AUTOMOBILE-ATTENUATOR COMPATIBILITY IN 1985: SOME DESIGNER GUIDELINES

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Extensive analysis of automobile accident data from the designer's point of view reveals, among other things, the importance of fixed-object collisions in automobile societal losses. Moreover, the analysis has yielded information about the distributions of speed and injury in such crashes. As a result, the fixed-object collision situation can be described rather completely in terms of societal cost and can be extrapolated by assumption to the situation to be expected 10 years hence when smaller cars in greater numbers will be using our highway system. When combined with results of recent subcompact car crashworthiness efforts, the analysis makes possible a rough engineering characterization of the optimal crash attenuator for the occupants of tomorrow's family car.

•AS PART of the U.S. Department of Transportation contract to develop a crashworthy car based on the Ford Pinto, Minicars, Inc., has produced an extensive analysis of the accident picture that combines mass accident data and detailed information from multidisciplinary accident investigations (MDAI) in a way that simultaneously allows broad economic projections and discovery of detailed design information (2, 3, 4, 5, 6, 7, 8). Tables 1 and 2 give the results. That they include a sizable indictment of the fixed-object problem is not too surprising. Collisions with fixed objects wider than 16 in. (41 cm) accounted for 8,500 fatalities and 179,000 disabling injuries during 1971. Although this loss includes some impacts with large trees, it is mostly due to interference with obstructions that are amenable to treatment by removal or attenuation. Narrow [< 16-in.-wide (<41-cm)] fixed-object impacts undoubtedly include many trees, utility poles, and signposts. Although they account for a sizable annual societal loss (7,000 lives, 197,000 injuries), in general they would not be best treated by installation of highway crash attenuator devices (HCAD) but rather by removal or relocation of the objects in question.

In economic terms proposed by U.S. DOT (8), the total societal loss, due to wide fixed-object collisions, amounted to more than $7.2 billion in 1971 (2). It is this loss that deserves the attention of crash-attenuator designers.

The available accident data can give us a more complete picture of the design challenge. Figure 1 shows an approximate distribution of societal costs in fixed-object collisions by clock position of principal force and by obstacle width. Note that the frontal (11, 12, 1 o'clock) modes predominate but that the side-collision modes are also important. Figure 2 shows the distribution of frontal and side-mode fixed-object crash casualties with impact speed; in Figure 3, these casualties are shown cumulatively. The average cost per injury as a function of impact speed, the societal costs as a function of speed, and the total societal cost versus impact speed for classes of fixed-object collisions are shown in Figures 4, 5, and 6 respectively. Although the data show considerable scatter in some categories because of small samples, they suggest trends of injury distributions.

Table 3 gives apportionment of injuries (and fatalities) and estimated costs by object struck, as reported in the 4-year Pennsylvania study and in the MDAI file (5, 9). Although there is some indication that guardrail and ditch accidents are underrated and that sign accidents are overrated in the MDAI file, the bridge abutment or pier data and pole and tree data correspond reasonably well, and the sources agree on one point that

Table 1. Vehicles, occupants, injuries, and fatalities by accident mode.

			Vehicle Accidents		
Accident Mode	Vehicles	Vehicle Occupants	Injuries (1)	Fatalities	Total
All accidents (2)	29,300,000	42,400,000	2,000,000	44,100	2,044,100
Fixed-object	2,210,000	3,310,000	389,000	16,200	405,200
Frontal	1,610,000	2,410,000	303,000	10,100	313,100
Narrow (3)	350,000	520,000	168,000	3,600	171,600
Wide (4)	1,260,000	1,890,000	135,000	6,500	141,500
Side	520,000	780,000	73,000	5,400	78,400
Narrow	160,000	240,000	29,000	3,400	32,400
Wide	360,000	540,000	44,000	2,000	46,000
Rear	80,000	120,000	13,000	700	13,700
Primary rollover (5)	310,000	460,000	75,000	3,800	78,800
Vehicle-to-vehicle	26,780,000	40,170,000	1,536,000	24,100	1,560,100
Frontal	13,050,000	19,570,000	841,000	11,500	852,500
Head-on	2,020,000	3,030,000	249,000	7,300	256,300
Front-to-side	5,520,000	8,280,000	379,000	2,600	381,600
Front-to-rear	5,510,000	8,260,000	213,000	1,600	214,600
Side	7,570,000	11,350,000	430,000	10,500	440,500
Side-to-front	4,910,000	7,360,000	372,000	10,000	382,000
Sideswipe	2,660,000	3,990,000	58,000	500	58,500
Rear	6,160,000	9,240,000	265,000	2,100	267,100

