

Simulation Optimization of the Crashworthiness of a Passenger Vehicle in Frontal Collisions using Response Surface Methodology

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ABSTRACT

Although computer simulation is regarded primarily as a tool for systems analysis, simulation can also be used in the process of systems optimization. This paper describes recent enhancements to a computer program package which enables the use of vehicle and occupant simulation models in determining the design of vehicles and restraints for maximum occupant impact protection. Also described is an application of this program package to determine the optimal design of a passenger vehicle involved in frontal collisions.

SINCE 1975, the National Highway Traffic Safety Administration (NHTSA) has sponsored research concerning the optimization of passenger vehicle designs for maximum crashworthiness. The approach adopted relies upon developing polynomial approximating functions for the response surfaces of vehicle and occupant simulation models. These approximating functions describe the simulated relationships between changes in a set of vehicle and restraint-system design variables and the corresponding changes in summary measures of vehicle and occupant dynamic responses, over a wide variety of accident conditions. A direct-search, constrained optimization algorithm employs these approximating functions to determine the levels of the design variables which minimize the aggregate expected social cost of injuries and fatalities associated with collisions involving the design vehicle.

The simulation optimization approach is embodied in a computer program package called the Safety Systems Optimization Model (SSOM). The SSOM currently comprises several accident and biomechanical databases, as well as eighteen major computer

programs. Major components of the SSOM include simulation models of the structural response of colliding vehicles; simulation models of the dynamic response of vehicle occupants; an experiment-design and regression-analysis package for developing approximating functions; an evaluation program for determining occupant injury levels and corresponding social costs; optimization routines for determining preferred vehicle designs; and various routines for model verification and validation, sensitivity analysis, and report generation.

The purposes of this paper are to (1) outline the current implementation of the SSOM and (2) to report a benchmark application of the simulation-optimization approach to the design of a passenger vehicle for maximum safety performance in frontal collisions. The SSOM was initially developed at the Ford Motor Company, during the period from 1975 through 1978 [1-3]*. Since that time, extensive modifications and refinements to the original program package have been implemented by researchers at the University of Virginia [4-9]. Major modifications of the SSOM include the incorporation of new AIS-based biomechanical transforms and new accident data bases using data from the National Crash Severity Study (NCSS) file. Details of the current biomechanical transforms and accident databases are given here. In addition, new features for univariate and multivariate sensitivity analysis and for accident-distribution report generation are demonstrated.

The application presented here is an extension and refinement of a prior study [10,11] and addresses many of the issues unresolved at that time. The application considers a 3000 lb automobile equipped with 3-point belts operating in the current U.S.

*Numbers in brackets designate references at the end of paper

accident environment. Application of the new sensitivity analysis features, together with comparisons of results of this study with results obtained by other researchers, permits the conclusions of the previous study to be significantly extended.

Results of the study reported here provide new insight into the relationship between structural and restraint requirements when the performance of the vehicle is considered from the perspectives of all accident victims involved in design-vehicle frontal collisions. Specifically, the need to balance the conflicting objectives of minimizing the aggressiveness of the design vehicle, while maximizing the protection of design-vehicle occupants, appears to favor a less aggressive structural design with correspondingly stiffer belts. The preferred structural design provides for maximum available crush and a progressive collapse structure, with relatively softer foreframe and relatively stiffer sheetmetal and aftframe. This preferred structure also appears to be relatively insensitive to belt-usage rates. Results of the study further indicate that the optimal design is relatively insensitive to univariate changes in the collapse forces of the occupant contact surfaces. We speculate that this is at least in part because of the stiffness of the restraints and in part because of distribution of accident exposures across seating position, impact mode, collision speed, and occupant stature.

PROBLEM STATEMENT

The problem addressed in this paper may be stated formally as the following nonlinear program:

$$\min_x S(x,u) = \sum_{i=1}^n p_i s_i(x,u) \quad (1)$$

$$\text{s.t. } w(x) \leq w_{\max} \quad (2)$$

$$c[x,w(x)] \leq c_{\max} \quad (3)$$

$$x_{\min} \leq x \leq x_{\max} \quad (4)$$

The objective expressed in Eq. (1) is to select the value of the vector of design variables x that minimizes the total social cost of injuries and fatalities $S(x,u)$ for a given level of belt usage u . Total social cost is defined as the sum of the average annual social cost of injuries and fatalities $s_i(x,u)$ for each of $i=1,2,\dots,n$ accident encounters, each encounter weighted by the correspond-

ing annual expected frequency of exposure p_i . The weight of the design $w(x)$ is constrained to a maximum w_{\max} in Eq. (2) and the cost of the design $c(x)$ (including the cost of materials substitution to reduce weight, if necessary) is constrained to a maximum c_{\max} in Eq. (3). The design itself is constrained to the feasible region of the design space, defined by the vectors of minimum x_{\min} and maximum x_{\max} design values in Eq. (4). This nonlinear program is solved for each of $j=1,2,\dots,m$ belt usage levels $0 \leq u_j \leq 100\%$ to determine the sensitivity of the optimal design $x_{\text{opt}}(u_j)$ and corresponding total social cost $S[x_{\text{opt}}(u_j), u_j]$ to assumed belt usage rates.

DESIGN VARIABLES

The design variables x selected for this study are divided into two categories. Structural variables refer to selected properties of the front structure of the design vehicle. Occupant variables refer to selected properties of the occupant restraint system and the occupant-compartment contact surfaces.

Figure 1 depicts a one-dimensional lumped-mass model of a vehicle during front-to-fixed-object collisions. Design variables for the present study describe selected parameters of the quasi-static force-deflection curves which define the properties of the nonlinear, energy-absorbing springs (EA's) connecting the masses. These variables are:

- X_1 = constant collapse force of EA46 (foreframe)
- X_2 = constant collapse force of EA34 (aftframe)
- X_3 = constant collapse force of EA37 (sheetmetal)
- X_4 = available crush length of EA46 (foreframe)
- X_5 = available crush length of EA34 (aftframe)

The remaining parameters of the lumped-mass models are fixed at baseline values. For this study, baseline values are for a 1975 Ford Pinto. These values were determined from barrier crash tests of the vehicle and from controlled crush tests of each significant structural member by Ford [1].

