

Safety Considerations in Optimal Automotive Vehicle Design

by

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LIST OF ABBREVIATIONS

ABS	anti-lock braking system
AIS	Abbreviated Injury Scale
ATD	anthropomorphic test device
BMI	body mass index
CAFE	Corporate Average Fuel Economy
CBC	choice-based conjoint
CDS	Crashworthiness Data System
CPI	Consumer Price Index
DOE	design of experiments
DRI	Dynamic Response Index
EA	energy-absorbing
EPA	Environmental Protection Agency
ESC	Electronic Stability Control
EuroNCAP	European New Car Assessment Program
EVC	Enhancing Vehicle-to-Vehicle Compatibility Commitment
FARS	Fatality Analysis Reporting System
FMVSS	Federal Motor Vehicle Safety Standards
GES	General Estimates System
GWU	George Washington University
HMMWV	High Mobility Multipurpose Wheeled Vehicle

IED improvised explosive device
IIHS Insurance Institute for Highway Safety
ISS Injury Severity Score
kph kilometer-per-hour
mpg miles-per-gallon
mph mile-per-hour
MRAP Mine Resistant Ambush Protected Vehicle
NASS National Automotive Sampling System
NATO North Atlantic Treaty Organization
NCAC National Crash Analysis Center
NCAP New Car Assessment Program
NHTSA National Highway Traffic Safety Administration
OLHS optimal Latin hypercube sampling
PISC Post-Impact Stability Control
PMHS post-mortem human surrogate
POD proper orthogonal decomposition
SPARK Self-Protection Adaptive Roller Kit
SSF static stability factor
WHO World Health Organization

LIST OF SYMBOLS

α_D	Dealer markup, as a percentage
α_{eng}	Engine-related design attributes
α_{other}	Non-engine-related design attributes
β	Coefficient of fixed effects between consumers and vehicles
β_{eng1}	Cost model regression coefficient for engine type
β_{eng2}	Cost model regression coefficient for engine design attributes
β_{ik}	Matrix element relating consumer i to vehicle attribute k
β_{other}	Cost model regression coefficient for non-engine attributes
δ	Coefficient representing fixed preference for attributes
Δv	Change in velocity
ϵ_{ij}	Stochastic part of utility that consumer i perceives in product j
μ	Coefficient of stochastic effects between consumers and products
μ_p	Mean occupant sitting position
π	Profit of an automaker
σ_p	Standard deviation of occupant sitting position
$\Phi(a_{peak})$	Normal probability distribution function of a_{peak}
ϕ_{bmv}	Percentage of military blast events striking multipurpose vehicles
ϕ_{fcc}	Percentage of military fuel convoys with a casualty
ϕ_{fmv}	Percentage of military fuel consumed by multipurpose vehicles
$0-60$	Vehicle acceleration time from 0-60 mph, in seconds
$0 - 60^*$	Optimal vehicle acceleration time

a	Airbag inflation rate and total mass flow
a_{peak}	Peak upward acceleration of a vehicle due to blast impact
b	Stiffness of seat belt material
b_{ij}	Demographic interactions between consumer i and product j
C^*	Optimal vehicle manufacturing cost
c	Steering column travel stiffness
c_f	Fixed costs of production
C_{int}	Critical intercept value for neck compression
c_v	Variable costs of production
d	Airbag deflation rate (vent size)
$D_{chest,th}$	Occupant chest deflection threshold as a function of human size
d_j	Vector of product attributes for vehicle j
$E(AIS3+)$	Expected number of serious injuries
E_{int}	Critical intercept value for neck extension
E_P	Expected probability of injury given a frontal crash
F_{25mph}	FMVSS standard for 25-mph frontal crash with unbelted ATD
F_{30mph}	FMVSS standard for 30-mph frontal crash with belted ATD
$F_{femur,th}$	Occupant femur force threshold as a function of human size
F_{int}	Critical intercept value for neck flexion
F_{lumbar}	Axial force in the lower lumbar spine
F_{neck}	Axial force in the upper neck
F_{static}	FMVSS standard for static out-of-position airbag deployment
F_{tibia}	Axial force in the lower tibia
FE	Fuel economy of a vehicle
\overline{FE}	Sales-weighted average FE of new vehicles
FE^*	Optimal vehicle fuel economy
FC	Fuel consumption of a vehicle

FC_{fleet}	Total fleet fuel consumption
\overline{HP}	Sales-weighted average horsepower of new vehicles
h	Stature, or standing height, of a vehicle occupant
HIC_{15}	Head Injury Criterion
k	Knee bolster stiffness
M	Total size of the automotive market for a given year
m	Mass of a civilian consumer vehicle
m_b	Baseline mass of a military multipurpose vehicle
m_c	Mass of an explosive charge beneath a vehicle
m_{ij}	Random interactions between consumer i and product j
m_{rear}	Lumped mass in the rear part of the multi-body vehicle model
m_v	Mass of a military multipurpose vehicle
n_{be}	Number of blast events occurring per year
N_{blast}	Number of blast-related military casualties per year
N_{convoy}	Number of fuel convoy-related military casualties per year
n_{fc}	Baseline number of military fuel convoys per year
N_{ij}	Neck Injury Criterion
n_{opv}	Average number of occupants per military multipurpose vehicle
P	Price of a vehicle, as seen by the consumer
\overline{P}	Sales-weighted average price of new vehicles
P^*	Optimal vehicle price
p	Longitudinal position of an occupant's seat
P_{AIS2+}	Probability of moderate (AIS level 2) or worse occupant injury
P_{AIS3+}	Probability of serious (AIS level 3) or worse occupant injury
P_{chest}	Probability of occupant chest injury
P_f	Probability of failure to meet military injury thresholds
P_{femur}	Probability of occupant femur injury

P_{head}	Probability of occupant head injury
P_{neck}	Probability of occupant neck injury
P_{rand}	Probability of injury as a function of random variables
Q	Quantity sold or demanded of a new vehicle model
Q^*	Optimal vehicle quantity sold
r	Seat belt retractor stiffness and load-limiting function
R_{fc}	Ratio of new to baseline military fuel consumption
s	Structural stiffness of the front frame rails
s_c	Stiffness of the seat cushion
s_{EA}	Stiffness of seat energy-absorbing structure
s_f	Stiffness of the floor padding
t	Airbag release time after the moment of impact
T_{50th}	FMVSS injury thresholds for 50th percentile male
T_{5th}	FMVSS injury thresholds for 5th percentile female
T_{int}	Critical intercept value for neck tension
U_{accel}	Part worth of acceleration time for utility function
$U_{fuelcon}$	Part worth of fuel consumption for utility function
U_{ij}	Utility that consumer i perceives in product j
U_{price}	Part worth of vehicle price for utility function
U_{safety}	Part worth of occupant safety for utility function
U_{total}	Combined utility function for market systems model
v	Speed, measured by change in velocity, of a frontal crash
V_{ij}	Systematic utility for consumer i and product j
V_{og}	Utility of the outside good
w	Load-limiting webbing function
\bar{W}	Sales-weighted average weight of new vehicles
W^*	Optimal vehicle weight

x	Vector of design variables
x_B	Engine bore diameter
x_{BPow}	Hybrid-electric vehicle peak battery power
x_{BtS}	Engine bore-to-stroke ratio
x_c	Longitudinal (fore-aft) coordinate of an explosive charge
x_{FD}	Final drive ratio
x_{H101}	Vehicle height
x_l	Vector of lower bounds on design variables
x_{L101}	Vector of design variables
x_{L103}	Vehicle length
x_{PGR}	Hybrid-electric vehicle planetary gear ratio
x_u	Vector of upper bounds on design variables
x_{W105}	Vehicle width
y_c	Lateral (left-right) coordinate of an explosive charge
z	Percentile of human size, based on height
z_{jk}	Relationship between product j to attribute k

ABSTRACT

While automobiles provide society with an unprecedented amount of mobility, motor vehicle crashes are a leading cause of injury and death worldwide. Designing safer vehicles is a priority of governments and automakers alike; however, other requirements such as increased fuel economy and performance have driven designs in conflicting directions. Because society benefits from reductions in traffic injuries and fuel consumption, governments impose standards and incentives for safer and more fuel efficient vehicles. One form of incentive is a consumer-information test, such as a New Car Assessment Program (NCAP), using standardized crash tests in various impact directions to help customers compare the crashworthiness of different automobiles. Automakers strive to perform well on these tests by optimizing vehicle designs to the specified scenarios. Another type of standard uses injury thresholds to ensure a minimum level of protection, such as the U.S. Federal Motor Vehicle Safety Standards and the U.S. Army ground vehicle blast protection criteria.

This dissertation uses these standards to examine the impact of safety optimization formulations and tradeoffs on vehicle design and competing objectives. Physics-based modeling is used to simulate crash or blast events, and computational designs of experiments are conducted with the resulting data fit to response surfaces. Single- and multi-objective optimization formulations are developed to demonstrate relationships between occupant protection and vehicle weight for civilian vehicle crashes and military vehicle blast events. Using these formulations, the civilian case study is extended to understand the impact of the frontal NCAP test speed on injuries in frontal on-road crashes, as well as the effect safety considerations have on manufac-

turer profit-maximizing decisions and consumer behavior in a competitive market. The military case study is also expanded to demonstrate how high vehicle weight and fuel consumption increase the need for convoys, posing additional injury risks to personnel and thereby making fuel economy a safety objective in a casualty-minimization formulation.

The results of these studies demonstrate the need for designers and engineers to consider safety in new, more holistic ways, and this dissertation establishes a new type of design thinking that can contribute to decreased vehicle-related injuries while also accounting for other objectives.

CHAPTER I

Introduction

“Ah, to build, to build! That is the noblest art of all the arts.”

-Henry Wadsworth Longfellow

1.1 Introduction

Two of the grand challenges facing automobile designers today are to enhance safety and increase fuel efficiency, and while both of these areas have seen significant advances in recent decades, customers continually demand better, safer, and more efficient vehicles. It is also in the interest of society for individuals to drive vehicles that reduce road traffic injuries, which place a burden on societal healthcare costs, and to curb fuel consumption, which causes harmful global and local emissions while depleting nonrenewable resources. For these reasons, governments place standards and incentives to drive improvements for both of these criteria. In the United States, these criteria are the responsibility of the National Highway Traffic Safety Administration (NHTSA) for safety and the Environmental Protection Agency (EPA) for fuel economy.

Most people have an intuitive understanding that there is a basic tradeoff between consumer vehicle crashworthiness and fuel economy, where the link between the two is vehicle weight. Heavier vehicles generally consume more fuel per mile than their

lighter counterparts, and basic physics explains that in multiple-vehicle crashes a heavier vehicle has a crashworthiness advantage. However, in the new vehicle design process, this is rarely viewed as a tradeoff. Designers determine the mass of the vehicle based on segment, structural requirements, styling, and powertrain components, and then the components and features that contribute to crashworthiness are optimized to provide real-world safety and perform well in government tests, which typically do not account for the advantages of high vehicle mass. This dissertation will provide further discussions and insights on the relationships among consumer vehicle safety, fuel economy, and weight, starting with the relevant literature that has been produced on this topic and then diving deeper into new methods for safety optimization under fixed and variable vehicle weights. A computational methodology for evaluating the effectiveness of consumer-information frontal crash tests is developed and explored, as well as an implementation of design for market systems with safety considerations.

A further component of the dissertation research is to examine the parallels between consumer vehicle crashworthiness and military vehicle blastworthiness, which has similar dependencies with vehicle weight and fuel consumption. Heavier military ground vehicles can better withstand underbody blast loading from improvised explosive devices (IEDs) due to higher inertia, but they also consume more fuel. While a primary requirement of any military operation is personnel safety, fuel consumption itself impacts safety because it creates a need for fuel convoys to traverse dangerous terrain in hostile territories. These threats can be modeled jointly with the single objective of minimizing troop casualties, and other tradeoffs that contribute to occupant safety can be simultaneously accounted for. As with civilian vehicles, military vehicle design standards regulate blast safety performance, but these standards fail to address the design optimization needs for overall personnel safety. Later chapters in the dissertation address these issues by developing and assessing the impact of new design optimization formulations and frameworks that address the specific concerns

of military vehicles.

1.2 The State of Vehicle Safety Research

The World Health Organization (WHO) attributes roughly 1.2 million deaths and 39 million injuries to traffic incidents each year (*Peden et al.*, 2002). In the United States alone, the year 2009 saw nearly 34,000 motor vehicle-related fatalities (*NHTSA*, 2011a), which is the lowest number in over three decades despite increasing vehicle prevalence and usage, as well as an additional estimated 2.3 million adult injuries (*CDC*, 2011b). Vehicle design engineers aim to reduce these fatalities and injuries through the development of safer vehicles equipped with sophisticated active and passive safety systems. This effort is supported by government regulations and a consumer pull for safer vehicles, making occupant safety a key concern in automotive design.

Vehicle occupant safety can be classified into two broad areas: the degree to which a vehicle protects its occupants in a crash, known as crashworthiness, and the extent to which the vehicle enables the driver to lower his or her chances of being in a crash, known as crash avoidance (*Wenzel and Ross*, 2005). Much academic and industrial research has been devoted to optimizing the performance of safety systems that aid in crashworthiness, including the designs of vehicle structural systems and restraint systems. Passive safety systems are vehicle components that respond to a crash or blast event to protect occupants from injury, whereas active safety systems are features that constantly act to reduce the possibility of such an event (*Hamid*, 2007). Standard vehicle body structures such as energy-absorbing frontal frame rails, bumpers, and hood support beams are optimized to produce the best possible crash pulse (the acceleration history of the occupant compartment during a crash). Occupant restraint system components, such as seat belts, pretensioners, load limiters, and air bags, can then be optimized given a vehicle crash pulse to

reduce the likelihood of occupant injury (*Sieveka et al.*, 2001; *Good et al.*, 2008). Newer passive restraint configurations, such as belt-integrated seats and four-point seat belts, have been explored in research studies, but they have not been implemented widely (*Rouhana et al.*, 2003; *Park and Park*, 2001). Recently, engineers have focused on developing advanced crash avoidance and active safety systems, such as anti-lock braking systems (ABS) and Electronic Stability Control (ESC), which have been developed, optimized and implemented to prevent or mitigate accident severity.

In recent years, considerable attention has been given to environmental sustainability, particularly with regard to automobiles. Sustainability refers to the ways in which our actions impact the environment, and, in turn, how those impacts affect the ability of ourselves and of future generations to sustain the lifestyle we have become accustomed to (*World Commission on Environment and Development*, 1987). A study of the life-cycle environmental impact of motor vehicles by Keoleian et al. (1997) found that approximately 85 percent of a vehicle’s impact is concerned with the “use phase” of the vehicle, particularly fuel consumption. Vehicles in the United States consume over 140 billion gallons of gasoline each year (*EIA*, 2011), emitting roughly 1.25 billion metric tons of carbon dioxide into the atmosphere (*EPA*, 2005). The impact of petroleum consumption raises concerns for national security, the economy, and resource depletion, and carbon emissions affect air quality, human health, and global climate change. Efforts to curb motor vehicle fuel consumption include the development of various engine-efficiency technologies and alternative powertrains, including hybrid-electric vehicles, electric vehicles, bio-fuels, and hydrogen fuel cells. These technologies have not fully penetrated the markets for several reasons, including cost, infrastructure concerns, fuel availability, and overall uncertainty on their total environmental impact. Reducing automobile mass is another method for improving fuel efficiency, and studies indicate that reducing a vehicle’s mass by ten percent improves its fuel economy by between five and eight percent, along with corresponding emissions

reductions (*Defense Science Board*, 2008). However, lowering mass raises occupant safety concerns, and further understanding of the relationship between sustainability and safety is warranted.

For decades, researchers have investigated vehicle safety and its relationship to mass, as well as methods for optimizing vehicle designs for safety. Chapter II will discuss highlights from the vehicle safety literature, with focuses on efforts to understand these design relationships using empirical crash data, technologies and techniques used to enhance vehicle safety, and methods for modeling safety from both a pure engineering viewpoint and from a business viewpoint.

Many researchers have investigated the empirical relationships between vehicle mass, fuel economy, and some measure of occupant safety. Some authors conclude that there is a causal relationship between vehicle mass and safety, while others conclude that other factors such as size, price, or driver behavior have a stronger relationship with safety. Because of these confounding factors along with the pace of technological improvements in vehicle design, broader design conclusions from these studies are limited. Chapters III and IV present computational methods for understanding this relationship between vehicle mass and scenario-specific safety in civilian and military vehicles, respectively, focusing on the selection of physics-based modeling tools as well as the development of appropriate optimization formulations. The use of computational simulations of physical systems in these chapters eliminates many of the confounding factors that affect the empirical data analyses.

Other researchers have also presented vehicle safety design optimization results for specific vehicles under specific crash scenarios. These investigations often leverage advanced computational tools and modeling techniques to develop design recommendations that apply to those particular vehicles and scenarios. While these studies are useful for maximizing an automobile's crash test performance, they generally lack a consideration of the wide range of crash modes, crash speeds, and vehicle and oc-

cupant types that are seen on the road. Chapter V leverages the models developed in Chapter III to evaluate consumer-information test standards and their impact on the aforementioned range of crash types experienced on roadways. With regard to the military application, Chapter IV considers uncertainty in blast event parameters in formulating optimization problems, and Chapter VI expands upon this work by introducing an additional safety consideration that stems from high vehicle mass.

Lastly, efforts have been made to consider vehicle design from an automaker's perspective, where profits are of primary concern and performance influences the consumer demand for a vehicle. These studies combine knowledge from the engineering, marketing, and economics literature to develop a game-theory based approach to understanding how design fits into a competitive market. One area that this research has not yet tackled is modeling safety performance and consumer demand for safety, which to date has not been well understood and is addressed in Chapter VII.

1.3 Expected Contributions

This dissertation offers an approach to vehicle design for safety from an optimization perspective to examine mathematical formulations, tradeoffs, and ultimate impacts on society. Using quantitative, physics-based simulation tools, safety of civilian consumer vehicles and military ground vehicles is juxtaposed with additional design considerations that may complement or conflict with traditional ideas of vehicle safety. Tools from engineering design, computational optimization, and statistics are combined to develop and assess new modeling frameworks that support the design of safe vehicles.

The ensuing chapters describe research conducted over the past four years that sought to contribute to the state of engineering design knowledge through:

1. Exploration and quantification of the design relationship among vehicle occu-

- passenger safety and other design objectives,
2. Development and evaluation of optimization formulations for minimizing occupant injury probability under event uncertainty, and
 3. Assessment of safety standards and policies that support rational decision-making and design improvements for safer vehicles.

In short, this dissertation presents new ways to analyze the problems facing vehicle design for safety while leveraging engineering and mathematical modeling tools, all in order to understand the complex interactions and tradeoffs with non-safety design criteria.

1.4 Dissertation Outline

The ensuing chapters frame the topics surrounding vehicle safety and present new methods for design and investigation. Chapter II discusses the relevant literature as alluded to in Section 1.2, providing the reader with background knowledge on the state of vehicle safety, technology, and modeling tools and techniques, as well as motivating the contributions presented in the ensuing chapters. Chapter III discusses modeling tools for measuring vehicle frontal crashworthiness and fuel economy, developing a framework for combined optimization and showing a physics-based tradeoff relationship between fuel economy and occupant crash safety. These ideas are extended in Chapter IV to account for military vehicle blastworthiness, and in this case uncertainty is introduced in a way that requires careful consideration of the design optimization formulation. Three separate formulations are presented with results, and the relative merits of each is discussed. Chapter V uses the modeling tools developed in Chapter III to show how New Car Assessment Programs (NCAPs) influence optimal vehicle design and on-road safety, and counterfactual policies for different crash speeds are explored. Chapter VI leverages the blastworthiness modeling and

optimization results from Chapter IV along with data on military convoy casualties to optimize safety as a combined function of blastworthiness and fuel consumption. Chapter VII uses the civilian vehicle mass-safety relationship found previously to develop a market systems model that considers consumer demand for safety and vehicle engineering characteristics in a firm profitability formulation. Finally, Chapter VIII offers conclusions and summarizes the broader contributions of the dissertation.

CHAPTER II

Literature Review

*“The way to do research is to attack the facts
at the point of greatest astonishment.”*

-Celia Green

2.1 Introduction

This chapter will provide a review of the state of research in the areas of motor vehicle safety, computational modeling of vehicle crash events and design optimization, safety standards and policies, and econometric modeling of the automotive market, motivating a need to combine them in ways that address the unique desires of safety-driven automobile design and policy-making. It is here that this dissertation fits into the research community, developing a design optimization approach that addresses the broad safety needs and wants of the consumer vehicle market as well as strategies for military vehicle design that minimize personnel casualties.

This chapter organizes the relevant literature into five sections: The first is a discussion of how various authors measure vehicle safety and report statistics and trends. This is followed by an overview of vehicle safety fundamentals and how safety objectives relate to other vehicle attributes, citing empirical evidence and crash-related physics. Next is a summary of research that has sought to improve vehicle safety

through various technologies, devices, and regulatory standards, including a review of the evolution of safety-driven regulations. The fourth section discusses physics-based modeling tools that leverage the recent advances in computational abilities to improve the new vehicle development process and reduce the need for expensive physical crash modeling. The chapter will close with a look into the automaker's perspective where the firm's objective is to maximize profits in an econometric game theory scenario, with safety considerations becoming an attribute of consumer demand and regulatory constraints.

2.2 Measuring Vehicle Safety

Vehicle safety can be measured in a variety of ways, and most researchers do so using data from on-road crash events or physics-based analysis. Crash data are collected by both local and national authorities in the United States, and the federal government as well as some states have publicly-available crash and injury databases. The National Highway Traffic Safety Administration (NHTSA) publishes databases of crash and injury information through the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) as well as the NASS General Estimates System (GES) (*NHTSA*, 2011b), in which a large sample of tow-away crashes are reported each year from across the country. Additionally, all fatal crashes in the U.S. are documented in the NHTSA Fatality Analysis Reporting System (FARS) (*NHTSA*, 2011a).

From these databases, researchers quantify vehicle safety by observing and comparing statistics. These statistics are typically reported as the numbers of injuries or deaths in a particular vehicle type or model, and they are often normalized to compare vehicles across the same level of exposure to crash possibilities. Researchers use a variety of metrics to quantify this exposure, including vehicle miles traveled, registered vehicle-years, injury rates of pedestrians or occupants of vehicles with which

that vehicle crashes, or numbers of reported tow-away crashes (*Evans, 1985; Cameron et al., 2001*). In some cases, researchers use multiple exposure-normalizing metrics to support the robustness of their conclusions. Ross and Wenzel (2001) published a table of some popular studies and the denominators used in analyzing vehicle safety, shown in Table 2.1.

Metric for Normalizing Exposure	Source
Registered vehicles	Kahane 1997
Crash w/ at least one vehicle towed from scene	U.S. GAO 1995
Non-driver front-seat passenger fatality	Evans 1991
Not-at-fault driver/struck vehicle in 2-vehicle crash	U.S. GAO 1995, Kahane 1997
Pedestrian fatality	Evans 1991
Crash reported to the police	Joksch 1998
Vehicle miles traveled	information usually not available

Table 2.1: Denominators used in popular studies for empirical vehicle safety analysis (*Ross and Wenzel, 2001*)

When empirical data are inadequate or unavailable, it is often beneficial to reconstruct collisions using physics-based analysis of prescribed crash scenarios. This is typically done using mathematical calculations of highly simplified models (*White et al., 1985; Kim et al., 2001; Marler et al., 2006*) or with computational tools that can simulate a crash event (*Hou et al., 1995; Yang et al., 2005*). With the introduction of New Car Assessment Programs (NCAPs) that prescribe standardized crash tests that are published for consumers, these particular crash modes and scenarios have become the focus of comparison among vehicles, with frontal and side impact commanding most of the attention due to their high rates of occurrence and injury. Recent increases in computational capabilities have permitted simulations to take a much more prominent role in safety analysis and new vehicle product development (*Spethmann et al., 2009*). The George Washington University (GWU) National Crash Analysis Center (NCAC) publishes an online database of finite-element vehicle crash models using U.S. NCAP crash scenarios (*Opiela, 2011*).

When comparing injuries from empirical or theoretical sources, it is important to be consistent among the type and severity of injury included. The most common tool for categorizing injuries is the Abbreviated Injury Scale (AIS), which categorizes types of injuries on a 6-point scale as minor (1), moderate (2), serious (3), severe (4), critical (5), or maximum (6) (*AAAM*, 1990). For example, the U.S. NHTSA standards and regulations all consider the probability of a serious or worse (AIS3+) injury. Since crash victims often have multiple injuries of varying severities in different parts of the body, there are several ways to categorize injured people on the AIS, including but not limited to:

- Maximum AIS (MAIS): Take the highest, or maximum, of all the AIS scores for the injuries in a body,
- Combined probability of injury: For a particular AIS level, this is calculated using the product of the probabilities of each injury not occurring, e.g.,

$$P_{combined,AIS3+} = 1 - (1 - P_{head,AIS3+}) \times (1 - P_{chest,AIS3+}) \times (1 - P_{leg,AIS3+}),$$
 and
- Injury Severity Score (ISS): Calculate by summing the squares of the three highest AIS injury severities (*Baker et al.*, 1974).

The research presented in this dissertation uses the combined probability of injury approach, as this is common in NHTSA regulations and it is an intuitive method for simplifying something as complex as an injured person into a single measurement of injury probability.

2.3 Vehicle Safety Fundamentals

2.3.1 Safety Effects of Mass

One widely-held belief that exists in both the research community and the new vehicle consumer decision-making process is that heavier vehicles are safer than their

lighter counterparts. This idea has been under investigation for several decades, and researchers have analyzed this issue using empirical evidence as well as basic physics equations. Many academics agree that heavier cars on the road do indeed correspond with lower injury and death rates, although some argue that this relationship is actually caused by a highly correlated variable such as size, price, and driver behavior (*Wenzel and Ross, 2008; Evans, 2004; Padmanaban, 2003; Wood, 1997*). It is important to note that some of the older empirical studies may not be relevant to the current vehicle fleet given the newer safety technologies deployed, but many of the trends are still applicable.

Some of the earliest studies on the impact of vehicle mass on safety were conducted by NHTSA and the University of North Carolina using state-collected empirical data from the early 1970s (*Stewart and Stutts, 1978; Campbell and Reinfurt, 1973*). These studies found a basic relationship in car-to-car crashes where the frequency of serious injuries was negatively correlated to vehicle weight, yet in single-car crashes such as “ran-off-the-road” events there was no significant correlation between injury probability and vehicle weight. Stewart and Stutts (1978) used these analyses to construct linear categorical models for a driver’s probability of serious injury as a function of vehicle weight, region of impact, crash speed, and driver age, separating the data based on single- versus multiple-vehicle crashes as well as belted versus unbelted drivers. Their main conclusions were consistent with their a priori beliefs: Higher predicted occupant injury rates were observed for single-vehicle crashes, crashes in rural areas, and vehicles in the lightest weight class.

Jones and Whitfield (1984) used a Washington state database of police-reported one- and two-car crashes to develop statistical models for relative risks associated with downsized cars, separately investigating the effects on belted drivers and unbelted drivers. They found that an extra thousand pounds of vehicle mass corresponds with decreasing the risk to unbelted occupants by 34 percent and to belted occupants

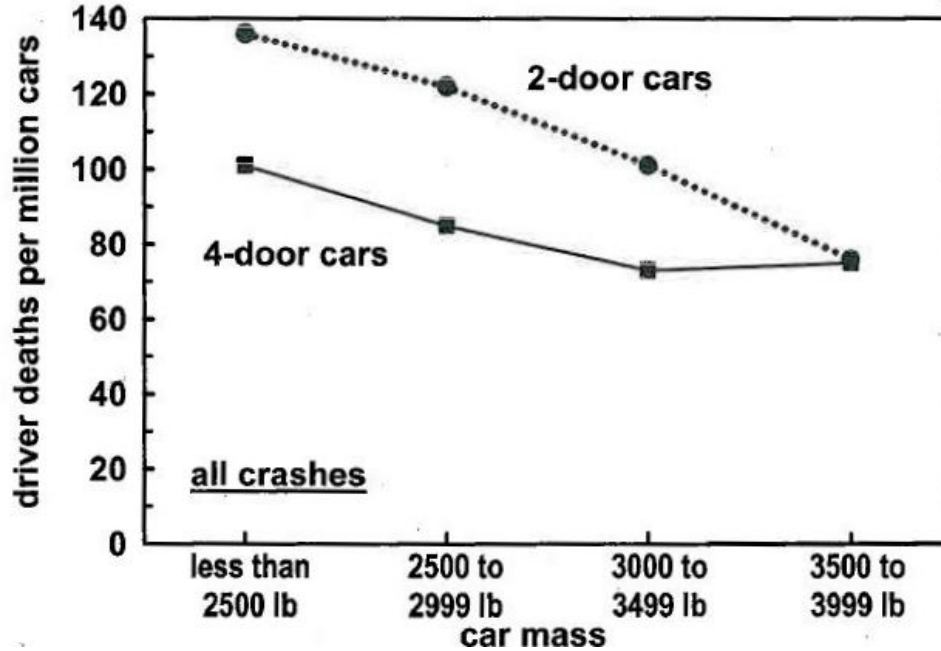


Figure 2.1: Driver deaths per million registered vehicles using 1995-98 IIHS data of 1994-97 model year vehicles (*Evans, 2004*)

by 25 percent, with restraint use itself lowering an occupant's risk by 66 percent. The authors equated a belted driver's probability of injury in a 2,500-pound car to an unbelted driver's injury probability in a 4,325-pound car. Tolouei & Titheridge (2009) used a database of British crashes to find that a 100-kilogram increase in mass decreases a driver's risk of injury in two-car crashes by 3 percent. Other studies of empirical data have found the impact of a 100-kilogram reduction in vehicle mass to reduce a driver's risk by anywhere from 1.5 to 8 percent, where still other researchers found no significant correlation (*Fildes et al., 1993*).

Leonard Evans of General Motors Research Laboratories has been one of the most prolific researchers in this area, and his use of physics equations and mathematical models to explain empirical relationships is frequently cited in the crashworthiness literature (*Evans, 2004*). Figure 2.1 shows a basic relationship from FARS data for a subset of vehicles driven in the mid-1990s, which clearly shows that drivers of heavier vehicles are less likely to die in a crash than those of lighter vehicles. It is also evident

from the plot that two-door cars experience more driver deaths than four-door cars, which may be attributed to either driver behavior or the size of the vehicles. Evans went on to discuss the effect of mass in two-vehicle crashes based on simple mechanics, noting that the change in velocity (Δv) of two vehicles crashing head-on is inversely proportional to their masses, as in Equation (2.1).

$$\frac{\Delta v_1}{\Delta v_2} = \frac{m_2}{m_1} \quad (2.1)$$

To support the physics and to show that a higher Δv equates to a higher risk, which is discussed further in Section 2.3.3, Evans investigated two-car frontal crashes in the FARS database between 1975 and 1998 to see how the ratio of masses between the vehicles impacts fatality rates. A plot of this relationship is shown in Figure 2.2, which shows a clear correlation between relative vehicle mass and relative fatality risk. Using this relationship, he derived what he calls the “first law of two-car crashes,” which explains that the fatality ratio R is related to the mass ratio μ as the power function given in Equation (2.2). This equation indicates that in a crash involving a mass ratio of two, i.e., one car weighs twice as much as the other, the driver of the lighter car is twelve times as likely to die as the driver of the heavier car. However, he claims, this is uncommon; a more common scenario would be a 20-percent difference in vehicle mass, in which the driver of the lighter car has twice the risk of fatality as the driver of the heavier vehicle (*Evans*, 2004).

$$R = \mu^{3.58} \quad (2.2)$$

Because these data may be confounded by the fact that heavier vehicles tend to be larger, Evans conducted a similar empirical analysis to show the benefit of adding a passenger to a car. This corresponds with adding 75 kilograms to the vehicle, on average, without any changes to size or vehicle type. Plotting the data from FARS

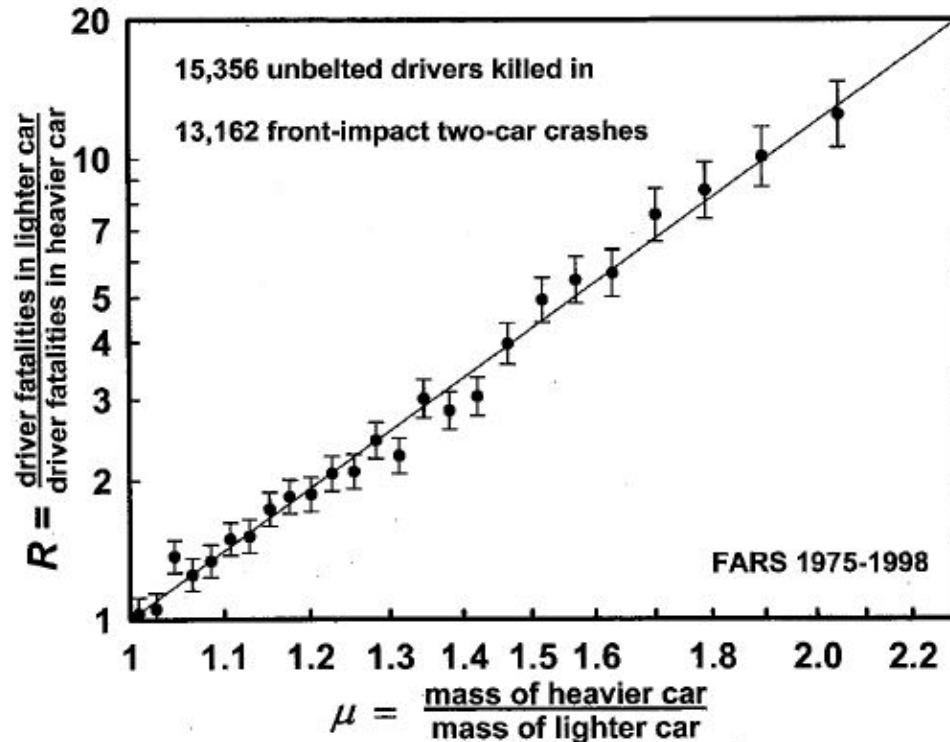


Figure 2.2: Driver fatality ratio in two-car frontal crashes as a function of vehicle mass ratio (*Evans, 2004*)

and fitting a similar curve to the data, he concluded that the relative fatality risk to a driver who is accompanied by a passenger is approximately 14 percent lower than if he or she were driving alone (*Evans, 2004*).

Evans’s “second law of two-car crashes” addresses situations in which two cars of equal mass crash into one another, and using data from 1991-1999 model-year vehicles he concluded that lower-mass vehicles still pose higher risks to one another. His categorical analysis showed that in lighter vehicles (less than 2,950 pounds) a 100-pound reduction corresponds with a 4.9-percent increase in fatality risk, and in heavier vehicles the same absolute mass reduction results in a 3.2-percent increase in fatality risk.

Eyges and Padmanaban (2009) conducted a similar analysis to Evans’s first law, using FARS data from 1981-2006 and arriving at similar conclusions. They fit the same relationship as Evans did in Equation (2.2), but found the coefficient to be

slightly lower at 3.13 rather than 3.58. Their plotted results also show the clear relationship between mass ratio and fatality risk, given in Figure 2.3. The authors used their derived models to predict the societal effect of reducing vehicle mass by 100 pounds and compared their results to those of previous research studies by Kahane (1997; 2003) and Van Auken and Zellner (2005). Eyges and Padmanaban found that reducing the weight of passenger cars by 100 pounds increases fatalities in car-to-car crashes by 0.4 percent and in light truck-to-car crashes by 3.4 percent, which was consistent with Kahane's results but contradictory to Van Auken and Zellner's results, who included wheelbase in their statistical model. Lastly, they looked at a host of driver and vehicle factors that contribute to the probability of driver fatality, and found that the mass ratio is by far the most important vehicle factor, though it is less important than driver age and belt use. They plotted the percent contributions of these attributes, shown in Figure 2.4, where the vehicle components include the logarithm of the mass ratio, the distance between the front axle and windshield (FAW), the presence of airbags, and the vehicle age.

In the late 1970's and early 1980's, U.S. federal fuel economy regulations required manufacturers to quickly increase fuel economy. Manufacturers were forced to quickly find ways to reduce fuel consumption, and in large part this was done by reducing vehicle size and weight. Crandall and Graham (1989) used data from this period to estimate the impact of the regulations on vehicle weight, the mix of large and small vehicles on the road, and overall on-road vehicle safety. They concluded that manufacturers responded by reducing vehicle weight by an average of 23 percent and selling a higher proportion of cars in smaller class sizes. Citing the research of Evans, Crandall and Graham estimated that the Corporate Average Fuel Economy (CAFE) standards caused reductions to fleet vehicle mass that increased occupant fatality risks by 14-27 percent.

One important point on the topic of vehicle mass and safety is that increasing the

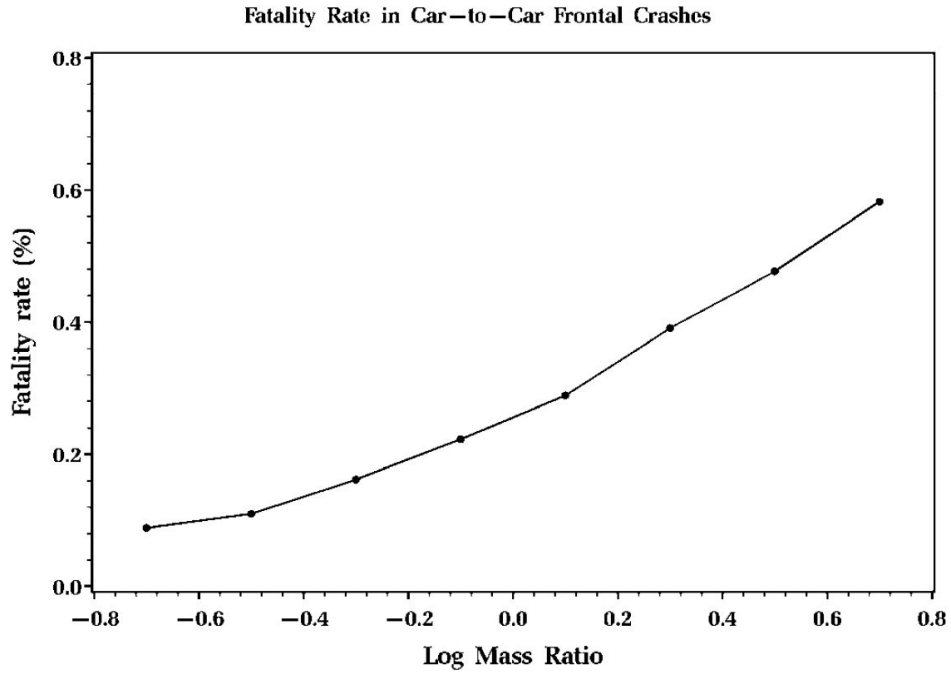


Figure 2.3: Driver fatalities as a response to vehicle mass ratio in two-vehicle non-rollover crashes (*Eyges and Padmanaban, 2009*) from FARS 2005 data

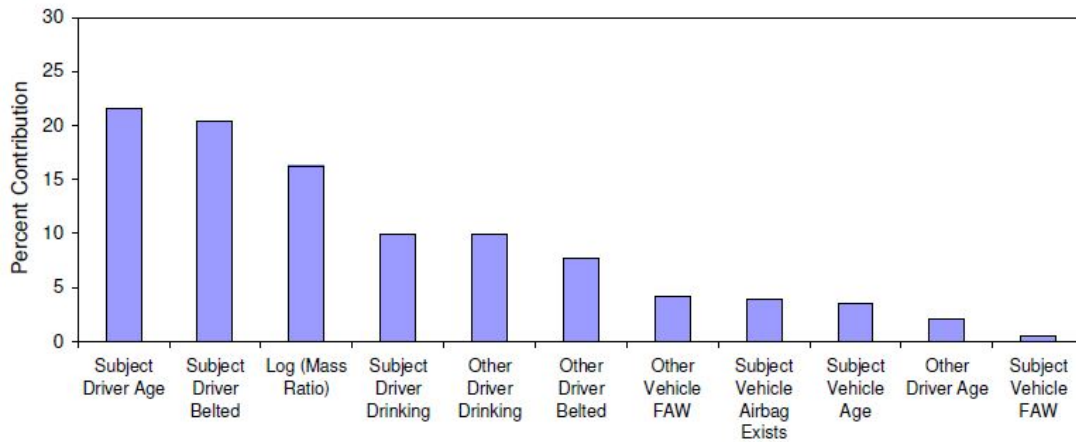


Figure 2.4: Factors contributing to driver fatality risk in two-car frontal crashes (*Eyges and Padmanaban, 2009*)

mass of one vehicle, while decreasing the risk to occupants of that vehicle, increases the risks to occupants of vehicles with which it collides. This follows from the same logic of Equations (2.1) and (2.2). Anderson and Auffhammer (2011) consider this to be an “external” safety cost of vehicle weight, and without regulation it creates an “arms race” among vehicle consumers who seek to maximize their own safety. Their estimates indicate that a 1,000-pound increase in vehicle weight increases the probability of fatality in the cars that it collides with by 47 percent, and the authors argue that a gas tax on the order of \$1.08 per gallon would internalize these safety costs of high weight.

2.3.2 Safety and Fuel Economy

Much of the literature discussed in Section 2.3.1 explores the relationship between vehicle mass and safety, and it is well known that increasing vehicle mass leads to higher fuel consumption and therefore lower fuel economy ratings. Since the desire to lower vehicle mass is largely driven by fuel consumption concerns, some studies directly look at the empirical relationship between fuel usage and occupant safety. Just as Crandall and Graham (1989) found a correlation between stricter fuel economy standards and higher fatality rates in the U.S., other researchers examine these trends on a vehicle-by-vehicle basis.

Symmons and Haworth (2003) defined their own “crash rating” as the likelihood of serious injury given at least one vehicle towed away from the crash site, where a higher rating indicates a higher injury risk. They calculated and plotted these values for specific vehicles in the Australian fleet with their relationship to mean fuel consumption, where a higher value indicates a less efficient vehicle. The results are shown in Figure 2.5, and they exhibit the existence of an apparent tradeoff between safety and sustainability (defined by fuel consumption in the use phase). The authors identified the vehicles that are convincingly on the lower-left side of the best fit line

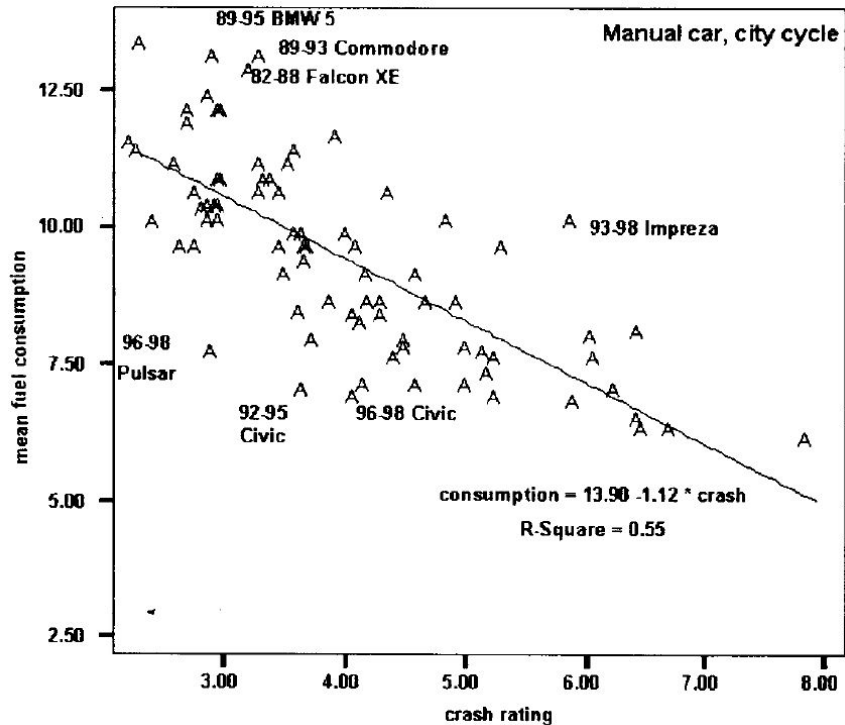


Figure 2.5: Crash rating versus mean fuel consumption in city driving (*Symmons and Haworth, 2003*)

including the Nissan Pulsar and Honda Civic, which have better-than-average fuel consumption and crash ratings; they also point out the vehicles on the opposite side of the spectrum, such as the Subaru Impreza and the Ford Falcon, for which the unsafe trends can likely be attributed to differences in driver characteristics and behavior.

Other studies over varying time spans and geographies have examined the claims made by Symmons and Crandall and Graham, and their conclusions vary. Noland (2005) plotted the trends of average fuel consumption in parts of Europe, North America, and Australia from 1970 through 1996 and compared them to vehicle weight and roadway fatalities. His results show that fuel economy has no general effect on traffic fatalities, and the recommendation was to increase fuel economy standards seeing that they have little or no adverse effect on safety. Part of Noland's claim was that the observation-based relationship between fuel economy and occupant safety is highly dependent on the time period chosen for study. In response to this claim, Ahmad

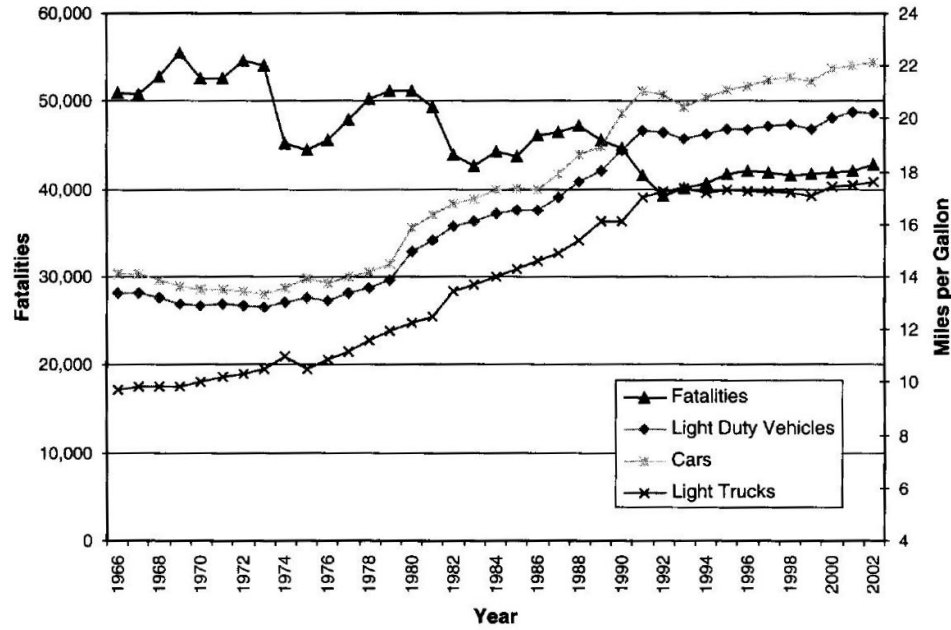


Figure 2.6: U.S. vehicle fuel economy and traffic fatalities, 1966-2002 (*Ahmad and Greene, 2005*)

and Greene (2005) conducted a similar study looking at U.S. traffic fatalities over the time span from 1966 to 2002, finding that fuel economy increases appear to correspond with decreases in traffic fatalities, as shown in Figure 2.6. Much of this trend, however, can be attributed to improvements in fuel economy technology, as vehicle mass trends show steady increases since the aforementioned drop in the early 1980s. More recently, Zachariadis (2008) looked at the European New Car Assessment Program (EuroNCAP) crash test results and compared them to mass and carbon dioxide emissions, and he too concluded that “there is almost no trade-off between better car safety and carbon dioxide emissions reduction”; however, these crash tests are independent of vehicle mass.

