A VALUE-IMPACT APPROACH FOR REGULATORY DECISION MAKING: AN APPLICATION TO NUCLEAR POWER

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ABSTRACT

This paper presents an extended value-impact methodology which aids decision makers in ranking various alternative actions for reducing the risk associated with nuclear power reactors. It extends the state-of-the-art value-impact methodology by using the Analytic Hierarchy Process (AHP), a formalized decision making tool for ranking various alternatives based on judgment. The method has been applied to a value-impact study of the implementation of either a vented-containment system or an alternative decay heat removal system as a means for reducing risk at the Grand Gulf nuclear power plant. A ranking of several policy actions which could reduce the economic risk of nuclear power is performed herein. The results of this analysis show that the method provides considerable insight to the solution of topics of interest in the decision making area of nuclear power risk management.

KEY WORDS: Risk assessment; Decision analysis; Analytic Hierarchy Process (AHP); Nuclear reactor regulation; Cost-benefit; Value-impact

1. INTRODUCTION

Decisions regarding Light Water Reactor (LWR) safety involve processing large amounts of information. Major decisions require input from experts in technical, economic and political areas, as well as from those who have some interest in the future of nuclear power; these interested parties are called stakeholder groups and include the Nuclear Regulatory Commission (NRC), electric utility, ratepayers, investors, and the Public Utility Commission (PUC). Therefore, a method is needed to organize the decision maker's thinking process and to include data, both quantitative and qualitative. The purpose of this paper is to provide a formalism for structuring complex decisions in such a way as to incorporate subjective judgment in a quantifiable procedure.

The method proposed to accomplish this objective is the Analytic Hierarchy Process (AHP) developed by T. L. Saaty (1977). The AHP handles qualitative as well as quantitative factors in an organized structure, which allows for the use of multiple attributes. Although this formal analysis cannot be guaranteed to improve decision making, it can clarify a decision by making explicit the assumptions on which the decision is based.

The purpose here is to investigate the use of the AHP method in multiple criterion decision making in the nuclear industry. The goal is to derive weights for a set of policy actions in order to determine the most important alternative with respect to the objective of insuring the future of the nuclear industry. Importance is usually judged according to criteria which may be the objectives themselves, or measurable qualities of alternatives, as well as intangible qualities of alternatives. The weights reflect the importance of both quantitative and qualitative criteria, named attributes herein. The arrangement of the attributes into levels and these ranked one above another defines the hierarchical structure.

The methodology developed in this study is described briefly below, it requires that the decision maker compare attributes two at a time in order to determine how important one is relative to the other. The series of comparisons is called pairwise comparisons (PWCs). This data is analyzed by the largest eigenvalue approach. In this paper, the AHP method shall be used in an iterative approach to discover the most effective policies to assure the nuclear industry's future.

2. METHODOLOGY

The Analytic Hierarchy Process (AHP) is used to organize problems within a framework that allows for interaction and interdependence among factors. It still enables the decision maker to consider them in a simple and logical way, and to determine the relative importance of each attribute. The AHP, like many other decision methods, consists of 1) identifying alternatives, and 2) generating information on the outcomes of alternatives. Unique to the AHP is a third step which allows for assessing the preferences of the decision maker and stakeholders. This is accomplished by translating a series of paired comparisons into weights for the attributes in the hierarchy. These weights determine the contribution of each alternative to the objective. The method is described below, in terms of types of attributes to use, how to construct the hierarchy, and the evaluation of the AHP. A description of the mathematics in the AHP is provided in References 1, 2, and 3.

2.1 <u>The Attributes</u>

The attributes making up the hierarchy may be quantitative and qualitative; that is, measurable by some method, or only qualifiable through some measure of judgment. Potentially measurable attributes such as risk reduction may be quantified through Probabilistic Risk Assessment (PRA) methods. In addition, less tangible effects such as changes in public opinion regarding nuclear power are considered decision attributes. These attributes may be evaluated through questionnaires. If a value-impact analysis is to be performed, the attributes consist of costs and benefits of the alternatives. If the analysis is to include stakeholder groups, the attributes consist of the stakeholders and their objectives. While there is no restriction as to the number of attributes allowed, it is more efficient to restrict the number of attributes to nine per level; it has been found that more than this would be too many for the decision maker to compare (Miller, 1956).

2.2 <u>The Hierarchy</u>

The AHP consists of dividing the decision into attributes which are organized into a structure called the hierarchy. Figure 1 is provided as an illustrative example. The top level of the hierarchy is concerned with choosing the best plant for a particular electric company. The bottom level includes the three alternatives to be considered: nuclear plant, fusion plant, or coal plant. The remaining levels of the hierarchy consider the time frame, in level 2, and the importance of cost, energy demand, feasibility and public opinion, in level 3. The fourth level contains measurable attributes of the plants, i.e. capital costs, experience with the technology involved, etc.

2.2.1 Guidelines

Some guidelines have been developed in this study. Figure 1 shall be used to illustrate these recommendations for structuring the hierarchy. A hierarchy is complete when each level connects to all elements in the next higher level. The placement of the levels should be such that the relation between a given level and the one above explains why the attributes of the level are important, the level below explains how the attributes on the given level may be achieved; the intermediate level should link the adjacent levels. Furthermore, it is convenient to place any quantifiable attributes on the level directly above the alternatives.

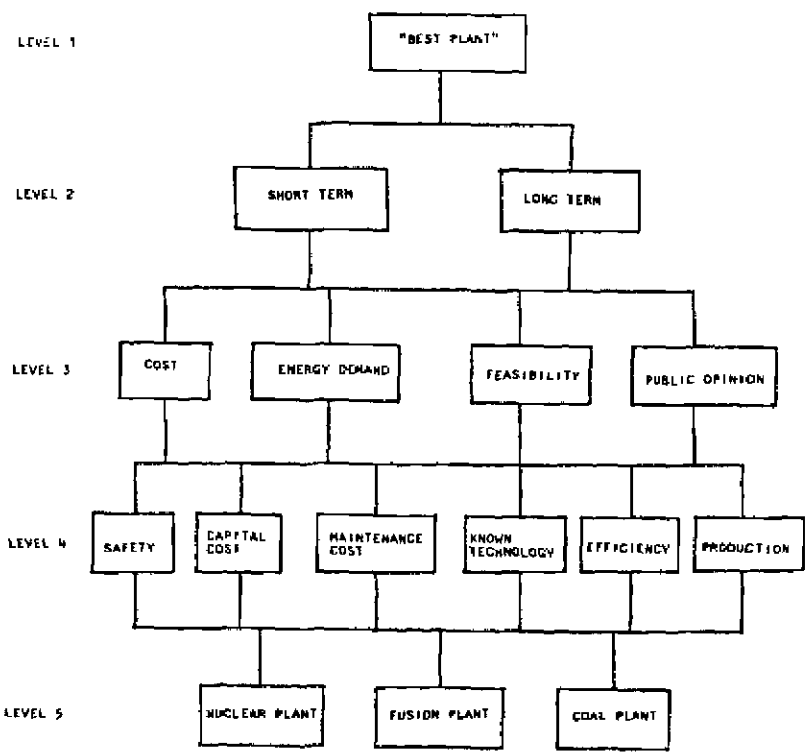


Figure 1

Sample Hierarchy

For example, consider level 4 in the sample hierarchy in Figure 1. This level contains the measurable attributes of the alternatives, safety, capital cost, maintenance cost, known technology, efficiency, and production. How these are achieved is through implementation of the alternatives, in the level below. Why they are important is to obtain information about cost, energy demand, feasibility, and public opinion, in level 3, and to relate the alternatives to the attributes in level 3 through level 4, for which data exist. More details on how to structure a hierarchy can be found in Reference 2.

In addition to providing a tool for analysis, the hierarchy is a representation of the decision maker's thinking, and the decision maker should devote sufficient time to the structuring step and review of the suggested structures. Once the hierarchy has been established, the evaluation is conducted.

2.3 Evaluation

In order to quantify the hierarchy, a comparison is made for each pair of attributes in a level with respect to each attribute on the higher level with which they are linked. These pairwise comparisons (PWCs) result in a ranking number which assesses the degree of importance or the likelihood of one attribute over another, and is reflected in a scale of nine units developed by Saaty (Saaty, 1977). In this scheme, a "1" reveals equal importance and a "9" absolute importance of one attribute over another; the intermediate numbers are shown in Table 1. The process of assigning values for the pairwise comparisons translates subjective judgment into a numerical ranking of the attributes in each level. Finally, the values for the pairwise comparisons are arranged into a matrix form, and matrix manipulation yields the relative values of the alternatives in the bottom level with respect to the objective defined for the assessment.

Especially important in the analysis of nuclear regulatory decision making is the way in which stakeholders' interests are included. Stakeholder groups include the regulatory organisms, the electric utilities, the ratepayers, the investors, nuclear opponents such as intervenor groups, etc. Although each group may have a stake in the outcome of the decision, the group's opinion may or may not affect the decision. For a very technical choice, the knowledge and expertise may lie with the utility; for a decision regarding whether or not to pursue further risk reduction, which ultimately involves the question of how safe is safe enough, the stakeholders may prove to be extremely important, each playing a different role in the economic, political, social and technological areas.

Special emphasis can be placed on the integration of varying opinions into decisions in two ways. First, a number of people may be asked the questions necessary to quantify the hierarchy, and second, stakeholder groups' objectives may be included in the hierarchical structure. The first approach is suitable for establishing a consensus and evaluating the sensitivity of extreme opinions; the latter approach has been found to be more helpful when the stakeholders have some control in the outcome. The geometric mean was found to be the best way to represent the collection of results as a consensus. In this manner, the extreme values did not distort the results as can be the case when using the arithmetic mean. One way to handle digressing opinions is to perform sensitivity studies using the extreme values as input to the hierarchy. If the ordinal ranking of the alternatives is changed in any of the cases, further work is required to resolve the inconsistency.

