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User adaptation to injury protection systems: its effect on fatalities, and possible causes

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User adaptation to injury protection systems: its effect on fatalities, and possible causes

by

Offer Grembek

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Professor Samer M. Madanat
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Fall 2010

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Abstract

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Professor Carlos F. Daganzo, Chair

Although it is generally believed that people drive less carefully when their vehicles are equipped with new protection systems, the possible impact of such behavior on fatalities has never before been quantified. A meta-study across a diverse set of injury protection systems strongly suggests that users do adapt to new protection systems in a way that increases fatalities, and that the effect is more intense for systems that are easily perceived by the user. Perceptibility was quantified and found to be higher for injury protection systems that require user activation; for these systems, it is estimated that about 9% of the fatalities can be attributed to adaptation.

To Mirit,
more than anything else.

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Chapter 1

Introduction

1.1 Motivation

The loss to society from traffic-related fatalities is distressing. The growing number of automobiles in developed countries has made traffic fatalities the most prominent reason for accidental death and the leading cause of death for the 1-34 age group [28]. It is estimated that by the year 2020 road traffic accidents would be the third largest cause of the global burden of disease [33].

Researchers and professionals relentlessly seek technological and public interventions to reduce this loss. In parallel, significant efforts are dedicated to develop statistical tools to evaluate the effect of such interventions. Sadly, not all effective interventions are appropriate for large scale implementation. Consequently, evaluation studies are used to assist decision-makers in prioritizing alternatives. The evaluation of safety interventions is therefore a critical component of the challenge to improve safety.

The safety of a trip is comprised of two major intertwined risk categories: a category of static risk encompassing the inanimate physical traits of the vehicle and its infrastructure, and a category of dynamic risk resulting from the behavior of the users and other changes in the environment. The behavior of the human operators, or the people being transported, introduces a lot of uncertainty to the dynamic risk category. Moreover, in traffic safety, the contribution of the human factor is considered the most substantial factor and therefore complicates prediction [49]. The majority of traditional econometrical tools are designed to capture static effects, but are limited in evaluating dynamic effects. Therefore, despite considerable efforts, the traffic safety community is still short of establishing sound fundamental guidelines for the problems at hand.

To better serve society it is important to understand how these two risk categories interact to establish the level of safety observed in the field. An important realization of such interactions is user adaptation. The idea behind this is that when safety systems are introduced (static risk change) drivers may adapt to the improved safety and may take additional risks (dynamic risk change).

Adaptation is not a hypothetical phenomena, but rather a realistic trait of human and driver behavior. Researchers have identified a variety of conditions in which drivers adapt their behavior. For example, narrowing of eye fixations when closely following another vehicle [35], or increasing driving speeds with studded tires driving on icy roads, such that the skid margin approached those of drivers with regular tires [57]. In fact, some systems are specifically designed to facilitate a behavior change. For example, football players are provided with protection to accommodate more aggressive maneuvers [36]. Other examples such as personal protectors for loggers or protection gloves for meat cutters are designed to allow the employee to work faster.

The problem at hand is therefore not that adaptation exists, but rather that it is unintended or unpredictable by the designers. If adaptation has a significant impact on safety, it would have implications for the design and the evaluation of safety systems. The impact on safety of such behavioral responses is the focus of this dissertation.

A major challenge in studying adaptation is that changes in human behavior typically evolve slowly and are therefore difficult to measure. When little is known about the causal mechanism of a problem it is sometimes useful to generate a perturbation and observe the long-term response. If done repeatedly it might be possible to identify attributes of the perturbation that affect the long-term outcomes, without actually understanding the mechanism. Similarly, introducing a new safety system generates a discrete perturbation in the environment and a behavioral response over time. This creates an opportunity to observe and quantify whether a safety system induces user adaptation. In light of this, this thesis developed a framework that systematically quantifies the impact of such responses to new safety systems.

Data to study adaptation needs to be synthesized from different data sources and is therefore very noisy. As a result, studying adaptation of individual systems may be inconclusive. In view of this, the data is collectively analyzed here with a meta-study that treats each safety system as an observation. By including many protection systems, it may be possible to detect attributes of these systems that induce adaptation. The literature has suggested several factors that affect adaptation, such as the extent to which a user perceives that a safety system exists [16, 7]. However, these conjectures have never been systematically tested.

Adaptive behavior is intrinsically human and may also manifest itself in activities other than driving. For example, are you more likely to carelessly place a medication container when it has childproof caps? or, are you more likely to spend more time in the sun during high radiation hours because you are wearing sunscreen? In view of this, a multidisciplinary analysis is a logical way of enriching the data set, and it is pursued here.

1.2 Scope of research

To preform a meaningful comparative analysis it is necessary to define clearly the scope of the research. Even though the exact mechanism of adaptive behavior is not well known, the general mechanism clearly involves a behavioral reaction in response to a change in the conditions of an activity. Therefore, the relevant users, activities, safety systems, behavioral responses and outcomes are described below.

Users

This study only considers activities in non-professional settings. Employees are often measured for their productivity and safety performance. Therefore, their behavior with respect to risk may be governed by different dynamics than those in the general population. Moreover, as mentioned earlier, many systems in professional settings are designed to facilitate a behavior change. Therefore, behaviors in professional settings are not included here.

Safety-critical activities

We define safety as the lack of damaging incidents to people or property. Consequently, measures of safety, such as fatality rate, actually quantify how unsafe an activity is. Some activities, such as driving, carry an inherent risk for damaging incidents. For these activities maintaining the physical well-being of the user affects how the activity is performed. Such activities are labeled safety-critical, and are a natural context to study the interaction between adaptive behavior and safety.

Injury protection systems

This study considers safety systems that provide injury protection in a direct or indirect manner. *Direct injury protection systems* typically serve as a physical barrier that restricts the damage inflicted to the user in an accident. Examples are helmets and restraint systems such as seat-belts and airbags. *Indirect injury protection systems* typically enhance (or impair) the users' capability to prevent (or cause) an accident, and reduce (or increase) its severity. Some systems enhance visibility (e.g., daytime running lights) or the operational control of a vehicle (e.g., electronic stability control), while other systems impair the operational control of an individual (e.g., childproof doors).

Safety systems for non-transportation activities also fall under the same categories. For example: condoms and sunscreen are *direct injury protection systems*; childproof medication caps and childproof lighters are *indirect injury protection systems*. Table 1.1 below summarizes safety systems that fall within the scope of this study: transportation on top and other activities on the bottom.

Table 1.1: Safety systems for transportation and non-transportation activities

Direct injury protection systems	Indirect injury protection systems
Airbags	Anti-lock braking systems
Bicycle helmets	Daytime running lights
Motorcycle helmets	Electronic stability control
Seat-belts	Center high mounted stop lamps
Side impact improvements	
Head restraints	
Condoms	Childproof lighters
Sunscreen	Childproof medication caps
Ski helmets	Lawnmower blade control
	Personal flotation device

User adaptation

Both the conditions triggering the behavioral response, and the nature of the response itself are used to define the type of user adaptation considered here. First, only adaptations in response to long-term sustained changes are considered. For example, increasing the tendency to run a red light in response to longer all-red intervals is relevant since it involves a long-term response to a sustained change in the signal timing. Conversely, running a red light when pressed for time, is not studied here since it is a reaction to a temporary condition. Second, only reactions that alter the way the user performs the activity are considered, while reactions that increase the frequency of the activity are not part of this study. For example, faster driving when a vehicle is equipped with anti-lock brakes is a relevant reaction, while increasing the trip frequency for vehicles equipped with anti-lock brakes is outside the scope of this study.

Fatalities

The objective is to study the impact of user adaptation on safety. Fatalities are used as the measure of safety since they are naturally consistent across all disciplines and fatality data is a reliable measure of safety.

1.3 Dissertation overview

1.3.1 Main contributions

The first contributions of this thesis is from quantifying the effect on fatalities of user adaptation to injury protection systems. Adaptation has been an elusive concept for many years and researchers disagree as to whether it significantly increases fatalities. Providing the first systematic quantitative analysis of user adaptation would facilitate a more concrete discussion of this topic.

The second contribution is from quantifying attributes of protection systems that may contribute to user adaptation. Perceptibility (the extent to which a protection system can be sensed) is an attribute that was quantified and found to be higher for injury protection systems that require user activation. This is an important association that may help evaluate how perceptible a system is.

The third contribution is from testing how different attributes of protection systems affect adaptation. The analysis strongly suggest that adaptation is more intense for systems that are easily perceived by users. This contribution has both scientific and practical significance. First, it provides insights on human behavior with respect to changes in risk. Second, such knowledge would help safety professionals develop more successful injury protection systems.

1.3.2 Organization

The thesis is organized as follows: Chapter 2 provides a literature review of user adaptation and summarizes what is known and what gaps still exist. Chapter 3 introduces the adaptation index and the methods used to estimate it. Chapter 4 defines the attributes of the safety systems that are used as explanatory variables, and describes the survey which was used to quantify the perceptibility level. Chapter 5 presents the results which show what attributes of protection system are more likely to induce adaptation. Chapter 6 then discuses the practical significance of these results and further research ideas.

Chapter 2

Literature Review

The following chapter reviews the existing literature. Prominent models of user adaptation are described, including the insights and gaps of these models. The chapter also describes factors which have been identified in the literature as potential factors affecting adaptation. The current practice of road safety evaluation is described followed by two case studies of adaptation.

2.1 Models of user adaptation

In the traffic safety field, the idea of user adaptation goes back to the late 40's. Since then it has evolved through a variety of labels including risk compensation, offsetting behavior, the lulling effect, and more. The first time it appeared in the spot light was in a divisive paper claiming that the effects of the major Federal Motor Vehicle Safety Standards (FMVSS) introduced in the late 60's were ineffective [45]. The basic assumption in this paper was that drivers trade safety as an economic good, and if their trip is too safe they would trade safety for driving intensity or time. This paper started a long debate on whether driver adaptation exists, what induces it, and if it is even significant enough to matter. A range of models and theories have been developed throughout this debate, including the controversial risk homeostasis theory. Several publications provide a good review of these issues [18, 16].

The existing literature can be roughly divided into three categories: (i) utility maximization models; (ii) physiological and psychological models; and (iii) studies seeking to identify adaptation in empirical data. The prominent studies in each category are described below.

2.1.1 Utility maximization models

Models in this category are based on the utility maximization problem of microeconomics. According to these models users maximize their utility by trading any additional utility provided by the safety systems with productivity of the relevant activity. Some researchers relate the disutility (i.e., the efforts) of safe behavior to the expected loss in case of an accident [1, 61]. Other researchers propose a decision-theory model of danger compensation with respect to speed choice [42]. Figure 2.1 illustrates how drivers, motivated to arrive at their destination as soon as possible, will compensate for the improved safety provided by seat belts.

Let point A in Figure 2.1 represent the optimal combination of safety (vertical axis) and speed (horizontal axis, labeled as "other") for an individual driver (S_1 units of safety, and O_1 units of speed). Curve 1 is defined as the combinations of S and O that provide the same utility as S_1, and O_1. Introducing a new safety system, such as seat belts, would increase the amount of safety to S_2, without affecting the amount of speed. This new point is labeled B. It is now possible to trade away units of safety for units of speed to reach point D. This point has a higher overall utility (curve 3 > curve 2), and will also get the driver to his destination faster. Note that the level of safety at point D (S_3) is still higher than what it was originally, but lower than the level of safety at point B.

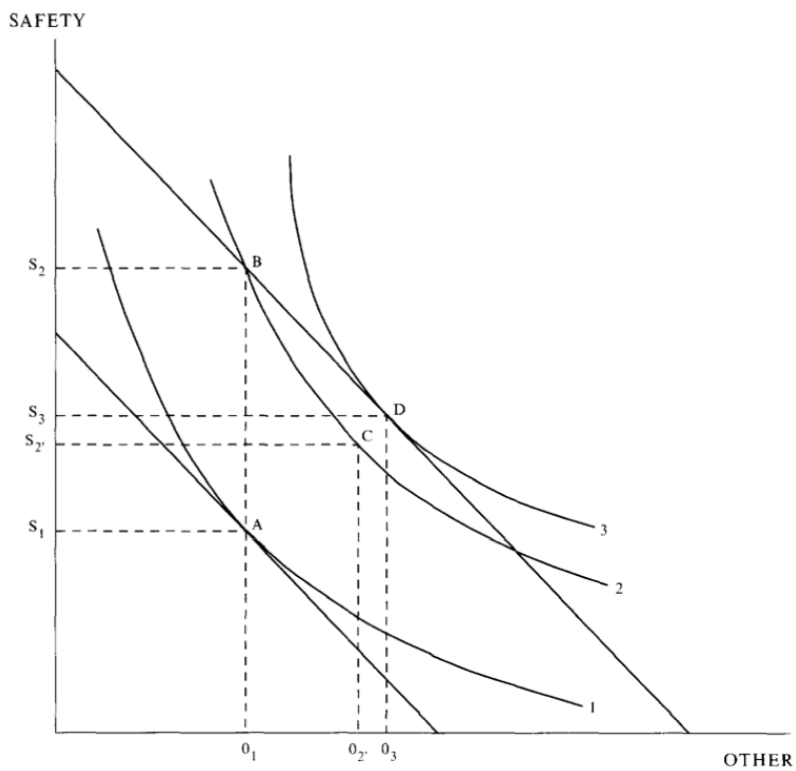

Figure 2.1: Utility maximization models for user adaptation, taken from Dulisse [6]

2.1.2 Physiological and psychological models

Models in this category conjecture that people seek to achieve some inherent level of risk. These models address, to some extent, a comparison between a desired level of risk and the perceived level of risk. The dominant approaches of this concept are outlined below.

