

THE IMPACT OF SAFETY STANDARDS AND POLICIES ON OPTIMAL AUTOMOBILE DESIGN

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ABSTRACT

Much of the recent decline in road traffic injuries and fatalities in developed nations is attributed to government regulations and institutional crash test ratings. While the regulations provide minimum performance or equipment requirements, crash tests provide a standardized method for crashworthiness comparisons between vehicles, and they do so using prescribed crash scenarios that aim to represent real-world crashes. Because the results of these tests influence consumer demand for vehicles, automakers commonly optimize vehicle designs to perform well in these specific crash scenarios. This study explores the impact of three particular specifications of the NHTSA NCAP frontal crash test on optimal automobile design, including the speed of impact, the injury severity measured, and the ratings system used to present the results. Optimal vehicle designs for the crash test are compared with those of alternative test scenarios, and the real-world impact of such designs is discussed. Findings show that scenarios representative of more frequently-occurring on-road circumstances appear to produce safer vehicles for their occupants, and a more precise ratings system is suggested.

Keywords: Automobile design optimization, vehicle crash safety, safety standards and policy

1 INTRODUCTION

Developed nations have experienced declines in per capita road traffic injuries and fatalities over the past several decades, which are often attributed to improvements in road design, vehicle design, traffic management and risk awareness [1]. The United States National Highway Traffic Safety Administration (NHTSA) estimates that improvements in vehicle safety technology alone reduced U.S. traffic fatalities by 43 percent in 2002 [2]. 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. The first motor vehicle safety legislation worldwide was the U.S. National Traffic and Motor Vehicle Safety Act of 1966, through which the government imposed standards that automobile manufacturers were required to meet, and Europe and Australia followed shortly after with their own standards [3]. These standards required automakers to self-certify that their vehicles were equipped with particular safety features such as windshield wipers, rearview mirrors, and seat belts, but the regulations lacked any standardized testing or evaluation. The first physical crash test-based standards, the NHTSA New Car Assessment Program (NCAP) didn't emerge until 1987, followed by the Australasian NCAP in 1993, tests by a private agency in the U.S. called the Insurance Institute for Highway Safety (IIHS) in 1995, and the European NCAP and Japanese NCAP in 1996. Each of these standards has a four- or five-point rating system that informs consumers of the probability of being injured in various crash scenarios. These standards have driven designers to decrease risks of injury in the scenarios tested.

Three important technologies implemented in practically every car produced today are seat belts, air bags, and energy-absorbing front frame rails. However, it is not enough to simply include these devices and features: They must be optimized for each individual vehicle and for a particular expected crash scenario. Crash test standards make this a simpler decision for automakers, who typically tune vehicle designs to perform as well as possible in the specific scenarios represented by the crash tests they are required to undergo [3]. Since these tests are the most straightforward way that consumers can compare vehicle crashworthiness, it is expected that this practice should be optimal for maximizing sales, a major objective of automotive firms. However, collisions occur in a diverse set of scenarios, and four to five tests cannot cover the entire range of possibilities. Rather than creating additional crash tests that would significantly increase the cost of vehicle development, this paper advocates for

ensuring that the few tests that are conducted are the best possible tests to drive improved on-road safety.

Evidence suggests that current NHTSA NCAP tests are not, in fact, optimal in representing on-road crashes as they are observed to occur. For example, neither the NHTSA nor the European NCAP side-impact test addresses risks when vehicle intrusions strike the head of an occupant, which is a leading cause of fatal injuries in on-road side crashes. These same tests fail to address scenarios when vehicles with higher front ends such as SUVs or pickup trucks strike the sides of vehicles [3]. A study by Brumbelow (2007) shows that frontal crash standards in the U.S. have driven manufacturers to install load limiters that may have actually caused more fatalities in on-road crashes [4]. 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 will impact the airbag with enough force to strike the steering wheel through the bag. Brumbelow argues that automakers were setting their load limiter thresholds too low in order to perform well on the test, which in turn was detrimental to actual vehicle crash performance. Lastly, a recent report by the IIHS revealed that new airbag designs in the U.S. have been optimized for unbelted drivers [5], but in doing so they actually pose increased risks to belted drivers, which currently represent 85 percent of American drivers [6]. From these examples, it is evident that the existing crash test standards have room for improvement.

