FINAL REPORT

Volume I of IV

on Contract FH-11-6685

INTEGRATED SEAT AND OCCUPANT RESTRAINT PERFORMANCE

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INTRODUCTION

This report summarizes the results of a concentrated research effort concerning integrated seat/restraint systems. This research effort has determined the current state of the laws pertinent to the subject as well as defined the technological state of the art pertinent to such systems.

Using the techniques of the systems engineer, a mathematical model has been developed which relates the occupant and his geometry to the mechanical and spatial conditions of the vehicle's seat and/or restraint system during a crash. Using similar techniques, a computer-oriented economics model has been proposed to measure the cost/benefit ratio for current and future seat and restraint systems.

Based upon the systems models a methodology is proposed for setting and evaluating new Federal standards for integrated seat and restraint systems for both near- and long-term implementation. The specific, detailed results of this study are presented in appended supplements A, B, and C which are concerned with the law, technological state of the art, and the occupant model respectively. This report only attempts to summarize those results. The reader should refer to the supplement in question for a detailed treatment.

CURRENT STATE OF THE LAWS RELATING TO AUTOMOBILE SEATS AND RESTRAINT SYSTEMS

A complete review of the state laws which are related to seats and occupant restraint systems is given in Appendix A of this report. That appendix may be summarized by noting that forty states have initiated some legislation on this topic. While the individual state laws varied, they commonly contained the authorization for a Commission to set standards and approve seat belt assemblies. These laws also specified the SAE standard requirement as a minimum acceptable level for compliance. A less commonly stated requirement specified that the sale or transfer of used vehicles would only be possible if seat belts were installed.

SUMMARY OF THE STATE OF THE ART OF INTEGRATED SEAT/RESTRAINT SYSTEMS

A survey of the technical literature in the fields of Biomechanics, Economics, Engineering, Psychology and Medicine yielded a total of approximately 2500 articles dealing with seats, restraint systems and integrated seat/restraint systems. These were critically evaluated and ultimately reduced to the approximately 650 pertinent entries which are included in Appendix B. These articles were professionally coded and indexed. In addition, they were classified using the computer-compiled KWIC system. This coding is also included in the Appendix.

The current state of the art as determined from this literature review and discussions with the automobile manufacturers led to the conclusion that two states of the art exist. The first is that which is represented by the very latest published scientific data relating to the subject. The second concerns systems which are older in point of time but which have been tested extensively. For these systems tooling and production capability exist and thus they may be classified as systems for which economic data is available for determining cost/benefit ratios. The time lag between the two states of the art varies according to the tooling and production capability available as well as the lead time required to develop manufacturing techniques required for mass production. Although the lead time required for tooling is a rather well-defined quantity, the total time required to put a system into production will vary as a function of the demand. If Federal standards specify a certain device, automobile suppliers and manufacturers can vary resource allocation based upon the assured demand for the goods and thus shorten the lead time requirement.

The current scientific state of the art cannot be summarized by referring to a specific device or restraint currently proposed but rather must be discussed in terms of several devices and ideas which could be integrated with the interior design to provide the optimum in passenger restraint and protection. The integrated seat/belt system as typified by the Cox or Liberty Mutual seats offer more protection against lateral, rearward or spin forces than is provided by the common bench seat presently offered in most production vehicles. The most widely used seat of this type is the passenger and crew seat provided in airplanes. These seats, however, are not designed primarily for impact attenuation but rather for passenger tie-down during turbulence and rough landings. They are not adequately designed for impact use and in fact have a history of failure under moderate loads (6G's). They do indicate, however, that production seating in which passenger restraint and seating are coordinated is feasible.

The crew seats incorporate a four-point harness which is easily worn and which should be investigated in the Phase II test program. The four-point restraint system is similar to that presently available with the Shelby Ford GT. The Shelby Ford system is unique in that it incorporates an inertial locking device which permits motion of the upper torso during the normal driving task and yet locks during impact to provide upper torso restraint for all impacts as well as head restraint during rear impact.

Only a limited amount of material exists in the literature regarding passive restraint systems (systems not requiring active participation by the user to enjoy their benefits). Foremost among these, however, is the air bag system. Recent studies have shown that these systems are rapidly approaching the point where they may be feasible for incorporation into production vehicles. These systems, which are electronically activated, can provide frontal protection for belted or unbelted occupants in the front and/or rear seats. As yet unresolved are the questions of cost, reliability, noise level during activation, effective fail-safe measures.