Figure 2 depicts a two-dimensional lumped-mass model of a driver restrained by three-point belt. The occupant interacts with the vehicle through the belt system, through the seat back and cushion, and through a set of contact surfaces representing the profile of the interior of the occupant compartment. Occupant design variables for the present study describe selected parameters of the dynamic force-deflection curves which define the properties of the

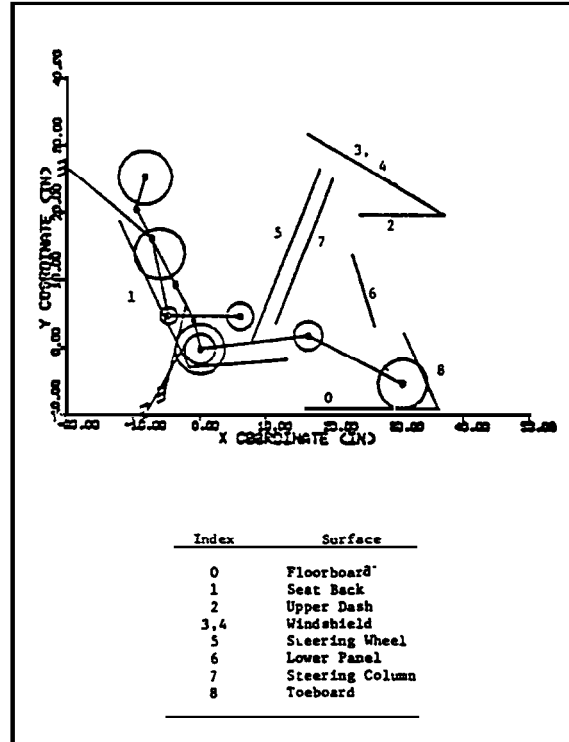
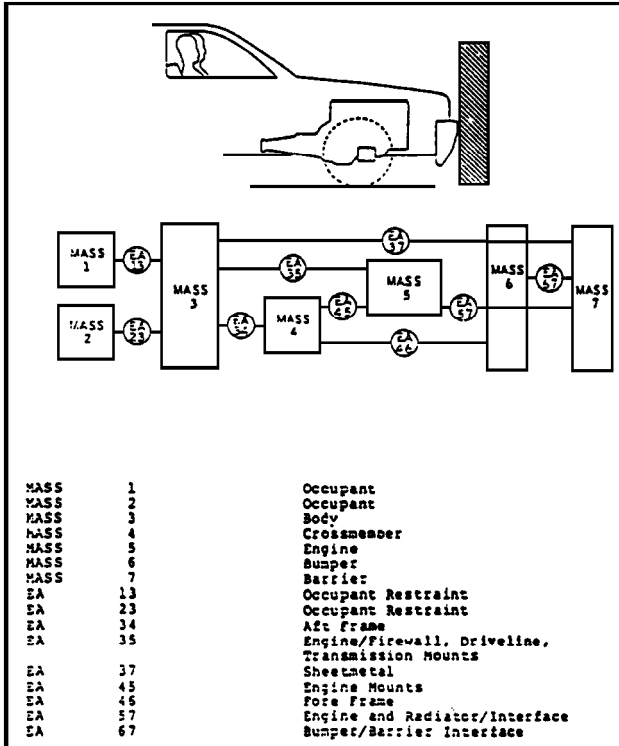


Figure 1. One-dimensional lumped-mass model of the passenger vehicle front end, showing design variables.

Figure 2. Two-dimensional lumped-mass model of the occupant and occupant compartment, showing design variables.

belts and contact surfaces. These variables are:

- X_6 = stiffness of the belts
- X_7 = constant collapse force of S7 (steering column)
- X_8 = constant collapse force of S2 (upper instrument panel-driver side)
- X_9 = constant collapse force of S6 (lower instrument panel--driver side)
- X_{10} = constant collapse force of S2 (upper instrument panel--passenger side)
- X_{11} = constant collapse force of S6 (lower instrument panel--passenger side)

The remaining parameters of the occupant models are fixed at baseline values. For this study, the baseline values are for a 1975 Ford Maverick. These values were determined by Ford [1-3].

APPROXIMATING FUNCTIONS

Occupant and vehicle responses are determined from a set of approximating functions which represent the response surfaces of corresponding occupant and vehicle simulation models. These approximating functions are third-order polynomial equations of the form

$$y = b_o + \sum_{p=1}^k b_p z_p + \sum_{p=1}^k \sum_{q=1}^k b_{pq} z_p z_q + \sum_{p=1}^k \sum_{q=1}^k \sum_{r=1}^k b_{pqr} z_p z_q z_r$$

where y is the (transformed) response variable, z_p are the k (coded) predictor variables, and the b_p , b_{pq} , and b_{pqr} are constants. For frontal collisions a total of twenty-one approximating functions, one for each parameter describing the occupant and vehicle responses, are required.

The significant structural response of a vehicle is described by the vehicle deceleration profile or "crash signature". Vehicle deceleration profiles determined from the vehicle crash simulations are approximated by the piecewise-linear TESW (Tipped Equivalent Square Wave), as shown in Figure 3. While apparently crude, the TESW has been shown [12] to provide a consistently accurate summary of the vehicle response (the so-called "first collision") as this response is transmitted to the vehicle occupants (the so-called "second collisions"). The TESW has the advantage that it can be completely specified by four parameters which are easily identified from the simulated deceleration

profiles. These parameters are:

- V_o = vehicle initial velocity
- V_r = vehicle rebound velocity
- X_{max} = maximum dynamic crush
- t_m = time to maximum dynamic crush

Since the initial velocity is an input parameter of the simulation, three approximating functions in general are required to specify the remaining vehicle response variables. (For barrier collisions only two approximating functions are required, since t_m can be calculated from the remaining variables for this case). Separate approximating functions are required for car-to-fixed-object collisions and for car-to-car collisions, for a total of eleven vehicle approximating functions for frontal collisions.

The predictor variables for the vehicle approximating functions are the five vehicle design variables defined in the preceding section, together with the closing speed and weight of the other vehicle for car-to-car collisions. The coefficients of the vehicle approximating functions are determined by multiple, stepwise, least-squares regression on design/response data derived by simulating collisions for each replication in a specified experimental design. As many as two-hundred simulation runs and polynomials with as many as eighty terms are required for accurate representation of the vehicle simulation response surfaces.

