VEHICLE SAFETY RESEARCH AND THE "TOTAL" VEHICLE

Vincent J. Esposito, Office of Vehicle Safety Research, National Highway Traffic Safety Administration

The vehicle safety research of the National Highway Traffic Safety Administration is leading to total vehicle concepts that will have a balance of safety, economy, energy conservation, and environmental protection. In 1968, the Experimental Safety Vehicle Program initiated the development of the total vehicle system in which all aspects of safety including crash avoidance and crashworthiness were considered. Four experimental safety vehicles were built in the United States, and nine were constructed in other countries. The next step is the Research Safety Vehicle Program, which has as its goal a vehicle that weighs less than 1361 kg (3000 lb), that reduces the societal cost of automobile accidents in the 1985 time period, and that attains national goals in energy conservation, environmental protection, and life-cycle economy. The first phase of this program defined the role and projected operating environment for passenger vehicles of the mid-1980s and developed performance specifications of a vehicle concept based on societal benefit studies. Fuel costs and kilometers driven are expected to increase, but the percentage of family budget for automobiles will not. This will result in the demand for a smaller, more efficient automobile, which will lead to a dramatic increase in the societal cost of small-automobile accidents. The preliminary designs of the research safety vehicles by the five contractors were based on those types of considerations. Features of the designs include low weight, optimized structure and restraints, and compatibility with vehicles of other sizes.

The research efforts of the National Highway Traffic Safety Administration have two primary thrusts. The first is to reduce the frequency and severity of highway crashes by improving the characteristics of motor vehicles, which influence the dynamic performance of the driver-vehicle system. We call this crash-avoidance research. The second is to reduce the frequency and severity of injuries, fatalities, and economic loss resulting from accidents involving motor vehicles. We call this crashworthiness research.

Our 8 years of experience working under motor vehicle legislation has taught us that significant safety advances require carefully prepared federal rule-making action, backed by authoritative, conclusive research and development. The more radical or innovative the proposed engineering change is, the longer the lead time and the more positive the proof of safety payoff have to be.

NHTSA directs a substantial portion of its research and development program toward support of near-term rule-making actions that will affect automobiles of the 1970s. We believe our rule-making strategy, backed by this research and development, will bring proven safety features to the public as soon as practicable.

Recognizing, however, that major advances require longer lead times, we have intentionally focused a significant portion of research on the longer range, more difficult total vehicle goals that we hope can be met by a new generation of vehicles in the 1980s and beyond. This longer range look at our total vehicle research and development is the subject of this paper.

The background to our approach must begin with a discussion of our Experimental Safety Vehicle (ESV) Program, which began initially in 1968. It was aimed at demonstrating advanced safety concepts for a family sedan of the early 1970s time period and was our first activity in the total vehicle design area.

The program considered all aspects of safety, including crashworthiness and crash-avoidance features. In crashworthiness, the goal was to protect occupants from serious injury in crashes equivalent to a head-on barrier crash at 80 km/h (50 mph), side pole impact at 24 km/h (15 mph), and rollover at 113 km/h (70 mph) without requiring active restraint systems or presenting unnecessary hazards to other vehicles. In accident avoidance, the goals were to meet stringent requirements for braking, steering and handling, lighting, visibility, and other features to aid the driver in avoiding crashes. The vehicles were also designed to meet the 1973 federal emission standards.

Experimental vehicles designed and built by four contractors were tested by NHTSA. The contractors were AMF, Fairchild Industries, Ford Motor Company, and General Motors Corporation.

The AMF design, shown in Figure 1, incorporated a tubular space-frame structure and a fiberglass skin. Crash energy was absorbed by hydraulic cylinders, which were attached to the high-strength bumpers. This vehicle has survived numerous crashes into a barrier at 80 km/h (50 mph).

The Fairchild Industries ESV, shown in Figure 2, was based on a semimonocoque construction in which both the frame and metal skin were load-bearing elements. The front bumper was attached to hydraulic cylinders for crash-energy absorption. The vehicle incorporated a collapsible elastomeric nose, which provided a no-damage feature in low-speed impacts. This feature has been used subsequently in production automobiles.