The only other feasible passive system suggested to date has been the collapsible steering column employed in all 1968 motor vehicles. This system, however, suffers from the same fault as the air bag in that it is ineffective for anything but a frontal collision. It does illustrate, however, what can occur when controlled deformation of vehicle components is used to absorb kinetic energy of the vehicle occupant.

The literature contains references which indicate that controlled plastic deformation of the belt anchor points, plastic elements in series with the belt, critically damped belt materials and more highly damped seat structures all could combine to provide greater control over occupant motion. Our preliminary studies with a simplified mathematical model (of front and rear occupant response) indicate that the interaction of front and rear seat passengers would be less severe or possibly would not occur at all if more damping were present in the upper torso restraint.

The production state of the art is best illustrated in the 1968 model motor vehicles. These vehicles include those devices for which tooling and manufacturing capability now exist in sufficient magnitude to equip the present production expectations.

The primary changes from the 1967 vehicles consist of increased numbers of belts as well as more original approaches to the problem of belt storage and housekeeping. No manufacturer, however, has indicated any change in the belt webbing material. Thus no improvement in the energy-absorbing capability of the restraint system is anticipated.

Although one manufacturer did indicate that seat parameters such as spring rate and compliance are a factor in seat design with respect to impact attenuation, no specific evidence was cited to confirm the statement. Certainly such parameters can play a major role and should be integrated into the design process.

An example of this is the case cited by an industrial source when questioned about head rests or higher seat backs. It was indicated that substantial deflections of the seat back allowed lap belt slack, resulting in greater angular rotation of subject's head and neck and thus potentially increasing hyperextention-hyperflexion injuries, when a large occupant is involved in a rearward collision. Such a situation can be avoided by the use of systems models and total design integration of the seat and belt system, in addition to the use of properly gathered anthropometric data. This design integration does not necessarily imply that seats with the belts attached to the seat frames offer the optimum solution. It does imply that the design of the seat and restraint system should be considered as a total package. Specifically, trade-offs between the comfort and impact performance of the seat may be required.

THE HSRI VEHICLE-OCCUPANT MATHEMATICAL SIMULATION PROGRAM

As an important phase of its research into integrated seat and occupant restraint performance, the Highway Safety Research Institute has developed a program using mathematical techniques to simulate the dynamic behavior of a motor vehicle occupant. This program consists of three parallel efforts: development of simple one, two, or three mass element bodies simulating human motion in a collision situation; development of sophisticated digital computer programs simulating an automobile crash victim in a front-rear collision; and development of more general simulations. It is felt that all three phases of this research have already yielded results useful in the development of safety performance standards and in general understanding of collision dynamics.

The simple model program has been started quite recently. Already it has been found that a very simple model can be used to predict gross interaction depending on restraint system material parameters between front and rear seat passengers in an auto when the front-seated passenger is restrained by both a seat belt and a shoulder harness and the rear-seated passenger is restrained only by a seat belt. See Appendix C for details. Briefly, the simple model considered 95th percentile males occupying front and rear seats restrained as indicated. In the absence of damping in the upper torso restraint for the forward passenger a 20-mph collision was predicted to produce dynamic motions yielding impact between the forward and rear passengers. The model demonstrated that if the upper torso restraint has been given a proper damping (energy absorption) characteristic this impact would have been impossible. It is considered that no additional sophistication of the model is needed to draw such a conclusion and to provide a valid empirical field solution. Such a solution would, of course, not be optimum but, since no other aspect of the current state of the art may be considered optimum at this date, it would be as justifiable as any other aspect of current seating standards or practice. A refinement of this model which includes seat belt elasticity and damping is a present being prepared by the Highway Safety Research Institute for visual display as the output from an analog computer simulation. A special report will be released based upon this model, which will more graphically illustrate the point with a variety of practical parameters values. A three-mass body simulation is the next step in the analog computer efforts which are part of the ongoing research program of the Highway Safety Research Institute. Work is presently being initiated for considering the motion of these simple bodies in three dimensions. It is felt that this program involving simple models is particularly germane because near-term results are realistically attainable as witnessed by the simple occupant interaction model noted above.

The second phase of the Highway Safety Research Institute's packaging research program has developed a definite direction during the course of this project. The digital computer program for simulating occupant dynamics which is currently being tested against results from similar programs is slightly more sophisticated than the earlier efforts documented in the literature. The main differences are in the number of allowed body contacts with the vehicle interior. The occupant is still approximated by an eight-segment articulated system of links. This computer program, by virtue of its existence, is now being used by the Highway Safety Research Institute for current parametric studies of the relation between the occupant, his restraint system, and the auto interior. Again this program of research has the advantage that its results can be used in the near-term development of performance standards on integrated seat and occupant restraint performance.

