impact of a mass point on a rigid wall.

The angle at which the auto is traveling after impact with respect to the smooth wall is

$$|\delta| = \tan^{-1}(E \tan\theta) \ . \qquad \text{D(1)}$$

The total angular change is this $|\delta| + |\theta|$. Note that for $E = 1$, elastic impact $|\delta| = |\theta|$, and that for $E = 0$, inelastic impact $|\delta| = 0$, and the car slides along the wall with velocity = $V_1 \cos\theta$ (or, in the limiting case $\theta = 90°$ comes to rest.)

$$\text{Energy Loss} = \frac{MV_1^2}{2}(1 - E^2)\sin^2\theta \ ; \qquad \text{D(2)}$$

$$\text{Momentum change} = MV_1 (1 + E)\sin\theta \ . \qquad \text{D(3)}$$

Velocity Change perpendicular to wall:

$$\Delta V_x = V_1 (1 + E)\sin\theta \ ; \qquad \text{D(4)}$$

Velocity Change parallel to wall:

$$\Delta V_y = 0 \ ; \qquad \text{D(5)}$$

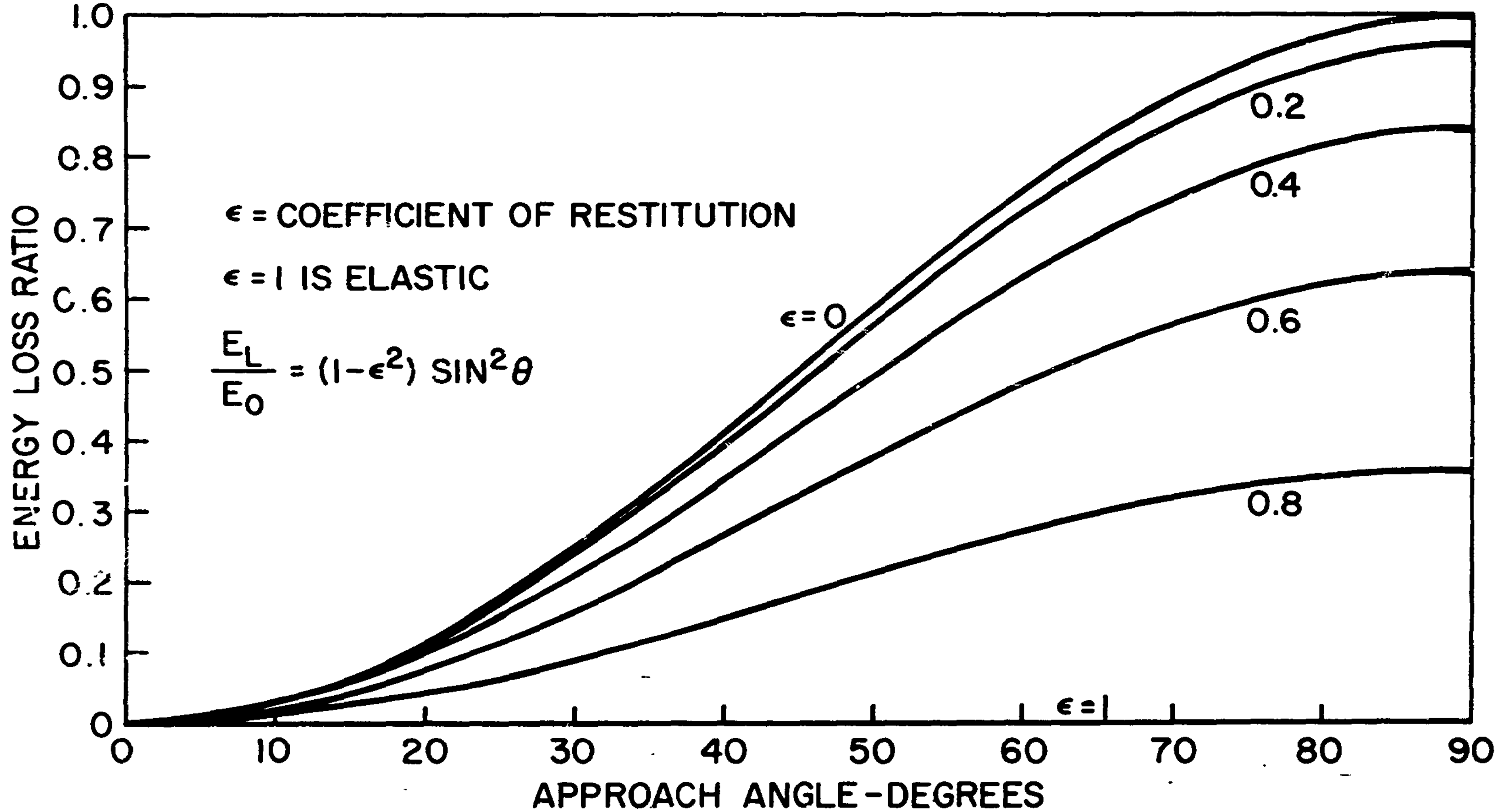


Fig. 15 - Ratio of Energy Lost to Initial Kinetic Energy

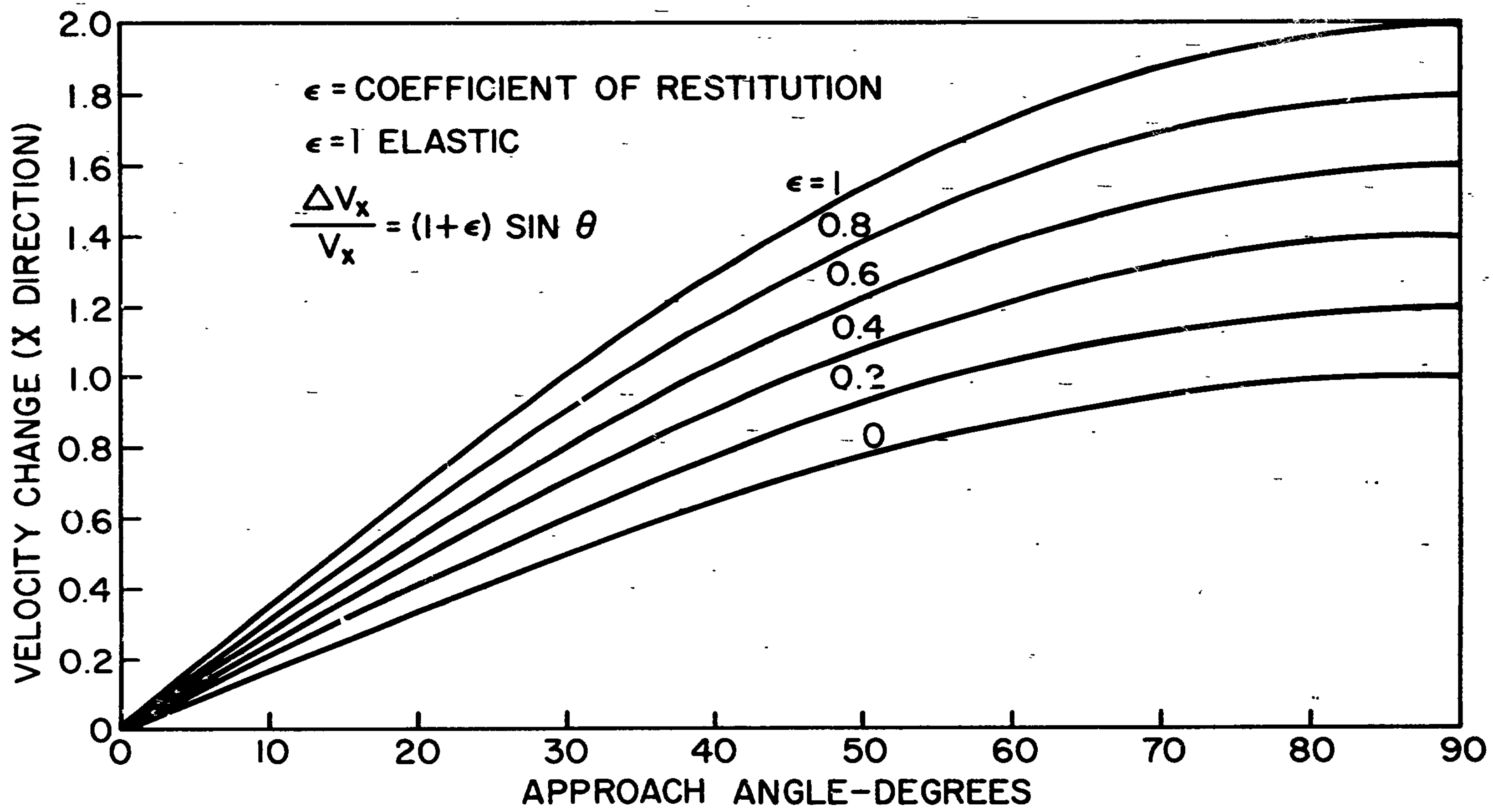


Fig. 16 - Impact with smooth rigid wall: velocity change

Figure 15 is a plot of the Ratio of the Energy Absorbed in the Impact to the Total Energy Available for Various E's.

Figure 16 is the change in lateral velocity of the car. This is the response that would tend to cause loose interior objects to slide. Note that a totally elastic collision causes this component to have its largest possible value.

A special case of interest is the head on crash, $\theta = 90°$. Then the equations reduce to

$$|\delta| = \tan^{-1} \theta, = 90° \text{ or } 180° , \qquad \text{D(1a)}$$

$$E_L = \frac{MV_1^2}{2} [1 - E^2] , \qquad \text{D(2a)}$$

$$\Delta V_x = V(1 + E) . \qquad \text{D(4a)}$$

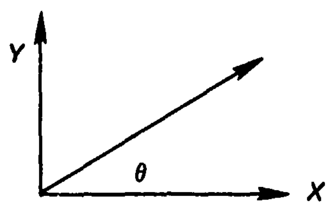
The energy loss is a parabolic function of E approaching 0 as E approaches 1. The velocity change in the direction of the impulse is a linearly increasing function of E as the car becomes more elastic.