A National Academy of Science study developed a proposal to change the CAFE standards to be weight-based, which would avoid the tendency discussed by Crandall and Graham (1989) for automakers to reduce vehicle weight to meet these standards (*IIHS, 2002*). However, this could lead to up-weighting vehicles to get around

the regulation, which would produce the opposite effect of that which was intended. Instead, the latest CAFE standards, which were released in 2011, are based on the vehicle footprint, or wheelbase multiplied by track width, which incentivizes manufacturers to increase vehicle size without specifically targeting weight (*LaHood and Jackson*, 2010).

2.3.3 Safety Effects of Size and Other Attributes

Much of the literature discussing the effects of vehicle mass on safety has mentioned the fact that in existing vehicles, mass is highly correlated with various metrics of vehicle size, such as wheelbase, track width, and the distance from the front axle to the windshield. While the physics equations demonstrating the safety benefits of mass cannot be refuted, empirical evidence that heavier cars are safer can be interpreted as *larger* cars being safer. There is a large body of literature on the impact of size on vehicle safety, and also some studies that exhibit high correlations between occupant safety and other factors such as vehicle price, driver factors, and event characteristics.

To determine which of these factors have the highest correlation, a significant amount of vehicle crash data must be collected and analyzed. Wenzel and Ross (2008) have reported on several studies of the FARS data, and they have plotted information of the most popular vehicle models and their “risk-to-driver” criterion, which is defined as the number of driver fatalities that occur for every million registered vehicle-years. They also consider the “risk-to-others,” which represents the number of driver deaths in other vehicles with which the particular models collide, also per million registered vehicle-years. This criterion represents what some authors call vehicle “aggressivity,” or how dangerous a vehicle is to occupants of other vehicles on the road. Figure 2.7 illustrates this information by vehicle type, splitting up risk-to-drivers into rollover and non-rollover crashes; the data indicate that luxury import cars have the best safety record in all categories, pickup trucks and vans have the

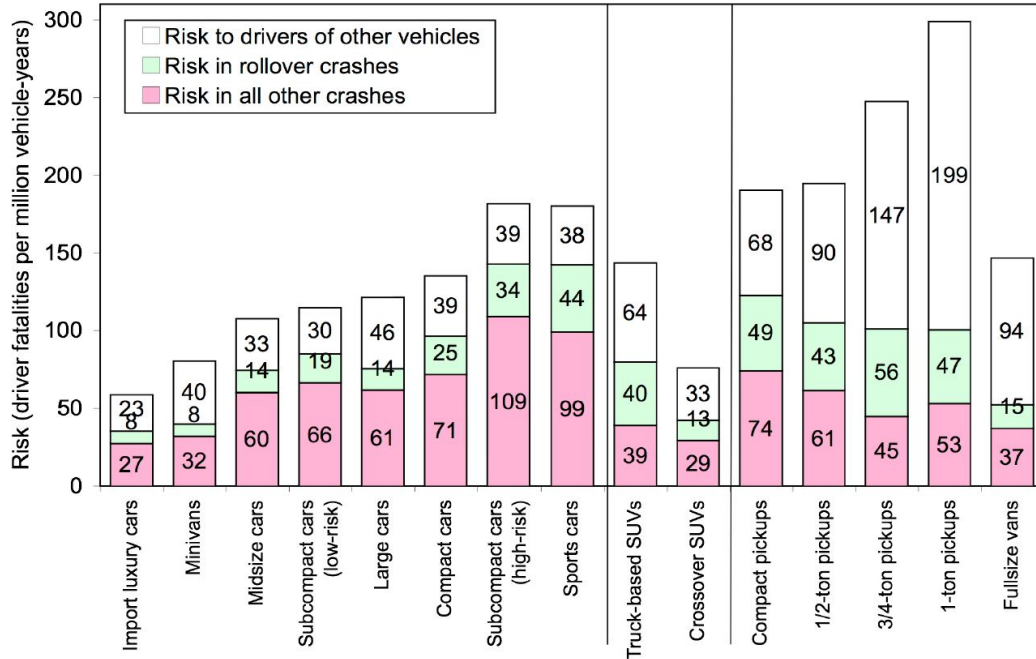


Figure 2.7: Average fatality risk for vehicle types (*Wenzel and Ross, 2008*)

highest aggressivity, the high-risk category of subcompact cars pose the greatest risk to their own drivers, and sports cars and pickup trucks have the highest statistic for rollover deaths. Figure 2.8 shows this information for each of the most popular vehicle nameplates in the U.S., plotting the risk-to-others against the risk-to-drivers in all types of crashes, using different symbols for different vehicle segments.

Using these data, *Wenzel and Ross (2008)* revealed correlations between driver risks and several non-vehicle-specific factors. They observed that males have a higher risk than females, with young male drivers posing the highest risks to themselves. Using a criterion they called “bad driver rating,” defined by driver age, gender, and driving record, they found that driver risk appears to be affected by this rating when looking at certain vehicle types such as minivans and sports cars. Plotting their bad driver rating against risk-to-drivers and fitting a linear regression model revealed a coefficient of determination (R^2 -value) of 0.51, as compared to a value of 0.17 for regressing risk-to-drivers against vehicle mass. Another strong non-vehicle-specific correlation that *Wenzel and Ross* observed is that between fatality rates and

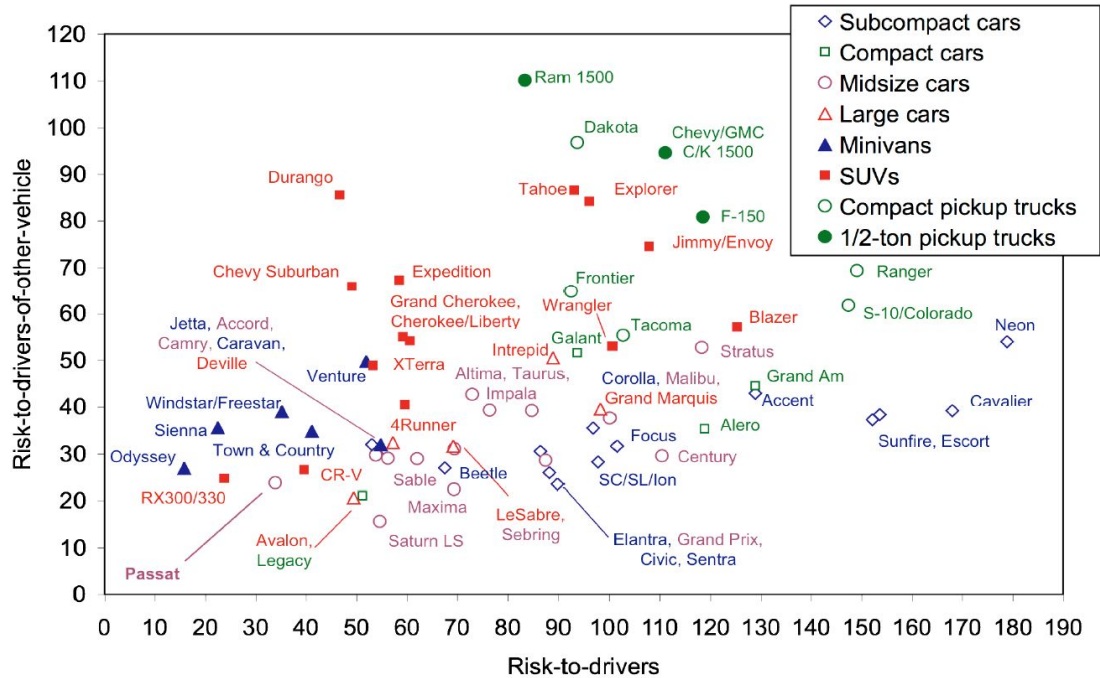


Figure 2.8: Risk-to-others versus risk-to-drivers by individual nameplate; vehicles closest to the bottom-left corner have the best track record for involvement in fatal crashes (Wenzel and Ross, 2008)

population density, which measures the degree to which an area is urban or rural. As population density decreases, risks for driver fatality per vehicle on roadways in that area rise; the authors attribute this trend to poor road conditions and less traffic law enforcement on rural roads.

The strongest vehicle-specific influencing variable found by Wenzel and Ross (2008) was the vehicle resale value after five years, which was fit to a power regression model with an R^2 -value of 0.82. The data are shown with the fit in Figure 2.9, where the individual vehicles are categorized by manufacturer location as U.S., Korean, or Japanese/German. Since this parameter has a much stronger correlation with safety record than vehicle mass, the authors argue that technological improvements, which may add to the price of the vehicle, are much more influential on safety performance than vehicle mass; however, this model does not account for the driver types associated with more expensive cars, who are likely to be more experienced and more

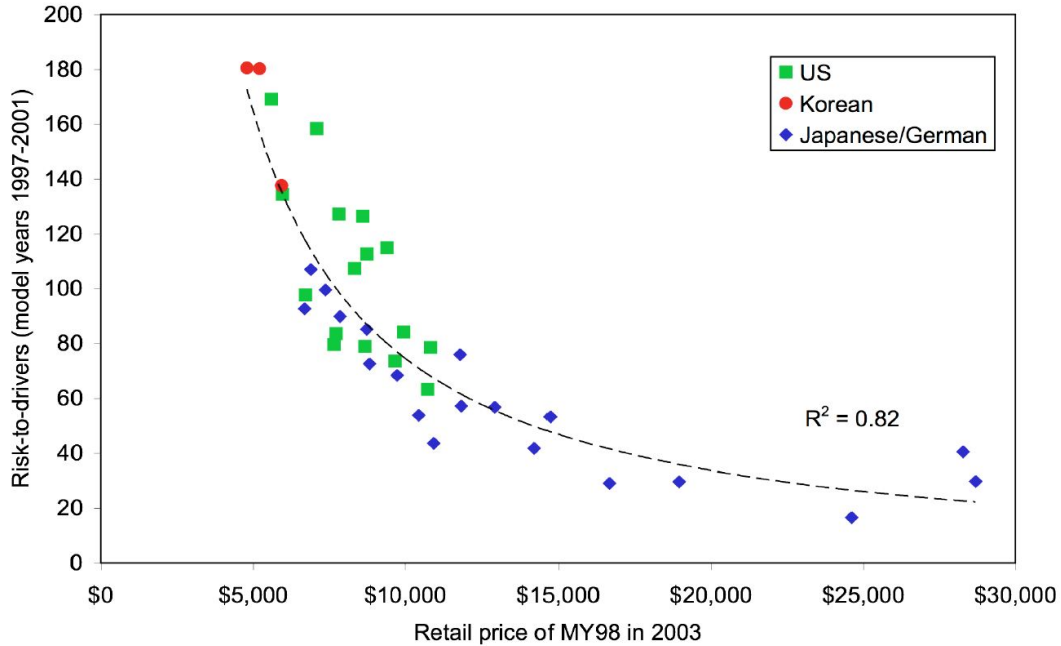


Figure 2.9: Risk-to-drivers versus 5-year resale value of individual nameplates, categorized by manufacturer nationality (*Wenzel and Ross, 2008*)

cautious drivers.

Other researchers have examined and reported on these trends in attempts to understand which vehicle size parameters independent of mass play a significant role in safety statistics. Evans (2004) noted that vehicle size, particularly wheelbase, has an impact on safety that might be viewed in the field data as a mass effect, given that mass and wheelbase are strongly coupled in existing vehicles. He then used empirical models to show that increases in a vehicle's wheelbase coupled with decreases in mass would result in the greatest increase in safety to all drivers on the road. Ross and Wenzel (2001) also studied the relationship between size and safety, finding, too, that wheelbase is more significant than weight for increasing safety. They cited basic physics principles of crash, stating that larger sizes allow for more crush space, which can reduce the acceleration levels experienced by the occupants. Padmanaban (2003) studied the impact of different size variables including bumper height, width, and front overhang size, with his results indicating that the primary design factor impacting

vehicle safety is size rather than mass. Wood (1997) combined the theories concerning mass and size and determined that the important safety variable in collisions between similar vehicles, such as car-to-car or light-truck-to-light-truck crashes, is the vehicle size or length, while the important factor in dissimilar collisions, such as car-to-light-truck crashes, is the vehicle mass.

Compatibility, which is neither an occupant nor a vehicle attribute but rather a crash event attribute, has also been studied in detail to quantify its effect on crash safety. Incompatibility among different vehicle models exists in four different modes, as shown in Figure 2.10: (a) Structural incompatibility, particularly in offset and angled crashes that don't engage the full crush capacity of the structure, (b) mass incompatibility, which is accounted for by conservation of momentum, (c) stiffness incompatibility, which dictates how the vehicles crush against one another, and (d) geometry incompatibility, in which the structural components might not contact one another due to dissimilarities in height or configuration (*Elmarakbi and Zu, 2004*). Crash testing, which is discussed in Section 2.4.3, addresses structural and stiffness incompatibilities to some extent. Some structural incompatibility factors are addressed by IIHS and international NCAP offset crash tests, and improvements are driven by these standards. Stiffness incompatibility of the front end of vehicles is an artifact of manufacturers seeking to maximize performance on these tests, which only simulate vehicles crashing into other vehicles of the same mass and stiffness. Thus, vehicles of higher mass are designed to be stiffer, making them less compatible with vehicles of lower mass.

Much attention has been lent to geometric compatibility in bumper and frame rail height, particularly in North America where light trucks are the most common (*Hermann et al., 2008*); while vehicles that are classified as passenger cars are required by law to provide protection in the region 16 to 20 inches above the ground, usually in the form of a bumper and energy-absorbing frame rails, light trucks have no

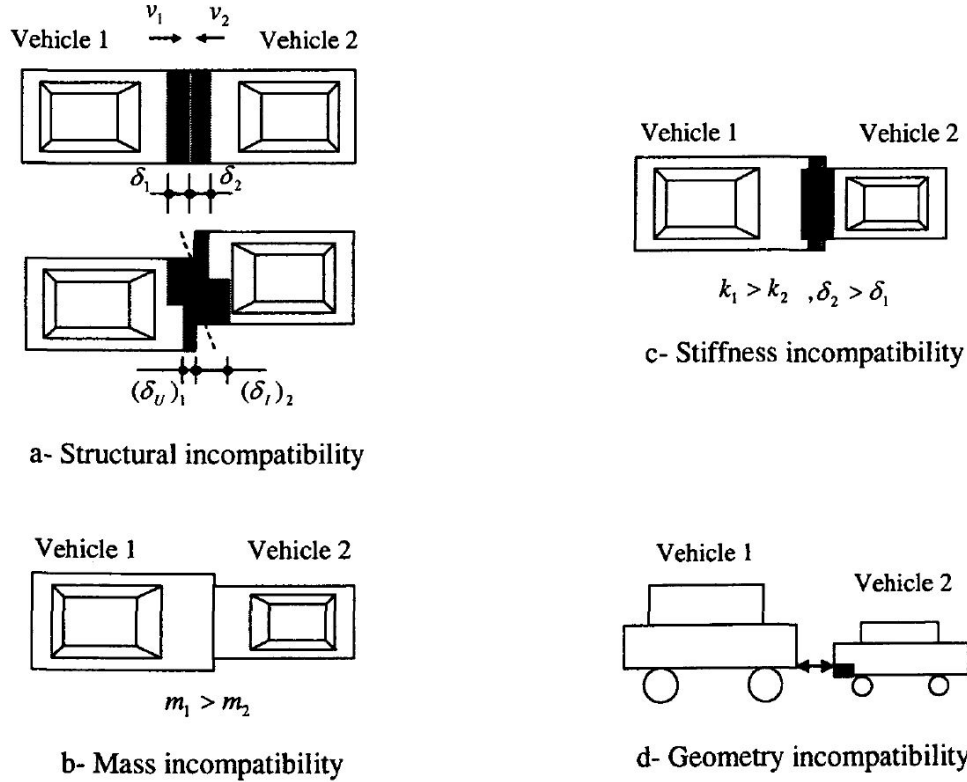


Figure 2.10: Categorization of crash incompatibilities (*Elmarakbi and Zu, 2004*)

such regulation (*NHTSA, 2009*). Due to increasing incidents of bumper height mismatches and pressure from NHTSA, many automobile manufacturers have agreed to the Enhancing Vehicle-to-Vehicle Compatibility Commitment (EVC) (*Barbat, 2005*). This voluntary standard seeks to better align the energy-absorbing structures of light-duty trucks to match the height zone requirement of cars, either through the lowering of the truck primary energy-absorbing structures themselves or the addition of a secondary structure to transfer lower loads to the trucks' energy-absorbing rails. A model by Baker (2008) calculated that if all light trucks were to comply with this standard, fatalities from car-to-light-truck collisions would decrease by 19 percent. As of July 2008, 80 percent of light-duty trucks in production in the United States complied with the terms of the agreement; due to the high levels of manufacturer compliance, EVC is no longer a high-priority initiative of NHTSA (*O'Donnell, 2008*).

The simple mechanics behind mass incompatibility were given in Section 2.3.1

and Equation (2.1), which is a consequence of the law of conservation of momentum and assumes that the colliding vehicles will crumple into one another and act as one mass post-crash. Equation (2.1) shows that a more massive vehicle in a head-on collision would have a smaller Δv than a less massive vehicle would, and its occupants would therefore have a lower risk of injury or death. Joksch (1993) explored this relationship with field data from NASS and developed a “rule of thumb” for a driver’s probability of death in a collision with another vehicle. This relationship is given as Equation (2.3), and it assumes that any collision that results in a velocity change of 71 miles per hour (mph) or more has a 100-percent chance of the driver dying, and a crash with zero Δv has no chance of driver death. The power of four also shows that the rate of change is slow at lower speeds, and it rises rapidly as the crash speed approaches the upper limit of 71 miles per hour.

$$P_{driverdeath} = \left(\frac{\Delta v}{71} \right)^4 \quad (2.3)$$

2.3.4 Military Vehicle Safety

In military ground vehicles, the major threats to drivers and passengers are not due to collisions with other vehicles, but rather they are from artillery fire and underbody explosions. Causes of U.S. military personnel casualties over the past ten years have shifted heavily toward underbody blast events, particularly from improvised explosive devices (IEDs). While much of the data surrounding military threats is classified, limited information is available from government reports and news agencies. According to Department of Defense reporting, approximately 63 percent of the total personnel casualties in the Global War on Terror were caused by explosive devices (*Defense Manpower Data Center*, 2011), motivating research in the areas of ground vehicle blast protection.

An independent organization called iCasualties (*White*, 2011) compiles informa-

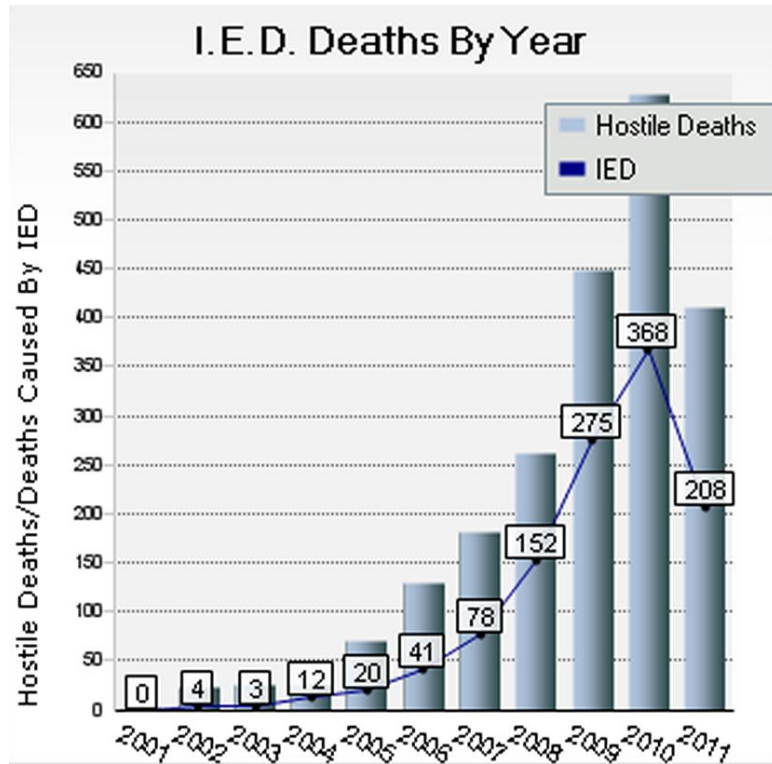


Figure 2.11: Afghanistan casualties caused by IEDs, per year (White, 2011)

tion from multiple news sources and publishes data on coalition fatalities in Iraq and in Afghanistan, categorized by year, month, nationality, province, and in Afghanistan only, IED-related versus non-IED-related. Figure 2.11 shows the numbers of total hostile deaths per year, plotted along with the numbers of fatalities caused by IEDs. The trends show that fatality numbers have increased dramatically over the past ten years of operations in Afghanistan, but also the percentage of those deaths caused by IEDs has increased.

This trend of increased IED threats has led to the replacement of relatively compact multipurpose vehicles, such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV), with larger, more blast-protective ones such as the Mine Resistant Ambush Protected Vehicle (MRAP). Much of the improved blastworthiness of the MRAP is tied to its mass, which is approximately four times that of the HMMWV (Connors and Foss, 2009; Kelly et al., 2011), with a consequent decrease

in mobility and fuel economy. Fuel consumption has long been targeted for improvement by environmental and national security initiatives, but both commercial and military vehicle manufacturers have often considered it a tradeoff with safety. However, recent reports indicate that convoys transporting fuel to military operations have become a major target of adversaries (*Eady et al.*, 2009), with approximately one in twenty-four convoys experiencing a casualty. Thus, using vehicles that consume more fuel might be disadvantageous to broader safety objectives, a subject that will be explored in Chapter VI.

2.4 Improving Vehicle Safety

2.4.1 Safety Technology

In terms of safety technology, the seat belt has seen the greatest success: NASS estimates indicate that over 12,000 lives were saved in the U.S. by seat belts in 2001 alone (*NHTSA*, 2002), and many other studies have demonstrated the positive safety impact of seat belts. A 2001 study reported by NHTSA suggested that front-seat passengers with proper seat belt use have a reduced risk of injury by 45-60 percent (*NHTSA*, 2001). A 1996 study by Turbell estimated that if all of Europe increased its seat belt usage from its then-present rate to 100 percent, 6,000 lives would be saved annually. Based on these results, he advocates the implementation of interlock systems, which disengage the starter when occupants are unbelted, and Turbell claims that the cost-benefit savings of such a system would be 100 to 1 (*Turbell*, 1996). However, the results of the previously-cited studies may be somewhat inflated by the theory that seat belt use is an endogenous variable; seat belt users tend to drive more responsibly than nonusers, resulting in nonusers being involved in more serious collisions and therefore having higher injury rates (*Eluru*, 2007; *Evans*, 2004).

Regardless of whether the data are inflated, the safety belt is widely accepted

as a life-saving device, and many studies have been conducted to design and test improved belt systems. New belt architectures have been studied for their safety benefits, including four-point seat belts (*Rouhana et al.*, 2003) and belt-integrated seats (*Park and Park*, 2001), and belt features like load limiters and pretensioners have been studied and optimized under various crash modes and conditions (*Sieveka et al.*, 2001; *Good et al.*, 2008).

Hou (1995) conducted computational optimization of a General Motors restraint system, using eight design variables describing the airbag, the seat belt, and the seat. He found that the optimal design, when tested in a physical sled environment, reduced the measure of injury probability by 31 percent over the baseline design. This result, of course, is dependent on the frontal crash scenario for which he was optimizing the restraint system, and may not be optimal for other scenarios. Adaptive restraint systems are an emergent technology in some high-end vehicle models, in which the restraint components respond and adjust to occupant and crash characteristics to provide improved protection (*Kent*, 2006, 2007). Restraint system technologies have little impact on the mass or fuel economy of the vehicle, and thus they are a candidate for improving occupant safety in low-mass vehicles without adverse fuel economy consequences.

Various active safety features have emerged in recent decades, which aim to make crashes less severe or even avoid collisions altogether. Anti-lock braking systems (ABS) were one of the first widespread active safety features, which automatically pump the vehicle's brakes to allow more controlled stopping; while the technology is sound and ABS performs well in tests, it has not been statistically shown to reduce crash occurrences or severity (*Burton et al.*, 2004; *Vaa et al.*, 2007). Electronic Stability Control (ESC) is another popular active safety feature, which provides braking to individual wheels to maintain control when the system detects potential for skidding or spinning out. Early estimates by NHTSA and other sources claim that ESC

would reduce crashes and injuries by 34 to 59 percent, annually saving 5,300 to 9,600 lives (*Schewel, 2008; Burton et al., 2004; Vaa et al., 2007*). Zhou (2009) developed and modeled a Post-Impact Stability Control (PISC) system, which is designed to complement ESC technology to mitigate uncontrolled motion of a vehicle after a crash has occurred.

Crash-avoidance technology has advanced significantly in recent years, and certain luxury brands have begun to incorporate new features in their vehicles. Several of these were highlighted in a 2008 IIHS Status Report: Forward collision warning, emergency brake assistance, lane departure warning, blind spot detection, and adaptive headlights. Some of these features use radar to detect the presence of other vehicles and cameras to detect lane boundaries, and they react by either alerting the driver or providing automatic braking or steering corrections (*IIHS, 2008*).

While analysis of these new technologies along with statistics of current driving behavior can often predict significant reductions in crashes, injuries, and fatalities, the statistical impact of the features often show much less benefit. The economics literature explains this phenomenon as customers compensating for safer vehicles by adjusting and adopting riskier driving styles (*Viscusi, 1985*). Peltzman (1975) claimed that because of this effect, regulations have not resulted in decreased highway deaths, but an analysis a decade later by Graham and Garber (1984) suggests that mandates and standards have indeed saved lives, but not as many as the original policy-makers had expected. This idea is defined by Wilde (1998) as “risk homeostasis,” which he argues to be the reason ABS has not shown to reduce collisions; however, critics such as O’Neill (1998) have statistically shown that risk homeostasis does not completely compensate for technological safety improvements. The case of ABS suggests that drivers may be more likely to adjust their behavior in ways that reduce the benefits of technologies when they regularly perceive the effects of those technologies. In contrast, drivers do not see their airbags until after the crash, and there is no evidence

that the safety benefits of airbags or seat belts are offset by a compensatory increase in risk-taking.

2.4.2 Fuel Economy

Significant research is also underway in increasing vehicle fuel efficiency without reducing vehicle mass, which is important for driving improved safety amid more stringent fuel economy regulations and demands. These technologies include aggressive shift logic, camless valve actuation, continuously variable transmission, cylinder deactivation, electric power steering, engine shut-off during idling, torque converter lockup, turbocharging, variable valve lift, and variable valve timing (*Wenzel and Ross, 2008*), as well as other improvements that can be realized with reductions in air drag, engine friction, and tire rolling resistance. All of these technologies increase the cost of the vehicles, and Wenzel and Ross compiled these and plotted them arranged by cost-effectiveness for a variety of vehicle segments, shown in Figure 2.12. The authors claim that these technologies can increase the fuel economy of existing vehicles by over 50 percent in a cost-effective way when gas prices are at 3 dollars per gallon or higher. Alternative fuels and powertrains such as hydrogen fuel cells, homogeneous charge compression ignition (HCCI), hybrid electric, and plug-in hybrid electric can also improve fuel economy without reducing mass, but as of the time of the study they were not cost effective (*Wenzel and Ross, 2008*). A similar compilation of fuel economy technologies was performed by Whitefoot (2011), which she used as a “tech” variable when optimizing over fuel economy, acceleration time, and price.

Researchers have also examined ways to reduce vehicle mass without negative safety consequences. Muser et al. (1996) conducted restraint system optimization of a “low-mass vehicle,” defined by having a curb weight lower than 600 kilograms. They showed that appropriate optimization of restraint systems can allow low-mass vehicles to pass U.S. and European safety mandates. Niederer et al. (1995) investigated a

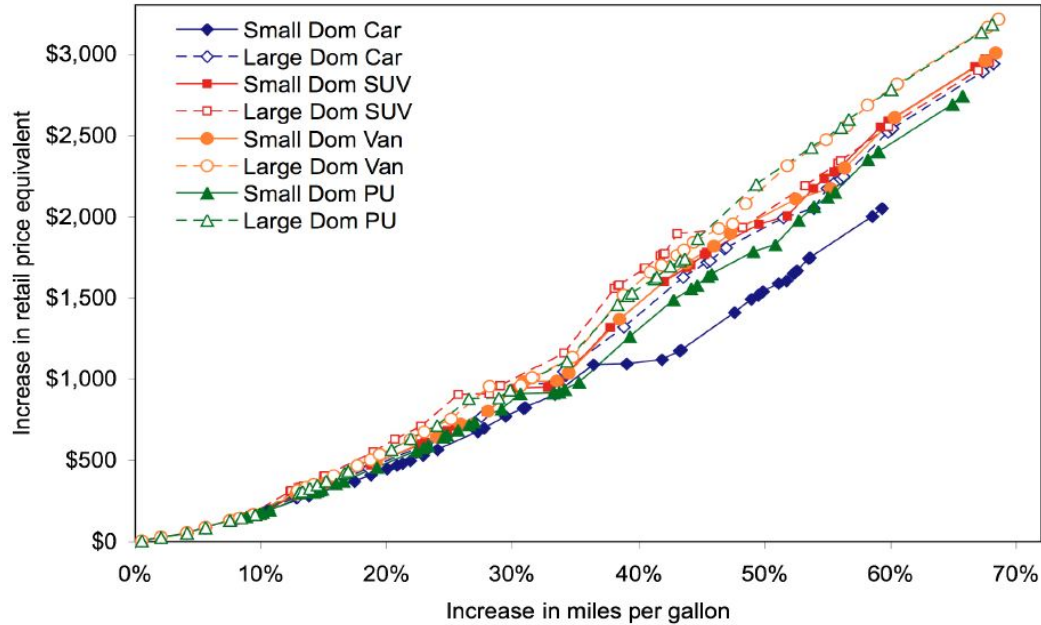


Figure 2.12: Cost estimates for increasing fuel economy in domestic vehicles (*Wenzel and Ross, 2008*)

low-mass vehicle model with a rigid-belt-body structure, which proved to provide adequate protection without presenting compatibility problems due to its stiff front end. Lotus Engineering (2010) analyzed and discussed ways to achieve lightweight vehicles at low costs, and predicted that with the anticipated technology of the year 2020, the Toyota Venza crossover utility vehicle could achieve a 38-percent reduction in mass, excluding the powertrain, for only a 3-percent increase in costs. Based on U.S. Department of Energy estimates, reducing total vehicle mass by 33 percent can result in a 23-percent reduction in fuel consumption (*Lotus Engineering Inc., 2010*), and the Rocky Mountain Institute similarly claims that a 10-percent reduction in mass leads to a 7-percent increase in fuel economy (*Schewel, 2008*). Together, these studies indicate that reducing vehicle mass has the potential to help automakers reach fuel economy regulations without compromising safety, though only if the vehicle and restraint system designs are optimized.

2.4.3 Crash Tests and Standards

Many of these vehicle safety improvements have been supported by legislative requirements and published crash test ratings by governmental and private institutions, though they are typically first developed by automakers and their suppliers. The first such motor vehicle safety legislation worldwide was the U.S. National Traffic and Motor Vehicle Safety Act of 1966, through which the government established a mechanism for imposing safety requirements on automobile manufacturers. Europe and Australia followed shortly after with their own standards (*O'Neill, 2009*). The U.S. Federal Motor Vehicle Safety Standards (FMVSS) promulgated by NHTSA specify hundreds of design and performance requirements that vehicle manufacturers must certify that they meet. For example, vehicles are required to be equipped with steering wheels, seats, airbags, and safety belts meeting certain performance requirements. The FMVSS describe procedures to be used to evaluate the standards. Dynamic performance standards in FMVSS 208 (frontal crash protection) and 214 (side impact protection) specify a number of dynamic whole-vehicle crash tests that are performed using crash dummies to quantify occupant protection.

In addition to test requirements relating to regulation, auto manufacturers take into consideration consumer-information test programs. The first of these, the U.S. New Car Assessment Program (NCAP) emerged in 1987, and was followed by the Australasian NCAP in 1993, the European NCAP in 1996 and the Japanese NCAP also in 1996. Additionally, the IIHS, a private organization in the United States, began a crash test program in 1995. Each of these has a four- or five-point rating system that informs consumers of their probability of being injured in various crash scenarios, and together these have encouraged designers to decrease risks of injury in those scenarios tested.

NCAP and other consumer-information testing has been effective in driving vehicle design improvements, based on the improving scores over the years. However,

some researchers have concluded that the current NHTSA NCAP tests encourage vehicle design that is not optimal in actual on-road crash scenarios. The IIHS has been a leader in assessing the effects of regulatory testing on vehicle design and the consequent effects on safety in the field. O’Neill (2009) discussed how neither the U.S. nor the European NCAP side-impact tests address risks when vehicle intrusions strike the head of an occupant, which is a leading cause of fatal injuries in on-road side-impact crashes. These same tests also fail to address scenarios when vehicles with high front ends such as SUVs and pickup trucks strike the sides of vehicles. However, IIHS testing focuses on these specific scenarios.

A study by Brumbelow (2007) suggests that frontal crash standards in the U.S. have driven manufacturers to install seat belt load limiters that may have actually caused more fatalities in on-road crashes. Load limiters are intended to lessen the forces and accelerations imposed on the occupant by the seat belt by lengthening the belt at certain force thresholds. If these thresholds are set too low, the occupant may impact the airbag with enough force to strike the steering wheel through the bag. Brumbelow argues that automakers have been setting their load limiter thresholds too low in order to perform well on the NCAP frontal impact test, which in turn was detrimental to actual vehicle crash performance. Another recent report by the IIHS (2010) suggested that the FMVSS 208 test requirements for unbelted dummies may result in airbag designs that are less than optimal for the 85 percent of U.S. drivers who are belted (*CDC*, 2011a). These few examples show that existing crash standards may not be optimal for minimizing road traffic injuries.

The analysis presented in Chapter V considers the U.S. NHTSA NCAP frontal barrier crash test, which is a 35 mph, or 56 kilometer-per-hour (kph), full-engagement crash into a flat, rigid barrier. Star ratings are assigned based on measurements taken from a mid-size-male anthropomorphic test device (ATD) seated in the driver seat and a small-female ATD in the passenger seat. Automakers consider this crash scenario

when optimizing the structures and restraint systems of their vehicles.

2.4.4 Safer Military Ground Vehicles

As discussed in Section 2.3.4, today's military vehicle safety considerations place a heavy emphasis on blast protection. This has spurred several innovations, both for avoiding blast events altogether as well as mitigating the impact transferred to the occupants when a blast occurs. An example of the former is the Self-Protection Adaptive Roller Kit (SPARK), which was deployed as an attachment to the front end of HMMWVs and other vehicles (*Borjes, 2008*). This device detonates pressure-sensitive IEDs before the vehicle is above the explosive, thereby reducing the probability that the vehicle or occupants will be harmed in a blast event. This apparatus, however, only addresses explosive threats that are triggered by pressure and does not address remote detonation.

Innovations for mitigating the impact from a blast that is transferred to the occupants are addressed by vehicle manufacturers, which are typically U.S. government contractors. Military vehicle designers focus on two general areas for occupant safety: The vehicle structure itself and the occupant compartment with the seating system. On the structural side, innovations include the development of materials that are better suited to protect against blast threats. Ma et al. (2010) developed a nanocomposite material that has shown to be effective against ballistic and blast threats, and Lockheed Martin has developed a Macro-Composite Protection System with better protection and lighter weight than traditional materials (*Vanbebber, 2006*). Such materials can be implemented in new vehicles to improve safety, but adding mass continues to enhance blastworthiness regardless of the material. Structural design has also seen improvements with v-shaped hulls to deflect blast energy (*Ramasamy et al., 2009*). Occupant compartment design has made similar strides with energy-absorbing seat systems (*Tabiei and Nilakantan, 2007*) and impact-absorbing floor pads such as

Skydex (*Deligio*, 2010).

The North Atlantic Treaty Organization (NATO) published a report that compiled the results of several studies on how forces and accelerations in different body parts correspond with the likelihood of injury (*RTO Task Group 25*, 2007). Since then, researchers such as Champion et al. (2009) and Gondusky and Reiter (2005) have used empirical data to better understand the frequencies of different injury types, but new public standards have not yet been established. The U.S. military standards for new ground vehicles require that occupants have no more than a 10-percent probability of moderate (AIS2+) injury in blast scenarios, as measured by the metrics outlined in the NATO report and discussed further in Section 2.5.3.

2.5 Modeling Vehicle Safety

2.5.1 Physics-Based Modeling

Computational modeling of vehicle crashworthiness has been done for many years, and in recent decades, advances in computational power have allowed higher fidelity models to continually emerge. State-of-the-art finite element vehicle crashworthiness models can have upwards of one million elements and take more than a day to simulate a crash. While these sophisticated models are now widely available, they require a large amount of computational time and resources; depending on the stage in the design process and the desired accuracy of the simulation, lower fidelity models are sometimes preferred.

In optimization, it is necessary to have functions that can be evaluated quickly, and crashworthiness optimization has been done extensively using simplified vehicle models. White et al. (1985) developed and optimized over a one-degree-of-freedom vehicle model coupled with a two-degree-of-freedom occupant compartment model. Kim et al. (2001) used a one-degree-of-freedom model of the front horn of a vehicle,

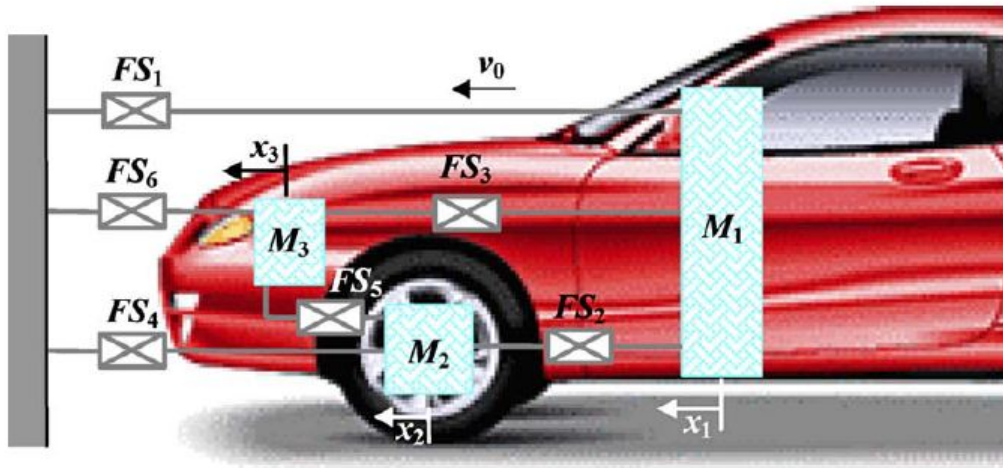


Figure 2.13: Three-degree-of-freedom lumped mass model for vehicle crashworthiness (Marler *et al.*, 2006)

simplified as a lumped mass behind a thin-walled tube being crashed into a wall, to perform optimization. Marler *et al.* (2006) showed the usefulness of optimizing a three-degree-of-freedom lumped mass model, shown in Figure 2.13, in the early stages of vehicle design. Despite the use of highly simplified models, all of the aforementioned studies used response surface methodology for optimization rather than using the models directly.

In the late 1990s, TNO Automotive Safety Solutions collaborated with NHTSA, the European Commission, and the Dutch Ministry of Traffic and Transport to develop a set of multi-body vehicle models in TNO's MADYMO software (Kellendonk *et al.*, 2005). They developed nine different vehicle models from different vehicle classes and makes in order to perform analyses of the vehicle fleet and how changes to front-end structures would change vehicle safety. These models were benchmarked against finite-element models with sufficient validity; their benefits over the more sophisticated finite-element models were that large numbers of crashes could be simulated relatively quickly, and they also contained an occupant and restraint system model inside the vehicle. Thus, large numbers of frontal offset crashes with each

combination of vehicles could be conducted to understand the more general impacts of changes to the vehicle fleet. Chapter III discusses a design optimization approach using the 1995 Ford Explorer from this set of models.

While the previously-discussed models are useful, the most trusted models use finite element analysis to simulate crash events, using a variety of programs including RADIOSS, PamCrash, and LS-DYNA (*Hou et al.*, 1995). The GWU NCAC maintains a publicly-available database of LS-DYNA vehicle crash models of various makes, classes, and years, as well as different levels of fidelity (*Opiela*, 2011). A reduced model of a 2000 Chevrolet C2500 pickup truck in the archive contains ten thousand elements, while a 2001 Ford Taurus model is comprised of over one million elements. These models are typically designed for specific crash scenarios, such as NCAP standards, and they are benchmarked against experimental test results to demonstrate their validity. They do not, however, contain vehicle interiors, seats, or occupant models, and so common practice is to use finite element analysis to obtain a crash pulse, and then input the crash pulse into a multi-body occupant and restraint system model to assess injury criteria. Chapters V and VII discuss optimization using the 2003 Ford Explorer model from this database.

Military vehicle modeling and simulation has followed closely with the progress for civilian vehicles. Among others doing similar studies, Kargus et al. (2008) developed a test methodology and conducted physical experiments with vertical and horizontal shock machines to evaluate the impact of three different seating systems on ATD loading. Bocchieri et al. (2009) proposed a vehicle design framework using physics-based simulations, using a pickup truck-based vehicle model with a separate occupant “sub-model” to separate the vehicle response and the occupant and seating system response. Arepally et al. (2008) in their work considered only the occupant and seating system subsystem, using data from vertical drop tower experimentation to develop and validate a mathematical model for occupant response to blast loading,

and a parametric study was conducted with a range of blast pulses and different seating design configurations. They concluded that the proper implementation of seating system energy-absorbing (EA) devices improved all critical injury criteria with the exception of lower extremity forces, which could be improved with toe pan foam padding.

2.5.2 Crash Biomechanics

Researchers in biomechanics have conducted a great deal of experimental research to understand the mechanisms of injury, particularly under the forces and moments experienced during a vehicle crash event. Research is typically conducted using post-mortem human surrogates (PMHSs) which are commonly referred to as cadavers, anthropomorphic test devices (ATDs), computational models of ATDs or humans, human volunteers, and animals to understand how bodies respond to different types of impact (*Crandall et al.*, 2011). Each of these has its advantages and disadvantages for modeling the response of live humans in crash situations, and a summary of their relative merits is presented in Table 2.2. Cadavers and animals have been used for centuries to better understand human injury mechanisms, whereas human volunteers, ATDs, and computational models have emerged more recently. Researchers use these tools to develop injury criteria that can be measured in an ATD or a computational model to predict the likelihood of particular types of injury.

	ATD	Animal	Models	Human volunteers	Cadavers
Human anthropometry	Yes	No	Yes	Yes	Yes
Human anatomy	Partial	No	Yes	Yes	Yes
Physiologic response	No	Yes	Potential	Yes	No
Testing to injurious levels	Yes	Yes	Yes	Not prospective	Yes
Direct observation of injury	No	Yes	Potential	No	Yes

Table 2.2: Suitability of different types of human surrogates used in injury biomechanics research (*Crandall et al.*, 2011)

ATDs are the most common human surrogates used in regulatory and experimental testing, and models of the most common ATDs have been developed for computational simulation to predict performance in these tests. General Motors engineers developed widely-used ATD models, including the early VIP series of dummies and the later Hybrid I and Hybrid II models (*General Motors*, 1997). The hybrid series are so named because, when they were developed in the early 1970s, they combined the best features of the VIP series and another set of ATDs developed by Sierra Engineering Co. The Hybrid III emerged in 1976 as a joint development between NHTSA and General Motors, and it has since been used in front-impact regulatory testing in the United States. The Hybrid III's main advantages over previous versions are its biomechanically-based head, neck, thorax, and knee covering, along with its human-like seated posture and internal transducers for measuring loads and deflections (*Foster et al.*, 1977). Today, the family of Hybrid III ATDs includes a small female, a large male, and several child dummies along with the original mid-size male.

The U.S. NCAP uses four criteria, as measured in Hybrid III dummies, to assess restraint performance, all of which are concerned with a “serious” injury, defined on the AIS as a level 3 injury or higher (*AAAM*, 1990). These criteria, which are extracted as outputs of occupant and restraint system physical or simulated models, are the Head Injury Criterion (HIC_{15}), the Neck Injury Criterion (N_{ij}), chest compression in millimeters, and femur axial compression in kilonewtons. Each of these has an associated injury curve that yields probability of an AIS level 3 or higher (AIS3+) injury in that body region as a function of the criterion, although the femur injury criterion considers moderate, or AIS2+, injuries. These curves have been derived from laboratory test data (*NHTSA*, 2008), and they are currently used to assess new vehicle star ratings in the U.S. from physical ATD measurements.