The third phase of this project has been as active as the first two. This phase was concerned primarily with advancing the state of the art in a myriad of directions. A sophisticated simulation has been developed and is the primary subject of Appendix C of this report. This new model includes changes and improvements of the earlier model which can be made without increasing the number of degrees of freedom of the auto occupant. However, pitch and vertical motion of the vehicle are included in this model as well as a rear-seat passenger and occupant injury criteria. The flow diagrams for digital simulation are included in Appendix C and the actual programming is scheduled to begin soon.

Another aspect of the third phase which has received considerable thought is three-dimensional modeling. The Biomechanics group of the Highway Safety Research Institute has developed a theory for the three-dimensional modeling N-body problem of physics which is particularly adaptable to a system of articulated links (body elements) moving in three dimensions. The theory has been developed with digital computation in mind. It is planned that more sophisticated models than those considered in Phase I will be studied.

The Highway Safety Research Institute has also initiated a joint effort with the Mathematical Modeling Committee of the Automobile Manufacturers Association to develop a reference vehicle interior for use with mathematical models of occupant dynamics. This would provide a uniform interior configuration with appropriate geometry, load-deflection characteristics, and acceleration-time inputs for use by University, government, and industrial researchers in the field of occupant modeling. Such a configuration will allow any model to be mathematically compared with previous models. Thus it will provide a common base of knowledge for all interested parties.

The Automobile Manufacturers Association is the most logical organization to develop such a uniform body of data inasmuch as it will reflect the best judgment of the industry as a whole. The Highway Safety Research Institute, as a university research organization, is in the best position to serve the interests of the government and industry in such a coordinated effort.

The Highway Safety Research Institute of The University of Michigan has a particular capacity for undertaking a research program of the type described above. These considerations have led to the definition under this project of a research program which is already beginning to yield a payoff in the understanding and simulation of auto occupant collision dynamics.

PHASE II TEST PROGRAM

Based upon the results of the Phase I program, it is possible to describe a research program for a Phase II effort which will serve to define, analyze, and test integrated seat/restraint systems, where an automotive seat/restraint system is defined to be that set of physical units which support and restrain a human body during the rapid acceleration or deceleration of a vehicle. Its effectiveness is a function of its ability to protect the body from unnecessarily harsh contact with the vehicle interior when the vehicle undergoes violent motion in any direction.

As such, the seat/restraint system consists of a finite number of subsystems, each of which can be characterized by a set of engineering parameters. The subsystems of geometrical and physical characteristics, anthropometrics, weight, and human tolerance to external forces all combine to provide the conditions defining passenger seating and restraint. Design can be accomplished either on an intuitive and/or art form base using rules of thumb and good engineering practice to yield an empirical engineering solution, or by means of a systems or semianalytical approach based upon a well-defined set of criteria. However, only by the use of systems engineering techniques can the optimum integration of the totality of factors involved be achieved.

Some of the subsystems which combine to provide occupant seating and restraint are:

(1) Head rest

(2) Seat back

(3) Seat pan

(4) Seat track & structure

(5) Upper torso belts

(6) Lap belts

(7) Foot support

(8) Knee support

(9) Restraint anchor points

Each of the above may be characterized by its geometry and by pertinent physical parameters describing dynamic load-deflection response. If we use the seat back as an example, the geometrical variables include:

(1) Total height

(2) Depth with respect to a reference surface

(3) Radius of gyration

(4) Lateral support prousions, location and configuration

(5) Mass

To these must be added the deformation characteristics of:

(1) Load-deflection response of the spring structure as a function of location.

(2) Load-deflection of the seat structure for forward, rearward, lateral, and oblique loading.

(3) Damping characteristics of the springs and seat structure as a function of force direction and rate of loading.

All of these variables must be quantified for each subsystem and then combined mathematically in an ordered matrix to study their interrelationships. Based upon the computer simulation of the total system, the experimental verification of results will allow the establishment of specific numerical criteria which will serve as the basis of future Federal standards. Furthermore, it will allow seating and restraint systems to be developed in a manner similar to that accepted as normal procedure in the aerospace, communications, and defense industries.

It is important to realize that at this time no integrated seat/restraint system for automotive use exists which is predicated upon ordering and optimizing all the logical subsystems into a useable package. Although from the standpoint of comfort, the study of seating has produced some empirically derived design parameters, the systematic determination of functional forms for impact attenuation is not yet a reality.

In order to study the totality of factors involved and integrate them using systems engineering techniques, the numerical characterization of existing seats, seat structures, and restraint systems must be achieved. At present, these parameters exist only for a limited sample, and the gaps in the available knowledge are filled intuitively rather than explicitly. Such parameters development is a straightforward engineering laboratory procedure requiring only commonly available techniques and equipment.

