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An Optimization Approach to Occupant Safety and Fuel Economy in Vehicle Design

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1. Abstract
A major challenge in automotive design is the creation of safe vehicles with minimal environmental impact. This study presents a modeling framework for evaluating and optimizing body designs for improved occupant safety and fuel efficiency. Vehicle body mass is considered as the main link between safety and sustainability. The modeling framework includes frontal crash energy absorption, restraint system design and fuel economy. Preliminary results indicate a Pareto-optimal curve between safety and sustainability may exist when other factors are not taken into account. A more complete modeling framework that includes more sophisticated sustainability and safety metrics, cost and other market considerations, is suggested in order to support better design and regulatory decisions.
2. Keywords: Automotive body structures, fuel economy, occupant safety, optimal vehicle design, restraint systems

3. Introduction

The World Health Organization (WHO) attributes roughly 1.2 million deaths and 39 million injuries to traffic incidents each year [1]. Vehicle design engineers aim at minimizing 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 areas: crashworthiness, i.e., the degree a vehicle protects its occupants in a crash, and crash avoidance, i.e., measures taken by the vehicle that enable the driver to avoid a crash [2]. Much academic and industrial research has been devoted to optimizing the performance of safety systems, including structural systems and restraint systems. Vehicle body structures such as frame rails, bumpers, and hood support beams have been optimized to produce the best possible crash pulse, or the acceleration history of the occupant compartment during a crash. Other passive safety systems, such as seat belts, pretensioners, load limiters, and air bags, have been optimized given a vehicle crash pulse to reduce the likelihood of occupant injury [3, 4]. New restraint configurations, such as belt-integrated seats and four-point seat belts, have been explored in research studies, but have not been implemented widely yet [5, 6]. Active safety systems, such as antilock brake systems and electronic stability control, have been developed, optimized and implemented to prevent or mitigate accident severity.

An additional concession that society has made for the convenience and utility of personal vehicles is that of sustainability. Automobile use jeopardizes fuel resource availability and air quality, mainly due to fossil fuel combustion. While fuel consumption is not the only sustainability concern associated with automobiles, life-cycle analyses show that it contributes to approximately 85% of the life-cycle environmental impact of a vehicle [7]; it is estimated that over 140 billion gallons of gasoline are consumed per year [8]. Several studies have indicated that reducing a vehicle's mass by ten percent improves its fuel economy between five and eight percent, along with corresponding emissions reductions [9]. As a result of this correlation, as well as cost reductions and improvements in vehicle handling, many manufacturers are making efforts to reduce the mass of their vehicles.

While mass reduction is perhaps the easiest way to improve vehicle fuel economy, many researchers argue that this can have negative safety consequences. In 1989, Crandall and Graham investigated trends in the United States when large-scale mass reductions occurred due to stricter government fuel economy regulations in the late 1970's, and claimed that mass reductions caused an additional 2,200 to 3,900 annual fatalities on U.S. roadways [10]. The literature often references the law of conservation of momentum to support this cause, indicating that in car-to-car collisions the change in velocity is higher for the less massive of the two vehicles [11]. Evans developed an empirical relationship which predicts that the additional mass of an extra passenger can decrease the risk of the driver's death by approximately 14 percent [12]. Other studies by Wenzel and Symmons support these observations, where data from U.S. and Australian roadways show a clear negative correlation between fuel economy and occupant safety [2, 13].

This conclusion is far from unanimous, however, and three referenced studies have come to the conflicting conclusion that no trade off exists between occupant safety and fuel consumption [14, 15, 16]. Other studies have shown that in existing vehicles, mass is coupled with other size variables including wheelbase [12], bumper height, track width, and front overhang size [17], indicating that size or geometry may affect safety at least as much as mass. Two separate studies have shown that for increasing occupant safety, increasing a vehicle's length or wheelbase is more influential than increasing mass [12, 18]. Wood has investigated this theory and concluded that size is indeed more important in collisions between similar vehicles, yet in collisions between dissimilar vehicles (e.g., car-to-light truck) mass is more influential [19]. The variety of conclusions drawn by these authors demonstrates that there is no clear consensus as to whether mass or size has more authority over the occupant safety of a vehicle.