The particular standard of interest in this study is the U.S. NHTSA NCAP full frontal barrier crash test. When automakers optimize the front ends of their vehicles for this particular standard, they are designing vehicles to perform as well as possible in a full-engagement 35 mile-per-hour crash with a rigid barrier or identical car moving at the same speed in the opposite direction, when there are precisely two male dummy occupants whose dimensions are average in every way and are sitting upright in a particular prescribed position. As of October 2010 a 5th percentile female replaced the mid-size male passenger. The dummies have no muscle reactions to stimuli, and the only noted response of interest is in how likely they are to sustain a “serious” or worse injury, defined as a level 3 injury by the Abbreviated Injury Scale (AIS) [7], and more particularly whether they have less than a 10-percent probability of serious injury or between an 11- and 20-percent probability. Each of these factors plays a role in the outcome of the optimally designed vehicles and, ultimately, in the on-road performance of these vehicles. This study seeks to show the impact of three of these factors on two structural design variables and two restraint system variables, with case studies focusing on the test speed, injury severity of interest, and rating scale groupings. Section 2 outlines the methodologies used to conduct the case studies, and Section 3 reports on the case study results of optimizing vehicle designs for different crash scenarios. Concluding remarks and suggestions for future research are offered in Section 4.

2 METHODOLOGY

Crash testing in recent decades has shifted to rely heavily on virtual modeling to reduce time, cost and equipment requirements, and this study takes advantage of previously developed and validated computational models of vehicles and occupant compartments. The crash event itself is broken down into two manageable subproblems, the motion response of the vehicle structure to the crash event and the injury response of the occupant and restraint system to the vehicle’s motion. The models for these simulations are outlined in the ensuing subsections. Due to computational expense and the need to conduct optimization, surrogate models of the full simulation responses are developed and discussed in Section 2.3.

2.1 Full Vehicle Model

The first stage of the computational simulation employs a full finite element model of a 2003 Ford Explorer undergoing the 35 mile-per-hour (56 kilometer-per-hour) NHTSA frontal barrier crash test, acquired from the National Crash Analysis Center at the George Washington University [8]. The model, shown in Figure 1, was modified to allow different vehicle mass values and frontal stiffness properties; mass was chosen as a variable because of the common conception that heavier vehicles are safer (which the results will show is indeed the case for the frontal barrier test), and stiffness was chosen for its impact on the deceleration profile of the vehicle. In practice, these variables can be modified in vehicle design by using different materials such as high-strength steels and varying the geometry of structural components. Both input variables were allowed to range from 40 percent of

their original values in the 2003 Explorer to 160 percent, and a computational design of experiments (DOE) was conducted across this two-dimensional design space using a full factorial sampling scheme. As the simulations typically required 10-20 hours each, the DOE was limited to 49 equally-spaced crash tests using a full factorial sampling scheme.

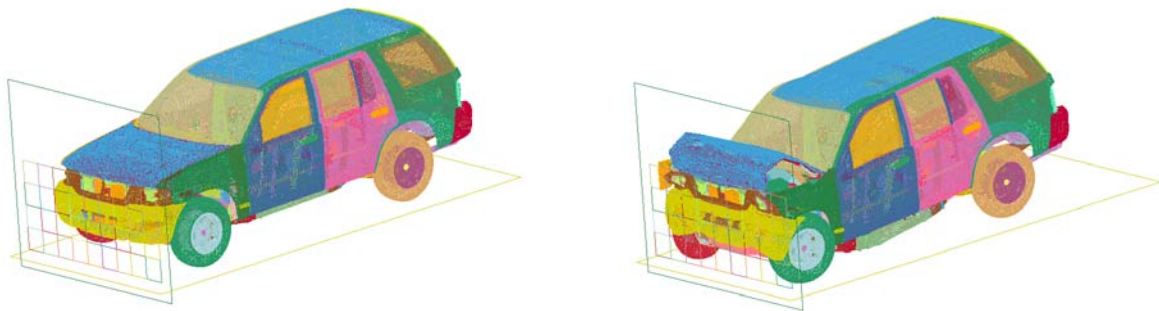


Figure 1. Full vehicle LS-DYNA model before (left) and after (right) crash

The main output of interest was the acceleration versus time profile for the first 120 milliseconds of the event, known as the crash pulse, located on the floorboard where the driver's seat would be mounted. Due to excessive mathematical noise seen in the resulting curves, a 60-point moving average (where each measurement is a tenth of a millisecond) was used as a filter before transferring the pulse to the occupant model.