Since this is akin to the problem of a car bumper head on to a rigid wall, note that for a perfectly elastic bumper the velocity change is twice the original velocity. A 10 MPH impact would cause the passengers to undergo a 20 MPH velocity change if they were rigidly attached to the car. In a plastic impact they would undergo 10 MPH. The car is then damaged.

CASE II.

A. Mechanics

Assume two automobiles are moving in a plane with parameters;



M_1 = Mass Vehicle 1,

V_1 = Speed Vehicle 1,

θ = Direction of Motion.

Fig. 17. Coordinates for vehicle 1 in two-car system

Therefore, components of velocity are $V_x = V_1 \cos \theta$, $V_y = V_1 \sin \theta$, where $0 \leqslant \theta \leqslant 180°$;

and

M_2 = Mass Vehicle 2

V_2 = Velocity Vehicle 2 to the right only;

then

$$\theta_2 = 0.$$

$$V_F = \text{final speed at } \sphericalangle \Phi .$$

Now assume the 2 masses collide plastically, i.e., they move off together as one body of mass $M_1 + M_2$. Then:

$$V_{FX} = \frac{M_1 V_1 \cos\theta + M_2 V_2}{M_1 + M_2} , \tag{D(6)}$$

$$V_{FY} = \frac{M_1 V_1 \sin\theta}{M_1 + M_2} , \tag{D(7)}$$

and, the final direction of motion is

$$\Phi = \tan^{-1} \frac{\sin\theta}{\cos\theta + \dfrac{M_2 V_2}{M_1 V_1}} . \tag{D(8)}$$

The final Velocity becomes

$$V_F^2 = \frac{M_1^2 V_1^2 + M_2^2 V_2^2 + 2 M_1 M_2 V_1 V_2 \cos\theta}{[M_1 + M_2]^2} . \tag{D(9)}$$

The Energy Absorbed during the collision is

$$\Delta E = \frac{M_1 M_2}{2[M_1 + M_2]} (V_1^2 + V_2^2 - 2 V_1 V_2 \cos\theta) . \tag{D(10)}$$

The Internal Impulse required to effect the change,

$$|I| = \frac{M_1 M_2}{M_1 + M_2} \sqrt{V_1^2 + V_2^2 - 2 V_1 V_2 \cos\theta} . \tag{D(11)}$$

The Angle of the impulse is

$$\beta = \tan^{-1} \frac{V_1 \sin\theta}{V_1 \cos\theta - V_2} . \tag{D(12)}$$

The velocity change cars 1 & 2 in the direction of the impulse is:

$$\overline{\Delta V_1} = \frac{M_2}{M_2 + M_1} \sqrt{V_1^2 + V_2^2 - 2 V_1 V_2 \cos\theta} , \tag{D(13)}$$

and

$$\overline{\Delta V_2} = \frac{M_1}{M_2 + M_1} \sqrt{V_1^2 + V_2^2 - 2V_1V_2 \cos\theta} \ . \qquad \text{D(14)}$$

The change in kinetic of energy each vehicle $\{1/2\, M_K[\vec{V}_K^2 - V_f^2]\}$ is; $k = 1, 2$;

$$\Delta E_{1f} = \frac{1}{2}M_1\overline{\Delta V}_1^2 = \frac{1}{2}\frac{M_1M_2^2}{[M_1 + M_2]^2}(V_1^2 + V_2^2 - 2V_1V_2\cos\theta) \ , \qquad \text{D(15)}$$

and

$$\Delta E_{2f} = \frac{1}{2}M_2\overline{\Delta V}_2^2 = \frac{1}{2}\frac{M_2M_1{}^2}{[M_1 + M_2]^2}(V_1^2 + V_2^2 - 2V_1V_2\cos\theta) \ . \qquad \text{D(16)}$$

Note that

$$\Delta E_{1f} + \Delta E_{2f} = \Delta E, \text{ or } \frac{\Delta E_{1f}}{\Delta E} + \frac{\Delta E_{2f}}{\Delta E} = 1 \ .$$

B. <u>Interpretation of Equations:</u>

1. Dividing Eq. 13 by 14, and 15 by 16 yields the interesting result

$$\frac{\overline{\Delta V_1}}{\overline{\Delta V_2}} = \frac{\Delta E_{1f}}{\Delta E_{2f}} = \frac{M_2}{M_1} \ .$$

Therefore both the ratios of velocity changes and kinetic energy changes are directly proportional to the ratio of the opposing vehicle to your vehicle. In the case of say a collision between a sports car $W_1 = 1500$ lbs, and a large passenger car $W_2 = 4500$ lbs

$$\Delta V_1 = 3\overline{\Delta V_2} \ ,$$

and

$$\Delta E_{1f} = 3\overline{\Delta V}_{2f} \ .$$

2. The Head on Crash

The head on crash is the most spectacular and has the capability of causing the greatest velocity changes and energy losses. Under these conditions $\theta = 180°$ and the important parameters become:

$$V_F = \frac{M_2V_2 - M_1V_1}{M_2 + M_1} \ , \text{ (final velocity)}$$

$$\Delta E_{1f} = \frac{1}{2} \frac{M_1 M_2^2 [V_1 + V_2]^2}{[M_1 + M_2]^2} ,$$

$$\Delta E_{2f} = \frac{M_1}{M_2} \Delta E_{1f} ,$$

$$\Delta E = \frac{1}{2} \frac{M_1 M_2}{M_1 + M_2} [V_1 + V_2]^2 ,$$

$$|\Delta V_1| = \frac{M_2}{M_1} |\Delta V_2| = \frac{M_2}{M_1 + M_2} (V_1 + V_2) .$$

If $M_1 V_1 = M_2 V_2$ then the collision for each auto has the same effect as if they individually ran directly into a solid barrier. Under these conditions

$$V_1 = \frac{M_2}{M_1} V_2 , \qquad \text{and} \qquad \frac{\Delta E \ @ \ \theta = 180^\circ}{E \text{ Total}} = 1 .$$

For $M_2 V_2 > M_1 V_1$ both vehicles move off to the right (positive direction).

Although the energy lost is not the total energy involved the velocity change for M_1 is

$$\frac{\Delta V_1}{V_1} = \frac{1 + K \frac{M_1}{M_2}}{1 + \frac{M_1}{M_2}} ,$$

where K is the ratio of

$$\frac{M_2 V_2}{M_1 V_1} > 1 .$$

If V_1 should happen to be zero the above equation must be modified to that of the equivalent "rear end" type crash and the new V_1 becomes

$$V_F = \frac{M_2 V_2}{M_1 + M_2} .$$

For M_2,

$$\Delta V_2 = \frac{V_2}{1 + \frac{M_2}{M_1}} .$$

If the struck mass (M_1) is small ΔV_2 is small, etc.

Fig. 18 is the plot of the Energy Absorbed Ratio for Various Head on Crashes.

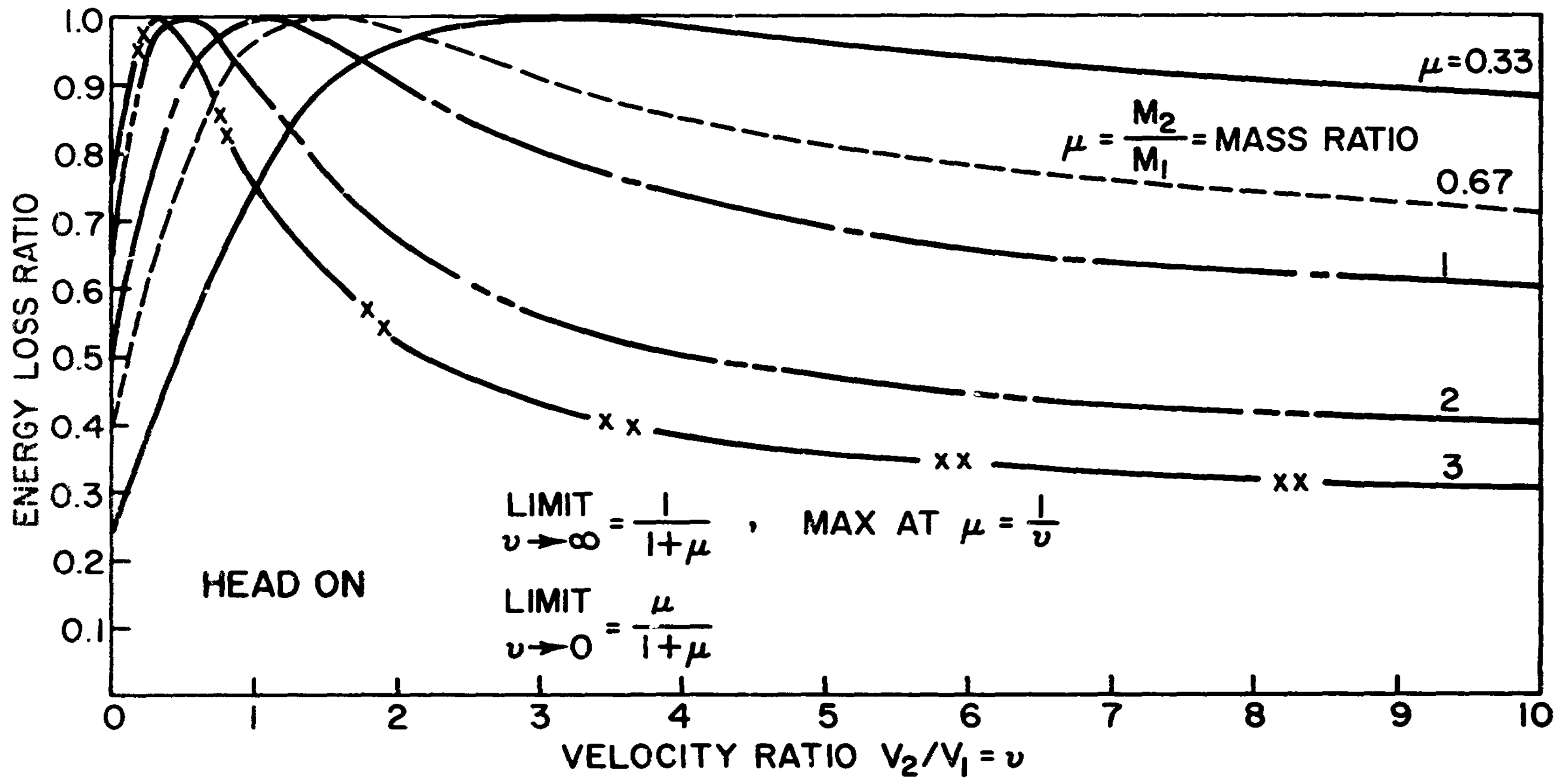


Fig. 18 - Energy Absorbed in Crash Divided by Total Energy Available

3. The General Case:

Let

$$\frac{M_2}{M_1} = \mu , \qquad \text{and} \qquad \frac{V_2}{V_1} = \upsilon .$$