Plots of the four injury curves are shown in Figure 2.14; close inspection of the neck injury curve reveals that the minimum possible value is near four percent. This

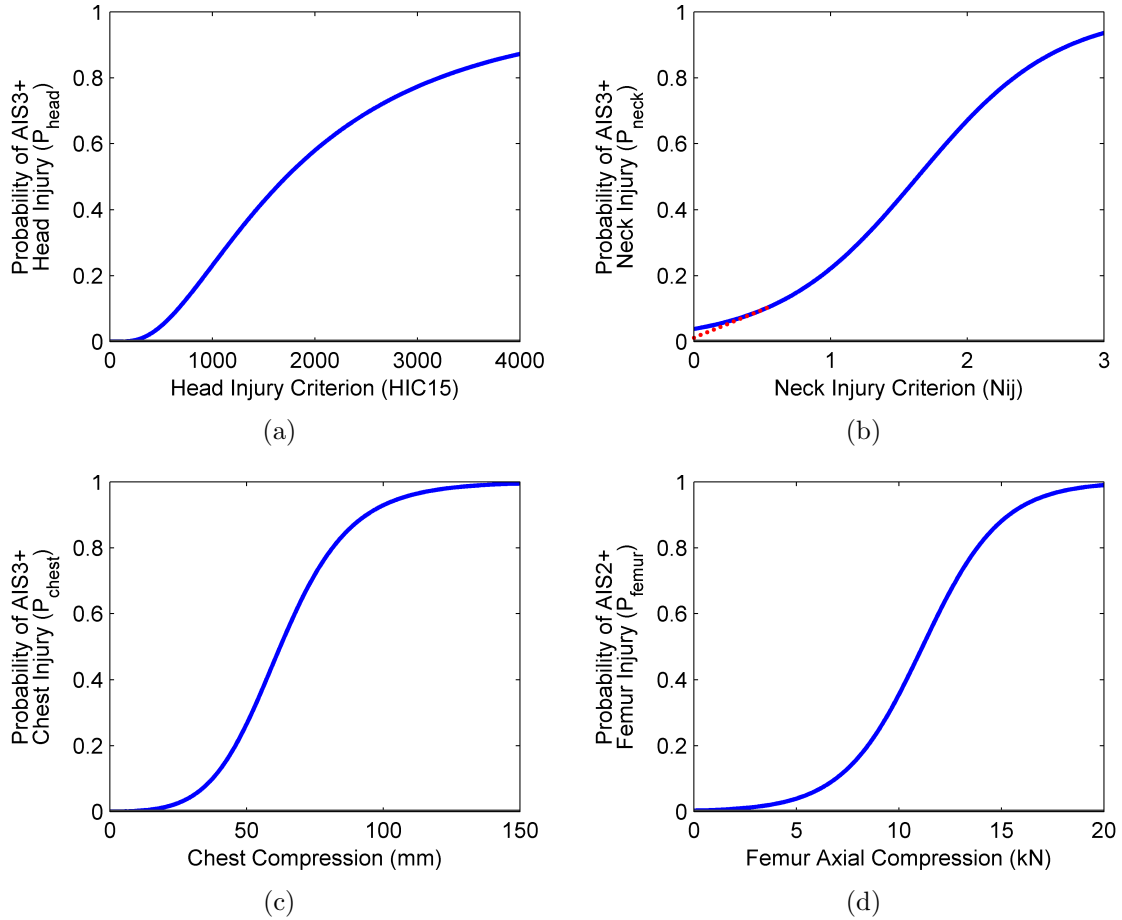


Figure 2.14: NCAP curves representing probability of injury as a function of criteria in the (a) head, (b) neck, (c) chest, and (d) thigh regions

is problematic for predicting injury probability in low-speed crashes, which is done in Chapters V and VII, and so the curve was amended for this study by fitting a line from the origin that intersects the curve on a tangent, shown as a dotted line in the lower-left corner of Figure 2.14b. Neck injury probability is then calculated as a piecewise function using the dotted line when the N_{ij} value is below the intersection and using the solid curve elsewhere.

To combine these four curves and obtain a single probability of injury, Equation (2.4) is used, which yields the overall probability of sustaining an injury in at least one of the four locations. This single value is then used to assign star ratings, and in optimization it is often used as the objective function to optimize manufacturer

design decisions.

$$P_{overall} = 1 - (1 - P_{head})(1 - P_{neck})(1 - P_{chest})(1 - P_{femur}) \quad (2.4)$$

An older set of curves is also used in this dissertation because they are not limited to AIS3+ injury levels; these curves were developed by Prasad and Mertz and include information about injury probability in each body region for AIS2, AIS3, AIS4, and AIS5 injury levels (*NHTSA*, 1995, 1999). While using these curves might provide very different predictions of an occupant's probability of serious (AIS3) injury from the newer functions in Figure 2.14, they can still reveal useful information about the relative probability of injury and how it relates to the different injury severity levels.

2.5.3 Blast Biomechanics

For the reasons expressed in Section 2.3.4, vehicle occupant protection under blast loading is a subject of increasing interest, and many studies have been done by academic and government institutions with aims to improve occupant survivability under explosive threats. Due to the high costs of physically testing the responses of vehicles and occupants to underbody explosions, computational models have been developed to measure such outcomes, which are typically validated using physical experimentation (*Bocchieri et al.*, 2009). Central to the validity of physical and computational tests is the biofidelity of the human dummy models, and much research has gone into understanding how injuries occur to the human body in blast events. Currently, researchers make frequent use of the Hybrid III ATD to measure occupant responses to blast loading, but their conclusions are often questioned because the Hybrid III was not developed or validated for vertical accelerations. Research efforts are underway to develop improved ATDs specifically for blast loading, but to date no new model has been adopted.

2.6 Market Systems: Profit-Driven Vehicle Design

While the objective of this dissertation is to explore methods for *how* to optimize vehicles for maximum safety, it is important to step back and look at *why* companies make the design decisions they do. The answer, as it is for nearly every company in every industry, is to make profits. When the vehicle design process is looked at from a profit-maximization perspective, it is necessary to understand why customers purchase a particular vehicle over another. To address this question quantitatively requires knowledge from engineering to model how design changes impact the performance of the vehicle seen by the customer, knowledge from psychology to model how the customer chooses a vehicle, and knowledge from economics to model the ways that competitors respond to design and pricing changes in an open market. Following the convention established by Georgiopoulos (2003), Michalek (2005), and Frischknecht (2009), this type of problem is referred to as “market systems” modeling and analysis. Frischknecht’s framework is presented in Figure 2.15.

When automakers design vehicles to optimize for safety or any other product attribute, that attribute is no longer viewed as an objective in the market systems framework. Rather, it is internalized as a constraint or as part of the consumer choice model. Customers with perfect knowledge will choose safer vehicles over less safe vehicles, but they may be willing to trade safety for other desirable attributes like price, fuel economy, acceleration speed, or style. So, in a market systems framework, an understanding of how these attributes relate to one another from an engineering perspective is necessary, as well as an understanding of how people make these trade-offs when purchasing vehicles. This section will discuss both of these ideas, starting with an overview of economic game theory modeling to frame the problem of how manufacturers compete in a free (or nearly-free) market.

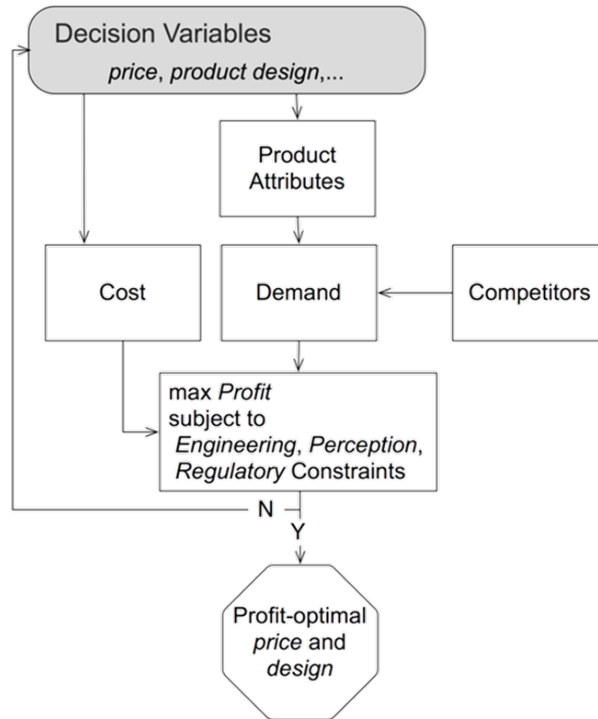


Figure 2.15: Market systems approach for firm profit-driven design (*Frischknecht, 2009*)

2.6.1 Economic Game Theory

Game theory is a widely-used method for assessing strategic decision-making of competing entities. In a dynamic game such as that of the new vehicle market, manufacturers are allowed to continually update their decisions, such as pricing or designs, in order to maximize their utility, depending on available information and time constraints. Firms sequentially respond to the actions of other firms until eventually no further response is strategically beneficial and the market has reached an equilibrium. In the new vehicle market systems framework used in this dissertation, the 2006 U.S. passenger car and light truck market consists of 473 vehicle nameplates from 21 manufacturers. Each of these vehicle manufacturers is allowed to make price changes in response to the actions of other firms, and typically one vehicle of interest from one firm is modified in its design. The firms' objective, profit (π) over a one-year

period, can be formulated as Equation (2.5) (*Frischknecht and Yoon, 2008*), where Q represents the quantity sold, P is the vehicle price paid by the consumer, α_D is the dealer markup as a percentage, and c_v and c_f are the variable and fixed costs of production, respectively.

$$\pi = Q \left(\frac{P}{1 + \alpha_D} - c_v \right) - c_f \quad (2.5)$$

2.6.2 Consumer Choice Modeling

The demand modeling literature includes several different methods for estimating consumer choice as a function of vehicle design and price, and two particular models of interest are described in this section: simple multinomial logit and mixed multinomial logit. Both types of model require an estimate of utility (U_{ij}), or the value that consumer i perceives in product j , which is broken down into systematic utility (V_{ij}) and stochastic utility (ϵ_{ij}) as shown in Equation (2.6).

$$U_{ij} = V_{ij} + \epsilon_{ij} \quad (2.6)$$

That utility is used to estimate the probability that a consumer will choose product j' over all of his or her alternatives, given by Equation (2.7).

$$\Pr(j') = \frac{e^{V_{j'}}}{e^{V_{og}} + \sum_{j \neq j'} e^{V_j}} \quad (2.7)$$

Here, V_j is the systematic part of utility for consumer i choosing vehicle j and V_{og} is the utility of the outside good, i.e., the utility of not choosing any vehicle from the market (*McFadden, 1974*). The numerator accounts for the utility of the particular vehicle of interest, while the denominator considers the utility of all other choices, including the other vehicles on the market as well as the outside good.

This value can be used to estimate the quantity demanded of vehicle j by multi-

plying the probability of a consumer choosing that vehicle by the size of the market M , as in Equation (2.8).

$$Q_j = M \times \Pr(j) \quad (2.8)$$

A simple logit model is “simple” in that it does not account for heterogeneity in consumer taste, i.e., every consumer follows the same distribution of product preferences. A general form of systematic utility (V_{ij}) for a simple logit problem is given as Equation (2.9), where β_{ik} is the coefficient that relates consumer i to attribute k and z_{jk} is the matrix of products j with attributes k .

$$V_{ij} = \sum_{k=1}^K \beta_{ik} z_{jk} \quad (2.9)$$

Mixed logit modeling accounts for not only product attributes, but also individual demographics, interactions between product attributes and demographic characteristics, and other factors. Frischknecht (2009) employed three separate mixed logit models, and the original was adopted from a (1995) paper by Berry et al., which included factors for price, fuel economy, acceleration time, and style. This model, as well as two additional models developed by Frischknecht, follow the utility function of Equation (2.10).

$$V_{ij} = \delta d_j + \beta b_{ij} + \mu_i m_{ij} \quad (2.10)$$

Here, V_{ij} is again the systematic component of utility that consumer i perceives in product j , d_j is a linear combination of product attributes for each vehicle j and δ its corresponding fixed preference coefficient, b_{ij} are the interactions between consumer i 's demographics and product j 's attributes with β the fixed effect coefficient, and m_{ij} are the random interactions between consumer i and product j with parameter μ defined on a consumer basis.

Frischknecht employed both types of models and demonstrated the advantages

of different types of mixed-logit demand models (*Frischknecht et al.*, 2011). In Chapter VII, a simple logit model is constructed and employed following Equations (2.6), (2.7), (2.8), and (2.9).

2.6.3 Safety-Related Consumer Choice

While researchers have postulated many phenomena regarding the relationships between safety and sustainability in design practice, it is important for automakers and designers to understand how consumers view these attributes when purchasing a new vehicle. Sustainability is often judged simply by the miles-per-gallon (mpg) rating reported on the sticker, but safety is more difficult for consumers to quantify. In the United States, NHTSA and IIHS both conduct standardized crash tests on some of the most popular vehicle models each year, the former reporting results on a five-star scale, and the latter rating vehicles on a four-point, qualitative scale from “good” to “poor.” A study by Pruitt and Hoffer (2004) found that there is no evidence to link NHTSA and IIHS crash ratings with increased sales or demand. However, other studies have revealed considerable consumer interest in safety, but most research shows that price, appearance, and reliability are apparently more important than safety (*Koppel et al.*, 2008). A recent American survey about safety features reported that the five most important safety attributes in a new vehicle purchasing decision are front airbags, ABS, traction control, crumple zones, and side airbags (*The Dohring Company*, 2007).

A European survey of Spanish and Swedish prospective car buyers shows that safety is the most important of fifteen vehicle attributes inquired about (*Koppel et al.*, 2008). When asked to list the top three factors considered in a vehicle purchase decision, 36 percent of Swedish respondents and 19 percent of Spanish respondents listed safety as their number-one factor. When later given a list of fifteen factors to rank the importance of in purchase decisions, the EuroNCAP score was ranked first

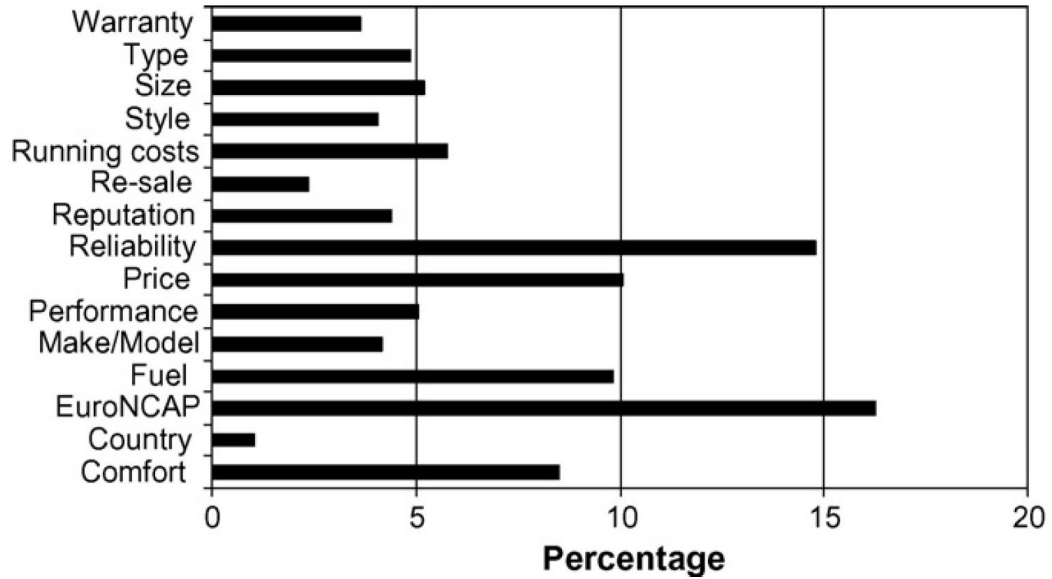


Figure 2.16: Factors ranked as “most important” by survey takers when considering a new vehicle purchase decision (*Koppel et al., 2008*)

by 16 percent of respondents, as shown in Figure 2.16. Notably, the trends seen in the Spanish market and the Swedish market exhibited considerable differences, and these results cannot be applied to the American market without further research. The broad results of these studies suggest that consumers look for the presence of specific safety features rather than the effectiveness or quality of standard items like seat belts and body frames, and the degree to which they value these components is not yet fully understood.

In recent work on the perception of sustainability from a vehicle’s shape or silhouette, Reid et al. (2010) show that perception-based attributes can be quantified in a systematic manner, and they are useful for creating new and improved designs. Early results from Reid et al. show evidence that vehicle shapes play a role in perceptions of safety as well, and such perceptual modeling could also be incorporated to forecast demand.

2.6.4 Engineering and Cost Modeling

Another important aspect of the profit-maximization formulation is to understand how design changes impact production costs and the design attributes seen by consumers. Costs of production are embedded in the profit calculation of Equation (2.5), where variable costs (c_v) are multiplied by the quantity sold (Q) and the fixed costs (c_f) are treated as independent of quantity. Two popular cost modeling techniques that can be used in a market systems framework include a “top-down” approach, where the prices and invoices of existing vehicles are gathered to estimate the marginal costs of different attributes, and a “bottom-up” approach, where all of the fixed and variable costs of materials and production must be estimated. A bottom-up approach requires a large amount of reliable information that is generally not available to individuals outside of the companies who actually produce vehicles, and so top-down approaches are more suitable to those outside the industry.

Finally, engineering models are used in market systems to understand how the choices of designers influence the attributes seen by consumers as well as the regulatory requirements imposed by governments. An example of a design change is the engine cylinder bore diameter, which would influence design attributes such as fuel economy, acceleration performance, and the size of the vehicle. Consumers typically don’t consider bore diameter when shopping for new vehicles, but the attributes listed generally play a role in the purchase decision. This necessitates engineering models, which may take the form of computational simulations of performance or regression equations, to be integrated with marketing and economic models to study how design changes ultimately impact consumer choice as discussed in Section 2.6.2.

CHAPTER III

Simulation Tools for Crashworthiness and Vehicle Mass Optimization

*“As far as the laws of mathematics refer to reality,
they are not certain, and as far as they are certain,
they do not refer to reality.”*

-Albert Einstein

3.1 Introduction

A major challenge in automotive design is the creation of safe vehicles with minimal environmental impact. Whereas Section 2.3 reported on statistics and trends regarding the safety and sustainability impact on society that motor vehicles have, this chapter addresses the vehicle design perspective. Particularly, methods are shown for modeling these impacts on society using engineering tools, and preliminary results demonstrate the conflict and potential tradeoffs in the requirements for safety and sustainability.

In a typical vehicle design process, the engineering of the crash performance of the front structure of the vehicle occurs prior to the specification of the restraint system components. Structural engineers work to produce a desired crash pulse, or acceleration versus time profile, through design of the bumper, frame rails, and

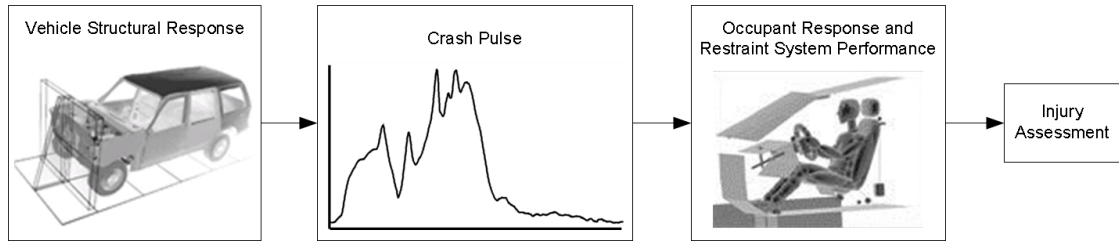


Figure 3.1: Typical vehicle safety design process

hood supports. Occupant restraint engineers work with the crash pulse from the structural engineers to optimize the restraint system, manipulating variables such as airbag deployment timing and inflation characteristics, belt anchorage locations, belt pretensioning and load limiting, and knee bolster location deflection characteristics. Relatively little opportunity is available for occupant restraint system design to influence the optimization of the vehicle front structure. In particular, many of the component choices that affect restraint system cost are made after the vehicle structure has been designed, per the design process shown in Figure 3.1.

An integrated modeling and optimization approach that accounts for interactions between structural and restraint system designs would be useful to quantify the impact of sustainability-driven weight reduction on occupant safety in early vehicle design decisions. This chapter outlines the development of such an integrated approach to evaluate and optimize vehicle designs with respect to occupant safety and fuel economy, with mass being the main link between the two. Three different types of modeling are presented and used for optimization, all of which include both automotive structure and restraint system variables. The focus is on methods and design trends rather than numerical values and specific recommendations. Preliminary design optimization results are outlined and discussed, and the relative merits of more advanced modeling techniques are evaluated.

3.2 Modeling Approach

A simulation-based modeling environment is developed here for understanding the safety and sustainability implications of individual vehicle design decisions. The decision model is developed as a bi-objective optimization formulation to minimize the probability of a severe injury (P_{AIS3+}), as defined on the AIS with a rating of 3 or higher, and to maximize the fuel economy (FE) in mpg. The probability of injury calculation is based solely on the NCAP 35-mph frontal barrier crash test, and the fuel economy calculation uses the FTP-75 federal urban drive cycle. This optimization formulation is shown generically as Equation (3.1).

$$\begin{aligned} & \underset{x}{\text{minimize}} && \{P_{AIS3+}(x), -FE(x)\} \\ & \text{subject to} && x - x_u \leq 0 \\ & && x_l - x \leq 0 \end{aligned} \tag{3.1}$$

The optimization problem is subject to constraints imposed as upper (x_u) and lower (x_l) bounds on the design variables (x), which represent structural and restraint system variables such as component mass, stiffness, and airbag and seat belt properties. Preliminary models have been constructed based on a compilation of software programs: MADYMO (*TASS Safe*, 2010) is used to simulate and measure occupant safety, AVL Cruise (*AVL*, 2005) is used to calculate fuel economy, and MATLAB (*The Mathworks*, 2010), OPTIMUS (*Noesis*, 2008), and R (*Venables et al.*, 2010) are implemented for model integration, post-processing, and optimization.

3.2.1 Multi-Body Vehicle Crashworthiness Models

The safety modeling approach taken in this study uses the full-vehicle MADYMO model of a 1995 Ford Explorer developed and validated by the U.S. NHTSA and



Figure 3.2: MADYMO-based vehicle simulation model of a 1995 Ford Explorer with mid-size male occupant

TNO described in Section 2.5.1, linked with the previously described OPTIMUS software package. The model is shown in Figure 3.2. These vehicle models use rigid bodies connected with variable joints for the majority of the vehicle structure and restraint system, and include some finite-element components where higher fidelity is needed, such as in the airbag. Using rigid body dynamics to compute the vehicle response, computational time is reduced substantially: Preliminary studies showed that the frontal barrier test simulations using rigid body dynamics models had a reduction in computational time over full finite-element models by a factor of 150 to 300. This is particularly advantageous due to the need for testing large numbers of design configurations in a reasonable amount of time; however, this comes with a potential loss in model fidelity. Therefore, crash responses are also investigated in Section 3.4.2 using LS-DYNA, a finite-element modeling tool widely accepted in the crashworthiness research community.

3.2.2 Fuel Economy

As a measure of sustainability, the model looks only at fuel economy, which accounts for roughly 85 percent of the life-cycle emissions of an automobile (*Keoleian et al.*, 1997). To model sustainability better in future studies, this measure could

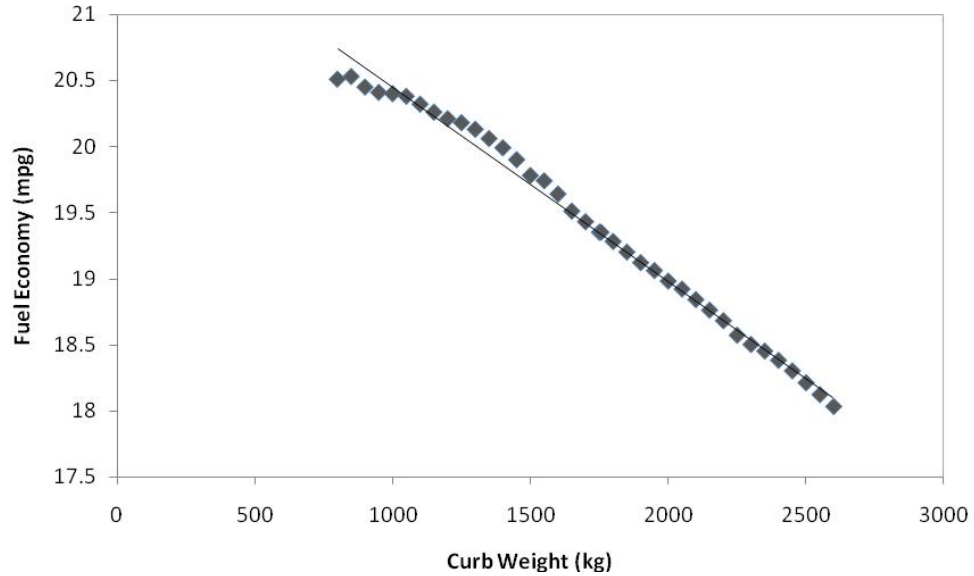


Figure 3.3: Fuel economy vs. curb weight

be expanded by conducting a life-cycle assessment to gather information about the impact of raw material extraction, processing, transportation, manufacturing, and disposal. The current model measures fuel economy using AVL Cruise 3.1 (AVL, 2005) to simulate the U.S. FTP-75 urban drive cycle (EPA, 1993). Cruise was chosen for its capability to rapidly assess vehicle designs for numerous criteria of interest, including drive quality, emissions, fuel consumption, and performance; while the current model only considers fuel consumption, the additional capabilities of Cruise will be useful if the framework is to be extended.

The only relevant variable that links the fuel economy performance of a vehicle with its crash test performance was determined to be the curb weight, or unloaded vehicle mass, and so fuel economy is represented as a function of vehicle mass. After running a batch of simulations varying the vehicle mass from 800 to 2600 kilograms, it was observed that the relationship between mass and fuel economy is essentially linear, and the model is simplified using a least-squares linear regression fit with a coefficient of determination (R^2 -value) of 0.99. The data and regression fit are shown in Figure 3.3, with the linear equation presented as Equation (3.2).

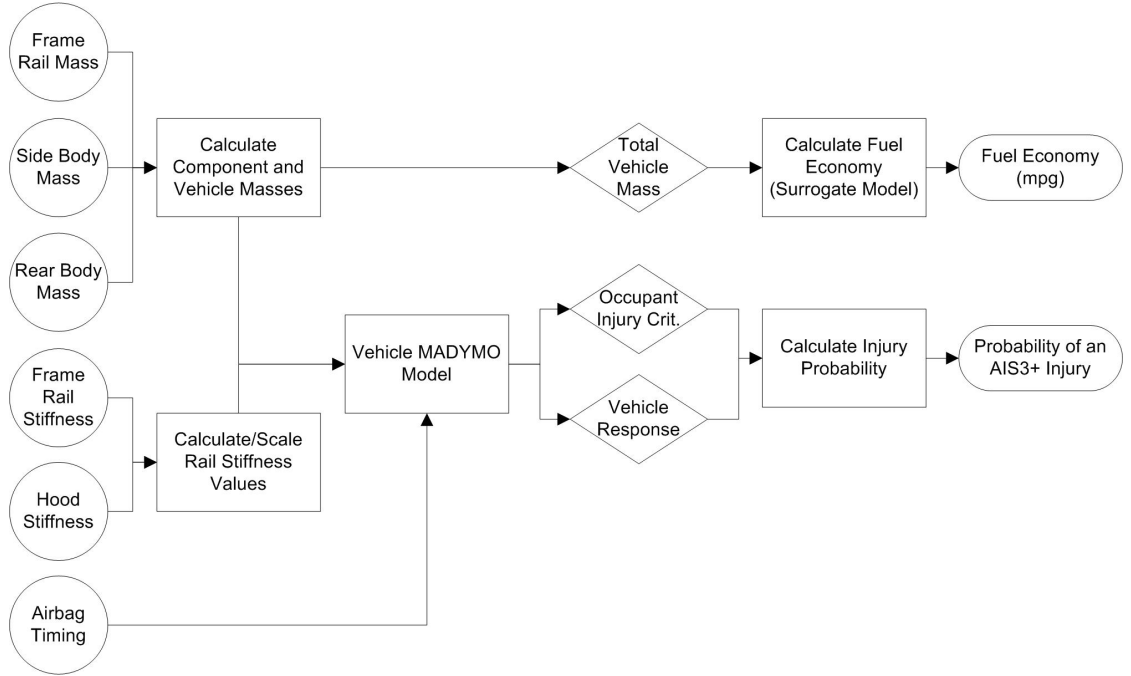


Figure 3.4: Integrated model process flow diagram

$$FE = 21.91 - 0.0015m \quad (3.2)$$

This fuel economy model is next connected with the safety model using OPTIMUS 5.2 (Noesis, 2008), which facilitates model integration and optimization studies. The developed model calculates the outcomes of a given design configuration by calling the safety software package for each design, determining the safety outcome from the simulation, and using the linear surrogate model derived from AVL Cruise for fuel economy based on vehicle mass.

3.2.3 Combined Model

The separate occupant safety and fuel economy models were combined using the Noesis OPTIMUS software package (Noesis, 2008). The model incorporates six input variables that affect vehicle mass, frontal crush properties, and restraint system behavior, and it yields output values that represent the safety and fuel economy performance characteristics. A diagram of the process flow is presented in Figure 3.4.

Three separate mass variables are included to represent changes in mass of different physical areas of the vehicle. The rear body mass is the largest mass component in the MADYMO model, accounting for roughly half of the total vehicle mass with 992 kilograms. The side body mass and frame rail mass variables each control dozens of smaller mass components; the OPTIMUS model scales all of these component masses proportionally by a scaling factor between 0.5 and 2.0, where 1.0 is the baseline value. By allowing explicit changes to the mass property itself, the assumption is that any part of the vehicle mass can be feasibly reduced or augmented without significantly modifying other structural or material properties. The other major structural properties that are modified are the stiffness of the frame rails and the hood support beams, both of which also use a scaling factor to modify the entire stiffness profile. Since this model uses rigid bodies, the stiffness is represented as a characteristic of the joints connecting each pair of rigid ellipsoids. This framework therefore assumes that this technique is a valid representative of modifying the stiffness properties of the frame rail material, which is actually a continuum rather than separated rigid bodies, and it also assumes that stiffness properties can change independent of other material properties, including mass. A final variable is the timing of the airbag release mechanism, and while this has little or no effect on the structure or complexity of the vehicle design, it exemplifies an independent restraint system variable that is expected to affect occupant safety.

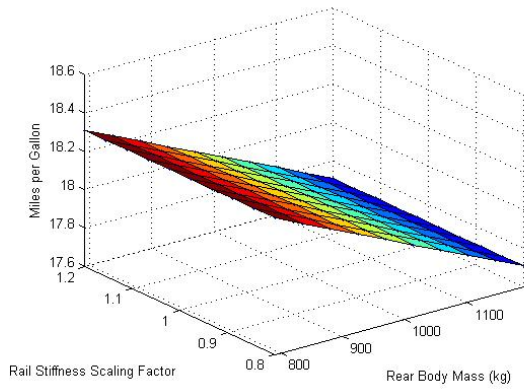
The outputs of the model are vehicle fuel economy and a single probability criterion for occupant safety. MADYMO generates output files with data on forces, torques, accelerations, and deformations throughout the dummy body as well as the vehicle structure. The integrated model uses several of these outputs, namely two head injury criteria (HIC_{15} and HIC_{36}), neck tension-extension (N_{TE}), peak chest acceleration (3ms clip, m/s), peak chest deflection (m), peak vehicle acceleration as measured on the driver-side door sill (m/s), and toe pan intrusion (m) to compute a

single occupant safety metric. Specifically, the probability of an injury that is rated 3 or higher on the AIS is calculated in four areas of the body using normal distribution data from Laituri (2003; 2006). Using these numbers, a calculation of the combined probability of a driver receiving any injury rated as “serious” or worse is found using Equation (2.4).

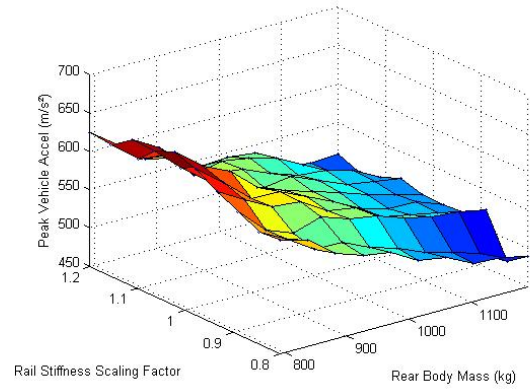
3.3 Results

Sensitivity analysis on the six design variables concluded that the hood stiffness did not have a significant effect on the outputs of interest, and the effects of the three mass variables had little differentiation. Since it represents the majority of the total vehicle mass, the rear mass was chosen to be modified as representative of vehicle mass. In preparation for subsequent optimization work, three computational design of experiments (DOE) studies were conducted using the integrated model. The first DOE study investigated the safety and fuel economy consequences of varying only the rear mass and the frontal frame rail stiffness. A second DOE study was conducted with airbag timing incorporated as a third variable. The results of each of these first two investigations were used to generate least-squares regression-based response surfaces, which were then utilized to conduct a preliminary multi-objective optimization study. An additional study investigated the behavior of the vehicle and the occupant response under changes in mass throughout the vehicle.

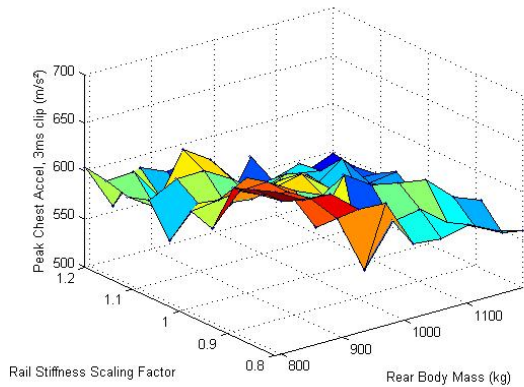
The first study investigated the relationships among the rear body mass (m_{rear}), the frame rail stiffness (s), and the output criteria; a 100-point, full-factorial DOE study was conducted over the design space of these two variables. Due to the underlying models, the trend for fuel economy is only dependent on mass and remains constant where the mass does not change, as shown in Figure 3.5a. Another clearly visible trend is for the peak vehicle acceleration: Shown in Figure 3.5b, there is steady decrease in acceleration with increasing mass values, whereas stiffness variance effects



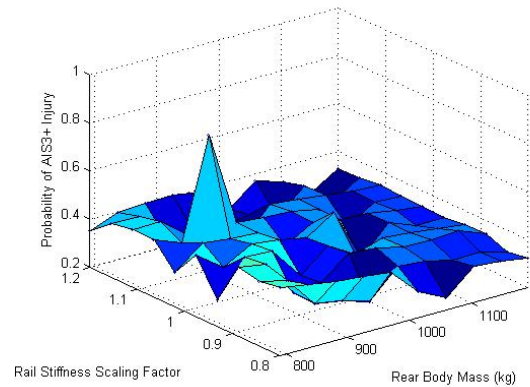
(a)



(b)



(c)



(d)

Figure 3.5: Plots of 100-point DOE varying rear mass and frontal rail stiffness

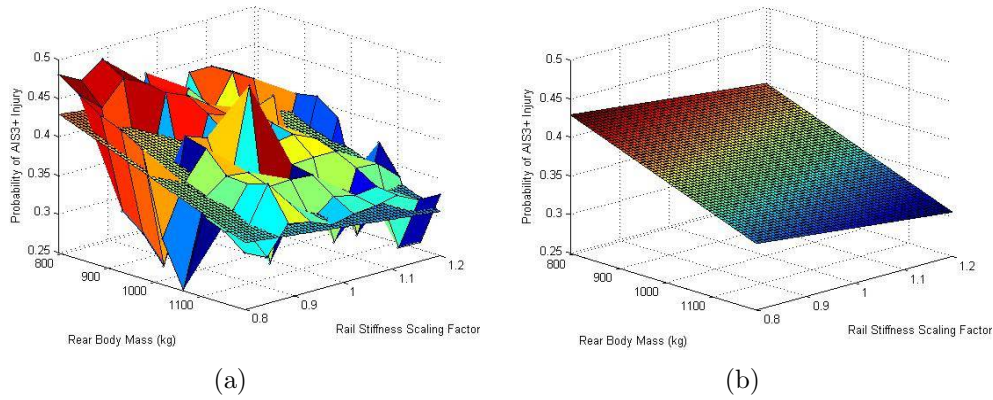


Figure 3.6: Linear response surface for PAIS3+; (a) superimposed on data, and (b) unaccompanied

are subtler. The two plots in Figures 3.5c and 3.5d show the chest acceleration (3 ms clip) and the probability of severe injury over the design space, respectively. The data concerning occupant injury represented in Figures 3.5c and 3.5d are noticeably irregular, yet there are still apparent trends that seem to correspond with the vehicle acceleration; as the mass increases, the chest acceleration and the probability of injury decreases, while the stiffness does not have an obvious effect on the response. This type of irregularity in data is common when using finite-element vehicle models or full-scale physical ATDs, but it poses challenges when the user intends to use gradient-based optimization algorithms. Therefore, response surfaces are necessary for design optimization studies.

An orthogonal least squares regression was established with a linear fit using the injury probability data from Figure 3.5d, and Figure 3.6 shows a plot of the response surface. The obvious outlier from Figure 3.5d has been removed from the data, and the linear response surface seems to represent the general trend observed in the data adequately. Quadratic and cubic polynomial response surfaces were also generated, but the corresponding R-squared values were not sufficient to justify their selection over a linear response surface. Equation (3.3) characterizes the obtained linear response surface.

$$P_{AIS3+} = 0.6713 - 0.0002326m_{rear} - 0.07236s \quad (3.3)$$

As a first step towards an integrated approach to structural and restraint system design, the second DOE study includes airbag release time as a design variable. A DOE study was conducted to obtain injury probability values as a function of rear mass (m_{rear}), rail stiffness (s) and airbag firing time (t). Since the baseline model released the airbag 15 milliseconds into the crash, a range from 5 to 25 milliseconds was considered. The obtained DOE results showed that the best airbag release time for a given configuration is different for each design configuration, confirming the hypothesis that restraint system variables should be simultaneously optimized along with the structural variables. A bilinear response surface fit the data best relative to linear and quadratic alternatives, and the response surface is given in Equation (3.4).

$$P_{AIS3+} = 1.8 - 0.001m_{rear} - 1.1s + 4.8t + 0.001m_{rear}s - 0.001m_{rear}t + 7.8st \quad (3.4)$$

Using the generated regression models for fuel economy and probability of severe injury, a bi-objective optimization problem was formulated as shown in Equation (3.5). The Pareto set generated by solving this equation is shown in Figure 3.7. It quantifies the tradeoff that exists between injury probability and fuel economy given the particular problem formulation and modeling.

$$\begin{aligned} & \underset{m_{rear}, s, t}{\text{minimize}} && \{P_{AIS3+}(m_{rear}, s, t), -FE(m_{rear})\} \\ & \text{subject to} && 792 \leq m_{rear} \leq 1192 \\ & && 0.8 \leq s \leq 1.2 \\ & && 5 \leq t \leq 25 \end{aligned} \quad (3.5)$$

A third set of simulations was conducted to examine the changes in the acceler-

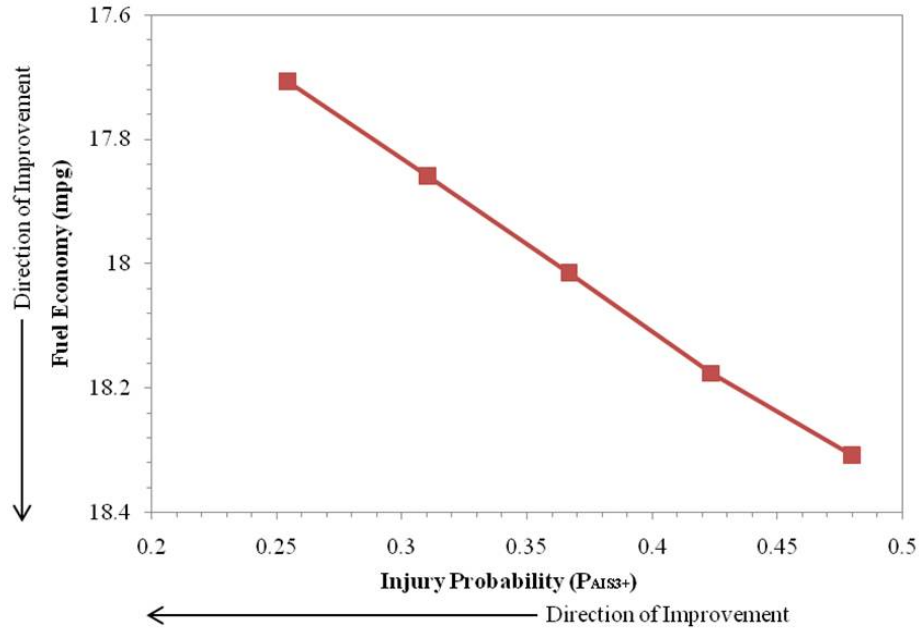


Figure 3.7: Pareto frontier for bi-objective optimization

ation profiles as the total vehicle mass shifts. Five simulations were conducted: The first had rear, side and frame masses uniformly scaled so that the vehicle is 20 percent less massive than the baseline case, the second with the mass values scaled down by 10 percent, the third being the baseline case, and the fourth and fifth with masses scaled up by 10 and 20 percent, respectively. The acceleration pulses as measured on the driver side door sill and on the driver’s thorax are shown in Figure 3.8a and Figure 3.8b, respectively. In both plots, the curve with the highest peak represents the lightest vehicle and the lowest curve represents the heaviest vehicle.

Examination of the plots in Figure 3.8 reveals two important behavior aspects of the model. The first can be seen from examining Figure 3.8a, where it is evident that the highest acceleration in the lighter two cases occurs near the first “peak” near 45 milliseconds, and the peak acceleration in the heavier cases occurs closer to 60 milliseconds, or at the second peak. This “peak shifting” may account for non-uniform behavior when observing any peak acceleration criteria as it changes over different vehicle designs. A second behavior of note is seen in Figure 3.8b, where the thoracic

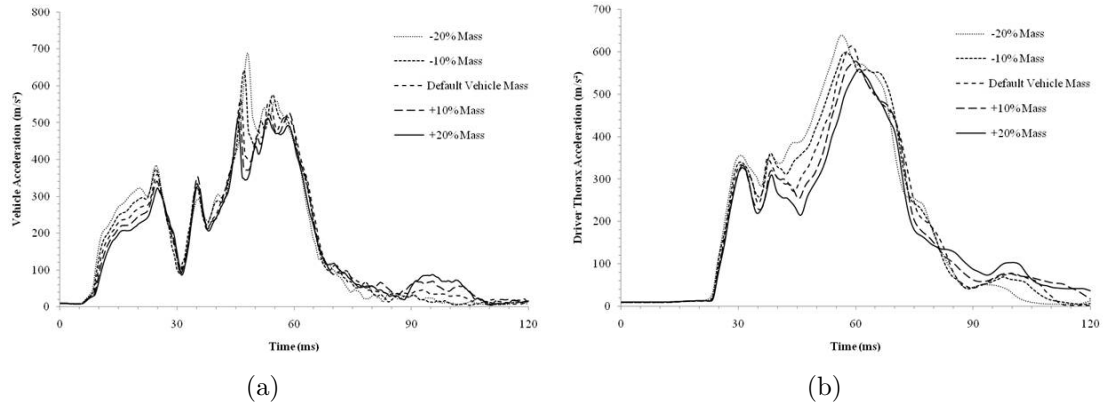


Figure 3.8: Acceleration vs. time with varying mass of (a) vehicle and (b) driver thorax

peak acceleration does not follow a linear trend from the heaviest to the lightest vehicle, but there is an unexpected higher value on the default case acceleration curve. This is indicative of the irregularities seen in the plots of Figure 3.5, and it shows that although the vehicle is responding as expected, dummy interactions with different body parts or vehicle components can have significant effects on the model response; for example, the dummy’s head may slip around the airbag and strike the steering wheel or dashboard. These nonlinearities in simulation outcomes demonstrate that dummy contact or non-contact with a particular vehicle structure can produce sharp changes in dummy response as the independent variables are manipulated.

Preliminary results using the described optimization approach support the hypothesis of the existence of a relationship between safety and sustainability, and thus the need for an integrated approach to modeling and optimization. A comprehensive formulation built upon this framework could provide designers with a preliminary quantitative understanding of how their decisions will affect the performance of a vehicle line.

An additional study was conducted to see the impact of engine design on vehicle crashworthiness. It was hypothesized, based on basic crash mechanics, that a smaller engine would yield greater crush space under the hood, which would allow for

a smoother deceleration profile and lower occupant injury probabilities. The modification of bore and stroke to the engine characteristics would impact the length and mass of the engine, and in the AVL model, these two variables would have an additional impact on fuel economy; however, this effect was neglected. The results of the study show no significant difference when the length of the engine changes over a range of 355 to 490 mm; in fact, the correlation shows a slight relationship suggesting that longer engines yield lower peak vehicle accelerations, which is the opposite of the anticipated effect. Upon inspecting the animation output files from the multi-body dynamics simulations, it appears that the deformation of the front end is the same distance regardless of the engine length, and two of these vehicles with engines of different length are shown in Figure 3.9. This indicates that more complex structural changes are needed to see an increase in actual crush space, and these rigid-body models were deemed inadequate for making such changes without compromising validity.

3.4 Alternative Approaches to Safety Modeling

The safety modeling approach described in Section 3.2.1 using a multi-body full-vehicle model had two clear disadvantages: The first is that the results had irregularities that may be due in part to the crudeness of the models, and the second is the criticism that came with using these less valid vehicle models. This section presents two alternative approaches that require more computational time, but provide more meaningful results.