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 through design of the bumper, frame rails, and hood supports. Occupant restraint engineers work with the crash pulse produced in simulations of the intended front-end structure 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. In current practice, relatively little opportunity is available for occupant safety outcomes 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, as shown in Figure 1.

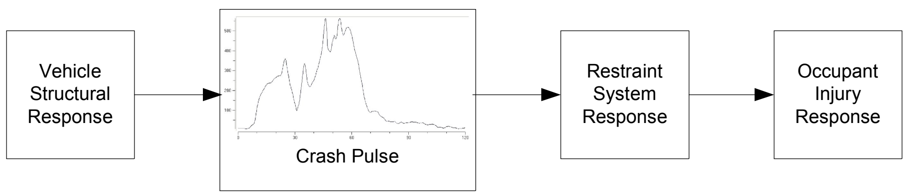

Figure 1: Typical vehicle safety design process

Therefore, an integrated modeling and optimization approach that accounts for interactions between structure and restraint system design would be useful to quantify the impact of sustainability-driven weight reduction on occupant safety. This paper 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. A model that includes both automotive structure and restraint system variables is presented, preliminary multi-objective optimization results are obtained, and the next steps towards a comprehensive design and optimization methodology are discussed.

4. Modeling Approach

The modeling framework is built using the MADYMO multi-body dynamics and finite element analysis package to compute vehicle crash response and occupant injury criteria, along with AVL Cruise software to predict vehicle performance and fuel economy [20, 21].

4.1. Occupant Safety Model

A common approach to assess vehicle occupant safety is to use a vehicle finite element model combined with a MADYMO restraint system model. With this technique, the vehicle finite element model is used first to simulate a crash under prescribed conditions, and the crash pulse is computed over the appropriate time period. The crash pulse is then input into a MADYMO multibody simulation of the occupant (crash dummy) and restraint system. Forces, torques and deformations of the dummy model are computed, and the obtained data are used to predict survivability and injury rates. This method is well accepted in the automotive design practice, where vehicle and restraint system models are validated using physical crash tests.

Another method for simulating occupant safety has been used to understand the safety implications of vehicle compatibility issues and large-scale vehicle design changes. This approach uses full-vehicle MADYMO models developed and validated by the U.S. National Highway Traffic Safety Administration (NHTSA) and TNO, the developer of the MADYMO software [22]. These 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 seat belt and air bag. Using rigid body dynamics to compute the vehicle response, computational time is reduced substantially: a simulation using rigid body dynamics models has been found to take less than one-third of one percent of the amount of time it takes to compute a full finite element response.

The present study uses full vehicle MADYMO models to estimate the effects of vehicle design changes on driver safety in frontal impact. This approach was chosen due to the need for a relatively speedy modeling method which could be used for testing large numbers of design configurations in a reasonable amount of time. The simulation considers a 35 mile-per-hour frontal barrier crash of a vehicle representative of a 1995 Ford Explorer with a single midsize-male Hybrid-III dummy representing the driver.

4.2. Fuel Economy Model

To predict vehicle fuel economy, the AVL Cruise software package is used to simulate an FTP-75 U.S. urban drive cycle [23]. Vehicle design can be changed through different structural and engine configuration variables. The vehicle is again representative of a 1995 Ford Explorer with a curb weight of 1840 kilograms. Figure 2 depicts predicted fuel economy for a wide range of vehicle mass deviations from the baseline value.

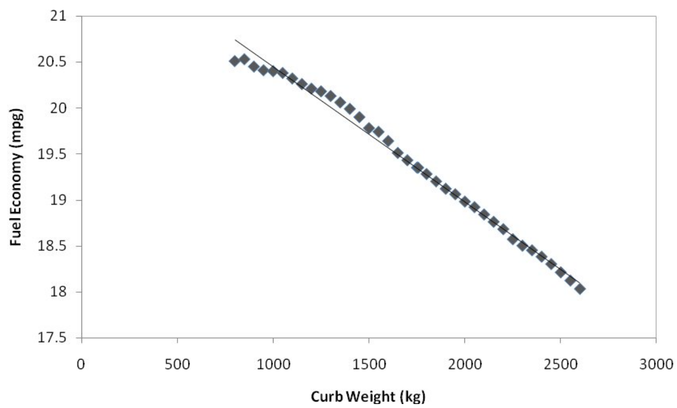

Figure 2: Fuel consumption vs. curb weight

As expected based on previous literature [9], the relation between fuel economy and vehicle mass is practically linear. Therefore, we used the obtained data to build a linear polynomial model to reduce computational expense in subsequent optimization studies. This linear model for fuel economy (FE) as a function of rear mass is shown in Eq.(1), where the units of fuel economy are miles per gallon (mpg), and the units for rear mass are kilograms (kg).