Then the Ratio of Energy loss to energy lost in a head on crash is:

$$\frac{\Delta E_\theta}{\Delta E_\pi} = \frac{1 + \upsilon^2 - 2\upsilon \cos\theta}{[1 + \upsilon]^2} . \qquad \text{D(17)}$$

Now since

$$\lim_{\upsilon \to 0} \frac{\Delta E_\theta}{\Delta E_\pi} = 1 , \qquad \text{and} \qquad \lim_{\upsilon \to \infty} \frac{\Delta E_\theta}{\Delta E_\pi} = 1 ,$$

and $(\Delta E\pi/2)/\Delta E\pi < 1$, there must exist a minimum,

The minimum of Eq. D(17) with respect to ν is independent of θ and occurs at $\nu = 1$, so that

$$\left.\frac{\Delta E_\theta}{\Delta E_\pi}\right|_{\nu=1} = \frac{1 - \cos\theta}{2} .$$

Figure 19 is a plot of several ratios for:

θ = 135° is head on oblique crash
θ = 90° is side on crash
θ = 45° is rear end oblique crash
θ = 0° is rear end crash, versus several velocity ratios.

Note Figure 19 is independent of the masses involved.

Other Angles

Figures 20 thru 23 inc. show the energy lost ratio versus velocity ratio for several mass ratios as a function of the impact angle.

Figure 24 represents the Kinetic energy changes for a Head-On Oblique Crash at $\mu = 3$.

(GJO'H)

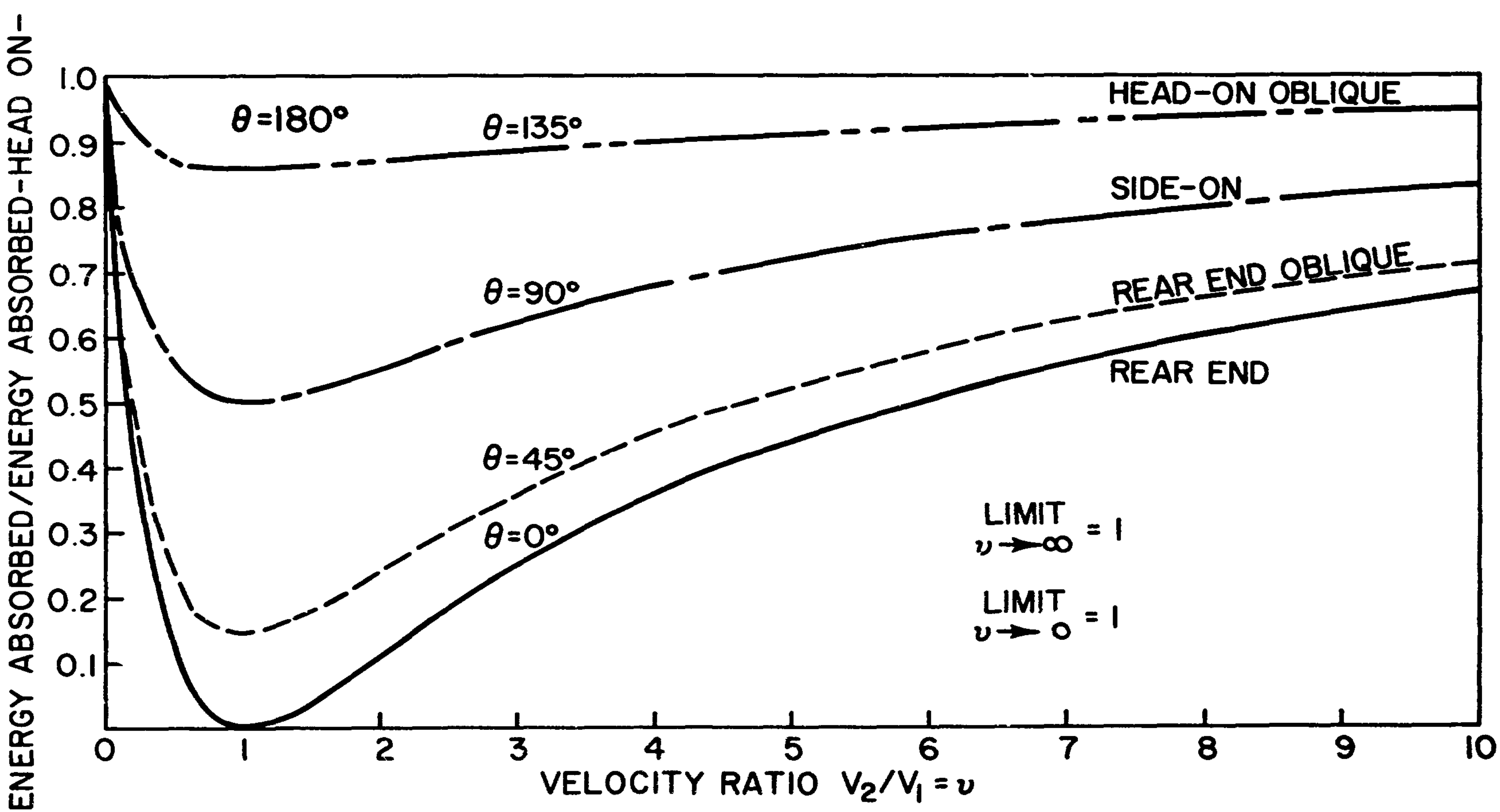


Fig. 19 - Ratio of energy absorbed at several angles versus head-on collision in two vehicle impact