Table 2. Distribution of casualties and societal cost by crash mode.

Crash Mode	Casualties	Societal Cost[a]	Crash Mode	Casualties	Societal Cost[a]
Narrow frontal fixed-object	171,600	3.4	Vehicle-to-vehicle front-to-side	381,600	2.1
Narrow side fixed-object	32,400	2.0	Vehicle-to-vehicle front-to-rear	214,600	2.7
Wide frontal fixed-object	141,500	4.6	Vehicle-to-vehicle side-to-front	382,000	5.7
Wide side fixed-object	46,000	2.7	Sideswipe	58,500	0.3
Rear fixed-object	13,700	0.1	Vehicle-to-vehicle rear	267,100	1.5
Primary rollover	78,800	3.0	Total	2,044,100	34.2
Vehicle-to-vehicle head-on	256,300	6.1			

[a] In billions of dollars.

Figure 1. Societal cost by clock position of principal force.

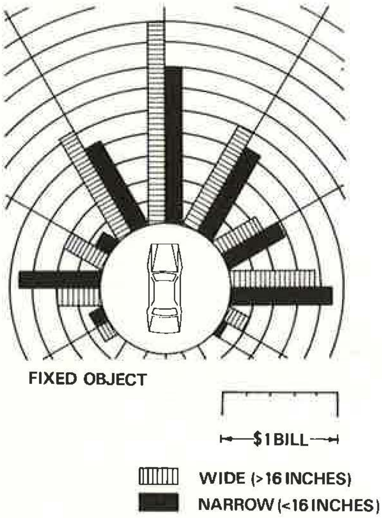


Figure 2. Distribution of casualties by velocity range.

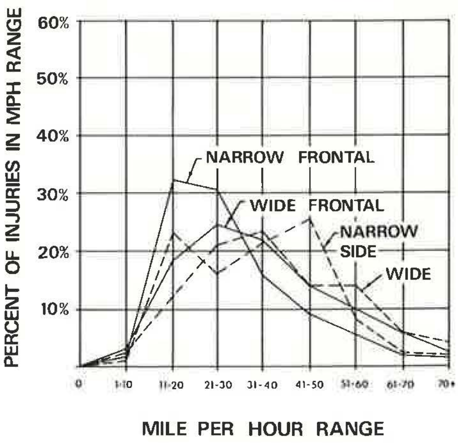


Figure 3. Cumulative distribution of collisions in fixed-object injuries.

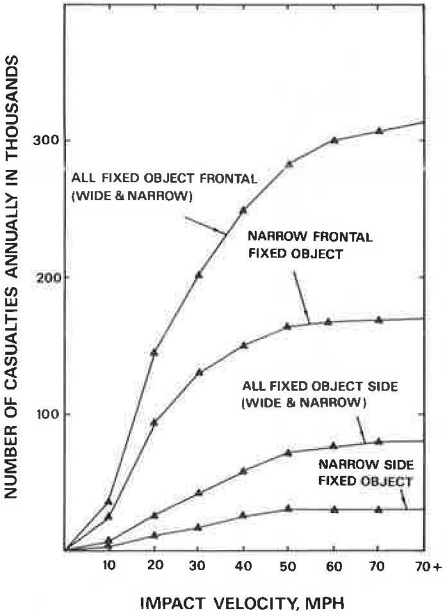


Figure 4. Frontal fixed-object average cost per injury.