Table 1. Descriptions for the five point scale

Description	Rating
A & B "are equally important" "equally contribute" "equally perform"	1
A "is somewhat more important than" B "contributes somewhat more than" B "somewhat outperforms" B	3
A "is strongly more important than" B "strongly contributes more than" B "strongly outperforms" B	5
A "is demonstrably more important than" B "very strongly contributes more than" B "very strongly outperforms" B	7
A "is absolutely more important that" B "absolutely contributes more than" B "absolutely outperforms" B	9
B "more important than" A	reciprocals

Source: NUREG/CR-3447

Finally, if a level is to be incorporated into the hierarchy which contains the stakeholder groups, the next level down should contain a set of independent objectives for each group. This approach works best in a planning application of the AHP. In the case that the actors have some control over the outcome, the AHP is very useful in determining policies which may be incorporated in order to achieve some desired future. For this approach, the importance of the groups must be assessed with respect to each of the criteria above. An example of this use of the AHP follows.

3. APPLICATION: POLICY CHOICE

This example illustrates the use of the AHP as a planning tool: the goal of the application is to rank policies which, if implemented, could direct the nuclear industry toward a desired future. The costs of implementing such policies are not included here and will be the subject of a future paper. Given the costs, a value-impact analysis could be performed as a way to compare the value-impact ratios of implementing a policy and backfitting a system, in order to prioritize the many options for improving nuclear power plant safety.

The AHP is used in an iterative process in this example. First, a hierarchy is constructed in such a way as to determine the weighting of several scenarios given the stakeholders, their objectives, and the future they project. This is the first forward hierarchy; the results of which are used in the next step, the construction of the backward hierarchy. In the backward process, the objective on the top level is set as the desired future as opposed to the projected future as in the first forward process. The solution of the backward hierarchy informs which policies, on the bottom level, would have to be employed by the stakeholders in order to achieve the desired future. Finally, another forward hierarchy is constructed similar to the previous forward hierarchy, except the objective is now a projected desired future. This is because the top-ranked policies from the backward process are inserted as stakeholders' objectives, in addition to those in the first forward hierarchy, in order to test the effect on the ranking of scenarios.

3.1 First Forward Hierarchy

The weighting of the stakeholder groups in level 2 in Figure 2 was obtained from the responses to a questionnaire, in the form of PWCs, ie the participants compared each pair of stakeholders with respect to their importance to the future of nuclear power. Then, the geometric mean of the resulting eigenvector was used to best express a concensus. Of course this weighting is subject to change. The objectives of the stakeholders are located on level 3; the priorities of the objectives were taken from a study performed for an electric company in Reference 2, for which the stakeholders' priorities were solicited. It was necessary to construct 15 3x3 PWC matrices in order to compare the scenarios' impacts on each objective in level 3 above. The first of the scenarios is a continuation scenario of the present status of the industry, which means that the present short term policies would be pursued. The second scenario indicates pursuing alternative forms of energy other than nuclear, such as coal. The third scenario is to pursue and plan for an assured industry; this is described as being financially stable, able to satisfy the energy demand, and prestigious. Finally, the matrix multiplication is performed and the results are indicated in the figure. The evaluation of the hierarchy ranks the diversification scenario above the others given the objectives of the stakeholder groups which are specified in the figure.

3.2 Backward Approach

Given the insight and structure of the forward hierarchy, the backward hierarchy was developed and is shown in Figure 3. Although diversification was found to be the most likely scenario in the forward process, an assured industry is assumed to be the more desired future, and is thus located on the first level. In addition to this change from the first forward hierarchy, this hierarchy determines the effectiveness of some suggested policies in achieving the desired scenario, an assured industry. The attributes of an assured industry, financial stability, satisfaction of energy demand, and prestige, are located on the second level of the backward hierarchy. The importance of the three are taken to be equal; the weightings may be varied in order to check sensitivity. The third level contains problems associated with achieving the desired scenarios. A few are briefly described here. Lack of safety incentives indicates that there exists little motivation for self regulated modification by the utility. Equity investor problems contain the investors' concerns of receiving steady, high returns. Excessive regulation refers to the utility's costs of disproving the necessity of a proposed NRC modification for the reactor. Next, the stakeholder groups that can affect the problems are included in the fourth level in order to model their ability to do so. The bottom level contains the policies which are introduced in order to test their effectiveness in reaching the desired scenarios in level 2.

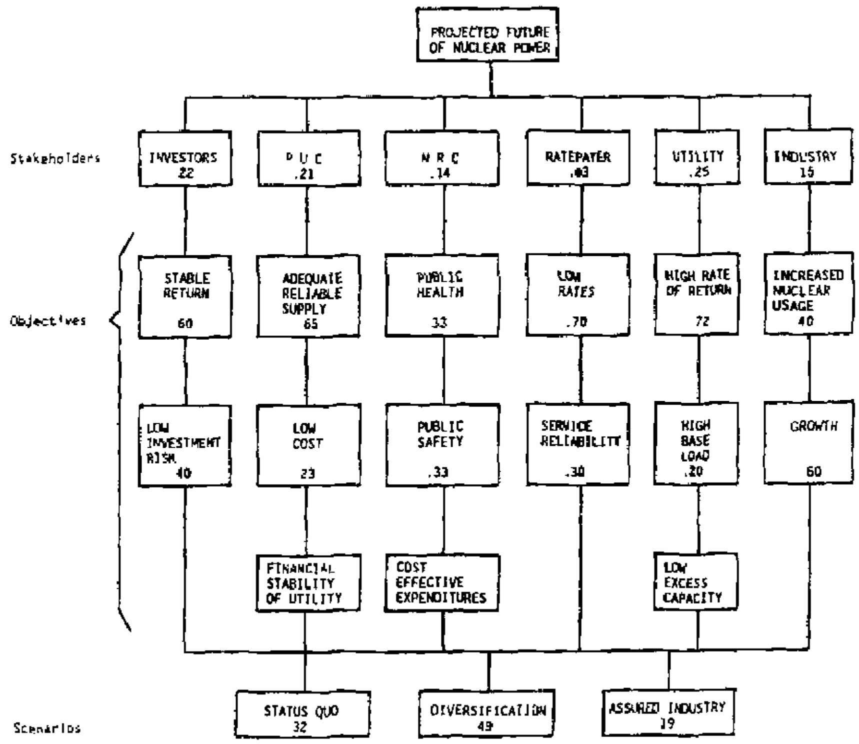


Figure 2

First Forward Hierarchy

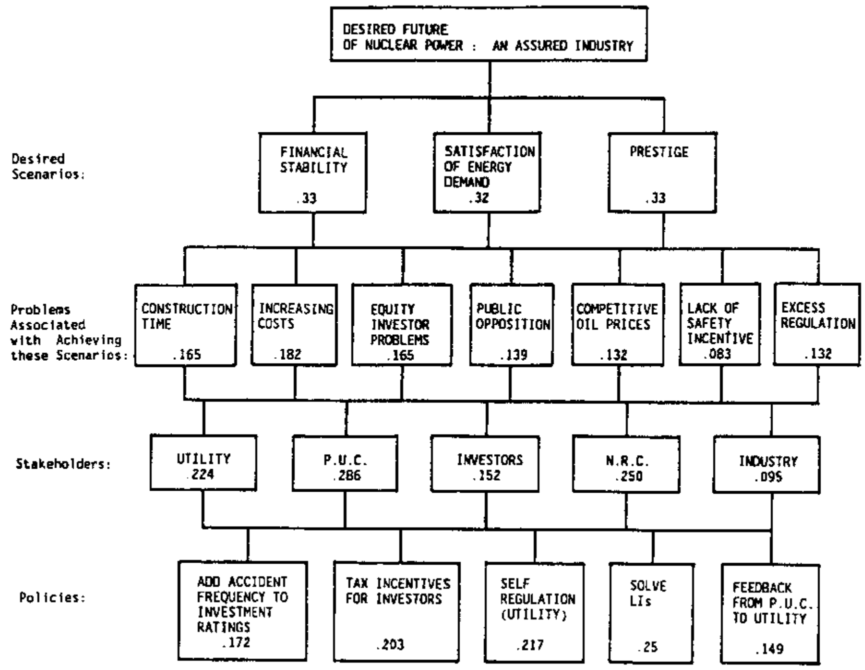


Figure 3

Backward Hierarchy

The policies employed here are derived form a previous study for which a digraph method was used to model the relationships between stakeholder groups and policy actions (Nelson, 1985). These policies are compared with respect to their effect on the stakeholder groups on the level above. The rest of the levels are compared following the usual AHP procedure. The final rankings for each level are shown in Figure 3; these show that solving Licensing Issues (LIs), increased self-regulation. and tax incentives are the preferred policies. These policies are discussed next.

3.2.1 The policies

The policies were introduced from a logical extension of the digraph method in a previous study. In this study, financial issues were found to strongly influence the future of a nuclear power company. For this reason, investors were considered important stakeholders, especially those with investments in companies with nuclear plants under construction. Therefore, several of the policies generated include goals to improve investor perception which could alleviate some of the financial pressures of today. The policies were generated through solving a digraph system which includes the stakeholder groups and major attributes which may influence the nuclear industry, such as accident frequency goal, nuclear companies' investment ratings, and licensing time. Then, for instance, licensing time was decreased to detect the overall effect on utility expenditure. A large effect constitutes a policy suggestion, such as solving licensing issues. Also, arcs were introduced where the influence of one attribute on another was found to be negligible, generating several policy suggestions. For example, decreasing plant accident frequency had little effect on investment ratings; an arc was introduced between these two attributes which generated a large cost decrease thus suggesting that those investing in plants with low accident frequency receive a tax break. The preferred policies obtained from the backward process are discussed below; implementation is beyond the scope of this study

Solving licensing issues

Solution of Licensing Issues (LIs) by the NRC was introduced as a policy to reach the desired scenario of an assured industry. Because licensing delays increase plant costs, this issue is directly related to economic issues. Licensing issues are not directly related to protecting the health and safety of the public. They include issues related to increasing knowledge, certainty, and understanding of safety issues in order to increase confidence in assessing levels of safety; improving or maintaining NRC capability to make independent assessments of safety; establishing, revising and carrying out programs to identify and resolve safety issues, documenting, clarifying, or collecting current requirements and guidance; and improving the effectiveness of the review of applications.