The significant response of occupants during collisions is determined by the deceleration profiles of each occupant's head and chest. Deceleration profiles for the occupant head and chest body segments determined from the occupant crash simulations are each summarized by a standard injury measure. These are HIC (the Head Injury Criterion) and CSI (the chest severity index), defined as

$$HIC = \max_{(t_2 > t_1)} \left[\left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a_h(\tau) d\tau \right]^{2.5} (t_2 - t_1) \right]$$

$$CSI = \left[\int_{t_1}^{t_2} a_c(\tau)^{2.5} d\tau \right]$$

where a_h is head acceleration in g's and a_c is chest acceleration in g's. For HIC, t_1 and t_2 are any two points in time during the collision such that $t_2 > t_1$. For CSI, t_1 and t_2 are the initial and final times of the collision, respectively. These measures have been shown to provide a consistently

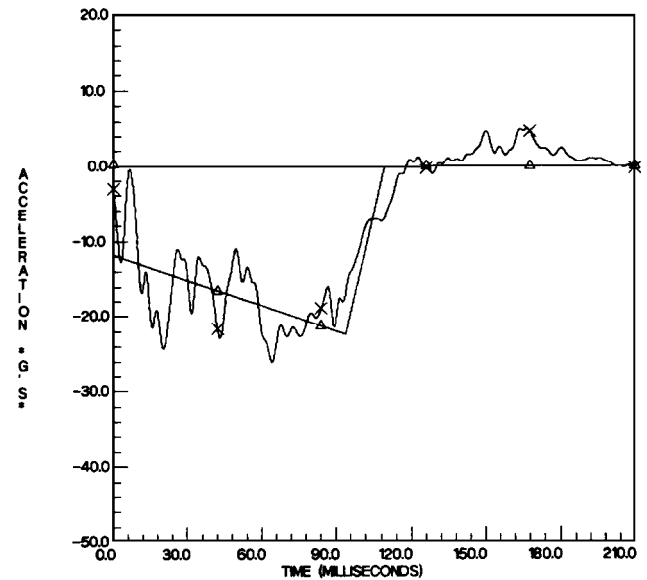


Figure 3. TESW (Tipped Equivalent Square Wave) approximation of the vehicle crash signature.

accurate summary of occupant response for the purpose of determining the extent and severity of injuries resulting from frontal impacts. Separate approximating functions are required for drivers and passengers and for restrained and unrestrained occupants for frontal impacts, while a single approximating function represents all drivers and passengers (whether or not restrained) for side impacts. This represents a total of ten occupant approximating functions.

The predictor variables for the occupant approximating functions are the six vehicle design variables defined in the preceding section, together with the five vehicle response measures and the occupant height class. The coefficients of the occupant approximating functions are determined by the same procedure used to derive the vehicle approximating functions, using multiple, stepwise, least-squares regression on design/response data derived by simulating collisions for each replication in the experimental design.

BIOMECHANICAL AND SOCIAL COST MODELS

The social cost of an individual collision $s_i(x,u)$ is determined from vehicle and occupant dynamic response measures by two related transformations. First, for each occupant, an overall measure of injury severity (the expected average injury level) is determined by aggregating two independent measures of injury severity derived from the two independent occupant dynamic response measures. This transformation is called the biomechanical transform. Second, the social cost of the collision is deter-

Table 1. Weighting coefficients for *rcm* calculation (after Hollowell [15]).

AIS number	Severity code	Absolute social cost (\$)	Weight
6	unsurvivable	287,175	1.0000000
5	critical	192,240	0.6694176
4	severe	86,955	0.3027945
3	serious	8,085	0.0281536
2	moderate	4,350	0.0151476
1	minor	2,190	0.0076260

mined by aggregating the overall measures of injury severity for each occupant of each vehicle involved in the collision. This transformation defines the SSOM unit of social cost or, equivalently, the SSOM measure of vehicle crashworthiness.

For frontal collisions, the biomechanical transform relies upon determining the maximum average expected AIS (abbreviated injury scale [13]) number for an occupant resulting from one of two causes: (1) injuries sustained to the head, AIS_h , and (2) injuries sustained to the chest, AIS_c . Intrusion effects are considered implicitly (see [14] for the potential limitations of not explicitly accounting for intrusion effects). The average expected AIS_h and AIS_c for an occupant are determined from HIC and CSI using the curves depicted in Figure 4. The overall AIS number (OAI) is set to the maximum of the two AIS values as

$$OAI = \max [AIS_h, AIS_c]$$

HIC and CSI are determined from the corresponding approximating functions.

The social cost of the accident to the occupant is calculated using the OAI number by interpolation on the table of weights depicted in Table 1. The weighting coefficients are intended to represent the social cost of injuries for the corresponding OAI number relative to the social cost of injuries classified as AIS=6 (injuries which always result in a fatality). The unit of (relative) social cost in this calculation is called the *rcm*, (relative crashworthiness measure).

The *rcm* is the fundamental unit of (relative) social cost in this method of evaluation and the total number of *rcm*'s associated with a vehicle design is used as a figure of merit for assessing the crashworthiness of that design. The total number of *rcm*'s associated with a design is the sum of the annual expected number of *rcm*'s resulting from each type of accident involving the vehicle. This expectation is achieved by weighting the number of *rcm*'s for a single encounter of that accident type by the

annual expected frequency of occurrence of that accident type in Eq. (1). The number of *rcm*'s for a single encounter, in turn, is the sum of the *rcm*'s sustained by each of the occupants of each of the vehicles involved in the corresponding collision, as calculated by the method described in this section.

ACCIDENT ENVIRONMENT

The accident environment for which the design vehicle is optimized in the current study includes accident encounters in which the design vehicle is a 3000 lb striking vehicle in front-to-front, front-to-side, and front-to-fixed object collisions. Accident exposure data are derived from a range of sources [1-3,17,18] as reported by Pilkey and White [4]. Data approximating the current U.S. accident environment are given in Table 2.

RESULTS AND DISCUSSION

The problem described in the preceding section was solved using the SSOM program package. Five

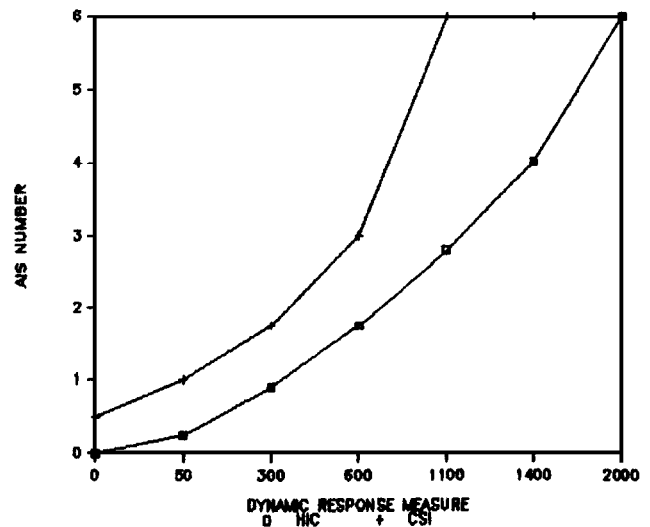


Figure 4. Biomechanical transform of the occupant summary response measures into occupant injury severity numbers (note irregular scale).