2.2 Occupant Compartment and Restraint System Model

The motion resulting from the full vehicle crash model was then applied to the occupant compartment and restraint system model to measure the impact of such movement on a seated occupant inside the vehicle. The model, shown in Figure 2, was developed in the MADYMO software package by Ford Motor Company to represent a raised vehicle such as a crossover utility vehicle (CUV) or sport utility vehicle (SUV) [9]. This type of occupant-restraint system model is commonly referred to as a “sled test” because of the way in which the occupant compartment is mounted to slide in the fore-aft direction in physical modeling. Two additional inputs were varied within this model: the stiffness of the seat belt and the inflation rate of the airbag. These parameters play a role in the way the occupant is coupled with the vehicle during the crash, thereby having a significant impact on an occupant's outcome in a crash event. Each crash pulse from the 49-point DOE of the vehicle model was used to run a computational DOE of 49 configurations of the occupant compartment sled, and forces and accelerations in the occupant's body were recorded. Thus, a total of 2,401 vehicle designs were sampled for the 35-mile-per-hour crash scenario.

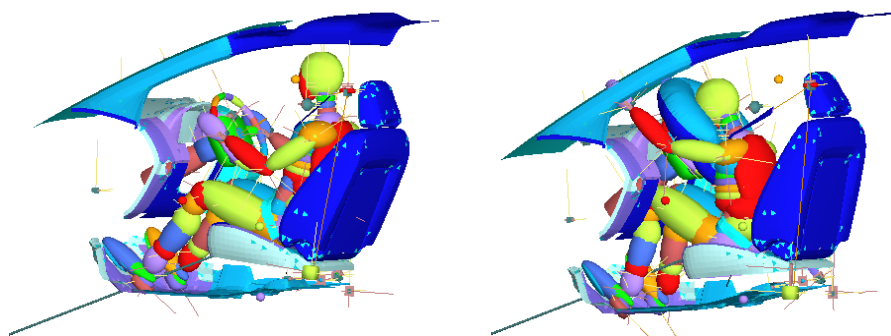


Figure 2. Occupant compartment MADYMO model before (left) and after (right) crash

The NHTSA NCAP frontal barrier test specifications are based on the occupant's probability of sustaining a serious injury, and this analysis uses the published NCAP injury curves that are derived from observed means and standard deviations from laboratory test data [10]. These curves calculate the probability of a serious or worse (AIS3+) injury (P_{injury}) in three different body regions as functions of the Head Injury Criterion with a 15 millisecond filter (HIC_{15}), the neck injury criterion calculated using measured forces and moments (N_{ij}), and maximum chest deflection measured in

millimeters (D_{max}). Additionally, the probability of moderate (AIS2+) lower extremity injury is calculated as a function of and maximum femur force in kilonewtons (F_{femur}). Equations (1-4) present the injury curves, and Equation (5) combines these to represent an occupant's overall probability of sustaining at least one injury. For optimization, this final quantity ($P_{overall}$) is the objective to be minimized.

$$P_{head} = \frac{1}{2}[1 + \operatorname{erf}((\log(HIC_{15}) - 7.45231)/(0.73998\sqrt{2}))] \quad (1)$$

$$P_{neck} = 1/(1 + \exp(3.2269 - 1.9688N_{TE})) \quad (2)$$

$$P_{chest} = 1/(1 + \exp(10.5456 - 1.568D_{max}^{0.4612})) \quad (3)$$

$$P_{femur} = 1/(1 + \exp(5.795 - 0.5196F_{femur})) \quad (4)$$

$$P_{overall} = 1 - (1 - P_{head})(1 - P_{neck})(1 - P_{chest})(1 - P_{femur}) \quad (5)$$

Plotting these injury curves in Figure 3 reveals that the P_{neck} equation has a minimum value near four percent, which is problematic when calculating the probability of injury in low-speed crashes. As a response, this curve was amended at low speeds so that a zero neck injury criterion corresponds with a zero probability of injury, created by fitting a line from the origin that intersects the curve on a tangent. This adjustment is shown as a red dotted line in Figure 3.

