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
$F_{25\text{mph}}$	FMVSS standard for 25-mph frontal crash with unbelted ATD
$F_{30\text{mph}}$	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
$HIC15$	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-aborbing 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
$\overline{W}$	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.