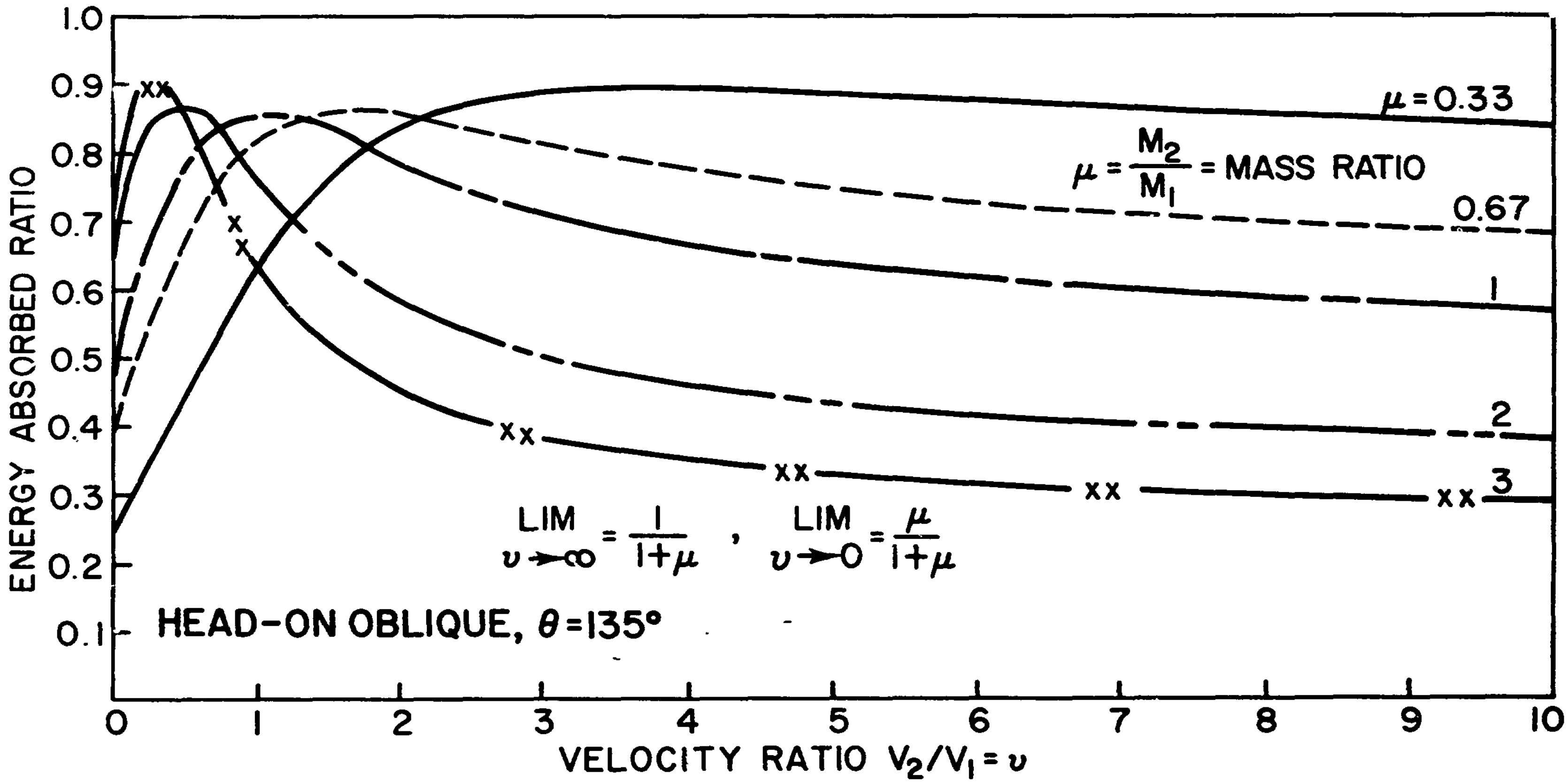


Fig. 20 - Energy Absorbed to Total Energy Available
Two Vehicle Impact

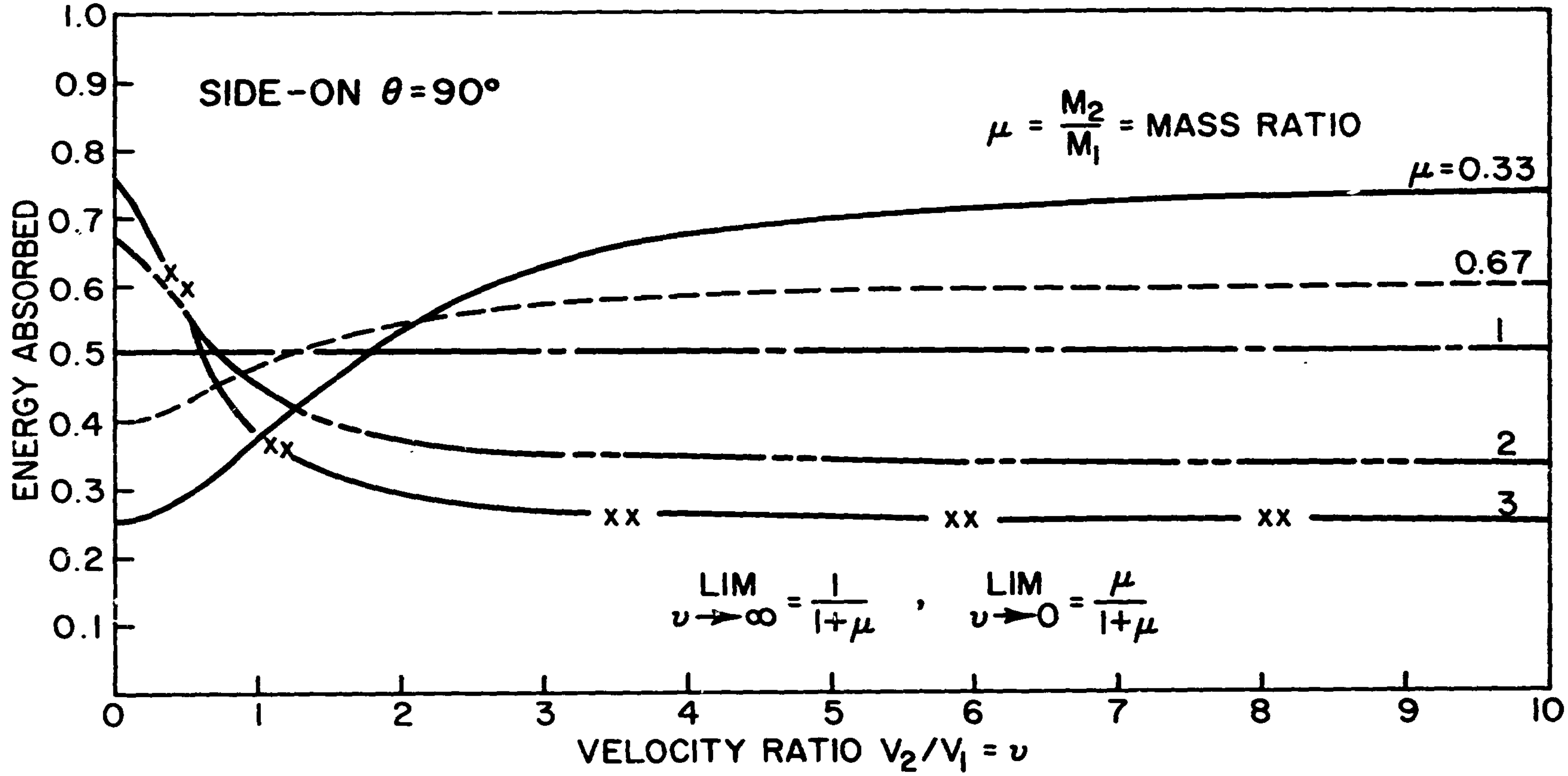


Fig. 21 - Energy absorbed to total energy available in two vehicle impact

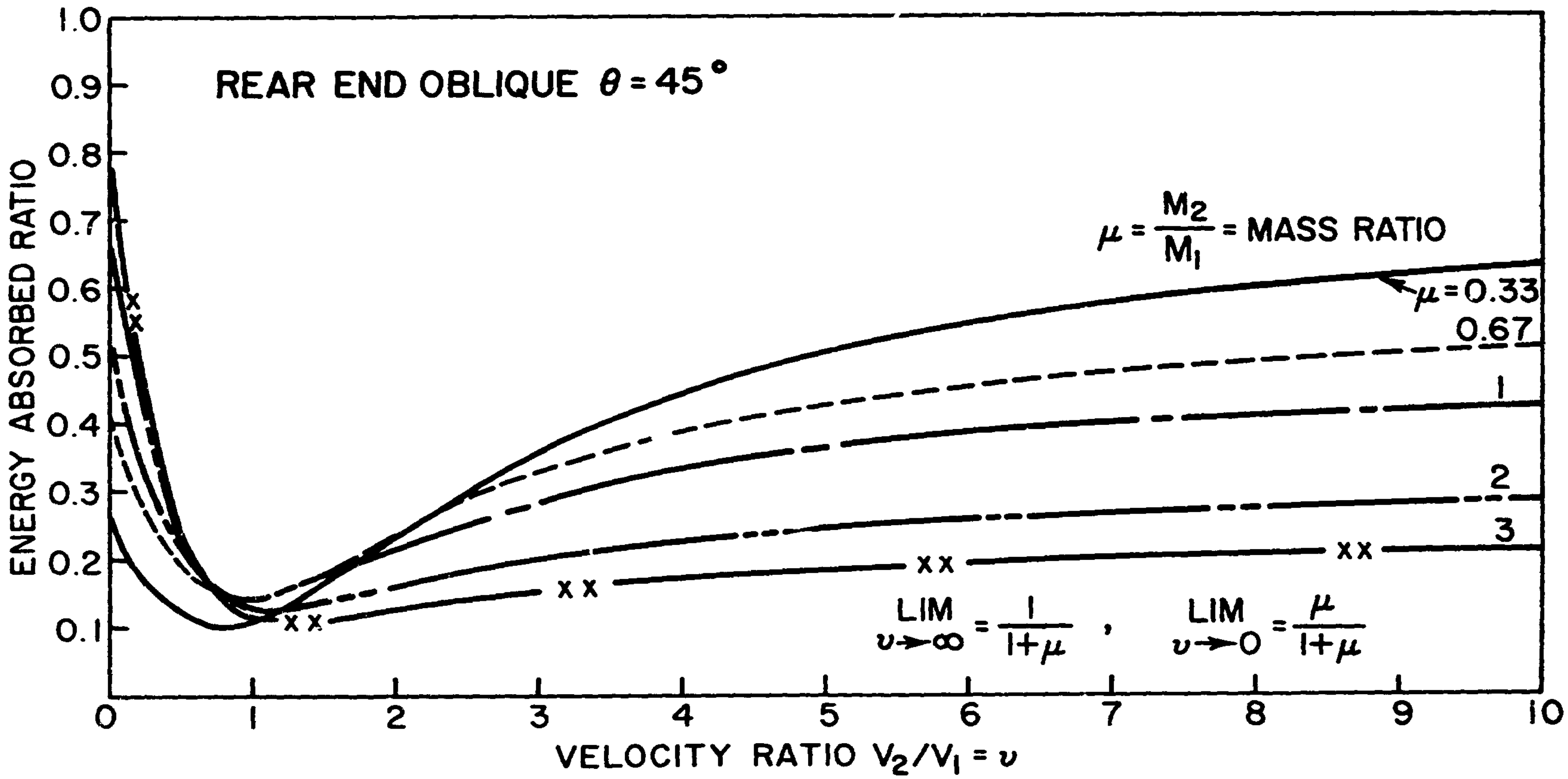


Fig. 22 - Energy Absorbed to Total Energy Available

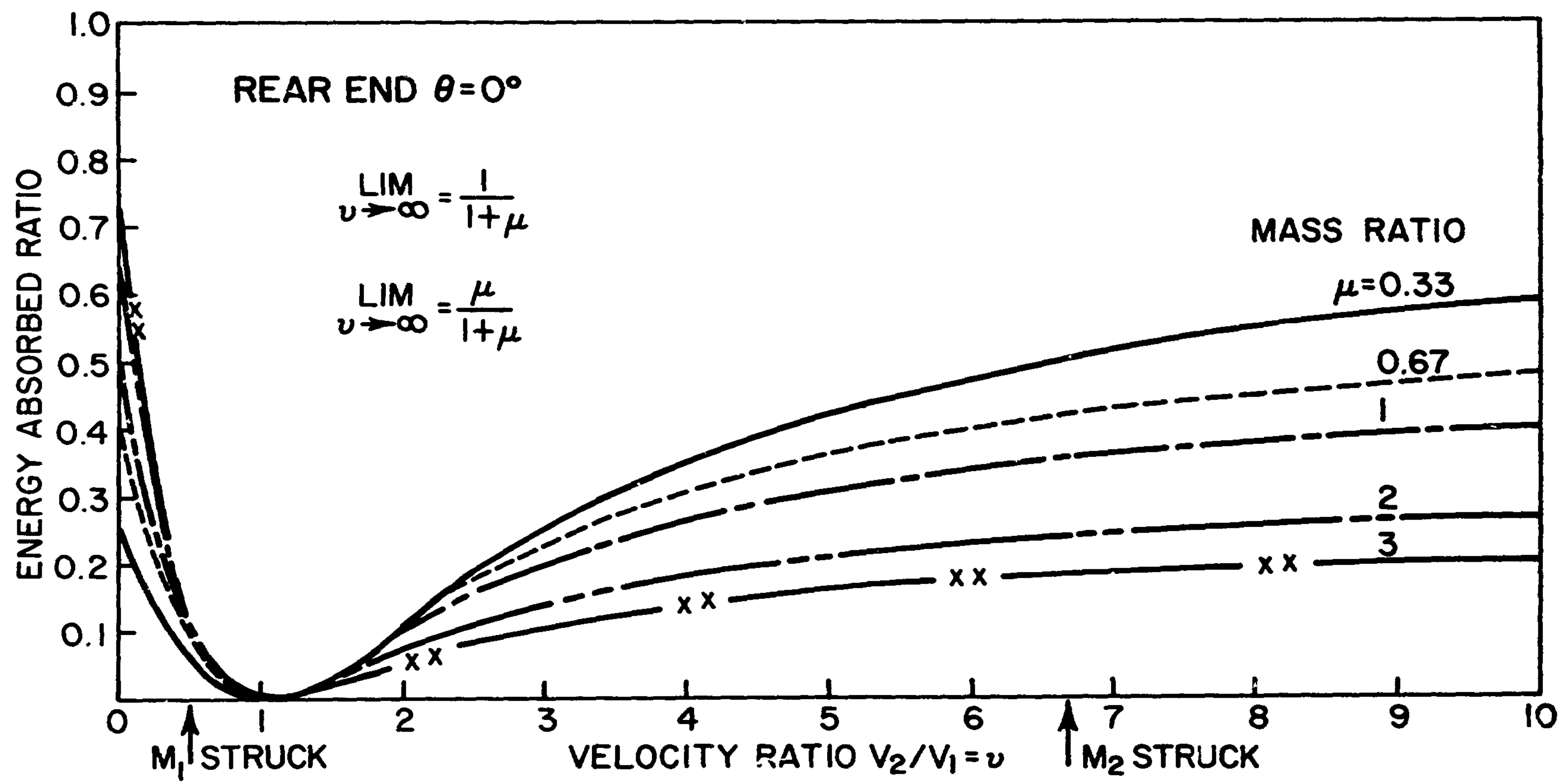


Fig. 23 - Energy Absorbed/Total Energy Available

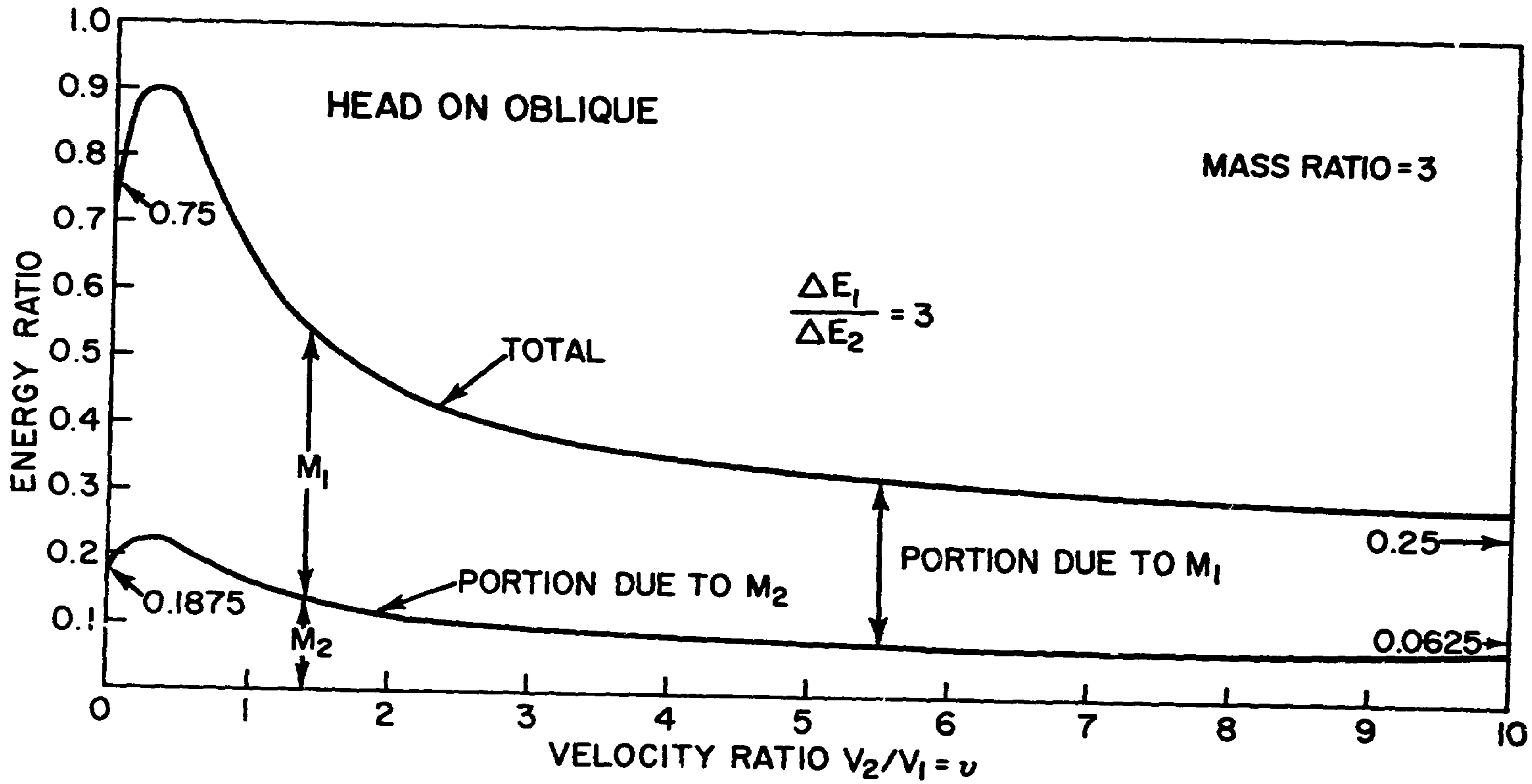


Fig. 24 - Change of kinetic energy of each mass

E. Matching of Bumpers

1. Deflection and Energy Absorption Properties

Requirements on desired elastic and energy absorbing characteristics of bumpers and the corresponding axial bumper deflections are discussed elsewhere in this report particularly in Sections III - C and IV. It is taken for granted in this connection that such bumpers will protrude sufficiently in front of vital and non-vital car structures to minimize damage while at the same time providing safety, according to the concept of graduated damage. These considerations need not be discussed in further detail in the present section.

2. Height Considerations

It is axiomatic that bumpers can perform both their safety and damage control functions only if their height on different kinds of vehicles is standardized. If at all possible, even trucks and semi-trailers should be equipped with bumper devices at this standard height. Moreover, to insure as much as possible the safety of an occupant of a vehicle being struck on the side, it is necessary that the other car's bumper should impact a relatively rigid component of the car being struck, which in this case must be its frame. Therefore the frame along the side of the automobile should also be at the standard bumper height. Needless to say, the bumpers should be required to extend along the entire front and rear dimension of an automobile, in addition to wrapping as far as practical around the four corners. These requirements are somewhat at variance with present practice where bumpers have to such a large extent acquired the status of ornamental rather than useful devices, that some sport-type automobile makes have discontinued their use entirely particularly in the central portions of the car.

3. Shape Considerations

In the horizontal direction bumpers should be gently convex to interface properly with other bumpers over a range of potential impact angles as well as to minimize the chance of needless injury to pedestrians. We can think of no valid reason for having V-shaped or knife-edged protrusions, or even the old style bumper guards which tend to break off when lateral force is applied. In a vertical cross section, bumpers must first of all possess sufficient vertical dimension to insure that they will still meet, even if in a rear-front collision the front end of the rear vehicle dips because of last minute maximum application of the brakes in an attempt to avoid the collision. In addition to having sufficient vertical dimension, the vertical section of the bumpers should properly interface without a tendency to override or underride. Most present day bumpers have a vertical cross section which is round at the top and then slopes backward and downward, perhaps mostly because of style considerations. A