The risk homeostasis theory

The risk homeostasis theory predicts that as safety systems are added to vehicles and roads, drivers tend to increase their exposure to risk because they feel better protected [64, 63]. The main conjecture is that when a person drives he is acting as a homeostatically controlled self-regulated process. This means that drivers constantly evaluate the risk associated with the activity (perceived risk) and compare it with the level of risk they are willing to accept (target risk). Whenever these two risk levels are different the driver would take action to regulate the perceived risk with the target risk. A key feature of this theory is the fact that risk is defined as collision rate per time unit of driver exposure, as opposed to the commonly used measure of collision rate per unit distance.

Figure 2.2 illustrates the dynamics of this theory. The boxes in the diagram that are marked by letters represent the core homeostatic process while the numbered boxes on the outside represent individual features that affect this process. The homeostatic process starts when a driver compares the current perceived risk (box b) with the target level of risk (box a). When there is a discrepancy the driver wishes to reduce it (box c) and takes some adjustment action (box d). All actions taken by all drivers in a jurisdiction over a period of time, like one year, determine that year's loss from road vehicle crashes in that jurisdiction (box e). The amount of loss is aggregated and is determined by the actions of all drivers.,This loss in turn affects the levels of risk perceived by drivers and may influence their subsequent decision making. This effect may be delayed in time as represented in the diagram by f. Thus, the process may be seen as a closed loop $b \rightarrow c \rightarrow d \rightarrow e \rightarrow f \rightarrow b$. Where behavior determines the amount of loss, and the amount of loss determines behavior. The fact that the target level of risk (box a), is outside the loop is fundamental to this theory.

The figure also places people's perceptual, decision making and vehicle handling skills outside the closed loop. Perceptual skills (box 4) determine the extent to which the perceived risk corresponds to the real risk. Decisional skills (box 2) refer to the driver's ability to decide what should be done in box d in order to produce the desired adjustment in box c. Vehicle handling skills (box 3) determine whether the driver can effectively carry out what should be done for this purpose. The level of performance attributable to all three types may be improved by driver education, by licensing standards, or by an ergonomically designed environment, including road geometry, signalization, and controls and displays in vehicle design. However, according to the

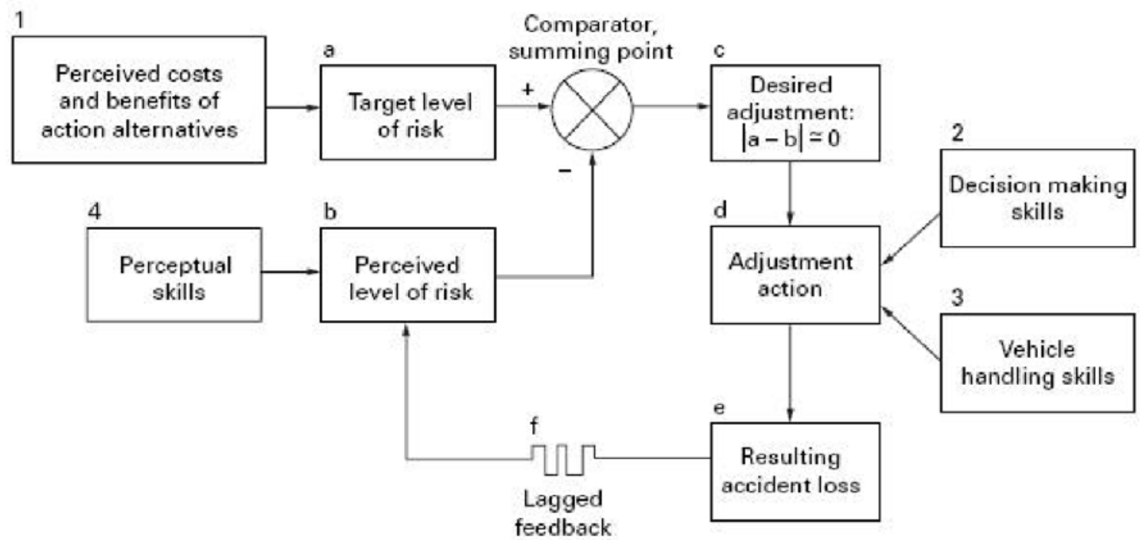

Figure 2.2: Homeostatic mechanism, taken from Wilde [64]

theory, such improvements are unlikely to have a lasting effect upon the accident rate because the target risk level is eventually restored. Therefore, these skill factors only represent the drivers ability to be safe. For example after a car is equipped with an airbag, the perceived level of risk (box b) will decrease and the adjustment action taken (box d) will be riskier than before to reduce the discrepancy between perceived and target level of risk.

As mentioned earlier, the target level of risk (box a), unlike the perceived level of risk, is outside the homeostatic loop. It is the only parameter that controls the systems output in the long-term (box e). In other words, the target level of risk is the only factor that represents the willingness to be safe. According to theory the amount of risk that people are willing to take (box a) is a result of a utility maximization over four factors [65, 66]:

1. The expected benefits of risky behavior alternatives (examples: gaining time by speeding, fighting boredom, increasing mobility);

2. The expected costs of risky behavior alternatives (examples: speeding tickets, car repairs, insurance surcharges);

3. The expected benefits of safe behavior alternatives (examples: insurance discounts for accident-free periods, enhancement of reputation of responsibility);

4. The expected costs of safe behavior alternatives (examples: using an uncomfortable seat belt, being called a coward by one of is peers, time loss).

The level of risk at which the net benefit is maximized is called the target level of risk to illustrate that people do not try to minimize risk, but instead attempt to optimize it. The theory claims that the risk is invariant regardless of road geometry and states that *"the sum of sins is constant"*. This does not mean that the target level of risk is constant, but rather that the target level of risk is constant in time, unless the values of the four utility factors change. Therefore, the essence of this theory is that if measures to improve safety don't address at least one of these four factors they should be ineffective.

Zero-risk theory of driver behavior

The zero-risk theory conjectures that drivers control risks on the basis of simple cues and features in traffic situations and normally avoid behavior which elicits fear or the anticipation of fear [37, 56]. This theory receives its name from the assumption that car drivers adapt to the risks of driving to such a level that they generally do not feel or anticipate any risk in a traffic situation. Drivers avoid the feeling of risk just as they avoid pain. The assumption is that there is a risk threshold above which the risk is experienced as aversive. A driver feels the risk, or the anticipation of risk, of a collision as an immediate emotional experience.

It has been suggested that it is too complicated to constantly estimate risk and optimize utility; more plausibly according to zero-risk theory drivers operate out of habit and only do something when they feel a threat. Drivers do not create a target level of risk. Instead, they satisfy their mobility needs by adjusting the drivers activity so as to avoid cognition of accident risk. Thus, the limits of safety and the avoidance of unpleasantness, as well as fear, play an important role in determining driver behavior.

According to this theory adaptation occurs when the driver decides to change an existing action pattern due to a new perception or a change in motivation. For example adaptation after a road has been widened could be explained by the perception of better driving conditions, while a change in driver behavior due to a time-critical trip could be explained by a change in motivation.

2.1.3 Empirical models

Human behavior feedback

The notion of human behavior feedback does not provide a theoretical explanation for adaptation but rather it suggests a basic framework which can be used to describe it [9, 10]. According to this model, when a change is introduced into the traffic system it is expected to change safety by some fraction, ΔS_{Eng}, assuming users continue to behave as they did before the change. Since road users may alter their behavior, the actual realized percent safety change, represented by ΔS_{Act}, may differ from ΔS_{Eng}. These quantities are assumed to be related in the following simple way:

$$\Delta S_{Act} = (1 + f)\Delta S_{Eng} \tag{2.1}$$

where f is a feedback parameter which characterizes the degree to which users respond to the safety change. If users do not change behavior in response to the safety change, then $f = 0$ and the safety change is just as expected on engineering grounds. If the change is in the expected direction, but of lesser magnitude than expected, then $f < 0$, and the safety change is discounted compared to the expected amount. If, the engineering action is fully discounted by adaptation and has no effect on safety (as in the homeostatic model) then $f = -1$.

Evans reviewed the literature to identify what values of f can be found. Two categories of studies are considered: (i) studies that aim to improve safety with $\Delta S_{Eng} > 0$; and (ii) studies which are introduced for reasons other than safety and are expected to reduce safety with $\Delta S_{Eng} < 0$. The formulation presented in equation 1 applies equally to positive and negative values of ΔS_{Eng}. Figure 2.3 shows 13 cases of changes that were expected to increase safety, which produced 4 different outcomes: (i) increase in safety as expected; (ii) increase in safety less than expected; (iii) no increase in safety, and (iv) decrease in safety. In other 11 cases, changes that were expected to reduce safety provided three different outcomes: reduction in safety as expected, reduction in safety less than expected, and even increase in safety.

From these results Evans concludes that driver adaptation exists, and that safety can change in different directions, but a trend could not be identified. However, no case of a safety change invisible to road users generated a measurable user response. This suggests that changes that are not readily apparent to the driver are very unlikely to induce user response.

2.1.4 Summary of user adaptation models

Insights

The literature demonstrates that user adaptation has been modeled with different approaches and is of interest to many transportation scientists. The most valuable insight, however, from the literature is empirical: adaptation exists. As stated by a scientific expert group [40]: *"Behavioural adaptation exists, and does have an effect on the safety benefits achieved through road safety programs . . . behavioural adaptation does not eliminate the safety gains, it does reduce the effectiveness"*.

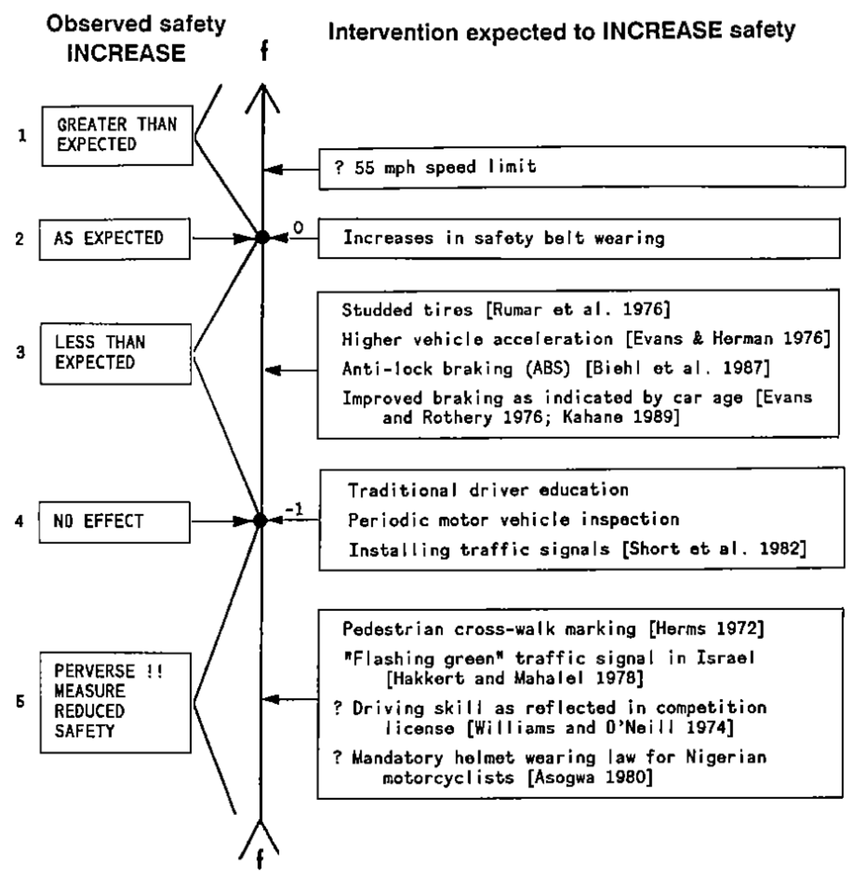

Figure 2.3: Human behavior feedback for safety changes expected to increase safety, taken from Evans [10]

Gaps

The most prominent gap in the literature is that user adaptation has not been systematically quantified. Each study develops a dedicated model and provides empirical support for special cases. Moreover, although behavioral theories hypothesize about the cognitive reaction of drivers with respect they do not link risk to attributes of the safety systems. This gap might be one reason for the extensive debate surrounding validation attempts of these theories. Many of the theories provide supporting evidence by observing a certain outcome that the theory predicts if the perceived risk decreases; then they describe why the safety systems reduces the perceived risk.