The Ford ESV, shown in Figure 3, was based on a standard production automobile. It incorporated front and rear energy-absorbing bumpers for low-speed impacts. High-speed impact energy was absorbed by a collapsing fixed-force structure such as convoluted frame sections and corrugated sheet metal.

The General Motors ESV, shown in Figure 4, used a conventional structure, but substituted significant amounts of aluminum and vanadium alloy steel in order to provide the desired structural characteristics. High-speed energy absorption was provided by programmed failure of structural elements. Low-speed impacts were accommodated by energy-absorbing bumpers, which were later incorporated in production automobiles.

All of the ESV's incorporated antiskid braking systems and air-bag protection for the occupants. The family sedan ESVs were impractically heavy when judged by today's demands for fuel economy. However, many of the features of these vehicles can be seen in vehicles on the road today: energy-absorbing bumper, damage resistant "soft nose," and structural designs that are programmed to fail at a fixed force to provide crash-energy management. In addition, features such as air bags and antiskid braking are now available as optional equipment on several models and may become standard in the future.

As the family sedan ESV program progressed, it became apparent that a broader participation of automobile manufacturers was desirable. Accordingly, the U.S. ESV program became the foundation for a broader international ESV program. Nine additional ESVs have been constructed under various memoranda of understanding between governments and industries (Table 1). The overseas manufacturers have been aggressive in adopting ESV features in their production automobiles. The following are examples of features that have reached production.

1. Toyota has incorporated portions of the malfunction analyzer from its ESV (Figure 5) into an electrosensor panel on its production automobiles. This panel (Figure 6) monitors key service areas and warns of troubles.

2. Mercedes-Benz (Figure 7) has incorporated a number of ESV features on its production automobiles, including hydraulic regenerative shock absorbers. One of the other interesting features is the "corrugated" taillights that stay bright by resisting dirt buildup through aerodynamic action.

3. The July 1975 issue of Road and Track Magazine notes in a road test report, "Volvo, more than any other car maker, has jumped on the safety/damage-resistance bandwagon and made it a product philosophy and marketing tool." The adaptation of ESV structural design is clearly evident in a comparison of its ESV (Figure 8) with the 240 series (Figure 9). According to Road and Track, the new structure gives the same

Figure 1. AMF experimental safety vehicle.

Figure 2. Fairchild experimental safety vehicle.

Figure 3. Ford experimental safety vehicle.

Figure 4. General Motors experimental safety vehicle.

Table 1. International experimental safety vehicles.

Country	Vehicle	Weight (kg)	Wheel Base (cm)
Germany	Mercedes	2097	285
	Volkswagen	1452	280
Japan	Nissan	1248	255
	Toyota	1148	230
	Honda	772	235
Italy	Fiat	794	184
	Fiat	1167	245
	Fiat	1289	242
Sweden	Volvo	1443	270

Note: 1 kg = 2.2 lb; 1 cm = 0.4 in.

Figure 5. Toyota experimental safety vehicle.

Figure 6. Toyota experimental safety vehicle panel.

Figure 7. Mercedes-Benz experimental safety vehicle.

passenger compartment acceleration in 64-km/h (40-mph) barrier crashes as the old structure did in 48-km/h (30-mph) barrier crashes.

4. Volkswagen has also worked much of its ESV (Figure 10) occupant-protection performance into its new Rabbit model. The July 1975 Consumer Reports notes that the VW Rabbit did well on those safety-related factors that could be easily measured: handling, braking, control layout, and driver's view of the road. In addition, at the Fifth International Technical Conference on Experimental Safety Vehicles in London in 1974, VW introduced crash-test data from experimental safety automobiles that were based on the Rabbit. The degree of occupant protection provided by those safety automobiles greatly exceeded present government requirements for production automobiles. Many of the design features of the safety vehicle have been incorporated into the Rabbit.

The next step in the evolution of our systems approach is illustrated by the Research Safety Vehicle

Figure 8. Volvo experimental safety vehicle.

Figure 9. Volvo production vehicle.

Figure 10. Volkswagen experimental safety vehicle.