serious effect of the present shape is to tend to make this bumper ride over another car's bumper, especially if its sloping parts can meet the round portion of the impacted one. Clearly the best all around protection can be provided if the vertical cross section of bumpers were designed to minimize the possibility of override and underride, even under brake-dip conditions. This objective might be accomplished best by having the vertical cross section essentially flat at the interface, although the possible advantages of large horizontal ridges to assist in locking two impinging bumpers in a vertical direction might be worthy of consideration. Actually even such a refinement would provide an advantage only if the bumpers are not sufficiently high to do the required job without them.

4. Bumper Related Considerations

It has been correctly stated that providing safety enhancing and damage limiting bumper systems consists of more than attaching a different strip of metal onto the front and back of the car. If bumpers are built somewhat higher in order to mitigate against brake dip, then they must also be appropriately supported so that they can resist the moment generated by forces applied away from their vertical center. Their supporting and energy absorbing structures, discussed elsewhere in this report, must also be designed so as to appropriately transmit impact forces back to the frame of the vehicle. Moreover, there will be other parts of the car which must be designed to conform with such bumper systems. For example, if a present-day automobile were subjected to the impact forces of which well-designed bumper systems might be capable without exterior damage to the car, it is quite possible that such other components as engine mounts might fail as presently designed. Such other components must therefore also be appropriately strengthened to prevent damage.

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IV. REVIEW OF PROPOSED APPROACHES

A. Department of Transportation Experimental Safety Vehicle Program

The National Highway Safety Administration of the Department of Transportation has awarded four contracts for the development of prototype Experimental Safety Vehicles (ESV). By the end of 1971, contractors are to deliver one prototype and a backup vehicle to NHSA. The prototypes will be tested against each other, and the winning company will be awarded a contract for twelve additional vehicles for further testing. Effectively, the competition is between Fairchild Hiller's Republic Aviation Division (contract $4.5 M) and AMF, Inc. ($3.2 M). The other contractors, General Motors Corporation and Ford Motor Company, each submitted bids of one dollar, but do not expect to have prototypes available until mid-1972 or later. It is reported that Volkswagen is also developing an experimental vehicle to meet NHSA specifications. In addition, Chrysler Corporation is a major subcontractor to Fairchild Hiller. The Fairchild Hiller proposed design is essentially that of the Safety Sedan developed for the New York State Department of Motor Vehicles in 1967, while AMF is working with a group of companies including the Cornell Aeronautical Laboratory, which has conducted considerable research into vehicle crash performance.