In addition to this, the models only discuss how adaptive behavior would change the risk of the users (i.e., drive faster). However, these models don't provide any insights regarding the effect on safety.

The literature is limited by the statistical difficulties inherent in traffic safety studies. This is even worse for user adaptation studies since data bases are not designed to study adaptation and therefore data must be compiled from various sources.

An additional limitation is related to the narrow scope of the studies. The fact that it has been very difficult to find reproducible patterns regarding adaptation in empirical data might be a result of a observing only a single type of system. By observing only a single narrow task we may be missing causal factors that would become apparent if we expand the scope and examine many safety-critical tasks together.

2.2 Factors contributing to user adaptation

Several researchers have discussed potential factors that influence adaptation [40, 16, 7]. Table 2.1 summarizes five factors that represent a similar factor which refers to how well a system is sensed, or perceived, by the user. Table 2.2 shows other potential factors which are related to additional utility to be gained from adapting, and the level of control available to the user. Other researchers have also suggested that regulation may affect on user adaptation [61]. These factors have never been systematically studied.

Table 2.1: Comparable factors of adaptation as described by different researchers

Reference	Factor	Descriptive question (if *yes* may generate adaptation)
Elvik [7]	Noticeability	Does the system introduce changes to the road or the vehicle that are easily noticed by drivers?
Hedlund [16]	Visibility	How obvious is the change produced by the safety system? Can I know if I was not told?
Hedlund [16]	Direct feedback	Does the change affect my physical performance of the task through direct sensory feedback?
OECD [40]	Immediacy of feedback	Does the driver have an immediate feedback on the effect of the system?
OECD [40]	Interaction with measure	Does the driver perceives more or less consciously the effect of the systems?

Table 2.2: Additional factors of adaptation as described by different researchers

Reference	Factor	Descriptive question (if *yes* may generate adaptation)
Hedlund [16]	Motivation	Does the driver have a reason to change his behavior?
Hedlund [16]	Control	Is the behavior of the driver not heavily controlled?
OECD [40]	Driving goals	Does the change fit in with driving aims related to the pleasure/thrills of driving?

2.3 Methods to evaluate road safety

There are two typical methods to estimate the effectiveness of road safety measures, before-after studies and cross-sectional studies. In before-after studies we measure safety before the treatment by counting the number of collisions in the 'before' period and then measure again by counting the number of collisions in the 'after' period. If nothing else changed, the difference is attributed to the treatment. However, the traffic environment changes with time. Therefore, we need to compare the safety that would have been experianced in the 'after' period had treatment not been applied, to the expected safety of the treated entity in the after period [15].

In cross-sectional studies we compare the safety of one group of entities with some common feature to the safety of a different group of entities not having that feature, in order to asses the safety effect of that feature.

2.4 Case studies of adaptation

2.4.1 Anti-lock braking systems

A well studied example of unfulfilled predictions is found in Anti-lock Braking System (ABS). The first studies of ABS effectiveness were proof-of-concept studies, in which drivers drove at a set speed and then braked. Researchers found as expected, that braking distances were decreased on wet surfaces and that directional control was maintained during braking on wet or dry surfaces [48]. Based on such studies, it was predicted that severe damage crashes in Germany would diminish by 10 to 15 percent for vehicles using ABS [30].

Later cross-sectional studies acknowledged adaptation and tried to estimate its effect on performance measures like speed and headways. A test track study showed that when drivers could choose their speed, they traveled slightly faster. The result was that the emergency stopping distance was no different than with standard brakes. Researchers also observed taxi drivers en-route to an airport and found that taxi drivers with ABS accepted shorter time headways than taxi drivers without ABS [52].

An extensive study was performed, to evaluate the impact on collision rate. The study compared claim frequency and value between 1991 models without ABS, and 1992 models with ABS; no significant differences were found in either claim frequency or value [17].

Based on these studies, it was suggested that drivers with ABS might have adapted by trading safety for mobility and used up some of the ABS benefits for mobility [54].

However, no theory assists us in interpreting this or more importantly predicting this a-priori and it remains unclear.

2.4.2 Center high mounted stop lamps

Center High Mounted Stop Lamps (CHMSL) are a supplemental brake light mounted at the height of the rear window that has been required on all new cars sold in the U.S. starting with the 1986 model year. It was intended to reduce the number of rear-end collisions by improving the braking signal recognition of following drivers. The requirement was based on three different fleet cross-sectional studies in the late 70's which estimated a reduction of about 50 percent in rear-end collisions [32, 47, 46]. Since about two-thirds of all rear impact crashes involve pre-impact braking by the lead vehicle, these results are equivalent to a 35 percent reduction of rear-impact crashes of all types. This encouraged the National Highway Traffic Safety Administration (NHTSA) to regulate CHMSL.

Post-implementation studies reported much lower reduction rates. Studies in the late 80's estimated an 11%-15% reduction in rear-end crashes [20, 21]. The estimated effectiveness dropped to 5%-9% in the 90's and questions regarding adaptation to the lamps were raised [12]. The original estimates were updated and found that the long-term effectiveness has converged to a level of 4.3% percent Kahane and Hertz [27]. Figure 2.4 shows the the different estimates over the years.

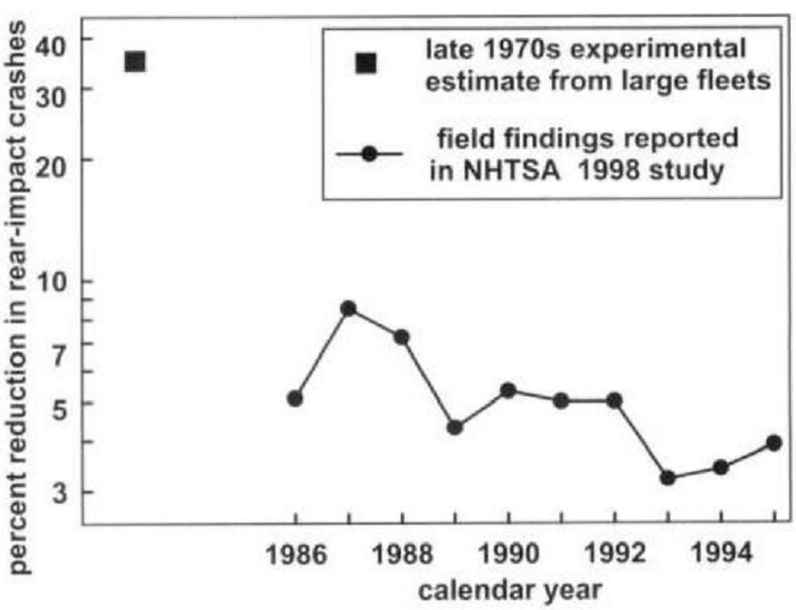

Figure 2.4: Percent reductions in rear impact crashes associated with CHMSL, taken from [27]

This case study emphasizes again the importance of studying adaptation, but it also shows that adaptation is a long-term behavioral response.

Chapter 3

Response Variable: The Adaptation Index

In the meta-study an injury protection system study represents an observation. Each observation consists of an estimate of user adaptation, as the response variable, and a list of attributes of the protection system, as explanatory variables. A set of relevant studies is the sample. This chapter describes the method and the data required to estimate user adaptation.

3.1 Method

The multidisciplinary nature of this analysis requires a common terminology to describe generically the problem to be solved. An, *accident*, A, is defined as an unintended (accidental) event which results in property damage or injury. For road safety an accident is an automobile collision, while for childproof caps an accident is unsupervised ingestion of medication by children. A risk for an accident exists when a user performs some safety-critical activity. Here, an *activity* is defined as the smallest unit of exposure in which an accident can occur only once.

For any *activity* the probability of an injury is the product of two probabilities: the probability that an accident will occur (*frequency*) and the conditional probability that an accident will result in an injury of a certain severity level (*severity*). As mentioned in Chapter 1, *Fatalities*, F, are used as the injury level representing *severity* because this level is naturally consistent across all disciplines. An *Injury protection system*, i, is defined as a technological mechanism designed to affect either the *frequency* or the *severity* for a certain type of *pertinent accident*, A_i. Equation

(3.1) gives the fatality probability in accidents pertinent to protection system i:

$$P_i(F) = P(A_i) \times P(F \mid A_i) \tag{3.1}$$

User adaptation can affect both $P(A_i)$ and $P(F \mid A_i)$. This manuscript focuses on the latter because it is more readily measured. However, some protection systems primarily designed to reduce $P(A_i)$ can also result in adaptation with respect to $P(F \mid A_i)$. For example, drivers may affect $P(F \mid A_i)$ by maintaining shorter headways when driving a vehicle equipped with anti-lock brakes system, which are primarily designed to reduce $P(A_i)$. Other less intuitive examples include: safety lighters which may reduce the severity of a fire by reducing the number of objects ignited; or childproof medication caps that may encourage children who succeed in overcoming the cap to ingest a greater amount of medication. On the other hand, for other protection systems, given an accident, the severity is not affected at all by the protection system. For example, the use of a condom at the onset of an HIV infection does not affect the fatality risk. In view of this, only systems with a chance to impact the fatality probability in pertinent accidents were included.

3.1.1 The adaptation index

In physically invariant systems, user adaptation is reflected in the discrepancy between the short-term realization of safety, prior to any behavioral change, and the long-term safety. The following definitions and assumptions are used to develop an estimator for user adaptation.

Let $F_i(t) \doteq P(F \mid A_i, t, i)$ be shorthand for the fatality probability in a pertinent accident for protection system i that occurs t months after the system is introduced, and with the protection system in use. Likewise, define $\overline{F_i}(t) \doteq P(F \mid A_i, t, \bar{i})$ as the fatality probability in a pertinent accident for protection system i that occurs t months after the system is introduced, and with the protection systems not in use.

We are interested in comparing $F_i(0)$ and $F_i(\tau^+)$, where τ^+ represents a period long enough to allow for a behavioral change. To this end, define the user adaptation index as:

$$\alpha_i = \frac{F_i\left(\tau^+\right)}{F_i\left(0\right)} \tag{3.2}$$

This parameter captures the long term behavioral effect in response to protection system i for pertinent accidents. When $\alpha_i = 1.0$, no fatalities can be attributed to adaptation. When $\alpha_i > 1.0$, the percent of observed fatalities that can be attributed to adaptation is $100(\frac{\alpha_i - 1}{\alpha_i})\%$.

The way adaptation affects the fatality probability can be shown by expressing $F_i(t)$ as the integration across all levels of crash severity, s:

$$F_i(t) = \int f_i(s) g_i(t, s) ds \tag{3.3}$$

where s is the level of kinetic energy released in an accident, $f_i(s)$ is the fatality probability in a pertinent accident for protection system i of crash severity s, with the protection system in use, and $g_i(t,s)$ is the density function of the crash severity for a pertinent accident for protection system i, with the protection system in use. It is reasonably assumed that $f_i(s)$ is time-independent since users cannot affect it by changing their behavior. By expressing equation 3.2 in terms of equation 3.3 we see that user adaptation affects the index α_i only through $g_i(t,s)$. In other words, if users adapt by engaging in more risky behavior, they may become involved in more severe accidents and affect $g_i(t,s)$, which in turn would affect α_i.

Explicit empirical data to estimate $F_i\left(t\right)$ are not always available. Thus, it would seem that α_i cannot be estimated. Fortunately, commonly available in safety studies are estimates for the *actual effectiveness* and the *engineered efficacy* of protection systems which can be expressed as ratios of $F_i\left(t\right)$ and $\overline{F_i}$. It is shown below that these ratios can be used to estimate α_i.