Increased utility self regulation

This is suggested as a way in which to increase safety incentives and decrease costs. Three suggestions are found in the industry. 1) A utility "good practice manual" has been suggested by the Office of Nuclear Reactor Regulation (Speis, 1984). The manual would include potential actions not passing a cost-benefit test, which the NRC believes the utilities should implement voluntarily NRC action to encourage such an effort could be proposed as a commission action, perhaps in a safety-goal context. 2) A "five or ten year plan" could be established which would propose the implementation plan for self-regulated reactor modifications (Nandy, 1984). This would decrease both NRC regulation and disagreement over generic issues not applicable to a specific reactor. 3) An "integrated living schedule," first suggested by the Delian Corporation in 1983, consists of a continuing process of selecting and scheduling plant betterment activities in order to optimize the allocation of resources (Delian Corp., 1983). It would encompass either plant modifications initiated by utilities or backfits mandated by the NRC.

Tax incentive

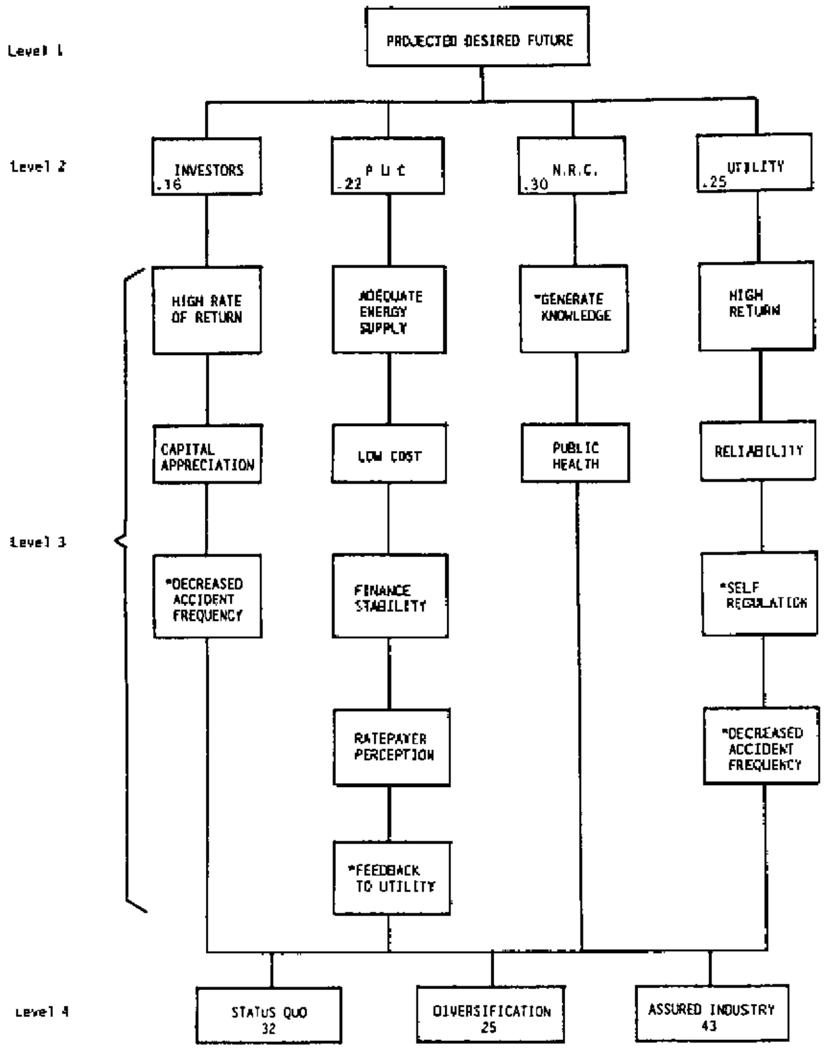
Tax rates for investors in an electric utility could be based in part on the reactor's accident frequency. This could be modelled after tax incentives created for energy conservation in the past. In addition, including accident frequency in investor ratings could further influence investors, which in turn provides safety incentives for the utilities.

3.3 Second Forward Process

A second forward hierarchy was constructed which incorporates the insight obtained from the backward process. The first step is to recalculate the weights of the stakeholder groups as shown in Figure 4. This is done by multiplying the final ranking of the policies by the ranking of the stakeholders in the backward process and normalizing to one. In this, the NRC and the PUC are the most influential in implementing policies to achieve the desired scenario. The policies from the backward approach are incorporated in the third level of the hierarchy, which represents the objectives of the stakeholders. Finally, the possible scenarios are ranked again. This time, however, due to the changes in objectives and weighting of the important groups, an assured industry has resulted as the more likely scenario.

4. CONCLUSION

An attempt has been made to introduce and rank policies which could increase the outlook of the nuclear power industry. The AHP is employed in an iterative approach to rank the policies in such a way as to attain a desired future for the stakeholders. First, the forward hierarchy was used to determine the plan of action to follow given the future projected by the present state of the nuclear industry; the results indicate diversification. Next, given that an insured future for pursuing nuclear power is desired, a backward hierarchy was used to indicate the policies necessary to achieve this goal. The policies are directed toward increasing investor perception through solving Licensing Issues which speeds up the licensing process, providing incentive for the electric utility to decrease accident frequency through tax incentives, and increasing utility self-regulation to decrease unnecessary expenditures. Finally, a second forward hierarchy is constructed to see the effect of implementing the policies on the decision of which scenario to pursue; in this case, pursuance of a strong nuclear future is ranked highest given the implementation of the suggested policies. The backward hierarchy could be evaluated again, adding more policies or changing the weights, in order to detect the sensitivity in the results of the second forward hierarchy. Of course, this is a static analysis; further study is necessary in order to include changes in the industry in time.



*These are the new stake holder objectives obtained from the backward process

Figure 4

Second Forward Hierarchy

The strengths of the method have been highlighted in the paper. The flexibility and ease of use are central to its desirability. Its ability to incorporate non-quantifiables, compare incommensurables, include stakeholders' opinions, and obtain numerical rankings from qualitative comparisons is especially useful in regulatory decision making.

The weaknesses of not only the AHP but of all decision methods is their inability to solve a problem. Decision methods rather provide a structure for thinking. In the AHP specifically, a hierarchy which is developed to study decision alternatives is not a unique structure; it is highly dependent on expert opinion. Finally, the method is excellent for clarifying a problem, displaying the decision process, and performing sensitivity analysis; however, it is not suited for determining quantitative criteria.

4.1 Future Work

As mentioned, further study is needed to incorporate the costs of the policies in order to prioritize implementation of various policies and backfits according to their value-impact ratios. Future work is needed in the development of standardized hierarchies for decisions involving similar attributes, in addition to better defining the limitations of the AHP. Better techniques for including uncertainty in the AHP could increase the applicability of this method. Further study of the AHP could prove useful to regulatory and utility planning. The major task yet remaining is to implement the AHP in regulatory decision making.

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IMPROVING AUTOMOTIVE SAFETY:

THE ROLE OF INDUSTRY, THE GOVERNMENT, AND THE DRIVER

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ABSTRACT

This paper identifies three groups that can improve automotive safety. The three groups are the automotive industry by designing into cars such safety devices as seat belts, roll bars, or air bags; the government by taking such measures as improving road conditions, enforcing seat belt usage laws, or enforcing stricter anti-drunk-driving laws; and finally, the driver by modifying driving habits such as wearing seat belts and not driving while intoxicated.

Of the seven strategies we define for improving automotive safety, this paper argues that "as low as reasonably achievable" (ALARA) is the most applicable risk reduction strategy within the context of improving automotive safety. By applying the ALARA principle to past and proposed safety improvements, we demonstrate that the most lives saved per dollar spent would occur if drivers modified their driving habits.

KEY WORDS: Automotive, Safety, Regulation, Design, Driver habit, Air bags, Seat belts, and Drunk driving

PREFACE

This paper is written in briefing format and is intended to serve two purposes. First, it was presented at The International Society of Risk Analysis meeting (October 1985, Washington, D.C.), and second, it supports a Rand Graduate Institute course and a University of California at Los Angeles tutorial entitled ***Risk and Uncertainty in Public Policy Decisions.***

The paper examines alternative means of improving automotive safety.

. OBJECTIVES

The purpose of this paper is to attain the following four objectives:

- Review generic risk reduction, or safety improvement, goals;
- Select one particular goal to examine in detail;
- Apply this goal to improving automotive safety; and
- Discuss how three distinct groups can implement this goal.

The goals will be discussed later. With regard to our fourth objective, the three groups that can implement our selected goal are industry, the government, and drivers themselves. Industry can improve safety by adding protective devices such as seat belts and air bags to automobiles [1-8]. Government can improve safety at each of three levels: federal, state, and local administrations [2, 3, 6-12, 13].

Each level of government must play its respective role to the fullest to attain the highest possible automotive safety standards. For example, the state must maintain highways and roads sufficiently. State and local law enforcement agencies must strictly enforce laws against speeding, moving violations, and drunk driving. Judicial systems must strictly punish lawbreakers to prevent recurrent offenses as well as to deter prospective offenders. Last, each driver can influence safety through good driving habits. Buckling seat belts, obeying speed limits, and not driving while intoxicated are several positive habits that will improve automotive safety [2, 3, 6-8, 14-17].

2. DEFINITIONS

Identifying Alternative Risk Reduction Goals

Although the safety level of any technology can always be improved, there is no unique approach or philosophy for making such improvements [18-20]. Several prior studies have identified a number of distinct philosophies for reducing risk associated with various technologies. Seven measures to reduce risk and achieve specific safety levels are discussed below [18]. Imbedded within this discussion are examples specific to automotive safety.

What Are Some Alternative Risk Reduction Goals?

Minimizing maximum accident consequence is one method to reduce the risk associated with automobile operation. For example, we can eliminate all accidents involving a large number of fatalities in a single transportation event. This could be achieved, for example, by preventing all fully occupied buses from driving on any highway or road. Because the maximum number of passengers on board a bus could be 50 or 60, the worst possible accident would cause the death of 50 to 60 people. This particular philosophy seeks to reduce total risk by minimizing the maximum number of people that could be killed in any single accident. Another application of this philosophy is to require that not more than two people occupy any one car at a time, and that cars be positioned far enough apart to eliminate the possibility that two cars could ever by involved in an accident. We would minimize the maximum number of fatalities per accident to four in this case. Of course, this is neither a realistic nor a feasible risk reduction goal when applied to automotive safety. The impracticality of trying to reduce the number of people riding in any one vehicle at a given time outweighs any benefits gained.