$$FE = -0.0015 \cdot (1608 + m_{rear}) + 21.909 \quad (1)$$

4.3. Integrated Model

The separate occupant safety and fuel economy models have been integrated using the Noesis OPTIMUS software package [24]. The current stage of the model incorporates six input variables that affect mass, crush properties, and restraint system behavior, and it yields output values that represent the safety and fuel economy performance characteristics. A diagram of the full process flow is presented in Figure 3.

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 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, we operate under the assumption that any mass can feasibly be 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, cost, 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 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 (HIC15 and HIC36), neck tension-extension (N_{TE}), peak chest acceleration (3ms clip, m/s²), peak chest deflection (m), peak vehicle acceleration as measured on the driver-side door sill (m/s²), 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 Abbreviated Injury Scale (AIS) is calculated in four areas of the body using normal distribution data from Laituri [25, 26]. Using these numbers, a calculation of the combined probability of an occupant receiving any "serious"-rated injury is found using Eq.(2).

$$P_{AIS3+} = 1 - (1 - P_{head})(1 - P_{neck})(1 - P_{chest})(1 - P_{lower}) \quad (2)$$

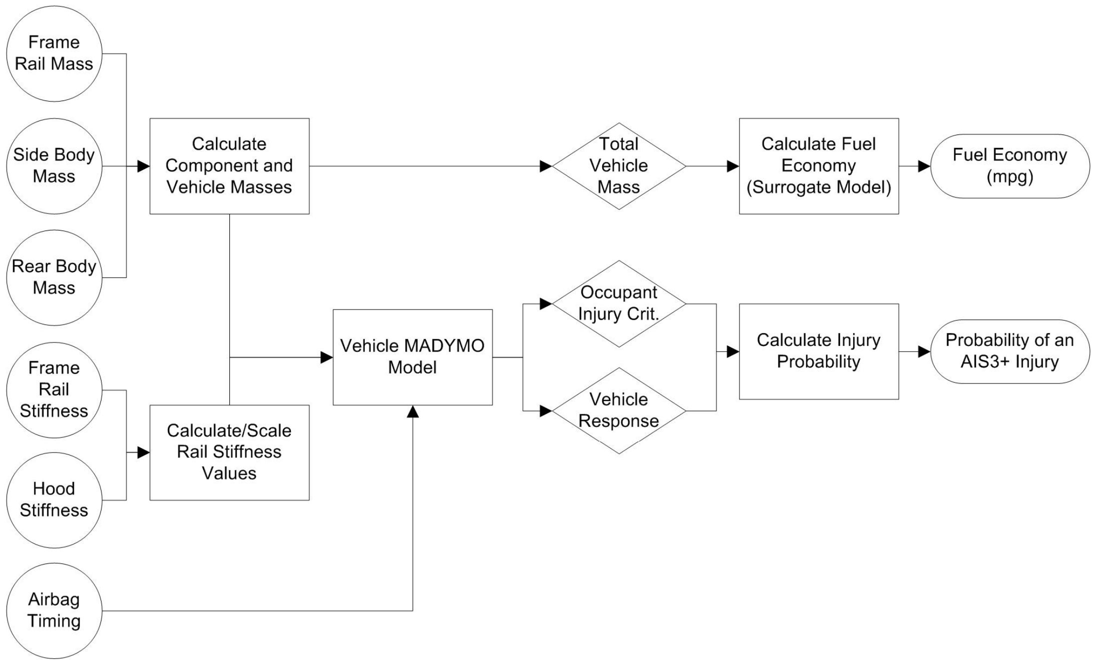

Figure 3: Integrated model process flow

5. Preliminary Results

In preparation for subsequent optimization work, 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 rail stiffness (the hood stiffness was found to not have a significant effect on the outputs). A second DoE study was conducted with airbag timing incorporated as a third variable. The DoE results were used to generate a response surface, which was 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.