Inherent in such a program is the availability of a highly developed mathematical simulation of the occupant and the seat/restraint system. This simulation capability should not be contingent upon vehicle interior impact per se unless the interior is designed to act specifically as a part of the restraint system. That is, the occupants' displacement and velocity envelopes should be determined and minimized consistent with human tolerance information, but the vehicle structure as such is not considered to be a part of this research program. This simulation capability will allow the evaluation and optimization of all the factors involved, including concepts that may seem currently impractical, to provide the foundation for justifiable standards which shall be appropriate from the standpoint of the pertinent human factors, engineering, and biodynamic considerations. After the feasibility of the design concepts is established then economic evaluation will be used to provide additional information regarding the feasibility of implementation. The automobile industry has been actively developing such a capability within the past two years. The results of their programs and the performance of the seating and restraint subsystems are not available in the open literature,although it is known that comparative studies of seating and restraint system are being performed. If the Bureau is to properly evaluate their designs and set adequate standards, it must have the capability to perform independent analysis, test, and verification of existing and proposed seat/restraint systems.

In order to achieve the above requirements, the following information must be determined by a comprehensive research program involving engineering characteristics, simulation, and validation.

Such a program should include the following information in its early phases before testing specific seats and restraint devices.

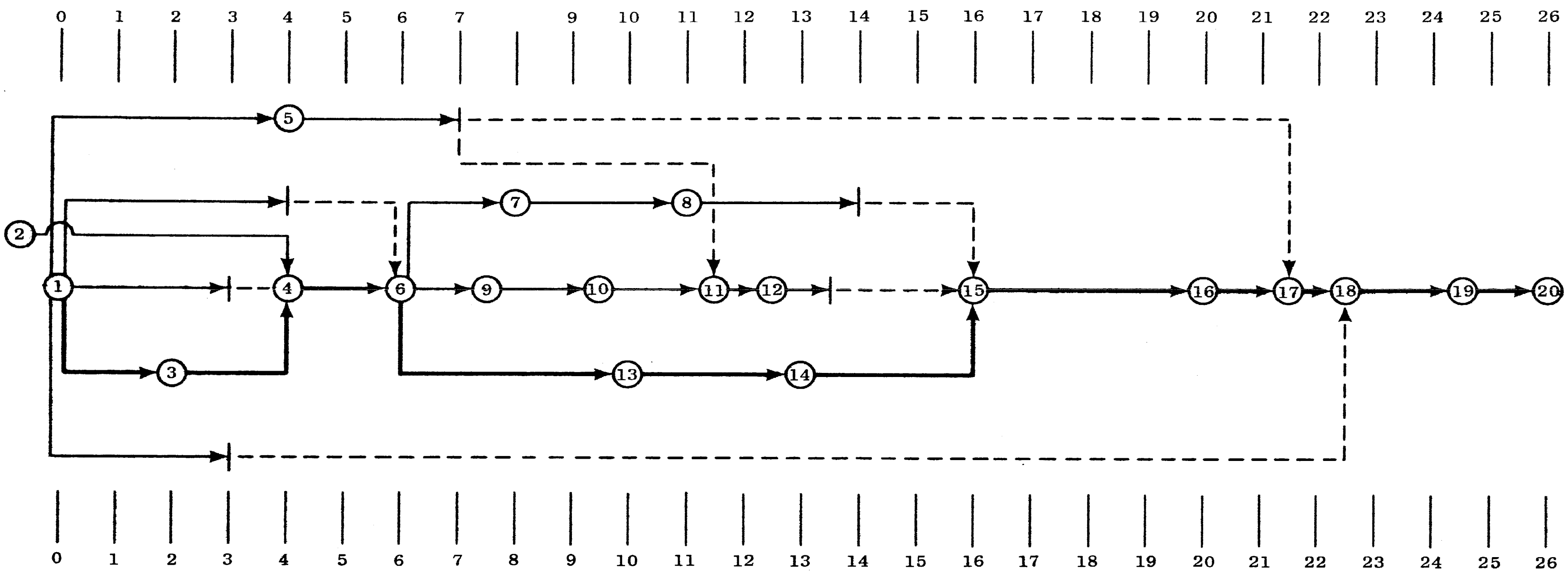
1. A standard set of anthropomorphic data representative of the population of vehicle occupants being developed needs to be agreed upon. The necessity for such agreement is illustrated by the recent controversy over Federal standard 201. One of the primary areas of disagreement revolved around the lack of accord over a representative set of such data.
2. A matrix of geometrical and physical characteristics for current product and prototype seat and restraint subsystems must be determined to provide a data bank for use in the simulation of seat/restraint performance. When such data are available, further documentation of the present state of the art will be possible and the performance of future seats and restraint systems can be accurately measured against those now available.
3. A computer simulation of occupant response involving simple analog and more detailed digital models should be formulated and experimentally verified, using the above data.