Minimizing the probability of occurrence for the most probable types of accidents is a second method of improving safety which thereby reduces risk. Because rear-end collisions are a common type of accident, an extreme application of this approach would seek to eliminate all rear-end collisions [2, 3, 9-13]. To fully ensure that all rear-end accidents are eliminated we would have to permit only one car on the road at a time, an obviously impracticable solution. A more practicable one requires the use of center-mounted, high positioned brake lighting. Use of such a light would reduce rear-end collisions by more than half [2, 3, 10-12] and avert as many as 1800 fatalities per year. We would also try to identify other types of common accidents to reduce their probability as well.

Minimizing the total accident risk is a third risk reductional goal. Risk is defined as the probability of an event times the consequence (or outcome) of that event integrated over all negative events Therefore, as we apply this goal to automotive safety we find that we need to reduce both the total *number* and the *intensity* of accidents (i.e., limit both the total number of buses on the road and the number of passengers per bus).

Eliminating all accidents is a fourth risk reduction goal that appears to be unattainable in any context, however it is applied. Enforcement of the Food and Drug Act's Delaney Clause has prevented the use of any carcinogenic food additive [18]. Presumably this would eliminate the incremental cancer risk that we derive from using food additives. However, within the context of automotive safety, the only way to eliminate all occurrences of property damage, injuries, and fatalities would require that no automobile is every permitted to operate.

Requiring those who partake in the benefits to take proportional share of the risk is a fifth risk reduction goal. Applying this broad goal to automotive safety, we find this is exactly what happens. For example, the more miles one drives per year, either as a driver or passenger, the greater one's probability of being involved in an accident [2, 3]. When this goal is applied to other aspects of automotive safety it becomes complicated. Risks and benefits are not always comparable. The risk of injury to passengers of small cars is greater than the risk to those in large cars. However, the benefits of smaller cars are different Smaller cars offer better fuel economy--a benefit that may compensate for the higher risk of injury.[1]

Minimizing the socially perceived risks is risk reduction goal number six. These are risks *perceived* to be large, but are not technically or quantitatively large [18-20]. For instance, suppose a passenger bus with 40 occupants falls off a 100-foot cliff, and there are no survivors. This is socially perceived as far worse than 40 individual, fatal accidents. By eliminating all spectacular or well-publicized events we minimize the socially perceived risk. Another example of minimizing this risk is to eradicate all fire-related automobile accidents, regardless of whether or not the fire caused the fatality. While we may perceive this risk reduction measure as socially desirable, it may in fact be costly to implement, and may not reduce the annual number of fatalities.

Reducing risk to as low as reasonably achievable (referred to here as ALARA) is our seventh risk reduction goal. Application of the ALARA goal to industry, government, or individual drivers required a fixed budget to reduce the total accident risk to *as low as reasonably achievable.*

Table 1 summarizes these seven risk reduction goals.

Which Goal Makes the Most Sense?

We will deduce which one of the seven goals makes the most sense when applied both to general situations and to the specific issue of automotive safety. First, Goal 1 (minimize the probability) and Goal 2 (minimize the

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[1]It is interesting to note that passengers of sports cars have a more severe injury and fatality rate than their counterparts in larger cars [14]. Yet, sports cars are far less likely to cause an accident [18].

consequence) are contained in Goal 7, the ALARA Goal. Therefore, we will not lose anything by eliminating Goal 1 or Goal 2 as long as we still consider the ALARA Goal.

Minimizing total risk, Goal 3, is really a special case of the ALARA Goal. In this special case, there is not budgetary constraints. We minimize total risk without considering how much it costs to minimize such risks and there is not risk/cost tradeoff.

Goal 4 seeks zero total accident risk. The only way to completely avoid all automobile accidents is to eliminate all vehicles from the road. Obviously, this solution is not practicable when applied to Automotive safety, even though it may have been for carcinogenic food additives (Delaney Clause).

Table 1

ALTERNATIVE RISK REDUCTION GOALS

(1) Minimize the maximum accident consequence (e.g., eliminate accidents involving large number of mortalities in a single event).

(2) Minimize the probability of the more probable accident types (e.g., determine the rear-end collisions are a probable type of accident and reduce their frequency).

(3) Minimize total accident risk (e.g., for all types of automotive accidents, reduce the product of their frequency and outcome).

(4) Reduce total accident risk to zero (e.g., zero fatalities per year and zero injuries per year (i.e., eliminate the automobile).

(5) Share risks and benefits equitably (e.g., the more miles you drive per year, the higher the risk you take).

(6) Minimize socially perceived risks (e.g, eliminate spectacular accidents such as a bus falling off a 100-foot cliff)

(7) Reduce risk to ALARA (e.g., for a fixed budget, reduce total accident risk to a low as possible.

Minimizing socially perceived risks is also difficult to attain (Goal 5 includes removing large-scale or spectacular accidents). In addition to being difficult to attain, this philosophy does not have a predictable payoff. We have illustrated that total risk may remain unchanged (recall the 40 passenger bus accident versus the 40 individual accidents). In fact, Goal 5's application could result in a substantial increase of total risk if different types of accidents are traded off against one another [18-20].

As we have discussed, Goal 4 (sharing risk proportionately with benefit) is implicit in any automotive design issue.

Finally, we feel the ALARA Goal makes the most sense. By definition it is intended to provide the most safety at the smallest dollar cost.

Why ALARA?

Let us examine ALARA more carefully and try to understand why it is a sensible goal for the automotive safety application. Realistically speaking, our society is constrained in expenditures and budgetary resources. Therefore, we cannot spend an infinite amount of money to avoid a fatality. currently, approximately 50,000 fatalities and hundreds of thousands of injuries result each year from automobile accidents. If everyone drove a Sherman tank at a speed of 3 mph or less, these statistics would be reduced substantially (but not likely eliminated). On the other hand, the costs associated with this scenario are insurmountable. This example illustrates how impractical it is to eliminate risk without regard to budgetary constraints. Therefore, as long as we drive there will be a finite probability of a fatality. As another example of minimizing risk without a budget constraint imagine eliminating air-travel risk. This would mean that all cross-country travel by aircraft would stop. If someone needed to travel from Los Angeles to Washington, D.C., the traveler would be forced to take a slower, safer means of transportation such as a train. But for some people, safer means of transportation do not compensate for resource costs (such as time lost). Consequently, this does not efficiently allocate resources.

From these examples the ALARA risk reduction goal is clearly the most sensible. When speaking of automotive safety we want to minimize risk of injury, death, or property damage but budget constraints do exist. By using the ALARA Goal we achieve our goal while considering resource costs.

Before applying the ALARA principle to automotive safety and design, we must emphasize the fact the ***there is no unique definition of ALARA*** as it is applied to improving automotive safety. We can conceive of at least three rather distinct, operational definitions.

(1) For a fixed societal expenditure, we can maximize automotive safety--reduce the risk of driving to as low as possible;
(2) For some prescribed level (accepted standard) of safety, we can spend whatever it takes to achieve that; or
(3) We can weigh the marginal costs of reducing risk against the marginal benefits that result. The optimal decision is to add automotive safety measures until the benefit of the safety measure is equal to, or exceeds, its cost. However, this approach requires that the value of human life be explicitly stated.

We do not contend that any one of these three is better than the other two, but, for the purpose of our demonstration, we have elected to pick the first operational definition.

Assuming a fixed societal expenditure, how do we maximize automotive safety? We propose that a specific way of implementing such a measure would be to enforce the most cost-effective measures first. We would see the highest payoff-in terms of improved safety--at the lowest dollar cost [6]. A good example of this is a mandatory seat belt law which will be discussed later in more detail.

Defining Roles in Improving Safety

As discussed earlier, three groups can control the safety of automobiles--the industry, the government, and the driver. The industry could add seat belts or air bags or make other design changes to improve safety. At the state level, the government could improve highway conditions and add road signs, the police and law enforcement agencies could provide stricter enforcement of drunk-driving and speed limit laws, and the judicial system could more stringently penalize offenders. Last, the driver could improve driving habits in many ways such as by reducing speed and using a seat belt at all times. Associated with each of these actions is a cost. For these examples, cost is in the form of dollars expended or time lost Whoever pays these costs is determined by the measure taken.

We find that some issues are rather distinct in terms of who can control safety; the voluntary maintenance of one's automobile is clearly the driver's prerogative. Other issues are hybrid; that is, a combination of the government, or the industry, or the driver exercises some control. An example of a hybrid issue is seat belt use. The industry puts the seat belt in the car and the driver elects to wear it. Figure 1 succinctly summarizes the interrelationship between industry, law enforcement agencies, and the individual driver.

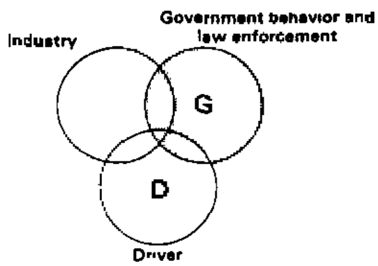

Figure 1. Defining industry/law enforcement/driver role in improving safety: a typical issue.

In some states, law mandates the use of seat belts. In the specific cases of child restraint seats and seat belt use there is a move toward mandatory use. In the State of California, and a number of other states, the parent (or any other person) driving with a child under 4 years old is obligated to keep that child restrained in a state approved car seat while riding in an automobile. In addition, a number of Air Force bases, including Kirkland Air Force Base in Albuquerque, New Mexico, require the driver and all passengers to wear seat belts while driving on base even though the speed limit seldom exceeds 30 miles an hour. Anyone caught without their seat belt will be fined.

3. ANALYSIS

Costs of Risk Reduction

Before discussing our analysis, we must define *reduced risks* for automotive design and the *costs* associated with reducing them Reducing risks, improving safety, and increasing benefits are equivalent events An increased benefit may be a decreased probability of incurring death or severe injury. Improved safety can be accomplished in a number of ways' and each method of improving safety has its own cost and benefit implications. It is up to the policymaker to determine which methods have the optimal mix of cost and benefit.