Among the specifications set for the ESV by NHSA are requirements that under conditions of 50 m/h frontal barrier crash, 30 m/h side impact, or 70 m/h rollover without collision, the passenger compartment shall suffer no loss of integrity sufficient to allow any part of an occupant to protrude from it, and moreover a properly restrained occupant shall sustain relatively minor injuries. No damage to the ESV body is to result from 10 m/h frontal barrier collision, and the ESV is to have dimensions typical of conventional 5-passenger sedans with a weight no more than 4200 lb. It is hoped that the last restrictions would hold the cost of the production vehicle to something comparable to today's larger sedans.

B. Implementation of Possible Mechanisms, Frontal Collisions.

To illustrate how the considerations of the foregoing sections could be incorporated into a vehicle design meeting NHSA requirements, let us divide the basic vehicle structure into three substructures: a bumper mechanism intended primarily to protect the vehicle's structure from the effects of low speed collisions, an energy-absorbing mechanism to provide controlled deceleration of the passenger compartment in higher speed collisions, and the passenger compartment itself. It should be noted that these substructures may be divisions of function more than physically separable pieces of hardware.

(i) The bumper function may be served by an elastic element. It is reasonable to infer that if passenger protection is adequate for a 50 m/h impact it is adequate for a 10 m/h elastic impact. Some consideration should be given to ameliorating the effects of the collision on the object struck, which may be a pedestrian. This would indicate that the bumper mechanism should produce relatively low forces if possible. This can be done by a thick elastomer coating over the bumper (as Fairchild Hiller, which also incorporates deformable material) or by a velocity-sensitive mechanism which produces low forces at low impact speeds. Both AMF and Fairchild Hiller employ hydraulic bumpers described as velocity-sensitive. Low impact forces and some energy absorption would also be desirable from the standpoint of passenger comfort.

(ii) The bumper function tends to blend naturally into the energy-absorption function. The use of long-stroke bumper mechanisms allows the introduction of devices which can dissipate large amounts of energy with little or no permanent deformation. The velocity-sensitive hydraulic springs of AMF and Fairchild Hiller dissipate energy through their dash-pot action and have a stroke of about a foot before contact is made with the front of the body. (The Fairchild Hiller bumper is deployed automatically from its retracted position at a speed of 37 m/h, while the AMF is extended at all times.) A shorter stroke bumper using hydraulic dissipative springs has been proposed by Taylor Devices, Inc. The springs would be similar to those used as pulse-shaping elements in large drop-test machines. They handle high loads and dissipate considerable energy. Other devices which can dissipate very great amounts of energy without damage are volute springs, ring springs, and parallel-stacked Belleville springs. These share with hydraulic springs the disadvantage of requiring guides if lateral thrust is present and tend to be relatively stiff, particularly the last two. In addition to these some elastomers (such as polyurethanes) have a fairly long relaxation time, and are good energy absorbers at high loading rates. The harder mixes of polyurethane support heavy loads in addition, although they gradually deteriorate with use. Advantages of elastomers are that a large volume could be used (the entire width of the vehicle, for example) and that their action is essentially omnidirectional.

Next in order of inconvenience are controlled slip devices such as interference tubes. A set of these consists of a tube which fits within another with some amount of interference. They are simple, produce a constant force for a long stroke, can dissipate a great deal of energy, and when once collapsed can be restored by jacking. They are, unfortunately, susceptible to damage from lateral loads.

Another method of energy control utilizes one-shot elements which must be replaced after use. This class includes a gamut ranging from slotted tubes forced over oversized pegs and square pegs forced into round holes to frangible tubes (progressively shattered by being forced end on against an everting die) and reversing tubes (thin tubes fastened by a lip at one end and turned inside out by pressing on the other). Highly ductile elastic-plastic materials like solder can be formed into elements which flow under impact. Energy is absorbed both by plastic deformation and by accelerating the material outward. All of these can absorb large amounts of energy and can be replaced fairly easily.

When mechanisms of this intermediate type have been exhausted by the collision process the next energy absorber called into play is the structure of the vehicle itself. This is the method which present automobiles utilize exclusively, and can be very effective. It can be made more so by the introduction of special frame members such as Z-bars to provide plastic hinges at selected locations (Cornell Aeronautical Lab. experimental vehicles), designing the frame with an area which serves as a hinge point and ultimate structural separation point (Fairchild Hiller), and by installing the engine somewhere other than the front (Cornell Aeronautical Lab), which increases the crush distance.

(iii) The development of a structural separation point during the energy-absorption process (as exemplified by the Fairchild Hiller design) serves the purpose of getting the engine out of the way. This supplies greater crush distance and reduces the risk of having the engine penetrate the passenger compartment. Equally effective methods are the compression strut, which maintains a minimum separation between the engine and passenger compartment, and the sliding ramp, which allows the passenger compartment to ride up so that the engine passes below it. Both methods have been demonstrated experimentally by the Cornell Aeronautical Lab. The passenger compartment should be an independent capsule. Accident statistics indicate that many injuries result from intrusion of outside objects into the passenger compartment and from occupants either being thrown completely out or having parts of their bodies protrude. A properly constructed passenger compartment would resist the deformation which permits intrusion of external objects, and the springing open of doors and loss of glazing which permit passenger expulsion. The Fairchild Hiller design achieves this by a semi-monocoque structure in which the frame is built up by adding formed sections to the basic body shell. The AMF approach is to build a strong, heavy, tubular frame and build the body shell around it with deformable panels; this construction is similar in principle to that resulting from the extensive structural modifications made on the Cornell Aeronautical Lab experimental vehicles. Internally, both designs feature a strong bulkhead at the B pillars (center post in a 4-door sedan) to which the front seats are attached. Both also provide lateral passenger restraint by deformable structures on the inside surfaces of the doors and between occupants.

(iv) In summary, a collision would involve these protective mechanisms in stages. Impacts up to 10 m/h would be handled by the elastic bumper mechanism with a travel of some 3 in. The elastic element could be a fairly large volume of elastomer distributed to provide protection from lateral as well as direct load components. Impacts up to 20 m/h would call into play self-resetting energy dissipation devices, such as hydraulic springs or lossy elastomers, which would be the dominant mechanisms for the next 9 in. of displacement. At this point the sheet metal of the front of the car would be contacted and start to deform. The front body structure should consist of easily replaceable modules for cheap repair. The dominant protection mechanism for the next foot and speeds to 30 m/h would be replaceable energy absorbers--frangible tubes or interference tubes combined with metallic elements which flow plastically, and which can be arranged to absorb energy from lateral load components. Damage to the automobile would consist mainly of crumpling sheet metal modules. For speeds above 30 m/h the major energy absorber must include the structure of the automobile itself. Appropriate engine compartment layout may be expected to allow the next two feet of deformation to result in controlled crushing of the structure, controlled in the sense that the structure includes plastic hinge members, etc., which encourage it to deform in the most advantageous way. The protection capability to this point would be around 50 m/h. Further structural deformation must include removing the engine from a position to interfere with the passenger compartment. A combination of sliding wedges and plastic hinge formation could move the engine down and back while the passenger compartment rises to clear it. A great deal of energy can be consumed in this process, and protection is probably adequate to speeds of 65 m/h. This sequence is illustrated below. (Fig. 25). Rear engine placement would provide good crush distance in the front, and eliminate the need to dispose of the engine in a frontal collision, although at the expense of rear crush capability. Since rear end collisions are less frequent than front end, this may be an acceptable alternative.

Some of these elements can be combined. For example, the hydraulic bumper employed by the Fairchild Hiller design protrudes about a foot in front of the car and is expected to provide full protection up to 50 m/h impact. It thus provides the function of the first three elements described above as well as part of the fourth.

Distance inches	Absorption Mechanism
0 to 3	elastic
3 to 12	self-resetting absorber
12 to 24	renewable absorber
24 to 48	structural crush
48 —	engine removal

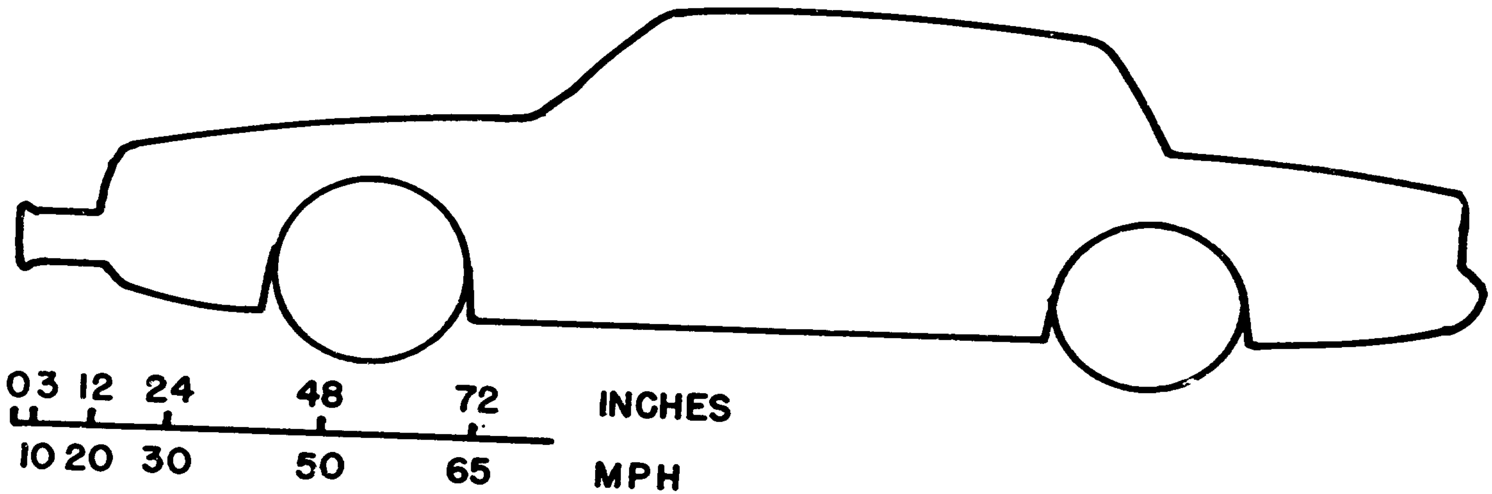

Fig. 25 - Outline of the effective regimes of various protective mechanism. The scale shows the distances at which the successive mechanisms become dominant in the disposal of the collision energy, and the approximate corresponding impact speeds. The table describes the dominant mechanism operating in each displacement zone.