5.1. Varying Rear Mass and Frame Rail Stiffness

To understand the relationships among the rear body mass, the frame rail stiffness, and the output criteria, a DoE study spanning 100 points was conducted over the design space of these two variables. As expected, the trend for fuel economy is only dependent on mass and remains constant where the mass does not change, as shown in Figure 4a. Another clearly visible trend is for the peak vehicle acceleration; as shown in Figure 4b, there is steady decrease in acceleration with increasing mass values; stiffness variance effects are subtler. The two plots in Figures 4c and 4d show the chest acceleration (3 ms clip) and the probability of severe injury over the design space.

The data concerning occupant injury represented in Figures 4c and 4d exhibit noticeable noise, 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 trend. This type of noise is common when using finite element vehicle models or full-scale physical anthropomorphic test dummies, 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 4d, and Figure 5 shows a plot of the response surface. The clear outlier was removed from the data, and the linear polynomial 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 polynomial response surface. Eq.(3) characterizes the obtained linear response surface.

$$P_{AIS3+} = 0.6713 - 0.0002326 \cdot m_{rear} - 0.07236 \cdot k_{rail} \tag{3}$$

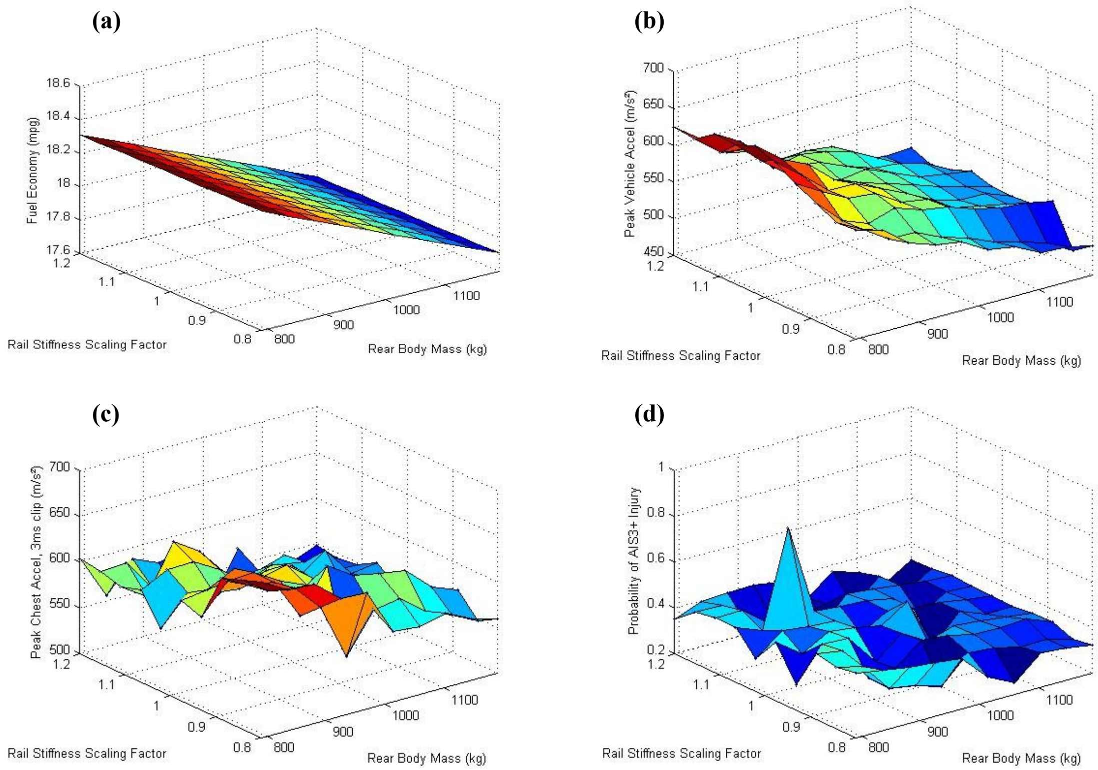

Figure 4: Plots of 100-point DoE varying rear mass and frame rail stiffness

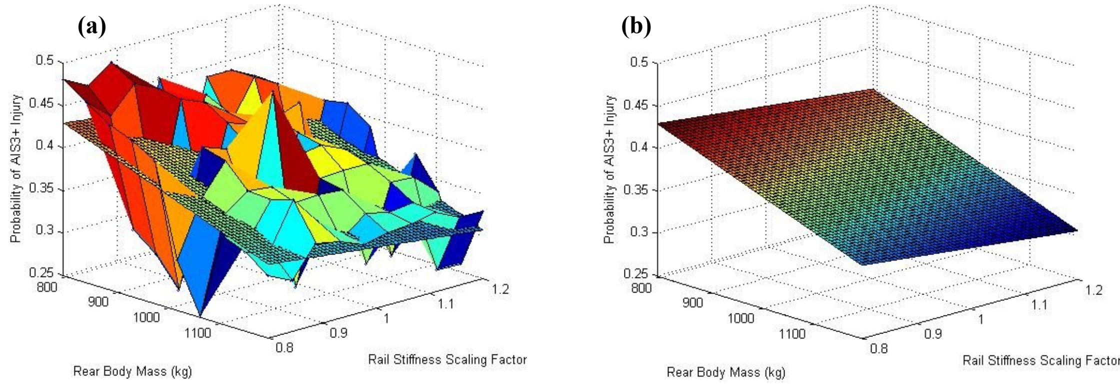

Figure 5: Linear response surface for P_{AIS3+}; (a) superimposed on data, and (b) unaccompanied

5.2. Three-Variable Optimization Study