One measure of policy effectiveness is the number of fatalities averted per year. Before 1974, the speed limit on U.S. highways was 65 to

70 miles per hour and statistics showed in average of 55,000 deaths annually. When the speed limit was reduced to 55 miles per hour during the 1974 gasoline crisis. we saw a rapid decline in the number of fatalities per year to approximately 45,000. Currently, the number of fatalities has leveled to around 50,000 per year. Therefore, we see a reduced risk or increased benefit associated with a particular action. The benefit is the lower probability of death and the action is decreasing the speed limit. As we can see, there are additional benefits associated with this action--a lower probability of both severe injury and extensive property damage. Furthermore, because there are fewer accidents, there are fewer investigations by insurance companies, less compensation by insurance companies, and so on, resulting in even more dollars saved Changing the speed limit will give rise to costs in the initial public announcement campaign, replacement of road signs, and law enforcement.

What are the costs of taking measure to reduce risks? The first thing that we want to consider is who is responsible for the cost. There is a cost to the industry for installing seat belts and other safety devices on cars, but that cost is very typically passed on to the consumer by adjusting the purchase price of the car. The consumer pays an incremental amount for each safety device that is added. Clearly, there is a cost associated with improving roads, adding road signs, and enforcing driving laws. This is a cost to the government that is passed on to the taxpayers. Commercials on television or on billboards that say "buckle up," don't drive while intoxicated," and other such public service announcemelts may be paid for by large companies and organizations. In a sense, a public service announcement is something that the consumer or the taxpaper ends up paying for in the form of higher product costs or tax benefits enjoyed by the organization offering the commercial.

Approximate Dollars Spent per Averted Fatality

In Tables 2A through 2E we list a number of measures that can be taken to reduce the risk associated with automobiles.* In some instances, we have identified the number of fatalities, injuries, and occurrences of property damage that are reduced. Also, we have compared the estimated benefit of implementing the measure. with the cost of putting the measure into place. We will discuss a few of the examples shown.

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* Symbol definitions for Tables 2A through 2E are as follows:

G = Government has primary control over safety improvements measure.
D = Driver has primary control over safety improvement measure.
I = Industry has primary control over safety improvement measure.
ΔF = Decrease in fatalities per year should safety measure be implemented on all cars.
ΔI = Decrease in injuries per year should safety measure be implemented on all cars.
ΔC = Decrease in accident dollar cost per year should safety measure be implemented on all cars.
ΔS = Cost of implementing measures per year, industry-wide.
$/averted fatality = Cost per averted fatality measured in thousands of dollars.

Table 2A

Measure		Benefits			Cost	$/averted fatality (thousand $)
		ΔF	ΔI	ΔN	Δ$	
Stronger drunk laws	G	Up to 25,000	100,000+	200,000?	Billions	50
Stronger seat belt laws	G	Up to 15,000*	100,000+	0 or small	Billions	200
Voluntary seat belt	D	Up to 28,000**	200,000+	0 or small	Billions	100*
Roll bars — Jeep	I	100's	1000's	0 or small	100's millions	1000
Bumpers — 2 5/5.0 mph	I	0	~0	20% reduction	25% reduction	∞
Child car seat	G	500***	1000's	Small	Billions	100
Rear light	I/G/D	1800	60% reduction	60% reduction	1.29 billion	30
1966-1970 auto equip	I					260

*50% effect
**90% effect
*** 4 yrs

*Public service commercials

Table 2B

Measure		Benefits			Cost	$/averted fatality (thousand $)
		ΔF	ΔI	ΔN	Δ$	
Steering column *	I					200
Airbags	I	6 000-9 000	300% reduction			640
Tire inspection	I/D					800
65 mph to 55 mph limit	G/D	7 000-10,000	~100 000			50
Rescue helicopters	G	10's				130
Passive 3 pt. harness	I					500
Passive torso belt	I					220
Driver ed.	G/D	100's				180
Highway maintenance	G G					40

Table 2C

Measure		Benefits ΔF	ΔI	ΔN	Cost Δ$	$/averted fatality (thousand $)
Signs	G	1000's				68
Guard rail improvement	G	100's				68
Skid resistance	I	~500				84
Bridge rails	G	250-500				92
Wrong way entry	G	250+				100
Impact absorbers	G	1000's				216
Break away signs	G	500+				232
Median barrier improvement	G	1000's				456
Clear recovery	G					586
Remove trucks	G	1,250				very large

Table 2D

Measure		Benefits ΔF	ΔI	ΔN	Cost Δ$	$/averted fatality (thousand $)
Remove large cars	G	10 000's				very large
Eliminate all auto fires	I	250				1000's +
Eliminate all auto fires rear end only	I	100				1000's +
Standard 301	G	100's				200
Pink cars	G/D	1000's				5 (?)
Anti-skid brakes	I			10%		
Tube tire vs. non tube	D/G			360%		50 (?)
Recap tube vs non tube	D/G			480%		50 (?)

Table 2E

Measure		Benefits			Cost Δ\$	\$ averted fatality (thousand \$)
		ΔF	ΔI	ΔN		
Tube vs. recap tubeless	D/G			260%*		50 (?)
Depth of tread	D/G			200%*		50 (?)
Lights on in day	D/G			Δ15% in front end		
Reflective plates	G			13% in rear end		
Mud flaps	D			1.3%		

As stated previously, there are approximately 50,000 fatalities per year due to automobile accidents [2, 3]. One-half of these result because at least one of the drivers involved was driving while intoxicated [6]. Imagine if all drunk driving was eliminated, by some fortunate method. We could prevent up to 25,000 fatalities and hundreds of thousands of injuries per year. Based on estimates by Solomon, Batten, and Phelps [6] the cost of such a measure might be approximately \$50,000 per fatality averted.

An innovative and practical method to deter driving under the influence of alcohol has taken in Midwest City, Oklahoma, by implementing a "scarlet letter" approach [21]. Specifically, when a driver has been convicted of driving while intoxicated he or she makes a choice between spending 30 days in jail or agreeing to flaunt an ostentatious bumper sticker stating the the driver has been convicted of drunk driving, and asking other vehicle operators to report any odd or erratic driving to the police. Drivers who choose to "wear the scarlet bumper sticker" may not park outside of any bar or liquor store and must display it for a full six months; any violators of these simple rules risk being sent to jail for 30 days.

On the other hand, let us examine a measure that improves driving habits *voluntarily*, such as seat belt use. If this measure proved 90 percent effective, as many as 28,000 lives might be saved. The financial campaign (the public service commercial associated with it) could cost only \$100,000 per fatality averted [6]. Another measure, a law *requiring* seat belt use, may save as many as 10,000 to 15,000 lives [6]. This assumes that the law was only about 50 percent effective in increasing seat belt use. We estimate that the cost of implementing such a measure might be \$200,000 per fatality averted.[2]

The State of New York implemented a mandatory seat belt law in December 1984, and began enforcement on January 1, 1985 [22]. This move already has proved very effective, leaving many officials stunned at the dramatic decrease in fatalities. By the end of January this year, the State of New York documented its lowest motorist fatality statistics since 1926. And, the 15 percent of New York drivers who previously used their seat belts on a regular basis increased to a remarkable 70 percent.[3] A total decrease in fatalities of 27 percent was recorded in New York State after the first three months of 1985 [23]. Figure 2 relates the occurrence of fatalities and use of seat belts.

Officials believed that passage of the mandatory seat belt law would go largely ignored [22], but fines of $10 to $50 for failure to use a seat belt have proven an effective way to decrease fatalities. The increase in the percentage of seat belt users proves that adherence to the law, though considered a great annoyance by most drivers, is not an inconvenience too great to be overlooked in hopes of not being caught. The public is now showing support for the law. After seeing the actual statistics, appreciation for the benefits gained (reduction of serious injuries and fatalities, lower insurance rates, and a feeling of making a positive move to reduce their own risk) are clearly outweighing any inconvenience.

Even though the fines incurred from noncompliance are minimal, the measure remains cost-effective because enforcement agencies are not going out of their way to seek out every offender. Rather, almost all of the 4,500 offenders cited in January had been initially stopped for another violation [22]. The automotive industry has contributed about $15 million to help pass these laws to avoid costly design reformations to include air bags and implementation which they have long fought to avoid.

After observing statistics in Canada and Great Britain, countries which have enforced the mandatory seat belt law for several years, researchers note that the automobile operators most likely to be involved in a serious or potentially fatal accident are also those least prone to adhere to the seat belt law [22]. Hopefully, continued stringent enforcement of these laws will eventually conform the views of those motorists who still may tend to defy the law by showing the further decline in the number of highway fatalities

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[2]Reference 14 suggest that if everyone used seat belts, we might see a reduction of about 10,000 fatalities per year Reference 6 speculates that up to 15,000 fatalities might be averted.

[3]Estimates from the U.S. Department of Transportation state that national seat belt use averages 15 percent, and that 100 percent compliance would mean a 50 percent reduction in serious injuries and fatalities [22].

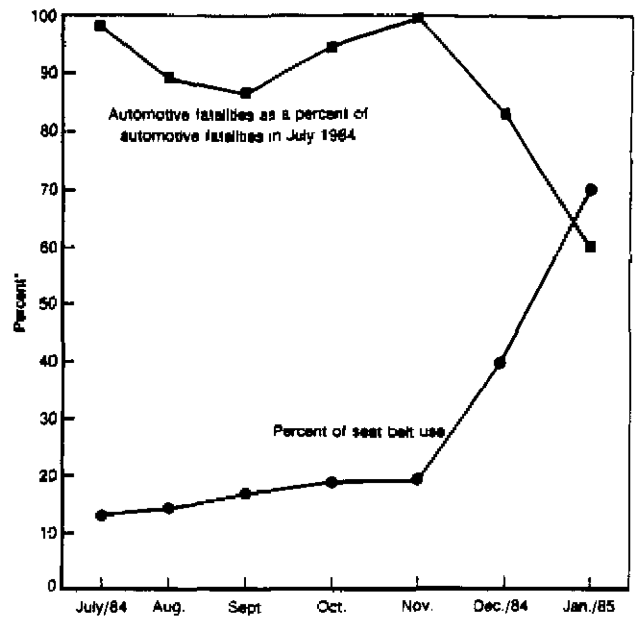

Figure 7. Fatalities and use of seat belts. "Percent" refers both to seat belt use and to fatalities. For seat belt use it refers to the percentage of drivers who wear seat belts; this figure varies from 15 percent use in July 1984 to 70 percent use in January 1985. The percentage of fatalities is measured relative to 100 percent in July 1984, so that, for example, in January 1985 fatalities were reduced to 60 percent of what they were in January 1984. Source: [22]

We can look at some examples where the industry has made design changes, thereby reducing fatalities and injuries. The installation of roll bars on utility vehicles (jeeps) has eliminated hundreds of fatalities per year at a cost of hundreds of millions of dollars. The cost per fatality averted is one the order of a million dollars [6]. Another industry design change, bumpers that prevent damage to cars if accidents are below 2.5 mph for rear bumpers, or 5 mph for front bumpers, generally does not reduce the number of fatalities. This makes sense because we would not expect any fatalities in an accident under 5 mph. Also, the improved bumper design probably did not reduce the number of severe injuries by very much, but there was clearly a reduction in property damage.[4] Based on estimates in [13] there is a dramatic dollar savings in repair costs associated with improved bumper design. These savings can be represented as a percentage savings relative to 1972 designs. Model 1973 cars were the first to have the 2.5/5.0 mph bumpers. The savings in repair costs are clearly a function of the relative sizes and weights of the bullet car and the impacted car. Table 3 illustrates the percentage savings across all sizes and weights from 1973 through 1978.

