

# Safety Considerations in Optimal Automotive Vehicle Design

by

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A dissertation submitted in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
(Mechanical Engineering)  
in The University of Michigan  
2012

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## ACKNOWLEDGEMENTS

I must begin by acknowledging my co-authors and collaborators, who have contributed many of the ideas and even some of the wording to my conference and journal publications, and hence, the chapters of this dissertation. Many members of the Optimal Design Laboratory, notably Dr. Michael Alexander, Dr. Bart Frischknecht, Kwang Jae Lee, John Whitefoot, and Dr. Katie Whitefoot, contributed ideas and codes that have impacts throughout this dissertation. Much of Chapter III comes from a paper at the 2009 World Congress on Structural and Multidisciplinary Optimization, co-authored with Dr. Panos Papalambros, Dr. Michael Kokkolaras, and Dr. Matthew Reed. Chapter IV is derived from a recently-accepted paper to a special issue of the International Journal of Vehicle Design, co-authored with Mr. Sudhakar Arepally of the U.S. Army Tank Automotive Research Development and Engineering Center, Dr. Kokkolaras, and Dr. Papalambros. Chapter V comes from a recently-submitted paper to the International Journal of Vehicle Design, co-authored with Dr. Reed, Mr. Yannaphol Kaewbaidhoon who worked with me as an Undergraduate Research Opportunities Program student, and Dr. Papalambros. Chapter VI is from a paper at the 2011 Ground Vehicle Systems Engineering and Technology Symposium, written with Mr. Arepally, Dr. Kokkolaras, and Dr. Papalambros, and the recipient of a Best Paper Award. Finally, Chapter VII is an as-of-yet unpublished extension of Dr. Frischknecht's Ph.D. work here at the University of Michigan, with intellectual contributions from Dr. Frischknecht and Dr. Papalambros.

I also gratefully acknowledge the financial support of the Department of Mechan-

ical Engineering, Ford Motor Company, and the Automotive Research Center, a U.S. Army Center of Excellence in Modeling and Simulation of Ground Vehicles led by the University of Michigan. Other essential support came from the developers and suppliers of the original modeling tools used throughout this dissertation. The George Washington University National Crash Analysis Center developed the 2003 Ford Explorer finite element model that was made public to be used in various studies, and Aida Barsan-Anelli of the National Highway Traffic Safety Administration provided me with the multi-body dynamics full-vehicle models used in Chapter III. Dr. Saeed Barbat of Ford Motor Company allowed me to use occupant and restraint system models developed by his research group, which includes Mr. Tony Laituri and Dr. Para Weerappuli, for the crashworthiness studies, and Mr. Arepally supplied me with the vertical drop tower model that he developed for occupant blast protection analysis.

I would like to thank my committee members for their role in my development as a researcher and as a professional, as I appreciate their commitment and willingness to help me along the way to my doctorate. Dr. Kokkolaras has been a constant resource on optimization tools and methods, and Dr. Reed has been of invaluable assistance in helping me understand crash safety and injury mechanisms. Dr. Barbat helped me get started with an industry perspective on safety and modeling tools. Dr. Ken Powell and Dr. Noboru Kikuchi, both professors of mine during the coursework portion of my graduate education, taught me valuable tools that have been useful throughout my graduate research and will continue to be useful down the road.

And of course, the main reason that I came to Michigan was to work in design optimization under the mentorship of my committee chair and research advisor, Dr. Panos Papalambros. Panos, you have been a role model to me in so many ways, and I am lucky to have had the opportunity to work with you. It was a privilege to work with you, and I honestly could not see myself completing a doctorate with any

other advisor. I appreciate all of the support you have given me during my time at Michigan as an advisor, a colleague, and a friend.