(RSV) Program. One of the lessons learned from the U.S. family sedan ESV project was that the next generation of safety vehicles must consider all major societal goals for the automobile, not safety alone. The RSV program considers societal goals in energy, economy, and environment as well as safety. The specific goals may be summarized as follows:

1. The safety goal is to design a vehicle that weighs less than 1361 kg (3000 lb) and that will reduce to the maximum extent practical the societal costs of automobile accidents in the 1985 time period.
2. The energy goal is to achieve a fuel economy level of 12.8 km/l (30 mpg) for the EPA-combined cycle.
3. The economy goal is to impose careful constraints on production and maintenance costs and to produce for features included on the RSV a societal benefit that is greater in value than the life-cycle cost of the feature.
4. The environment goal is to have a vehicle that meets or exceeds the 1977 EPA emission standards.

Phase 1 of the RSV program was completed in May 1975. The five contractors who participated in this phase were AMF, Calspan Corporation, Ford Motor Company, Minicars, and Volkswagen. The objectives of this phase were to define the role and projected operating environment for the family-sized vehicle of the mid-1980s and to develop the performance specification for this vehicle based on societal benefits versus cost. The following summarizes some of the results of phase 1 of the RSV program.

Figure 11 shows a projection of the trends in the total number of automobiles in use. In spite of the present depressed market in automobiles, the number of automobiles is expected to increase during the long term. The increasing number of drivers is considered to be the strongest influencing factor that will cause the increase in automobile population. Likewise, the number of vehicle-kilometers is projected to increase during the long term (Figure 12). Higher fuel costs and improved public transportation may slow down the rate of increase, but are not expected to reverse the trend.

The current distribution of consumer expenditures is shown in Figure 13. The percentage devoted to automobiles is approximately 12 percent and is not expected to increase in the 1985 time period because other demands on the budget will continue to remain strong. In the 1985 time period, fuel costs and miles driven will increase, yet the percentage of the family budget devoted to the automobile will not. The net result will be continued demand for smaller, more efficient automobiles.

Figure 14 shows the distribution of automobiles by weight class in 1975 and 1985. In spite of the recent trend to smaller automobiles, the 1814-kg (4000-lb) class is still the most predominant in 1975. By contrast, the 1985 projection shows a large shift to the small automobile at the expense of other classes.

Figure 15 shows the societal costs of accidents that can be attributed to each weight category of automobile. The percentage of societal costs that will be borne by the small automobile dramatically increases in 1985. Moreover, as the numbers of automobiles and the number of kilometers driven increase, the number of accidents is also expected to increase. The total societal cost of these accidents is expected to increase from \$15.6 billion in 1975 to \$20.12 billion in 1985. Clearly, the most profitable weight class for an RSV design for the 1985 time period is 1361 kg (3000 lb) and lower.

Figure 16 shows the societal cost of accidents for the 1975 time period. The accident data have been translated into an equivalent condition of an automobile striking a fixed barrier in a given direction and at a

Figure 11. Operating automobiles and population driving age in the United States.

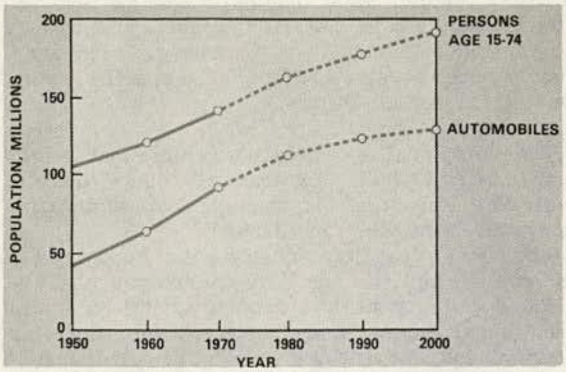


Figure 12. Projected vehicle-miles.