Actual effectiveness, θ_i

Actual effectiveness is a measure of the capability of the injury protection systems to produce an effect in real-life settings. It is the ratio of the long-term fatality probabilities in pertinent accidents with and without the system. In our notation, this is:

$$\theta_i = \frac{F_i\left(\tau^+\right)}{\overline{F_i}\left(\tau^+\right)} \tag{3.4}$$

Engineered efficacy, ϵ_i

Engineered efficacy is a measure of the capability of the injury protection systems to produce an effect under isolated conditions without any behavioral change. It is the ratio of the short-term fatality probabilities in pertinent accidents with and without the system. In our notation, this is:

$$\epsilon_i = \frac{F_i\left(0\right)}{\overline{F_i}\left(0\right)} \tag{3.5}$$

Estimating the adaptation index

It is assumed that the fatality probability without a protection systems is time-independent such that $\overline{F_i}\left(t\right) = \overline{F_i}$. This is a reasonable assumption since no new protection system was applied and the performance of the activity remains unchanged. Therefore, the ratio of equations (3.4) and (3.5) reduces to the adaptation index from equation 3.2:

$$\frac{\theta_i}{\epsilon_i} = \frac{F_i\left(\tau^+\right)}{F_i\left(0\right)} = \alpha_i \tag{3.6}$$

Equation 3.7 and equation 3.8 are used to produce consistent point and interval estimates of α_i, by combining consistent estimates of θ_i and ϵ_i. These equations were developed by applying a two-term Taylor series expansion, as shown in Appendix A.1.

$$\hat{\alpha_i} = \frac{\hat{\theta}_i}{\hat{\epsilon_i}} \frac{1}{[1 + \hat{\gamma_{\epsilon_i}}]} \tag{3.7}$$

$$\hat{\alpha_i} \pm 1.96\sqrt{\mathrm{Var}\left(\hat{\alpha_i}\right)} \tag{3.8}$$

3.2 Data

An extensive review of published reports and several public databases was conducted, to identify all relevant information for protection systems that fall within the scope of this study. From this review point and interval estimates for θ_i and ϵ_i were derived – or directly obtained for 11 systems. More systems could not be analyzed because estimates for θ_i require extensive data with control groups such as matched-pair cohorts, which are rare; and because estimates for ϵ_i require specialized studies. The sample includes mostly protection systems for driving activities because the highway safety field is rich with data.

The sources of the data and the corresponding estimates for θ_i and ϵ_i that could be teased out from published studies, are summarized in Table 3.1. Two case studies are described in detail within this section, while the rest of the systems are described in Appendix A.2.

Table 3.1: Data sources and estimates of the θ_i and ϵ_i for the protection systems

Injury protection system	description	$\hat{\theta}_i$ (LB, UB)	$\hat{\epsilon}_i$ (LB, UB)
Airbags (frontal)	An automatic crash protection system mounted in the steering column or instrument panel of an automobile	.79 (.74,.85) [24]	.83 (.78,.86) [44]
Anti-lock Brakes System (ABS)	An electronic braking control mechanism for automobiles that activates under hard braking	.98 (.95,1.01) [26, p 25]	.99 (.88,1.06) [26, p 4]
Bicycle helmets	Protective headgear designed to provide protection from head injuries in a bicycle collision	.26 (.14,.48) [58]	.20 (.17,.24) [4, 34]
Center high-mounted stop lights	Additional brake lamps on the vertical centerline of the rear of an automobile located higher than regular stop lamps	1.01 (.74,1.28) [27, p 60]	.99 (.95,1.02) [53, 8]
Childproof lighters	Hand-held fire-setting devices with special mechanical features that require acquired handling to generate a flame	.98 (.74,1.28) [55]	.98 (.92,1.02) [60]
Childproof medication caps	Covers of medication containers designed to be significantly difficult to open for children under the age of 5	.97 (.92,1.02) [3]	.95 (.71,1.24) [60]
Daytime Running Lights (DRL)	Bright, white forward-facing lights for automobiles that operate automatically in daylight	.90 (.82,1.00) [62]	.87 (.84,.92) [29, p 147]
Electronic Stability Control (ESC)	Stability systems for automobiles that identify when the driver is about to lose control	.60 (.40,.89) [5]	.56 (.52,.64) [43]
Motorcycle helmets	Protective headgear designed to provide protection from head injuries in a motorcycle collision	.58 (.50,.68) [31, p 33]	.51 (.47,.56) [2, 38]
Structural side impact improvements	Modifications to the side beams and to the energy absorbing padding of automobiles	.79 (.72,.86) [25]	.77 (.65,.91) [25, p 40]
Three-point seat belts	Safety harness worn by occupants of automobiles to secure occupants in seats to prevent harm from sudden stops	.55 (.62,.49) [23, p 25]	.51 (.45,.55) [14]

3.2.1 Structural side impact improvements

Structural side impact improvements include modifications to the side beams and to the energy absorbing padding of automobiles. These improvements are designed to reduce $P(F \mid A_i)$ where A_i is the set of all side impact collisions.

Actual effectiveness

The data described here is from a large study by Kahane [25] for the National Highway Traffic Safety Administration (NHTSA). The study evaluated the effect of such improvements on the fatalities of front-seat occupants in passenger cars. The analysis is based on 15 vehicle make-models that underwent substantial structural side impact improvements. Data for crashes and fatalities involving vehicles up to three model years prior, and up to three model years after the improvements was analyzed. The analyses is preformed using data from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES) of the National Automotive Sampling System (NASS) over calendar years 1993-2005[1].

An estimate for θ_i was obtained using data from Table 2-5 in Kahane [25]. $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in side-impact accidents for vehicles with the safety improvements, and the number of side-impact accidents for the same set of vehicles. Similarly, $\overline{F_i}$ was calculated for vehicles without the safety improvements. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{1,096/440,109}{1,452/458,872} = 0.787 \tag{3.9}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/1,096 - 1/440,109 + 1/1,452 - 1/458,872} \tag{3.10}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.72, .86) \tag{3.11}$$

Engineered efficacy

The *engineered efficacy* is based on TTI(d) which is an experimental measure used in side impact crash tests to calculate the injury score on a side impact dummy.

[1] FARS is a census of the nations fatal crashes, but lacking information on crashes where nobody died. GES is a probability sample of the national crash involvements, and when GES cases are weighted by the inverse sampling fractions they generate unbiased estimates of national totals. For examples of analyses combining FARS and GES see Joksch [19]

The change in TTI(d) estimates the expected reduction in severity probability and is therefore assumed to also be valid to estimate expected reduction in fatality probability. Also, since these estimates are free from any behavioral effects they reflect the short term fatality probability. The same set of the 15 vehicle make-models with substantial TTI(d) improvements had a weighted TTI(d) reduction of 23.7 units relative to the same vehicles before the improvements were applied [25, p 40]. Each reduction of TTI(d) by one unit is associated with an estimated 0.927 percent reduction of fatality probability in side impacts [22]. Therefore the estimate for the engineered efficacy of structural side impact is $\widehat{\epsilon_i} = .77, (.65, .91)$, as is shown in Table A.1.

Adaptation index

The estimate for the mean and the confidence interval for the adaptation index is calculated using equations (A.5) and (A.7) is $\widehat{\alpha_i} = 1.01(.78, 1.30)$.

Airbags

Airbag is an automatic crash protection system mounted in the steering column or instrument panel of an automobile. They are designed to reduce $P(F \mid A_i)$ where A_i is the set of all frontal collisions.

Actual effectiveness

The estimate for θ_i comes from a matched-pair cohort design using data from FARS for calendar years 1990-2002 [41]. The fatality risk ratios in frontal crashes of vehicles with airbags was compared to that of vehicles with no airbag[2]. The estimate was adjusted for seat position, restraint use, sex, age, and all vehicle and crash characteristics.
$\widehat{\theta_i} = .79, (.75, .85)$

Engineered efficacy

The *engineered efficacy* is based on Head Injury Criterion (HIC) which is an experimental measure used in side impact crash tests to calculate the head injury score on an impact dummy. The change in HIC estimates the expected reduction in injury probability and is therefore assumed to also be valid to estimate expected reduction in fatality probability. HIC has been shown to be a good predictor of injury severity in frontal impact crashes [39]. Also, since these estimates are free from any behavioral effects they reflect the short term fatality probability. Crash tests of 142 vehicle make-models were used to estimate the difference in HIC for vehicles with

[2]frontal crashes were defined as those in which the principal impact on the car was between 11:00 and 1:00 (with 12:00 being the center front)

and without airbags [44]. The average HIC for vehicles with airbags was 885, and for vehicles with air bags was 461. By applying injury reduction curves the estimate for the engineered efficacy for air bags is $\widehat{\epsilon_i} = .83, (.78, .86)$.

Adaptation index

The estimate for the mean and the confidence interval for the adaptation index is calculated using equations (A.5) and (A.7) is $\widehat{\alpha_i} = .96(.87, 1.06)$.

Chapter 4

Explanatory Variables: Inducing User Adaptation

This chapter defines the explanatory variables used in this study. It also describes the steps taken to design, conduct and analyze a large survey used to quantify a level of perceptibility for each safety system.

The literature discussing potential factors that influence adaptation was summarized in Chapter 2. The predominant factor suggested is whether a user perceives that the protection system exists. Other potential factors relate to additional utility to be gained from a behavioral change and to the level of control available to the user. Another possible factor was related to regulation of safety systems. The three explanatory variables described in this chapter address these potential factors.

4.1 Obligatoriness

Definition: Whether the protection system is mandatory.

Conjecture: Optional protection systems give the users a choice over their level of protection, while regulated systems are mandatory and don't provide a choice. The conjecture is that a behavioral response may be affected by whether the protection system is chosen by the users or is mandated. Moreover, users of optional safety system are self-selected and may represent a different level of aversion to risk. This too may affect the observed behavioral response.

Data: This variable is binary and was extracted from publications of the Federal Motor Vehicle Safety Standards and the Consumer Product Safety Commission.

Table 4.1: Obligatoriness of the protection systems

i	**Injury protection systems**	*Obligatoriness*
1	Airbags (frontal)	Y
2	Anti-lock brakes system	N
3	Bicycle helmets	N
4	Center high-mounted stop lights	Y
5	Childproof lighters	Y
6	Childproof medication caps	Y
7	Daytime running lights	N
8	Electronic stability control	N
9	Motorcycle helmets	Varies by state
10	Structural side impact improvements	Y
11	Three-point seat belts	Y
12	Condoms	N
13	Lawn mower blade control systems	Y
14	Sunscreen	N

4.2 Specificity

Definition: Whether the protection system is specific to automobile driving.

Conjecture: The additional utility gained from a behavioral response when driving an automobile may be specific to this activity and therefore differ from that of other activities. Similarly, the level of control available to an automobile driver may be specific this activity since driving is a self-paced activity. The conjecture here is that the utility gained from adaptation and the level of control for the activity of driving and automobile is different than in other activities and may therefore exhibit different levels of adaptation.

Data: This variable is binary and automobile protection systems were classified as specific to the activity of driving while non-automobile protection systems were classified as non-specific. The level of control for motorcycle and bicycle riding is different from automobile driving since it requires a different set of skills. Also, the utility of such activities are different since motorcycling frequently includes a component of thrill and bicycling frequently includes a component of leisure. Therefore, motorcycle and bicycle helmets are not considered as specific to automobile driving.

4.3 Perceptibility

Definition: The extent to which a protection system can be sensed.

Conjecture: Protection systems are physically embedded in the users' environment and can therefore affect the interaction with the user. If users sense they are protected by a system they are more likely to adapt. Moreover, if the users are unaware that a system exists, they cannot adapt in response to that system.

Table 4.2: Specifity of the protection systems

i	**Injury protection systems**	*Specifity*
1	Airbags (frontal)	Y
2	Anti-lock brakes system	Y
3	Bicycle helmets	N
4	Center high-mounted stop lights	Y
5	Childproof lighters	N
6	Childproof medication caps	N
7	Daytime running lights	Y
8	Electronic stability control	Y
9	Motorcycle helmets	N
10	Structural side impact improvements	Y
11	Three-point seat belts	Y
12	Condoms	N
13	Lawn mower blade control systems	N
14	Sunscreen	N

Data: A large survey was conducted to quantify the perceptibility level of each protection system and is described in detail in the next section.

4.4 The perceptibility survey

The objective here is to study which safety systems are more easily perceived by the user and to identify design attributes that affect this level of perception. However, this is an abstract and subjective concept which cannot be easily measured. To accomplish this we utilize people's skill in comparing pairs of similar entities against a defined criteria [59]. Several techniques have been developed to obtain measurements from a series of such pairwise comparisons. The analytic hierarchy process is an technique developed to rank qualitative intangible factors using pairwise comparison judgments and is used for this survey [50, 51]. A scale of verbal judgments which indicates how much more perceptible one system is over another is needed to evaluate the comparisons. Each verbal judgment has a corresponding numerical value, as shown in Table 4.1. A scale of odd numbers between 1 and 9 was used as suggested in the literature [50].

Table 4.3: Pairwise comparisons scale

Numerical value	**Description**
1	Equally perceptible
3	Slightly more perceptible
5	More perceptible
7	Strongly more perceptible
9	Absolutely more perceptible

The safety systems evaluated in this survey are the injury protection systems defined in Chapter 3 as the sample for this study. However, the survey is also an opportunity to evaluate a perceptibility level for systems for which data to estimate an adaptation index is not available. As mentioned in the introduction, *early warning systems* designed to detect and warn the user of imminent danger have recently emerged in traffic applications. This survey can be used to compare whether early warning systems are more easily perceived by the user. Smoke detectors were the only *early warning system* included in the study since it was felt that the general population is not yet sufficiently familiar with traffic applications of *early warning systems* to provide reliable opinions. In total 15 safety systems were included in the survey.