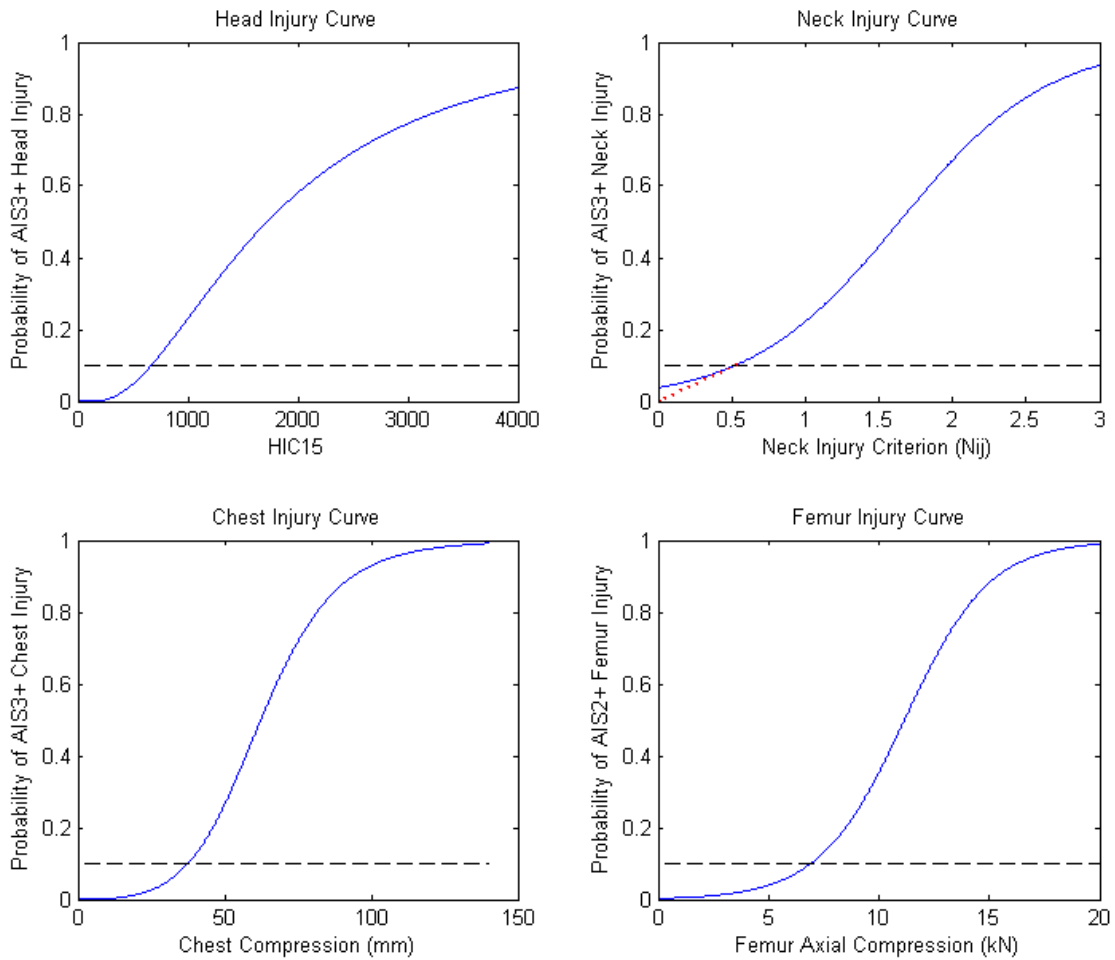


Figure 3. Injury curves from Equations 1-4, where the horizontal dashed line represents a 10% probability of injury

The results of the computational DOE provide information on how changes in the mass and stiffness structural variables and changes to the seatbelt and airbag properties impact the probability of serious injury to a driver. This relationship is quantified using surrogate models in the subsequent section, which are later used for optimization.