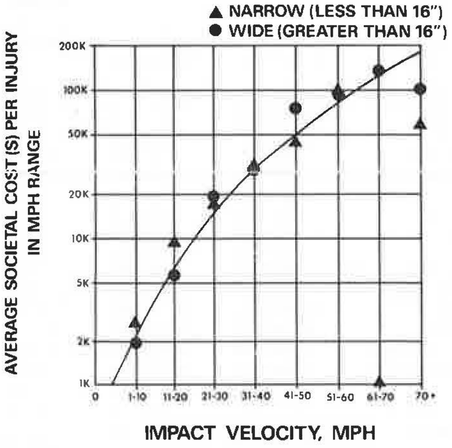


Figure 5. Cumulative societal cost of injuries in fixed collisions.

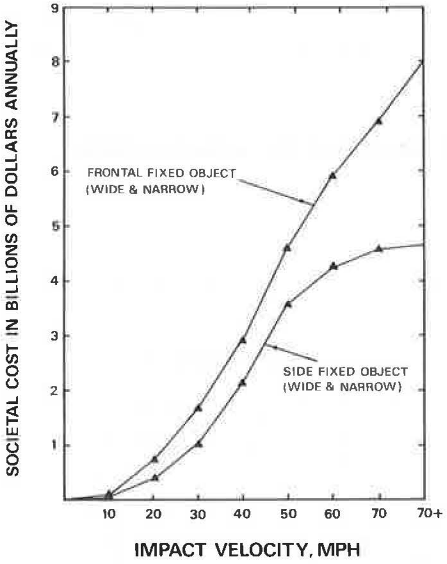
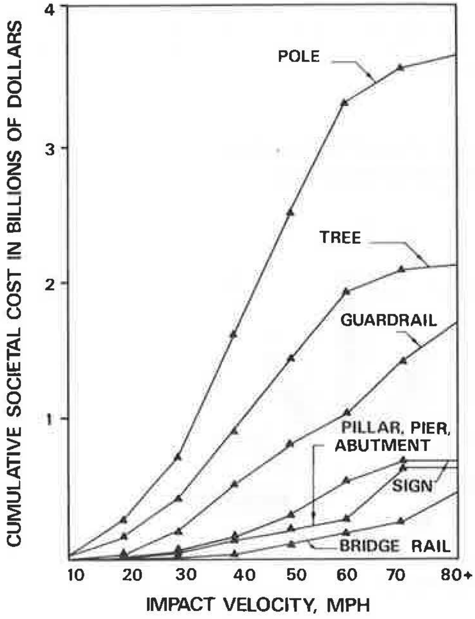


Figure 6. Societal cost as function of impact-speed, fixed-object crashes.



poles and trees are causing more than five times the losses caused by bridge structures and signs, the traditional sites for HCADs.

Figure 6 shows the task of the attenuator designer in the current accident picture, assuming widespread deployment of HCADs. It also shows that attenuator installations, in the traditional application, can only be a partial solution, unless each tree, pole, and sign is to be equipped. This is not to say that attenuator systems are ineffective; rather that abutments, piers, and pillars constitute only a modest part of the overall fixed-object problem.

Other factors must be considered before the HCAD program can be optimized. More important than any technical consideration in the current frame of reference is implementation. With fewer than 5,000 HCADs installed since 1967, there is much more to be done. In 1971, a total of 187,000 injuries were caused by wide fixed-object impacts, and for each object struck in a given year, there are probably several other fixed objects being narrowly missed. Attenuator implementation has so far reached less than 5 percent of the hazards. If implementation is to continue with priority given to those hazards having fatality experience, the designer should choose a high-speed system. If, on the other hand, an optimum benefit-cost ratio is sought, more hazards should be protected with lower speed attenuator designs; this means trading some losses in high-speed crashes for broader gains in obstacles protected. Although economic limitations may preclude installation of more than 30,000 attenuators of current design, development of ultracheap devices may expand candidate sites to as many as 1 million.