The survey was developed using the Hypertext Preprocessor (PHP) scripting language. The responses were stored in a MySQL database. The survey is available on-line at www.perceptibility.org [1].

4.4.1 Survey procedure

The survey begins with an introductory page describing its objective, and instructions of what is required from the participants; see Figure B.1. Subjects agree to participate by clicking on the *Continue* button at the bottom of the page. Next, the participants were shown some text and an image describing each of the safety systems (a screen shot is shown in Figure B.2, and the full list of descriptions in Figure B.3). A participant begins the survey begins by clicking on the *Start the survey* button at the bottom of the screen.

During the survey each participant was presented with $\frac{15\times14}{2} = 105$ possible safety system pairs in random order. A screen shot of the user-interface is shown in Figure 4.1. For each pair the participants were presented with the survey question: "*Which of the two do you think is more perceptible when being used?*". They participants indicated, by clicking on a button, whether the protection systems are *Both equally* perceptible or whether one of them is: *Slightly*; *More*; *Strongly*; or *Absolutely* more perceptible. After indicating a choice, the next safety system pair appears immediately. Each choice can only be made once and respondents cannot go back to change or see previous choices. The survey is complete after the participant has indicated a choice for all 105 pairs.

At the end of the survey the respondents were asked about their demographic characteristics including: age, gender, occupation, education level, ethnicity, country currently living, native language, and whether or not they have a driver's license.

[1] This survey has been reviewed and approved by the UC Berkeley committee for protection of human subjects. Protocol number: 2009-10-306

Figure 4.1: Screen shot of a pairwise survey question for structural side impact improvements and motorcycle helmets

4.4.2 Participants

The survey was completed by 117 participants and required on average 14.5 minutes. The respondents were 33.8 years old on average, 59.8% were females and 92% had a drivers‘ license. The cultural and social demographics varied. Distributions for the demographics are provided in Figures C.4 and C.5.

4.4.3 Results

The standardized perceptibility level and the Consistency Ratio (CR) were calculated for each respondent using the eigenvalue method of the analytic hierarchy process [50, 51].

The CR indicates how inconsistent were the judgments of an individual respondent, and was therefore used to filter out outliers. The amount of filtering was determined using Figure 4.2, which shows the mean perceptibility level for each system for different percentages of retained responses. The left end of the horizontal axis represents the perceptibility level based on the 20% (n=24) most consistent respondents in the sample, while the right end represents the perceptibility level for the entire sample (n=117). The dashed lines represent the different safety systems. The level of perceptibility exhibits only minor deviations when the precent of retained responses is between 35% to 80%. Therefore, 80% of the responses were retained, since this is the largest sample size within this stable range.

The perceptibility level for each system was calculated by taking the geometric mean of the individual rankings of the respondents, as is generally recommended [13], but the results with the arithmetic mean are very similar. See Figure B.6.

The perceptibility levels, including a 95% confidence interval, for the retained

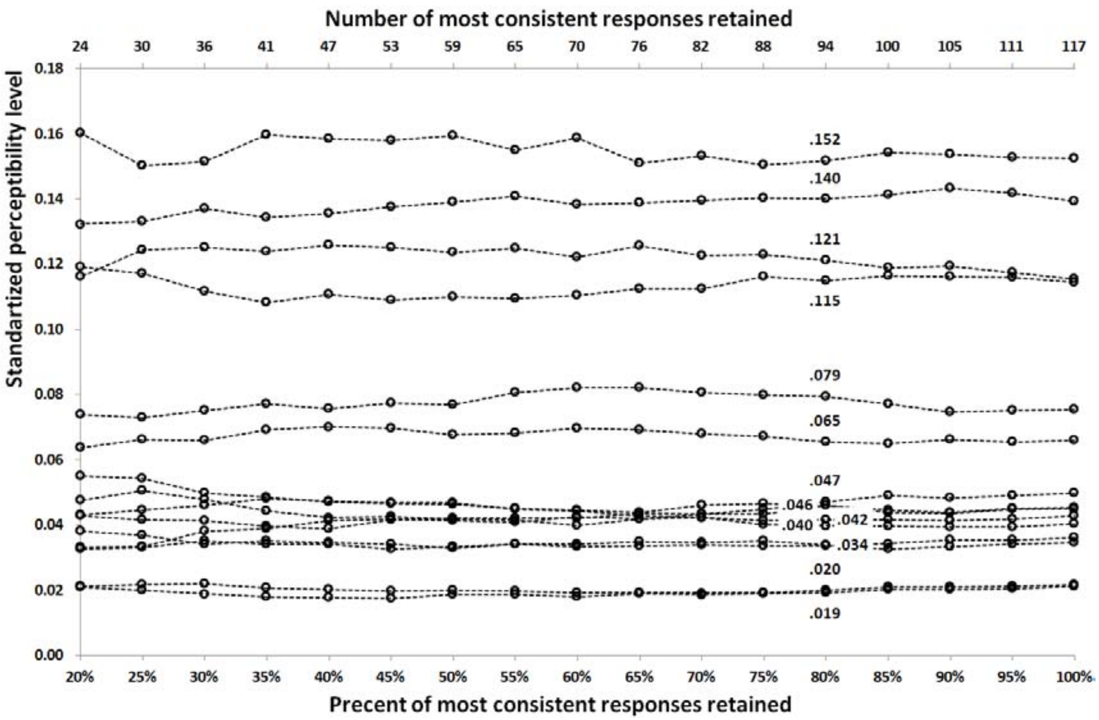

Figure 4.2: Perceptibility level for different percentages of retained responses

responses (i.e., the most consistent 80% of the total) are displayed in Figure 4.3. These results are the perceptibility levels used in this thesis.

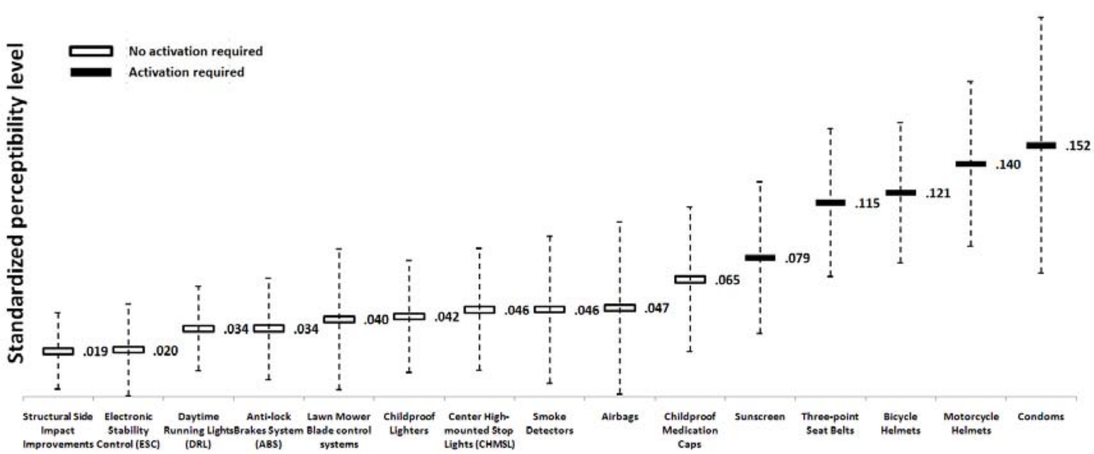

Figure 4.3: Ordered estimates of the perceptibility level ($n = 94$)

4.4.4 Discussion

The results of the survey show that perceptibility is associated with systems that require activation by the user. For example, motorcycle helmets require actively to be put on, while structural side impact improvements don't require any activation.

Note from Figure 4.3, that the five most perceptible systems (and only these systems) require activation. This association between activation and high perceptibility is not a coincidence, since the probability of this happening by chance alone is $1/\binom{15}{5} \approx 1/3000$. This result is logical since activating a safety system before every activity is likely to contribute to its perceptibility.

Furthermore, of the five systems that require activation (sunscreen, seat-belts, bicycle helmets, motorcycle helmets and condoms), two are non-transportation systems, which is that same proportion as in the full sample. This suggests that the association between perceptibility and activation can be generalized to injury protection systems across different activities.

No insights were obtained regarding other design attributes of injury protection systems. Similarly, no insights were obtained regarding the perceptibility level of early warning systems, as the only system included here demonstrated a medium level of perceptibility.

Chapter 5

Results

This chapter presents the results of the analysis using the data collected in Chapter 3 and Chapter 4. It shows how well the adaptation index is quantified for an individual system, and how the systems are collectively analyzed to test the effect of the explanatory variables.

5.1 The meta-table

Table 5.1 summarizes the data collected for both the response (i.e., the adaptation index), and the explanatory variables. The top part includes the 11 systems for which an adaptation index was estimated. The results show that the 95% confidence intervals for all protection systems include the value $\alpha_i = 1.0$. So, although α_i was quantified, the results for individual studies do not unambiguously indicate whether users adapt. This may explain why a consensus regarding user adaptation has not yet been reached.

The variance of each study is affected by the quantity of the data, and the type of design used to estimate θ_i and ϵ_i. For example, the confidence interval for bicycle helmets is very wide (.11, 10.82); reflecting the fact that data regarding bicycle accidents and fatalities are very limited, and that matched-pair studies can not be conducted. On the other hand, the confidence interval for airbags is the tightest (.87, 1.06); reflecting the high quality data documenting whether a vehicle is equipped with an airbags, and also the capability to conduced well controlled analyses.

Motorcycle helmets exhibit the highest precent of fatalities attributable to adaptation (12%). In total, the average precent of fatalities attributable to adaptation for the system in this study is 2.9%, but not statistically different from 0%.

Table 5.1: The Meta-table

i	**Injury protection systems**	**Adaptation index** α_i	σ_{α_i}	CI_{α_i}	**Explanatory variables** *Per.*	*Obl.*	*Spe.*
1	Airbags (frontal)	.96	.050	(.87, 1.06)	.047	Y	Y
2	Anti-lock brakes system	.99	.039	(.92, 1.07)	.034	N	Y
3	Bicycle helmets	1.09	1.17	(.11, 10.82)	.121	N	N
4	Center high-mounted stop lights	1.03	.121	(.81, 1.29)	.046	Y	Y
5	Childproof lighters	.99	.140	(.76, 1.31)	.042	Y	N
6	Childproof medication caps	1.00	.067	(.91, 1.18)	.065	Y	N
7	Daytime running lights	1.04	.162	(.73, 1.37)	.034	N	Y
8	Electronic stability control	1.03	.069	(.50, 2.16)	.020	N	Y
9	Motorcycle helmets	1.12	.182	(.78, 1.60)	.140	-	N
10	Structural side impact improvements	1.01	.124	(79, 1.28)	.019	Y	Y
11	Three-point seat belts	1.07	.148	(.80, 1.43)	.115	Y	Y
12	Condoms		-		.152	N	N
13	Lawn mower blade control systems		N/A		.040	Y	N
14	Sunscreen		N/A		.079	N	N

5.2 Perceptibility and adaptation

When the studies are analyzed collectively with the explanatory variables a sharper picture emerges. Due to the small sample size, a multiple regression analysis is not appropriate. Therefore, the three explanatory variables were tested separately for association with adaptation. Regression analysis revealed that *Obligatoriness* and *Specificity* had no significant association with the adaptation index, but *Perceptibility* was highly significant (p value = 0.005; $R^2 = 0.55$; $\hat{a} = 0.98$; $\hat{b} = 0.86$). The results of this regression are shown in Figure 5.1.

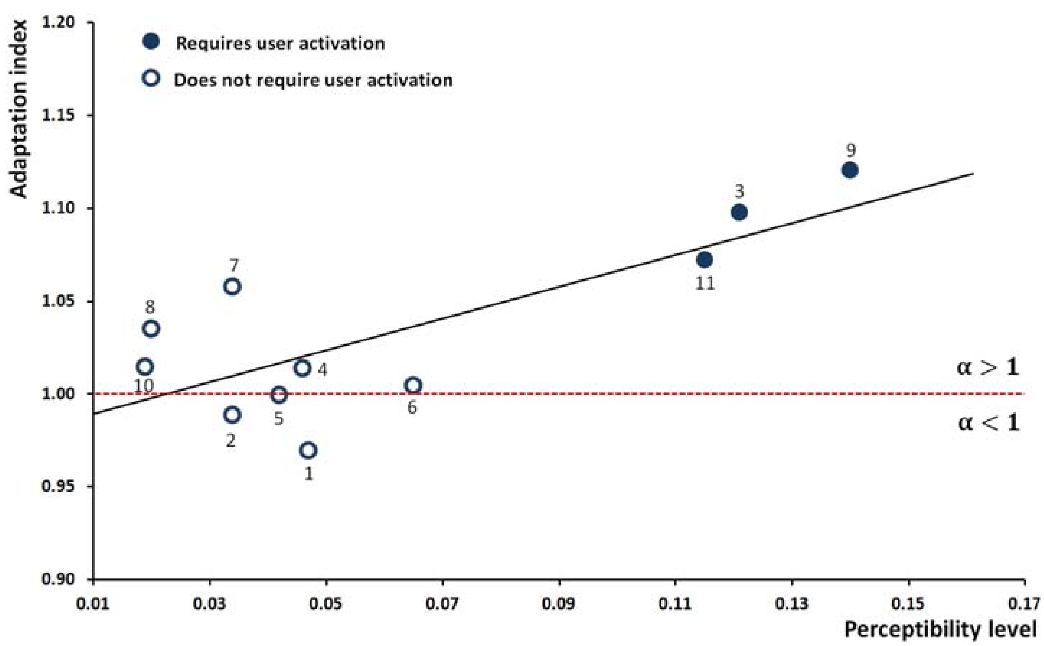

Figure 5.1: Regression results for adaptation index vs. perceptibility level

Observations above the horizontal line represent protection systems for which adaptation increased fatalities. By simply looking at the scatter-plot two clusters of observations are visually identified. It can be seen that the three most perceptible systems (seat belts, bicycle helmets and motorcycle helmets) also have the highest adaptation index, while the rest of the systems are evenly scatted around $\alpha_i = 1.0$.