In another case, if the government required nationwide that children under 4 years of age use child restraint seats, then the number of deaths for children under 4 years old would be reduced by 500 per year, at a minimum. The cost of enforcing such a law would be millions of dollars and we might see about a $100,000 cost per fatality averted. All would agree that this was very cost effective. Unfortunately, only a few states presently enforce the use of child car restraints.

A number of studies have considered the effect of having a rear brake light at approximately the height of the bottom of the car's rear window. Several concluded that as many as 50 or 60 percent to all rear-end accidents could be reduced by using this rear light.[5] The number of fatalities reduced might be as many as 1,000 to 2,000 per year and the cost of implementing such a system could be as high as a billion dollars. So, we see that dollar cost per death averted is $30,00 per year. Again, such a measure would be very cost effective.

Table 3

REPAIR COST SAVINGS FROM
1973 IMPROVED BUMPER DESIGN

Year*	Percent Savings
1973	4 to 17
1974	21 to 35
1975	8 to 26
1976	19 to 33
1977	1 to 32
1978	4 to 24

*Compared with 1972 models.

[4]Before 1973, roughly 20 percent more accidents were reported. This 20 percent corresponds to those accidents resulting in damage in rear-end and front-end bumpers for impacts under 2.5 mph and 5 mph, respectively. The 1978 design improvement eliminated most of these claims.

[5]Reference 16 credits at 66.6 percent reduction in rear-end crash probability, and states that the cost of the average rear-end accident would be reduced from $1,041 to $398. References 11, 12 estimate that 1,200 fatalities per year would have been averted if all passenger cars were equipped with such a light. They further estimated that nearly 150,000 injuries could be averted, and that insurance companies could save perhaps $1.3 billion in 1979 alone.

We can look at a number of other entries on Tables 2A through 2E and demonstrate by example how the cost per averted fatality was estimated. The use of air bags on all cars (roughly 100 million cars), which would clearly be a design change, could save as many as 6,000 to 9,000 lives per year, and could reduce injuries by 300 percent. Because air bags might cost up to $1,000 per car to install, the cost per fatality averted could be as high as one or two million dollars. If we assume that air}bags cost $1,000 per car to install and, in one year, they are installed in all cars manufactured in that year (roughly 10 million cars), then the cost to install air bags in all cars manufactured in one year would be Table 3

$$(\$1{,}000 \text{ per car})(10 \times 10^6 \text{ cars}) = \$10 \times 10^9,$$

or 10 billion dollars. Because 10 million cars represent about 10 percent of the total number of cars on the road, then perhaps 500 lives could be saved per year. If we further assumed that each car with air bags had a life expectancy of 10 years, then during the lifetime of these 10 million cars perhaps 5,000 lives could be saved. Then the cost per averted death could be estimated at

$$\frac{(\$10 \times 10^9)}{5 \times 10^3 \text{ lives}} = \$2 \times 10^6/\text{life}$$ [6]

Some studies suggest that if air bags were used on all cars (about 100 million in the United States) then some number substantially less than 5,000 lives could be saved and, hence, the cost per death averted would be substantially greater than two million dollars.

Further, the use of air bags may, in fact, increase risks in a number of ways:

- They may provide a false confidence and cause people who would otherwise wear seat belts not to wear them. (The air bag is designed to work in only frontal-type crushes, and people not waring seat belts in other types of crashes could be more severely injured, or even killed, if they neglected to wear seat belts.)

- Air bags have been known to fail, even in fatal crashes.
- When the air bags function properly, they may by their very nature induce specific injuries. Since air bags are designed to expand within one-fortieth of a second, the additional amount of energy that must be managed immediately following a frontal impact is increased. This increased energy, by its very nature, may cause injury. For example, the unrestrained child learning against the windshield before a frontal collision could be thrown back instantaneously as the air bag explodes.

- The propellants used in air bags may be carcinogenic. If air bags are installed in all cars on the road, we might expect to have to dispose of roughly twenty million canisters (2 per car for 10 million cars) of carcinogenic propellant per year.

If we perform an extremely conservative calculation of the worth of

[6] These terms are stated in scientific notation. The term "$10 x 10^9" translates to ten billion dollars; the term "5 x 10^3 lives" translates to 5,00 lives; and the term "$2 x 10^6/life" translates to two million per averted fatality.

air bags, we might disregard the negative features of air bags discussed; we might assume that air bags installed on 100 million cars would save 10,000 lives per year, and that air bags would cost only $640 per car to install. Using these very conservative assumptions, we would estimate a cost per averted death of $640,000--still a high number.[7] The use of air bags would be considered far less cost effective than the use of child restraint seats.

These tables list a number of other measures that could be taken by government, industry, or drivers, stated in dollars per averted fatality. Cost per averted fatality ranges from as low as $30,000 to as high as several million dollars.

<u>What the Automobile Industry Has Done to Improve Safety</u>

Figure 3 divides measures that have actually beel implemented from those that have not. It also illustrates cost per death averted and whether the measures are predominately controlled by industry, government, or drivers. For measures actually implemented, we find that approximately $150,000 to $600,00 per fatality averted has been spent by the auto industry These measures include: adding skid resistant properties to the braking systen, improving steering columns, adding additional rear reflectors, and offering a three point harness seat belt

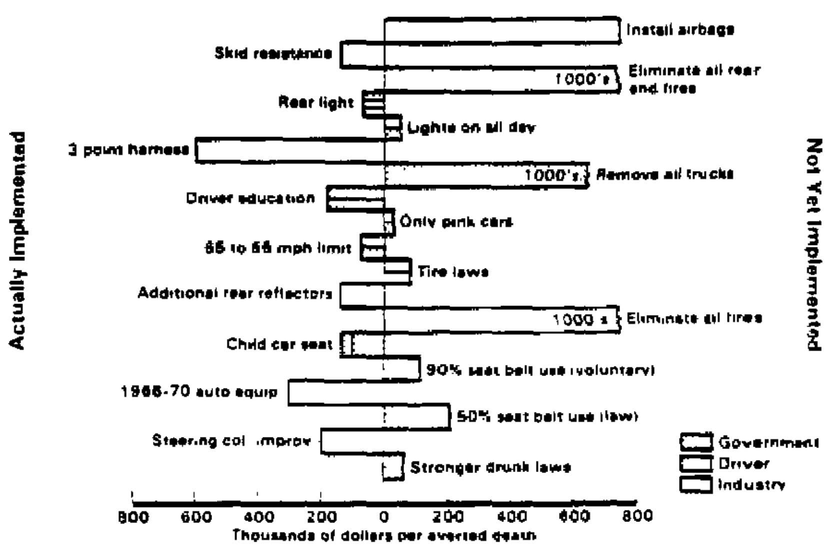

Figure 3. Measures implemented by the automotive industry to improve safety

[7]It is interesting to note that if air bags were used in conjunction with much stricter anti-drunk-driving laws, the cost per averted fatality for air bag use would increase, since many of the accident-causing drunk drivers would be no longer on the road.

To look at what several state governments have spent to reduce the number of fatalities per year we consider the law requiring child restraint seat use. The cost of implementing child care seat laws to these states is approximately $100,000 per fatality averted. Other possible measures subject to government control are reducing the speed limit from 65 to 55 mph and mandating the use of the high, center-mounted rear brake light. Each measure would cost on the order of $30,000 to $50,000 per death averted.

If we compare measures that were actually implemented with those that have not been implemented, we see a rather interesting contrast. Of those not yet implemented, we can divide the measures into two general categories: those that are very expensive to implement (millions of dollars per fatality averted), and those that are relatively inexpensive to implement (typically, $50,000 to $200,000 per fatality averted). Of those that are very costly, three of the four fall on the industry's shoulders; these are (1) to eliminate specifically, rear-end fires in automotive accidents, (2) to eliminate all fires in automotive accidents, and (3) to install air bags. The fourth, to remove all trucks from highways, falls on the regulatory branch of the government.[8]

On the other hand, for relatively modest costs a number of fatalities could be prevented. Such fatality-averting measures might include, stronger drunk-driving laws[9] or a requirement that headlights be on all day. The former requires government action, and to a lesser extent, driver action. The latter is more a function of driving habit, but in fact could also be a function of law enforcement agencies. Both would save a fatality for approximately every $50,000 expended.

Take what seems to be a ridiculous situation, requiring that all cars be pink. We find that the cost of implementing such a measure would be fairly modest relative to the number of lives saved. This is partly due to the belief that pink cars are least likely to be involved in accidents. In all fairness, this is a correlation as opposed to a causation. That is to say, it is not because they are pink that they are involved in fewer accidents; it is that perhaps people who drive pink cars tend to be more cautious. In any event, if we took the information rather

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[8]While trucks account for 6 to 8 percent of total freeway mile use, they contribute to as many as 50 percent of the fatalities due to rear-end collisions [16]. A typical accident involves a car rear-ending a slow-moving truck on a freeway.