Other factors must be considered that are related to the vehicle system likely to be in use when attenuators now in design stages can finally be implemented (1). Events that have transpired during the past year suggest a high probability that widespread restraint use is likely to become a reality by 1980 (10, 11) and that vehicles having built-in frontal crashworthiness of >40-mph (>64-km/h) barrier equivalent velocity (BEV) will likely be available on showroom floors shortly thereafter (10, 12). These potentialities must be considered in a proper attenuator design. Widespread restraint use by itself can allow the reduction of attenuator size and cost by 50 percent or more since allowable vehicle forces can be doubled without increased probability of serious injury (13). Improvements in vehicle crashworthiness will further the trend toward greater numbers of smaller, cheaper attenuators and may preclude altogether the need for installations at some sites. A notable achievement in this vein is that of a modified subcompact structure and restraint system capable of >40-mph (>64-km/h) BEV frontal and improved side, rollover, and pedestrian crashworthiness, all at the expense of less than 100 lb (45 kg) of additional weight and $200 per car additional cost in a Pinto-sized vehicle (14).

SOME PROJECTIONS: THE 1985 ATTENUATOR CUSTOMER

Recent projections for 1985 suggested a total population of 150 million vehicles, 40 percent subcompacts, and improved crashworthiness for all passenger cars (1). The recent energy situation has significantly hastened the trend to small cars. By the end of 1973, 38.5 percent of all registered U.S. automobiles weighed less than 3,400 lb (1524 kg). The 1971-1973 U.S. new-car sales in the under 2,800-lb (1270-kg) class were estimated to be 25.6 percent (15). Today, with the benefit of some other opinions, more reasonable projections for the year 1985 are as follows (15, 16):

1. There will be 140 million vehicles, of which 125 million will be passenger cars;
2. Accidents will increase 25 percent over present levels;
3. Subcompact and smaller cars [<2,200 lb (<998 kg)] will represent 60 percent of new cars sold and 50 percent of all passenger miles (kilometers) accumulated; and
4. Improved construction in terms of restraints (passive and active use) and structures will bring the average car to a crashworthiness level exceeding proposed 1976 requirements [e.g., 30-mph (48-km/h) BEV frontal crashworthiness].

New standard, intermediate, and compact cars [>3,000 lb (>1361 kg)] marketed in

1985 will likely reflect some structural changes to achieve not only fixed-object impact survival but also compatibility in car-to-car crashes with likely collision partners, many of which will be less massive. Subcompacts and smaller cars [<2,000 lb (<907 kg)] on the other hand will require significant [but technically and economically feasible (14)] restructuring, in both the occupant compartment and the chassis frame.

The effect of these vehicular changes is estimated in Figure 7 for frontal crash casualties. If proposed U.S. DOT crashworthiness standards are implemented, over 30 percent of fatalities and well over half of nonfatal injuries could be avoided without any change to the highway environment.

FUTURE VEHICLE CHARACTERISTICS

One must use the best possible prediction of future vehicle performance as a basis for HCAD design. One such design specification was developed to meet a vehicle crush force of about 80,000 lbf (356 000 N) (1). It now appears, based on analysis of the accident casualty loss studies referred to above, that slightly lower vehicle crush forces can be tolerated. This is based primarily on the fact that offset, angular collisions among vehicles make up most of accident losses and that frontal structures that optimize flat barrier crash performance are probably less cost effective than those that optimize car-to-car performance. As a result of a car-to-car compatibility study, a modified subcompact car has been constructed that is theoretically safe and that has an advanced airbag restraint at the closing speeds in car-to-car collisions as shown in Figure 8 (17). This result suggests that present standard-sized [3,500 to 4,000-lb (1588 to 1914-kg)] cars have about the right frontal crash characteristics as they are and require relatively minor structural adjustments to smooth out peaks and valleys of crush force to give an average frontal structure force of about 80,000 lbf (356 000 N). It also suggests that the subcompact car frontal crash pulse will not exceed 85,000 lbf (378 100 N) in a barrier crash. Hence, attenuators should be designed to have a crush force not to exceed, say, 75,000 lbf (334 000 N) and could very well yield the same general pulseform as the standard-car frontal structure.