I would also like to thank everyone who has supported me during my four and a half years in Ann Arbor, as well as the twenty-two years that led me here. I am nothing without family and friends, and I have been fortunate to have encouragement from the many different groups of people in my life. My support group in Ann Arbor has been incredible, and I have had opportunities to make friends from all different graduate and professional programs through existing friends, roommates, intramural sports, the Jewish community, the Department of Mechanical Engineering, and the Optimal Design Laboratory. The friends that I have made here are friends that I will have for the rest of my life, no matter where I am in the world. All of my friends, you know who you are, have made this Ph.D. experience so much more interesting, entertaining, and worthwhile.

To the Michigan football team and fans: Each year we begin with new hope for a great season, regardless of history, statistics, or realistic expectations. Many times during the course of my Ph.D. program I needed to regroup, refresh, and find new hope, and Michigan football taught me how this can be done in the face of unlikely success. That being said, I have a tremendous amount of respect and loyalty to the Michigan football team, and I will continue to proudly root for Michigan for the rest of my life. I look forward to the next national championship as much as I look forward to national championship teams at the University of Maryland.

Finally, I owe a great deal of gratitude to my parents, Richard and Linda Hoffenson, and my sister, Andrea. The three of you have shaped me into the person I am today, directly and indirectly developing my strengths, interests, and desires to do something meaningful in engineering research. While you may have questioned my decisions to spend so much time in school, each of you holds some responsibility for my being here and my accomplishments here, and I am thankful to you for that.

# TABLE OF CONTENTS

<b>ACKNOWLEDGEMENTS</b> . . . . .	ii
<b>LIST OF FIGURES</b> . . . . .	ix
<b>LIST OF TABLES</b> . . . . .	xii
<b>LIST OF APPENDICES</b> . . . . .	xiv
<b>LIST OF ABBREVIATIONS</b> . . . . .	xv
<b>LIST OF SYMBOLS</b> . . . . .	xvii
<b>ABSTRACT</b> . . . . .	xxii
<b>CHAPTER</b>	
<b>I. Introduction</b> . . . . .	1
1.1 Introduction . . . . .	1
1.2 The State of Vehicle Safety Research . . . . .	3
1.3 Expected Contributions . . . . .	6
1.4 Dissertation Outline . . . . .	7
<b>II. Literature Review</b> . . . . .	9
2.1 Introduction . . . . .	9
2.2 Measuring Vehicle Safety . . . . .	10
2.3 Vehicle Safety Fundamentals . . . . .	12
2.3.1 Safety Effects of Mass . . . . .	12
2.3.2 Safety and Fuel Economy . . . . .	19
2.3.3 Safety Effects of Size and Other Attributes . . . . .	22
2.3.4 Military Vehicle Safety . . . . .	28
2.4 Improving Vehicle Safety . . . . .	30
2.4.1 Safety Technology . . . . .	30
2.4.2 Fuel Economy . . . . .	33

2.4.3	Crash Tests and Standards . . . . .	35
2.4.4	Safer Military Ground Vehicles . . . . .	37
2.5	Modeling Vehicle Safety . . . . .	38
2.5.1	Physics-Based Modeling . . . . .	38
2.5.2	Crash Biomechanics . . . . .	41
2.5.3	Blast Biomechanics . . . . .	44
2.6	Market Systems: Profit-Driven Vehicle Design . . . . .	45
2.6.1	Economic Game Theory . . . . .	46
2.6.2	Consumer Choice Modeling . . . . .	47
2.6.3	Safety-Related Consumer Choice . . . . .	49
2.6.4	Engineering and Cost Modeling . . . . .	51
<b>III.</b>	<b>Simulation Tools for Crashworthiness and Vehicle Mass Op- timization . . . . .</b>	<b>52</b>
3.1	Introduction . . . . .	52
3.2	Modeling Approach . . . . .	54
3.2.1	Multi-Body Vehicle Crashworthiness Models . . . . .	54
3.2.2	Fuel Economy . . . . .	55
3.2.3	Combined Model . . . . .	57
3.3	Results . . . . .	59
3.4	Alternative Approaches to Safety Modeling . . . . .	65
3.4.1	Multi-Body Vehicle Models Linked With Dedicated Restraint System Models . . . . .	65
3.4.2	Finite-Element Vehicle Models Linked With Dedi- cated Restraint System Models . . . . .	69
3.5	Discussion . . . . .	74
<b>IV.</b>	<b>Optimization Formulations for Blastworthiness and Vehicle Mass . . . . .</b>	<b>76</b>
4.1	Introduction . . . . .	76
4.2	Modeling Approach . . . . .	79
4.2.1	Vehicle Structure Surrogate Modeling . . . . .	84
4.2.2	Occupant Compartment Surrogate Modeling . . . . .	86
4.3	Optimization . . . . .	88
4.3.1	Minimizing Probability of Failure . . . . .	88
4.3.2	Minimizing Normalized Forces . . . . .	90
4.3.3	Minimizing Postulated Injury Probabilities . . . . .	91
4.4	Results and Discussion . . . . .	93
4.5	Summary and Conclusions . . . . .	97
<b>V.</b>	<b>NCAP Frontal Test Standards and Design for Safety . . . . .</b>	<b>100</b>
5.1	Introduction . . . . .	100