As a first step towards an integrated approach to structural and restraint system design, airbag release time is included as a design variable. A DoE study was conducted to obtain injury probability values as a function of mass, rail stiffness and airbag release time. While 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 these variables should be simultaneously optimized along with the structural variables. A bilinear response surface was proven to fit the data best (relative to linear and quadratic alternatives); the obtained polynomial response surface is given in Eq.(4).

$$P_{AIS3+} = 1.75 - 0.00135 m_{rear} - 1.12 k_{rail} + 4.84 t_{airbag} + 0.00101 m_{rear} k_{rail} - 0.00122 m_{rear} t_{airbag} + 7.81 k_{rail} t_{airbag} \quad (4)$$

Using the generated polynomial models for fuel economy and probability of severe injury, a bi-objective optimization problem was formulated as follows.

$$\begin{aligned} &\min_{m_{rear}, k_{rail}} \left\{ P_{AIS3+}\left(m_{rear}, k_{rail}, t_{airbag}\right), \; -FE\left(m_{rear}\right) \right\} \\ &\text{s.t. } 792 \le m_{rear} \le 1192 \\ &\quad\; 0.8 \le k_{rail} \le 1.2 \end{aligned} \quad (5)$$

The Pareto set generated by solving problem (5) is shown in Figure 6. It quantifies the tradeoff that exists between injury probability and fuel economy given the particular problem formulation and modeling.

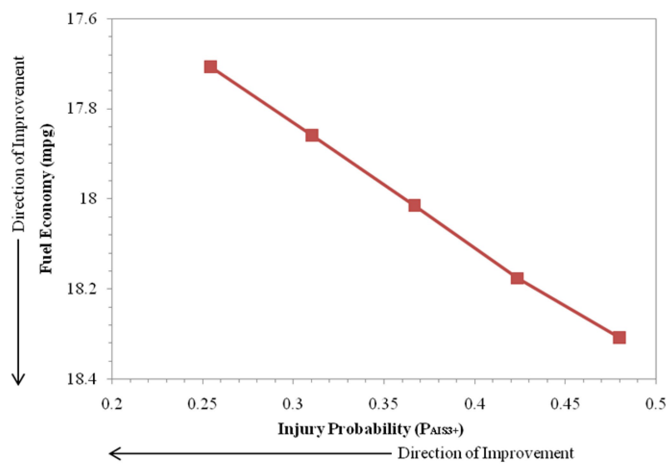

Figure 6: Pareto frontier for bi-objective optimization

5.3. Vehicle and Occupant Response

A third set of simulations was conducted to examine the changes in the acceleration profiles as the total vehicle mass shifts. Five simulations were conducted: the first had rear, side and frame masses uniformly scaled so that it 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 Figures 7a and 7b, respectively. In both plots, the curve with the highest peak represents the lightest vehicle and the lowest curve represents the heaviest vehicle.