The figure also shows that these systems are the only ones in this sample that require user activation. This association between perceptibility and activation is not a coincidence; considering the full sample of the perceptibility survey (including condoms and sunscreen) the five systems that require activation still turn out to be the most perceptible. As mentioned in Chapter 4.4 the probability of this happening by chance alone is about 0.6%, strongly suggesting that adaptation is influenced by activation. The figure also shows the best-fit line quantifying this relationship. It is estimated from this line that about 9% of the fatalities among users of systems that require activation are due to adaptation.

Chapter 6

Discussion

By developing definitions that are consistent across different safety systems, this thesis was able to quantify user adaptation for injury protection systems and confirm conjectures that were never systematically tested before.

The results strongly suggest that perceptibility and activation induce a form of adaptation that increases fatalities. Thus, for the same *engineered efficacy*, passive protection systems with low perceptibility should be preferred over highly perceptible alternatives.

The findings do not mean, however, that highly perceptible protection systems are undesirable or ineffective; only that they are less effective than anticipated. For example, motorcycle helmets, which exhibited the highest precent of fatalities attributed to adaptation (12%) still reduce the fatality rate by about 40% compared to not wearing a helmet.

Even though this study does not provide a tool to accurately predict adaptation, researchers and professionals should consider these findings when developing safety systems. Designing safety systems that are less perceptible to the users, or do not require activation, would increase the chances that additional safety provided to the user by a protection system, would achieve its objective and reduce fatalities.

The findings could also have implications with respect to marketing protection systems as they are frequently used as a selling point for automobiles. Advertising is intended to increase the desirability of a certain feature and may perhaps increase its perceptibility. This may have an unintended effect of reducing some of the benefits of new protection systems and should be studied.

Collecting the data for this analysis was laborious since estimates for θ_i and ϵ_i were derived from a wide range sources, none of which were designed to study adaptation. This affects the quality and availability of the data, and may introduce a selectivity bias since the sample is limited to available data. To this end, this thesis represents a way to utilize the existing data. However, as more data become available, updated studies over a larger number of safety systems would alleviate some of these limitations.

This study can also be expanded with respect to its scope. First, the effect of user adaptation on accident probability was not quantified. The major limitation in this respect, is the shortage of data to estimate the number of activities. Overcoming this shortage would allow for a more comprehensive study of how user adaptation affects the severity and the frequency of accidents. Second, this analysis is performed over the entire population. However, different population segments may behave differently with respect to safety. It could therefore be valuable to estimate an adaptation index for different age or gender groups.

Finally, since this study focuses on protection systems, it could also be useful to study user adaptation to early warning systems. Such systems don't provide any physical injury protection and are designed to warn the user of a potential hazard. Warning systems are a major focus of many new intelligent transportation systems designed to improve safety, and are considered very promising in the struggle to reduce collisions. Building on the ideas developed in this thesis, it would be beneficial to study user adaptation in response to such system. Understanding the effect of user adaptation to early warning system would allow engineers to develop systems whose effectiveness can be sustained over time, and help save lives.

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Appendix A

Supporting material for the adaptation index

A.1 Approximations for point and interval estimates

Let a random variable Z be defined by $Z = f(X, Y)$, where X and Y are independent random variables with means (μ_X, μ_Y) and variance (σ_X^2, σ_Y^2). Then, if Z admits a two-term Taylor series expansion it is well known that for small σ_X^2 and σ_Y^2:

$$Var(Z) \approx f_x(\mu_X, \mu_Y)^2 Var(X) + f_y(\mu_X, \mu_Y)^2 Var(Y) \tag{A.1}$$

$$E(Z) \approx f(\mu_X, \mu_Y) + \frac{f_{xx}(\mu_X, \mu_Y)Var(X) + f_{yy}(\mu_X, \mu_Y)Var(Y)}{2} \tag{A.2}$$

In the special case where $Z = \frac{X}{Y}$, the derivatives are: $f_x = \frac{1}{Y}$, $f_y = -\frac{X}{Y^2}$, $f_{xx} = 0$, $f_{yy} = \frac{2X}{Y^3}$, and the expansion reduces to:

$$E\left(Z\right) \approx \frac{E(X)}{E(Y)} + \frac{\mathrm{Var}(Y)E(X)}{E^3(Y)} = \frac{E(X)}{E(Y)}\left[1 + \gamma_Y\right] \tag{A.3}$$

$$\mathrm{Var}\left(Z\right) \approx \frac{E^2(X)}{E^2(Y)}\left[\frac{\mathrm{Var}(X)}{E^2(X)} + \frac{\mathrm{Var}(Y)}{E^2(Y)}\right] = \frac{E^2(X)}{E^2(Y)}\left[\gamma_X + \gamma_Y\right] \tag{A.4}$$

where $\gamma_X = \frac{\mathrm{Var}(X)}{E^2(X)}$ and $\gamma_Y = \frac{\mathrm{Var}(Y)}{E^2(Y)}$

The corresponding unbiased estimates for (A.3) and (A.4), assuming that the constant γ is known, are:

$$E\left(\hat{Z}\right) = \frac{E(X)}{E(Y)} \frac{1}{[1+\gamma_Y]} \tag{A.5}$$

$$\mathrm{Var}\left(\hat{Z}\right) = E^2(\hat{Z}) \frac{\gamma_X + \gamma_Y}{[1+\gamma_Y]^2} \tag{A.6}$$

The mean and variance of $\hat{X}$ can be estimated using equations (A.5) and (A.6). Simply replace $(E(X), E(Y), \gamma_X, \gamma_Y)$ in these equations, by the estimated values $(E(\hat{X}), E(\hat{Y}), \hat{\gamma_X}, \hat{\gamma_Y})$. The approximate 95% confidence interval for $\hat{X}$ is obtained by:

$$E\left(\hat{Z}\right) \pm 1.96\sqrt{\mathrm{Var}\left(\hat{Z}\right)} \tag{A.7}$$

A.2 Description of the data used to estimate the adaptation index

Airbags

Airbag is an automatic crash protection system mounted in the steering column or instrument panel of an automobile. They are designed to reduce $P(F \mid A_i)$ where A_i is the set of all frontal collisions.

Actual effectiveness

The estimate for θ_i comes from a matched-pair cohort design using data from FARS for calendar years 1990-2002 [41]. The fatality risk ratios in frontal crashes of vehicles with airbags was compared to that of vehicles with no airbag[1]. The estimate was adjusted for seat position, restraint use, sex, age, and all vehicle and crash characteristics.
$\widehat{\theta_i} = .79, (.75, .85)$

Engineered efficacy

The *engineered efficacy* is based on Head Injury Criterion (HIC) which is an experimental measure used in side impact crash tests to calculate the head injury score on an impact dummy. The change in HIC estimates the expected reduction in injury probability and is therefore assumed to also be valid to estimate expected reduction in fatality probability. HIC has been shown to be a good predictor of injury severity in frontal impact crashes [39]. Also, since these estimates are free from any behavioral effects they reflect the short term fatality probability. Crash tests of 142 vehicle make-models were used to estimate the difference in HIC for vehicles with and without airbags [44]. The average HIC for vehicles with airbags was 885, and for vehicles with air bags was 461. By applying injury reduction curves the estimate for the engineered efficacy for air bags is $\widehat{\epsilon_i} = .83, (.78, .86)$.

Adaptation index

The estimate for the mean and the confidence interval for the adaptation index is calculated using equations (A.5) and (A.7) is $\widehat{\alpha_i} = .96(.87, 1.06)$.

[1] frontal crashes were defined as those in which the principal impact on the car was between 11:00 and 1:00 (with 12:00 being the center front)

Anti-lock braking systems

Actual effectiveness

The data described here is from a large study by Kahane and Dang [26] for NHTSA. The analyses is preformed using data from FARS and GES over calendar years 1995-2007. An estimate for θ_i was obtained using data from Table 2-2 and Table 3-1 in Kahane and Dang [26]. $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in culpable accidents for vehicle models with four-wheel ABS, and the number of culpable accidents for the same set of vehicles. Similarly, $\overline{F_i}$ was calculated for vehicles without ABS. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{7,902/1,212,573}{7,814/1,177,281} = 0.982 \tag{A.8}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/7,902 - 1/1,212,573 + 1/7,814 - 1/1,177,281} \tag{A.9}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.95, 1.01) \tag{A.10}$$

Engineered efficacy

Fatality reduction curve applied to a 5% reduction in stopping distance for ABS enabled vehicles.

Adaptation index

The estimate for the mean and the confidence interval for the adaptation index is calculated using equations (A.5) and (A.7) is $\widehat{\alpha}_i = 1.01(.78, 1.30)$.

Bicycle helmets

Actual effectiveness

The estimate for θ_i comes from a case-control design using data regarding bicycle collisions between 1992 and 1994 [58]. The data consisted of 62 bicycle accidents with severe brain injury (cases) and 2,633 bicycle accidents without non-head-injury (controls). The estimate was adjusted for age and whether the crash involved a motor

vehicle.
$\widehat{\theta}_i = .26, (.14, .48)$

Center high-mounted stop lamps

Actual effectiveness

The data described here is from a large study by Kahane and Hertz [27] for NHTSA. The analyses is preformed using data from FARS, and a representative sample from 8 states over calendar years 1986-1995. An estimate for θ_i was obtained using data from the table on page 44 (accidents) and from Table 3-1 (fatalities). $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in rear-impact multi-vehicle accidents for 1986 model year vehicle, and the number of rear-end multi-vehicle accidents for the same model year. Similarly, $\overline{F_i}$ was calculated for the 1985 model year vehicles. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{792/67,546}{692/60,027} = 1.017 \tag{A.11}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/792 - 1/67,546 + 1/692 - 1/60,027} \tag{A.12}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.74, 1.28) \tag{A.13}$$

Engineered efficacy

Estimated using the Power Model for the ratio between the fatality probabilities with different reaction times for vehicles with and without CHMSL.

Childproof medication caps

Actual effectiveness

The data described here is from a study by Clarke and Walton [3]. Number of child ingestion reports from Table II; number of fatal ingestions from Table IV.

$$\widehat{\theta}_i = \frac{50/11,450}{196/43,550} = 0.970 \tag{A.14}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/50 - 1/11,450 + 1/196 - 1/43,550} \tag{A.15}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.92, 1.12) \tag{A.16}$$

Daytime running lights

Actual effectiveness

The data described here is from a large study by Wang [62] for NHTSA. The analyses is preformed using data from FARS, and a representative sample from 9 states over calendar years 2002-2005. An estimate for θ_i was obtained using data from the table on page 3-42 (accidents) and from Table 3-22 (fatalities). $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in daytime vehicle with car/ped/... accidents for vehicles with DRL, and the number of daytime vehicle with car/ped... accidents for vehicles with DRL. Similarly, $\overline{F_i}$ was calculated for vehicles without DRL. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{1,869/94,592}{1,899/87,097} = 0.906 \tag{A.17}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/1,869 - 1/94,592 + 1/1,899 - 1/87,097} \tag{A.18}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.82, 1.00) \tag{A.19}$$

Engineered efficacy

Fatality reduction prediction curve for average U.S. latitudes of 38.0.

Electronic stability control

Actual effectiveness

The data described here is from a large study by Farmer [11]. The analyses is preformed using the State Data System maintained by NHTSA for 10 states over calendar years 2001-2003. An estimate for θ_i was obtained using data from the Table IV (accidents) and from Table VI (fatalities). $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in single vehicle and multi-vehicle adverse accidents for vehicles with ESC, and the number of single vehicle and multi-vehicle adverse... accidents for vehicles with ESC. Similarly, $\overline{F_i}$ was calculated for vehicles without ESC. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{79/2,373}{142/2,553} = 0.60 \tag{A.20}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/79 - 1/2,373 + 1/142 - 1/2,553} \tag{A.21}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.40, .89) \tag{A.22}$$

Motorcycle helmets

Actual effectiveness

The estimate for θ_i comes from a meta-analysis using case-control studies [31]. Page 33. $\widehat{\theta}_i = .58, (.50, .68)$

Structural side impact improvements

Structural side impact improvements include modifications to the side beams and to the energy absorbing padding of automobiles. These improvements are designed to reduce $P(F \mid A_i)$ where A_i is the set of all side impact collisions.