5.2	Modeling Framework . . . . .	102
5.2.1	Modeling and Simulation . . . . .	104
5.2.2	Manufacturer’s Optimization . . . . .	107
5.2.3	Societal Uncertainty . . . . .	112
5.3	Results . . . . .	116
5.3.1	Optimal Vehicle Designs . . . . .	118
5.3.2	Injury Probabilities . . . . .	119
5.4	Discussion . . . . .	122
5.4.1	Manufacturer Vehicle Design . . . . .	122
5.4.2	Societal Injury Probability . . . . .	123
5.4.3	Broader Implications . . . . .	124
5.5	Conclusions . . . . .	125
<b>VI. Blastworthiness and Mobility Considerations in Design for Safety . . . . .</b>		<b>127</b>
6.1	Introduction . . . . .	127
6.2	Model Development . . . . .	128
6.2.1	Blast Protection Modeling . . . . .	128
6.2.2	Fuel Consumption Modeling . . . . .	132
6.2.3	Combined Casualties Model . . . . .	132
6.3	Results . . . . .	137
6.4	Discussion . . . . .	139
6.4.1	Dynamic Environment Considerations . . . . .	140
6.4.2	Intervention Approaches . . . . .	141
6.4.3	Opportunities for Model Enhancement . . . . .	142
6.5	Conclusions . . . . .	143
<b>VII. Safety Considerations in a Market Systems Framework . . . . .</b>		<b>144</b>
7.1	Introduction . . . . .	144
7.2	Baseline Market Systems Model . . . . .	145
7.3	Safety Considerations . . . . .	148
7.3.1	Engineering Performance . . . . .	149
7.3.2	Consumer Choice . . . . .	153
7.4	Results . . . . .	157
7.4.1	Impact of Adding Safety . . . . .	157
7.4.2	Impact of Changing Crash Speed Distribution . . . . .	161
7.4.3	Impact of Revised Frontal NCAP Test Speed . . . . .	164
7.5	Conclusions . . . . .	168
<b>VIII. Summary and Conclusions . . . . .</b>		<b>169</b>
8.1	Summary . . . . .	169
8.2	Summary of Contributions . . . . .	172



8.3	Opportunities for Further Research . . . . .	173
8.3.1	Civilian Vehicle Research Opportunities . . . . .	173
8.3.2	Military Vehicle Research Opportunities . . . . .	175
<b>APPENDICES</b>	. . . . .	176
<b>BIBLIOGRAPHY</b>	. . . . .	195