Table 2 Accident exposure of a striking passenger vehicle as a percentage of all frontal collisions.

	Other Vehicle					Total
	None	20001b	30001b	40001b	50001b	
Front-to-fixed object	42.1					42.1
Front-to-front		2.7	2.4	3.1	4.4	12.6
Front-to-side		9.7	8.6	11.0	16.0	45.3
Total	42.1	12.4	11.0	14.1	20.4	100.0

optimizations were completed using a modified Box algorithm and assuming belt usage rates of $u = 0, 25, 50, 75,$ and 100% , respectively. These usage rates apply to all occupants of all vehicles for a given optimization. In addition, for each optimization, weight was constrained to a maximum of 180 lb above the weight of the baseline vehicle and cost (including the cost of materials substitution to reduce weight) was constrained to a maximum of \$300 (at 1976 materials costs) above the cost of the baseline vehicle. Separate SSOM evaluations of the baseline vehicle at each belt usage rate were made for comparative purposes.

In the following sections, results of the study are examined and, where possible, comparisons with published results from other studies are drawn. Four areas are of principal interest: (1) the overall crashworthiness of the vehicle for frontal collisions

and the relationships among social cost, belt usage rate, and design optimization; (2) the optimal vehicle design and the relationships among structural requirements, restraint requirements, and belt usage; (3) the sensitivity of the optimal design to variations in design variables and the relationships between these sensitivities and the distribution of accident exposures in terms of seating position, impact mode, and condition of restraint; and (4) the distribution of injuries and injury reductions for the optimized design between the design vehicle and other vehicles for various collision modes.

OVERALL CRASHWORTHINESS--Figure 5 shows the substantial benefits both of increasing belt usage and optimizing vehicle design. For both baseline and optimal designs, social cost is monotonically decreasing with respect to increasing belt usage. For all belt usage rates, optimization

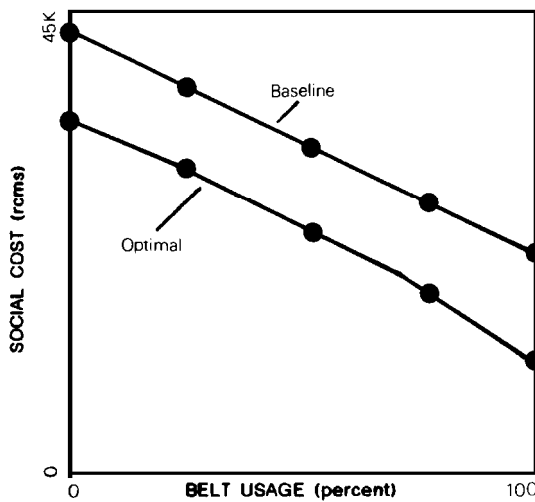


Figure 5. Social cost of injuries and fatalities for the baseline and optimal vehicle designs.

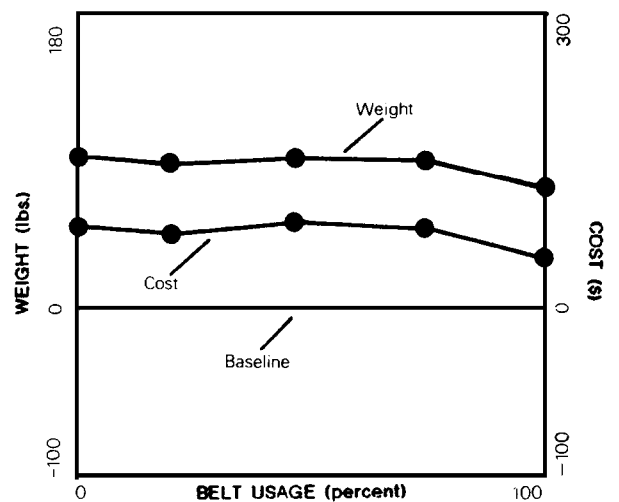


Figure 6. Weight and cost of the optimized vehicle above baseline vehicle design.

results in significant reductions in social cost from the baseline. Moreover, while social cost is a linear function of belt usage for the baseline vehicle, social cost is a concave function of belt usage for the optimized vehicle (a 6398 rcm or 14.7% reduction from the baseline at u=0% and a 10748 rcm or 46.3% reduction at u=100%). This suggests that while both increasing belt usage and optimizing vehicle design are highly desirable individually, adopting both approaches to injury mitigation simultaneously yields synergistic benefits. Stated somewhat differently, vehicle optimization can be more effective at reducing the social costs of injuries and fatalities when the occupant population is effectively restrained.

These trends appear to be reasonable and consistent with the limiting performance of structure and restraints under given constraints on design variability (see Zimmermann [19] and Hofferberth and Tomassoni [20]). Moreover, belt usage rates in the

U.S. are estimated to be between 10% and 18% and reductions of 25% in fatalities and 50% in injuries are thought to be possible if all occupants were belted (see Geller, et al. [21] and Campbell [22]). These figures compare favorably with reductions of 40-45% in social cost predicted by the study for similar changes in belt usage for the baseline design.