2.3 Surrogate Models

It is desirable in optimization to have a smoothly continuous objective function that can be evaluated in fractions of a second, which is why the simulations described in Sections 2.1 and 2.2 were conducted as a design of experiments (DOE) rather than used directly in optimization. The data were fit to two different types of surrogate models for comparison, and one type was selected for optimization. The first technique employed least-squares linear regression using all first, second, and third-order polynomial terms in the input space, using the R software package for fitting and pruning terms by the Akaike Information Criterion [11]. Because of the complexity of the calculation, each body region was fit to a separate model and combined later to calculate the injury probability. In some cases, the Box-Cox method was used to transform the response [11]. For the 35 mile-per-hour test scenario, the regression models for the head, neck, chest, and femur had coefficients of determination (R^2 -values) of 0.90, 0.87, 0.92, and 0.51, respectively. The combined probability over the two structural variables is plotted on the left side of Figure 4, where black circles represent the DOE data. The second technique used artificial neural networks with radial basis functions to construct a surrogate model with hidden nodes, using the MATLAB Neural Network toolbox [12]. This is an exact-fit method, where every response point from the training set is guaranteed to match the prediction from the neural network; other points are interpolated using radial basis functions. However, the user must input a spread constant, which tells the network how wide-reaching the radial basis functions should be, and a seven-set cross-validation was used to minimize the mean square error (MSE) of different spread constants. The resulting neural network when solely varying the structural variables is plotted on the right side of Figure 4, where again black circles represent the DOE data.

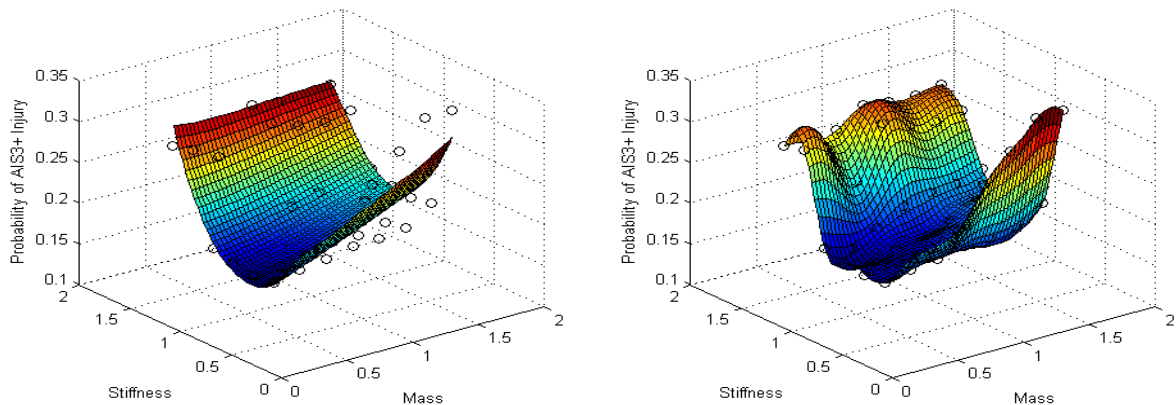


Figure 4. Surrogate models for 35mph data: linear regression (left) and neural networks (right)

One major advantage of using regression models is that the objective function has a formula, rather than the black box of the neural network, from which the relationship between the inputs and outputs can be interpreted without a need for graphing. However, because of the computational noise seen in the data, the results from optimizing the regression models did not outperform some of the data points from the DOE sample. To combat this, the sample space was trimmed to remove some of the outliers that were overtly far from the optimum, reducing the sample space from 2,401 to 785 points. From here, a new regression was performed, and the resulting optimum was selected as the best design. This type of model smoothes over some of the irregularities in the data, and thus it provides a more robust optimum than would be expected from the neural network model, which has several local minima.

3. CASE STUDIES

Case studies were conducted to show the implications of three selected assumptions found in the NHTSA NCAP full-engagement frontal barrier crash test. While these are not exhaustive in that there are many more assumptions embedded in the testing procedure, they demonstrate some interesting phenomena regarding the choices of test speed (35 miles per hour), injury severity (AIS3/serious) and the rating scale. The results are outlined and discussed in this section, and broader conclusions are drawn in the final section.