[9]Implementation of such a measure as stronger drunk-driving laws may have significant social costs associated with it such as increased police patrols, busier courts, larger jails, and so on. The issue of how to implement stronger drunk-driving laws will be the subject of a forthcoming paper.

literally and did not assess it carefully, we might facetiously say that if everyone drives pink cars, the cost of reducing the number of annual fatalities is rather modest.

A number of other measures could be taken by the government and drivers which, if implemented, would cost a rather modes amount of money to prevent deaths.

4. IMPLICATIONS

The $10,000,000 Menu

How many lives can be saved for a $10,000,000 expenditure? Another way of comparing risk reduction measures is to consider that we have only a limited amount of money to spend. Suppose you had ten million dollars. There are several ways in which to spend this money, and each way determines a different number of fatalities that could be averted.

Figure 4 summarizes seven ways to save lives given a fixed resource of ten million dollars. In Case One, you would mandate that all automobile fires be eliminates, and you can spend ten million dollars in a lump sum to eliminate these deaths. Each ten million dollar expenditure will prevent approximately one death. We have already seen a 300 percent reduction in fire deaths when Federal Vehicle Safety Standard (FMVSS) 301 was implemented. This standard, FMVSS 301, dictates certain test requirements that cars and trucks must satisfy. These standards reduce the probability of fire. An example is that passenger cars must be able to withstand a 30 mph frontal barrier impact with fluid loss of less than 1 ounce per minute. Case Two, a situation that has been implemented, reduces the speed limit from 70 or 65 miles an hour to 55 miles an hour. Each ten million dollars expended will buy you approximately 200 averted deaths. In Case Three, stricter enforcement of seat belt laws, each ten million dollars will buy you approximately 50 averted deaths. To some extent, that has been implemented in New York State and on several Air Forces bases. In Case four, stronger drunk-driving laws, each ten million dollar expenditure will buy you perhaps 200 averted deaths. We have seen stronger and stronger drunk-driving laws being implemented over the past few years. Case Five, child car seat enforcement, suggest perhaps 100 averted deaths for each ten million dollar expenditure. child car seat laws are required as of mid-1984 in 7 states. Air bags, Case Six, will buy about 12 averted fatalities, and pink cars, Case Seven, might buy 2,000 for each ten million dollars expended.[10]

[10] As discussed earlier, the use of pink cars is only correlated with reduced accidents, and does not likely reduce accidents themselves. People who drive pink cars may be more careful drivers. Also, if all cars were pinks, we may not expect much of a decrease in accidents.

Case 1:	**Eliminate all death by fire** **~about 1 averted death**
Case 2:	**Reduce speed limit from 65 to 55 mph** **~about 200 averted deaths**
Case 3a:	**Seat belt enforcement law** **~about 50 averted deaths**
Case 3b:	**Voluntary seat belt use** **~about 100 averted deaths**
Case 4:	**Stronger anti-drunk laws** **~about 200 averted deaths**
Case 5:	**Child car seat** **~about 100 averted deaths**
Case 6	**Install airbags** **~about 12 averted deaths**
Case 7:	**Buying only pink cars** **~about 2,000 averted deaths**

Figure 4. The $10,000,000 menu: Save as many lives as you can.

The Bottom Line

Industry has, in fact, implemented a number of cost-effective measures to date. Changing driving habits and stricter law enforcement will lead to more cost-effective means of saving lives.

While the means of implementing measures to improve safety is beyond the scope of this presentation, it suffices to say that more effective and stricter law enforcement against drunk drivers and people who fail to use seat belts and child restraint seats will provide the greatest benefit per dollar spent.

The decision by the State of New York to enforce the mandatory seat belt law is a direct and effective step in improving safety on our highways. Enforcement in New Jersey, Illinois, Michigan, and Missouri for seat belt use will begin this summer, and 32 other states are considering instating such a law. Should the implementation and enforcement spread nationwide, a great number of fatalities will be averted in the future. Hopefully, law enforcement agencies will be influenced enough by the statistics of deaths averted to enforce this law stringently. And, agencies hopefully will go after the drunk driver with a rigid campaign to help rid our highways of another great hazard--a hazard over which the drinker has sole control--to provide more complete safety for law-abiding motorists.

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SELFISH SAFETY OR REDISTRIBUTED RISKS? TRADE-OFFS AMONG AUTOMOBILE OCCUPANTS' ACCIDENT FATALITY RISKS

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1. INTRODUCTION

For a long time it has been known that large cars are safer than small cars. Recently, this has been widely publicized by The Car Book (1980), published by the National Highway Traffic Safety Administration under President Carter's administration, and in publications of the Highway Loss Data Institute (HLDI, 1981), some findings of which were cited by General Motors Corp. in newspaper advertisements in 1982.

The Car Book states that: "Of the automobiles currently on the road, a 4000 pound car is twice as safe as a 2000 pound car (p. 18)." Several graphs are offered to support this summary statement. A reader of the HLDI reports (and of the GM advertisements) will immediately recognize that the 19 car models with the best insurance injury claim experience (i.e., the lowest) are larger and heavier than the 17 models with the worst experience--3500 pounds versus 2200 pounds. Readers of these publications receive a clear message that buying a heavier car will reduce fatality and injury risk in a crash.[1] If automobile manufacturers believe that lower injury and fatality risk is a selling point for their cars--as is reflected by the General Motors advertisements--they should have an incentive to produce heavier cars; on the other hand, the higher cost of heavier cars and the Corporate Average Fuel Economy standard which implicitly favors lighter cars counteract this incentive. Consumers have a choice among many manufacturers' products, and manufacturers attempt to influence it, of course. If manufacturers and/or consumers should tend to promote or elect the purchase of heavier cars, then certain consequences--including important ethical ones--follow. We intend to pursue these consequences in what follows.

2. THE CRASH INJURY AND FATALITY RISKS FOR OCCUPANTS OF LIGHT AND HEAVY CARS: THE EMPIRICAL BASIS

2.1 Structuring the Problem

One must first note that occupant injuries or deaths-per-vehicle-year reflect (1) the effects of vehicle miles driven per year, (2) occupants per vehicle, (3) the accident risk per mile of travel, and (4) the risk of injury or death in an accident. The first two factors do not depend on the vehicle; the third depends more on the driver and the environment but may be influenced by vehicle factors; only the last depends strongly on the vehicle (and also on the accident severity, e.g., as measured by impact speed). Therefore, the occupant injury and fatality risk in an "average" crash is the best measure of the car's safety, except in those cases where a car might have a definitely higher accident risk.

The weight of a car plays very different roles in single car in contrast to multivehicle accidents. In single car accidents, where a car hits a fixed object, or rolls over, there is no physical reason why a heavier car should be safer than a lighter one (except in situations where a heavier car could break an obstacle that results in a "softer landing").

Empirical data reveal that the injury and fatality risk in a single vehicle crash depends relatively little on car weight; the effect is probably indirect because heavier cars tend to be larger, and larger cars can better absorb the impact. In car-car crashes, however, weight plays an important and direct role: the changes in velocity that the two cars experience are proportional to the weights of the cars--the lighter car experiencing the greater change of velocity. This change of velocity has been found to be the single most important variable influencing the occupant injury and fatality risk. Empirical investigations have shown the strong effects of car weight in car-car collisions. Collisions between cars and trucks are similar to collisions between cars, but the stiffer and higher frame of trucks further complicates the analysis. Although multicar collisions are similar to collisions between two cars, we shall restrict our discussion to the most common types: (1) single car accidents, and (2) car-car collisions.

2.2 Quantitative Relations

The effects of the weights in tw car collisions on the occupant injury risk were first quantified in the early 70's (D. Mela, 1974). This relation shows that the injury risk for occupants of a car of weight w (in 100 lbs.) colliding with a car of weight w' is proportional to

$$\exp(-.05w + .02w')$$

More recently, H.C. Joksch (1983) reviewed all the available information on injury and fatality risk in car crashes and found that a formula of this structure still gave an adequate representation of the data, though the exact shape of the relation may be somewhat different, and individual car models may deviate, because characteristics other than weight also play a significant role. For the fatality risk, Joksch found the relation

$$\exp(-.07w + .055w').$$

For the fatality risk in single car accidents, the relation is much less certain:

$$\exp(-.02w)$$

gives an adequate representation of the empirical data. One should note that this relation is nearly the same as in collisions between two cars of the same weight, $w=w'$. This is plausible because a collision with another car of the same weight is equivalent to a collision with a fixed object; it would be exactly equal, if the coefficients were slightly different:

$$\exp(-.07w + .05w').$$

We will use this relation for conceptual clarity. This equation can then be written as follows:

$$\exp(-.02w)*\exp(-.05w + .05w').$$

The first factor represents the intrinsic crashworthiness of the car of weight w and the second factor is the advantage or disadvantage it has when colliding with a car of weight w'. If we look at the corresponding equation for the other car, then

$$\exp(-.02w')*\exp(-.05w' + .05w).$$

We see that the effect of the weight difference on the second car is exactly the inverse of its effect on the first car. Whereas the first factor reflects a true reduction of injuries or deaths, the second factor simple reflects shifts to deaths and injuries from heavier to lighter cars. A closer look, however, reveals that this is not just a simple shift: If the second factor serves to reduce the risk for the occupants of heavy cars to one half, then it doubles that for occupants of light cars. This amounts to the sacrificing of two lives in order to save one. The first factor, however, reduces this effect. To illustrate these relations, we shall consider three cars with weights of 2000, 3000, and 4000 lbs., respectively. This describes most of the present range of weights. Table 1 reflects the fatality risks relative to that in a collision between two 3000 lb. cars.

Table 1

Illustration of Relative Car Driven Fatality Risks In Collisions of Two Cars and in Single Car Accidents

Weight of Victim's Car (lbs.)	Weight of Other Car (lbs)			Single Car
	2000	3000	4000	
2000	1.22	2.01	3.32	1.22
3000	.62	1.00	1.65	1.00
4000	.30	.50	.82	.82

2.3 Modeling the Overall Effect of Car Variety

To study the overall effects of having cars of different weights on the road, and the effects of shifts in "car population," we shall assume a car population composed of three types of cars, with the proportion p, q, and r for the light, medium and heavy cars, respectively. Hence, $p+q+r=1$. We shall also assume that the probability of accident involvement is independent of car weight, and that cars in accidents are randomly mixed. We can then say, 'the proportion p*p' of crashes involves two light cars; '2*p*q' a light and a medium weight car, etc. The total number of occupants killed is a quadratic function of p,q, and r: $t=1.22pp + 2.63pq + qpq + 3.62pr + 2.15qr + 0.82 rr$. Since only two of these proportions are independent, one may represent the vehicle mix in a plane, as in Figure 1.