STRUCTURAL DESIGN--Figure 7 shows the optimal values of the four structural design variables for different levels of belt use. The optimal design is highly sensitive to foreframe force level and crush length and relatively less sensitive to sheetmetal and aftframe force levels. Relative to the baseline, the optimal front end is longer, softer in the front, and stiffer in the rear. This is what we have referred to as a "progressive collapse structure". This preferred structural design appears to be relatively insensitive to belt usage rate, except that the preferred aftframe force level

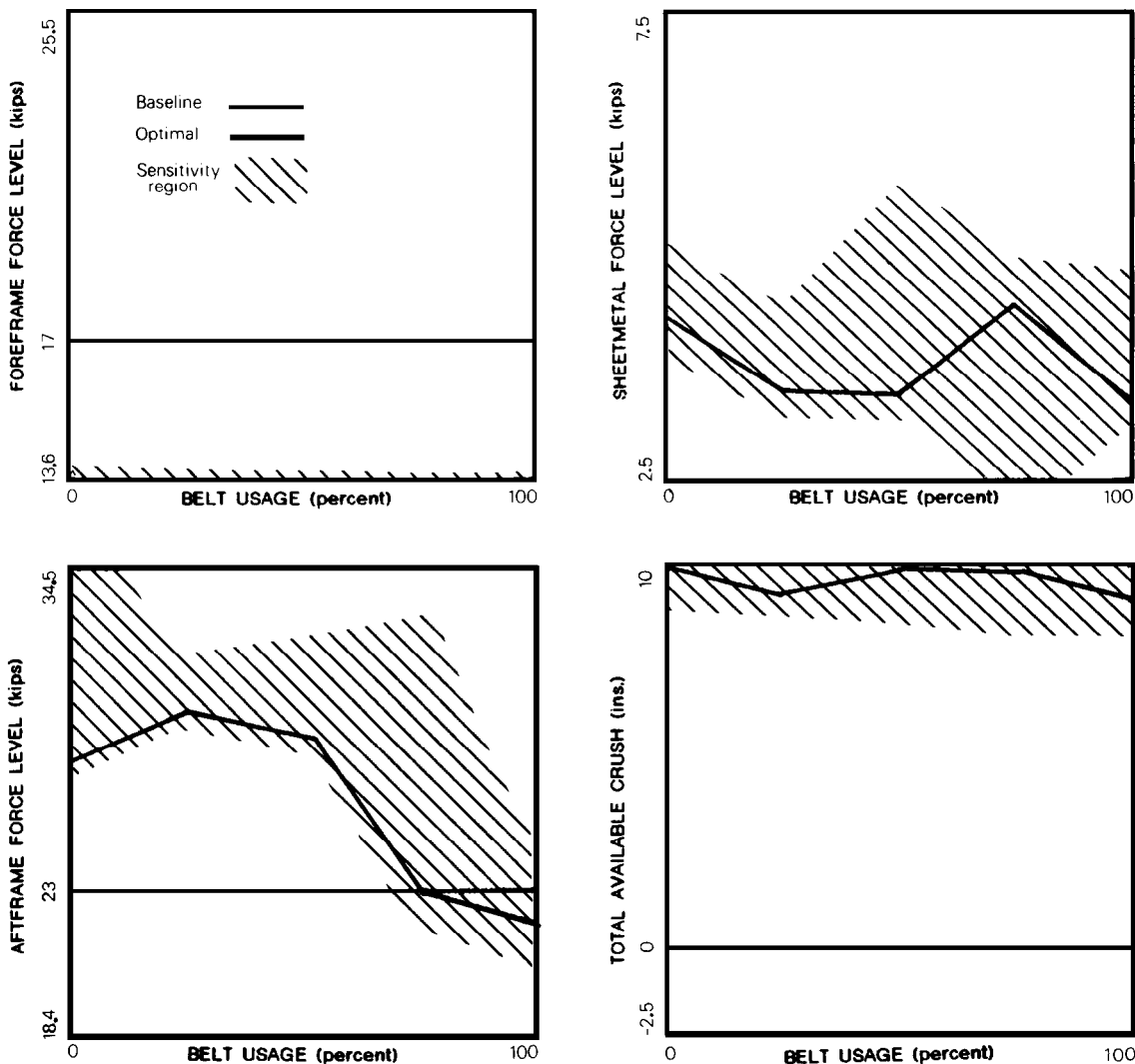


Figure 7. Optimal values of the structural design variables as a function of belt usage rate.

appears to decrease moderately as a function of increasing usage.

The optimal structural design determined here is both intuitively appealing and in general agreement with previously reported studies. In terms of available crush length, it appears to be universally accepted [19,20,23] that for improved crashworthiness crush length should be made as great as is consistent with good vehicle handling. Since neither weight nor cost constraints are binding at any usage level (see Figure 6), the crush length is at this expected design maximum. The progressive collapse structure of the design appears to provide a unique solution to the three basic requirements for prevention of death or serious injury defined by Hofferberth and Tomassoni [20]:

- (1) the structure must be sufficiently "soft" to prevent excessive acceleration loads to the occupant,
- (2) the structure must be sufficiently "hard" to maintain occupant compartment integrity, and
- (3) the vehicle must not be accessively aggressive to any other vehicle when involved in a car-to-car crash.

These three requirements must be balanced by the vehicle design, in an effort to make the design as compatible as possible with its own restraint system and with (its exposure to) the vehicle fleet. This balance is provided in the progressive collapse structure by softening the foreframe to achieve requirements (1) and (3), while stiffening the aft-frame to achieve requirement (2).

RESTRAINT SYSTEM AND OCCUPANT COMPARTMENT DESIGN--Figure 8 shows the optimal values of the six occupant variables for different levels of belt use. In comparison with these structural variables, the optimal design appears in general to be less sensitive to univariate changes in the occupant variables. The principal exceptions to this are belt stiffness and lower panel collapse force (driver side). Relative to the baseline, stiffer belts and softer steering columns are preferred at all levels of belt usage. Harder upper panel and softer lower panel are indicated for the driver side for low belt usage rates, with a decided preference for increasing the lower panel stiffness as restraint usage increases. On the passenger side, a softer interior is preferred, with a trend toward increasing upper panel stiffness at the highest usage rates.

To a greater degree than the structural variables, the occupant variables appear to exhibit some sensitivity to belt usage rate. Higher usage

appears, in general, to permit some strengthening of the occupant compartment. This trend is most apparent in the lower panel on the driver side. Belt stiffness alone appears to remain almost invariant at different usage rates. This can be explained by the considerable body of evidence relating vehicle crush and occupant restraint system design [19,20,23]. Stiffer belts serve to decelerate the occupant in the initial phase of the crash, in order to use as much of the significant increase in available crush made possible by the progressive collapse structure of the optimized front end.