These requirements have been included as one phase of a multi-phased research program of 26-month duration. This program has been designed to provide the Federal Highway Safety Bureau with the following information.

1. A complete data bank which documents the performance of currently available seat and restraint systems. (6 months)
2. A program which will provide the engineering, psychological, biodynamic, and economic data required to produce standards suitable for near-term implementation. It is anticipated that agreement by government, industry, and research organizations can be reached within one year and a standard method of analysis (via simulation) which will pre-test seat/restraint systems against a set of realistic performance measures. This will allow design flexibility on the part of manufacturers and serve as a basis for precertification of design concepts. (13 months)
3. A program which will analyze, construct, and test integrated seat/restraint systems which may meet economic cost/benefit criteria and thus be suitable for long-term implementation. (26 months)

A time-scaled flow chart shows the interaction of the major events of the total research program. This program is an outline of part of the projected activity of the Biomechanics Department of the Highway Safety Research Institute. As such it will utilize the large hybrid analog-digital computer facility which is being acquired and which will be used for further studies of two- and three-dimensional occupant kinematics. Impact sleds capable of simulating front, rear, lateral, and oblique impacts are being purchased and will be supplemented with a limited electronics and optical instrumentation package. The sleds

FLOW DIAGRAM FOR PHASE II TEST PROGRAM



JOB	JOB DESCRIPTION
1-3	Acquire Anthropometric Dummies
1-4	Set Up Impact Sled
1-5	Gather Economic Data for Benefits Model
1-6	Determine Dynamic Properties of Current Seats, Belts, and Belt Tie-Down Systems
2-4	Continue Mathematical Modeling Program for 3-D Models
3-4	Determine Dummy Mass and I Values
4-6	Verify Computer Model with Sled Tests
5-11	Program Cost/Benefits Model for Near-Term Restraint Systems
5-17	Program Cost/Benefits Model for Final Integrated System
6-7	Perform Analysis for Integrated Seat
6-9	Perform Analysis for Optimum Belt Parameters
6-13	Perform Analysis for Air Bag System
7-8	Build Prototype Seats
8-15	Test Prototype Seats
9-10	Build Prototype Belt Systems
10-11	Test Prototype Belt Systems
11-12	Determine Cost/Benefits Ratios
12-15	Write Proposed Near-Term Standards and a Report
13-14	Build Air Bag Systems
14-15	Test Air Bag Systems
15-16	Analyze and Test Combination Systems
16-17	Acquire Cost Data for Combination Systems
17-18	Determine Cost/Benefits Ratios
18-19	Write Proposed Standards
19-20	Write Final Report

will be complemented by a high-velocity impact machine now on order which will be used to characterize the dynamic mechanical properties of seat and restraint subsystems.

The internal Institute program in the area of seat and restraint systems will be funded at the annual rate of four man years for the next five calendar years regardless of external contract support. At the end of five years it is expected that the research objectives above will have been achieved. At the inhouse level of effort it is expected that approximately one sled run per week will be produced and that two rather than five anthropometric dummies will have been used.

We would recommend that the Bureau supplement our proposed program at the level of seven man years per year in order to accomplish the desired results in the shorter time period shown on the time-scaled flow chart. This cooperative program would allow an effort of approximately twenty-two to twenty-four man years directed toward achieving the three major elements described previously. In tabular form below are indicated the major elements and the man years/year provided by the Highway Safety Research Institute and the proposed Bureau support.

HSRI Facilities (minimum instrumentation)	HSRI Program per year	DOT Program per year
Analog-Digital Hybrid Computer	1/2 Man Year	1 Man Year
Digital Computer Simulation	1 Man Year	2 Man Years
Impact Sleds (large #1,000 payload) (small #200 payload)	2 Man Years	3 Man Years
Plastech Impact Machine and Mechanical test devices	1/2 Man Year	1 Man Year
	4 Man Years	7 Man Years

In addition to the support required for personnel, funds will be required for computer time charges and further instrumentation sophistication.

PROPOSED STANDARDS FOR NEAR AND LONG TERM IMPLEMENTATION

The development of future Federal standards concerned with the integration of the seat and of restraint systems can logically be organized into those which can be accomplished within a period of twenty-four months (near term) and those which are suggested for future implementation when the necessary tests, production feasibility, and cost/benefits criteria are firmly established.