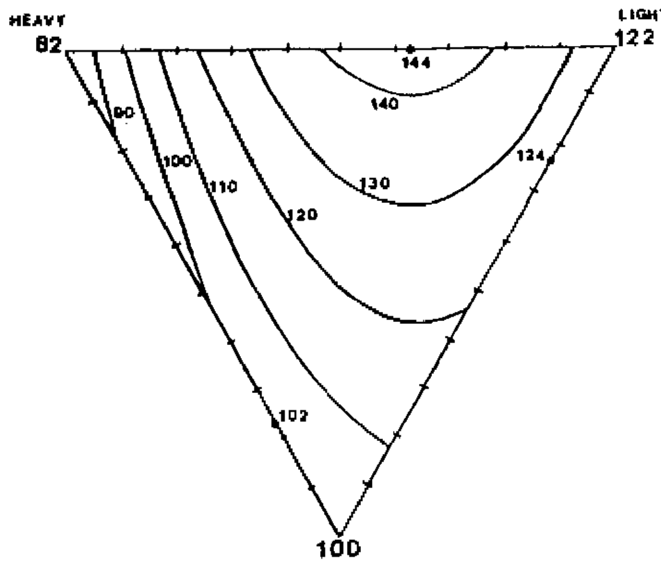

Figure 1. Total occupant deaths in car-car collisions as functions of the composition of the car population. Each potential mix of the three car classes (heavy--4000 lbs.; medium--3000 lbs.; light--2000 lbs.) is represented by a point in the triangle, the corners representing fleets of all heavy, all light, and all medium cars. Curves of constant numbers of total deaths are shown. The numbers are total fatalities relative to that for a fleet of all medium-weight cars.

Each corner of the triangle represents a car population which consists of only one type of car; a population with one-third of each of the three types is represented by the point in the center of the triangle; a population of one-half heavy and one-half light cars is represented by the midpoint on the upper edge.

The absolutely minimal number of deaths occurs in a fleet of all large cars (82). The absolutely largest number, however, does not occur for a fleet of all light cars: it occurs at a point at the upper edge of the triangle which represents about one-third large and two-thirds light cars. To illustrate the implications of this in some detail, let's assume a fleet which corresponds to the point (on Figure 1) with the highest number of fatalities - 144. This point, then, represents 63% of light cars and 37% of heavy cars. If there were not the interaction of car weights in crashes, then there would be (.63 * 122) 77 deaths in light cars, and (.37 * 82) 30 deaths in heavy cars. The total number of deaths would be 107, of which 72% occurred in light and 28% in heavy cars. However, the difference of car weights in collisions increases total fatalities by 38, which is equal to 36%; this also alters the distribution: 88% of those who die were in light cars; and only 12% of those who die were in heavy cars.

Imagine a fleet of all light cars (*viz*. upper right corner): If an owner would replace his light car by a medium or heavy car (without adding a car to the fleet)[2], this would shift the point which represents the car population to the left or lower left. The situation is similar if several owners do this. Except if this shift is very large, the result is an increase in the total number of deaths.

Figure 2 describes the results of a more detailed analysis. If the fleet is represented by a point right of the line A, then a small shift from light to medium cars (leaving the proportion of heavy cars unchanged) results in an increase in the total number of deaths. A shift from light to heavy cars (leaving the proportion of medium cars unchanged) leads to an increase in the total number of deaths, if the starting point is right of line B. Similarly, line C is defined for a shift from medium to heavy cars.

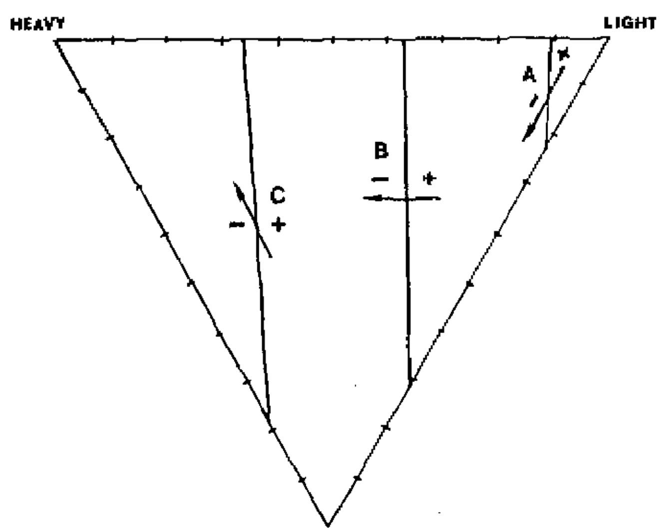

Figure 2. Changes in total occupant deaths in car-car collisions resulting from changes in the car mix. A change in the car mix in the direction of the arrows increases deaths on the right sides of the lines dividing the triangle and decreases them on the left sides of the lines.

If someone shifts from a lighter to a heavier car, he will reduce his own fatality risk. However, from this model we must draw the conclusion that this does not necessarily reduce the number of total fatalities. Depending on the current composition of the fleet, he may so increase the risk to others--in cars lighter as well as heavier than his--that overall there will be an increase in the total number of deaths in car-car collisions. On the other hand, someone shifting to a lighter car will increase his or her own fatality risk, but may so decrease that of others such that the number of total fatalities decreases. Whether this condition will actually prevail depends upon the exact composition of the current automobile fleet. Figure 2 illustrates how different the results of a shift in the composition of the fleet can be, depending on the initial position of the fleet.

The model has to be modified slightly if one includes single car accidents. They contribute the terms

$$1.22p + 1.00q + .82r$$

to the total number of deaths. Since about the same number of car occupants die in single car accidents as in multivehicle accidents, we may combine the models so that for a fleet of all medium cars half of the deaths occur in single vehicle accidents and half in car-car collisions.

The results of this model are shown in Figure 3. The overall pattern of the function of total deaths is similar to that in Figure 1; however, the function is much "flatter." There is one difference as is shown in Figure 4: there is no dividing line corresponding to line A in Figure 1, here a shift from light to medium cars will never increase the total number of deaths.

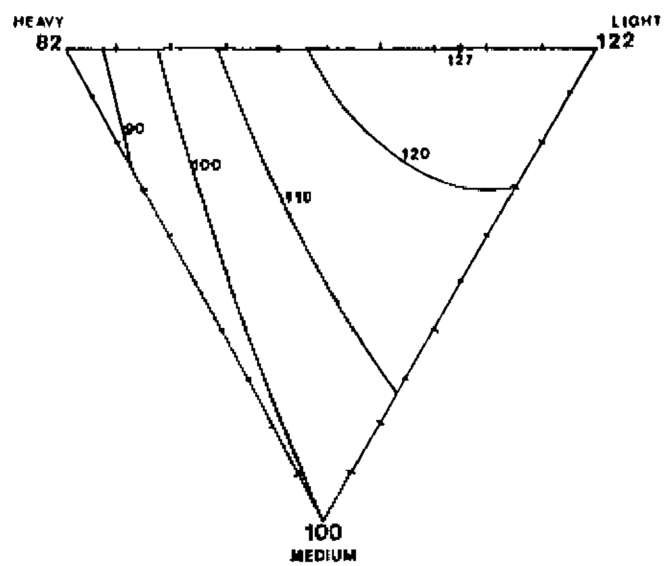

Figure 3. Total occupant deaths in car-car and single-car collisions. Each potential mix of the three car classes (heavy--4000 lbs.; medium--3000 lbs.; light--2000 lbs.) is represented by a point in the triangle, the corners representing fleets of all heavy, all light and all medium cars. Curves of constant total deaths are shown. The numbers are total deaths, relative to that for a fleet of all medium cars where half of the deaths occur in single-car and half in car-car accidents.

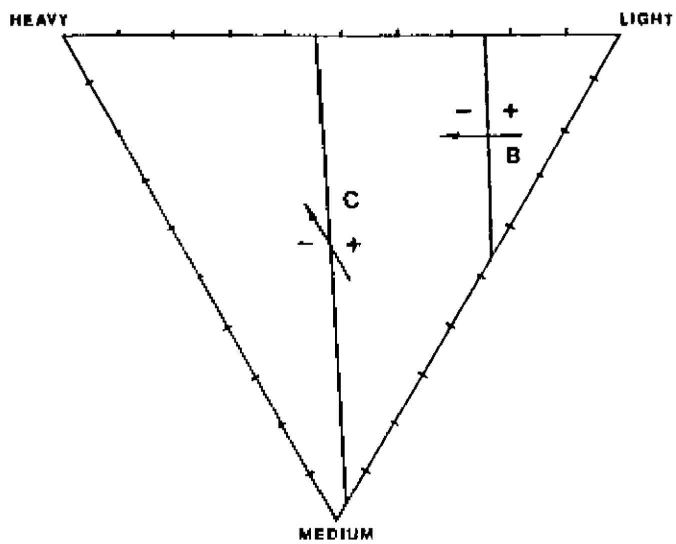

Figure 4. Changes in total occupant deaths in car-car and single-car accidents resulting from changes in the car mix. A change in the car mix in the direction of the arrows increases deaths on the right sides of the lines dividing the triangle and decreases them on the left. A change from light- to medium-weight cars will always reduce total deaths.

In short, our model shows that someone might decrease his own fatality risk by shifting from a lighter to the heavier car. One certain consequence of this choice is that is will increase the fatality risk for certain other car occupants and possibly to such a degree that the total number of deaths will also be increased.

2.4 Limitations of the Model

Though our model probably offers a realistic, qualitative picture of the real automobile accident world, the numerical results may not be quite accurate, for a few reasons: First, the empirical relations are based on the experience of 1980 and earlier car models; second, the relation that exists between weight and risk is probably far more complicated than our model reveal; third, though the effect of weight is always manifest in car-car collisions, other factors also play a role in energy management in crashes. Finally, the real automobile fleet is composed not of three types of cars, but of many, thereby covering a rather wide range of automobile weights.