UNIVARIATE SENSITIVITY ANALYSIS--

Additional results were obtained in conjunction with postoptimality analysis. For the optimal design at each belt usage rate, a univariate sensitivity analysis was conducted. Evaluations of the optimal design were completed where each of the design variables was varied from its minimum to maximum value, in variable increments, one variable at a time, all other variables remaining at optimal values. Results (not shown) confirm that the approximate optimal design was found in each case. For each variable at each belt usage rate, the 5% relative sensitivity bounds determined from this analysis have been plotted as the sensitivity region in Figures 7 and 8. This region defines the range of variation of the variable about its optimal value for which the gains from the optimization are reduced by no more than 5% (assuming all other variables remain optimal). Absolute sensitivity bounds are themselves sensitive to belt usage rates (since the extent of injuries and fatalities associated with the baseline vehicle is a function of belt usage). The 5% relative sensitivity bounds correspond to 0.859% absolute sensitivities at the zero belt usage rate and to 4.32% absolute sensitivities at the 100% usage rate.

The results of a univariate sensitivity analysis of the optimal vehicle designs shown in Figures 7 and 8 indicate that the optimal design is more sensitive to single-variable variations in the unified design of the front end and restraint system, than to corresponding changes in the design of interior contact surfaces. Results of the multivariate analysis (given in the next section) confirm that the greatest improvement in crashworthiness from the baseline design can be attributed entirely to three variables: the foreframe collapse force, the total available crush length, and the stiffness of the belts. This improvement ranges from nearly 60% of the total improvement at zero belt usage, to 90% of the total at the 75% usage rate.

These results may be explained in part simply on the basis of accident exposure data, as shown in Table 3. Note that while all victims are potentially affected by changes in the front structure of the design vehicle and 51.3% by changes in the belts,

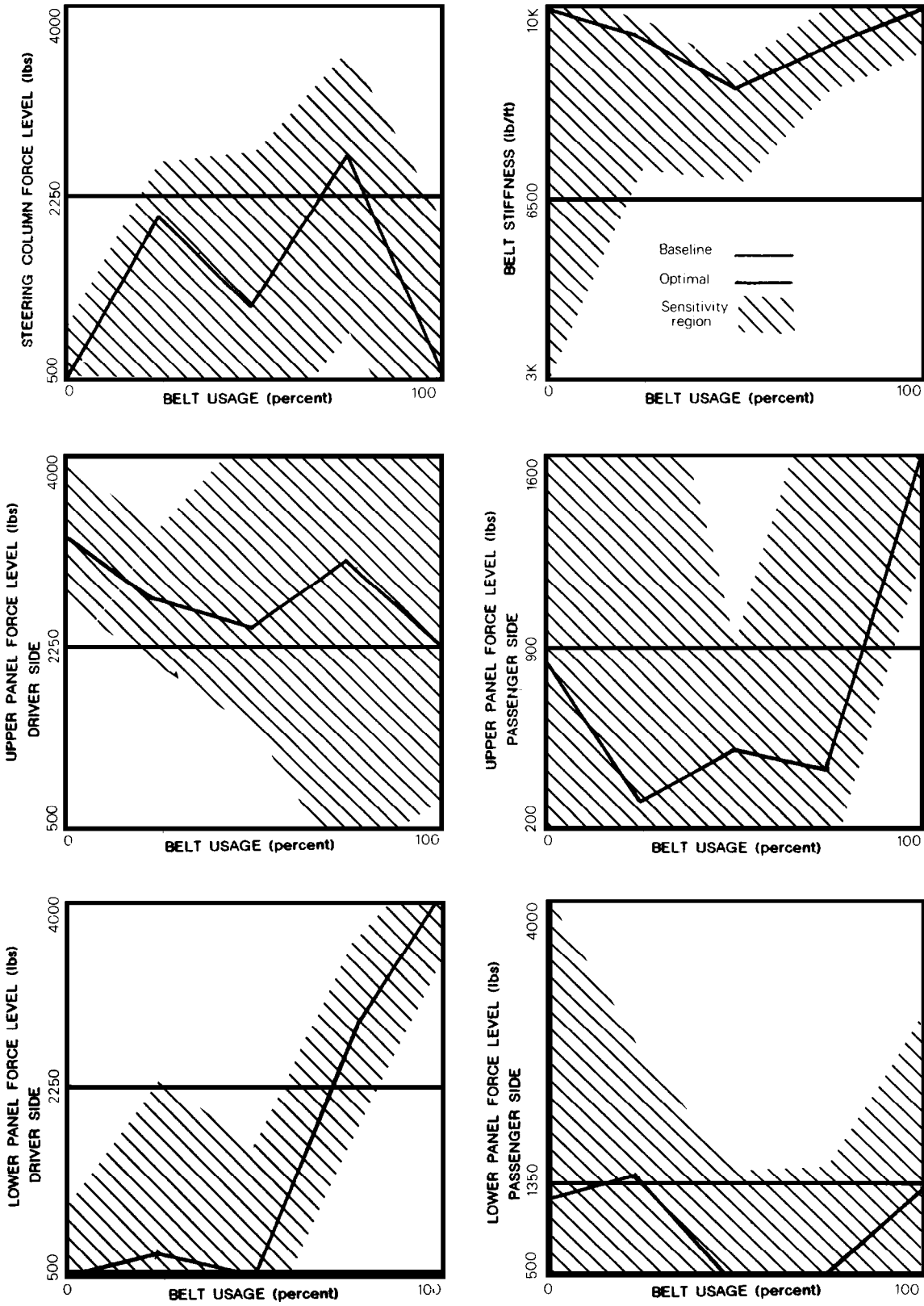


Figure 8. Optimal values of the occupant design variables as a function of belt usage rate.

Table 3. Distribution of accident exposures disaggregated by cross-impacts of effective design variables.

	Structural variables X ₁ -X ₅	Belt stiffness X ₆	Driver side variables X ₇ -X ₉	Passenger side variables X ₁₀ -X ₁₁	Percent of all victims
Design vehicle driver front impact	X	X	X		26.3%
Design vehicle passenger front impact	X	X		X	25.0%
All other victims	X				
Percent of all victims	100%	51.3u%	26.3%	25.0%	100%

only about a quarter of all victims will experience any affects from the other occupant variables. Moreover, for nearly half the accident victims the *only* means for injury mitigation rely on improving the design vehicle structure. This observation is supported in part by Zimmerman [19], who found that "side impact protection can be greatly improved by adequately designing the front end of the striking vehicle" and that "lowering the deformation energy in the upper part of the front-end/hood and upper wheelhouse improves side impact protection without having a major negative effect on front impact protection."