3.4.1 Multi-Body Vehicle Models Linked With Dedicated Restraint System Models

Upon further inspection of the multi-body vehicle model, it became clear that the seat belt and airbag models were over-simplified. Since the main source of the

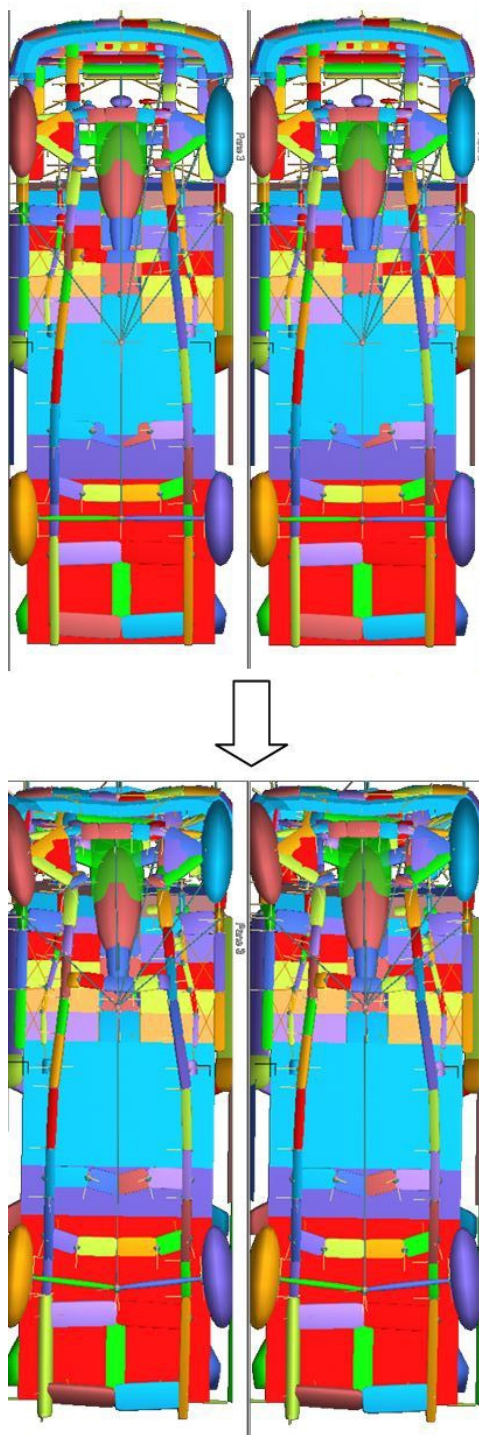


Figure 3.9: Two multi-body vehicle models with different engine sizes that appear to crush the same amount, (top) pre-crash, and (bottom) post-crash

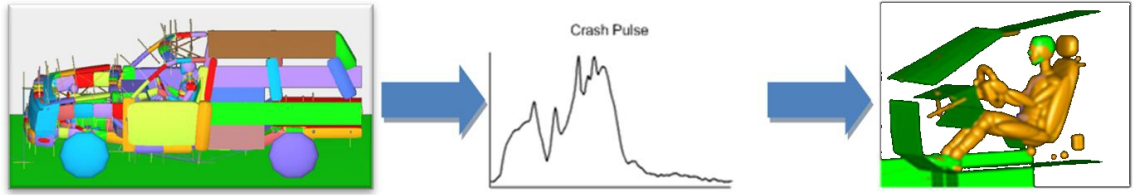
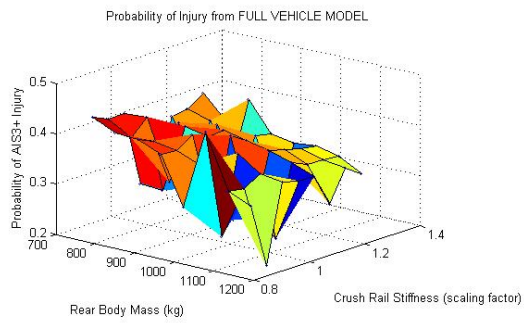


Figure 3.10: Data flow in approach 2; use multi-body vehicle model (left) to obtain blast pulse, and multi-body restraint system model (right) for occupant response

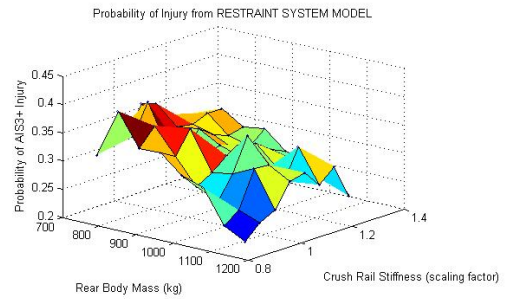
irregularities was in the chest injury probability, much of the computational noise in the data could be attributed to the highly simplified seat belt model. Therefore, the next approach was to use a more sophisticated occupant and restraint system model provided by Ford Motor Company, shown in Figure 3.10. In this case, the crash pulse is still obtained from the MADYMO full-vehicle model for its computational speed, and then a second simulation is conducted by inputting the crash pulse into the dedicated restraint system model.

A 64-point, full-factorial DOE study was run varying mass and stiffness, in similar fashion to the first DOE study from Section 3.2.1. Inspecting the injury outcomes from the restraint system model and comparing with those from the full-vehicle model shows a noticeable improvement in data smoothness, as indicated in Figure 3.11.

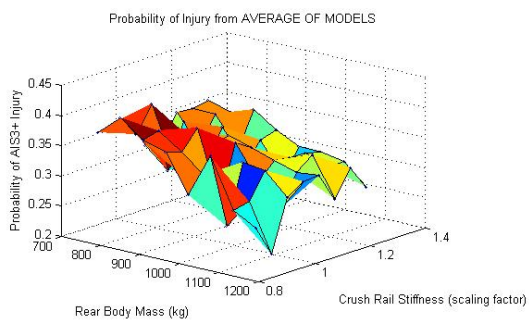
Linear regression models were fit to the data from the 64-point DOE study, and with a first-degree linear model the full-vehicle data had an R-squared value of 0.10 and the restraint system data had an R-squared value of 0.50. Due to the poorness of fit, a least-trimmed squares technique was used to re-fit the data, which removes the points with the highest residuals. The response surfaces both improved to approximate R-squared values of 0.7, and statistical bootstrapping estimated the confidence of the predictors to be 80 percent and 99 percent, respectively. The data with fitted surfaces are shown in Figure 3.12. Based on the results and goodness of fit, the technique of sequentially running full vehicle and restraint system models appears to be an improvement over the previous approach.



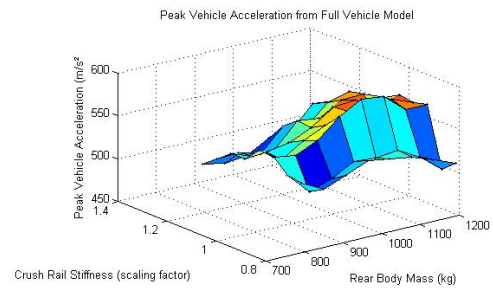
(a)



(b)

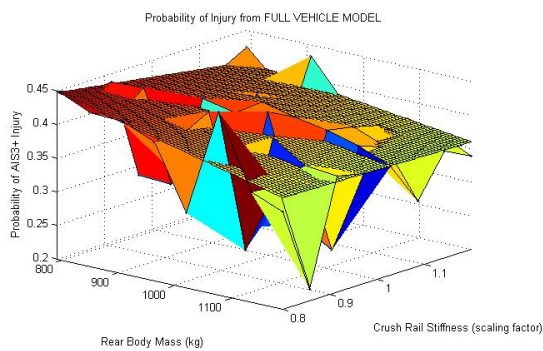


(c)

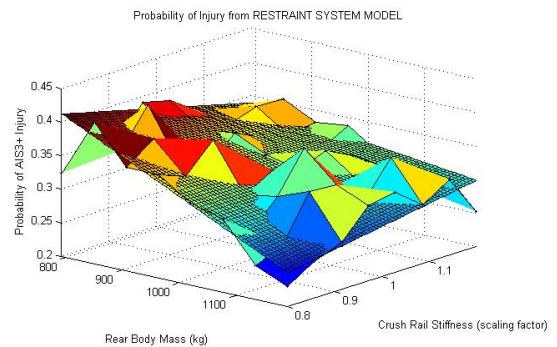


(d)

Figure 3.11: Results from 64-point DOE varying mass and stiffness



(a)



(b)

Figure 3.12: Data from 64-point DOE fitted with least-trimmed squares response surfaces

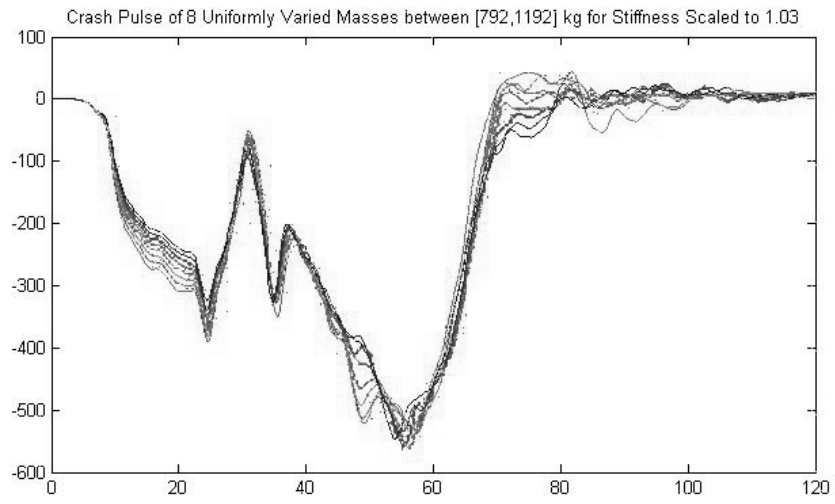
Additional analysis was conducted to examine the crash pulses themselves under univariate changes in mass and stiffness. Figure 3.13 shows the results of this study arranged from light grey to dark grey, where darker grey indicates a higher value.

Notable observations from the mass pulses in Figure 3.13a include that prior to 50 milliseconds, the pulses keep their order where the lightest vehicle (lightest grey) has the highest magnitude of deceleration. After this point, however, there is some crossing of pulses, which likely depends on how much energy is left to absorb and its relationship to the frontal stiffness properties of the vehicle. At the end of the pulse, as expected, the heavier vehicles (darker greys) have higher magnitudes of deceleration as a result of the greater total energy to be absorbed. The stiffness pulses in Figure 3.13b also start out with monotonic behavior as the least stiff vehicles (lightest grey) show the lowest decelerations, but after about 20 milliseconds they begin to cross paths.

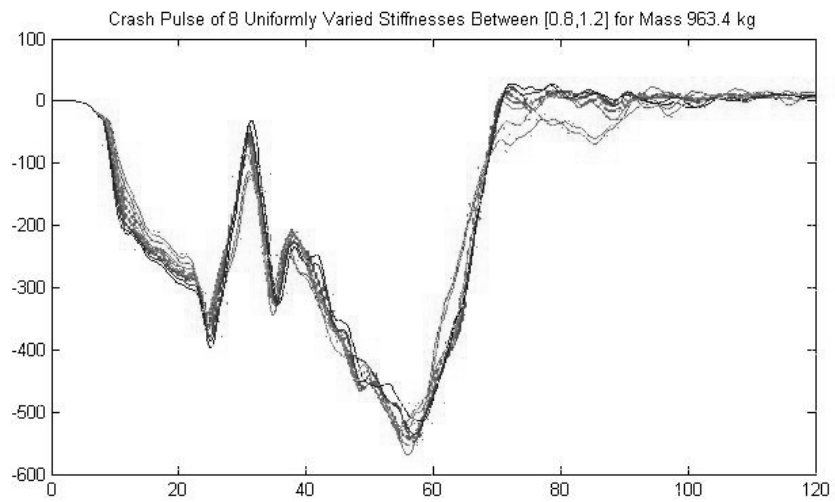
While this approach shows a marked improvement over the previous in terms of response surface fitting, the data still show significant irregularities. The next step is to investigate whether those irregularities are present using the higher-fidelity finite-element vehicle models.

3.4.2 Finite-Element Vehicle Models Linked With Dedicated Restraint System Models

A 2003 Ford Explorer finite-element model was obtained from the GWU NCAC website, which is formatted for the NCAP 35-mph frontal barrier crash test in the LS-DYNA software package (*LSTC*, 2007). This model was run in conjunction with the Ford-developed multi-body restraint system model, similarly to the approach outlined in Figure 3.10. In this case, vehicle stiffness can be modified more directly by changing the frontal rail material properties, where rail stiffness is a function of the yield strength of the material to the power of 0.57 (*Mahmood and Paluszny*, 1981). It should be noted that the single stiffness value used here is a generalization



(a)



(b)

Figure 3.13: Crash pulses from MADYMO simulation varying (a) mass and (b) stiffness, where darker grey indicates a higher value

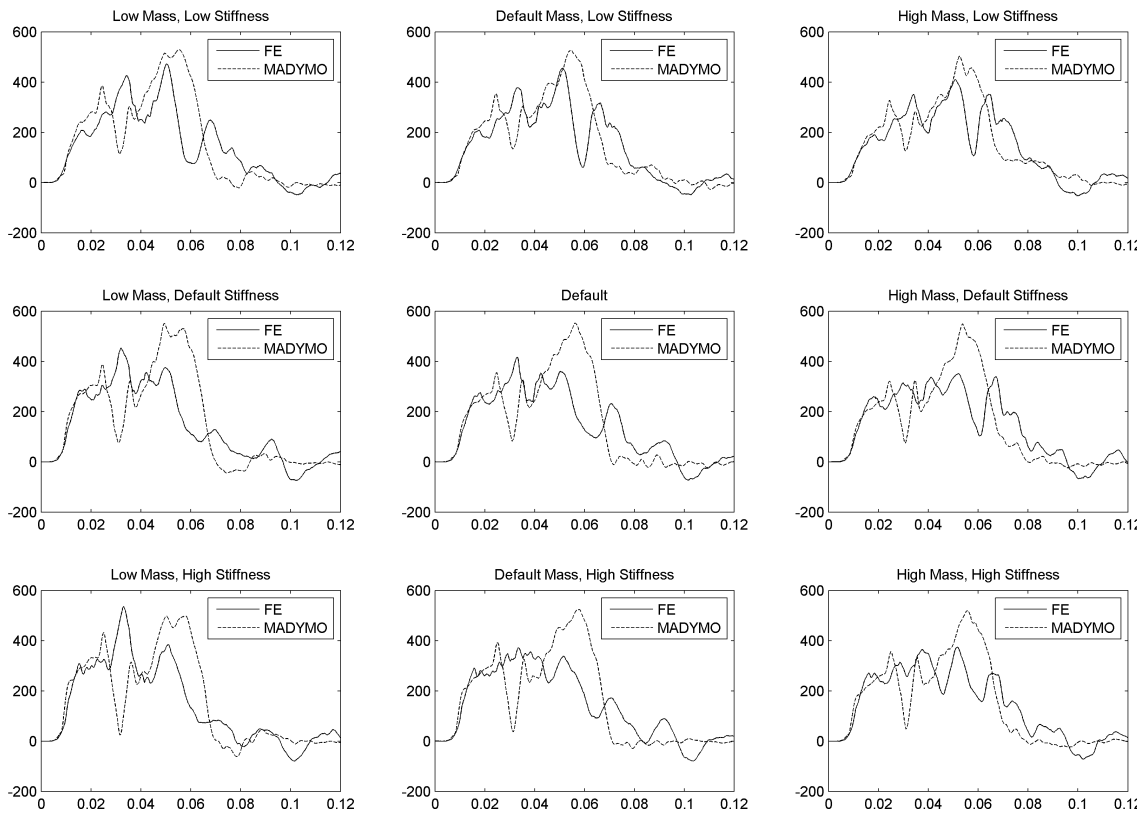


Figure 3.14: Crash pulses varying mass and stiffness for finite-element (FE) and multi-body (MADYMO) models

of the much more complex process of absorbing crash energy in the front end of a vehicle. In reality, many features may be tuned for energy absorption, including the thickness, geometry, and material of the frame rails and other structural supports; in this dissertation, these properties are simplified and modeled as a continuously-variable material yield strength of the frontal frame rails.

With this model, a 9-point, full-factorial DOE study was conducted, and the resulting crash pulses are shown in Figure 3.14. There is an immediately evident discrepancy between the previous multi-body model responses and the finite-element responses, and the latter are assumed to be more accurate due to higher detail in the modeling and more extensive validation with physical crash tests.

The trends seen in the results are rather intuitive: For lighter vehicles, lower

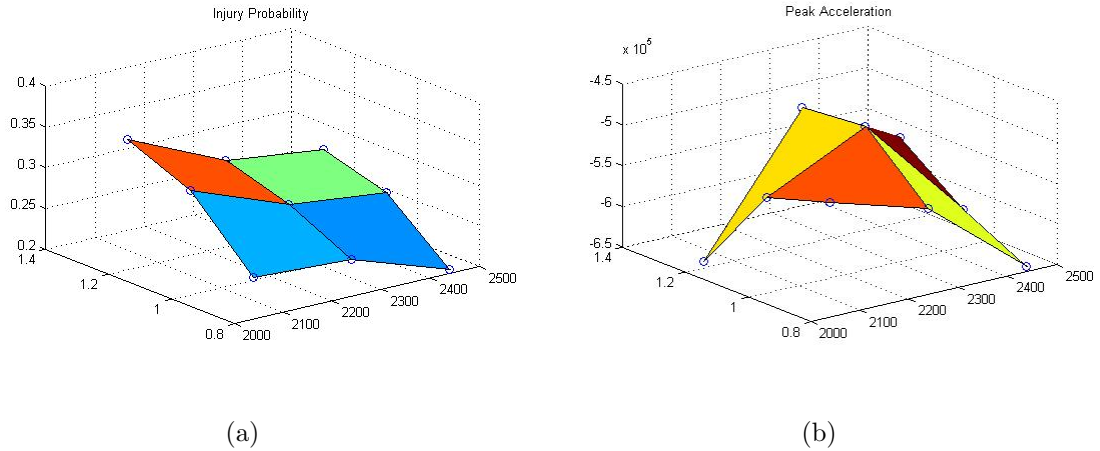


Figure 3.15: Results of 9-point DOE with finite-element vehicle model

stiffness values have the lowest peak accelerations, as a higher frontal stiffness would introduce more severe initial acceleration spikes; for heavier vehicles, higher stiffness values are better, as the lower stiffness values do not absorb enough energy at the beginning of the event, leaving higher acceleration spikes later in the crash pulse as the rigid engine block is impacted. The crash pulses from the finite-element responses were input to the multi-body restraint system model, and the resulting injury probabilities and peak accelerations are shown in Figure 3.15.

Interestingly, the occupant response in Figure 3.15a is rather monotonic, which is surprising when the peak acceleration plot of Figure 3.15b is visibly non-monotonic. Injury outcomes are not entirely correlated with the peak acceleration in the crash pulse, suggesting that the timing and duration of those peaks strongly influence the probability of occupant injury.

This study was extended to create a three-variable, 27-point full-factorial DOE study by running multiple cases of a new restraint system variable, seat belt material stiffness (*b*). The result also exhibits monotonic behavior, and a least-squares linear regression of the response yields the model shown in Equation (3.6) with an R-squared value of 0.92. Here, there is no significant interaction term like seen before with the MADYMO-only approach, but the fit is much better. The lack of interaction terms

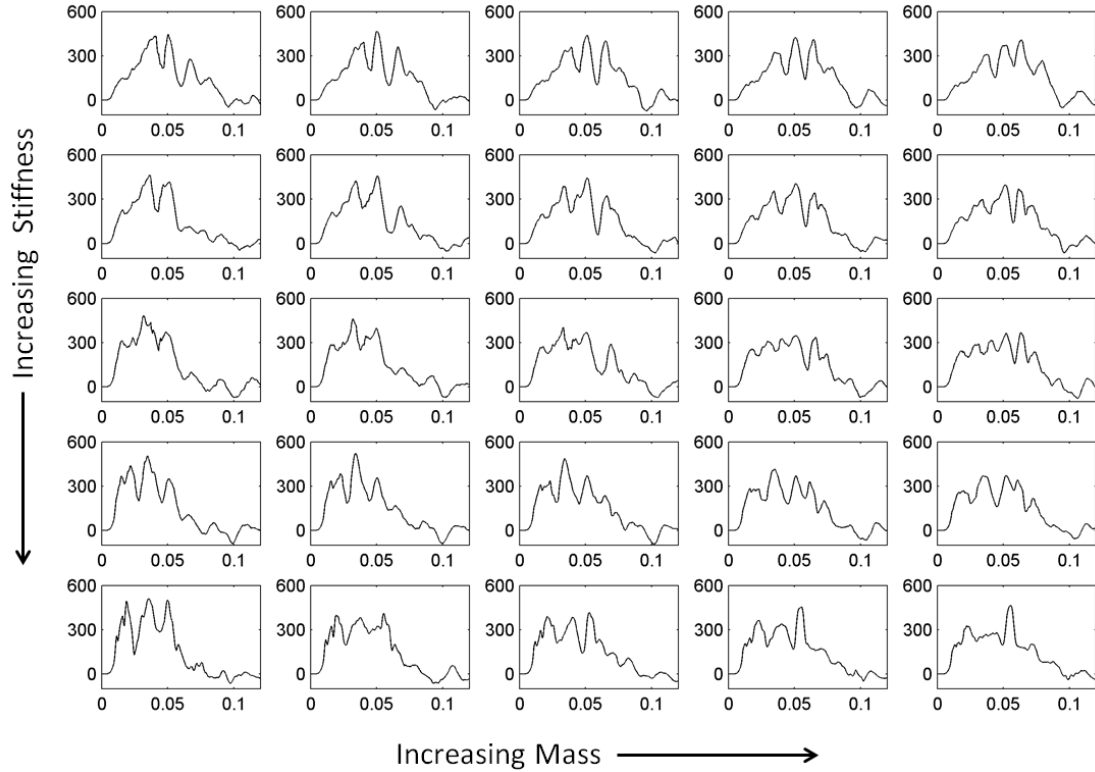


Figure 3.16: Crash pulses varying mass and stiffness using finite-element model

indicates that sequential optimization of the vehicle structure (mass and stiffness) followed by the restraint system will be nearly as good as joint optimization; however, since this response surface is based on a very small range of points, its accuracy is questionable.

$$P_{AIS3+} = 0.351 - 0.000204m + 0.190k + 0.196b \quad (3.6)$$

A larger set of computational experiments was conducted using the finite-element model to see how the results are affected, and 25 vehicle crash simulations were run with varying mass and stiffness values, with the results shown in Figure 3.16.

The same trends that were observed previously are now intensified with the larger range of inputs. The resulting crash pulses were input to a new restraint system model obtained from Ford Motor Company, which represents the interior of a high-seat-height crossover utility vehicle. Again, the belt stiffness was varied, completing

a 125-point full-factorial DOE. The results fit the response surface in Equation (3.7) with an R^2 -value of 0.90.

$$P_{AIS3+} = 0.2 - 0.2m + 0.1k - 0.04b + 0.04m^2 - 0.02k^2 - 0.03mk + 0.06mb - 0.05kb \quad (3.7)$$

Here, there are significant interaction terms between the mass (m), stiffness (s), and belt stiffness (b). This suggests that structural and restraint system variables are indeed interlinked, and an approach that simultaneously optimizes both will yield better results than a conventional sequential optimization approach.

When the gradients of this model are calculated and set equal to zero (for unconstrained optimization), the resulting vehicle design has a very high mass and stiffness, along with a low belt stiffness: $m = 1.89$, $s = 1.37$, $b = 0.47$. All of these are scaling factors from the baseline values, though the scaled mass only deals with certain parts of the vehicle. This optimal design corresponds with a vehicle that is roughly 890 kilograms heavier than the baseline Ford Explorer, indicating that higher-mass vehicles perform better in barrier crashes. However, barrier crashes in theory and practice generally do not favor higher vehicle mass, and these results may be attributed to simplifications embedded in the model, the limited number of design variables, and the range and sampling limitations of the study. Nevertheless, higher mass does improve safety outcomes in multiple-vehicle collisions as discussed in Section 2.3.1, which follows with the trends found in this study.

3.5 Discussion

Preliminary results exhibit a design tradeoff between optimizing for occupant safety and optimizing fuel economy, though the existing model relies on a number of assumptions: Only a single vehicle crash mode is considered, three variables are allowed to change, and a single drive cycle is simulated, to name a few. The model

can be enhanced by peeling away these assumptions and limitations, which would yield more definitive results. To broaden the scope of this work, other crash modes such as side impact and rollover could be simulated, more design variables included, and other sustainability metrics measured.

Because of the complications and irregularities found in the safety simulations, this preliminary study focuses on evaluating the different types of simulation models, each of which has its advantages and disadvantages. The first one involved fast simulations for which a large number of variations could be assessed, but this approach resulted in untrustworthy data. The third set of models involved highly-trusted, finite-element simulations for which fewer could be afforded in a specified time, and the middle approach was essentially a compromise between time and fidelity. Later chapters of this dissertation utilize the higher-fidelity, slower-evaluating simulations because (1) they can be parallelized on multiple computers and (2) the results can be presented with higher confidence. One future research possibility is to combine the high-fidelity and low-fidelity models using uncertainty management techniques from the aerospace research community, where the high-speed, low-fidelity models are used more frequently with occasional validation from the more expensive simulations (*Alexandrov et al.*, 2000; *Umakant et al.*, 2006).

CHAPTER IV

Optimization Formulations for Blastworthiness and Vehicle Mass

*“The important thing in science is not so much to obtain new facts
as to discover new ways of thinking about them.”*

-William Lawrence Bragg

Military ground vehicle design must consider the threat posed by underbody blasts to vehicles and their occupants, while also accounting for weight reduction goals for improving fuel economy and mobility. A two-stage process is presented in this chapter to model the blast event, using finite-element methods for simulating the vehicle response and multi-body analysis for the occupant response. Issues including computational expense, objective function formulation, and multi-objective seating system design optimization are addressed in detail, and three different blastworthiness optimization formulations are presented and evaluated.

4.1 Introduction

Improvised explosive devices (IEDs), often referred to as “roadside bombs,” pose one of the greatest threats to U.S. ground troops in overseas operations, accounting for over sixty percent of combat fatalities and injuries in Afghanistan and Iraq (*White*,

2011). Assuming that the vehicle hull remains intact, injuries and fatalities to ground vehicle occupants occur due to the rapid accelerations and hard contact experienced when an explosive such as an IED detonates beneath the vehicle. Ground vehicle designers must consider this threat when designing new vehicles and restraint systems; however, single-objective optimization for occupant survivability might compromise other objectives such as performance and range. Specifically, while increasing vehicle mass will decrease the acceleration pulse from a given explosive and improve occupant safety, it hinders the acceleration, fuel consumption, and range of the vehicle.

While many argue that safety is the top priority in vehicle design, it must be noted that acceleration, fuel consumption, and range are all inextricably linked to personnel safety. The ability of soldiers to rapidly move in and out of combat areas decreases their exposure to hostile situations, thereby making a case for improving safety by improving acceleration and top speed. Also, the need for additional fuel to be transported to military bases exposes additional convoys of vehicles to danger, pressing the need for improved fuel economy to enhance personnel safety. A final safety consideration of vehicle performance is that longer driving ranges would allow bases to be safely located farther away from hostile environments. Thus, even if safety is the sole priority in vehicle design, designers must simultaneously consider all of the aforementioned performance objectives along with more obvious safety objectives such as missile protection and blastworthiness.

The relationship between these design objectives is evident when comparing the HMMWV and the MRAP, two ground vehicles used extensively by the United States Army. The HMMWV, which has been the primary light tactical vehicle in the U.S. Army since 1985, is a 4-ton vehicle with a 75-mph top speed, 275-mile range, and a fuel economy of 11 mpg (*Lardner, 2008; United States Army, 2010*). In response to high casualty rates for HMMWV occupants under IED attacks, the U.S. Army introduced the MRAP, which weighs 17 tons, has a 65-mph top speed, 420-mile

range (due to a fuel tank three times the size of the HMMWV), and can travel with approximately 6 mpg of fuel consumption. The MRAP has been successful in protecting occupants from underbody blast events due to its greater mass, higher ground clearance, and v-shaped hull; however, its size prohibits maneuvering over difficult terrain and bridges, and it consumes twice as much fuel as the HMMWV. This apparent tradeoff motivates a need to study the relationship between vehicle weight and blastworthiness.

Blast and crash testing procedures vary greatly within the research and design community; however, like in the civilian automotive industry, a common trend is the extensive use of virtual modeling and testing to reduce time, cost, and prototyping requirements. Computational modeling has its own considerable tradeoff when choosing between a high-fidelity model that may take days to simulate and a less sophisticated model that runs in minutes. Regardless of whether the modeling is done physically or computationally, researchers typically study the vehicle response to the blast event separately from the occupant response to the vehicle motion. This serves to break down the problem into manageable subproblems, allowing for specialized testing and software for the structural response of the vehicle as well as for the biomechanical response of the occupant or dummy.

The first procedure evaluates the vehicle response to a crash or blast event, where the outputs of interest are the resulting motion and deformation of the vehicle at the position of the occupant's seat. The second procedure inputs that motion to the occupant and vehicle interior, resulting in profiles of the forces and accelerations experienced by different parts of the occupant's body. The latter test often takes the form of a "drop tower" test, in which the occupant, seat, floor, and restraint system are positioned on rails that allow them to move together in a prescribed manner in the upward or downward (z -) direction. From the occupant data, scientists make predictions regarding the probability of different injury mechanisms. This anal-

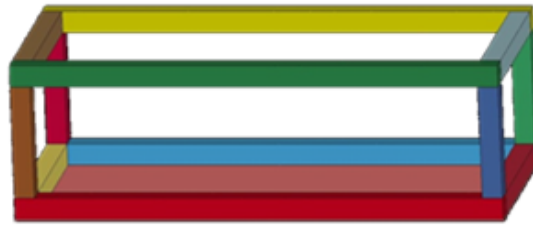
ysis considers the opportunity to tune the seating system design parameters with a prescribed vehicle mass and blast pulse to minimize the occupant’s probability of moderate injury.

This chapter presents a general modeling approach for use in optimization tradeoff studies in Section 4.2, including the development of surrogate models for the vehicle’s structural response and occupant compartment. Section 4.3 presents three optimization formulations with different design objectives. Section 4.4 presents and discusses the results obtained from solving the optimization problems, and Section 4.5 offers conclusions.

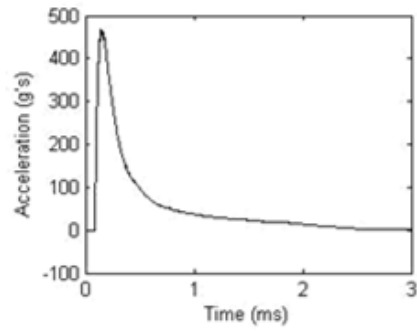
4.2 Modeling Approach

Underbody vehicle blast events are modeled as the two-stage process outlined in the previous section and shown in Figure 4.1. With this in mind, a computational multi-body and finite-element model for the seating system is used, which was developed to replicate the behavior of the physical vertical drop tower sled tests commonly used to study aircraft seat ejection and ground vehicle blast events. This model was created and evaluated in MADYMO, a mathematical dynamic modeling program that integrates multi-body dynamics with finite-element analysis to replicate the behavior of physical systems (*TASS Safe*, 2010; *Arepally et al.*, 2008). The vertical drop tower sled shown in Figure 4.2 includes a floor, seat, seat-back, and seat cushions, and the simulated version on the bottom of Figure 4.1 also includes an energy-absorbing (EA) damper that allows limited travel between the seat bottom and floor, a lap belt, a shoulder belt, and a MADYMO-provided Hybrid III dummy; this system travels along rigid vertical (z -direction) rails with the prescribed motion of the input blast pulse. MADYMO reports the forces and accelerations experienced at different locations within the occupant model.

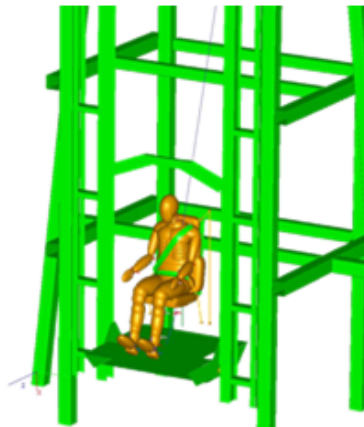
To obtain the blast pulse, a less sophisticated model of the vehicle and blast



Underbody Blast Simulation
(Vehicle Model)



Blast Pulse of Vehicle



Drop Tower Simulation
(Occupant Model)

Figure 4.1: Models and approach



Figure 4.2: Photograph of the physical drop tower set-up at the Selfridge Air National Guard Base

charge is employed, which simulates the acceleration response of a vehicle-sized box to an air blast. While this simplifies the vehicle to a rigid body, not allowing for underbody deformation, it evaluates quickly, is non-proprietary and unclassified, and adequately demonstrates the *relative* impact of vehicle mass and charge parameters on the acceleration pulse. The vehicle mass varies with prescribed changes to the material density properties, and the explosive charge is altered using the CONWEP function built into the LS-DYNA software (*Randers-Pehrson and Bannister, 1997; LSTC, 2007*), where the charge intensity (in TNT mass-equivalent) and charge location (longitudinal/*x*- and lateral/*y*- direction) are varied. Thus, a general prediction can be obtained of the impact that vehicle mass, charge intensity, and charge location have on the acceleration pulse experienced by the occupant. It should be noted that this study only examines the response at the position of the driver's seat, though it is expected that passengers should experience a comparable range of acceleration pulses given that the blast positioning is uniform and random.

Linking these simulations, the vehicle acceleration response is simulated for different vehicle masses and charge parameters, and then that response is entered into the occupant model to optimize the seating system design for occupant safety. As injuries can occur in many different locations and modes throughout the body, it is practical to simplify the analysis by choosing the particular injury types that are most likely to occur in blast scenarios and are also indicative of other injuries that are likely to occur. NATO published a report to this effect in 2007 that establishes three particular injury modes to be monitored in blast events: Upper neck compressive injury, vertical loading of the lower lumbar spine, and lower tibia fracture (*RTO Task Group 25, 2007*). The upper neck injury criterion was developed by Mertz et al. (1978) and is used as the indicator for all neck and head injury modes that may occur in a blast scenario; the limit for axial compression in the upper neck is at 4 kN for an instantaneous event and 1.1 kN for a 30-millisecond pulse, representing a 10-percent

probability of a moderate (level 2) injury on the AIS (*AAAM*, 1990). The lower lumbar injury criterion that represents the probability of injury in the occupant torso is specified by NATO as the Dynamic Response Index (DRI); however, this metric was found by Chandler (1985) to correlate strongly with axial compression of the lower lumbar spine, and for simplicity and consistency this study considers the compression measure. The threshold for a 10-percent probability of moderate lumbar spine injury is 6.7 kN, regardless of duration. Lastly, lower extremity injuries are characterized by a fracture injury in the lower tibia, following a report by Yoganandan et al. (1996) on the compressive force associated with such fracture; this sets the 10-percent threshold for lower tibia compression at 5.4 kN, also independent of event duration.

The present study uses this linked-model approach to optimize a vehicle's seating system at particular mass values. As IED blasts are by nature unpredictable in location and energy, the explosive charge parameters are prescribed as postulated distributions. These distributions are based on estimates that are entirely independent of any actual blast data, which is unavailable to the authors and for publication. Therefore, the optimization must account for this uncertainty in the formulation, and three separate formulations are presented for comparison.

Initially, the vehicle blast response finite-element model required approximately 3 hours for evaluation; this model was simplified by removing the surfaces unaffected by the blast and increasing the time step so that the final model required only 20 minutes of computation without any noticeable change in the results. The multi-body occupant response model is evaluated in approximately 8 minutes. Since most optimization schemes require a large number of function evaluations for convergence, it is impractical to embed the vehicle and seating system models in an all-at-once optimization formulation. A common method for optimizing under such circumstances, and the method employed in this study, is to conduct a DOE analysis to sample the design space, and then to use response surface methods to create mathematical

surrogate models whose computational time is relatively small (*Myers et al.*, 2009).

4.2.1 Vehicle Structure Surrogate Modeling

The finite-element vehicle blast model was simulated 100 times with an optimal Latin-hypercube sampling (OLHS) strategy (*McKay et al.*, 1979) over the four vehicle input parameters listed in Table 4.1: Vehicle mass (m_v) in kilograms, charge longitudinal x -position (x_c) in meters, charge lateral y -position (y_c) in meters, and charge mass (m_c) in kilograms-TNT-equivalent. As vehicle mass is an input that can be designed for, the sample for m_v is taken uniformly with a lower bound of 2,000 kg, corresponding with the weight of an unloaded HMMWV, and an upper bound of 12,000 kg, approximately the weight of an unloaded MRAP. Since many IEDs are remotely detonated and not necessarily triggered by pressures on the ground, an assumed uniform distribution of the charge position in the x - and y - directions spans the entire footprint of the vehicle with equal probability. Other studies have used a standard 5-kilogram or 10-pound (4.5-kilogram) charge, and so the charge size in this study is assumed to be distributed normally with a mean of 5 kilograms and a standard deviation of 2 kilograms, not allowing for negative values (which mathematically would occur but are physically impossible). While these distributions are more important for optimization than for surrogate modeling, they are used in the sampling to assure that metamodel fidelity is highest where it will be evaluated most often.

The results of these simulations were examined to determine the most appropriate way to parameterize the output of interest, which is the blast pulse. The pulses had a common shape and duration similar to that shown in Figure 4.1, with the only significant difference among simulations being the magnitude, or intensity, of the pulse. Thus, the entire blast pulse was parameterized by this single value of peak acceleration magnitude (a_{peak}), measured in g . The data were then fit with a linear

<i>Symbol</i>	<i>Name</i>	<i>Type</i>	<i>Model</i>
m_v	Vehicle mass	Input parameter	Vehicle
x_c	Charge longitudinal position	Input random variable	Vehicle
y_c	Charge lateral position	Input random variable	Vehicle
m_c	Charge mass	Input random variable	Vehicle
a_{peak}	Peak acceleration magnitude	Parameterized linking variable	Vehicle (output) & occupant (input)
s_{EA}	Seating system EA system stiffness	Input design variable	Occupant
s_c	Seat cushion stiffness	Input design variable	Occupant
s_f	Floor pad stiffness	Input design variable	Occupant
F_{neck}	Upper neck axial compression	Output injury criterion	Occupant
F_{lumbar}	Lower lumbar spine axial compression	Output injury criterion	Occupant
F_{tibia}	Lower tibia axial compression	Output injury criterion	Occupant

Table 4.1: Inputs and outputs of simulation models

regression model using the R software package (*Venables et al.*, 2010) to approximate a_{peak} as a function of the four inputs, m_v , x_c , y_c and m_c . Prior knowledge that the mass of the vehicle impacts peak velocity with an inverse relationship was used, and a second-order response surface model was then fit to the data (*Myers et al.*, 2009). The insignificant terms were pruned using backward elimination (*Faraway*, 2005), resulting in the linear regression model given as Equation (4.1) with an R-squared value of 0.96.

$$\begin{aligned}
a_{peak} = & 52.1 + 575,000 \frac{1}{m_v} - 30.9x_c - 220y_c - 2.53m_c + 373,000 \frac{x_c}{m_v} \\
& + 1,630,000 \frac{y_c}{m_v} + 518,000 \frac{m_c}{m_v} + 34.9y_c m_c - 129y_c^2
\end{aligned} \tag{4.1}$$

As the goal with this first simulation is to understand how vehicle mass impacts the distribution of a_{peak} , the above polynomial model is evaluated at different vehicle

masses with the distributed charge inputs. For each m_v , between 2,000 and 12,000 at intervals of 500 kg, a 3,000-point data sample was evaluated to observe the output distributions. These distributions were all very well approximated as normal, and the means and standard deviations were plotted as a function of vehicle mass. They were fit with power function regressions, and the resulting equations are given as Equations (4.2) and (4.3), both with R-squared values above 0.999. Combined, these equations allow interpolation of the distribution of peak accelerations experienced by any vehicle mass within the simulated range.

$$\mu_{a_{peak}} = 4 \times 10^6 m_v^{-1.023} \quad (4.2)$$

$$\sigma_{a_{peak}} = 2 \times 10^6 m_v^{-1.035} \quad (4.3)$$

4.2.2 Occupant Compartment Surrogate Modeling

A DOE study was also conducted to develop appropriate surrogate models for the occupant compartment model. Here, the inputs to be varied included the peak acceleration as well as the three seating design parameters: Seat EA system stiffness (s_{EA}), seat cushion stiffness (s_c), and floor pad stiffness (s_f), all of which are scaling factors of the original material force-deflection curves. A 300-point OLHS was constructed varying each input uniformly across its practical range, and polynomial surrogates using second-order and interaction terms were fit for the occupant neck, lumbar spine, and tibia responses (*Myers et al.*, 2009). Preliminary tests revealed a strong correlation between the left and right tibias, and as a result the two tibia responses were averaged and combined into one model. Each surrogate was pruned using backward elimination until all higher-order terms had p -values below 0.001 significance (*Faraway*, 2005), and the Box-Cox method was employed when applicable for response transformation, resulting in exponential terms (*Box and Cox*, 1964). The resulting models had R-squared values of 0.95, 0.95 and 0.98, respectively, and they

are presented as Equations (4.4), (4.5) and (4.6):

$$F_{neck} = e^{(3.84+0.12s_{EA}+0.88s_c+0.002a_{peak}+0.058s_{EA}s_c+0.000084s_{EA}a_{peak} - 0.000063s_c a_{peak} - 0.058s_{EA}^2 - 0.14s_c^2 - 0.00000054a_{peak}^2)} \quad (4.4)$$

$$F_{lumbar} = e^{(5.66+0.12s_{EA}+0.81s_c+0.002a_{peak}+0.062s_{EA}s_c+0.000087s_{EA}a_{peak} - 0.000068s_c a_{peak} - 0.059s_{EA}^2 - 0.13s_c^2 - 0.00000056a_{peak}^2)} \quad (4.5)$$

$$F_{tibia} = 332 - 245s_c - 80.2s_f + 1.30a_{peak} + 35.8s_c s_f + 14.0s_f^2 + 0.0012a_{peak}^2. \quad (4.6)$$

From these equations, a strong correlation is evident between the neck and the lumbar responses, which is expected given that both are positioned along the spinal column; however, given the differences in the injury force thresholds, these remained separate for optimization. As expected, the floor pad is not a significant variable in the neck and lumbar responses, nor is the EA system significant for the tibia response. The seat cushion, which is significant for all three forces, has opposite effects on lower extremities versus the upper body; increasing the cushion stiffness tends to increase the forces in the neck and spine while decreasing the forces in the tibias. In other words, the seat cushion stiffness can be tuned to shift the load between the spine and the lower legs, and seat cushion designers must seek a balance when choosing an appropriate seat cushion stiffness; however, these responses are strongly posture-dependent and related to the biofidelity of the dummy, which was not designed for vertical loading. Peak acceleration, as expected, has a strong positive correlation with all occupant force responses.

4.3 Optimization

Given that the overwhelming majority of military vehicle-related casualties involve underbody blast events, the primary objective of seating system design is to protect occupants against these threats. More specifically, the goal is to minimize the occupants' probability of being injured; however, this is complicated by a number of factors, three of which are presented here. The first is that this approach considers three separate injury mechanisms, and minimizing one injury criterion does not necessarily correspond with reducing the other two criteria; in fact, minimizing one injury criterion often competes with the minimization of other criteria. The second factor is that the knowledge that connects the model outputs, which are force quantities, to the objectives, which are injury probabilities, is incomplete. The Yoganandan report on lower tibia injury (1996) does present complete functions for moderate injury probability as a function of axial force; however, the other two injury modes in the neck and spine simply present the 10-percent threshold values. Because of this, injury probability cannot be confidently minimized, as the knowledge is incomplete regarding how forces outside of the threshold values translate to probabilities. The final factor is the uncertainty introduced in the blast parameters, which is input as a range rather than a single set of values. Since these factors complicate the formulation of a straightforward objective, this section presents three different optimization formulations and specifies the strengths and limitations of each.

4.3.1 Minimizing Probability of Failure

Based on the NATO report on protecting vehicle occupants from landmine effects, the ground vehicle safety benchmark is for occupants to have no greater than a 10-percent probability of moderate injury (AIS2+). Unfortunately, it is impractical (if not impossible) to guarantee that this benchmark will be met in all possible blast scenarios given that there is no upper limit to the size of an underbody explosive.

However, the distribution of blast scenarios can be used to minimize the percentage of such events that exceed the 10-percent threshold. In this formulation, shown in Equation (4.7), the cumulative distribution function of the normally-distributed peak acceleration ($\Phi(a_{peak})$) is used in the objective to minimize the probability of failure (P_f) to meet the injury threshold. Here, the seating system variables s_{EA} , s_c and s_f are allowed to vary along with the peak acceleration itself, a_{peak} , and the surrogate models for occupant forces are constrained at the threshold values:

$$\begin{aligned}
& \underset{s_{EA}, s_c, s_f, a_{peak}}{\text{minimize}} && P_f = 1 - \Phi(a_{peak}) \\
\text{where} &&& \Phi(a_{peak}) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{a_{peak} - \mu_{a_{peak}}}{\sqrt{2\sigma_{a_{peak}}^2}} \right) \right] \\
&&& \mu_{a_{peak}}(m_v) = 4 \times 10^6 m_v^{-1.023} \\
&&& \sigma_{a_{peak}}(m_v) = 2 \times 10^6 m_v^{-1.035} \tag{4.7} \\
\text{subject to} &&& F_{neck}(s_{EA}, s_c, a_{peak}) \leq 4.0 \\
&&& F_{lumbar}(s_{EA}, s_c, a_{peak}) \leq 6.7 \\
&&& F_{tibia}(s_c, s_f, a_{peak}) \leq 5.4 \\
&&& lb \leq s_{EA}, s_c, s_f \leq ub.
\end{aligned}$$

By accounting for function monotonicity, constants, and scaling factors, this formulation yields equivalent resulting designs as maximizing a_{peak} under the same constraints. Following this logic, the formulation essentially optimizes the seating system design for the most extreme blast pulse scenario that can meet the injury thresholds, regardless of vehicle mass. The resulting seating system designs will thus produce acceptable, but not necessarily optimal, results in the more frequently-occurring, lower-intensity blast scenarios, and could consequently produce a greater absolute number of injuries.

An additional limitation of this formulation is in the presentation and interpreta-

tion of the results; if the evaluation of a vehicle converges to a 1-percent probability of failure, then a single occupant of that vehicle has a 1-percent probability of sustaining body forces that correspond to a 10-percent probability of moderate injury. However, that same occupant may have a much higher probability of sustaining body forces corresponding to a 9-percent probability of moderate injury, but such information will not be communicated by this formulation. Most stakeholders in the military vehicle design process would have difficulty interpreting and analyzing results in the form of a percentage of a percentage.