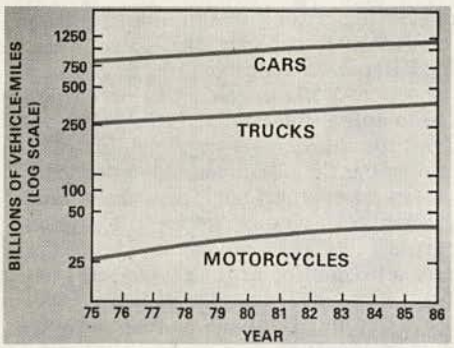
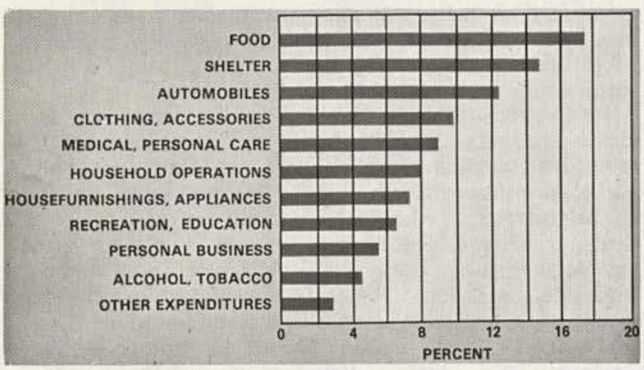


Figure 13. Consumer expenditures.



given velocity. The length of the bars represents the societal costs for a given direction of impact. The costs attributed to speeds below 32 km/h (20 mph), below 80 km/h (50 mph), and above 80 km/h (50 mph) are also shown. The general distribution of accidents shown in Figure 16 is not expected to change for the 1985 time period. However, the severity may be expected to increase because of the larger number of small automobiles interacting with larger automobiles in the 1985 vehicle mix. A conclusion that may be drawn is that forward crashworthiness is most important with sideward, secondary, and reward tertiary. This type of analysis assists us in deciding on the level of protection that is required and its value to society.

The preliminary designs of RSVs proposed by the five contractors were based on these types of considerations and are worth reviewing here.

Figure 14. Vehicle weight.

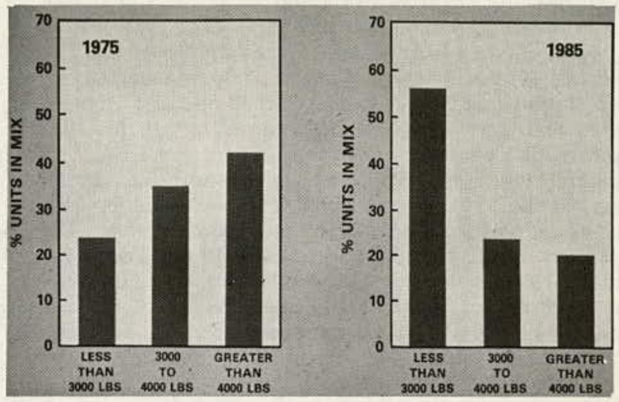


Figure 15. Societal cost of accidents by vehicle weight.

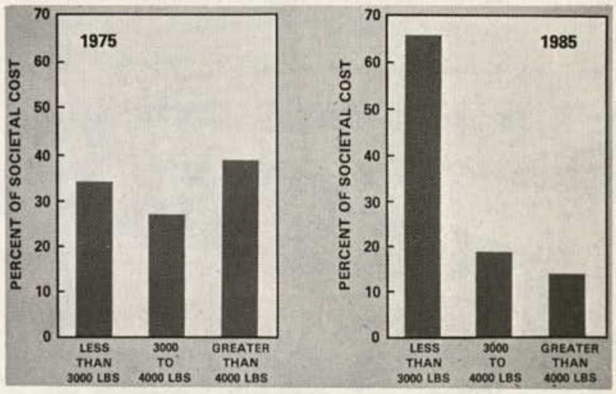
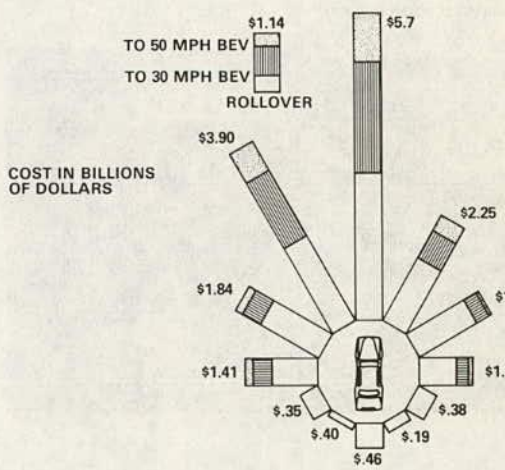


Figure 16. Societal cost of accidents by direction and severity of impact.