We suspect that these result also can be explained in part by a process of smoothing or averaging of the optimal occupant compartment design across occupant stature, impact speed, and restraint condition. While Zimmermann [19] and Hofferberth and Tomassoni [20] suggest that, when designed in conjunction with appropriate restraints, vehicle

structural designs can be found that perform well over a wide range of accident encounters, the same may not be entirely true of the occupant compartment. Thus, what is best for one occupant in one accident encounter may well average with what is best for that same occupant in another encounter or for an occupant of different stature in the same encounter. Preliminary results of model tests of the steering column confirm that this may well be the case.

It should be emphasized that these results do not imply that the design of the occupant compartment is immaterial to vehicle crashworthiness. The worst case suboptimal design, described in the following section, shows that there exist designs which are unsafe for most occupants and, indeed, suggests just how diastereous improper occupant compartment designs can be. Rather it appears that there is a region in the design space--a region which includes both the baseline and optimal designs--for which efforts to improve structural and restraint system design pre-

Table 4. Comparison of social cost of baseline, optimal, and suboptimal designs as a function of belt usage rate

Belt usage rate (1)	Baseline design (rcms) (2)	Optimal design (rcms) (3)	Suboptimal design (rcms) (4)	Col. (2)-(3) (rcms) (5)	Col. (2)-(4) (rcms) (6)	Col. (6)/(5) x(100%) (7)
0%	43644	37246	39963	6398	3681	57.5%
25%	38533	32310	33588	6223	4945	79.5%
50%	33422	26208	27733	7214	5689	90.0%
75%	28311	20386	21182	7925	7129	90.0%
100%	23199	12451	14840	10748	8359	77.8%

dominate those which would further improve the occupant compartment.

MULTIVARIATE SENSITIVITY ANALYSIS-

Because the univariate analysis indicated that the optimal design was relatively insensitive to the majority of design variables when varied one at a time, a multivariate sensitivity analysis was undertaken to determine the effects of combined changes in these variables. A new, partially optimized design was defined and evaluated. This suboptimal design consisted of the three most sensitive univariates (foreframe force level x_1 , crush length x_4 plus x_5 , and belt stiffness x_6), set to optimum values as previously determined and the remaining design variables reset to baseline values. The results of these evaluations are shown in Table 4.

To determine whether or not this suboptimal design was at all sensitive to the nonoptimal variables, the worst-case suboptimal design was determined by fixing foreframe force level, crush length, and belt stiffness at optimal values, as before, and then maximizing social cost over the remaining design variables. The maximization forced aftframe, steering column, and driver upper panel forces to minima and sheetmetal, driver lower panel, and passenger upper and lower panel forces to maxima. Social cost increased to 68003 rcms, or 210% of the social cost of the fully optimized design.

INJURY DISTRIBUTIONS--In order to determine how improvements in crashworthiness are achieved as the result of design optimization and in order to consider the equity of distribution of the resulting benefits, the social cost of injuries and injury reductions was disaggregated along several dimensions. Figure 9 shows the social cost of injuries for the optimal design disaggregated by design-vehicle/other-vehicle occupants, by collision mode, and by weight class, each as a function of belt usage rate. Figure 10 shows the difference in social cost between the baseline and optimal vehicle designs disaggregated by design-vehicle/other vehicle victims, by accident mode, and by weight class.

Figure 9 shows a breakdown of the social cost of injuries and fatalities after design optimization, disaggregated by vehicle occupied, by collision mode, and by weight class, each as a function of belt usage rate. From the figure it is apparent that injury levels in the "other car" have a social cost of about 10,000 rcms, regardless of belt usage. This insensitivity to belt usage rate can be explained by the small proportion of head-on collisions, meaning that virtually all of the occupants of other vehicles are side-struck by the design vehicle. The SSOM models all side-struck occupants as unrestrained, in accordance with the assumed ineffectiveness of belts in providing adequate occupant protection in such cases.

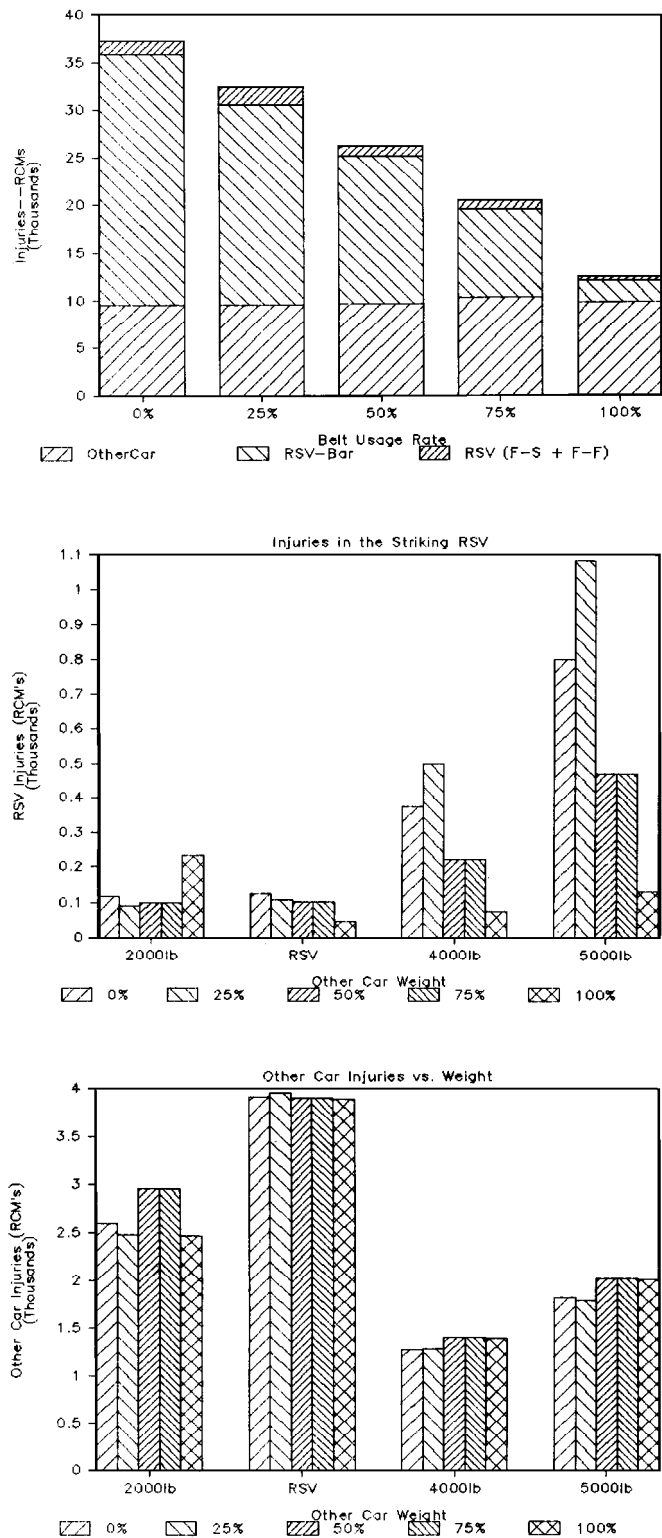


Figure 9. Distribution of injuries in frontal collisions involving the optimized vehicle