Examination of these plots reveals two important behavior aspects of the model. The first can be seen from examining Figure 7a, where it is evident that the peak acceleration in the lighter two cases occurs near the first "peak" at 45 ms and the peak acceleration in the heavier cases occurs closer to 60 ms, 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 7b, where the thoracic 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 noise seen in the plots of Figure 4, and it shows that although the vehicle is responding as expected, dummy interactions with different body parts or vehicle components can cause significant changes in the model response. These nonlinearities in data 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.

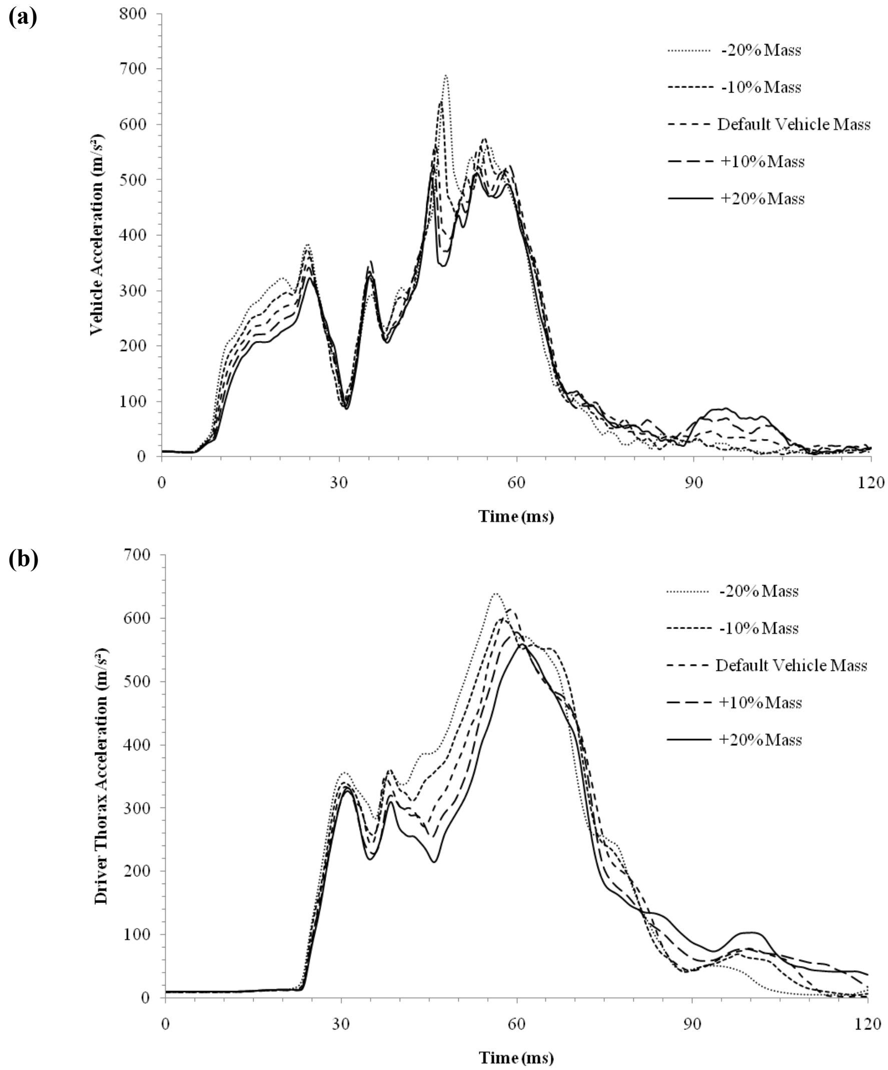

Figure 7: Acceleration vs. time with varying mass of (a) vehicle and (b) driver thorax

6. Conclusions and Future Work

Preliminary results using the described optimization approach confirm the hypothesis on 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 will provide designers with a preliminary quantitative understanding of how their decisions will affect the performance of a vehicle line.