1. The AMF design (Figure 17) is a 1317-kg (2900-lb) front-engine vehicle that features good visibility, foam-filled structure for side impact, and a soft elastomeric front end.

2. The Ford design (Figure 18) is a 1339-kg (2950-lb) front-engine, rear-drive automobile. The Ford design features an all-new family of automobiles in which the structure and restraint systems are optimized for maximum protection in the most probable accident speeds and modes.

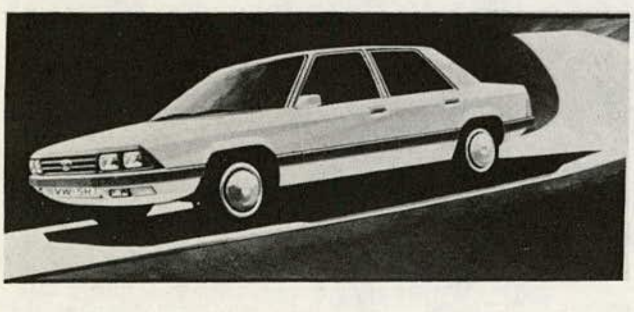
3. The Volkswagen design (Figure 19) is a front-transverse engine, front-drive automobile weighing 1230 kg (2710 lb). The design emphasizes compatibility with other smaller and larger vehicles in an accident.

4. The Chrysler-Simca C-6 automobile is the base car for the Calspan design (Figure 20). The C-6 is a front-transverse engine, front-drive automobile that is to be produced in France. It has demonstrated good inherent crashworthiness. The Calspan redesign of the C-6 modifies the C-6 structure to provide a crash pulse of the type shown in Figure 21. Three zones of deceleration are shown. The lowest zone provides low-speed pedestrian protection and minimizes vehicle damage at barrier impact speeds up to 16 km/h (10 mph). The middle zone gives the RSV compatibility when the side of another vehicle is impacted at speeds up to 48 km/h (30 mph). The upper zone provides crashworthiness up to an 80-km/h (50-mph) barrier impact. The crash pulse shown is for an 80-km/h (50-mph) barrier impact. Lower speed crashes would of course terminate in the lower zones. A mockup of the RSV proposed by Calspan is shown in Figure 22. The major structural changes from the C-6 are in strengthening the body compartment through the use of high-strength steel and providing additional crash structure and distance in the front. The Calspan vehicle design weighs 1225 kg (2700 lb).

Figure 17. AMF research safety vehicle.

Figure 18. Ford research safety vehicle.

Figure 19. Volkswagen research safety vehicle.



5. The Minicars design (Figure 23) is for an 872-kg (1920-lb), rear-transverse engine, rear-drive automobile. It features a foam-filled, sheet-metal structure that provides light and omnidirectional energy absorption. Two significant advancements in property damage protection proposed for this vehicle are shown in Figure 24. The bumper system combines elastomeric foam with spring steel to resist a 16-km/h (10-mph) frontal impact without damage. The body glove concept provides a dent resistant exterior surface that can be removed and replaced if heavily damaged. In the area of crash avoidance, the Minicars RSV incorporates a microprocessor and radar system (Figure 25) that provides collision warning and automatic braking in the event no action is taken by the driver to avoid an impending collision.

The RSV program has begun the difficult task of relating four major societal goals: safety, economy, environment, and energy in a single vehicle design. The result of this program will be a vehicle design that represents a well-balanced combination of performance specifications that will achieve, to differing degrees, a significant portion of each of the four societal goals. A question that immediately comes to mind is, Does this final RSV design represent the only acceptable combination of safety, economy, environment, and energy specifications for a vehicle in its class? A companion question might be, What are the design combinations relating these characteristics for heavier vehicles or lighter vehicles or special purpose vehicles such as intercity or urban vehicles?