PHYSICAL CHARACTERISTICS OF 1985 ATTENUATORS

The built-in crashworthiness of the average 1985 passenger car suggests two physical characteristics for attenuators of that vintage. First, the total energy absorption capacity can be less since vehicles will be designed to absorb their own 30 to 40-mph (48 to 64-km/h) crash energy unaided. Second, the force levels can be higher since vehicle structure will probably be sized for over 75,000-lbf (334 000-N) average crush force. Both of these effects work to the advantage of attenuator implementation. The 1985 attenuators can be shorter and much less expensive.

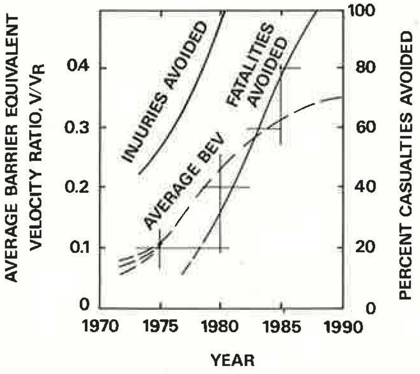
Figure 9 shows the theoretical stroke requirement for 75-kip (333 600-N) attenuators compatible with the projected 1985 passenger vehicle population. Note that an attenuator stroke of 8 ft (2.4 m) will provide adequate distance for a safe frontal crash stop of any 1980+ passenger car from a speed as high as 70 mph (113 km/h) and would safely stop a 30-mph (48-km/h) BEV crashworthy truck [6,000 lb (2722 kg)] from a speed of more than 60 mph (97 km/h). Assuming a stroke efficiency of 80 percent (typical of current HCADs), the total length can be less than 10 ft (3 m). Problems of site preparation and attenuator sophistication requirements would be greatly reduced because attenuator buckling tendencies would be eliminated. It is likely that the 1985 attenuator can be much smaller, much cheaper, and much more broadly implemented than is possible with the present designs, primarily because of improvements in restraints used and vehicle performance.

Table 3. Percentage of injuries, fatalities, and costs by object struck.

Object Struck	Pennsylvania[a] (9) Injuries	Pennsylvania[a] (9) Fatalities	MDAI File (5) Injuries	MDAI File (5) Societal Cost
Wide				
Guardrail	15.8	16.0	10.2	11.8
Bridgerail	5.4	8.3	4.2	3.5
Ditch	10.6	10.9	5.9	4.2
Tree	15.6	21.5	48.1[b]	39.3[b]
Pier, pillar, abutment	3.1	3.9	2.7	4.4
Other[c]	21.3	17.0	24.5	31.9
Narrow				
Sign	1.2	1.1	4.4	4.8
Pole	26.9	21.0	48.1[b]	39.3[b]

[a] Paths 66, 67, 69, and 71. [b] Pole and tree data are lumped together. [c] For example, a parked car.

Figure 7. Estimated effectiveness of announced U.S. DOT passenger car occupant protection standards in frontal impacts versus time.



V_R = 100 MPH (161 KMPH)

Figure 8. Estimated maximum head-on crash velocity for occupant survival in 1985 subcompact versus other mass cars.

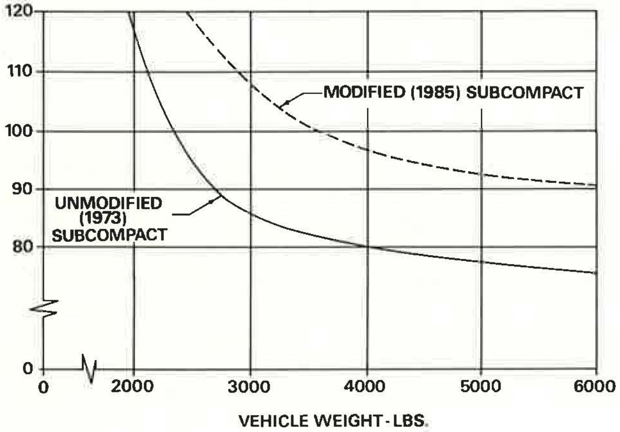
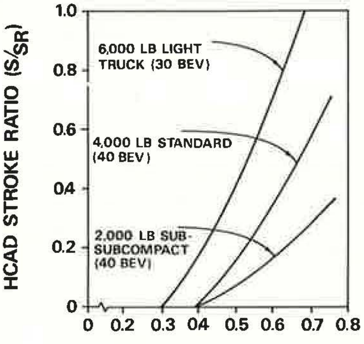


Figure 9. Fixed-force head crash attenuator device stroke versus impact velocity.