4.3.2 Minimizing Normalized Forces

In an attempt to account for the most common blast scenarios rather than the most extreme cases, the second optimization approach seeks to minimize the actual body force values in the most frequent case, using the knowledge that body forces are monotonic with respect to predicted probabilities of injury. To account for all three criteria, a minimax optimization formulation is used where the highest, or maximum, of the three forces is minimized, recognizing that the force which is initially the highest may shift during the course of the optimization. Known differences in the associated 10-percent probability forces are also accounted for by normalizing the force values according to their respective threshold values, essentially minimizing them as a percentage of their thresholds. Since the peak acceleration distribution is modeled as normal, the mode is equal to the median and mean. This optimization formulation is given as Equation (4.8):

$$\begin{aligned}
 & \underset{s_{EA}, s_c, s_f}{\text{minimize}} && \text{maximum} \left(\frac{F_{neck}}{4}, \frac{F_{lumbar}}{6.7}, \frac{F_{tibia}}{5.4} \right) \\
 & \text{where} && a_{peak} = \mu_{a_{peak}}(m_v) \\
 & \text{subject to} && lb \leq s_{EA}, s_c, s_f \leq ub.
 \end{aligned} \tag{4.8}$$

Here, the optimization scheme finds the best combination of values for the seating system parameters, s_{EA} , s_c and s_f , while the peak acceleration is fixed based on the vehicle mass. The forces represented in the objective function, F_{neck} , F_{lumbar} and F_{tibia} , are obtained from the surrogate models presented in Section 4.2.2. Since the peak acceleration is dependent on vehicle mass, this formulation, in contrast to the probability of failure approach, may yield different results for different vehicle weights. This provides opportunities to understand the effect of seat design parameter tuning on the safety of different vehicles and different vehicle configurations. However, the major limitation here is that this optimization approach only considers one scenario of a continuous set of possible blast inputs, and choosing that scenario as the peak acceleration mode is an arbitrary choice that affects the results.

4.3.3 Minimizing Postulated Injury Probabilities

The final optimization approach examined in this study is to minimize the overall probability of injury, as postulated by some force-injury probability curves. As a tibia force-probability curve has already been published (*Yoganandan et al.*, 1996), shown in Equation (4.11), only the lumbar and neck curves must be approximated. As most injury curves tend to be approximated by Weibull functions of the form $P = 1 - e^{-(F/\alpha)^\beta}$, where P is probability of injury on a scale of 0 to 1 and F is the axial force in kilonewtons, and the force associated with a 10-percent probability is already known, only one further point must be approximated for each injury mode to fit the two Weibull parameters (*Weibull*, 1951). Chandler (1985), who studied lumbar spine injuries, approximated some values of how the DRI relates to the probability of injury. Converting these values to an approximation of how compressive force relates to DRI, an approximation was made for a lumbar injury curve in Equation (4.10). Data for approximating the neck force-probability curve were not available, and so a curve was postulated to have a similar shape as the lumbar and tibia curves and

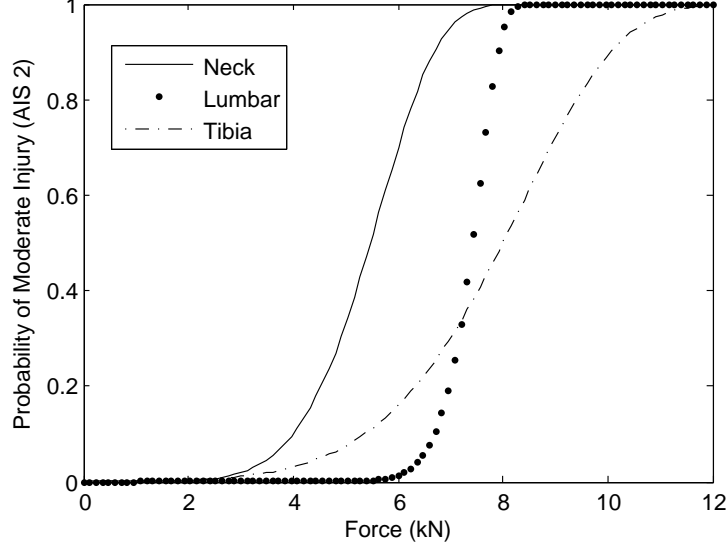


Figure 4.3: Postulated injury probability curves

pass through the 10-percent threshold at 4 kilonewtons. The neck injury probability curve is given as Equation (4.9), and all three functions are plotted in Figure 4.3.

$$P_{neck} = 1 - e^{-(F_{neck}/5.82)^6} \quad (4.9)$$

$$P_{lumbar} = 1 - e^{-(F_{lumbar}/7.57)^{18.5}} \quad (4.10)$$

$$P_{tibia} = 1 - e^{-((1.57+0.42F_{tibia})/5.13)^{7.43}} \quad (4.11)$$

Using these curves to represent the relationship between body forces and injury probabilities, the optimization problem in Equation (4.12) was formulated.

$$\begin{aligned} & \underset{s_{EA}, s_c, s_f}{\text{minimize}} && \int_0^{\mu_{a_{peak}} + 5\sigma_{a_{peak}}} P_{AIS2+} \cdot \phi(a_{peak}) \cdot da_{peak} \\ & \text{where} && P_{AIS2+} = 1 - (1 - P_{neck})(1 - P_{lumbar})(1 - P_{tibia}) \\ & && \phi(a_{peak}) = \frac{1}{\sqrt{2\pi\sigma_{a_{peak}}^2}} \cdot e^{-\frac{(a_{peak} - \mu_{a_{peak}})^2}{2\sigma_{a_{peak}}^2}} \end{aligned} \quad (4.12)$$

$$\text{subject to } lb \leq s_{EA}, s_c, s_f \leq ub$$

Here, the distribution of a_{peak} values was integrated across five standard deviations to account for the variance in blast scenarios; the integral is evaluated from zero through a maximum set at five standard deviations above the mean, which accounts for 99.9999 percent of the distribution. Also, a combined probability of injury is used, P_{AIS2+} , representing the probability of sustaining at least one moderate injury and accounting for the potential for multiple injuries in the same occupant, which should only be counted as one moderately injured person.

The main limitation of this formulation is that two of the injury curves have been postulated without adequate validation based on available data. The integral adds complexity to the model, but it reduces the need to select a scenario for optimization, such as the extreme case or the most frequent case used in the first two approaches. It is recognized that the normalized force minimization formulation could have used a similar integral to account for the range of inputs, but this was not done in order to show a wider range of approaches and result sets. It should also be noted that the three formulations presented in this section are not an exhaustive list of possible optimization formulations, but they illustrate how different formulations may lead to different conclusions.

4.4 Results and Discussion

The three optimization problems presented in the previous section were solved using a sequential quadratic programming algorithm in the MATLAB Optimization Toolbox (*The Mathworks*, 2010), and the results are presented in Table 4.2. A range of vehicle mass inputs was assessed parametrically in each formulation to demonstrate the relationship between vehicle mass and optimal seating system design. Since different vehicle masses respond to the same blast inputs with different acceleration pulses, one might expect that the seating system parameters could be tuned to optimize for the appropriate range of blast pulses.

m_v	<i>Minimized Probability of Failure</i>				<i>Minimized Normalized Forces</i>				<i>Minimized Postulated Injury Probability</i>		
	a_{peak}	s_{EA}	s_c	s_f	a_{peak}	s_{EA}	s_c	s_f	s_{EA}	s_c	s_f
2000	1755	0.25	4.00	0.10	1679	0.25	4.00	0.10	0.25	4.00	0.10
3000	1755	0.25	4.00	0.10	1109	0.25	1.65	0.75	0.25	4.00	0.10
4000	1755	0.25	4.00	0.10	826	0.25	1.25	1.25	0.25	4.00	0.10
5000	1755	0.25	4.00	0.10	658	0.25	1.02	1.43	0.25	4.00	0.10
6000	1755	0.25	4.00	0.10	546	0.25	0.87	1.57	0.25	4.00	0.10
7000	1755	0.25	4.00	0.10	466	0.25	0.76	1.89	0.25	4.00	0.10
8000	1755	0.25	4.00	0.10	407	0.25	0.67	2.00	0.25	4.00	0.10
9000	1755	0.25	4.00	0.10	361	0.25	0.60	2.09	0.25	4.00	0.10
10000	1755	0.25	4.00	0.10	324	0.25	0.54	2.16	0.25	4.00	0.10
11000	1755	0.25	4.00	0.10	294	0.25	0.50	2.21	0.25	4.00	0.10
12000	1755	0.25	4.00	0.10	269	0.25	0.46	2.27	0.25	4.00	0.10

Table 4.2: Optimized designs for 3 approaches varying vehicle mass

As described in Section 4.3.1, the first formulation is independent of vehicle mass, and the results expectedly have the same optimizers for every mass. The corresponding failure probabilities, shown in Figure 4.4a, are very different for each vehicle mass, beginning at almost 50 percent for the 2,000-kg vehicle and quickly declining to less than 1 percent around 4,000 kg. Under this optimization scheme, the seating system design would be optimized for a 1,750- g blast pulse, regardless of whether that falls in the 55th quantile of the blast pulse distribution as with the 2,000-kg vehicle or in the 99.9999th quantile as with the 6,000-kg vehicle. Due to the rarity of occurrence of a 1,750- g pulse in the higher-mass vehicles, this formulation may not produce the actual best designs for minimizing injuries.

The resulting designs of the normalized force minimization in Section 4.3.2 show a distinct shift as the vehicle mass increases. The first is that the seat foam stiffness tends to decrease as the vehicle mass increases. By observing the surrogate models and corresponding forces, it is evident that softening the seat foam decreases the loads in the spinal column (neck and lumbar spine) while increasing the loads in the legs. At the lowest vehicle masses, the tibia force is the active maximum that is

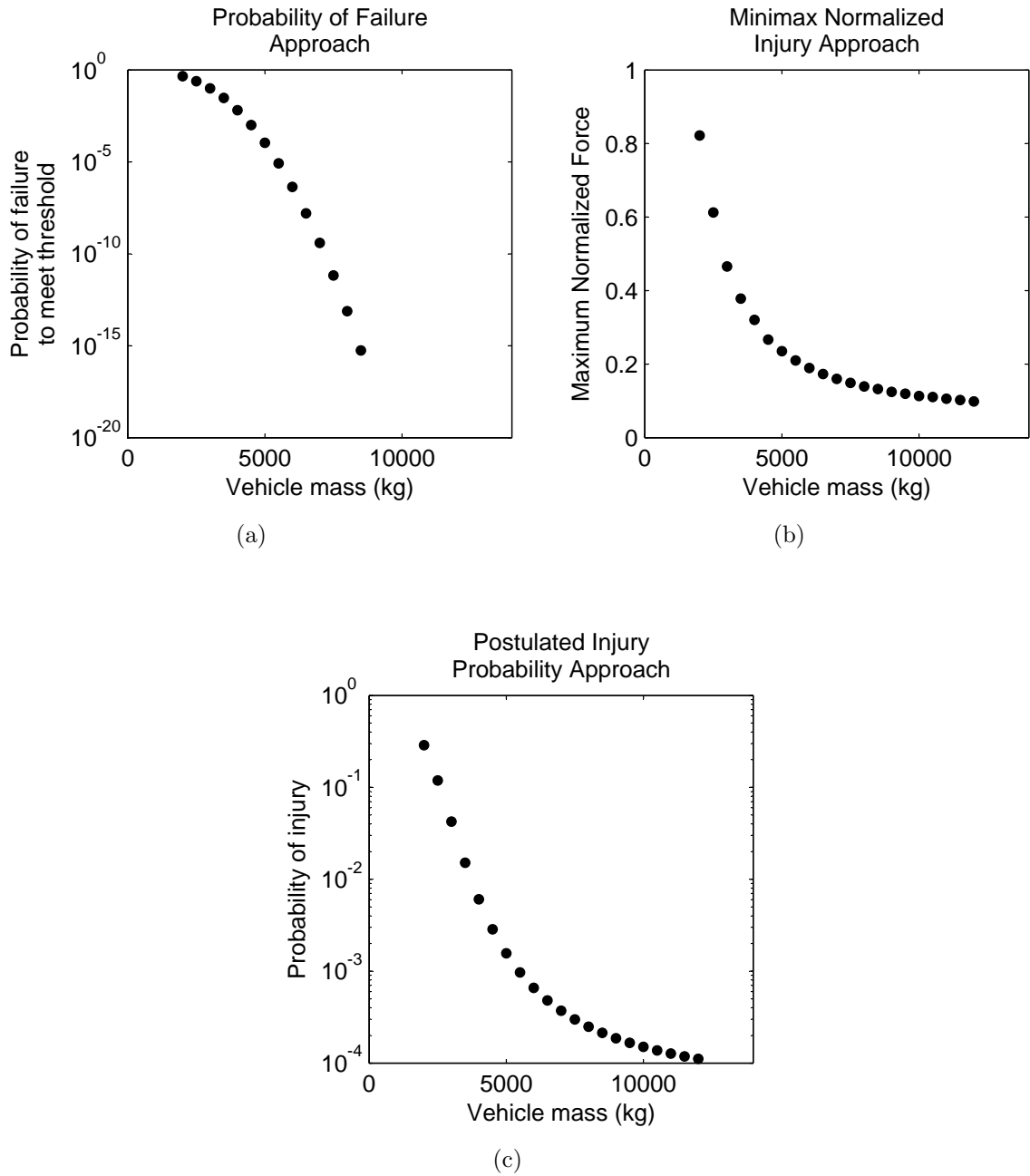


Figure 4.4: Pareto sets of the response versus vehicle mass for three formulations, where the objective scale is logarithmic for (a) and (c)

being minimized in the minimax formulation; as the vehicle mass increases, the tibia and lumbar forces become equal and both act as the active maxima, and so the seat cushion acts as the balancing variable that can shift the loads from the spine to the legs in order to minimize both body forces. The other trend seen is that the floor pad stiffness tends to increase as the vehicle mass increases, which implies that a stiffer floor support is desired at lower blast pulses for injury prevention. These results show how seating parameter tuning plays a role in blastworthiness optimization for different vehicle weights; however, they are based on an assumption that injury probability is directly and equally related to the percentage of its 10-percent force threshold across all three injury modes.

Lastly, the results with the postulated injury curves from Section 4.3.3 are identical to those of the failure probability formulation, reaching the lower bounds on EA stiffness and floor pad stiffness and the upper limit on seat cushion stiffness for all vehicles. This formulation, however, is not independent of vehicle mass, and so the consistency of the results across the range of masses is less obvious. Upon further examination, it became clear that these results are the same results obtained by solely minimizing the tibia forces (and thereby disregarding the neck and spine); also, the tibia appears to be the most sensitive to forces below the 10-percent threshold based on the approximated injury probability curves, as seen in Figure 4.3. Because of the sensitivity of the tibia injury curve, the tibia dominates this optimization formulation, and the results simply minimize the tibia force. Since the tibia force surrogate polynomial is monotonically related to any positive peak acceleration values, the vehicle mass does not influence the design outcome. It should again be noted that the validity of these results is based entirely on the assumed probability of injury curves.

While the seating system design outcomes might not change from one vehicle to another, the actual objective function values are affected by vehicle mass. The Pareto

frontiers in Figure 4.4 show that, for all three objectives, increasing the vehicle mass tends to decrease an occupant's probability of blast injury, illustrating the tradeoff in design between mass and blast safety. As vehicle mass has its own associated safety concerns previously mentioned, this is not as straightforward of a tradeoff as it may appear, and further work to assess and quantify the safety consequences of high-mass vehicles is discussed in Chapter VI.

4.5 Summary and Conclusions

This chapter discussed the use of a two-stage simulation to examine the impact of vehicle weight and seating design variables on occupant injury. Computational expense required the use of surrogate models, which were developed here using least-squares regression. Due to the complex nature of occupant safety optimization, three optimization problems were formulated and solved, each with its own assumptions and limitations. In two of the formulations, the optimal seating system outcome remained fixed regardless of vehicle mass, while in the other formulation vehicle mass played a role in determining the optimal seat cushion stiffness and floor pad stiffness. It should be noted that the first and third approaches, along with the low-mass evaluations of the second approach, all converge to the same optimal seating system design, with a minimum seat EA stiffness, maximum seat cushion stiffness, and minimum floor pad stiffness. In these cases, the tibia forces dominate the formulations, resulting in tibia-optimal seating system designs. However, it should be noted that the use of the Hybrid III dummy and its posture create an unrealistic coupling between the buttocks and tibia, and the results could be strengthened by using an ATD developed specifically for vertical loading and accounting for seated posture uncertainty. It is also evident from the obtained optima that the goals to decrease vehicle weight and to increase occupant blast safety are competing objectives. However, the reduced mobility and fuel economy of high vehicle weight will at some point offset the blast

safety benefits. While the absolute vehicle mass data presented may not be reliable due to the highly simplified vehicle model and the assumptions in the optimization formulations, the relative impact of vehicle mass is still apparent.

The three formulations presented in Section 4.3 each have strengths and limitations, but for general design-for-blastworthiness applications, the third formulation is recommended. While this approach is built on the assumptions that the postulated injury curves of Figure 4.3 are valid, the criteria are grounded by experimental data at the 10 percent thresholds, the solution accounts for the full range and probabilities of blast pulses, and the results are easily interpretable as a percentage probability of moderate injury. The other two formulations, which may easily have been adopted by designers due to the lack of clearly-defined safety objectives, have their own limitations that make them less suitable for the present application. The first formulation presented, minimizing the probability of failure to meet the 10-percent threshold, would be best suited if the main safety concern is protecting occupants in extreme scenarios, such as unusually high blast pulses; however, this is not generally the case, as it is important to consider the effects of the more common, average-intensity blast scenarios. This idea of designing for high- versus average-intensity event scenarios is discussed for the civilian vehicle case study in Chapter V. The second approach, which minimizes the normalized maximum of the axial forces in the body, would be useful in scenarios with low uncertainty (since it used the mode blast pulse rather than the distribution) and when the force percentages are directly related to injury probability (since normalized forces were used in the objective). These assumptions may not be far from reality, but the third approach improves upon both limitations.

More generally, this chapter reveals how designers should consider a variety of optimization approaches when faced with uncertainty in design parameters and physical relationships. Brainstorming different optimization formulations and evaluating their relative merits with physics-based simulations and response surface methods are early

steps of the design optimization process that can improve the accuracy, validity and communication of results. The example case in this chapter demonstrates how three iterations of design optimization formulations for blast safety can influence design outcomes and provide more meaningful information for decision-makers.

Further research is suggested to expand on optimization of occupant blast safety using the formulation from Section 4.3.3 for minimizing injury probability. One area that can be improved upon is the vehicle model itself, which as a rigid body with a flat hull contains many simplifications and assumptions. Modeling this vehicle response using deformable materials, including a v-shaped hull architecture, and adding the geometry of wheels would improve the realism of this model while adding potential variables for structural design optimization. A second area for improvement is the dummy model, which would benefit from a dedicated vertical-loading dummy model rather than the Hybrid III which was developed for longitudinal loads, as well as heterogeneity in occupant size and posture. Another interesting step would be to incorporate additional design considerations that might be affected by the design parameters and variables, such as occupant comfort or safety considerations that relate to mass and mobility. Individuals with sensitive or specialized knowledge regarding blast event frequency and intensity can use the described formulations with more precisely-validated simulations to develop actual recommendations for military ground vehicle design.

CHAPTER V

NCAP Frontal Test Standards and Design for Safety

*“The scientist is not a person who gives the right answers,
he’s one who asks the right questions.”*

-Claude Lévi-Strauss

5.1 Introduction

In Chapter III, a framework was developed for modeling and optimizing vehicle safety using different models with different levels of fidelity and computational cost. The present chapter addresses the final approach discussed in Section 3.4.2, using a finite-element vehicle model coupled with a multi-body dynamics-based model of a restraint system to simulate the frontal crash test prescribed by the U.S. NCAP. This test, which is a standardized crash event for comparing new vehicles in the automotive market, is conducted head-on at 35 mph into a flat, rigid barrier.

In developing this test, NHTSA has chosen an unusually severe frontal crash, considered on the basis of Δv , or change in velocity. The concern here is that the large majority of frontal crashes on U.S. roadways have Δv -values lower than 35 mph; in fact, 98.8 percent of frontal, tow-away crashes reported in the NASS CDS between 1982 and 1991 were at slower speeds than this standard (*Evans, 1994*). A histogram

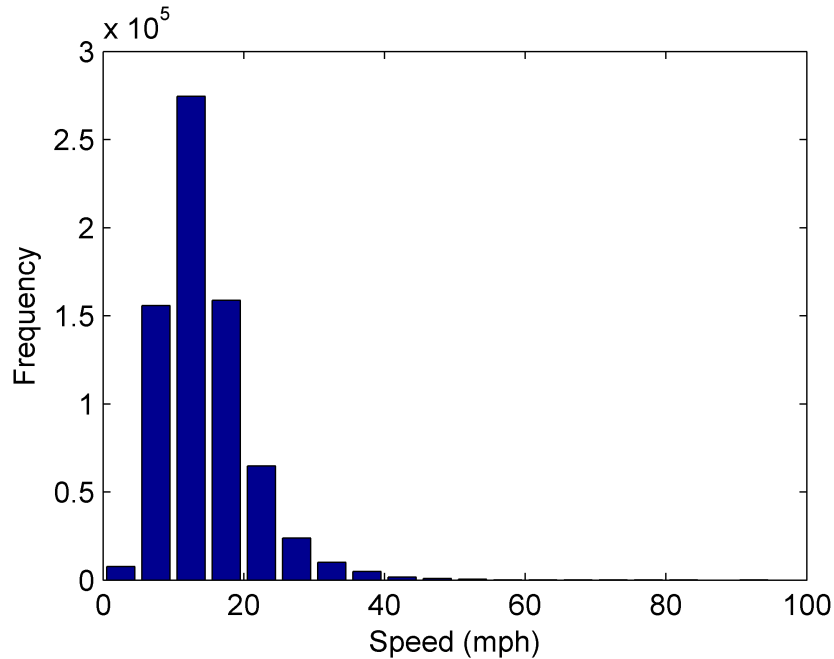


Figure 5.1: Distribution of crash speeds from on-road data, adapted from Evans (1994)

of those crash speeds observed is shown in Figure 5.1. The IIHS and other worldwide NCAP tests are conducted at an even higher speed, 40 mph, which is faster than 99.5 percent of the crashes shown in Figure 5.1, although IIHS uses an offset deformable barrier. The motivation for using high crash severities is that such crashes represent a large risk of death and injury. High-speed tests drive improvements in vehicle strength and structural performance and result in restraint systems that can handle high loads. An underlying assumption is that systems that produce good performance in high-speed crashes will also perform well in lower-speed crashes, which are much more common.

However, it is possible that vehicle designs optimized for these test conditions are not, in fact, optimal for protecting their occupants in more frequently-occurring lower crash speeds. Even though the risk of injury is lower at lower speeds, the far greater number of lower-speed crashes creates the possibility that optimizing for high crash speeds leads to more deaths and injuries than would be the case if a lower test speed

were chosen. The objective of this chapter is to assess the effects of changing the U.S. NCAP test speed on vehicle designs and on-road traffic safety. The next section introduces the problem formulation and the scientific approach used in the study, including the models used, the sampling technique, and the optimization approach. Section 5.3 presents the resulting vehicle designs and predicted societal impact, and Sections 5.4 and 5.5 offer discussions of the results and conclusions.

5.2 Modeling Framework

The system presented in this chapter describing the interactions among governments, manufacturers, and society is illustrated in Figure 5.2. A government regulatory agency sets a crash test standard with the hope of improving the on-road safety as measured by societal statistics, e.g., numbers of road traffic injuries or fatalities. Automobile manufacturers receive those NCAP standards and design vehicles to perform well on the tests, while also meeting the mandatory crash requirements of the region, which in the U.S. are defined by FMVSS. While the government has control over these standards, they are treated in this study as fixed so as to understand the impact of solely changing the star rating tests; thus, the FMVSS requirements are constraints in the vehicle design optimization formulation.

The automakers optimize their vehicle designs with respect to the NCAP standards, which in this study is simplified to five variables as detailed in Table 5.1: The structural frontal stiffness of the frame defined by the yield strength and force-deflection characteristics of the metal (s), the elongation stiffness of the seat belt material as defined by a force-deflection curve (b), the belt retractor stiffness and load-limiting function also defined by a force-deflection curve (r), the inflation rate of the airbag prescribed as the total mass flow over a fixed time interval (a), and the deflation rate of the airbag modeled by the size of the vents (d). The two seat belt-related variables, b and r , act in series with a pretensioner to couple the occupant

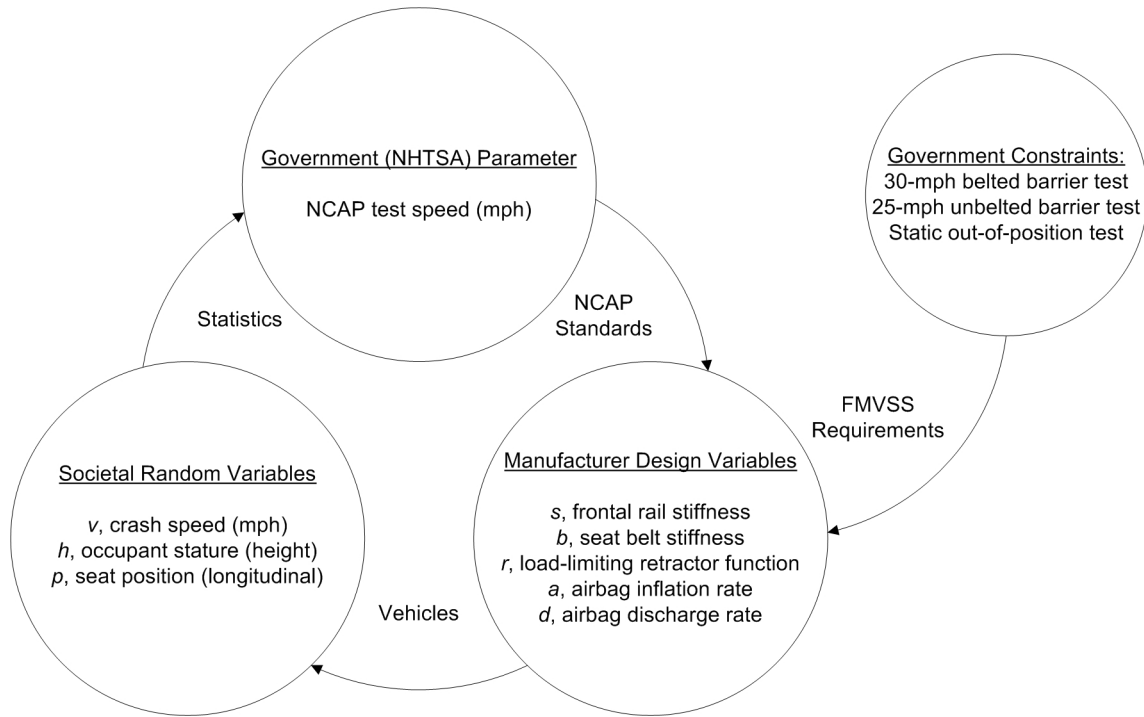


Figure 5.2: Framework of government, manufacturer, and societal interaction

with the seat and vehicle body, where the material stiffness (b) provides more control of the pelvis through the lap belt and the load-limiting retractor (r) controls the upper torso through the shoulder belt. Other variables, including the stiffness of the steering column travel (c), the knee bolster (k), and the seat belt load-limiting webbing (w), were considered but discarded as less important after conducting sensitivity analyses at the nominal crash condition.

After finding the optimal designs, manufacturers sell vehicles to customers, who drive them and may crash them in a wide variety of scenarios. Here, random variables are introduced, as drivers come in a variety of statures or erect standing heights (h), position their seats at varying distances back from the steering wheel (p), and crash their vehicles at a range of speeds (v), see Figure 5.1. Additional random variables exist in the field, and other occupant positioning variables (e.g., torso angle of recline and neck angle) were also considered and discarded after sensitivity analysis. Accounting for these three random variables, predictions of injury probabilities for a

Variable name	Symbol	Domain	Description
Frontal rail stiffness	s	[0.125, 2]	Scale factor for frame rail material yield strength and plastic deformation function (stress vs. strain)
Seat belt stiffness	b	[0.25, 6]	Scale factor for shoulder and lap belt material loading function (stress vs. strain)
Load-limiting belt retractor function	r	[0.25, 2]	Scale factor for retractor stiffness and load-limiting function (N vs. m)
Airbag inflation rate	a	[0.25, 2]	Scale factor for mass flow rate function (kg/s vs. s) and effective total mass flow
Airbag deflation rate	d	[0.721, 5.766]	Discharge coefficient for airbag vents

Table 5.1: Design variables used in manufacturer’s optimization

given vehicle design are generated and extrapolated as road safety statistics, which were mentioned previously as the main driver of safety policy.

This chapter presents a parametric study of NCAP frontal crash speeds, examining the impact on vehicle design and occupant injury probability when the standard is reduced or increased by 5 mph. Thus, the interactions described above are modeled and computed for each of three scenarios: A frontal crash test standard speed of 30 mph, 35 mph, and 40 mph.

5.2.1 Modeling and Simulation

This chapter leverages previously developed and validated computational models of vehicles and occupant compartments to understand how a vehicle design and crash scenario influence the occupant’s probability of sustaining an injury. As described in Section 3.4.2, the crash event is broken down into two separate models: The motion response of the vehicle structure to the crash event and the injury response of the

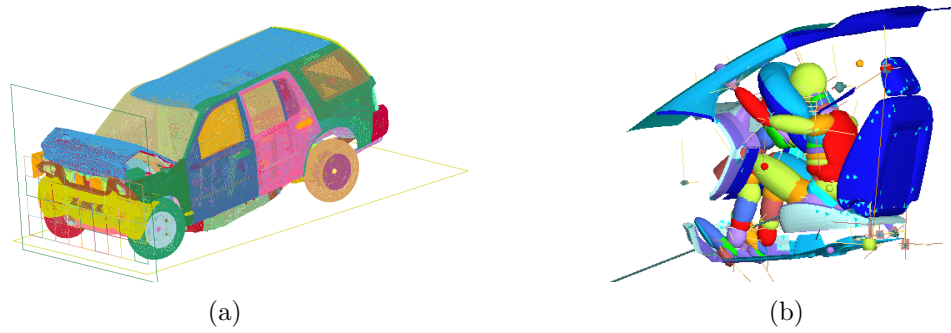


Figure 5.3: Simulation models of (a) vehicle and (b) restraint system

occupant and restraint system to the vehicle motion. The vehicle and restraint system are modeled separately because different software packages specialize in different applications, as well as the difference in the computational time to simulate, which averages 10 hours on a high-performance computing cluster for the vehicle crash and 6 minutes on a state-of-the-art personal desktop computer for the restraint system model.

The first part of the simulation is conducted using the LS-DYNA finite-element package (*LSTC*, 2007) to simulate the U.S. NCAP frontal barrier test for a 2003 Ford Explorer, using a model developed by the GWU NCAC. The model, shown in Figure 5.3a, was modified to allow different frontal stiffness (s) values by scaling the original values of the frame rail yield strength and force-deflection profile. Other researchers, such as Kamel et al. (2008), Liao et al. (2008), and Yang et al. (2005), have conducted optimization studies and used the thickness of the rail instead of the yield strength to modify frontal stiffness. These techniques were both tested and found to have similar effects on the motion response, and so the yield strength was chosen because it keeps the geometry of the model constant and eliminates computational problems that arise with such changes to geometry. In vehicle design practice, metal thickness, material substitutions, or other design changes may be adjusted to achieve the desired frontal stiffness. The output of interest from this vehicle model is the acceleration versus time profile for the first 120 milliseconds of the event, namely,

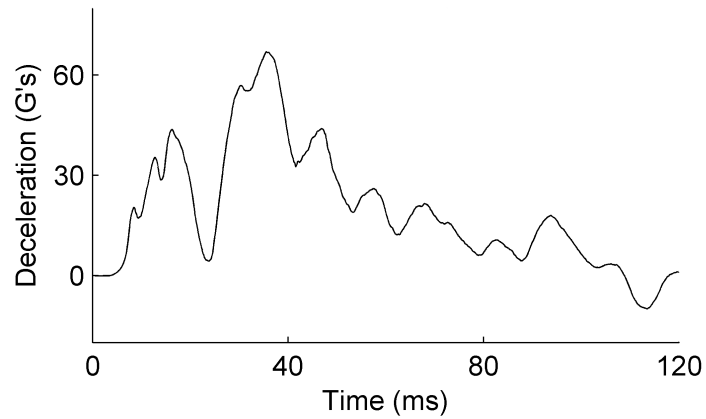


Figure 5.4: Sample crash pulse

the crash pulse, at the location on the floorboard where the driver’s seat is mounted. As is common in design practice, the numerically-noisy 1,200-point response curve is filtered with a 60-point moving average, and an example of a filtered pulse is shown in Figure 5.4.

The crash pulse is next applied to the occupant compartment and restraint system model shown in Figure 5.3b, which measures the impact of the prescribed motion on a seated mid-size male driver inside the vehicle. The model was developed by Ford Motor Company using the MADYMO multibody analysis and finite-element software package (*TASS Safe*, 2010) and represents a generic high-seat-height vehicle such as a sport utility vehicle (SUV) or crossover utility vehicle (CUV). The model was modified to explore the design space among the four restraint system variables: seat belt stiffness (b), load-limiting retractor function (r), and airbag inflation (a) and deflation (d) rates. These parameters affect the coupling of the occupant to the vehicle during the crash and therefore influence the probability of injury.

For simplification purposes, the small female passenger that is currently included in the NHTSA NCAP procedure is left out of this analysis; the assumption here is that the passenger seat restraint system can be optimized for the small female to perform well in the crash test, but this has not been explicitly confirmed.

The U.S. NCAP uses four criteria to assess restraint performance, all of which are concerned with a “serious” injury, defined on the AIS as a level 3 injury or higher (AAAM, 1990). These criteria, which are extracted as outputs of the occupant and restraint system model, are the Head Injury Criterion (HIC_{15}), the Neck Injury Criterion (N_{ij}), chest compression in millimeters, and femur axial compression in kilonewtons. Each of these has an associated injury curve that yields probability of an AIS level 3 or higher (AIS3+) injury in that body region as a function of the criterion, although the femur injury criterion considers moderate, or AIS2+, injuries. These curves have been derived from laboratory test data (NHTSA, 2008), and they are currently used to assess new vehicle star ratings in the U.S. from physical ATD measurements. The four injury criteria curves are described in detail in Section 2.5.2 and plotted versus probability of injury in Figure 2.14, and the curves are combined using Equation (2.4).

5.2.2 Manufacturer’s Optimization

The process followed for the manufacturer optimization and societal impact assessment is outlined in Figure 5.5, beginning with the previously-discussed sensitivity analysis over the design variables. This process is then followed for each of the three test speed scenarios, and includes several batches of simulations for each scenario as well as separate simulations for the FMVSS requirements, which enter the optimization formulation as constraints. The objective of this procedure is to obtain an expected probability of injury for the optimized vehicle design, given that a frontal crash occurs.

Due to the computational expense of the dynamic models of the vehicle and restraint system, design optimization is conducted using response surfaces that are generated from computational DOE samples. An optimal Latin hypercube sampling (OLHS) technique is employed (McKay *et al.*, 1979) to improve the efficiency

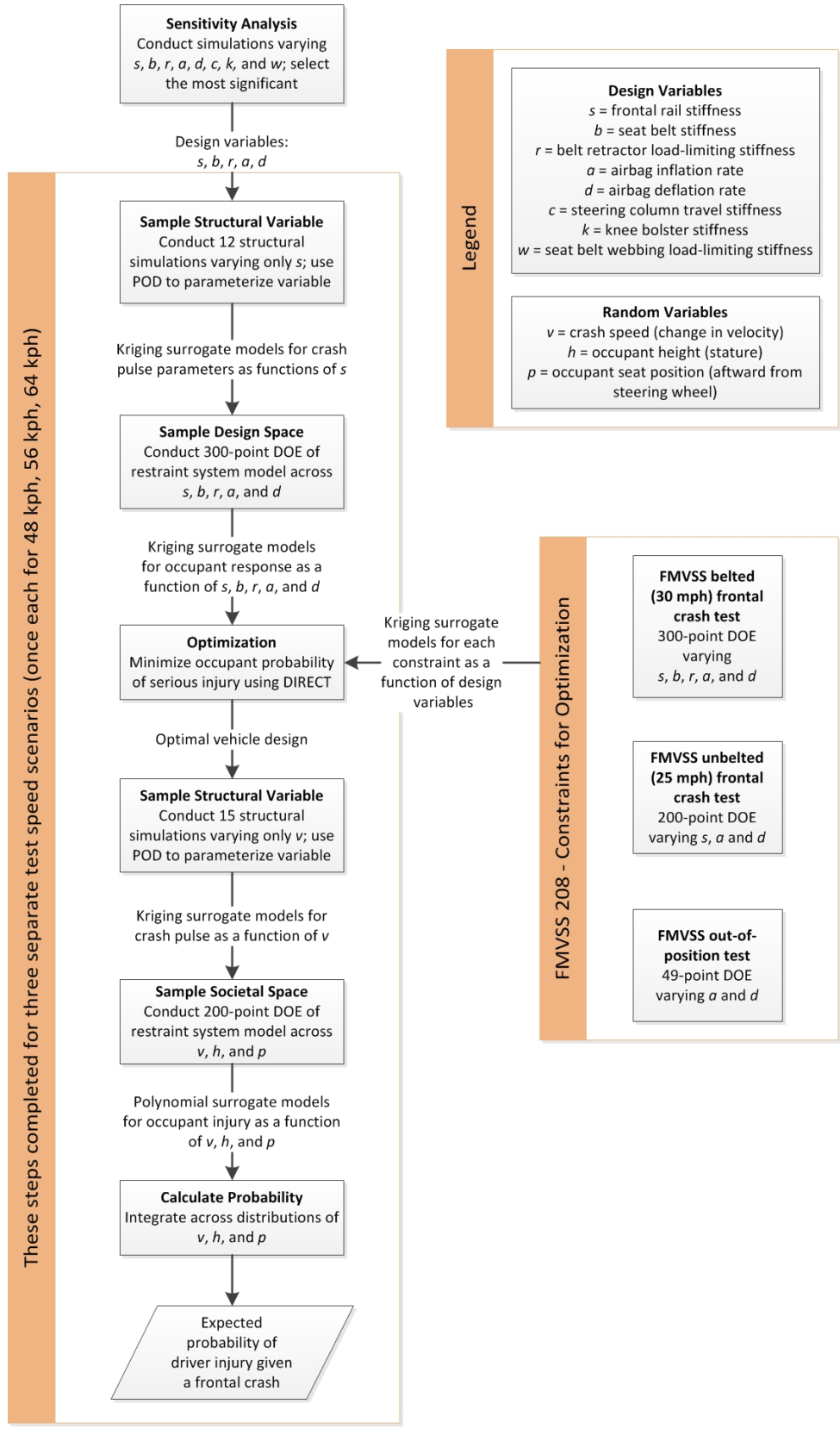


Figure 5.5: Process flow diagram for manufacturer optimization and societal modeling

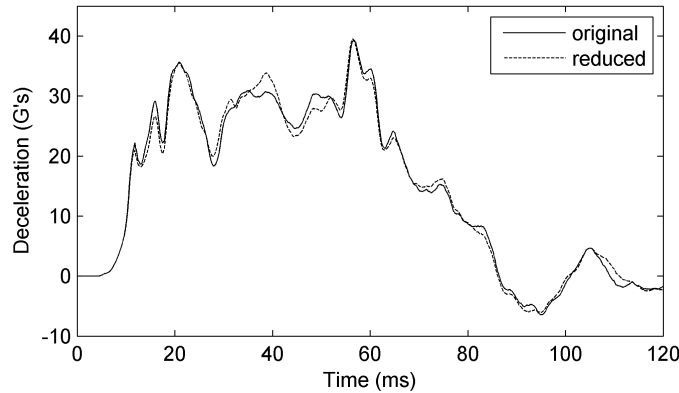


Figure 5.6: Original crash pulse with reduced representation using POD

of sampling over five design variables: frontal rail stiffness (s), seat belt material stiffness (b), load-limiting retractor function (r), airbag inflation rate (a), and airbag deflation rate (d).

However, this raises a problem by requiring that both the 10-hour vehicle and the 6-minute restraint system simulations be conducted for each sample, which is impractical. The crash pulse which links the two simulations is a 1,200-point vector, where each point represents the acceleration at each tenth of a millisecond during the vehicle response simulation. Since the curves are observed to share some commonalities in general shape, a batch of simulations for each of the three NCAP speed scenarios was conducted across the one-dimensional design space varying frame rail stiffness, and the curves were parameterized using proper orthogonal decomposition (POD), sometimes referred to as principal component analysis or eigenvalue decomposition (*Alexander et al., 2011*). The POD results showed that 5 parameters represented over 95 percent of the cumulative percentage variance, i.e., 95 percent of the original 1,200-point curves' characteristics are captured by just five variables. To achieve a full 1,200-point pulse from the five variables, the five-variable row vector is multiplied by a 5-by-1,200 transformation matrix, which means that knowledge of the five parameters can generate a full curve.

Figure 5.6 shows an example of an original curve with its parameterized, or re-

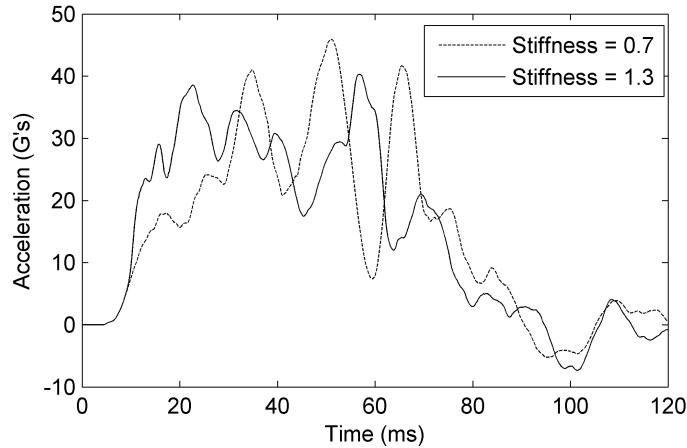


Figure 5.7: Comparison of low- and high-stiffness vehicle crash pulses

duced, representation, where it can be seen that the reduced representation very closely matches that of the actual crash pulse. Thus, kriging surrogate models (Lophaven *et al.*, 2002) were fit to find expressions for each of the five new parameters as a function of vehicle frontal stiffness, and those combined with the transformation matrix create a full crash pulse as a function of vehicle frontal stiffness. Samples of two curves produced using the kriging surrogate models and POD transformation are shown in Figure 5.7, where the dotted line represents a low-stiffness pulse and the solid line a high-stiffness pulse, both in a 35-mph crash scenario. The plot shows that the low-stiffness vehicle pulse has a slower initial rise in acceleration, but it has a higher peak later in the crash event than that of the higher-stiffness vehicle.

Each of the three NCAP scenarios was then simulated using a 300-point DOE sample of the restraint system model spanning the five-variable design space, and kriging surrogate models were fit to the response data.

Aside from maximizing performance in NCAP tests, vehicle manufacturers must also consider regulatory constraints that influence design decisions. Three FMVSS requirements were accounted for and incorporated into the optimization formulation as constraints. Each of these has injury thresholds that the ATD may not exceed, corresponding with a thirty-percent probability of injury in several body regions. Two

of these tests are full-engagement frontal barrier tests with mid-size male ATDs, one performed at 30 mph with a belted occupant and one performed at 25 mph with an unbelted occupant. The third test is a static out-of-position test with a small, unbelted female ATD, where the dummy's chin starts out on the rim of the steering wheel prior to inflating the airbag. For each of these, DOE studies were conducted across the applicable design variables, and surrogate functions were developed to be used in the constraints during optimization.

With the objective and all constraints represented as functions, the formulation can be represented mathematically as Equation (5.1):

$$\begin{aligned}
& \underset{s,b,r,a,d}{\text{minimize}} && P_{AIS3+} = 1 - (1 - P_{head})(1 - P_{neck})(1 - P_{chest})(1 - P_{femur}) \\
& \text{where} && P_i = f_i(s, b, r, a, d), \text{ for } i = \{head, neck, chest, femur\} \\
& && T_{50th} = \{700, 1.0, 63, 10\} \\
& && T_{5th} = \{700, 1.0, 52, 6.8\} \\
& \text{subject to} && F_{30mph,i} = g_{1_i}(s, b, r, a, d) \leq T_{50th,i}, \forall i \\
& && F_{25mph,i} = g_{2_i}(s, a, d) \leq T_{50th,i}, \forall i \\
& && F_{static,i} = g_{3_i}(a, d) \leq T_{5th,i}, \forall i \\
& && x_l \leq s, b, r, a, d \leq x_u.
\end{aligned} \tag{5.1}$$

Here, the objective function is the overall probability of injury from Equation (2.4), where each of the four injury modes is a kriging surrogate function f of the five design variables. Also, the injury thresholds T_{50th} and T_{5th} are the four values for the mid-size male and the small female, respectively, which correspond with a ten-percent probability of injury. These values are used in the three FMVSS constraints, which are functions of the design variables: the 30-mph crash with a belted mid-size male occupant ($F_{30mph,i}$), the 25-mph unbelted crash which is not a function of the two

belt-related variables, b and r , ($F_{25\text{mph},i}$), and the static out-of-position test ($F_{\text{static},i}$) which uses a small female ATD and is not a function of s , b , or r since there is no vehicle motion or seat belt. Lastly, lower and upper bounds were required for the five design variables, which were placed sufficiently far away such that no bounds would be active. Optimization was performed using the DIRECT global optimization algorithm (*Jones, 1999*), which was chosen because all of the functions are fast to evaluate. This formulation was optimized for each of the three NCAP test speeds, resulting in an optimal vehicle design for each scenario.

5.2.3 Societal Uncertainty

Each of these optimized vehicle designs was then placed in a simulated crash across the distributed range of the three random variables, occupant height (h), seating position (p), and crash change in velocity (v). In a similar manner to the previous DOE studies, the variable associated with the full vehicle model, v , was first simulated and parameterized for each of the three optimal vehicle designs. POD analysis was again conducted to parameterize the 1,200-point pulses to 5 parameters, again capturing at least 95 percent of the cumulative percentage variance. Using this, kriging surrogate models were developed so that a crash pulse for each of the optimal vehicle designs could be mathematically constructed for a given crash speed. Next, a 200-point OLHS DOE study of the restraint system model was conducted across the three continuous random variables, and linear regression was applied to the results to obtain polynomial functions for injury probabilities as a function of the three random variables, P_{rand} .

Height distribution data for American men from the National Health Statistics Report was fit to a normal distribution (*McDowell et al., 2008*), shown in Equation (5.2)

where h is measured in centimeters.

$$f(h) = \frac{1}{8.76\sqrt{2\pi}} e^{-\frac{(h-176.3)^2}{2 \times 8.76^2}} \quad (5.2)$$

To modify occupant height in the restraint system simulation model, a MADYMO feature called “madyscale” was invoked to generate ATD models of continuously varying sizes. Heights were specified according to the distribution in Equation (5.2), and other body size parameters were scaled in proportion to the height for an occupant with an average body mass index (BMI).