Near Term

The recent concern regarding impact between the front and rear seat occupants with the upper torso restraint worn by the front seat occupant could have been minimized had additional energy absorption been included in the upper torso restraint. If the energy which is irreversibly absorbed by the system is increased, there is every reason to believe that additional benefits in occupant impact reduction will be markedly increased.

Based on the available literature and our computer model studies it is suggested that a performance standard be established regarding the energy-absorbing capability of the anchor point-belt system. This would include the anchors, fasteners, belts and associated hardware in the total system.

Thus, it is proposed that the energy absorbed irreversably by the belts and anchor points for each model vehicle, when dynamically loaded and unloaded to a peak load of 80% of the 5,000-lb maximum of the present system, be doubled for the corresponding 1970 model vehicles. This should be done in a manner which will limit the deformation so that the occupant shall not contact the vehicle interior in a manner different from the previous year. This will allow the automobile manufacturers complete freedom of design in meeting the requirement and yet set a realistic level to be obtained with regard to impact attenuation. It should stimulate new research on the part of the companies into the methods of achieving such a goal.

It should be noted that sufficient methods such as new webbing materials, mechanically acting devices, and techniques for introducing controlled deformation of the elements of system are presently available so that all manufacturers can meet the requirement. Since SAE standards which specify the test techniques for determining anchor point and belt performance are already in existence, the new test procedure should not place an undue hardship on the industry, technically. If there is sufficient reason to believe that additional benefits can be derived by increased energy absorption then the standard can be raised for future model years.

Long Term

For long term standards it is suggested that performance criteria be established which are coupled to impact survival for a given level frontal impact into an SAE barrier, a prescribed lateral impact, and a rear impact. Such a standard could be tied to the average performance of all vehicles in a particular prior model year. In following years the level of all vehicles produced could then be required to exceed the performance of the average vehicle in the base year. The standard could thus pyramid, building on previous years, until an acceptable level of protection had been achieved. This procedure would allow the manufacturer complete freedom of design choice and yet achieve the desired objective of increasing crash-worthiness of automobiles. For example, it might be possible for one manufacturer to meet the standard by using lap belts and shoulder harnesses while another might use only lap belts and a third no active restraint system at all. Thus the competitive situation would encourage active company research and promotion of a specific design concept to the buying public.

Although the criteria for evaluating vehicle performance are yet unresolved, there is every reason to believe that adequate biomechanical data will be forthcoming to provide such a performance index.

ECONOMICS MODEL (COST/BENEFITS CRITERIA)

One of the pressing needs of a program oriented toward developing material for future Federal standards is the development of the economic base required to justify the cost/benefits ratios for proposed improvements. This need was recognized in the statement of work for this contract and the preliminary model proposed here is a first attempt to develop such a sound base for digital computer simulation of varying occupant positions and restraint systems to rank the priority of adoption of new systems and evaluate the performance of existing one.

The model is treated in two segments: benefits and cost. When their ratio is greater than one, the device is considered to be acceptable.

Benefits

The computation of costs and benefits is best handled on an occupant-by-occupant basis except in the case where a given restraint system is constructed so as to be applicable to a number of occupants. In this case the hardware costs would be calculated on the basis of the minimum incremental unit basis.

The benefit derived from the installation depends on a number of probabilistic factors: whether the vehicle is involved in an accident, whether the occupant is occupying a given location, and whether the occupant is using the device. Given these probabilities the benefit is the value of the reduced probability of death plus the reduced probability of injuries in a nonfatal accident.

$$B_{ij} = P(A)P(J)P(U)\{[Po(D)-P_1(D)]Cd + [1-Po(D)]\sum_{k=1}^{m} Po(T_k)Ct_k - [1-P_1(D)]\sum_{k=1}^{m} P_1(T_k)Ct_k\}$$

where B_{ij} = expected benefit of i-th device in j-th position

$P(A)$ = probability of vehicle being involved in an accident

$P(J)$ = probability of j-th position being occupied.

$P(U)$ = probability of i-th device being used.

$Po(D)$ = probability of death without the device

$P_1(D)$ = probability of death with the device

$Po(T_k)$ = probability of sustaining a k-th type trauma without device

$P_1(T_k)$ = probability of sustaining a k-th type trauma with device

Cd = cost of death

Ct_k = cost of a k-th type trauma.

The model given was derived in the most rigorous manner possible in order to clearly indicate the areas in which data must be sought and to indicate if necessary the effect of any compromises which deficient data might produce.