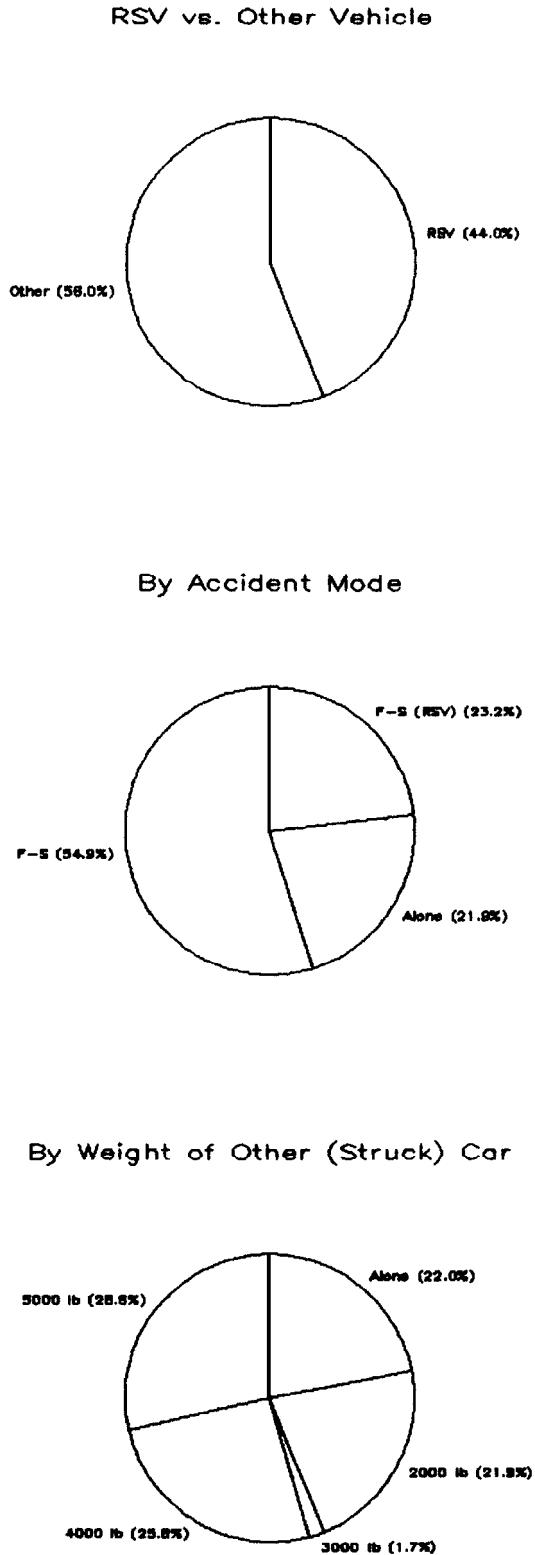


Figure 10. Distribution of optimization benefits for frontal collisions involving the optimized vehicle at 25% belt usage rate.

The greatest gains resulting from belt usage are for occupants of the design vehicle involved in barrier collisions, with more modest gains in front-to-side impacts.

From Figure 9, as well, it can be seen that the aggregate severity of two-car collisions as experienced by the occupants of the design vehicle increases with the increasing weight of the other vehicle, although it should be noted that the total number of rcm's for these accidents is relatively small. This trend remains true for the severity of individual two-car collisions obtained by normalizing the distribution of aggregate social costs by the weight class distribution. (Note that the assumed weight class distribution is 21.4%, 19.0%, 24.4%, and 35.2% for vehicles in the 2000 lb, 3000 lb (RSV), 4000 lb, and 5000 lb weight classes, respectively.) A similar trend is not observed for accidents as experienced by the occupants of the vehicle struck, however. For the striking design vehicle, belt usage has the most profound benefits in collisions with heavier vehicles.

Figure 10 shows where the reduction in social costs as a result of design optimization takes place. These results are for an assumed belt usage rate of 25%. We note that, in general, the distribution of benefits appears to be equitable, with reductions accruing about equally for the occupants of both the striking design vehicle and the vehicle struck. The majority of injury reduction occurs in front-to-side collisions, as a result of the reduced aggressiveness of the design vehicle, but the improvement in barrier collisions is also significant. When benefits are disaggregated by weight class, however, design vehicles which are struck (and this is primary side-struck) underperform vehicles in the other weight classes, although the benefits are still positive. This is evidence of the relatively weak side structure of the specific baseline design modeled, which is not upgraded in the frontal collision optimization.

CONCLUSIONS

The conclusions of this study are as follows: (1) significant injury mitigation in combined front-to-front, front-to-side, and front-to-fixed object collisions can be achieved through the optimal design of the front end of the striking vehicle at any level of belt usage; (2) a progressive front-end collapse structure (softer in the front and stiffer in the rear), combined with increased available crush and stiffer belts, appears to provide an optimal balance between conflicting design requirements for occupant

protection, while simultaneously reducing the aggressiveness of the design vehicle; (3) the conventional design of occupant compartment contact surfaces appears to be compatible with the optimal vehicle/restraint design defined in (2) above, over a wide range of belt usage levels; and (4) the reduction associated with the optimal design is roughly equally split between the occupants of the design vehicles and the occupants of other vehicles, with the principal benefits accruing to occupants of the design vehicle in front-to-barrier collisions and to the occupants of side-struck vehicles front-to-side collisions.

As is inevitable, these conclusions are hostage to the assumptions and limitations of the optimization technique employed and, especially, to the validity of the vehicle and occupant simulation models upon which technique depends. We believe and have attempted to demonstrate throughout, however, that the results presented are consistent with previously reported results on vehicle and restraint system crashworthiness design, when accident exposure data are taken into account.

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