C. Implementation of Protection Concepts for Other Types of Collision.

The above methods can provide excellent protection from front and rear collisions. Rollover is not a problem if the passenger compartment is designed as described above, since strong top members or roll-bars are necessary if the passenger compartment is to resist deformation adequately. In addition, both Fairchild Hiller and AMF designs incorporate rounding of the sides into the roof to discourage plastic deformation at the corner and possible roof collapse. Side impacts remain a problem, as very little crushing distance is available and the lateral effectiveness of some present and proposed occupant restraint devices is poor. The only measures available are to strengthen the passenger compartment against deformation, install thick doors incorporating energy absorbing material, and provide energy absorbing cushioning within the passenger compartment. When this is done, as illustrated by both Fairchild Hiller and AMF designers, the protection provided against side impacts is probably adequate for survivability, if by no means as good as that available against frontal and rear impacts.

D. Occupant Restraint

The essential component of any attempt at passenger protection is an adequate restraint system. It is probably feasible to protect vehicle occupants against serious injury in any possible collision at any speed if they are properly restrained. It is probably impossible to prevent serious injury in very minor mishaps if they are not. An adequate restraint system would be one which provides a degree of restraint equivalent to that derived from the combination of lap-belt and X- or H-harness (chest-strap and double shoulder-strap). The effectiveness of this particular harness arrangement is testified to by the occupation of stock-car racing. The structural modifications to these vehicles consists largely of installing an adequate roll-bar structure, yet crashes at extremely high speeds are demonstrated to be eminently survivable when lap-belt and H-harness restraints are used. It would appear that the options available are to enforce the use of such restraint harnesses or to develop passive restraint systems of equal effectiveness.

(EWC)

V. STANDARDS AND TESTS

A. Standards and Tests Presently Proposed

At the present time, two major new safety standards are in an advanced proposal and implementation stage. One of these, Occupant Crash Protection, will make obsolete almost all existing safety standards by requiring passenger survivability without serious injury in almost all accident situations up to 30 mph. The other proposed standard, Exterior Protection, is intended "to prevent low-speed collisions from impairing the safe operation of vehicle systems, and to reduce the frequency of override or underride in higher speed collisions."

In this section, we review and critically examine these two proposed standards.

Occupant crash protection. This standard will eventually require complete passive protection for all passengers in all collision situations (up to 30 mph with a fixed barrier) and rollover occurences. By passive is meant that no active passenger participation (such as buckling a seat belt) is required. As most recently proposed, the provisions of the standard will become applicable to front seat occupants in all but rear end collisions by 1 July 1974. Target dates for other occupants and rear end collisions have not yet been set. Compliance with the standard is to be shown by a variety of barrier collision tests with anthropoid dummies as passengers.

Needless to say, this proposed standard is the subject of much controversy. Manufacturers claim that with all encompassing passive protection is beyond the state-of-the-art and/or extremely costly. The only device actually mentioned in the standard is the air bag which (besides being the subject of much controversy itself) does not provide rollover or lateral impact protection. In fact, even in the most advanced safety cars (see Part IV), passive protection for rollover and lateral impact situations is not provided. The approaches to these collision situations all require active participation of the passengers by requiring that they strap themselves in with belts and harnesses. We believe that a preferable alternative to passive protection systems would be an active restraint system, so arranged that its deployment is requisite to operating the vehicle. Possible systems such as this are further described in Section B. below.

Exterior protection. This standard will require cars to withstand certain low speed impacts at the front and rear without damage to their lighting, fuel, exhaust, etc., systems. After 1 September 1972, each car must demonstrate this impact resistance by a forward barrier test at 5 mph and a rearward barrier test at 2.5 mph. In addition to this test, after 1 September 1973, each vehicle must demonstrate its resistance through a series of impacts by a pendulum-type test device.

The front-face of the pendulum has essentially the configuration of an automobile bumper. The frontal impact tests are to be at 5 mph and the rear impacts at 4 mph. The effective mass of the pendulum is to be equal to the mass of the tested vehicle.

In essence, the requirements of this standard, besides insuring prevention of low-speed damage to vehicle safety systems, will lead to a uniformity of automotive bumpers.

We would like to see added to this standard a requirement which we think would greatly enhance its effectiveness. Namely, all of the tests specified in the standard require the pendulum to strike the vehicle at the bottom of its swing. We would like to see added to the standard a series of tests whereby the pendulum test is to be applied at the full range of heights to which a vehicle might dip prior to impact as a result of hard application of the brakes.

B. Standards and Tests Considered Feasible

In addition to the comments and recommendations made in the preceding two sections on proposed automotive safety standards, we would like to take the opportunity in this final section to propose a viable alternative to passive occupant crash protection.

In light of the fact that the seat belt, torso harness combination greatly reduces the occurrence of both minor and major injuries and fatalities, we propose that the operation of a passenger car be contingent upon all passengers having this combination fastened and in place. We would like to see a standard written such that:

1. All passenger positions are provided with a seat belt, harness combination.

2. The ignition of the car is directly dependent upon all occupied passenger positions having the restraint combination properly fastened.

3. The restraint buckle is automatically locked during normal operation so that occupants cannot remove the combination after ignition.

4. A collision activated release is provided which automatically unlocks the restraint buckle following stoppage of motion after a collision.

In addition to the above standard, a second standard designed to prevent the severity of collisions should also be written. This standard would require that:

1. The front bumpers of all vehicles interface properly (do not override or underride) with the bumpers in front and back, and with the frames on the side, of all other vehicles.

2. That the front bumper have the capability of absorbing a 30 mph collision before contacting the automobile itself.

(RAS)

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Kroell, C. K., "A Simple, Efficient, One Shot Energy Absorber", Bulletin No. 30, Shock, Vibration and Associated Environments, Part III, pages 331 to 338, February 1962. (Experimental data are reported for turning thin-walled tubes inside out. One end of the pipe is turned back and connected to a lip. Pressing on the other end shoves the pipe through and around until it is all turned inside-out. Tests on tubes of 3003 aluminum showed 3-inch pipe produced constant force 200 pounds to 4000 pounds for wall thicknesses from 0.01 inch to 0.07 inch. A friction fit through the lip can increase energy absorption by 100 percent. Dynamic tests to 70 feet per second (only 15 percent increase in force) and tests of steel pipes are also reported.)

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McGehee, John R., "A Preliminary Experimental Investigation of an Energy-Absorption Process Employing Frangible Metal Tubing," Hampton, Virginia; National Aeronautics and Space Administration, Langley Research Center, NASA TN D-1477; NSRDC Library: NASA. TN D-1477, October 1962. (A die with a blunt point is pushed into the open end of a tube. It flares out the tube walls and breaks them into small fragments. Results of about 100 rests on tubes of 2024-T3 aluminum alloy, diameters 0.25 inch to 2 inches, wall thicknesses 0.020 to 0.065 inch, are reported for deflection rates 1 inch per minute to 13,000 inches per minute (12 miles per hour). Die was lubricated with oil and molybdenum disulphide. Forces 230 pounds to 7200 pounds for steady deformation but were about four times these values to initiate action in a new piece of tubing with a square end. Force increased 60 percent for the high-speed tests. If stress is limited by yield strength of the aluminum and buckling of the tube, the system can absorb 31,000 foot-pounds of energy per pound of tubing (die not included in weight). Tests were also made by dropping 1120 pounds at 13 feet per second onto a shock absorber made of four frangible tubes, with good results (deceleration of weight was nearly constant at about the design value of 6 g).

Mead, George E., "Fact Sheet, The AMF Experimental Safety Vehicle (ESV)", New York 10016. AMF Incorporated, May 3, 1971. (Five-page handout summarizes features of the ESV being developed by AMF Incorporated. Includes a velocity-sensitive hydraulic bumper.)

Miller, Patrick M., and Richard P. Mayor, "Basic Research in Automobile Crashworthiness - Summary Report", Buffalo, New York 14221. Cornell Aeronautical Laboratory Inc., Final Technical Report CAL number YB-2684-V-8 under Contract FH-11-6918, November 1969. (Summary report of 19 full-scale crash tests conducted with American Cars, some modified for greater crash resistance. Found that relatively minor design changes would allow front ends to crush 2 feet to produce average deceleration 30 g on collision with either a wall or a post. This distance of crush corresponds to a head-on collision at 40 mph and the deceleration is within limits which people can survive. Some cars demonstrated ability to withstand such collisions. Other changes aimed at reaching capability to withstand a 20-mph collision from the side were not as successful because sufficient crush space was not available. Changes to allow 4 feet of crush space from the front at 30 g, and thus allow head-on collisions at 60 mph, are described and some were tested but not at full speed.

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Perrone, Nicholas, "Crashworthiness and Biomechanics of Vehicle Impact", New York, N.Y. The American Society of Mechanical Engineers reprint, 1970 (not dated). (This is a short and simple summary in which Dr. Perrone gives simple and understandable answers for complicated problems. This is the best-organized discussion of automobile crashes which has shown up yet. There are 47 references.