Given the well-known limitations of data in the field, the model will still provide best estimates of the effectiveness of the systems. This may be further elaborated by providing secondary estimates showing the range of variation in the model for perhaps the .95 confidence interval.

Sources of the data are diverse. For national accident statistics and fatality data, present information sources such as state accident reports and NSC figures may be used. While these contain well-known sources of error, the proportion of fatal and serious personal injuries accidents indicated therein may be close to the true values.

As a supplement to this information the Institute's System Analysis Group has nearly completed the development of a comprehensive data bank on traffic incidents, including accidents, for Washtenaw County, Michigan. This data bank can provide a check against the accident figures for the national data and also provide valuable information on such problems as occupancy patterns in the automobile. With respect to injury data it is expected that the researchers will be able to draw upon current studies of the National Blue Cross and Blue Shield organizations concerning causes of hospitalization by cause and trauma type as well as the costs of such hospitalization. Further data will be derived from existing studies by the Public Health Service and other organizations.

With respect to the problem of useage of the devices well-defined data is primarily nonexistent. It is proposed that a series of survey-research type projects to indicate approximate values for this parameter be carried out. Furthermore, the results could be augmented with a sensitivity model with respect to this parameter. Standard economic data, while subject to difficulties of interpretation of interest primarily to the professional economist, should be readily available from standard government publications of the Bureau of Labor Statistics and the Office of Business Economics. Further sources may be derived from the large information bank of the University's Survey Research Center on consumer finances. The close working relationship between the staffs of the Highway Safety Research Institute and the Center should provide easy access to the available data plus invaluable counsel on the statistical problems.

Since the accidents do not occur at a single given point in time the parameters given in equation 1 should be related to time over the life of the vehicle. Given this formulation it is possible to state the present value of the benefits as

$$PU(B_{ij}) = B_{ij}e^{-rt}$$

where B_{ij} is as above

$PU(B_{ij})$ = present value of benefits

r = An interest rate

t = expected life-time of the vehicle

The parameters Cd and Ct_k are primarily economic data. The costs of a fatality, other than intangible losses such as the family's grief and the killed person's subjective valuation of his own life, are principally his lost earnings, his burial expenses, and the expenses of settling his estate. From these must be deducted the saving of his not consuming goods and services over the remainder of his heretofore expected life.

$$Cd = \sum_{\ell=0}^{t} \{[\frac{Y_\ell - C_\ell}{(1+r)^\ell}] + [B_\ell - \frac{B_t}{(1+r)^t}] + [E_\ell - \frac{E_t}{(1+r)^t}]\}$$

where Cd and r are as above and

Y_ℓ = earnings in year ℓ

C_ℓ = consumption year ℓ

B_ℓ = burial expenses in year ℓ

B_t = burial expense in year t

E_ℓ = estate expenses in year ℓ

E_t = estate expenses in year t

t = number of years till death otherwise

The measurement of consumption is a far from settled issue either in economic theory or practice. Given this uncertainty, one is reduced to making arbitrary definitions and assumptions. For the sake of convenience, we will accept the definitions of consumption used by the Bureau of Labor Statistics in their budget studies.

With respect to the specific problem at hand, there is a separate problem of measuring the consumption attributable to a particular individual. If society were composed of autonomous individuals, the determination of consumption for the individual would be a simple matter of determining what the consumption would be given his age, income, education, and geographic area. However, most individuals in society are associated with collective consumption units enjoying the benefits of joint consumption and of certain economies of scale.

Since there is no rational means of allocating joint costs, the measure of consumption must be confined solely to the consumption attributable to the given family member. As a practical matter, there are only a few means of achieving this attribution. One way is to compare consumption of families differing only in the presence or absence of the given individual under consideration; i. e., families in the Northeast with three and four children respectively. Alternatively, we could, on the basis of budget studies, impute certain expenditures to the given family member and assume that all other family consumption items were joint costs. Lacking the data for the above analysis, we could assume that x% of the family's expenditures were jointly consumed and that y% of them could be directly attributable to the given individual and then perform the analysis on the basis of the assumed percentages. Specific classes of family members should be considered for any seeming differences in the model suggested above.