Actual effectiveness

The data described here is from a large study by Kahane [25] for the National Highway Traffic Safety Administration (NHTSA). The study evaluated the effect of such improvements on the fatalities of front-seat occupants in passenger cars. The analysis is based on 15 vehicle make-models that underwent substantial structural side impact improvements. Data for crashes and fatalities involving vehicles up to three model years prior and up to three model years after the improvements was analyzed. The analyses is preformed using data from the Fatality Analysis Reporting

System (FARS) and the General Estimates System (GES) of the National Automotive Sampling System (NASS) over calendar years 1993-2005[2].

An estimate for θ_i was obtained using data from Table 2-5 in Kahane [25]. $F_i(\tau^+)$ was calculated from the ratio between the number of fatalities in side-impact accidents for vehicles with the safety improvements, and the number of side-impact accidents for the same set of vehicles. Similarly, $\overline{F_i}$ was calculated for vehicles without the safety improvements. The estimate for θ_i using equation 3.4 is therefore:

$$\widehat{\theta}_i = \frac{1,096/440,109}{1,452/458,872} = 0.787 \tag{A.23}$$

The standard error for $\ln \widehat{\theta}_i$ is:

$$SE(\ln \widehat{\theta}_i) = \sqrt{1/1,096 - 1/440,109 + 1/1,452 - 1/458,872} \tag{A.24}$$

The corresponding confidence intervals are constructed using a logarithmic transformation:

$$e^{\ln \widehat{\theta}_i - \pm 1.96 SE(\ln \widehat{\theta}_i)} = (.72, .86) \tag{A.25}$$

Engineered efficacy

The *engineered efficacy* is based on TTI(d) which is an experimental measure used in side impact crash tests to calculate the injury score on a side impact dummy. The change in TTI(d) estimates the expected reduction in severity probability and is therefore assumed to also be valid to estimate expected reduction in fatality probability. Also, since these estimates are free from any behavioral effects they reflect the short term fatality probability. The same set of the 15 vehicle make-models with substantial TTI(d) improvements had a weighted TTI(d) reduction of 23.7 units relative to the same vehicles before the improvements were applied [25, p 40]. Each reduction of TTI(d) by one unit is associated with an estimated 0.927 percent reduction of fatality probability in side impacts [22]. Therefore the estimate for the engineered efficacy of structural side impact is $\widehat{\epsilon}_i = .77, (.65, .91)$, as is shown in Table A.1.

Adaptation index

The estimate for the mean and the confidence interval for the adaptation index is calculated using equations (A.5) and (A.7) is $\widehat{\alpha}_i = 1.01(.78, 1.30)$.

[2]FARS is a census of the nations fatal crashes, but lacking information on crashes where nobody died. GES is a probability sample of the national crash involvements, and when GES cases are weighted by the inverse sampling fractions they generate unbiased estimates of national totals. For examples of analyses combining FARS and GES see Joksch [19]

Table A.1: Engineered efficacy for side impact modifications

Make	Model	Style	Model Years	TTI(d)	Model Years	TTI(d)	Reduction Abs.	Reduction Rel.	Variance	Registration before	Registration after	Weight
Dodge	Intrepid/Concorde/Vision	(4 door)	1993	79	1994-1996	65	14	0.86	0.008	142,475	589,158	0.06
Ford	Mustang	(2 door)	1991-1993	110	1994-1996	63	47	0.53	0.057	257,606	400,907	0.05
Ford	Taurus/Mercury/Sable	(4 door)	1993-1995	72	1996-1998	54	18	0.82	0.003	1,459,721	1,720,021	0.22
Chevrolet	Corvette	(2 door)	1994-1996	109	1997-1999	60	49	0.51	0.067	25,761	40,091	0.01
Chevrolet	Cavalier/Pontiac/Sunfire	(2 door)	1995-1996	111	1997-1999	81	30	0.70	0.005	328,743	899,381	0.09
Chevrolet	Monte Carlo	(2 door)	1997-1999	77	2000-2002	63	14	0.86	0.008	123,279	141,770	0.02
Pontiac	Grand Am/Achieva/Skylark	(2 door)	1994-1996	109	1997-1998	70	39	0.61	0.025	323,117	163,913	0.04
Nissan	Sentra/Sentra	(4 door)	1992-1994	92	1995-1997	66	26	0.74	0.001	347,531	332,581	0.05
Honda	Civic	(2 door)	1993-1995	86	1996-1998	71	15	0.85	0.007	315,821	465,026	0.06
Honda	Accord	(2 door)	1995-1997	72	1998-2000	63	9	0.91	0.020	120,588	138,676	0.02
Honda	Accord	(4 door)	1995-1997	77	1998-2000	59	18	0.82	0.003	896,241	1,030,677	0.14
Subaru	Legacy	(4 door)	1997-1999	68	2000-2002	48	20	0.80	0.001	325,095	373,859	0.05
Subaru	Impreza	(4 door)	1999-2001	72	2002	45	27	0.73	0.001	130,038	49,848	0.01
Toyota	Corolla/Geo/Prizm	(4 door)	1994-1996	91	1997-1999	66	25	0.75	0.000	880,374	982,805	0.16
Mitsubishi	Eclipse	(2 door)	1997-1999	89	2000-2002	52	37	0.630	0.019	194,469	223,639	0.03
							23.7	**0.771**	**0.008**	5,870,858	7,552,352	1.00

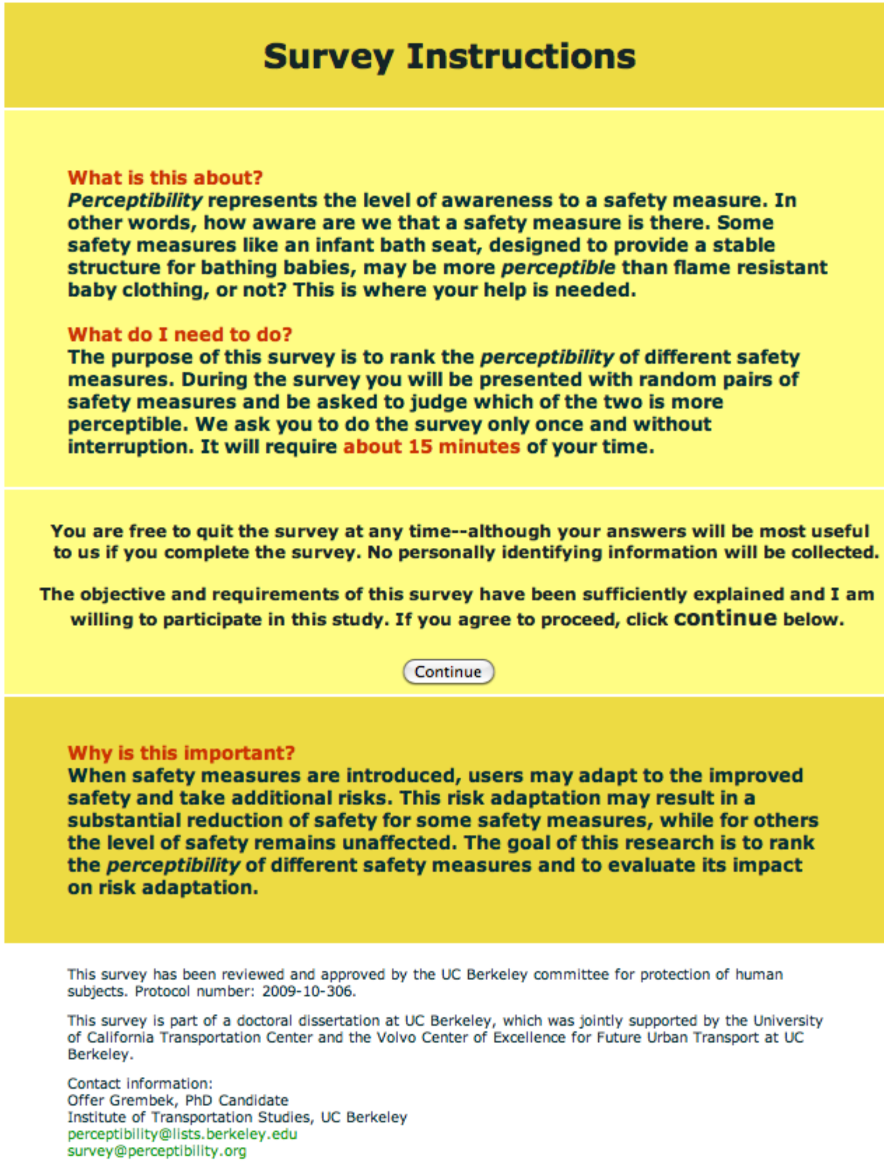
Three-point seat belts

Actual effectiveness

The estimate for θ_i comes from a matched-pair cohort design by Kahane [23] for NHTSA using data from FARS for calendar years 1986-1999 [23, p 22]. Adjusted for many things
$\widehat{\theta}_i = .55, (.49, .62)$

Appendix B

Supporting material for the perceptibility survey



Survey Instructions

What is this about?
Perceptibility **represents the level of awareness to a safety measure. In other words, how aware are we that a safety measure is there. Some safety measures like an infant bath seat, designed to provide a stable structure for bathing babies, may be more** ***perceptible*** **than flame resistant baby clothing, or not? This is where your help is needed.**

What do I need to do?
The purpose of this survey is to rank the ***perceptibility*** **of different safety measures. During the survey you will be presented with random pairs of safety measures and be asked to judge which of the two is more perceptible. We ask you to do the survey only once and without interruption. It will require about 15 minutes of your time.**

You are free to quit the survey at any time--although your answers will be most useful to us if you complete the survey. No personally identifying information will be collected.

The objective and requirements of this survey have been sufficiently explained and I am willing to participate in this study. If you agree to proceed, click continue below.

Continue

Why is this important?
When safety measures are introduced, users may adapt to the improved safety and take additional risks. This risk adaptation may result in a substantial reduction of safety for some safety measures, while for others the level of safety remains unaffected. The goal of this research is to rank the ***perceptibility*** **of different safety measures and to evaluate its impact on risk adaptation.**

This survey has been reviewed and approved by the UC Berkeley committee for protection of human subjects. Protocol number: 2009-10-306.

This survey is part of a doctoral dissertation at UC Berkeley, which was jointly supported by the University of California Transportation Center and the Volvo Center of Excellence for Future Urban Transport at UC Berkeley.

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Figure B.1: Screen shot of introduction page

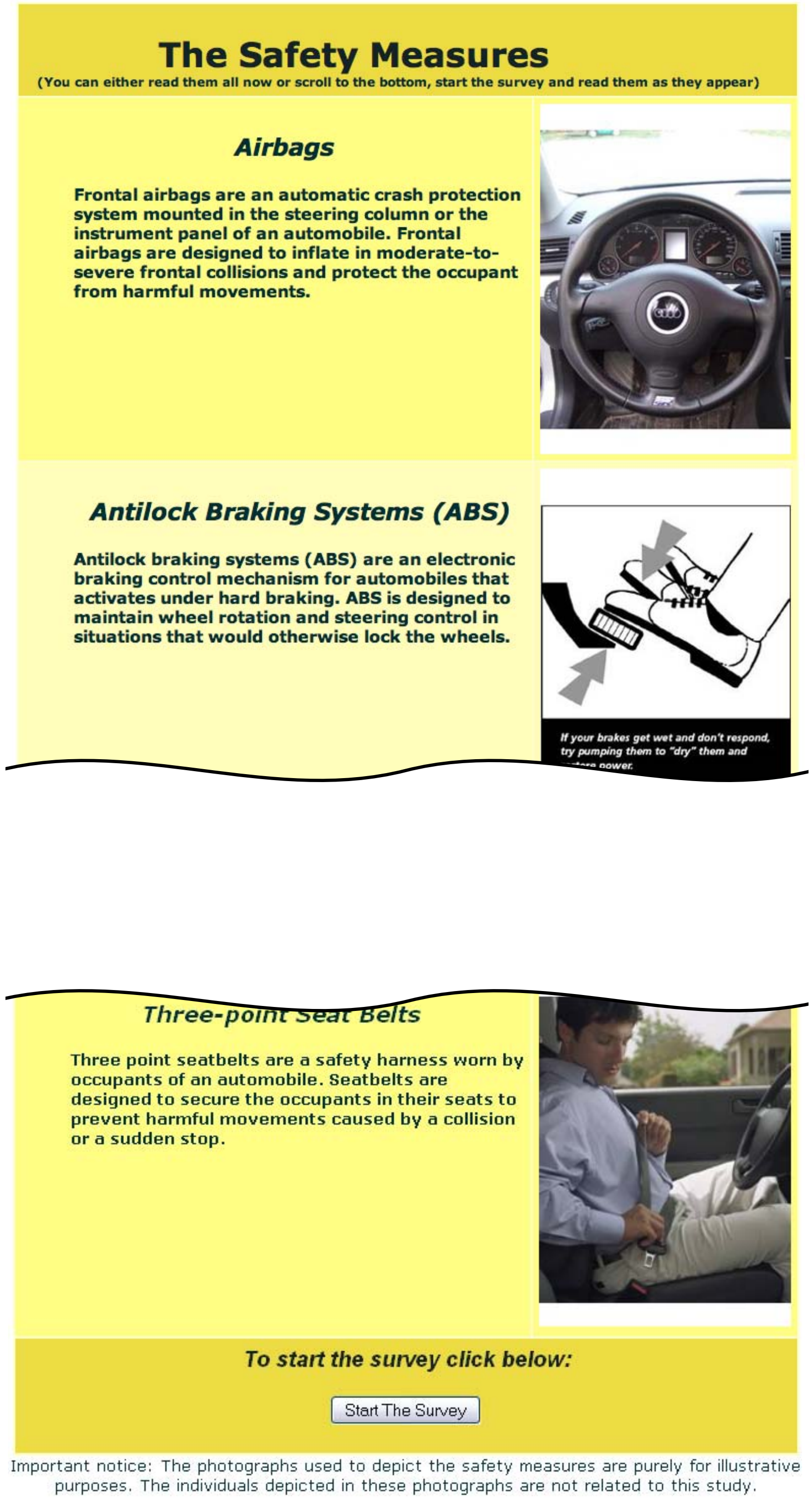


Figure B.2: Screen shot of the safety systems description page (partial)