IMPACT SPEED RATIO V/V_R

V_R = 100 MPH (161 KM/M)

S_R = 10 FT. (3.05 M)

Table 4. Estimated annual societal loss costs of large sign, abutment, pillar, and pier impacts.

Loss	Societal Cost	1985 Level[a]	1985 Cost Base[a]	Societal Benefit[b]	HCAD[c]
Fatalities	200,000	1,450	290,000,000	58,000,000	39,000,000
Injuries	6,000	35,000	210,000,000	54,000,000	94,000,000
Total	—	36,450	500,000,000	112,000,000	133,000,000

Note: All costs and benefits are in 1971 dollars.

[a] Assumes no change in design past 1971, 25 percent increase in accidents.

[b] Of preventives, 1985 car.

[c] 60 percent effective, full implementation.

ECONOMICS OF 1985 ATTENUATORS

From Tables 1 and 2, one can estimate that the total 1971 societal cost due to pillar, pier, and abutment impacts is about $555 million, or almost 4.4 percent of the total $12.7 billion loss in all fixed-object impacts. This should be added to some amount due to sign impacts so that large signpost crashes can be accounted for. This will be arbitrarily taken as half the total sign casualty cost or roughly $304 million. Hence, a reasonable total societal loss that may be moderated by the HCAD is roughly $850 million annually. [This is markedly lower than the crude estimate suggested by Warner (1)]. The dominance of pole and tree impacts, not capable of economical treatment by highway crash attenuators, is noteworthy. The rather distinct concentration of pillar, pole, and abutment casualties in the 50 to 60-mph (80 to 97-km/h) range is also striking. This may be an artifact of the rather small MDAI sample, but if true, it suggests that current HCAD designs [>60 mph (>97 km/h)] are about right for current automobiles and conditions; anything less would result in an abrupt decrease in benefit of those highway crash attenuator devices that are struck. On the other hand, if the cumulative benefits actually are better represented by the distribution labeled sign in Figure 6, a higher benefit-cost ratio may be achieved by reducing the full-stop velocity requirement to something like 50 mph (80 km/h). [Another reason for such reduction may be found if the national speed limit is set at 55 mph (88.5 km/h).]

Table 4 gives an estimate of the saving potential of a 60 percent efficient attenuator deployment—a societal benefit of $528 million/year.

If this benefit is to be fully accrued, the majority of pier, pillar, abutment, and large sign sites will need attenuators. If only 30,000 sites are involved, an average of $17,500/year may be expended to break even. If, on the other hand, 1 million sites are involved, any cost greater than $523/site/year represents a loss. Clearly, a more accurate idea about the number of appropriate sites is essential to valid economic forcasting of the benefit to be accrued.

There are those who claim that further safety expenditure is unwarranted in an inflationary economy; this is simply not true. Inflationary pressure is simply much stronger on labor-intensive health care, legal, and funeral costs than it is on manufactured goods (18). Highway safety, including HCADs, if properly engineered, can therefore become a better investment than it ever has been (19).

CONCLUSION

Crashworthiness compatibility between forthcoming passenger vehicles and the highway environment deserves some careful scrutiny in the immediate future. This paper shows the need for further, more detailed economic and engineering analysis. Its rough projections suggest that the HCAD of 1985, like the automobiles that will strike it, should be smaller, stiffer, and more cost effective than the current models. The techniques and analysis used in this paper can be applied in greater breadth and detail as a more quantitative and qualitative real accident data base develops. A broader and more effective implementation of cost-effective HCADs should be planned so that the economic and technical features of future attenuators are in harmony with the needs and features of future vehicles and highways.

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