Consideration of these questions and others like them leads to the following design concepts:

Goal	Element
Safety	Crashworthiness
	Crash avoidance
	Pedestrians
	Aggressiveness
Environment	Exhaust emission control
	Resource conservation
Energy	Fuel economy
Economy	Life-cycle costs
	Materials
	Manufacturability

These concepts can be used for judging how the personal automobile can best be planned to give mobility and yet satisfy the growing energy, environmental, and economic constraints. Although the RSV, as we have described it, may represent a well-balanced design for its class of vehicle, certainly no single design can meet all of the automotive needs of the future. What we envision is not a single design specifying a single set of safety, economic, environmental, and energy performance levels but rather a multidimensional envelope within which are an infinite number of possible design combinations, all of which achieve an acceptable performance.

Let me illustrate this four-dimensional, design-concept envelope by relating several of the elements. The interaction that we have given the most attention is that between safety and energy. We can plot energy in terms of fuel economy in kilometers per liter on one axis and safety as represented by some suitable parameter such as barrier crashworthiness in kilometers per liter on the other axis to shown the relation between these two elements (Figure 26). As safety requirements (and thus weight) increase, fuel economy necessarily comes down. Conversely, reducing the levels of safety required permits an increase in the fuel economy. The plot might be one in which other elements—economy, life-cycle costs, or exhaust emission control—are held constant.

Figure 27 shows fuel economy and emission levels as a percentage of some specific level, say, the proposed 1977 standards. Tightening up the emission requirements decreases fuel economy or, conversely, relaxing them increases fuel economy. On both curves in Figure 27 is a single point that marks the goals for the RSV program.

I am not implying by the data shown in Figures 26 and 27 that we have completely established definitive, smooth relations among the elements. Much work remains to be done to quantify properly the complex relations between energy and safety, energy and emissions, safety and emissions, and so forth. However, as we continue with programs such as the RSV and other basic research and development programs on structural crashworthiness and as we gather increasing data from other programs

Figure 20. Calspan research safety vehicle.

Figure 21. Deceleration versus displacement for Calspan research safety vehicle.

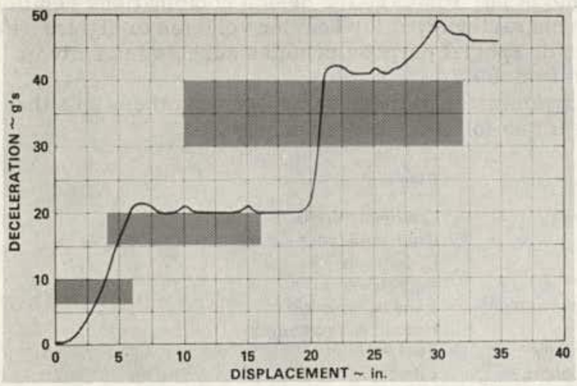


Figure 22. Calspan research safety vehicle mockup.

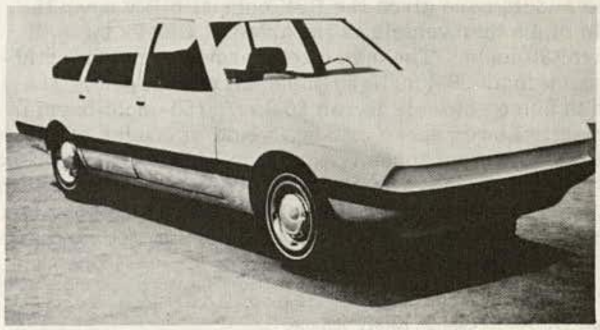


Figure 23. Minicars research safety vehicle.

Figure 24. Property damage protection features of Minicars research safety vehicle.