## LIST OF FIGURES

### Figure

2.1	Driver deaths per million registered vehicles using 1995-98 Insurance Institute for Highway Safety (IIHS) data of 1994-97 model year vehicles ( <i>Evans, 2004</i> ) . . . . .	14
2.2	Driver fatality ratio in two-car frontal crashes as a function of vehicle mass ratio ( <i>Evans, 2004</i> ) . . . . .	16
2.3	Driver fatalities as a response to vehicle mass ratio in two-vehicle non-rollover crashes ( <i>Eyges and Padmanaban, 2009</i> ) from Fatality Analysis Reporting System (FARS) 2005 data . . . . .	18
2.4	Factors contributing to driver fatality risk in two-car frontal crashes ( <i>Eyges and Padmanaban, 2009</i> ) . . . . .	18
2.5	Crash rating versus mean fuel consumption in city driving ( <i>Symmons and Haworth, 2003</i> ) . . . . .	20
2.6	U.S. vehicle fuel economy and traffic fatalities, 1966-2002 ( <i>Ahmad and Greene, 2005</i> ) . . . . .	21
2.7	Average fatality risk for vehicle types ( <i>Wenzel and Ross, 2008</i> ) . . .	23
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 ( <i>Wenzel and Ross, 2008</i> ) . . . . .	24
2.9	Risk-to-drivers versus 5-year resale value of individual nameplates, categorized by manufacturer nationality ( <i>Wenzel and Ross, 2008</i> ) .	25
2.10	Categorization of crash incompatibilities ( <i>Elmarakbi and Zu, 2004</i> ) .	27
2.11	Afghanistan casualties caused by improvised explosive devices (IEDs), per year ( <i>White, 2011</i> ) . . . . .	29
2.12	Cost estimates for increasing fuel economy in domestic vehicles ( <i>Wenzel and Ross, 2008</i> ) . . . . .	34
2.13	Three-degree-of-freedom lumped mass model for vehicle crashworthiness ( <i>Marler et al., 2006</i> ) . . . . .	39
2.14	New Car Assessment Program (NCAP) curves representing probability of injury as a function of criteria in the (a) head, (b) neck, (c) chest, and (d) thigh regions . . . . .	43
2.15	Market systems approach for firm profit-driven design ( <i>Frischknecht, 2009</i> ) . . . . .	46

2.16	Factors ranked as “most important” by survey takers when considering a new vehicle purchase decision ( <i>Koppel et al.</i> , 2008) . . . . .	50
3.1	Typical vehicle safety design process . . . . .	53
3.2	MADYMO-based vehicle simulation model of a 1995 Ford Explorer with mid-size male occupant . . . . .	55
3.3	Fuel economy vs. curb weight . . . . .	56
3.4	Integrated model process flow diagram . . . . .	57
3.5	Plots of 100-point design of experiments (DOE) varying rear mass and frontal rail stiffness . . . . .	60
3.6	Linear response surface for PAIS3+; (a) superimposed on data, and (b) unaccompanied . . . . .	61
3.7	Pareto frontier for bi-objective optimization . . . . .	63
3.8	Acceleration vs. time with varying mass of (a) vehicle and (b) driver thorax . . . . .	64
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 . . . . .	66
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 . . . . .	67
3.11	Results from 64-point DOE varying mass and stiffness . . . . .	68
3.12	Data from 64-point DOE fitted with least-trimmed squares response surfaces . . . . .	68
3.13	Crash pulses from MADYMO simulation varying (a) mass and (b) stiffness, where darker grey indicates a higher value . . . . .	70
3.14	Crash pulses varying mass and stiffness for finite-element (FE) and multi-body (MADYMO) models . . . . .	71
3.15	Results of 9-point DOE with finite-element vehicle model . . . . .	72
3.16	Crash pulses varying mass and stiffness using finite-element model . . . . .	73
4.1	Models and approach . . . . .	80
4.2	Photograph of the physical drop tower set-up at the Selfridge Air National Guard Base . . . . .	81
4.3	Postulated injury probability curves . . . . .	92
4.4	Pareto sets of the response versus vehicle mass for three formulations, where the objective scale is logarithmic for (a) and (c) . . . . .	95
5.1	Distribution of crash speeds from on-road data, adapted from Evans (1994) . . . . .	101
5.2	Framework of government, manufacturer, and societal interaction . . . . .	103
5.3	Simulation models of (a) vehicle and (b) restraint system . . . . .	105
5.4	Sample crash pulse . . . . .	106
5.5	Process flow diagram for manufacturer optimization and societal modeling . . . . .	108
5.6	Original crash pulse with reduced representation using proper orthogonal decomposition (POD) . . . . .	109
5.7	Comparison of low- and high-stiffness vehicle crash pulses . . . . .	110