a. The father, or principal income earner. The death of the father would reduce the family's consumption by at least the amount of the consumption directly attributable to him. The total family consumption will probably drop more than the preaccident consumption of the father alone due to the loss of his income. Initial consideration might indicate the we should measure this total drop in consumption, due to the income effect, but this would not be correct for the following reasons. First, it would be empirically difficult to determine the magnitude of this change. Second, it would be inconsistent with the model for individual imputation. Third, it would involve a form of double counting in that we are concerned with attempting to measure the net social loss; to indicate that the net social loss was reduced by its causing losses to a third party, the family, would involve a contradiction. It is true that the family suffers a reduction in consumption, but this is simply because they bear directly the loss of social output represented by the father's income. The logic of this can be more clearly seen if we consider two independent individuals, A and B. If A is removed from the labor force, net output drops; since this output has fallen, there is less for B to consume. Clearly, that B consumes less because there is less to consume does not represent a saving. Fourth, given the necessary partial nature of the analysis, it is necessary to cut off effects of the accident at some arbitrary point. Deprived of the father's income, the children might obtain a less complete education and thus would be less productive, entailing further social losses. Since this is primarily a matter of speculation, though, a more conservative and sound approach would simply be to measure what can be readily determined.

b. The mother's consumption poses no particular problems beyond that of the father's. However, her income may be rather difficult to estimate. If she were simply a housewife, on first approximation her income would be zero, but this would not measure the opportunity cost of her being lost to society. A more valid procedure would be to impute an income to her equal to that for female employees of the same age and education, since this would represent the income that she would have foregone to be a housewife and, consequently, must be an indication of the value of her services to the family.

c. In the short run, the consumption of dependent children is the easiest to estimate since it only involves determining the differences in consumption between families with n and n-1 children. For the expected lifetime loss from the death of the child, it is more difficult to determine. While sociological techniques may permit extrapolating the child's future income and consumption from that of the parents, it is still economically uncertain what path these parameters will take beyond approximately his eighteenth birthday. Beyond this point we would have to attribute to the child an income and consumption equal to the national per capita figures for each age bracket of his expected life.

From a data standpoint Ct_k cost of the k-th type trauma is a somewhat more involved variable. The principal elements of cost are the victim's medical expenses, loss of earnings, and additional consumption expenditures. There is a further problem of definition of recovery time and differentiation between costs of death and injury in the case of an individual who is not immediately killed, but whose injuries subsequently prove fatal. The arbitrary definition will be applied that any victim who does not expire within one month after the accident will be said only to have been injured. His subsequent death will be handled by appropriate variation of the parameters given below. The time to recovery shall be defined as that time when identifiable injuries cease.

$$Ct_k = \sum_{\ell=0}^{t} \frac{Y_\ell - Y'_{\ell k}}{(1+r)^\ell} + \sum_{\ell=0}^{t} \frac{C'_{\ell k}}{(1+r)^\ell} + \sum_{\ell=0}^{t} \frac{M_{\ell k}}{(1+r)^\ell}$$

where Ct_k, r, Y are defined as above and

$Y'_{\ell k}$ = income earned after returning to work after sustaining a k-th trauma in time period ℓ

$C'_{\ell k}$ = additional consumption necessitated by k-th type trauma in time ℓ

$M_{\ell k}$ = medical expense incurred in treating k-type trauma in time ℓ

The cost of the system or i-th device in the j-th position are far more straightforward. In the case of a device which may be installed in the j-th position for one cost and in the (j + 1)-th position for another, they may be combined in such a manner that the costs of installing both jointly are less than the sum of the individual positions, i. e.,

$$C_{ij} + C_{i,j+1} C_{(ij+i,j+1)}$$

Analysis should be conducted in terms of the devices independently and jointly. The cost of the devices is the sum of their hardware cost amortized over the life of the vehicle plus the cost of any device-induced injuries or deaths. This second cost should be clearly separated from the other past device injuries in concept.

$$PU(C_{ij}) = \sum_{\ell=0}^{t} \frac{CH_{ij}(\frac{t-\ell}{t}) + P(A)P(J)P(U)}{(1+r)^{\ell-1}} \{P_I(D)Cd$$

$$+ [1-P_I(D)] \sum_{k=1}^{m} P_I(T_k)Ct_k\}$$

Where P(A), P(J), P(U), Cd, Ct_k, and r are as above

and $PU(C_{ij})$ = present value of the cost of the i-th device installed in the j-th position

CH_{ij} = equipment cost of the i-th device in the j-th position

$P_I(D)$ = probability of device-induced death

$P_I(T_k)$ = probability of device-induced trauma of type k

While it leaves much to be desired, the simple cost-benefit ratio would seem to be appropriate for first approximations. A device which satisfied the criterion that

$$\frac{PU(B_{ij})}{PU(C_{ij})} > 1$$

would be considered acceptable. For purposes of ranking systems care must be excercised in choice of interest rates and in the absolute magnitudes involved because the cost of adopting a device which was expensive enough to affect significantly the cost of the vehicle might well affect the parameters, especially those involving use of the device and vehicle demand, which determine the benefits.