Humans of different sizes typically have different thresholds of forces and moments that can be withstood prior to injury. To account for this, the injury criteria outlined in Figure 2.14 were scaled in accordance with the conclusions found by Eppinger et al. (2000), which provide separate neck criteria critical intercept values, chest deflection thresholds, and femur compression thresholds for the three standard ATD sizes (small female, mid-size male, and large male). The Head Injury Criterion is identical for each of the three ATDs, and so no scaling was necessary for head injury probability. For the other three injury locations, the reported numbers were interpolated and extrapolated to find specific threshold values for any given percentile of human size (z) between 0 and 100, as determined in this model by the appropriate quantile from within the height (h) distribution. The neck injury criterion (N_{ij}) is calculated based on critical intercept values for tension (T_{int}), compression (C_{int}), flexion (F_{int}), and extension (E_{int}); these intercept values provided by Eppinger et al. were fit to linear regression models, which are provided as Equations (5.3), (5.4), (5.5), and (5.6).

$$T_{int} = 43.66z + 4254 \quad (5.3)$$

$$C_{int} = 39.56z + 3849 \quad (5.4)$$

$$F_{int} = 2.889z + 148.9 \quad (5.5)$$

$$E_{int} = 1.244z + 64.78 \quad (5.6)$$

For the chest deflection and femur compression injury mechanisms, values are given which correspond with a ten-percent probability of serious (AIS3+) injury (*Eppinger et al.*, 2000). To incorporate this into the same injury probability curves from Figure 2.14, the numbers measured from the range of human size models are scaled to “mid-size male equivalent” values. The scaling factors depend on the corresponding ten-percent probability thresholds, and least-squares regression on the values for the three standard ATDs provided Equation (5.7) for the chest deflection threshold ($D_{chest,th}$) in millimeters and Equation (5.8) for the femur compression force threshold ($F_{femur,th}$) in kilonewtons.

$$D_{chest,th} = -0.001z^2 + 0.2988z + 50.53 \quad (5.7)$$

$$F_{femur,th} = 0.0656z + 6.556 \quad (5.8)$$

Manary et al. (1998) conducted a study with human subjects to investigate how driver stature influences seat position in the fore-aft direction. Subjects were chosen that resemble the sizes of the three main dummies (small female, mid-size male, large male), and the mean seat position (μ_p) was recorded for each dummy size. These numbers were fit with second-order polynomial curves to estimate the impact of height on mean seat position, shown in Equation (5.9). An estimate of the standard deviation of the seating position (σ_p) is taken from Flannagan et al. (1998) to be 30 millimeters. Thus, with a given height h , a normal distribution was constructed using Equation (5.10) where p , μ_p , and σ_p are measured in meters.

$$\mu_p = -0.15h^2 + 0.88h - 0.93 \quad (5.9)$$

$$f(p) = \frac{1}{\sqrt{2\pi\sigma_p^2}} e^{-\frac{(p-\mu_p)^2}{2\sigma_p^2}} \quad (5.10)$$

The data have been adapted to coincide with coordinates of the occupant and restraint system simulation, and they represent MADYMO model adjustments to the positioning of the entire seat and seat belt system along with the occupant.

Finally, the frontal crash speed distribution shown previously in Figure 5.1 was fit to a log-normal distribution, and it is represented as Equation (5.11) where v is in mph.

$$f(v) = \frac{1}{v\sqrt{2\pi \times 0.44^2}} e^{-\frac{(\ln v - 2.58)^2}{2 \times 0.44^2}} \quad (5.11)$$

However, it is important to recognize that in multi-vehicle crashes and in crashes with non-rigid objects, a heavier vehicle will have a lower Δv . To account for this phenomenon, the speed distribution was adjusted according to the conservation of momentum equation, assuming contact with a vehicle of average U.S. fleet mass, approximated at 1,650 kilograms; the adjustment factor used is shown in Equation (5.12).

$$\frac{v_{adjusted}}{v_{original}} = \frac{2 \times 1650}{m + 1650} \quad (5.12)$$

According to data from the NASS GES (*NHTSA*, 2011b), approximately 75 percent of frontal crashes in 2009 involved more than one vehicle, and thus the adjustment factor of Equation (5.12) was applied to the crash distribution curve of Equation (5.11) for only 75 percent of the distribution, as given by Equation (5.13).

$$f_{adjusted}(v) = 0.75 \times f(v_{adjusted}) + 0.25 \times f(v_{original}) \quad (5.13)$$

Therefore, if the vehicle is heavier than the average fleet vehicle, the lower adjusted speed will shift the probability distribution function $f_{adjusted}(v)$ to the left, as shown in Figure 5.8. Because the data used do not categorize the crash distribution information by single- and multiple-vehicle events, this study assumes that the crash

speed distributions can be treated as identical. While occupant stature and sitting position have a clear relationship as defined by Equations (5.9) and (5.10), crash speed was assumed to be independent of the other two random variables.

To account for all three random variable distributions, the injury probability function was multiplied by the distributions from Equations (5.2), (5.10), and (5.11), and integrated across the appropriate ranges of each variable. The triple integral function given by Equation (5.14) was evaluated, yielding a single expected probability of injury $E[P]$ given that a frontal crash occurred at some random speed with some random, male driver inside.

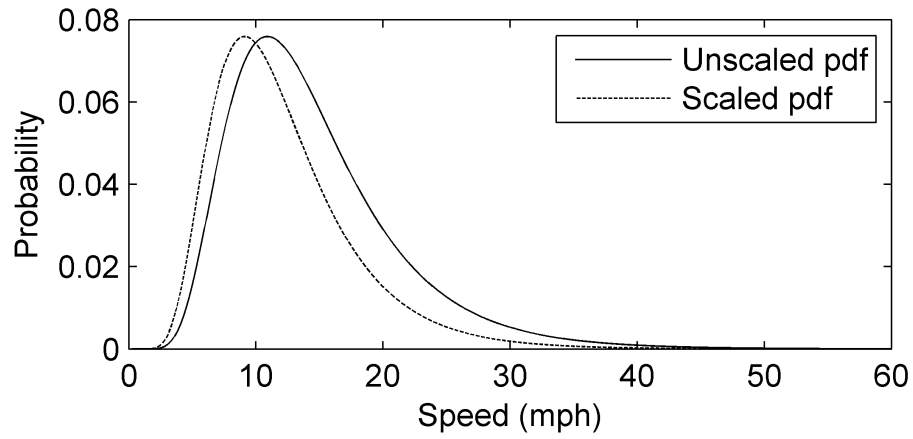
$$E[P] = \int_0^{75} \int_1^{19} \int_{150}^{200} P_{rand}(h, p, v) f(h) f(p) f(v) dh dp dv \quad (5.14)$$

This is the value that regulatory agencies should seek to minimize, as it corresponds to an expected total number of on-road injuries.

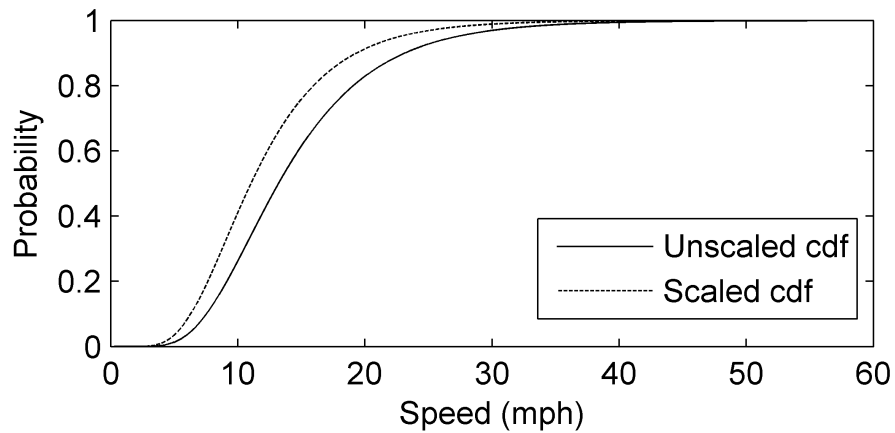
Another option for calculating the expected injury probability without integration is to run large Monte-Carlo simulations on the surrogate models, where the distributions of sampled points are representative of the random variable distributions previously described. Expected injury probability was calculated using both the integral and the Monte Carlo techniques, where the definite integral was computed using a quadrature function and the weighted Monte Carlo method included 100,000 samples, and the results exhibited the same trends using both methods. The results presented in the next section were derived using the integration approach described by Equation (5.14).

5.3 Results

Using the physics-based simulation tools in the manner described in Section 5.2, an optimal vehicle design for the 2003 Ford Explorer was obtained for each of the three



(a)



(b)

Figure 5.8: Probability distribution functions (top) and cumulative distribution functions (bottom) of frontal crash speeds; unscaled (solid line) is used for single car crashes, and scaled (dotted line) is used for two-car crashes involving the heavier Ford Explorer

NCAP scenarios: 30-mph, 35-mph, and 40-mph frontal barrier tests. These three optimal designs were then simulated across a range of uncertain societal variables and an expected probability of injury was calculated given that a crash occurred.

5.3.1 Optimal Vehicle Designs

The domain of each design variable was determined using sequential approximate optimization, where the computational DOE studies and subsequent optimization were iteratively conducted three times. Each iteration used information about the previous optimizers to determine the appropriate upper and lower bounds for each variable, and in the third iteration interior solutions were found. The final variable domains are presented in Table 5.2 along with the optimal vehicle designs from the manufacturer’s formulation, where all of the values are the scaling factors from the original simulation models described in Table 5.1. For variables that represent curves, a scaling factor of two indicates that all of the dependent values in the curve were doubled. None of the three regulatory constraints were active at the optimal solutions, indicating that for this particular vehicle, minimizing injury for NCAP is sufficient for meeting the FMVSS requirements.

Scenario Speed	Frontal frame stiffness, s	Seat belt material stiffness, b	Load-limiting retractor function, r	Airbag inflation rate, a	Airbag deflation rate, d
Variable domain allowed	[0.125, 2]	[0.25, 6]	[0.25, 2]	[0.25, 2]	[0.72, 5.77]
48 kph	0.80	3.81	0.72	1.12	4.76
56 kph (baseline)	1.79	2.63	1.05	0.88	4.47
64 kph	1.62	3.01	1.23	0.82	4.24

Table 5.2: Optimal vehicle designs for three NCAP scenarios

Some of the variable trends are clear in the table: As test speed increases, optimal retractor stiffness and load-limiting function (r) increases, exerting higher belt forces

on the occupant. The computations show that this effect causes the main belt force to occur while the occupant is in contact with the airbag, such that the retractor and airbag absorb the energy of the occupant simultaneously. Also evident is that both the optimal airbag inflation rate (a) and deflation rate (d) decrease as test speed increases. The slower deflation rate at higher speeds allows the occupant to “ride down” the impact for a longer duration, and the slower inflation rate balances out the total pressure inside the airbag that would otherwise be higher due to the lower deflation rate.

The frontal frame stiffness (s) increases sharply between 30 and 35 mph, followed by a slight decrease as the test speed is raised to 40 mph. It is expected that frontal stiffness should increase as speed of impact increases, seeing that more energy will need to be absorbed over the same crush distance. The decrease between 35 and 40 mph is unexpected, but upon further inspection it is evident that increasing the frontal stiffness of the frame elements above a 1.6 scaling factor does not significantly affect the crash pulse. Therefore, this decrease is an artifact of the model’s insensitivity to high stiffness values. Finally, seat belt stiffness (b) shows non-monotonic behavior, which indicates that either the belt variable is responding to changes in other variables, or the response is simply not very sensitive to small changes at the high seat belt stiffness values shown. It should again be noted that this variable acts in series with a pretensioner and the load-limiting retractor, and the interactions among these parameters and variables are likely affecting the optimal designs.

5.3.2 Injury Probabilities

The three vehicle designs from Table 5.2 were next simulated across the range of the three random variables so that an expected probability of injury given a crash is computed for each vehicle using Equation (5.14). For the baseline scenario, where the NCAP frontal test speed is 35 mph, the expected probability of injury is ap-

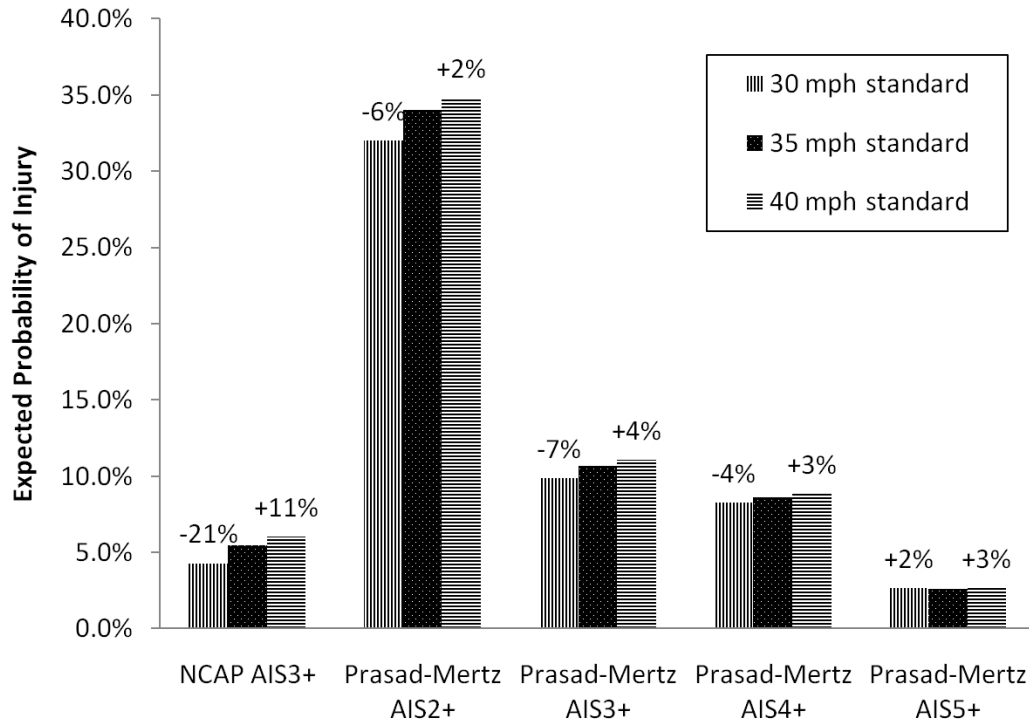


Figure 5.9: Expected injury probability for three NCAP scenarios using (left) NCAP serious injury probability curves and (right) Prasad-Mertz injury severity curves for moderate, serious, severe, and critical injury levels

proximately 5.4 percent. Decreasing the NCAP speed by 5 mph yields an expected probability of injury of 4.3 percent, a 21-percent decrease in injury probability, and increasing the speed by the same amount yields an expected injury probability of 6.0 percent, an 11-percent increase from the baseline scenario. These results are shown in the leftmost bar grouping in Figure 5.9. Therefore, if reducing serious injuries measured by the NCAP injury curves from Figure 2.14 is the only objective of policymakers, this analysis suggests that the frontal crash test should be conducted at a lower speed, closer to speeds in which the majority of on-road crashes occur.

One possible concern of these results is the impact on more severe injuries. While serious injuries may occur frequently at relatively low crash speeds, fatal injuries are rare at these low speeds and much more likely at high, less frequently occurring crash speeds. For the same three vehicles, the four rightward bar groupings in Figure 5.9 show the expected probability of four different injury severities from the AIS: mod-

erate (level 2), serious (level 3), severe (level 4), and critical (level 5), as computed using a set of injury curves developed by Prasad and Mertz (*NHTSA*, 1995, 1999). While fatal (AIS 6) injury curves could not be obtained, approximately half of all level 5 injuries result in death and are a reasonable indicator of fatality rates.

One further investigation was undertaken to determine the extent to which the uncertainty considerations influence the results. The three sources of uncertainty could be simplified out of the integral in Equation (5.14) by using the mean values, which would reduce the complexity of the calculation with a potential sacrifice in result validity. The integral calculations were conducted using combinations of mean values and probability distributions, and it was found that the position distribution is the least influential of the three, followed by the height and speed distributions. Substituting the seat position mean value for its distribution function lowered the expected probability of injury by 0.6-3.3 percent, whereas substituting the fixed mean value of occupant height lowered the expected probability of injury by 9-13 percent; substituting both the height and position functions together with mean values reduced the outcome by 10-15 percent. As expected, the speed distribution has a much stronger effects on the results, and using the mean value of 14.5 miles per hour reduced the expected probability of serious injury by 43-61 percent. This analysis shows that each of the random variables adds meaning to the results, with the position variable being the least influential and the first choice for removal if simplification is required. The influence of the crash speed distribution variable demonstrates the impact that this distribution curve has on the expected injury probability, and the analysis framework presented in this chapter would be useful for calculating the impact that changes to on-road crash speeds (e.g., from improved active safety measures or reduced posted speed limits) would have on expected injuries.

5.4 Discussion

5.4.1 Manufacturer Vehicle Design

The values presented in Table 5.2 may not be the true optimizers for occupant safety in these vehicle simulations. This is because surrogate models were used for optimization, and the results depend on the model architectures chosen and their goodness-of-fit; the kriging surrogates used are not an exact match for the simulation behavior, and therefore different surrogates yield different optima. To ensure that the solutions found are reasonable, full simulations for each of the three designs in each of the three speed scenarios were conducted. The results, shown in Table 5.3, clearly show that the stated optimal vehicle designs performed better in their respective frontal barrier tests than the other two; i.e., of the three vehicles crashed at 30 mph, the design optimized to 30 mph in Table 5.2 had the lowest occupant injury probability, and the same was true for the other two crash speeds.

Crash Speed	30 mph-optimal vehicle	35 mph-optimal vehicle	40 mph-optimal vehicle
30 mph	8.90%	10.05%	13.06%
35 mph	17.50%	10.07%	11.99%
40 mph	68.07%	13.18%	12.73%

Table 5.3: Simulated injury probability for each optimal vehicle design at each test speed

It is interesting, and perhaps counterintuitive, to note that in Table 5.3 the vehicle optimized for the high test speed performed worse in the lowest crash speed scenario than at the two higher crash speeds. Further inspection of the simulation output revealed that the stiff belt retractor function combined with the lower crash energy caused the majority of the occupant deceleration to occur prior to contact with the airbag, which resulted in more abrupt chest deceleration and neck moments inflicted by the seat belt acting alone. This is also evident, though to a lesser extent, with the

vehicle optimized to 35 mph at the slower crash speed. Another notable figure is the exceptionally poor performance of the vehicle optimized for the low test speed in the highest crash speed scenario, with a 68-percent probability of serious injury. This is a result of the softer belt retractor function and faster-deflating airbags causing hard contact of the head and chest with the rim of the steering wheel.

5.4.2 Societal Injury Probability

The serious level injuries computed with the Prasad-Mertz injury probability curves have about twice the probability of injury as from the NCAP curves, with the baseline at 9 percent rather than 5 percent as shown in Figure 5.9; also, the impact of changing the test standard is about half of that obtained with the NCAP formulas. These result discrepancies are a consequence of the differences in the injury probability curves, which stresses the importance of the accuracy of these curves. For each of the four injury severities measured by the Prasad-Mertz criteria with the exception of level 5, the probability of injury decreases with the lower NCAP test speed and increases with the higher NCAP test speed, supporting the results using the NCAP level 3 criteria. However, critical (AIS level 5) injuries increase slightly when the test speed is reduced, and they also increase when the test speed is raised. Thus, lowering the test speed is predicted to noticeably reduce moderate, serious, and severe injuries at the cost of slight increases to critical injury rates and possibly fatalities.

Repeating these calculations with different crash speed distributions from those presented in Figure 5.8 showed that the results are highly dependent on this input data. When the probability distribution function is shifted to the left, the results more strongly suggest a slower regulatory test speed, while shifting the curve to the right advises toward keeping the current standard or raising the speed. Further analysis could show how advances in technology such as pre-crash braking and forward collision

warning systems could potentially lower this speed distribution and therefore affect probable injuries and optimal regulations.

5.4.3 Broader Implications

While this chapter presents preliminary results for one specific crash scenario, motor vehicles on the road get crashed with a wide variety of directions, speeds, and occupants. To generate reliable recommendations for regulatory agencies, this process should be expanded to broaden the scope of the present study. Two potential areas to achieve more meaningful results are to include a wide sample of vehicles and incorporate tests for different crash modes. Vehicle types from different segments (e.g., compact, mid-size, SUV, pickup truck) and different makes should be simulated in the manner prescribed in this chapter to build a stronger understanding of the impact of the standards on the entire vehicle fleet.

The societal random variables considered in this chapter also hold a host of assumptions. First, only three random variables are considered, and not all of the potential interactions are explored, such as the interactions between driver stature and crash speed and between the number of vehicles involved and crash speed. The occupant modeling thus far only considers male statures with average body mass index and sitting height values. The value of the results would benefit from additional human size variables and female occupant models with the appropriate size distributions. Lastly, these results assume that the injury criteria curves are valid indicators of occupant injury probability, and also hold the premise that the dummy measurements correlate well with forces inside a human body.

One emerging technology with the potential to improve crash safety is the use of adaptive vehicle structures and restraint systems. By incorporating sensors and smart materials in vehicles that can change characteristics depending on an applied signal, different properties such as stiffness could be achieved in a single material

by simply changing the electronic signal. This would effectively allow one vehicle to achieve the characteristics of all three optimal designs presented in Table 5.2, as well as the optimal designs for any other crash scenario and occupant combination. The method presented in this paper could be used to evaluate the benefit of implementing adaptive materials, and different regulatory policies could be assessed to determine the best way to encourage the adoption of these technologies.

5.5 Conclusions

A simulation approach to examining the impact of the frontal NCAP standardized test on road traffic injuries has been introduced with preliminary counterfactual policy results. While this chapter considers only frontal crash modes and a single vehicle type and model, the outlined methodology could be extrapolated with a wider range of scenarios in order to draw more conclusive results. Although the procedure followed per Figure 5.5 is already computationally expensive, computer processing power and capabilities are continually improving over time and will make this type of large simulation-based analysis more practical.

For the single crash mode and vehicle used here, the results suggest that lowering the current 35-mph NCAP frontal crash test speed would drive vehicle design changes that improve overall occupant safety for non-critical injuries. A 5-mph decrease in the test speed is predicted to reduce occupant serious injury probability by as much as 21 percent, although this simulation-based analysis has important limitations. Additionally, since the optimal design for the 30-mph (lower-speed) test has a softer frontal frame, it would likely result in a less aggressive front end and be safer for occupants in vehicles with which it may crash, an added societal benefit that is not captured by the current analyses.

Further analysis with different types of standardized tests may show that optimal tests may be designed by considering the frequency of occurrence and the severity or

importance of the possible scenarios. The results of this chapter suggest that policy should be driven by these types of computational tools and scientific analyses, which would potentially yield significant improvements in social welfare.

CHAPTER VI

Blastworthiness and Mobility Considerations in Design for Safety

*“Technology is dominated by two types of people:
Those who understand what they do not manage, and
those who manage what they do not understand.”*

-Archibald Putt

6.1 Introduction

Occupant safety is a top priority of military vehicle designers, and in recent years this focus has shifted heavily toward the threat of underbody explosions due to landmines and IEDs, as discussed in Section 2.3.4. The MRAP has been replacing the HMMWV in many tactical situations because of its superior occupant protection in blast events. Much of the MRAP’s safety advantage is tied to its mass, where the MRAP is approximately four times that of its predecessor; however, this gives the MRAP comparatively poor fuel economy and mobility. Because of the link with vehicle mass, fuel economy improvements in military vehicles have been lagging because they are considered to trade off with safety. Since convoys transporting fuel to military operations have become a major target of adversaries (*Eady et al.*, 2009), using vehicles that consume more fuel can be disadvantageous to broader safety objectives.

Several arguments have been made over the years for improved fuel economy in U.S. military vehicles: The environmental impact of carbon emissions, national security concerns regarding dependence on supplies from geopolitically unstable regions, and costs. Safety advocates tend to claim that occupant safety is more important than fuel-related concerns, but this chapter shows the complex relationship between fuel consumption and overall personnel safety. The next section presents the development of a combined model to account for safety concerns related to both blastworthiness and fuel consumption, where unknown parameters are outlined and estimated. Subsequent sections present the results of optimizing this model under different scenarios and assumptions, along with discussions of the implications of these results and possible directions for further research.

6.2 Model Development

A mathematical modeling framework was developed to quantify the impact of vehicle and seating design variables on blast protection and fuel consumption, as well as the impact of fuel consumption on fuel convoy casualties. Here, a casualty refers to any personnel injury of at least moderate severity as defined by the AIS (*AAAM*, 1990), including more severe injuries and fatalities. The ensuing subsections present the blastworthiness modeling technique, which takes advantage of physics-based computational models of a vehicle and a vertical drop tower system; the fuel consumption model, which uses empirical data on military vehicles; and the joint systems optimization formulation that seeks to minimize total casualties by finding an optimal vehicle mass.

6.2.1 Blast Protection Modeling

This chapter uses the same military vehicle safety modeling approach as that described in Section 4.2, using the simplified rigid finite-element vehicle-representing

model combined with the multibody dynamics-based vertical drop tower model shown in Figure 4.1. The computational DOEs and surrogate models previously developed are used in this chapter for modeling the impact of vehicle mass and seating system parameters on the four injury criteria used to calculate the probability of a vehicle occupant casualty in a blast event.

As discussed in Chapter IV, the U.S. Army criteria for vehicle occupant blast safety are ambiguous, and three formulations for optimizing safety with respect to these objectives were presented and discussed. The present chapter assumes the objective for minimizing injury probability using postulated injury criteria curves from Section 4.3.3; while the injury probability functions may not represent accurate injury rates, this approach to optimization was determined to be the most meaningful for representing injury probabilities under blast uncertainty. The full optimization formulation is provided as Equation (6.4), with vehicle mass (m_v) as an input parameter and three design variable inputs: seat EA system stiffness (s_{EA}), seat cushion stiffness (s_c), and seat floor pad stiffness (s_f):

$$\begin{aligned}
& \underset{s_{EA}, s_c, s_f}{\text{minimize}} && \int_0^{\infty} P_{AIS2+} \cdot \phi(a_{peak}) \cdot da_{peak} \\
\text{where} &&& P_{AIS2+} = 1 - (1 - P_{neck})(1 - P_{lumbar})(1 - P_{tibia}) \\
&&& \phi(a_{peak}) = \frac{1}{\sqrt{2\pi\sigma_{a_{peak}}^2}} \cdot e^{-\frac{(a_{peak}-\mu_{a_{peak}})^2}{2\sigma_{a_{peak}}^2}} \\
&&& P_{neck} = 1 - e^{-(F_{neck}/5.82)^6} \\
&&& P_{lumbar} = 1 - e^{-(F_{lumbar}/7.57)^{18.5}} \\
&&& P_{tibia} = 1 - e^{-((1.57+0.42F_{tibia})/5.13)^{7.43}} \\
&&& F_{neck} = e^{(3.84+0.12s_{EA}+0.88s_c+0.002a_{peak}+0.058s_{EA}s_c+0.000084s_{EA}a_{peak} \\
&&& \quad -0.000063s_c a_{peak}-0.058s_{EA}^2-0.14s_c^2-0.00000054a_{peak}^2)} \\
&&& F_{lumbar} = e^{(5.66+0.12s_{EA}+0.81s_c+0.002a_{peak}+0.062s_{EA}s_c+0.000087s_{EA}a_{peak} \\
&&& \quad -0.000068s_c a_{peak}-0.059s_{EA}^2-0.13s_c^2-0.00000056a_{peak}^2)} \\
&&& F_{tibia} = 332 - 245s_c - 80.2s_f + 1.30a_{peak} + 35.8s_c s_f \\
&&& \quad + 14.0s_f^2 + 0.0012a_{peak}^2 \\
&&& \mu_{a_{peak}} = 4 \times 10^6 m_v^{-1.023} \\
&&& \sigma_{a_{peak}} = 2 \times 10^6 m_v^{-1.035} \\
&&& \text{subject to } lb \leq s_{EA}, s_c, s_f \leq ub.
\end{aligned} \tag{6.1}$$

The parametric results of optimizing the vehicle's seating system for a range of vehicle masses are presented again as Figure 6.1. These results represent a Pareto frontier with two design objectives: minimizing injury probability under blast loading and minimizing vehicle mass for improved fuel economy and mobility.

Fitting a curve to the Pareto data yields a closed-form expression for seating system-optimized occupant injury probability as a function of vehicle mass, shown in Equation (6.2), which decreases asymptotically toward zero as mass approaches

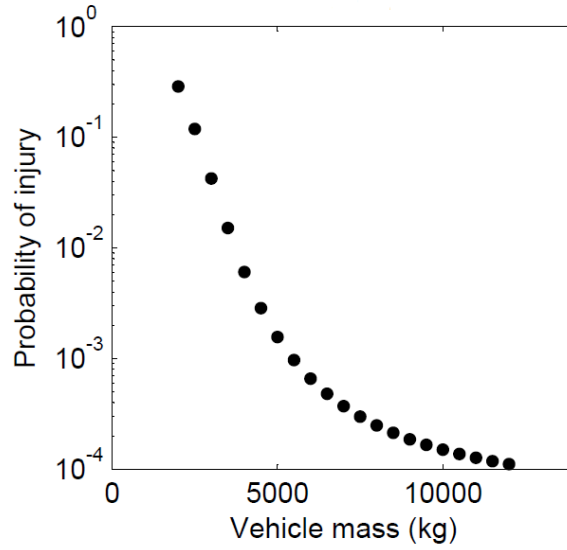


Figure 6.1: Pareto frontier for minimizing vehicle mass and occupant injury probability under blast loading

infinity:

$$P_{AIS2+} = 2.178 \times 10^{14} m_v^{-4.506}. \quad (6.2)$$

This property implies that, when solely considering blast protection, increasing vehicle mass will always decrease an occupant’s probability of injury; however, it is evident, especially considering the logarithmic scale of Figure 6.1, that the safety returns diminish significantly on a per-kilogram basis as the vehicle mass gets high. For example, increasing the mass of a 2,500-kilogram vehicle by 1,000 kilograms decreases an occupant’s predicted injury probability by 87 percent, whereas increasing a 10,000-kilogram vehicle by the same absolute amount only reduces the injury probability by 15 percent. This chapter was motivated by the hypothesis that the safety concerns associated with fuel consumption will at some point outweigh these marginal benefits, at which point overall safety improvements will no longer be realized with mass increases. The following subsection presents a model for fuel consumption as a

function of vehicle mass.

6.2.2 Fuel Consumption Modeling

The fuel consumption model was developed using empirical data, rather than mathematical simulation, based on publicly available specifications of presently employed U.S. ground vehicles (*Connors and Foss, 2009*). The database contains 48 U.S. Army ground vehicles that include information on vehicle curb weight, driving range, and fuel tank capacity, from which estimates of fuel consumption (in gallons per mile) for each vehicle were calculated. As expected, fuel consumption tends to increase as curb weight increases. A linear fit with coefficient of determination of 0.92 is presented in Equation (6.3) and shown, along with the data points, in Figure 6.2. Here, FC is fuel consumption and m_v is vehicle mass in kilograms.

$$FC = 2.053 \times 10^{-5}m_v + 1.971 \times 10^{-2} \quad (6.3)$$

This model intentionally disregards vehicle powertrain design parameters, and in doing so operates under the assumption that these data represent vehicles with powertrain designs optimized for their respective masses. If the model were enhanced to include such powertrain factors, constraints would be needed to ensure that the vehicles meet the specification requirements of the military, such as minimum acceleration and top speed. It is postulated that these performance attributes have their own contributions to the safety of ground personnel, and this is left as an opportunity for future research.

6.2.3 Combined Casualties Model

The two models are combined to generate a total number of casualties that can be expected when a particular multipurpose vehicle is in operation, based entirely

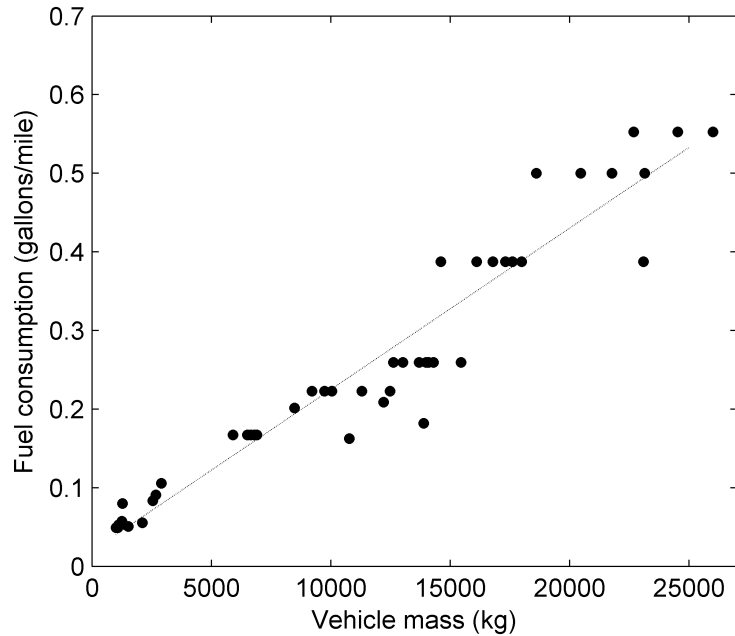


Figure 6.2: Fuel consumption vs. vehicle mass of 48 U.S. Army ground vehicles

on its mass with the assumption that other design parameters have been optimized accordingly. This framework is based on several estimates regarding the magnitude of some of the threats facing ground troops, which are difficult to verify due to a lack of publicly-available data. Therefore, the results presented here are not suitable for detailed decision-making; rather, the modeling and optimization process can provide insights on tradeoffs when designing new military ground vehicles and making strategic contracting and deployment decisions. The novelty of the approach is the inclusion of fuel consumption into the safety design optimization formulation of a multipurpose vehicle, such as the HMMWV or the MRAP, which accounts for a significant portion of ground personnel trips.

For such modeling purposes, estimates are needed for the total number of blast and fuel convoy casualties each year. From available data and assuming that devices are planted and detonated at the same rate, it can be inferred that approximately 16,800 blast events occur in a year (*Dreazen, 2011*). Additional information needed to

develop the model are the percentage of these blast events that strike the particular multipurpose vehicle of interest, as well as the average number of occupants traveling in these vehicles. For this scenario, it is postulated that 50 percent of all blasts strike multipurpose vehicles that typically contain four occupants each.

An estimate of total fuel convoy casualties per year in a particular theater is based on 6,000 fuel convoys deployed each year with an average of one casualty per 24 convoys (*Eady et al.*, 2009). In order to use the formulation in Section 6.2.2 to calculate the impact of multipurpose vehicle fuel consumption on these fuel convoy requirements, it is also necessary to estimate the percentage of total military fuel consumption that is used by multipurpose ground vehicles, as well as the mass of currently employed multipurpose vehicles. The results presented in the subsequent section are based on the assumptions that 20 percent of total fuel is used by multipurpose vehicles, and the average of these vehicles is 5,000 kilograms. This is slightly higher than the mass of a loaded and up-armored HMMWV to account for the smaller proportion of the heavier MRAP vehicles that are currently in use. The input parameters are summarized in Table 6.1.

Symbol	Parameter	Baseline value
n_{be}	Number of blast events per year	16,800
ϕ_{bmv}	Percentage of blasts against multipurpose vehicles	0.50
n_{opv}	Average number of occupants per vehicle	4
m_b	Baseline multipurpose vehicle mass (kg)	5,000
ϕ_{fmv}	Percentage of fuel consumed by multipurpose vehicles	0.20
n_{fc}	Baseline number of fuel convoys per year	6,000
ϕ_{fcc}	Percentage of fuel convoys with a casualty	0.042

Table 6.1: Combined optimization baseline scenario parameters

The purpose of combining these models is to find the optimal multipurpose vehicle mass for minimizing expected casualties. By assembling the parameters in the manner presented in Figure 6.3, Equations (6.2) and (6.3) are used to calculate the impact

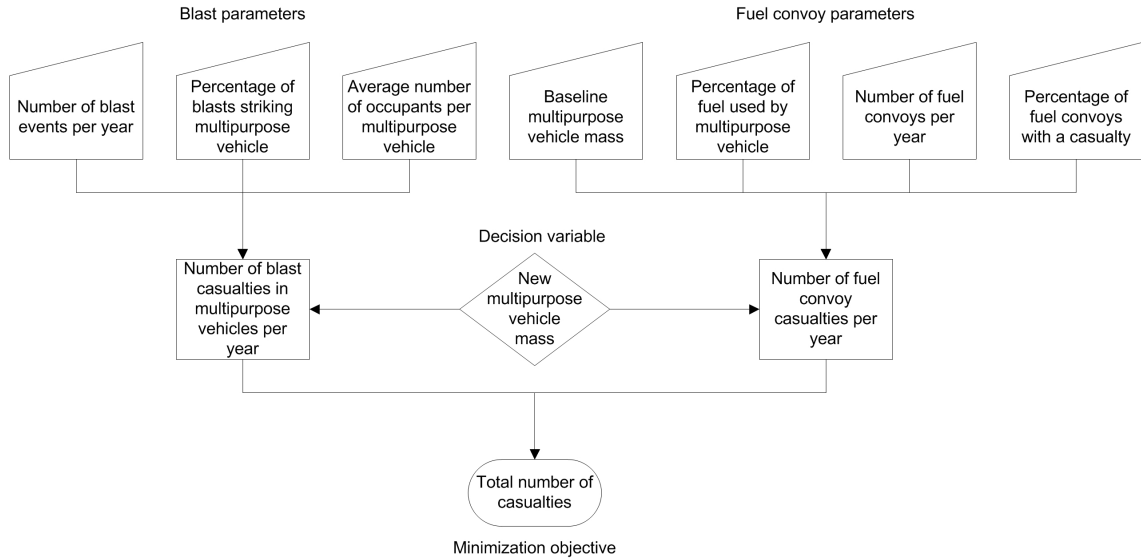


Figure 6.3: Combined casualty calculation framework

of a new vehicle mass variable on the total number of casualties. In order to account for different types of injuries that are not captured by the blast model, such as hard contact with the vehicle interior, ejection from the vehicle, and intrusion of vehicle components, Equation (6.2) was inflated by an arbitrary factor of 2. This assumes that the axial forces in the occupant’s body only account for half of the injuries that occur, and the remaining injury modes are correlated with vehicle mass in an identical manner to these forces. Since the blast protection model will drive the vehicle mass up and the fuel consumption threat model will drive vehicle mass down, a non-trivial optimal solution is anticipated.

Equation (6.4) presents the full optimization formulation, where N_{blast} is the number of blast casualties each year and N_{convoy} is the number of annual fuel convoy-related casualties:

$$\begin{aligned}
& \underset{m_v}{\text{minimize}} && N_{blast} + N_{convoy} \\
& \text{where} && N_{blast} = \phi_{bmv} \times n_{be} \times n_{opv} \times \min\{2P_{AIS2+}(m_v), 1\} \\
& && N_{convoy} = \phi_{fcc} \times n_{fc} \times R_{fc} \\
& && R_{fc} = \phi_{fmv} \times \frac{FC(m_v)}{FC(m_b)} + (1 - \phi_{fmv}) \\
& \text{subject to} && 2000 \leq m_v \leq 12000.
\end{aligned} \tag{6.4}$$

The number of annual blast casualties in multipurpose vehicles is calculated as the product of the percentage of all blasts that are against multipurpose vehicles (ϕ_{bmv}), the total number of blasts per year (n_{be}), the number of occupants per vehicle (n_{opv}), and the probability of injury as a function of vehicle mass (P_{AIS2+}) from Equation (6.2), which cannot exceed 100 percent. The fuel convoy-related casualties per year are calculated as the product of the fuel convoy casualty rate (ϕ_{fcc}), the baseline number of fuel convoys (n_{fc}), and the ratio of new scenario fuel consumption over baseline scenario fuel consumption (R_{fc}). This ratio is defined using the fuel consumption relationship of Equation (6.3) for the baseline vehicle (m_b) and the designed vehicle (m_v) as well as the percentage of total Army fuel used by multipurpose vehicles (ϕ_{fmv}). Here, the only constraints are that the vehicle mass stay within the bounds of the safety simulation to avoid extrapolation.

Since all vehicle masses within the allowable range have P_{AIS2+} values lower than 0.5, the objective function simplifies to Equation (6.5):

$$2\phi_{bmv}n_{be}n_{opv}P_{AIS2+}(m_v) + \phi_{fcc}n_{fc} \left(\phi_{fmv} \frac{FC(m_v)}{FC(m_b)} + (1 - \phi_{fmv}) \right). \tag{6.5}$$

The minimum of this equation can be solved explicitly by differentiating this equation and setting it equal to zero. Substituting Equations (6.2) and (6.3) and taking

the derivative with respect to the only design variable, m_v , yields Equation (6.6):

$$(-1.963 \times 10^{15})\phi_{bmv}n_{be}n_{opv}(m_v^*)^{-5.506} + (2.0528 \times 10^{-5})\frac{\phi_{fcc}\phi_{fmv}n_{fc}}{FC(m_b)} = 0 \quad (6.6)$$

Here, m_v^* is the optimizer, or the vehicle mass that minimizes the objective function. The equation can be rearranged to obtain an expression for m_v^* as a function of the input parameters from Table 6.1, and that formula is given as Equation (6.7):

$$m_v^* = 4255 \left(\frac{\phi_{fcc}\phi_{fmv}n_{fc}}{\phi_{bmv}n_{be}n_{opv}FC(m_b)} \right)^{-0.1816}. \quad (6.7)$$

The results presented in the following section use Equation (6.7) to explicitly solve for the optimizer, and the optimal number of casualties are calculated with Equation (6.5).

6.3 Results

The results of optimizing the baseline scenario are presented in Table 6.2. With the assumptions outlined above, it is clear that the blast threat dominates the formulation and the resulting optimal multipurpose vehicle mass is nearly double the original mass of 5,000 kilograms. Increasing the vehicle mass in this way reduces the annual number of casualties from 565 to 305, a decrease of 46 percent, and it is evident that the large majority of the resulting casualties are from fuel convoys.

	Pre-optimization	Post-optimization
Vehicle mass, m_v (kg)	5,000	9,472
Total annual casualties	565	305
Total blast casualties, N_{blast}	315	18
Total fuel casualties, N_{convoy}	250	288

Table 6.2: Optimization solution for baseline scenario

To better understand the effect that the input parameters have on the result-

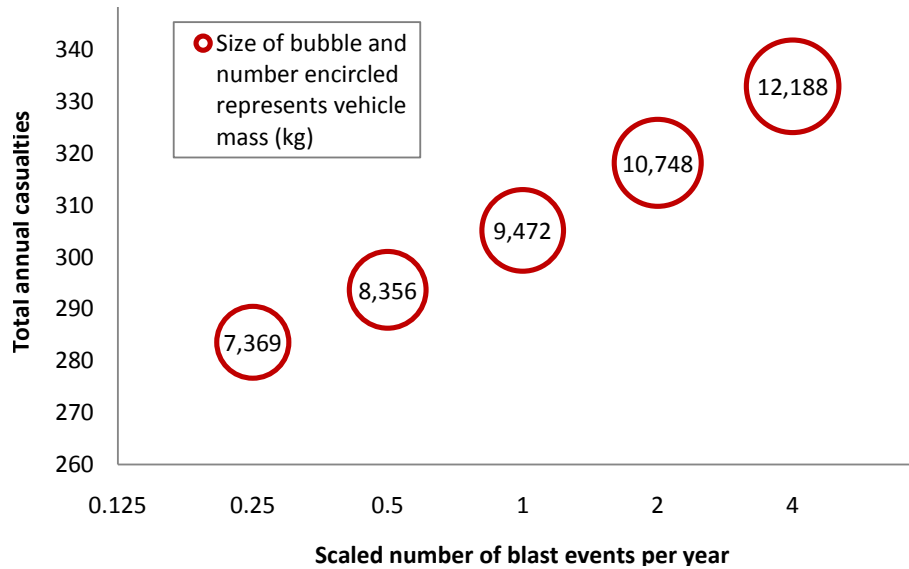


Figure 6.4: Parametric optimization results varying number of blast events per year

ing design and casualty rates, two parametric studies are presented, one varying a blast-related parameter and another varying a fuel convoy parameter. The former analysis parameterizes the number of blast events per year in order to study the effect of increased or decreased IED activity on the casualty-optimized vehicle design. Figure 6.4 presents these data, where the horizontal axis is the scaling factor for the number of blast events per year, e.g., for a scale factor of 2 the number of blasts per year is twice that shown in Table 6.1. The vertical axis represents the resulting number of total annual casualties, and the size of the bubble represents the safety-optimal vehicle mass. Here, it is evident that reducing the blast events per year will decrease both the mass of the optimal multipurpose vehicle and the number of total annual casualties. Noting the scale on the horizontal axis, the relationship between the number of blast events and the total optimized casualties is logarithmic, as is the relationship between blast events and optimal vehicle mass. There is a near linear relationship between optimal vehicle mass and casualties.

A similar parametric study was conducted, this time choosing the fuel convoy casualty rate to vary, and the results are shown in Figure 6.5. As expected, increas-

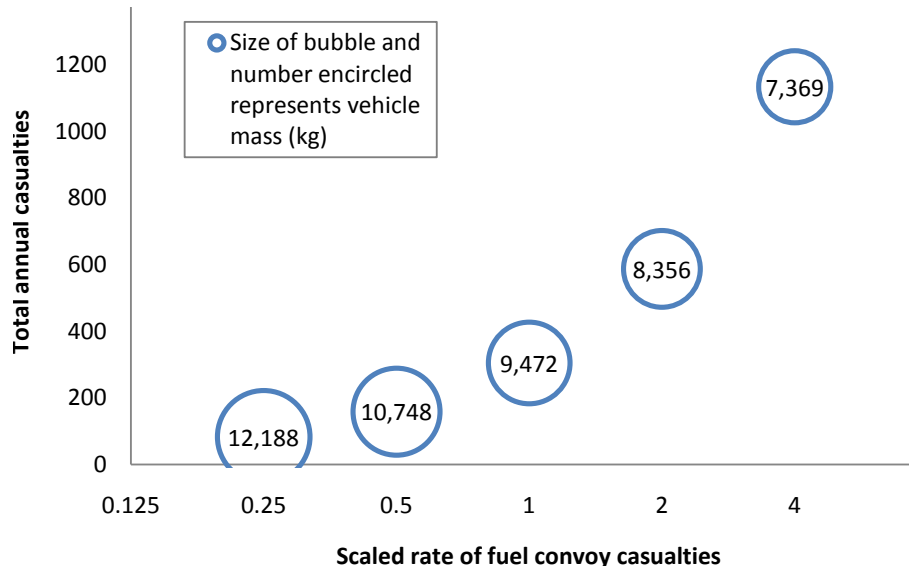


Figure 6.5: Parametric optimization results varying fuel convoy casualty rate

ing this rate decreases the optimal vehicle mass and increases the total predicted casualties. It is interesting, and perhaps intuitive when observing Equation (6.7), to note that the mass values are the same as those in the blast event parametric study of Figure 6.4; this implies that reducing a parameter in the blast protection model by some factor yields the same optimal vehicle design as increasing some element of the fuel convoy model by the same factor. However, the annual casualties on the vertical axis have a much higher variance when the latter rate changes, and it ranges from 83 to 1,138 as compared with the much tighter range from 284 to 333 in the blast parameter study. The relationship between fuel convoy casualty rate and total optimized casualties is nearly linear, while its relationship with optimal vehicle mass is logarithmic.