It is important to note that the results discussed here address safety only for one size occupant in one uncommon crash scenario, namely a high-speed, full-frontal barrier crash. Although this is an important type of crash test used for vehicle regulation and consumer information programs in the U.S., the current effort does not address many other crash modes that are important for safety. Barrier crash results likely underestimate the overall reduction in safety due to vehicle mass reduction, because mass is most important in multivehicle crashes. The simulations do not consider the effects of restraint system optimization other than gross changes in the airbag deployment timing; in a typical vehicle development process, many restraint system variables would be optimized to improve performance. The current simulations demonstrate the necessity for restraint system optimization if safety performance is to remain unaffected by changes in vehicle stiffness and mass.

The simulations also have not considered the effects of vehicle modifications on the safety of vehicle occupants other than the driver, occupants of crash partner vehicles, or the safety of pedestrians. The MADYMO vehicle model used in these simulations was validated by other researchers using certain performance variables [22], but no validation of the modified models used for these simulations has been performed. Finally, the fidelity of the safety analysis is limited by the validity of the crash dummy model, which is a simulation of a physical model of

the human occupant.
Planned extensions to the model include adding pertinent structure and restraint system variables, incorporating a more sophisticated sustainability metric that models engine characteristics as well as mass, developing and integrating a cost model to reflect expected financial ramifications, and conducting further vehicle design optimization studies. The current model operates under a variety of assumptions and a limited number of variables. In ongoing work, the authors are introducing more links to the vehicle structure and restraint system as variable inputs. This will allow for more flexibility and provide more insight into the behavior of the vehicle model under differing design configurations. It will also become clearer to what extent upgrading the restraint system content can compensate for or augment the performance of the structural crash response. Additional safety model content will include variations in the crash speed, crash mode, number of occupants, and size and gender of occupants to better represent more collision scenarios.
With regard to the sustainability model, the authors recognize that mass is not the sole factor impacting fuel economy, and that fuel economy is not the sole indicator of sustainability. There are other variables that have significant effects on fuel economy, including engine displacement, engine configuration, and drag coefficients, and there are many other factors that affect sustainability such as raw material consumption, manufacturing processes and wastes, and end-of-life disposal. These metrics will be introduced to the modeling framework as this is extended to ensure a realistic representation of sustainability.

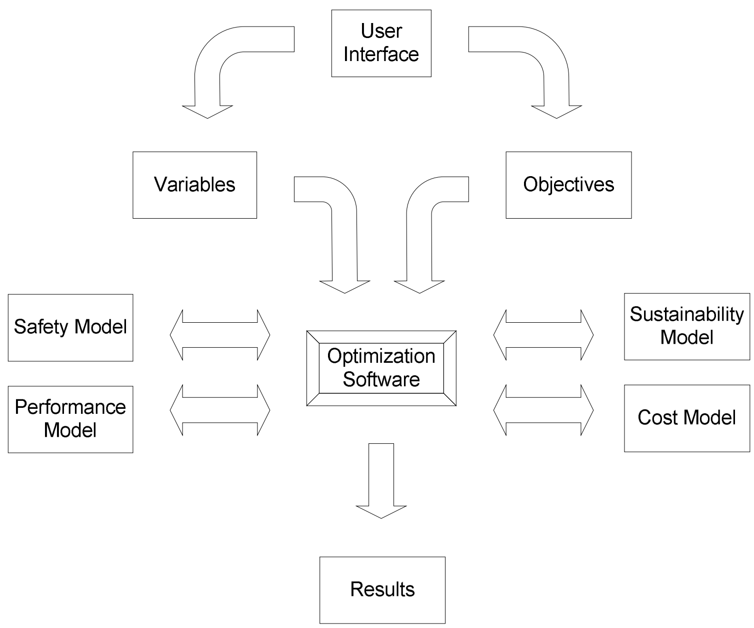

Figure 8: Framework of extended model

Another major assumption is the idea that changing various material properties such as mass and stiffness can be achieved readily. In reality, such changes might not be feasible or would incur varying costs due to material and manufacturing prices. Using such a tool, vehicle designers could optimize their vehicle designs with constraints on the cost, or even place constraints on the safety or sustainability criteria while minimizing cost. Other vehicle performance aspects such as ride, handling, comfort and styling should be incorporated in a similar manner, which will ensure that designers do not neglect other important vehicle attributes in the optimization process. Figure 8 presents a schematic of the framework with the planned extensions. It is expected that optimization results will provide vehicle designers with insight as to how vehicle design changes affect occupant safety and sustainability performance.

7. Acknowledgements
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