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 . . . . .	117
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 . . . . .	120
6.1	Pareto frontier for minimizing vehicle mass and occupant injury probability under blast loading . . . . .	131
6.2	Fuel consumption vs. vehicle mass of 48 U.S. Army ground vehicles	133
6.3	Combined casualty calculation framework . . . . .	135
6.4	Parametric optimization results varying number of blast events per year . . . . .	138
6.5	Parametric optimization results varying fuel convoy casualty rate . .	139
7.1	Flow chart describing development of engineering safety model . . .	152
7.2	Expected probability of serious injury varying vehicle mass . . . . .	153
7.3	Example CBC survey question . . . . .	154
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 . . . . .	155
7.5	Three different probability distributions of frontal crash speed . . .	162
7.6	Expected probability of serious injury by vehicle mass for three crash speed distribution scenarios . . . . .	162
7.7	Expected probability of serious injury varying vehicle mass, for each of three NCAP scenarios . . . . .	165

## LIST OF TABLES

### Table

2.1	Denominators used in popular studies for empirical vehicle safety analysis ( <i>Ross and Wenzel, 2001</i> ) . . . . .	11
2.2	Suitability of different types of human surrogates used in injury biomechanics research ( <i>Crandall et al., 2011</i> ) . . . . .	41
4.1	Inputs and outputs of simulation models . . . . .	85
4.2	Optimized designs for 3 approaches varying vehicle mass . . . . .	94
5.1	Design variables used in manufacturer’s optimization . . . . .	104
5.2	Optimal vehicle designs for three NCAP scenarios . . . . .	118
5.3	Simulated injury probability for each optimal vehicle design at each test speed . . . . .	122
6.1	Combined optimization baseline scenario parameters . . . . .	134
6.2	Optimization solution for baseline scenario . . . . .	137
7.1	Design variables for market systems framework ( <i>Frischknecht and Yoon, 2008</i> ) . . . . .	146
7.2	Engineering constraints used in Frischknecht’s market systems model	149
7.3	Comparison of market systems results with and without consumer safety considerations; designed vehicle is a Subaru SUV in a 39-vehicle market . . . . .	158
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 . . . . .	160
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 . . . . .	160
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 . . . . .	163
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 . . . . .	163

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 . . . . .	164
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 . . . . .	166
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 . . . . .	167
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 . . . . .	167

**LIST OF APPENDICES**

Appendix

A. Consumer Choice Survey . . . . . 177

B. Data from Consumer Choice Survey . . . . . 187

## LIST OF ABBREVIATIONS

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

$\alpha_D$	Dealer markup, as a percentage
$\alpha_{eng}$	Engine-related design attributes
$\alpha_{other}$	Non-engine-related design attributes
$\beta$	Coefficient of fixed effects between consumers and vehicles
$\beta_{eng1}$	Cost model regression coefficient for engine type
$\beta_{eng2}$	Cost model regression coefficient for engine design attributes
$\beta_{ik}$	Matrix element relating consumer $i$ to vehicle attribute $k$
$\beta_{other}$	Cost model regression coefficient for non-engine attributes
$\delta$	Coefficient representing fixed preference for attributes
$\Delta v$	Change in velocity
$\epsilon_{ij}$	Stochastic part of utility that consumer $i$ perceives in product $j$
$\mu$	Coefficient of stochastic effects between consumers and products
$\mu_p$	Mean occupant sitting position
$\pi$	Profit of an automaker
$\sigma_p$	Standard deviation of occupant sitting position
$\Phi(a_{peak})$	Normal probability distribution function of $a_{peak}$
$\phi_{bmv}$	Percentage of military blast events striking multipurpose vehicles
$\phi_{fcc}$	Percentage of military fuel convoys with a casualty
$\phi_{fmv}$	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.