Frontal airbags are an automatic crash protection system mounted in the steering column or the instrument panel of an automobile. Frontal airbags are designed to inflate in moderate-to-severe frontal collisions and protect the occupant from harmful movements.

Antilock braking systems (ABS) are an electronic braking control mechanism for automobiles that activates under hard braking. ABS is designed to maintain wheel rotation and steering control in situations that would otherwise lock the wheels.

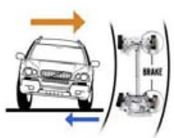
Bicycle helmets are protective headgear designed to provide protection from head injuries in a bicycle collision.

Center High Mounted Stop Lamps (CHMSL) are additional brake lamps located higher than regular stop lamps on the vertical centerline of the rear of an automobile. CHMSL are activated together with regular stop lamps and are designed to reduce reaction time to braking of upstream vehicles.

Condoms are flexible impermeable sleeves worn over a male's penis. Condoms are designed as a contraceptive or as a way to prevent the spread of sexually transmitted diseases like AIDS.

Daytime running lights (DRL) are bright, white forward-facing lights for automobiles that operate in daylight. DRL's are designed to improve automobile conspicuity in the daytime to increase detection by others.

Electronic Stability Control (ESC) are a stability system for automobiles that identifies when the driver is about to lose control. ESC is designed to automatically adjust both braking and engine power to prevent such loss of control.



Motorcycle helmets are protective headgear designed to provide protection from head injuries in a motorcycle collision.

Childproof medication caps are covers of medication containers with an operating mechanism designed to be significantly difficult to open for children under the age of 5.

Childproof lighters are hand-held fire-setting devices with special mechanical features that require acquired handling to generate a flame. Child proof lighters are designed to make operation difficult for children.

Structural side impact improvements are structural modifications of the side beams and the installation of energy absorbing padding of automobiles. These improvements are designed to protect occupants in a side impact collision.

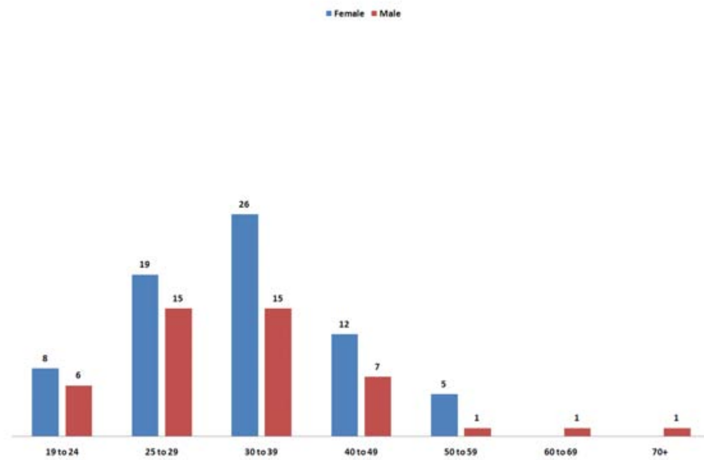
Smoke detectors are warning devices installed in an enclosed space to detect smoke. Smoke detectors are designed to issue an audible and/or visual alarm to warn household occupants of a fire.

Sunscreens are chemical substances applied on a person's skin. Sunscreens are designed to reflect and absorb ultraviolet radiation from the sun's rays to help protect the skin from damage that may lead to skin cancer.

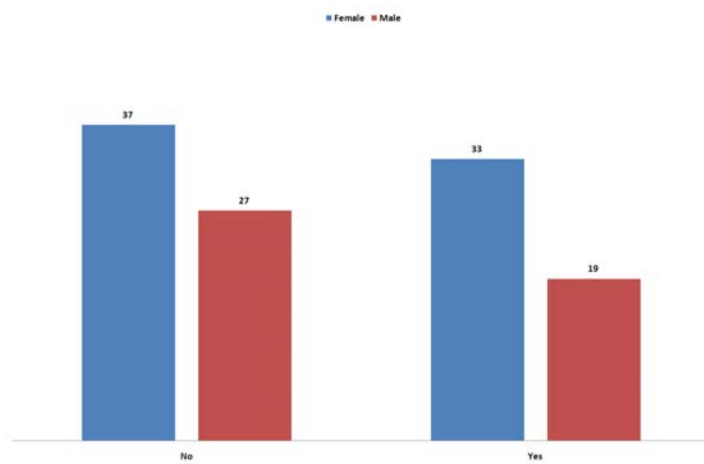
Lawn mower blade control systems are mechanical levers on walk-behind lawn mowers. They require continuous contact with the lever to rotate the blade and to completely stop rotation within 3.0 seconds of release. Blade control systems are designed to reduce injuries caused by contact with the blades.

Three point seatbelts are a safety harness worn by occupants of an automobile. Seatbelts are designed to secure the occupants in their seats to prevent harmful movements caused by a collision or a sudden stop.

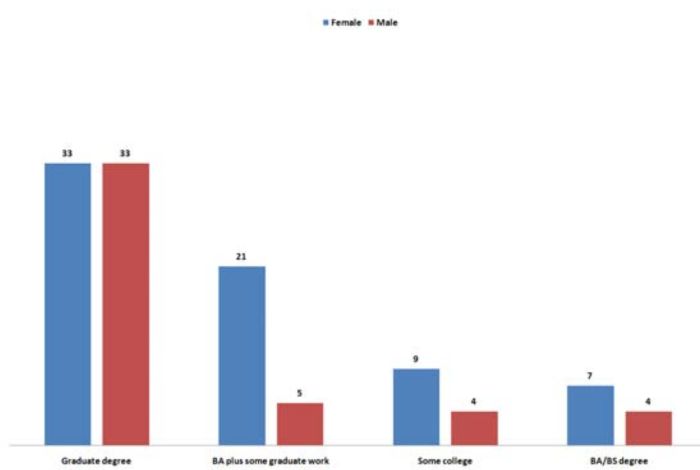
Figure B.3: Descriptions and image of the safety systems included in the survey



(a) Age

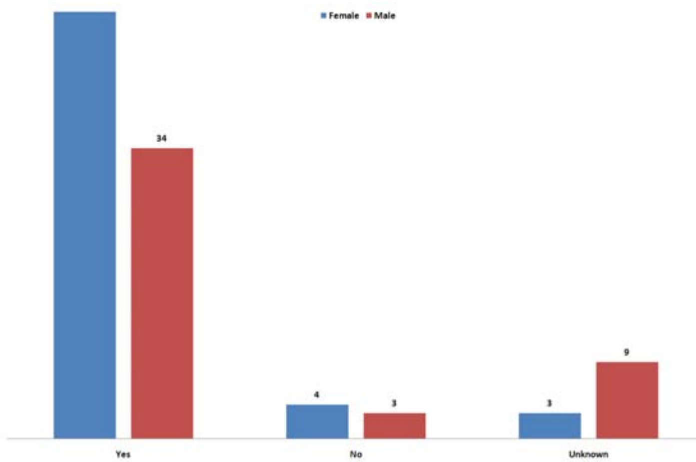


(b) Marital status

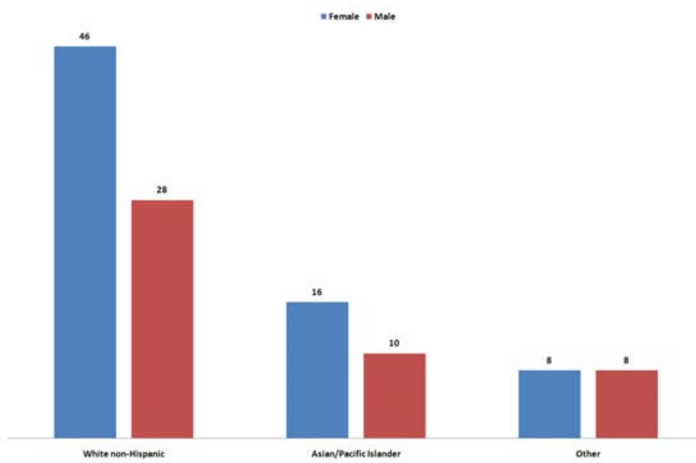


(c) Education level

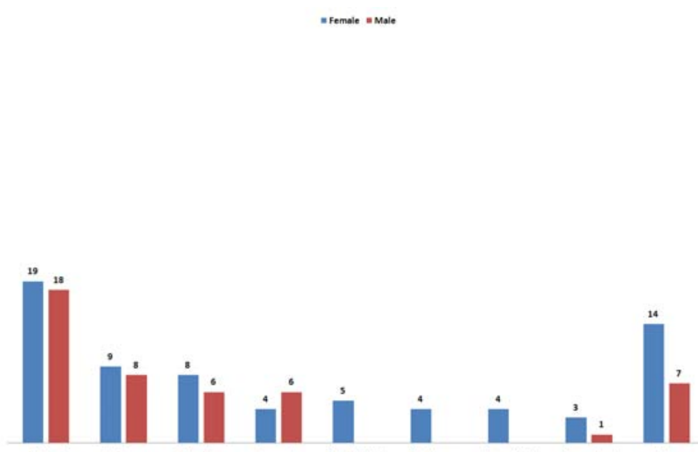
Figure B.4: Distribution of respondent demographics by gender (1 of 2)



(a) Drivers' license



(b) Ethnicity



(c) Occupation

Figure B.5: Distribution of respondent demographics by gender (2 of 2)

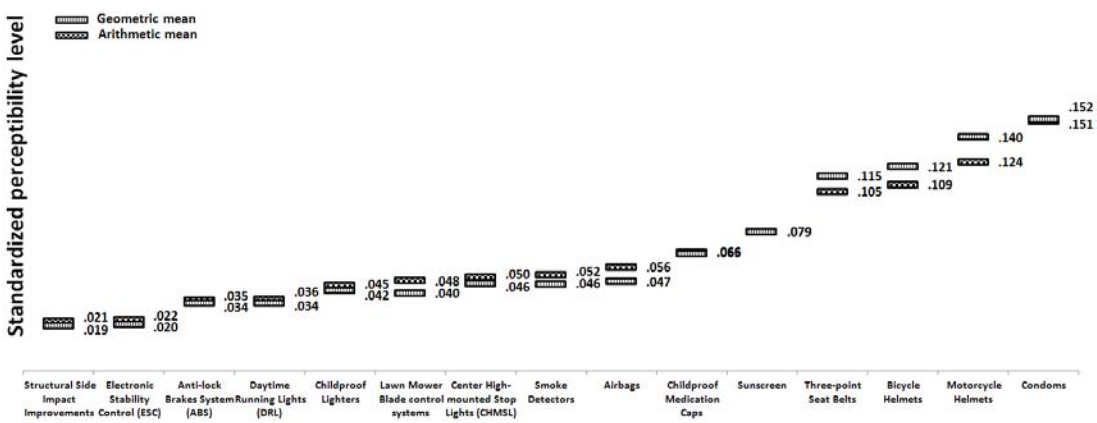


Figure B.6: Comparison of the Perceptibility level between the geometric mean and the arithmetic mean ($n = 94$)