6.4 Discussion

The results of the above parametric optimization studies for finding an optimal multipurpose vehicle mass when considering blast threats and fuel convoy vulnerability are generally intuitive. The blast threat drives mass up while the fuel convoy

threat forces vehicle mass downward; increasing the blast threat likewise increases optimal vehicle mass, and increasing the threats to fuel convoys has the opposite effect. When either threat becomes more serious, the number of expected casualties grows, but changes to the magnitude of the fuel convoy threat tend to have a stronger impact on the total number of expected casualties with the optimized vehicle mass. While these results only present changes to two of the seven input parameters (n_{be} and ϕ_{fcc}), modifying the other parameters by the same scaling factors should have precisely the same effects based on the multiplicative nature of the solution in Equation (6.7). For example, changing the percentage of blast events that occur against multipurpose vehicles by some factor should have the same effect on the resulting optimal m_v and number of casualties as shifting the total number of blast events per year by the same factor.

6.4.1 Dynamic Environment Considerations

It is important to recognize that vehicle mass cannot be rapidly changed in the field, and in fact it often takes several years to make large-scale shifts in vehicle fleet composition. This is due to a number of factors including the high costs and timeline of vehicle development and manufacturing, the process of design selection and auditing, and the logistics of removing older vehicles and deploying new ones. When the threats facing vehicles are changing at a much more rapid pace, it would be impossible to keep up while using this framework to completely redesign ground vehicles. One instance in which this type of model becomes useful is when the military has a confident forecast of enemy behavior for a several-year period; it can then calculate the optimal vehicle mass and design a new vehicle or choose an available multipurpose vehicle that is close in mass.

When reliable prediction of future enemy tactics is not possible, the framework may be deployed in a dynamic context that accounts for fleet-mixing. For instance, a

base may have at its disposal both HMMWVs and MRAPs, and the strategic decision-makers must make choices on the use and mix of each vehicle class. When the threats are observed to be at a particular level, the proper parameter values can be inserted in the model and used to calculate the optimal vehicle mass. Lighter vehicles can be used for some percentage of missions and heavier ones for the remainder, such that the weighted average of the vehicles in use adds up to the predicted optimal mass. It would then be a command decision on choosing the missions to deploy each vehicle such that this optimal mixing is achieved.

6.4.2 Intervention Approaches

An interesting application of this combined modeling framework is to study the effect of various interventions on the expected casualties and the safety-optimal vehicle mass. Planners always seek new ways to improve operations and personnel safety, and planning interventions may affect the input parameter values or calculation models. Interventions may improve the blastworthiness of vehicles, such as using stronger materials, crushable underbody components, or impact-reducing geometries, which would necessitate an update to the calculation in Equation (6.2). Other innovations such as the aforementioned SPARK would reduce the number of blast events on vehicles per year. This parameter could also be impacted by better detection or reduction in the number of landmines and IEDs.

Other strategies proposed would impact the fuel convoy part of the formulation, some of which are posed primarily for safety reasons and others for financial or environmental concerns (*Ward and Captain, 2009*). Two major potential areas for intervention are the total number of fuel convoys per year and the percentage of those convoys with a casualty. Techniques to reduce fuel consumption include implementation of solar or geothermal electricity generation, electrification of the vehicle fleet, improvement of energy efficiency in base structures, and microgrids (*Whitefoot et al.,*

2011). One study found that a spray-foam insulation technique could reduce building energy requirements by 80 percent, and in doing so it claimed savings of \$1 billion per year and a reduction of 11,000 fuel trucks (*Anderson, 2011*). Another obvious approach is to improve efficiency of the entire vehicle fleet in operation. Other efforts can be made to directly reduce the fuel convoy casualty rate (*Borjes, 2008*).

Planners can use the proposed framework to assess the broader impact of a proposed intervention on the expected casualties, objectively computing the benefit of the particular approach and comparing costs and benefits.

6.4.3 Opportunities for Model Enhancement

The model presented in this chapter is by no means complete. The formulation does not presently account for ballistic or missile protection capabilities. It also does not address the overlap in the data between multipurpose vehicle blast attacks and multipurpose vehicles acting as fuel convoy escorts that are attacked by explosive devices, and an additional parameter might be added to address the proportion of these events that are counted in both models. The model does not specifically account for the fuel saved from increased convoy efficiency and effectiveness, which itself would avoid the need for additional fuel convoys. Lastly, the model may be extended to include convoys that transport non-fuel items, which represent half of all convoys. Approximately 40 percent of these convoys are for water, and therefore implementing methods for obtaining and purifying local water sources could cut down on the need for water supply trucks (*Eady et al., 2009*).

Factors other than safety may also be considered in decision-making, such as economic or environmental impacts of fuel-related decisions. Cost can be directly correlated with fuel consumption, and an additional parameter for fuel pricing will change according to current prices and forecasts. A more complete model might deliver a quantification of the links between casualties, economic costs, and emissions,

and provide insights for better planning.

6.5 Conclusions

A new modeling framework for optimizing military ground vehicle design with respect to blast protection and fuel convoy safety was developed in this chapter, using a combination of physics-based modeling and empirical data. Assumptions about Army vehicle usage, fuel convoys, and blast events were made based entirely on publicly available information, and the results suggest that optimal ground vehicle mass should be somewhere between the mass of the HMMWV and that of the MRAP, depending on these initial conditions. Parametric studies were conducted to explore the impact of reducing the blast threat or the threat facing fuel convoys, and interventions were discussed that would impact several of the prescribed parameters in the model. This type of combined modeling introduces a novel capability to assist in the strategic reduction of personnel casualties.

CHAPTER VII

Safety Considerations in a Market Systems Framework

“Man is still the most extraordinary computer of all.”

-John F. Kennedy

7.1 Introduction

This chapter adds several non-safety considerations to the civilian vehicle crash-worthiness optimization formulations offered thus far. As discussed in Section 2.6, automobile manufacturers do not build vehicles solely for safety, but they balance a myriad of design objectives while satisfying regulatory constraints and market demand. However, as with any business, automakers must generate income, and typically the main objective of these firms is to maximize profits. Frischknecht (*Frischknecht*, 2009) has modeled this in a market systems framework that accounts for engineering performance, consumer demand, manufacturing cost, and firm competition modeled as an economic game.

This chapter contributes to Frischknecht’s original market systems model by accounting for safety in both the engineering performance and consumer choice models. Engineering performance is modeled in similar ways to those explored in Chapter V,

but in this chapter mass becomes a parameter in the optimization formulation that the design variables must be optimized to, and mass ultimately impacts the probability of injury once societal variables are accounted for. Using this modeling approach, a simulation-based engineering performance model is constructed to find an occupant's probability of injury in a random crash of a vehicle with a particular mass. Additionally, a survey is conducted and analyzed to produce a new simple multinomial logit consumer choice model for how new vehicle customers trade off safety attributes with fuel economy, acceleration time, and price.

Studies are conducted with this model to show how introducing safety in the demand model impacts a profit-maximizing firm's revenues, costs, market share, and the performance of the vehicles produced. Additional use of the model shows how improvements in vehicle safety can shift the injury probability curves and hence influence firm profits and vehicle performance. Finally, the counterfactual policies investigated in Chapter V where the NCAP frontal crash test speed is increased or decreased are assessed for impact within the market systems framework. Because of the assumptions made in constructing this model, the emphasis of the results in this chapter is on relative impacts and trends rather than absolute data and recommendations; however, the described approach captures the tradeoffs of interest, and with more reliable data this extended framework can be applied in a meaningful way to decision-making. The ensuing sections discuss Frischknecht's original model, the addition of safety considerations to the engineering and consumer choice models, and the results from implementing the safety-enhanced model.

7.2 Baseline Market Systems Model

The market systems framework is based on a model developed by Frischknecht for his doctoral work (*Frischknecht, 2009*), and it involves an economic game of the competitive new vehicle market surrounding the decisions an individual manufac-

turer makes when designing a vehicle, depicted in Figure 2.15. These decisions are based on assumed profit-maximizing behavior by all firms in the market, where the impacts of vehicle design changes on consumer demand as well as production costs are considered. Frischknecht includes and analyzes several different models for approximating consumer choice as well as manufacturing costs, and in this chapter a new consumer choice model that accounts for safety is used in conjunction with a regression-based cost model previously used by Frischknecht. The design variables that influence choice, cost, and engineering performance are given in Table 7.1, where the last two only apply for hybrid-electric vehicles (HEVs).

Variable name	Symbol
Engine bore	x_B
Engine bore-to-stroke ratio	x_{BtS}
Final drive ratio	x_{FD}
Vehicle length	x_{L103}
Vehicle width	x_{W105}
Vehicle height	x_{H101}
Wheelbase	x_{L101}
HEV planetary gear ratio	x_{PGR}
HEV peak battery power	x_{BPow}

Table 7.1: Design variables for market systems framework (*Frischknecht and Yoon, 2008*)

The formulation follows a game theory approach to firm behavior in the automotive vehicle market, where each firm is assumed to exhibit profit-maximizing strategic decision-making with respect to product pricing, and one particular vehicle from one firm is permitted to make design changes as well. This strategy seeks market equilibrium with an iterative approach, where firms respond to other firms’ pricing decisions until the market “converges” on a single set of product and price offerings, namely, the state of market equilibrium. The firms’ objective is modeled by Equation (2.5), where profit is a function of sales volume, price, dealer markup, and production costs.

For estimating consumer choice as a function of vehicle design and price, the

existing market systems framework is constructed for both simple multinomial logit and mixed logit demand models. Both types of modeling require estimates of utility, or the value that a consumer perceives in a product, and approximations of the resulting market demand, calculated by Equations (2.6), (2.7), (2.8), (2.9), and (2.10). Simple logit is preferred when data about demographics and demographic-preference interactions are limited or unavailable, making it suitable to the present chapter's objectives.

The simple logit model employed in the baseline market systems model was adopted from a (1980) paper by Boyd and Mellman, and its implementation follows in Equation (7.1), where the four attributes that contribute to demand are price (P), fuel economy (FE) in mpg, acceleration time ($\theta-60$), and a measure of style ($\frac{L+W}{H}$).

$$V_j = -0.000286 \times P - 0.339 \frac{100}{FE} + 0.375 \frac{60}{\theta-60} + 1.57 \frac{L+W}{H} \quad (7.1)$$

However, this model must be used with care, as the coefficients were fit to 1977 preferences and dollar values, and Frischknecht's model accounts for this by converting to 1977 dollars using the Consumer Price Index (CPI) and adjusting fuel economy and acceleration values according to the change in fleet averages between 1977 and 2006. In this chapter, a similar simple multinomial logit model is constructed and used following Equations (2.6), (2.7), (2.8), and (2.9), and this is discussed in Section 7.3.2.

A top-down cost estimation approach from Frischknecht's original model is employed in the present study to ensure that the costs match realistic figures in the actual new vehicle market, as well as to understand the cost factors specific to design changes. Using averages and estimates of dealer and manufacturer markups for each vehicle class, production costs for a vehicle were estimated from new vehicle price data, and regression functions were developed to relate design attributes and features to their associated costs. The regression function used in this chapter is provided as Equation (7.2), where β_{eng1} is a parameter for either spark-ignition or compression-

ignition engines, β_{eng2} is a vector of parameters for engine-related design attributes (α_{eng}) including engine power and a hybrid-electric vehicle dummy variable, and β_{other} is a vector of parameters for non-engine design attributes (α_{other}), which include all-wheel drive, vehicle class, anti-lock brakes, stability control, transmission type, and turbo-charging.

$$c_v = \beta_{eng1} e^{\beta_{eng2} \alpha_{eng}} + e^{\beta_{other} \alpha_{other}} \quad (7.2)$$

For the engineering analysis, the existing market systems model uses the AVL Cruise software package (AVL, 2005) to simulate powertrain performance, providing calculations of fuel economy, acceleration time, maximum speed, towing capabilities, and range. Additional regression- and geometry-based formulas are used to compute the physical size of the engine, width of the powertrain, outer dimensions of the body, mass and mass distribution, angles of approach and departure, rollover rating per the static stability factor (SSF), cargo volume, and frontal crush space. Of these, the dimensions of the body, fuel economy, and acceleration time are used in the consumer demand function and therefore enter the profit objective function, while the others act as constraints in the model. A summary of these constraints is given in Table 7.2.

7.3 Safety Considerations

While safety is considered within the constraints of Frischknecht's model, as shown in Table 7.2 with the incorporation of required frontal crush space and a limit on the peak deceleration in a frontal crash event, it does not play a role in the consumer choice model. This presents a problem when evidence suggests that consumers consider safety in their new vehicle purchase decisions, and this section discusses such evidence as well as a new model for incorporating safety considerations in the engineering and demand modeling.

Description	Formula
Minimum grade for towing at 65 mph	$5\% - Grad65Tow \leq 0$
Minimum angle of departure	$13^\circ - A107 \leq 0$
Minimum ramp breakover angle	$12^\circ - A147 \leq 0$
Minimum cargo volume index (CVI)	$29ft^3 - CVI \leq 0$
Maximum cargo volume index (CVI)	$CVI - 60ft^3 \leq 0$
5-star rollover score based on SSF	$Rollover - 0.1 \leq 0$
Minimum weight distribution on front wheels	$50\% - 100(1 - CG_{long} - \frac{L104}{L101}) \leq 0$
Minimum required payload capacity	$Payload + VehMass - GVWR \leq 0$
Minimum required frontal crush space	$MinCrushSpace - CrushSpace \leq 0$
Maximum 20-g deceleration in front crash	$MaxDecel - 20(9.81m/s^2) \leq 0$
Powertrain width fits in vehicle	$(2TireFlop + 2MidRailWidth + EngLength + 50.8) - (W105 - 254) \leq 0$
Maximum wheelbase	$L101 + L104 - L103 \leq 0$
Maximum speed at least 115 mph	$115mph - MaxSpeed \leq 0$
Seated passenger fits inside vehicle	$MinSitHeight - H101 \leq 0$

Table 7.2: Engineering constraints used in Frischknecht’s market systems model

7.3.1 Engineering Performance

To begin, it is necessary to understand how design changes affect the safety performance of a vehicle, as well as how those design changes impact the other components of the market systems model in engineering performance and cost. From the list of safety-related design variables used in the study of Chapter V, summarized in Table 5.1, it is evident that there are no common variables shared by the market systems model in Table 7.1 and those of the safety optimization formulation. This indicates that adding a safety model similar to those previously discussed in this dissertation will not influence the existing engineering performance calculations that contribute to consumer demand or the existing constraints.

However, manufacturing costs may change when modifying the restraint system and structural variables from Table 5.1. Little is known about these material-specific design variables for vehicles in the existing market, and so a top-down cost estimate for the impact of these variables would require extensive testing or insider knowledge on

the engineering characteristics of every firm's vehicle structures and restraint systems. It is also possible that the small changes in material properties or tuning of the airbag flow rates would not incur significant costs, seeing that the material quantities and manufacturing processes would remain largely unchanged. For these reasons, the cost model from Frischknecht described in Equation (7.2) is used without modification for the safety considerations, assuming that any adjustments to the safety design variables have a negligible effect on manufacturing costs.

Since previous research suggests that crash test ratings have no significant effect on consumer demand (*Pruitt and Hoffer, 2004*), safety must be quantified in a new way to enter the demand formulation and therefore the profit-maximization objective. The safety study of Chapter V assumed fixed vehicle mass, and while mass may not be a design decision that is commonly tuned for a vehicle's crash test performance, it does influence on-road safety in multiple-vehicle collisions as shown in Figure 5.8. The injury probability function considering societal uncertainty developed in Section 5.2.3 provides an overall probability of driver injury given a frontal crash, which can be a suitable attribute to consider for estimating consumer choice. This is an appropriate consumer demand attribute under either of the following conditions:

1. Consumers internally recognize the safety benefits of high vehicle mass, and they consider weight when purchasing a new vehicle in a manner that accurately predicts the safety benefits of high vehicle mass.
2. Crash test ratings that are posted on new vehicle stickers are modified to account for vehicle weight and distributions of crash speed, driver size, and seat position as described in Section 5.2.3.

Both of these conditions would follow the same engineering and choice modeling framework as discussed in the present section.

Modifications to the framework of Chapter V were made to include vehicle mass

as a fixed design parameter along with the five design variables of Table 5.1. Here, the objective is to develop an explicit formula that relates vehicle mass (m) to probability of driver injury (P_{AIS3+}), accounting for variability in crash speed, driver stature, and driver-specific seat position. Since an additional design factor (m) is considered, new computational DOE studies are conducted and new surrogate models are fit to the data in the manner outlined in Figure 7.1.

As in Chapter V, compliance requirements of the FMVSS are included as constraints in the design optimization formulation. The additional variable m necessitates new computational DOE studies for both the 30-mph frontal crash with a belted occupant and the 25-mph frontal crash with an unbelted occupant, whereas the static out-of-position simulation results, which are not a function of structural variables, are re-used from the previous study. The results of the three DOE studies were fit with polynomial surrogate models and used as constraints for optimization.

Following the results of the prior sensitivity analysis, the formulation is narrowed to two structural quantities (m and s) and four restraint system variables (b , r , a , and d). The structural quantities are first sampled across the two-dimensional design space and parameterized using POD methods into five parameters. These five POD parameters are fit with kriging surrogate models (*Lophaven et al.*, 2002) to estimate a full crash pulse as a function of m and s , and then a six-variable DOE study of the restraint system is conducted and fit with polynomial surrogate models. These surrogates are then optimized parametrically across a range of vehicle masses, subject to the constraints from the three FMVSS regulatory standards. In each of the studies described in the next section, all three constraints were inactive at the optima.

From the optimization results, regression models are made for the optimal design variables s , b , r , a , and d as a function of m , and then the random societal variables v , h , and p are sampled along with m and the respectively-optimized design variables. Finally, polynomial surrogate models are fit to these four variables, and an integral

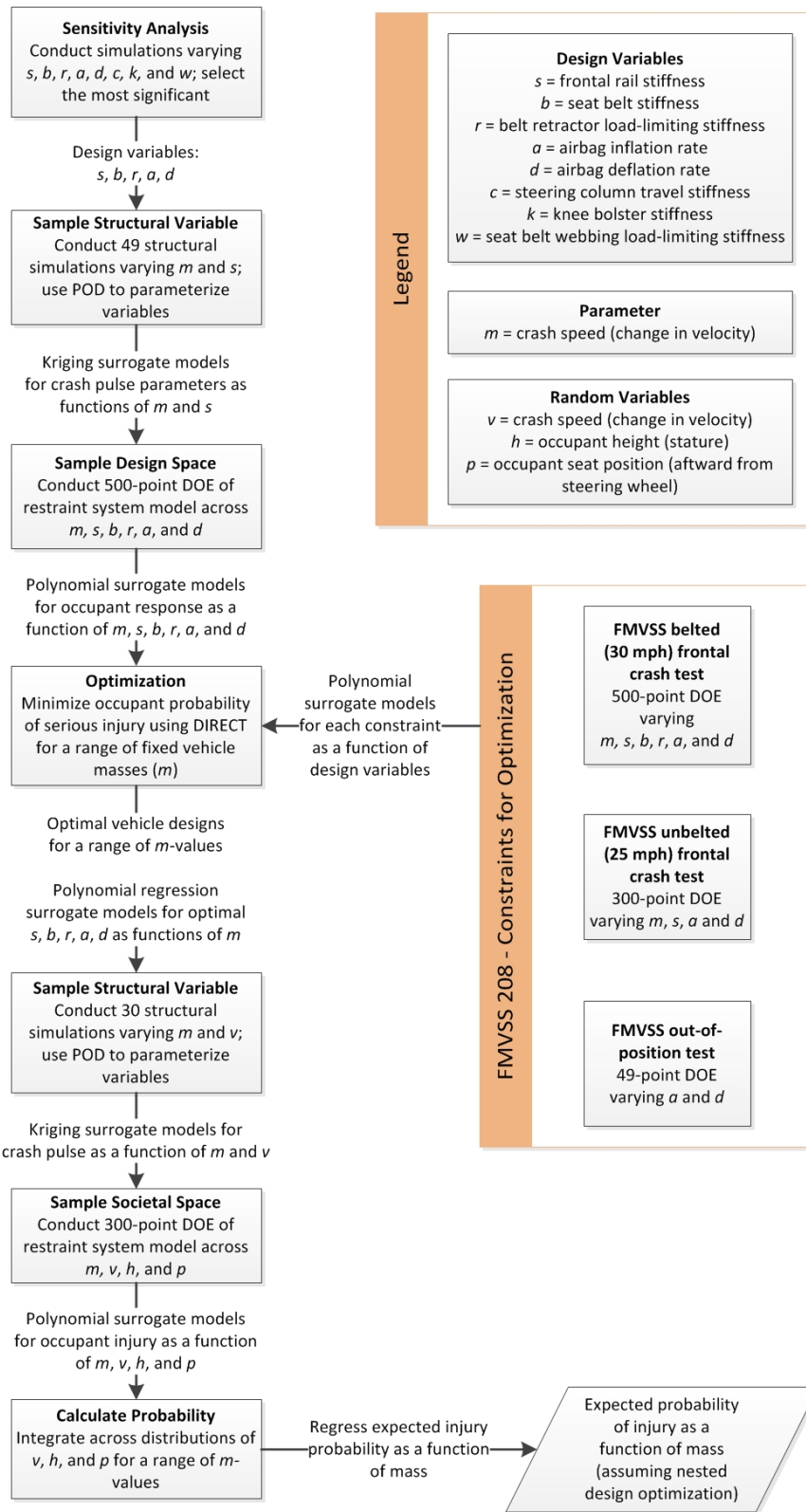


Figure 7.1: Flow chart describing development of engineering safety model

calculation of expected injury probability in a frontal crash is made for a range of vehicle masses as in Equation (5.14), with the results depicted in Figure 7.2.

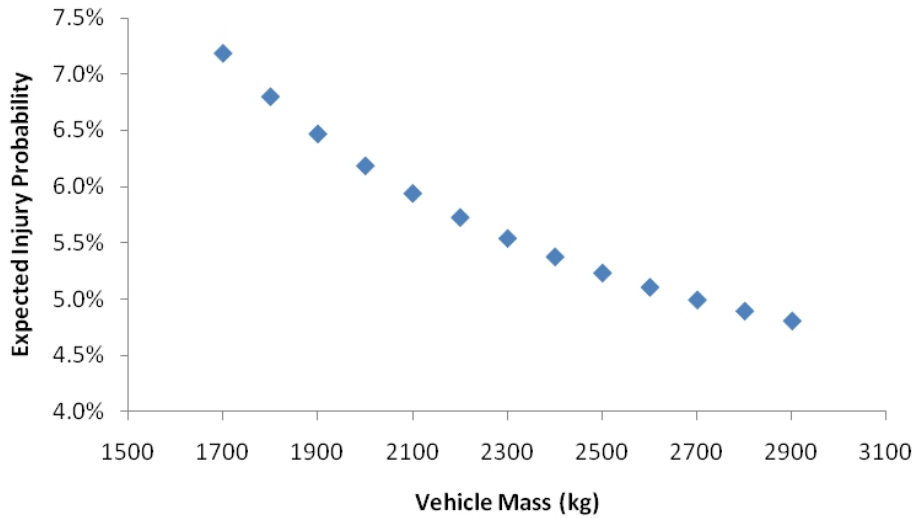


Figure 7.2: Expected probability of serious injury varying vehicle mass

A power regression on these data yields the driver’s probability of injury as a function of vehicle mass (m) in kilograms, and for the case of optimizing the vehicle to the 35-mph NCAP standard it is given as Equation (7.3):

$$P_{AIS3+} = 18.39m^{-0.7483}. \tag{7.3}$$

7.3.2 Consumer Choice

As discussed in Section 2.6.3, little is known about how American consumers perceive safety in their new vehicle purchase decisions, so building a consumer choice model requires new information. Choice information is typically gathered as either “revealed-choice” data, such as sales data or empirical knowledge of past behavior, or as “stated-choice” data through surveys, focus groups, and interviews that discuss hypothetical choice scenarios. Because existing revealed choice data is unavailable and typically does not contain a useful measure of safety, a survey was conducted

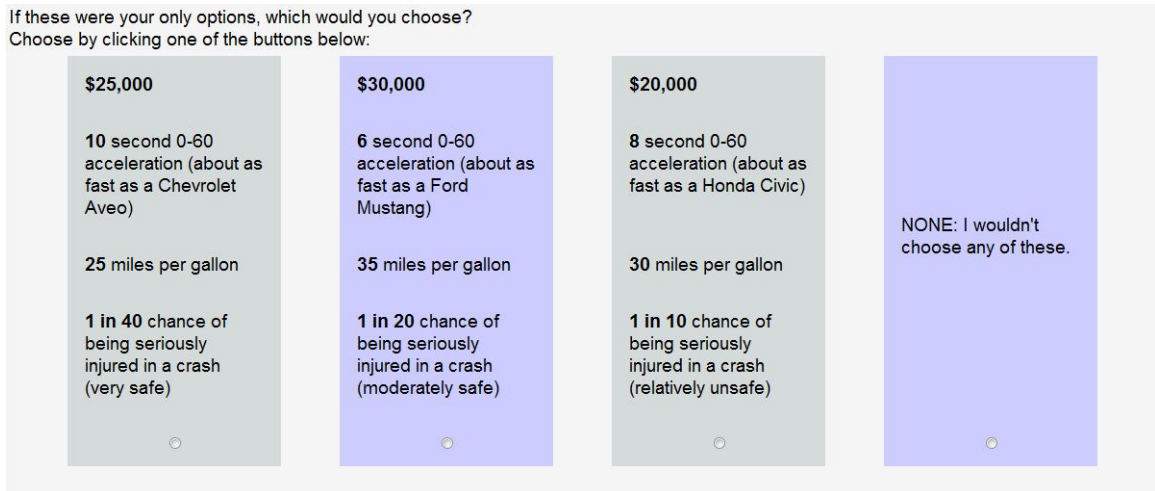


Figure 7.3: Example CBC survey question

in October of 2011 to reveal stated choices of potential new vehicle customers. The survey questions are provided in Appendix A, and the survey itself was constructed using Sawtooth Software (*Sawtooth Software, Inc.*, 2008) and distributed using Amazon Mechanical Turk (*Amazon*, 2011), capturing choice information from 543 U.S. respondents.

The main purpose of the survey was to obtain information on how consumers trade off different vehicle attributes using choice-based conjoint (CBC) questions. The CBC questions administered presented users with three different vehicles, each with specified attribute levels for safety, acceleration time, fuel economy, and price, and the users were asked to select the combination of attributes that they would be most likely to choose, with all other factors equal. An example of this type of question is shown in Figure 7.3. Prior to the CBC questions, the consumers were primed to think about vehicle purchasing with questions about vehicle use and general attributes considered in the new vehicle purchase decision. Following the CBC questions, additional questions asked the users about different factors considered when comparing vehicle safety, and the survey closed with demographic questions to understand the user base. From the responses to the CBC questions, a maximum-

likelihood estimation was used to compute the coefficients for an aggregate logit model. The coefficients for each attribute and level are presented in Appendix B along with the full survey results, and the values are plotted in Figure 7.4 along with piecewise linear regression surrogate models to interpolate the results.

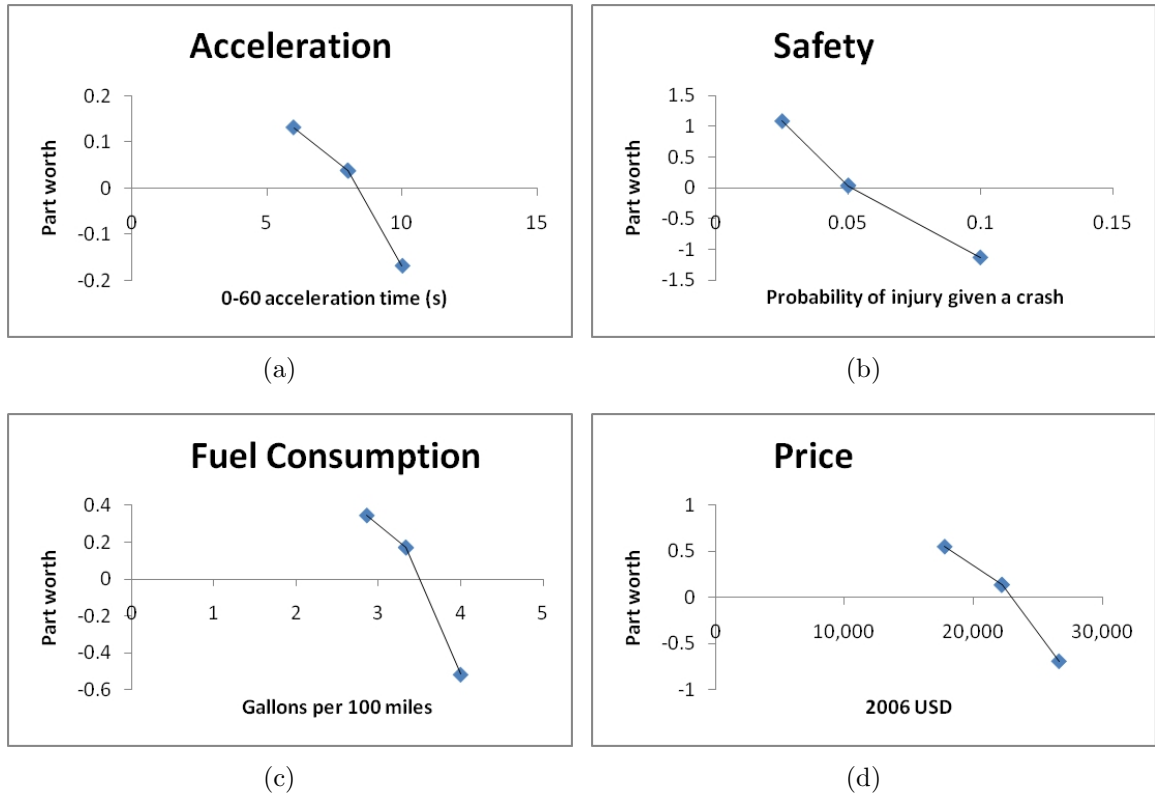


Figure 7.4: Part worth determination from CBC survey data for four attributes along with piecewise linear regression functions: (a) Acceleration, (b) safety, (c) fuel consumption, and (d) price

These values represent the part worth for each attribute-level, and as expected they vary monotonically for all four design attributes, with higher utility corresponding with faster acceleration times, lower probabilities of injury, higher fuel economy, and lower prices. Aggregating the part worth values for each attribute of a given product yields the utility of that product, and so combining the piecewise linear surrogates shown in Figure 7.4 allow for the determination of utility as the sum provided by Equation (7.4). In this equation, the U 's represent the utility component for each

attribute:

$$U_{total} = U_{accel} + U_{safety} + U_{fuelcon} + U_{price}. \quad (7.4)$$

Prices have been converted to 2006 dollars because the baseline market systems model considers the new vehicle market in 2006, and the survey was administered with respect to 2011 prices. The CPI, which estimates the buying power of a dollar in a given time period accounting for inflation and economic considerations, was used to convert the 2011 survey dollar values into 2006 dollar units. Thus, the original survey questions which asked users about vehicles in the range of 2011 \$20,000–\$30,000 have been converted to a range of 2006 \$17,800–\$26,700 (*Bureau of Labor Statistics*, 2011).

Measurements of utility are then used to predict the likelihood of a random consumer choosing a particular product using Equation (2.7), which can be interpreted as the market share of a given vehicle. Multiplying that market share by the market size M as in Equation (2.8) provides a prediction of vehicle sales to be used in the profit equation of Equation (2.5).

One limitation of this consumer choice approach is that the utility equations cannot be extrapolated outside the range for which they were fit. Since the CBC questions only presented choices in the price range from 2006 \$17,800 to \$26,700, the part worth interpolations from Figure 7.4 are only valid in that range. Of the 473-vehicle original market from the baseline model, 177 vehicles fit this price range. The boundaries for safety and acceleration in the survey were sufficient to encompass the full vehicle market; however, the majority of the remaining vehicles had initial fuel economy values outside of the 25–35 mpg range. Removing these vehicles brought the market size down to 39 vehicles, and while this new market fits the criteria upon which the consumer demand model was built without extrapolation, it has some disadvantages. The first is that the market systems model was designed around the crossover utility vehicle market, and unfortunately no vehicles from this segment remained in the 39-vehicle reduced market. The second is that with only a small

portion of the actual vehicle market being modeled, there is a limited variety of vehicles for consumers to choose from, and more consumers will choose the outside option. Since there are arguments for keeping the full vehicle model and for reducing it, the results of this chapter are presented for all three market sizes: The full 473-vehicle baseline 2006 new vehicle market, the 177-vehicle market that was reduced based on price range, and the 39-vehicle market that was further reduced based on fuel economy.

7.4 Results

The modified market systems model was simulated with several variations to understand the effect of including safety in the consumer demand model. The first set of simulations shows the impact of considering safety in the demand model versus a scenario where safety is not a factor in the consumer demand model. Next, the impact of shifting the injury probability curve in the engineering analysis is explored, representative of changes to the crash speed distribution. The final analysis considers the impact of changing the frontal NCAP test speed to 30 or 40 miles per hour, as in Chapter V. In each of these scenarios, design changes are allowed for one vehicle in the market, while price changes are allowed for every vehicle.

7.4.1 Impact of Adding Safety

Adding safety to the market systems model is expected to drive changes to the manufacturer's optimal vehicle design as well as changes to the consumer choice decisions. This causes every manufacturer participating in the economic game to adjust its prices according to expected consumer demand. Table 7.3 shows some of the notable differences between running the market systems model of the 39-vehicle market with and without the safety attribute of demand included. When safety is excluded, the same simple logit model described in Section 7.3.2 is used with the part worth for

safety fixed at zero; this assumes that consumers will value all vehicles in the same way that they value a vehicle with a 5.2-percent expected probability of injury, which is slightly worse than the “moderately safe” option in the survey.

	Safety excluded	Safety included	Percent change from adding safety
\bar{P}	\$22,876	\$22,925	+0.21%
\overline{HP}	167.5	167.7	+0.12%
\overline{FE}	26.86	26.79	-0.28%
\bar{W}	3,056	3,081	+0.82%
$E(AIS3+)$	1.300M	1.268M	-2.5%
FC_{fleet}	589,900	580,200	-1.65%
M	15.80M	15.50M	-1.92%
P^*	\$29,668	\$29,667	-0.00%
$0-60^*$	8.92	8.86	-0.74%
FE^*	23.28	23.29	+0.02%
W^*	3,649	3,655	+0.19%
C^*	\$24,122	\$24,114	-0.03%
Q^*	78,209	96,928	+23.9%

Table 7.3: Comparison of market systems results with and without consumer safety considerations; designed vehicle is a Subaru SUV in a 39-vehicle market

The fleet values are given as sales-weighted averages, and so \bar{P} is the sales-weighted average price of new vehicles in market equilibrium, that is, the average amount paid for a vehicle by everyone who purchases a vehicle in the market. \overline{HP} is the sales-weighted average of engine horsepower, \overline{FE} is the sales-weighted average of fuel economy in mpg, \bar{W} is the sales-weighted average of vehicle weight in pounds, and M is the total market size (all consumers who did not choose the outside good in a given year). The expected number of serious injuries is represented by $E(AIS3+)$, which is calculated assuming that every vehicle is in a frontal crash; this may not be strictly true, but it is an approximation for the number of vehicles in a frontal crash each year, and it appropriately accounts for the market size. FC_{fleet} is a measure of total fleet fuel consumption. The values with an asterisk (*) indicate optimal vehicle parameters, and these are the final parameters for the designed vehicle (either

a Subaru SUV or a Hyundai CUV): P is the price to the consumer, $0-60$ is the acceleration time in seconds, FE is the fuel economy in mpg, W is the weight in pounds, C is the cost to the manufacturer per vehicle, and Q is the quantity sold for that nameplate.

Many of the design parameters shift in intuitive directions when safety becomes a factor in the consumer choice model: Optimal vehicle weight (W^*) increases slightly, quantity sold (Q^*) increases significantly and drives down the manufacturing cost per unit (C^*). In the fleet, the sales-weighted average vehicle weight (\overline{W}) increases, and the expected number of injuries ($E(AIS3+)$) decrease accordingly. The weighted-average engine power (\overline{HP}) and price (\overline{P}) also see increases when safety is added to the demand model, which is likely a function of increased \overline{W} . The total size of the market (M) decreases, as the conflicting part worth values make the outside option of not purchasing a vehicle more attractive to some consumers. Lastly, even though the fleet-average fuel economy (\overline{FE}) decreases, the total fuel consumption of the new vehicle fleet (FC_{fleet}) actually decreases as well due to the smaller M . However, the fleet fuel consumption computation considers only new vehicles purchased in a year and implicitly assumes that people who choose the outside option do not drive at all, whereas in reality these individuals may continue to drive older cars and contribute to fuel consumption of the mixed new- and used-vehicle fleet. Therefore, the trends revealed by FC_{fleet} throughout this chapter are limited by this assumption and may overestimate the expected reductions in the national fuel consumption when the new vehicle market size decreases.

The effect is much smaller than anticipated, and so the market was simulated with the larger markets of 177 and 473 vehicles, with the results given in Tables 7.4 and 7.5.

With these larger markets, the main effects are similar, although the quantities sold (Q^*) decrease as the number of consumer options increase. Also, the sales-weighted averages (\overline{P} , \overline{HP} , \overline{FE} , \overline{W}) are more strongly affected when more vehicles

	Safety excluded	Safety included	Percent change from adding safety
\overline{P}	\$23,785	\$23,892	+0.45%
\overline{HP}	167.8	174.1	+3.8%
\overline{FE}	28.51	27.28	-4.3%
\overline{W}	3,197	3,290	+2.9%
$E(AIS3+)$	1.285M	1.247M	-2.9%
FC_{fleet}	605,100	621,700	+2.7%
M	15.98M	15.86M	-0.74%
P^*	\$27,093	\$27,094	+0.00%
$0-60^*$	8.92	8.86	-0.74%
FE^*	23.28	23.29	+0.02%
W^*	3,649	3,655	+0.18%
C^*	\$21,671	\$21,664	-0.03%
Q^*	53,937	63,900	+18.5%

Table 7.4: Comparison of market systems results with and without consumer safety considerations for medium-sized automotive market; designed vehicle is a Hyundai CUV in a 177-vehicle market

	Safety excluded	Safety included	Percent change from adding safety
\overline{P}	\$21,532	\$22,078	+2.5%
\overline{HP}	154.9	162.2	+4.7%
\overline{FE}	28.51	27.58	-3.3%
\overline{W}	2,990	3,097	+3.6%
$E(AIS3+)$	1.358M	1.320M	-2.8%
FC_{fleet}	588,900	606,300	+3.0%
M	16.05M	15.99M	-0.39%
P^*	\$27,156	\$27,131	-0.09%
$0-60^*$	8.92	8.86	-0.74%
FE^*	23.28	23.29	+0.02%
W^*	3,649	3,655	+0.19%
C^*	\$21,671	\$21,664	-0.03%
Q^*	23,034	30,314	+31.6%

Table 7.5: Comparison of market systems results with and without consumer safety considerations for full automotive market; designed vehicle is a Hyundai CUV in a 473-vehicle market

are in the market, which is likely because there is greater diversity in vehicle sizes and performance attributes to choose from. As such, the market size M does not decrease as dramatically as it did in the smallest market scenario. Finally, the fleet fuel consumption (FC_{fleet}) actually increases when safety considerations are added to the larger market simulations, which can be attributed to a combination of the greater diversity in vehicle attributes as well as the larger total market size (M).

7.4.2 Impact of Changing Crash Speed Distribution

Another effect that is explored using the market systems model is that of shifting the crash speed distribution, $f(v)$. New active safety features such as forward collision warning systems and pre-crash braking hold promise in reducing the numbers and severities of car crashes on the road (IIHS, 2008). If these features succeed in lowering the impact speeds of vehicles, the effect may be the equivalent of shifting the distribution curve from Figure 5.8 to the left. The current market systems model was simulated with decreased frontal crash speed distributions by 20 percent and 40 percent, shown in Figure 7.5, and the corresponding impact on injury probability is given in Figure 7.6. The results are provided in Table 7.6 for the smallest vehicle market, Table 7.7 for the market filtered by price only, and Table 7.8 for the full market.

From these data, it is evident that shifting the speed distribution on the road has little effect on the design of the vehicle (P^* , $0-60^*$, FE^* , W^* , and C^*) for all three market sizes; however, the quantity sold (Q^*) becomes lower for these relatively large crossover and sport utility vehicles, as consumers are predicted to place less emphasis on weight and opt for smaller vehicle types. Lowering the speed distribution shifts the probability of injury curve downward and thus creates subtle changes to buyer behavior en masse. Consumers tend to buy lighter vehicles with less powerful engines and higher fuel economy, and on average they pay less for each vehicle, as evidenced

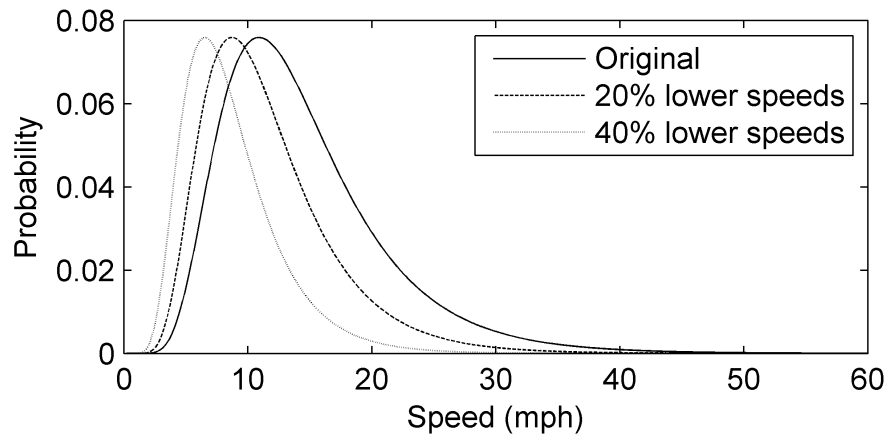


Figure 7.5: Three different probability distributions of frontal crash speed

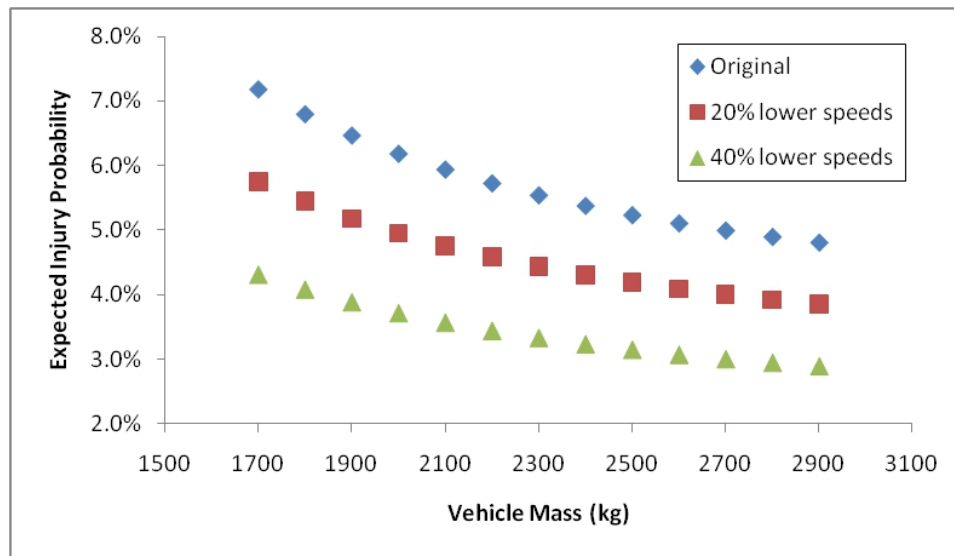


Figure 7.6: Expected probability of serious injury by vehicle mass for three crash speed distribution scenarios

	Original	20% lower speeds	40% lower speeds
\overline{P}	\$22,925	\$22,920	\$22,913
\overline{HP}	167.7	167.7	167.6
\overline{FE}	26.79	26.80	26.82
\overline{W}	3,081	3,076	3,072
$E(AIS3+)$	1.268M	1.028M	0.7781M
FC_{fleet}	580,200	586,900	591,500
M	15.50M	15.69M	15.82M
P^*	\$29,667	\$29,668	\$29,669
$0-60^*$	8.86	8.87	8.89
FE^*	23.29	23.29	23.29
W^*	3,655	3,654	3,653
C^*	\$24,114	\$24,116	\$24,117
Q^*	96,928	93,757	90,293

Table 7.6: Comparison of market systems results with lowered distribution of on-road frontal crashes; designed vehicle is a Subaru SUV in a 39-vehicle market

	Original	20% lower speeds	40% lower speeds
\overline{P}	\$23,893	\$23,869	\$23,846
\overline{HP}	174.1	172.8	171.6
\overline{FE}	27.28	27.50	27.74
\overline{W}	3,290	3,272	3,253
$E(AIS3+)$	1.247M	1.007M	0.7609M
FC_{fleet}	621,700	620,600	618,500
M	15.86M	15.94M	15.99M
P^*	\$27,094	\$27,095	\$27,095
$0-60^*$	8.86	8.87	8.89
FE^*	23.29	23.29	23.29
W^*	3,655	3,654	3,652
C^*	\$21,664	\$21,665	\$21,667
Q^*	63,900	62,159	60,291

Table 7.7: Comparison of market systems results with lowered distribution of on-road frontal crashes; designed vehicle is a Hyundai CUV in a 177-vehicle market

	Original	20% lower speeds	40% lower speeds
\overline{P}	\$22,078	\$21,964	\$21,853
\overline{HP}	162.2	160.7	159.2
\overline{FE}	27.58	27.76	27.95
\overline{W}	3,097	3,075	3,053
$E(AIS3+)$	1.320M	1.064M	0.8030M
FC_{fleet}	606,300	603,700	600,600
M	15.99M	16.03M	16.05M
P^*	\$27,131	\$27,137	\$27,142
$0-60^*$	8.86	8.87	8.89
FE^*	23.29	23.29	23.29
W^*	3,655	3,654	3,652
C^*	\$21,664	\$21,665	\$21,667
Q^*	30,314	28,847	27,379

Table 7.8: Comparison of market systems results with lowered distribution of on-road frontal crashes; designed vehicle is a Hyundai CUV in a 473-vehicle market

by the subtle trends in \overline{W} , \overline{HP} , \overline{FE} , and \overline{P} . The market size (M) increases as vehicle utilities relative to the outside good become higher, and the expected number of injuries ($E(AIS3+)$) decreases as expected. This decrease is approximately 19 percent for the 20-percent shift and 39 percent for the 40-percent decrease in crash speeds, where the slight discrepancy is due to the greater number of vehicles on the road and lower average vehicle weights. Total fuel consumption (FC_{fleet}) exhibits some interesting behavior, increasing for the small-market scenario and decreasing in the full-market scenario. This is likely due to the conflict between increased market size and increased fuel economy, where the fuel economy increase becomes more prominent in the larger and more diverse markets.