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Peterson, Ralph R., "A Method for Producing a 400G Square Wave 4 Millisecond Shock on a 3-inch Hyge Shock Machine", Institute of Environmental Sciences, 1963 Proceedings, pages 337 to 340, April 1963. (The hyge machine is used only to accelerate a carriage weighing 47 pounds to a velocity of 59 feet per second. The energy in the carriage is then used to drive a square peg into a round hole. Peg is a 5/8-inch square piece of tool steel. Hole is 0.710 inch in diameter in either 2024-T3 aluminum or brass. Impact drives the peg 1.4 inches into the hole at a constant force of 2800 pounds. Force is nearly independent of velocity of impact. A very simple and trouble-free system for absorbing impact energy.)

Platus, David L., "Cyclic Deformation Crew Attenuator Struts for the Apollo Command Module", The Shock and Vibration Bulletin, Bulletin 38, Part 3, pages 255-262, November 1968. (A 2-inch pipe fits into a 3-inch pipe to form a strut 3 feet long. A set of loose rings is between the pipes and on each loose ring is a set of small rings which roll between the pipe walls. Pipes are 6Al-4V titanium and rings are maraging steel. The rolling rings are too large for the space and deform into ellipses as they roll. One strut weighs 1[illegible] pounds complete, produces constant force 9[illegible]00 pounds as pipes slide for total stroke of 1[illegible] inches. Can be recycled a limited number of times before the inner rings begin to break (total stroke 11.[illegible] inches claimed). I figure 7[illegible] foot-pounds per pound of strut.)

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Shuman, A.B., "The Safety Cars Are Coming The Safety Cars Are Coming," Motor Trend Magazine pages 32 to 36, May, 1971. (Author reports on his test drive of an early model of the AMF Experimental Safety Vehicle and discusses the program. He feels that a strong program to eliminate drunken drivers, curb suicidal drivers, and improve the handling qualities of American automobiles would give more benefits than the safety-car program. Article includes a summary of the requirements for a safety car as given in the government contracts.)

Stech, Ernest L., "Introduction to Human Body Dynamics", The Journal of Environmental Sciences, Volume 7, Number 5, pages 36 to 40, August 1964. (Introductory article with emphasis on the danger of crushing or breaking vertebrae from accelerations applied to seated persons.)

Thornton, E. A., and R. R. Higginbotham, "Preliminary Evaluation of 5M10,000-H Sound Isolation Mounts Under Shock Loading", Portsmouth, Virginia. David Taylor Model Basin, Underwater Explosions Research Division F-1-64, January 1964. (Dynamic load-deflection curves obtained for rubber mounts supporting a turbine on a floating shock platform during shock tests at 12 feet per second show that the force supplied by the mounts was largest at the beginning of the motion (240,000 pounds per mount when velocity was high and deflection 0.3 inch) and that it decreased as the deflection increased to its maximum of 0.75 inch. The indicated dynamic characteristic of the rubber composition used in the mounts (high forces occurring promptly when struck by high velocities) may be useful for automobile bumpers.)

APPENDIX A - THE AUTOMOBILE AS A COMPONENT OF A TRANSPORTATION SYSTEM

I. INTRODUCTION

The automobile as we know it today, along with our systems of roads and other support facilities, is the product of some hundred years of evolution. During this time the automobile has undergone a rather significant population explosion which, perhaps even more than the design of the vehicles themselves, has created some problems which were at best dimly anticipated. Because of the numbers involved it is no longer possible to design, sell, and use an automobile without giving the strongest consideration to its place in its environment, both automotive and otherwise.

In recognition of this situation there is developing an increasing demand for additional safety in high speed collisions and for minimization of damage and correspondingly lower repair bills which result from relatively low speed collisions. Our report, The Mechanics of Automobile Collisions, is an attempt to put these demands in perspective and to evaluate, from the point of view of Applied Mechanics, the available methods of dealing with the safety and repairability problems. Government and Industry have already begun to respond to these new demands on the automobile, as demonstrated by new safety standards and the development of experimental safety vehicles. It is likely that the actions taken by the Government and the Industry in the next few years will have a profound influence on how the evolution of the automobile continues. It is clearly important that the decisions to be made in the near future should not be taken lightly. Even from the point of view of safety and damage mitigation, as pointed out in our main report, cars could be built much more to interact properly with each other for the benefit of all concerned. The need for such changes as standard bumper heights and shapes would seem almost too obvious to require mention. Again, the safety of the occupant of a vehicle struck on the side by another vehicle's front could be greatly enhanced by appropriate energy absorption devices on the front of all vehicles, especially because space on the side of cars for such devices is extremely limited.

However, this Appendix is written mainly because the author believes that rational future development of our automotive transportation system requires asking some broader questions than only the mechanical ones, and coming to grips with such other problems as air pollution and traffic congestion. And in parallel with air pollution we face the prospect of a significant shortage of energy resources including petroleum products. These problems may in the foreseeable future require a decrease in automobile horsepower and weight, and perhaps the replacement of the internal combustion engine as the backbone of our automotive system over a period of the next ten years or so. In this context it is significant that both of the major safety sedan programs are developing safety cars in the full size, or approximately 4,000 lb range. While such a vehicle will, without question, provide added safety for a motorist traveling at high speed, it cannot make any significant contribution to solving the problems of pollution, energy depletion, and traffic. Similarly, the current controversy concerning the possible use of air bags might well be viewed in the context that we shall, sooner or later, be forced to cut back on speed and horsepower in automobiles.

II. SOME SUGGESTIONS

Long range, I believe it is important that we begin developing our public transportation systems to a point that they become useable on a large scale. Since we also wish to retain the convenience of individual transportation, we should begin placing a really meaningful effort on the development of an engine to replace the inherently inefficient and polluting internal combustion engine.

Shorter range, we could solve a large part of the energy and pollution problems and no doubt help the traffic problem to some extent by discouraging the manufacture and use of large, powerful vehicles, and instead encourage widespread use of smaller cars. Such encouragement could take the form of a significant tax on the operation of vehicles having excess horsepower or weight. As an example, such a tax might take the form of $1.00 per year for each horsepower in excess of, say, 90 hp. Perhaps tax credits to encourage ride sharing and other means of reducing wasteful or unnecessary automobile mileage might be feasible.

III. INDIVIDUAL VEHICLE OR COMPONENT OF A SYSTEM?

We Americans take pride in our individuality. We also appreciate good salesmanship, and the desirability of power and speed is more or less taken for granted. All these attributes find a meeting place in the typical automobile sales room, where the vehicle is presented as an individual thing of beauty. There can be no doubt of its considerable appeal for its style, speed and power while rotating on a custom made platform to permit an unfettered view. In its sales brochures, the car is depicted more often standing on a lawn than on a road, and if indeed it is on a road, it is there by itself. Safety is seldom discussed. Indeed, many prospective buyers might feel less than complimented if it were even suggested that they are potential participants in an accident. The vehicle sold in a new car sales room is the true individual vehicle. No salesman in his right mind would accuse it of being a component of a transportation system. Indeed, the word "Transportation" is reserved by the salesman of used cars for his most hopeless pieces of junk.

Perforce, the individual car must join the system the day it is put into use. On that day its individually insignificant contribution to air pollution is added to that of millions of others like it. Its individually insignificant addition to traffic congestion is added to the already existing total, and it takes its proper place in using up scarce resources. Should the buyer be so unfortunate as to have an accident on his first day of ownership, he might find out quickly that the bumper designed to be appropriate for an individual vehicle is likely to ride either over or under that of his co-participant in the accident, causing considerable grief and expense to both. Bumpers tend to be designed to be stylish more than useful. They are often not at the same height for different vehicles, especially when prior to impact, one vehicle pitches because of brake action used in an attempt to avoid this collision. Apart from the height-matching problem of bumpers, including the problem of pitching, the bumper shapes can hardly be said to be optimized for damage prevention. Most modern bumpers are round near the top and slant back at about 45^{o} toward the bottom. This not only looks nice but also assists the individual car in climbing over the bumper of the opponent so that if damage should occur it preferably be done to the other fellow. Some bumpers presently have V-shaped protrusions which are not only lethal to pedestrians and damaging to other vehicles, but also induce unnecessary stress concentrations in the own-car. Some cars have no bumpers at all near the car center. If the individual car were asked to join the system while still in the factory one might expect that bumper shapes would be designed in such a way as to minimize the possibilities of override and underride, to preclude ornamental protrusions, and to wrap around the complete front and back of the vehicle.

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The prospective purchaser of an individual car does have one important choice to make. Should he be a good citizen and minimize pollution and energy consumption and buy a small vehicle, or must he take into account the millions of big other individual cars which might clobber him if he goes small. There can be little doubt that in the event of a collision of a 5000 lb car with a 2000 lb car, the chance for surviving the accident could be significantly greater in the larger car. The prospective purchaser's decision can be a lethal one either for himself or for someone else. This problem would not exist to any major extent if all cars on the road were small cars. At the same time, it will not be easy to find our way from our present mixed system of large cars and small cars to an all small-car system. There would be a substantial intervening period of necessary coexistence during which safety can be assured only by rigidly enforced traffic regulations, including especially those dealing with the use of alcohol and reasonable speed limits. But we must also come to grips with the question of where we want to or need to be in the more distant future, and to begin now going in the right direction. Since we are presently contemplating major changes in the system such as exemplified by the safety car programs and the prospect of introducing air bags as safety measures, it behooves us to carefully take into account the needs of the longer range future transportation system. In that context a strong case can be made for doing all that we can to increase safety and repairability, while at the same time cutting back on unnecessary and wasteful size, speed, and horsepower, and putting significant resources into the eventual replacement of the internal combustion engine with an inherently less polluting power plant.

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13. ABSTRACT

The damage and injury from automobile accidents is treated as a mechanical problem in mitigating the shock from collisions. General principles of energy and momentum are described and applied to the collision problem. Present work in the field of automobile safety during collisions is surveyed and possible mechanisms for dealing with excess kinetic energy during a collision are reviewed. It is recommended that passenger compartments be strong and rigid, that passengers be strapped into their seats at all times, that front bumpers of automobiles be required to interface properly with fronts, sides, and backs of all other vehicles on the road, and that front bumpers be required to absorb energy on a graduated-damage system.

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