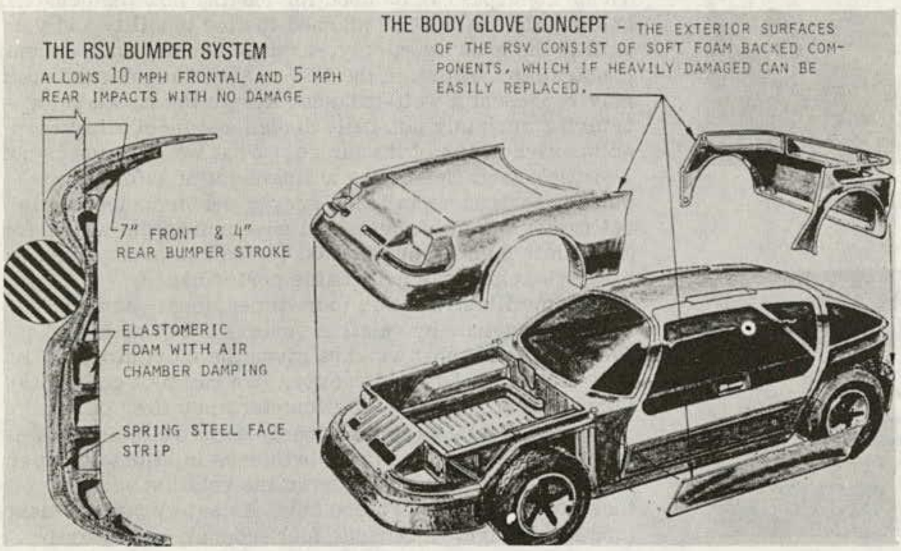


Figure 25. Vehicle electronics of Minicars research safety vehicle.

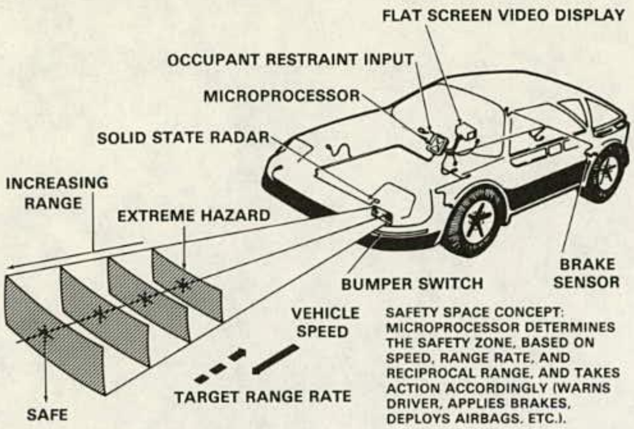


Figure 26. Safety versus energy.

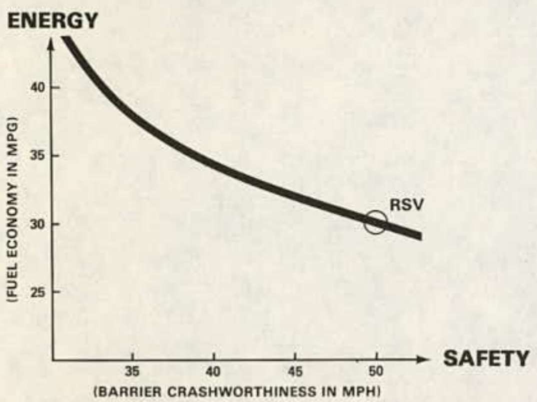
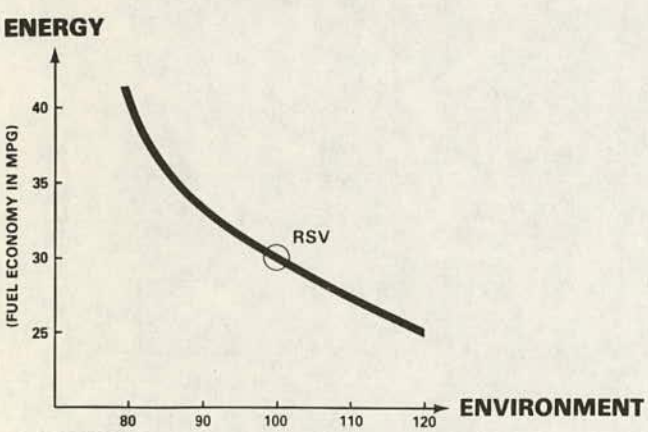