7.4.3 Impact of Revised Frontal NCAP Test Speed

The third and final study of this chapter uses the market systems model to demonstrate how changes to the frontal NCAP test speed would affect the new vehicle market as it accounts for safety. The previous method in Chapter V approached the same question from an engineering perspective, assuming that the market size and fleet mix

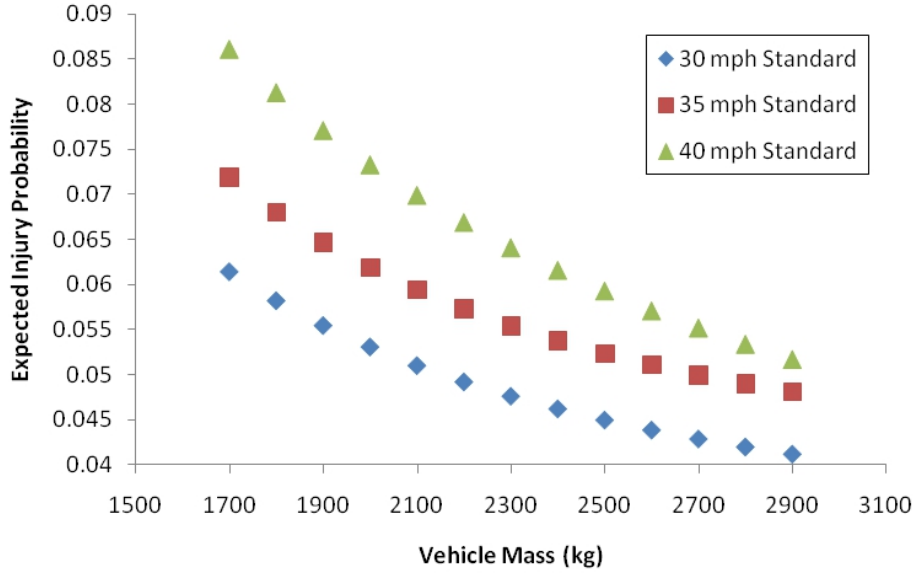


Figure 7.7: Expected probability of serious injury varying vehicle mass, for each of three NCAP scenarios

would not be affected by changing the standardized test speed. This section uses the market systems model to provide additional insights into how consumers respond to the changes in vehicle designs that result from the test speed. This analysis follows the framework from Figure 7.1 for each of the three speed scenarios: The baseline 35-mph frontal crash test, a reduced 30-mph test, and an increased 40-mph test. The results provide different relationships for each test speed between the expected injury probability given a crash and the vehicle mass, plotted in Figure 7.7.

Here, the same trends for serious injury probabilities are evident as in Chapter V, where decreasing the NCAP test speed effectively reduces expected serious injury probability given a crash by approximately 21 percent and increasing the speed raises injury probability by about 11 percent. From these data, power regression curves are fit in a similar manner to that of Equation (7.3), and they are given as Equation (7.5) for the 30-mph test scenario and Equation (7.6) for the 40-mph test scenario.

$$P_{AIS3+,30\text{mph}} = 15.22m^{-0.7436} \quad (7.5)$$

$$P_{AIS3+,40\text{mph}} = 103.0m^{-0.9534} \quad (7.6)$$

Using these equations in the market systems framework yields different resulting fleet mixes, expected injuries, and total fuel consumption for each frontal NCAP test scenario. The results are given in Table 7.9 for the small 39-vehicle market, Table 7.10 for the medium 177-vehicle market, and Table 7.11 for the large 473-vehicle market.

	30-mph NCAP	35-mph NCAP	40-mph NCAP
\bar{P}	\$22,921	\$22,925	\$22,950
\overline{HP}	167.7	167.7	167.8
\overline{FE}	26.80	26.79	26.74
\bar{W}	3,078	3,081	3,096
$E(AIS3+)$	1.095M	1.268M	1.563M
FC_{fleet}	585,300	580,200	566,900
M	15.64M	15.50M	15.12M
P^*	\$29,668	\$29,667	\$29,666
$0-60^*$	8.87	8.86	8.81
FE^*	23.29	23.29	23.28
W^*	3,654	3,655	3,660
C^*	\$24,115	\$24,114	\$24,110
Q^*	94,564	96,928	108,071

Table 7.9: Comparison of market systems results with three different NCAP frontal test speed scenarios; designed vehicle is a Subaru SUV in a 39-vehicle market

It is evident that in each of the three market sizes, the designed vehicle specifications are largely unchanged by the NCAP frontal crash test speed. However, the quantity sold (Q^*) decreases when the test speed is lower as consumers tend to place less importance on safety and shift toward smaller vehicles, also evidenced by the slight decrease in \bar{W} . As seen in the previous analysis, when the overall safety component of utility rises with the lower test speed, the market size increases due to a relatively less attractive outside option. As a result of this increased market size and the decreased fleet-average vehicle weight, the expected number of serious injuries is predicted to decrease by only 14 percent with the lower test speed; this demonstrates

	30-mph NCAP	35-mph NCAP	40-mph NCAP
\overline{P}	\$23,875	\$23,892	\$23,972
\overline{HP}	173.2	174.1	177.6
\overline{FE}	27.45	27.28	26.65
\overline{W}	3,276	3,290	3,344
$E(AIS3+)$	1.075M	1.247M	1.532M
FC_{fleet}	620,900	621,700	628,000
M	15.92M	15.86M	15.72M
P^*	\$27,095	\$27,094	\$27,092
$0-60^*$	8.87	8.86	8.81
FE^*	23.29	23.29	23.28
W^*	3,654	3,655	2,660
C^*	21,665	\$21,664	\$21,659
Q^*	62,603	63,900	69,337

Table 7.10: Comparison of market systems results with three different NCAP frontal test speed scenarios; designed vehicle is a Hyundai CUV in a 177-vehicle market

	30-mph NCAP	35-mph NCAP	40-mph NCAP
\overline{P}	\$21,993	\$22,078	\$22,437
\overline{HP}	161.1	162.2	166.9
\overline{FE}	27.72	27.58	27.02
\overline{W}	3,080	3,097	3,166
$E(AIS3+)$	1.135M	1.320M	1.642M
FC_{fleet}	604,400	606,300	615,900
M	16.02M	15.99M	15.91M
P^*	\$27,135	\$27,131	\$27,116
$0-60^*$	8.87	8.86	8.81
FE^*	23.29	23.29	23.28
W^*	3,654	3,655	3,660
C^*	21,665	\$21,664	\$21,659
Q^*	29,215	30,314	34,977

Table 7.11: Comparison of market systems results with three different NCAP frontal test speed scenarios; designed vehicle is a Hyundai CUV in a 473-vehicle market

a much lower impact than the results from Chapter V where vehicle weight and fleet composition were fixed and the expected probability of injury in the designed vehicle decreased by 21 percent with the lower test speed. These results indicate that the apparent benefits of reducing the frontal NCAP test speed are somewhat compensated for by the market with an increased number of vehicles on the road and a lighter average vehicle weight.

The one trend that changes as the market size increases is the total fleet fuel consumption (FC_{fleet}). In the smallest market, decreasing the NCAP test speed increases the total fleet fuel consumption, which is likely due to the increased market size accompanying a very slight improvement in fleet-average fuel economy. However, in the larger two markets, lowering the NCAP test speed decreases FC_{fleet} , pushed by stronger improvements to \overline{FE} .

7.5 Conclusions

This chapter provided an extension to Frischknecht's market systems formulation by incorporating consumer demand for safety, and the effects of the safety part worth functions were demonstrated. In general, safety considerations drive the market toward a higher-mass vehicle fleet, necessitating more powerful engines and coming at a cost to fuel economy. Complex interactions among market size, fuel economy, and vehicle mass cause the total number of expected injuries and the total fleet fuel consumption to respond to safety changes in non-obvious ways, and the simulated market compensates for expected safety benefits with increases in the number of vehicles sold and reductions in fleet-weighted average vehicle weight. A framework such as the one presented in this chapter that considers the economics, psychology, and engineering analyses of the new automotive vehicle market can provide insights on this market behavior.

CHAPTER VIII

Summary and Conclusions

“When we build, let us think that we build for ever.”

-John Ruskin

8.1 Summary

This dissertation addressed the importance of vehicle occupant safety and developed quantitative methods to explore its impact on overall vehicle design. Using existing computational simulation models in novel ways, designers can implement these methods to develop and evaluate new vehicles that provide optimal occupant protection when faced with uncertain conditions. Similarities seen in civilian vehicle crash safety and military vehicle blast safety were identified and exploited to demonstrate the applicability of design for safety thinking across both domains.

Chapter II presented an overview of previous research that has been done with regard to vehicle safety, laying a foundation for the new work presented in later chapters. The focus is largely on civilian vehicles, since the blast threats to military vehicles are relatively new and also highly sensitive to public discourse. Much research has been done to investigate the trends in past civilian vehicle models and the relationships among mass, safety, and fuel economy, but these analyses were largely inconclusive due to the rapid pace of new technology implementation and the cor-

relations among vehicle and driver variables. Other studies have shown methods for improving safety by adding new technologies, adopting regulatory and consumer-information crash tests, and optimizing physical crash tests and computational simulations; however, these studies tend to focus on specific results rather than broader implications and tradeoff analyses. The literature review closed with a discussion of recent market systems research, which places vehicle design objectives within a firm profit-maximization scheme to provide a more realistic business approach to simulation-based vehicle design. The current state of market systems modeling examines general trends and broad results, but it has not yet included considerations of safety with respect to design attributes or consumer demand.

In Chapter III, an exploration of simulation tools for occupant crash safety was conducted, and a framework was developed to link safety with fuel economy in a multi-objective optimization and tradeoff study. Three simulation methods were examined, beginning with the full-vehicle multi-body dynamics simulations that required approximately 20 minutes of computational time. The resulting relationships between the design variables and objectives were discussed, and higher-fidelity modeling tools were considered to obtain better predictions of vehicle behavior. The conclusion was that finite-element modeling for a vehicle structural response to a crash is much more computationally expensive at 10 hours per simulation, but if sufficient computing resources are available, the results are more meaningful and can be manageable for optimization.

These ideas were extended to military vehicle blast protection in Chapter IV, where a finite-element rigid-body vehicle blast simulation was linked with a multi-body dynamics occupant and seating system simulation. Using the U.S. Army requirements for blast safety as put forth by NATO, three different optimization formulations for designing seating systems were developed to account for the inherent uncertainty of IEDs, and the relative merits of each formulation were discussed. All

of the formulations exhibit a direct relationship between occupant blast safety and vehicle weight: Increasing vehicle weight is shown to increase occupant safety when the seating system is optimized to the vehicle weight. The third formulation, which used postulated injury curves across a full range of blast scenarios, was selected for later use due to its simplicity and interpretability.

Chapter V returned to the crashworthiness scenario and used the models discussed in Chapter III to study the impact of consumer-information crash tests on vehicle design and society. A framework was set forth describing the interactions among governments, manufacturers, and society. Using the U.S. NCAP frontal barrier test as a baseline, different test scenarios were analyzed to evaluate the impact of raising or lowering the test speed on driver injuries. Introducing uncertainty to the injury-causing event as in Chapter IV, the impact of changing the crash test speed on optimal vehicle designs was discussed as well as the impact of those vehicle designs on expected injury rates. Results indicate that lowering the NCAP crash speed could significantly lower sub-critical injury rates with a possible increase in critical and fatal injuries.

The military blast protection formulation from Chapter IV was then revisited in Chapter VI, and an additional aspect of safety was identified and added to the optimization objective. This aspect is the recognition that a significant portion of fuel convoys experience casualties, and therefore increasing military vehicle fuel consumption increases exposure of fuel convoys to potential casualties. Accounting for the ideas in Chapters II and III that increasing mass increases fuel consumption, an obvious conflict of safety interests between blast protection and fuel convoy exposure was identified and modeled. A single-objective, casualty-minimization optimization problem was formulated and solved under a range of input parameters, demonstrating the impact of blast rates or fuel convoy casualty rates on optimal ground vehicle mass.

Finally, Chapter VII built upon the surrogate models developed in Chapter V and the market systems models developed by Frischknecht (2009) to demonstrate a manufacturer's approach to profit-maximizing vehicle design. Trends in sales-weighted fleet averages were discussed, as well as the effects on optimized individual vehicle designs and societal outcomes from adding consumer safety considerations, shifting the vehicle crash speed distribution, and modifying the NCAP consumer-safety test speed. Results show the complex interactions among manufacturer decisions, consumer decisions, and the main outcomes of interest which include firm profits, total market size, expected crash injuries, and fleet fuel consumption, motivating the need for market systems analysis. Because of the assumptions made in constructing the market systems model, the emphasis is on relative impacts and trends rather than absolute data and recommendations; however, the described approach captures the tradeoffs of interest, and with more reliable data the extended framework presented can be applied to real decision-making.

The quantitative approaches developed in the preceding chapters provide decision-makers with new tools for analyzing the implications of vehicle designs on safety and its competing or conspiring objectives.

8.2 Summary of Contributions

This research contributes new methodologies for rational design decision-making to aid in the development of safety-optimized vehicles. Applications were studied for both civilian consumer vehicles and military ground vehicles, and in both cases modeling tools, formulations, and tradeoffs were analyzed to develop a better understanding of the interactions among safety objectives and other design criteria. The three main contributions can be summarized as follows:

1. Quantification of the design relationships among vehicle occupant safety and

other design objectives,

2. Generation and solution of multiple optimization formulations for minimizing vehicle occupant injury probability under uncertainty, and comparison of relative merits of the different formulations to support design decision-making, and
3. Development of a new approach for simulation-based assessment of safety standards and policies to support regulatory decision-making, accounting for design optimization, uncertainty, and producer objectives — possibly leading to different regulatory requirements than those presently in use.

8.3 Opportunities for Further Research

Although interesting conclusions have been drawn from the work presented in this dissertation, perhaps the most exciting findings are the doors that have been opened for further research. The frameworks developed here can be expanded to include additional considerations and transformed to adapt to the changing automotive industry. This closing section describes some of these opportunities for future research in design optimization for civilian consumer vehicle crash safety and for military ground vehicle blast safety.

8.3.1 Civilian Vehicle Research Opportunities

The civilian vehicle study concludes with a framework for evaluating the impact of the frontal NCAP test speed on optimal vehicle design and on-road safety statistics, as well as a preliminary implementation of safety modeling in a market systems framework. For the NCAP assessment, the results thus far only account for a single vehicle designed with five variables and considered with three random societal variables. Expanding the number of variables, and hence the number of required

computational simulations, would be an obvious way to add meaning to the results, particularly if there are important interactions captured among the variables.

Another way to expand the study would be to account for multiple vehicles, starting with a sample of vehicles from each of the major vehicle segments (e.g., subcompact, compact, mid-size sedan, full-size sedan, minivan, SUV, pickup) and possibly expanding to a more complete representation of the entire fleet. Finally, modeling multiple collision modes and directions, which could be accomplished either by using the same finite-element models as those of the frontal crash mode or by linking shared parameter values with the results of the frontal crash mode simulations, as well as accounting for new active safety features (e.g., forward collision warning, lane departure warning, pre-crash braking, blind spot detection) that can affect the rates and distributions of crash occurrences, would give the results more meaning on an overall safety perspective. Such large-scale studies will become more feasible with the use of multi-fidelity model management tools along with improvements in computational capacities.

In the market systems framework, there are opportunities to improve and expand the presence of safety in vehicle design formulations. On the demand side, thus far a simple multinomial logit consumer choice model has been implemented, but with more data a more sophisticated mixed-logit choice model could be constructed and implemented. This could account for not only injury probability, but also the safety features that have been identified as important. In terms of the engineering analysis, the impact of such safety features can be accounted for to build a more complex understanding of crash probability and injury probability. Additionally, the costs of these extra features will need to be accounted for in the cost model. A complete model such as this could be used to advise policy in the framework described in the previous paragraph, which should better account for the manufacturer's optimization part of the problem from the profit-maximization point of view.

8.3.2 Military Vehicle Research Opportunities

The methodologies presented here on military ground vehicle blast safety conclude with a strategic formulation for minimizing blast casualties as well as fuel convoy exposure. This study would benefit from an enhanced fuel economy model, a more sophisticated vehicle blast model, occupant uncertainty, and additional safety objectives and tradeoff considerations. The current model for calculating fuel consumption uses regression on range and fuel tank size data from 48 U.S. Army ground vehicles ranging from a 1,500-kilogram Jeep to a 23,000-kilogram Heavy Expanded Mobility Tactical Truck. It is likely that these range calculations were conducted using vastly different drive cycles, which are not necessarily the appropriate driving profile for a new multipurpose vehicle. One suggestion for improving this part of the formulation is to conduct a drive cycle simulation for vehicles of different weights and with different powertrain design options, allowing for the inclusion of a nested powertrain design optimization loop.

A more sophisticated vehicle blast model could show the benefits of v-hull architectures and material deformation, and two separate finite-element vehicle models are currently under investigation. Another model enhancement would be to account for random variables related to the occupant size, posture, and restraint use, in a similar manner to that in the civilian study of this dissertation. Finally, further safety considerations could be modeled and added to the objective function, including rollover resistance, crashworthiness, and projectile-resistant armor. Such additions to the models described in this dissertation would strengthen the applicability and validity of the results derived from the formulations. It is likely that such models will need to be developed outside the public domain if detailed data were to be included for realistic scenarios. However, the approach presented here points to how vehicle design optimization can assist strategic decision-making.

APPENDICES

APPENDIX A

Consumer Choice Survey

Welcome to our survey! Your time is appreciated, and this should only take about 5 minutes. Please answer all questions to the best of your ability.

Page Break

Please answer the following questions to your best ability:

Do you currently own or regularly drive a personal vehicle?

Yes

No

If yes, please tell us the make, model, and year (e.g., "Ford Focus 2010"):

Do you usually drive a personal vehicle to work or school?

Yes, at least every weekday

Yes, about half of weekdays

No

Are you interested in purchasing a new vehicle?

Yes, within the next year

Yes, within the next 5 years

Yes, but I'm not sure when

No

Page Break

What do you look for when shopping for a new car? Please list the top 3 factors that you would consider:

1st factor: _____

2nd factor: _____

3rd factor: _____

Page Break

If you were in the market for a new vehicle, how important would the following attributes be in your decision? (1 = not at all important, 5 = very important) *Attribute order is permuted randomly*

	Not Important 1	2	3	4	Very Important 5
Alternative fuel or powertrain (e.g., hybrid, electric, diesel, FlexFuel, natural gas)					
Brand loyalty					
Cargo space					
Fuel economy					
“Fun-ness” to drive (speed & handling)					
Infotainment system (stereo, navigation, etc.)					
Interior comfort (seats, upholstery, temperature, etc.)					
Price					
Number of cup holders					
Number of passenger seats					
Reliability (as per Consumer Reports or other reviews)					
Safety					
Style (aesthetic appearance)					
Vehicle type (e.g., coupe, sedan, luxury, SUV)					

The following questions ask you to choose among vehicles based on four specific attributes: personal safety, performance, fuel economy, and price. Imagine that you are in the market for a new vehicle, and all other features or specifications are equal aside from these four.

- **Price** is what you would pay for the vehicle, not including fuel and maintenance costs.
- **Fuel economy** is the average number of miles you can drive per gallon of fuel.
- **Personal safety** is the probability that you will be seriously injured if you are in a crash. Serious injuries include skull fractures, lung bruises, and leg injuries causing amputation.
- **Performance** is the 0-60 mile-per-hour acceleration time (how many seconds it takes to go from a dead stop to cruising at 60 miles per hour).

The next 6 questions will look very similar. Please read the options carefully and select your choices.

Page Break

Choice-Based Conjoint Questions

If these were your only options, which would you choose? Choose by clicking one of the buttons below:

Each respondent receives 6 separate choices on separate pages, where 3 random sets of the following four attributes are presented along with a “NONE: I wouldn’t choose any of these” option.

Attribute 1: Safety

- **1 in 40** chance of being seriously injured in a crash (very safe)
- **1 in 20** chance of being seriously injured in a crash (moderately safe)
- **1 in 10** chance of being seriously injured in a crash (relatively unsafe)

Attribute 2: Performance

- **6** second 0-60 acceleration (about as fast as a Ford Mustang)
- **8** second 0-60 acceleration (about as fast as a Honda Civic)
- **10** second 0-60 acceleration (about as fast as a Chevrolet Aveo)

Attribute 3: Fuel economy

- **25** miles per gallon
- **35** miles per gallon
- **45** miles per gallon

Attribute 4: Price

- **\$20,000**
- **\$25,000**
- **\$30,000**

Note: Halfway through (after 3 questions), an extra page appears that says “Halfway there! Please answer just three more of these questions”

When comparing the overall safety of two or more vehicles, what do you look for?

Page Break

If you were to compare the safety of two or more vehicles, how important is each of the following attributes? (1 = not at all important, 5 = very important) *Attribute order is permuted randomly*

	Not Important 1	2	3	4	Very Important 5
Active safety features (e.g., electronic stability control, collision warning systems, etc.)					
Braking distance (e.g., how long it takes to go from 60mph to a stop)					
Insurance industry (Insurance Institute for Highway Safety) crash test ratings					
Government (New Car Assessment Program) crash test star ratings (published on window stickers)					
Number of airbags					
Reviews and recommendations from acquaintances and other private sources (e.g., Consumer Reports)					
Size of the vehicle (length, width, and/or height)					
Visibility (e.g., blind spots)					
Weight of the vehicle					

You're almost done! Please provide the following information about yourself:

Gender:

Male

Female

Age: _____

Race:

American Indian or Alaskan Native

Asian or Pacific Islander

Black or African-American

Hispanic, Latino, or Spanish

White or Caucasian

Some other race

Number of adults in your household: _____

Number of children under 16 in your household: _____

Approximate annual household income:

Less than \$20,000

\$20,000 - \$50,000

\$50,000 - \$80,000

\$80,000 - \$110,000

More than \$110,000

Thank you for your time! Your response has been submitted.

APPENDIX B

Data from Consumer Choice Survey

The following results represent 543 respondents to the survey presented in Appendix A. The survey was administered using Sawtooth Software (*Sawtooth Software, Inc.*, 2008) and distributed with Amazon Mechanical Turk (*Amazon*, 2011).

Driving Behavior and Purchase Intentions

Currently own or regularly drive a personal vehicle:

Yes	443	81.6%
No	100	18.4%

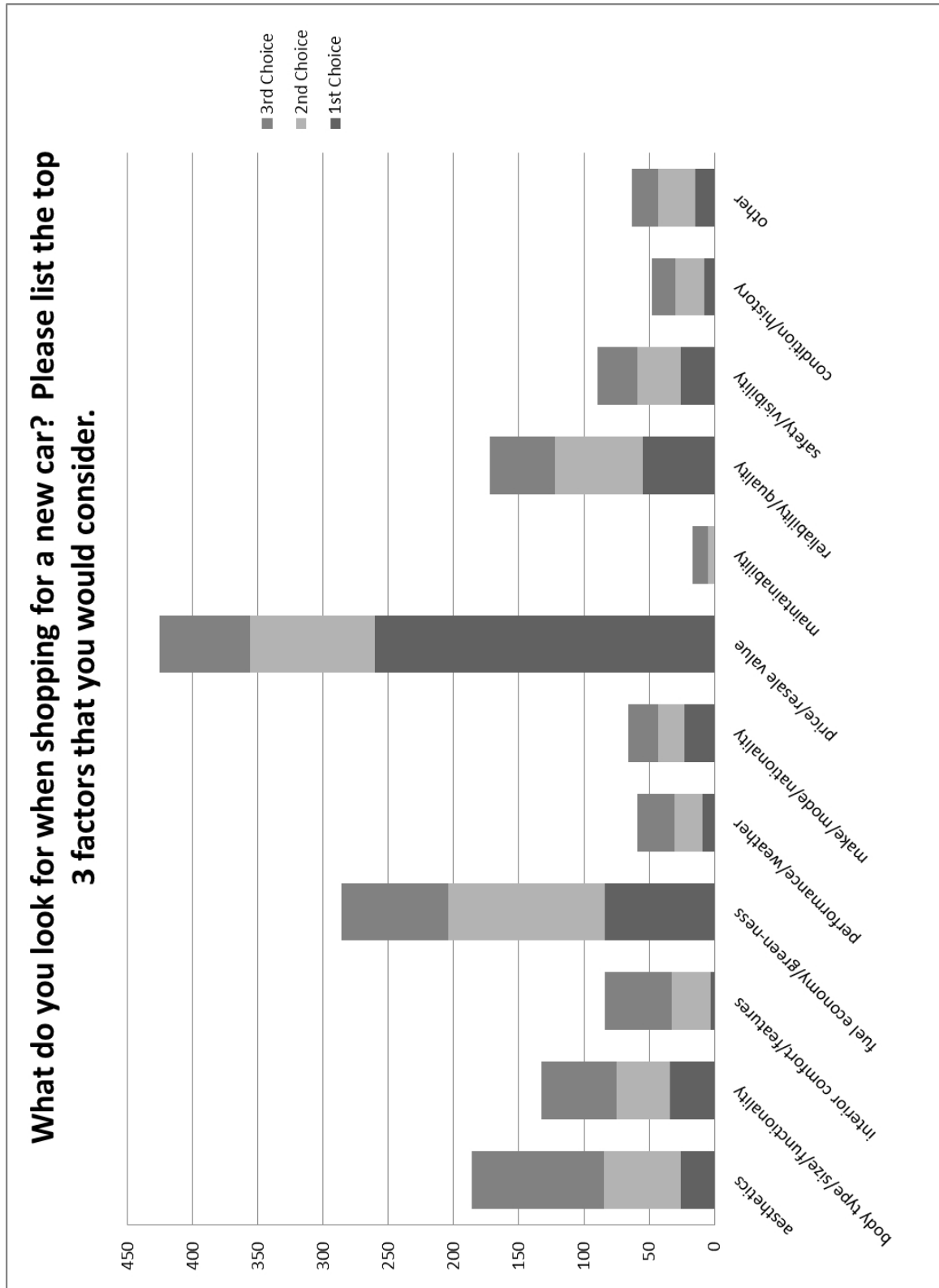
Usually drive a personal vehicle to work or school:

Yes, at least every weekday	257	47.3%
Yes, about half of weekdays	88	16.2%
No	198	36.5%

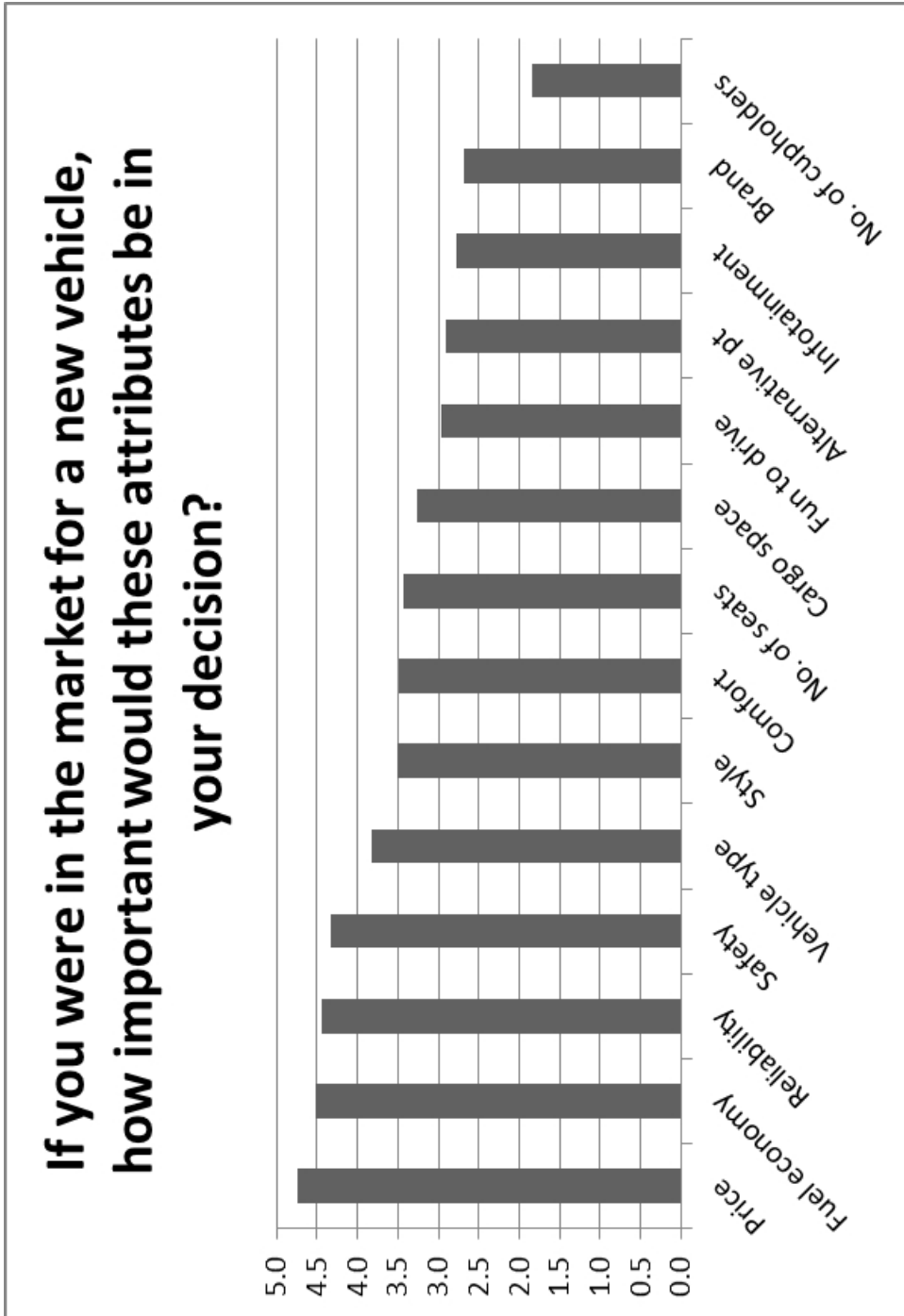
Interested in purchasing a new vehicle:

Yes, within the next year	87	16.0%
Yes, within the next 5 years	136	25.0%
Yes, but I'm not sure when	152	28.0%
No	168	30.9%

Unprompted Consideration of Vehicle Attributes



Prompted Consideration of Vehicle Attributes

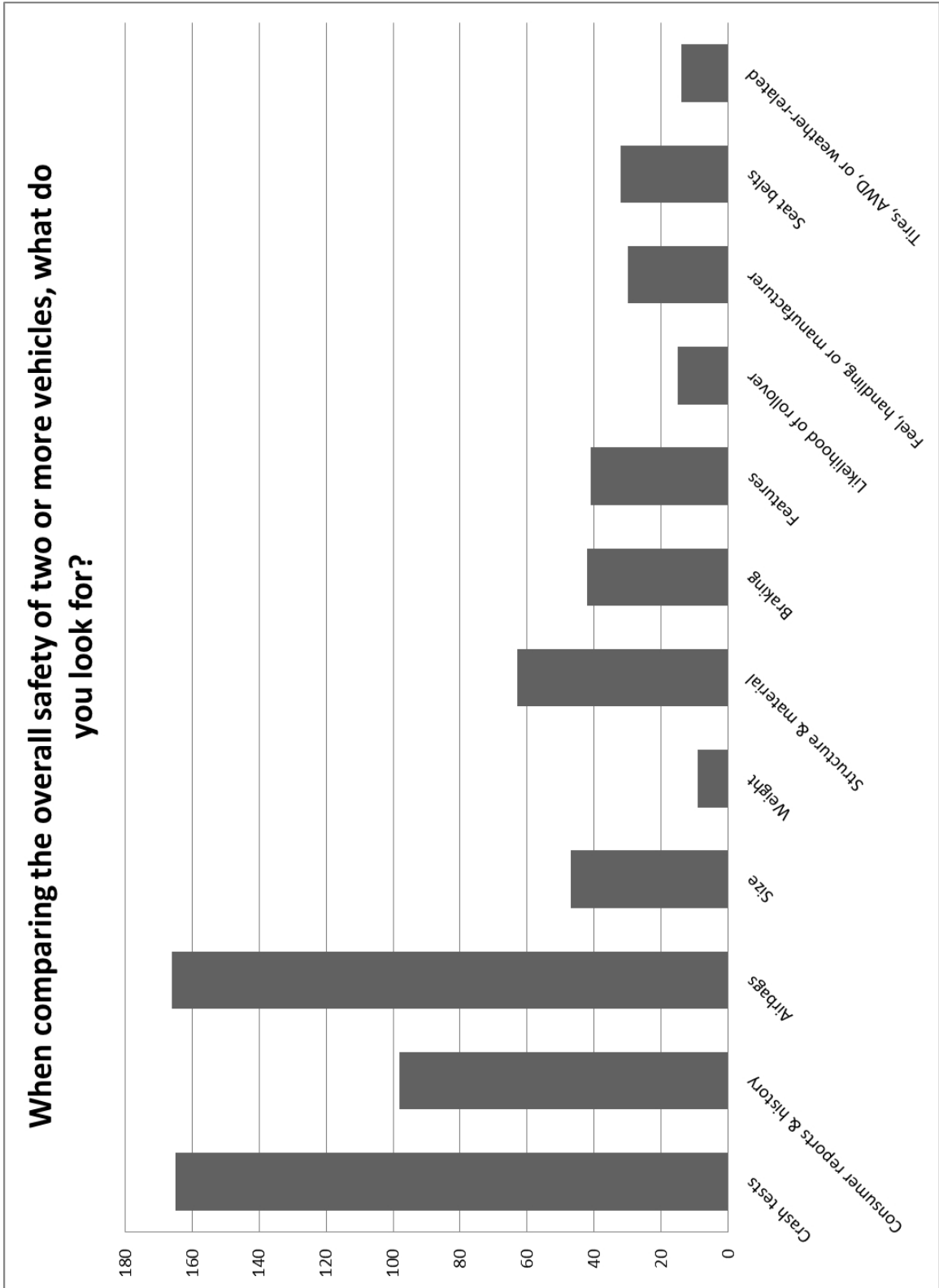


Choice-Based Conjoint Estimates

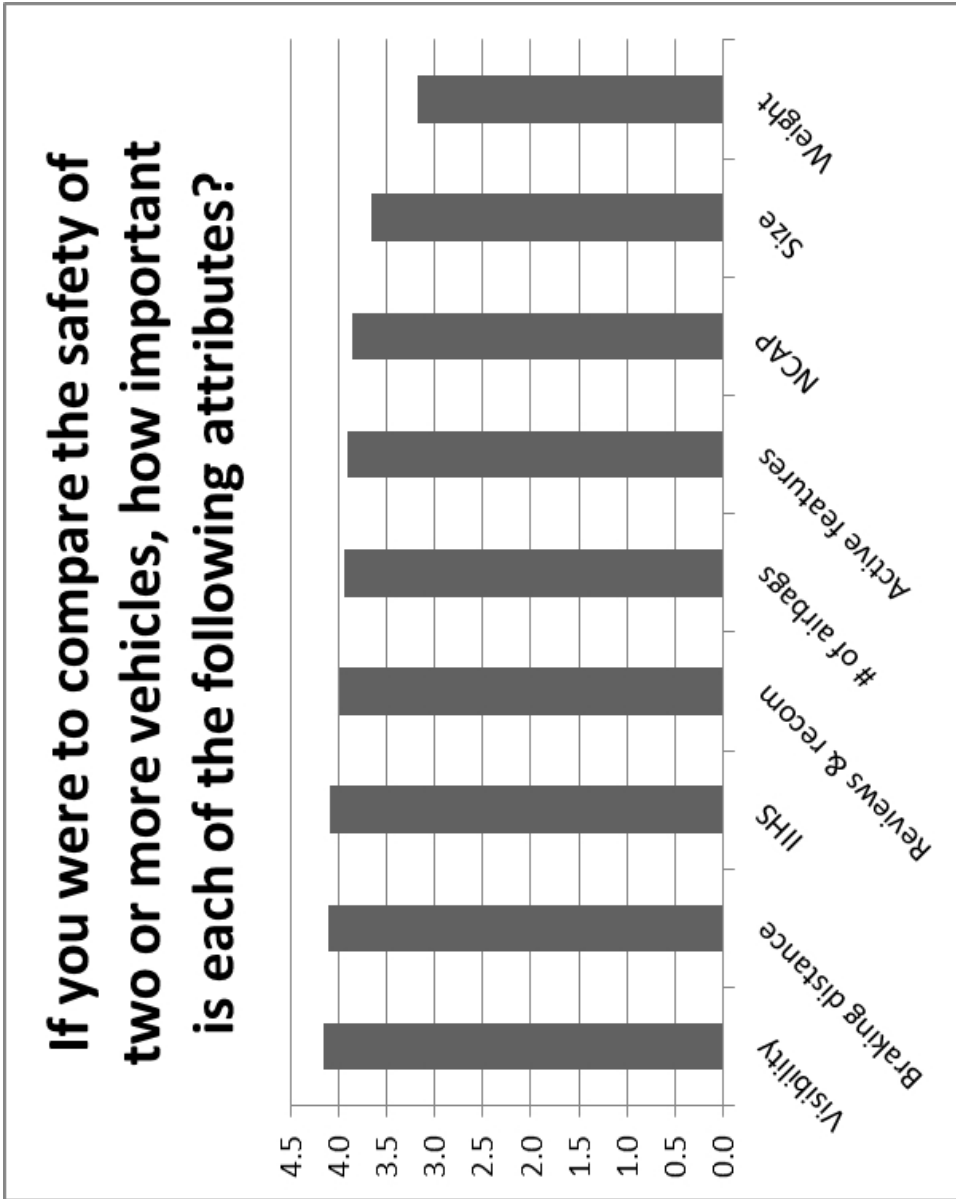
Because the software used to compute part worth estimates could only process a maximum of 250 respondents, the survey-takers were filtered based on their future new vehicle purchase intentions and the quality of their answers to the open-ended safety attributes question. Removing all respondents who gave generic responses to the safety attributes question, as well as the 168 respondents who are not intending to purchase a new vehicle, brought the field down to 243 respondents for processing the CBC information. The following table shows the results from the CBC multinomial logit estimation in Sawtooth, where “Effect” is the part worth of each particular attribute. The Chi Square value for the logit estimation is 1181.

Attribute Level	Effect	Std Err	t Ratio
6 second 0-60 acceleration	0.13110	0.04682	2.80008
8 second 0-60 acceleration	0.03761	0.04692	0.80158
10 second 0-60 acceleration	-0.16871	0.04857	-3.47381
1 in 40 chance of being seriously injured in a crash (very safe)	1.09099	0.04809	22.68432
1 in 20 chance of being seriously injured in a crash (moderately safe)	0.03808	0.05064	0.75205
1 in 10 chance of being seriously injured in a crash (relatively unsafe)	-1.12908	0.06766	-16.68752
35 miles per gallon	0.34568	0.04638	7.45359
30 miles per gallon	0.17055	0.04672	3.65023
25 miles per gallon	-0.51624	0.05266	-9.80241
\$20,000	0.55213	0.04682	11.79228
\$25,000	0.13849	0.04704	2.94397
\$30,000	-0.69061	0.05566	-12.40810
NONE	-0.65533	0.09358	-7.00292

Unprompted Consideration of Safety Attributes



Prompted Consideration of Safety Attributes

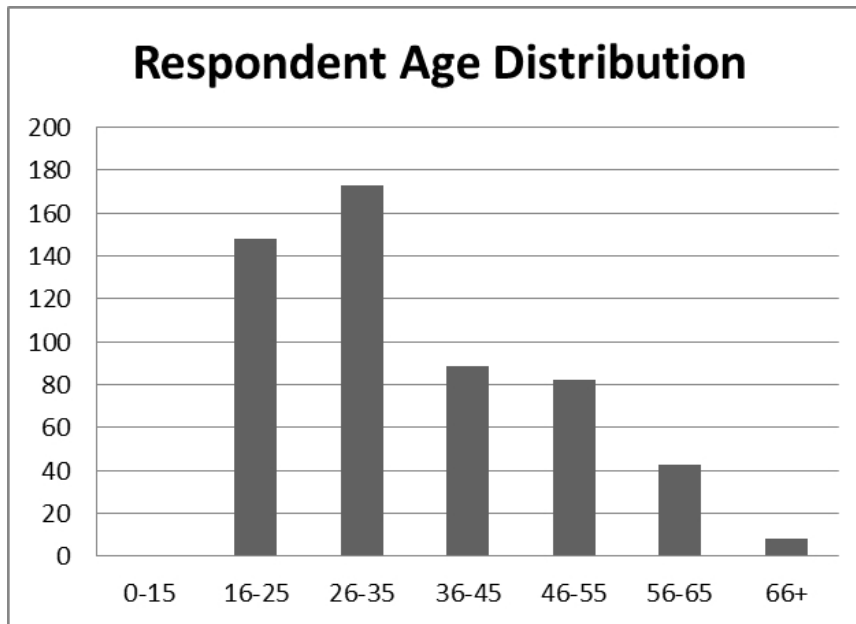


Demographic Distribution of Respondents:

Gender:

Males	214	39.4%
Females	329	60.6%

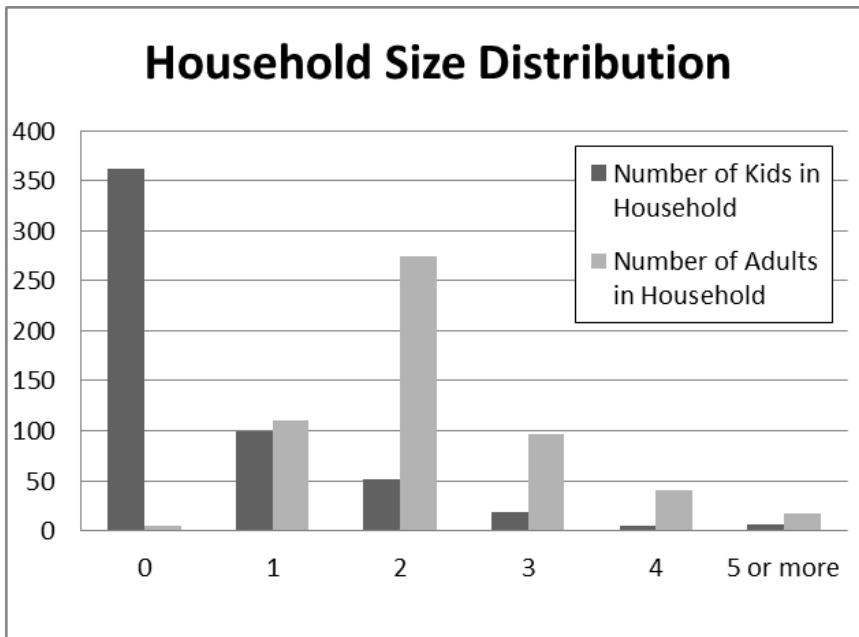
Age:



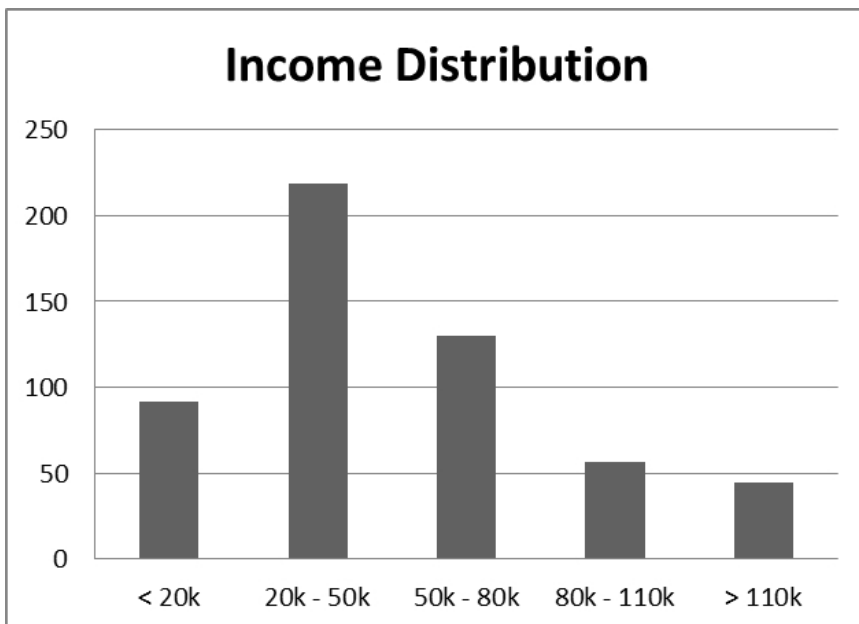
Race:

American Indian or Alaskan Native	4	0.7%
Asian or Pacific Islander	36	6.6%
Black or African-American	31	5.7%
Hispanic, Latino, or Spanish	28	5.2%
White or Caucasian	437	80.5%
Some other race	7	1.3%

Number of adults and children in household:



Approximate annual household income:



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