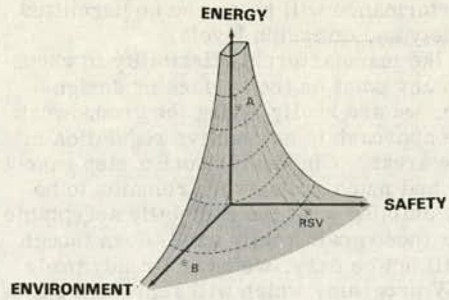
Figure 27. Energy versus environment.



in other agencies concerned with engine performance, mileage, and emission levels, we can begin to establish these relations, which then might be integrated into the total design concept.

To further illustrate the idea of a multidimensional envelope, we might combine three elements: energy, safety, and emissions (Figure 28). Rather than the two single curves shown before, Figure 28 shows a surface that represents the points that are societally acceptable combinations of energy, safety, and emissions. In theory, the vehicle designer might choose to provide

Figure 28. Relation of environment, energy, and safety.



high levels of safety with moderately high goals in terms of emissions and energy. This approach, which basically represents the RSV design, would fall at about the point shown on the surface. Conversely, the manufacturer might choose to seek high performance in terms of energy savings or fuel economy. According to the design concept, he or she would be permitted to achieve these energy goals at some compromise in levels of safety and emission performance. Thus, the design point might fall at point A. Such a vehicle perhaps might be designed primarily for urban use where high levels of crashworthiness might not be so appropriate or essential. A third design approach might stress minimum emission levels with the corresponding sacrifice in terms of safety and energy performance. This would be represented by design point B. If the design-concept envelope has been properly prepared, each of these designs would represent an acceptable approach from a societal benefit point of view.

There are other interesting characteristics of the design concept. First, the surface shown in Figure 28 reflects the energy, safety, and emission trade-offs permitted for some single measure of the economy goal. This economy goal might well be a measure of total life-cycle vehicle costs, including purchase, maintenance, repair, depreciation, insurance, and other costs, probably exclusive of fuel consumption costs since these are reflected in the energy goal. The economy goal might be set at some number, such as \$8000. A different value of this goal would result in a different shaped surface. For example, if we permit the life-cycle costs to increase to, say, \$10 000, more expensive materials, manufacturing processes, and engine drive-train combinations might be permitted, which would change the shape of the curves forming the surface. Conversely, a lower limit for the economy goal might restrict the engineering variations and materials that could be used, again changing the shape of the surface.

The surface or envelope shown represents an agreed-on mapping of acceptable societal values. It does not necessarily represent all of the currently achievable engineering combinations of the goals. For the three shown here—energy, safety, and emissions—certainly energy would be the driving factor from a marketability point of view. The manufacturer will, therefore, strive to increase the performance level in terms of this goal and lessen the performance level in terms of emissions and safety, which are not nearly so marketable from a public point of view. The limits of automotive technology, however, will ultimately restrict the ability to increase performance on the energy scale at the expense of safety and emission levels. If the manufacturer chooses to market a vehicle in this cost or economy class that achieves a certain energy performance in terms of kilometers per liter, then he or she must meet the corresponding emission and safety goals as represented by the point on the surface. Only by improving fuel economy performance will he or she be permitted to reduce the safety and emission levels.

In describing the manufacturer's flexibility in choosing designs from any point on the surface or design-concept envelope, we are really laying the groundwork for an innovative approach to automotive regulation in all three of these areas. Obviously, such a step cannot be taken lightly, and much groundwork remains to be done in carefully defining what the societally acceptable trade-offs among these goals really are. Even though achieving this will not be easy, we have already made a start. The RSV program, which will represent but one point on this multidimensional surface, is well on its way to becoming a reality. Additional programs in advanced engine technology are in progress in the U.S. Department of Transportation and in the Energy Research and Development Administration. The Environmental Protection Agency will no doubt continue to explore the complex problem of controlling vehicle emissions. As the results of separate studies in these areas are produced, they may help us define more carefully the interaction of the four goals and the construction of a surface, such as the one shown in Figure 28, that will represent what society really can afford in terms of its future automobile.