3.1 Impact of Test Speed

Every passenger vehicle sold in the United States must pass a set of mandated requirements, one of which is the Federal Motor Vehicle Safety Standard (FMVSS) 208 and requires that vehicles meet a certain set of standards in a 30-mile-per-hour (48-kilometer-per-hour) full-engagement frontal barrier crash test. That is, measurements of certain responses of a test dummy inside the vehicle must be below certain prescribed threshold values, placing a lower limit on frontal crashworthiness. For the NCAP test, which does not impose required standards but rather rates a vehicle's crashworthiness, NHTSA chose to set the speed at 35 miles per hour (56 kilometers per hour), a decision made primarily to show how well manufacturers went above and beyond designing for the minimum allowable crashworthiness [10]. However, the results from this test speed are all that the consumer sees (in the form of star ratings), and therefore manufacturers have an incentive to design specifically for optimal performance in this 35-mile-per-hour crash, provided that they meet the 30-mile-per-hour requirements.

This particular case study examines the design impact and on-road safety impact of optimizing vehicles for a 30- or 40-mile-per-hour crash test versus the current U.S. standard 35-mile-per-hour test. The DOE and regression surrogate modeling procedure from Section 2 was conducted once for each speed scenario, and the optima were calculated using the derivative-free DIRECT optimization algorithm [13]. The designs themselves all reach the upper bound placed on vehicle mass (3,680 kg), and the frontal stiffness expectedly increased with the test speed. To assess the on-road impact of each scenario, the optimized designs were each simulated in crashes of varying speeds; the speeds were chosen based on available data from the National Automotive Sampling System (NASS) regarding the frequency of different crash speeds in police-reported frontal crashes, which were grouped into 5-mile-per-hour bins [14]; this distribution is shown in Figure 5, and the data suggest that 98.8 percent of on-road frontal crashes occur at speeds lower than 35 miles per hour. It is important to note that these data only represent reported crashes; as one might expect, slower crashes are likely to be more frequent, but they are also likely to be less reported. Because of this phenomenon, the data and results presented in this section may be biased by too little emphasis on these lower speed ranges.

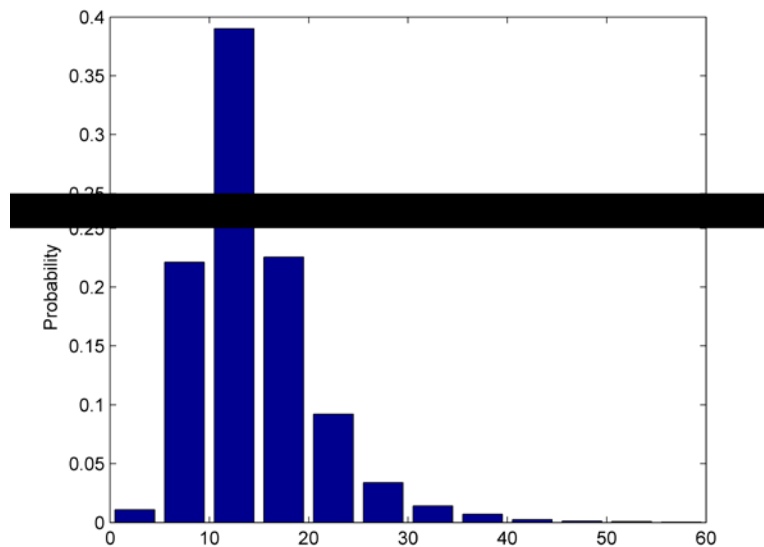


Figure 5. Distribution of on-road frontal crash speeds

One modification was made to the speed distribution in Figure 5 to account for the mass of the vehicle compared to other vehicles. In two-vehicle collisions, heavier vehicles experience lower changes in velocity (ΔV) due to conservation of momentum. To account for this, the vehicles were sampled at adjusted speeds, which would be the velocity change experienced by the sampled vehicle given that it collided with some vehicle of average fleet mass. This scaling is presented in Equation (6), where the average vehicle mass was estimated to be 1,650 kilograms, and m represents the optimized vehicle mass in kilograms.

$$\Delta V_{adjusted} = 2(\Delta V)1650/(1650+m) \quad (6)$$

Crashes of the three optimized vehicle designs were simulated at the adjusted average speed of each bin, and the calculated probability of injury is shown in Figure 6. From these data, it is clear that the 30-mile-per-hour optimized vehicle outperformed the other two in crash speeds lower than 30 miles per hour. At higher speeds, the 35-mile-per-hour optimized vehicle performed best, and at the very highest speeds the 40-mile-per-hour optimized vehicle was the best. This suggests that the optimized vehicle for the 40-mile-per-hour crash was in fact not optimal for that speed, but may be optimal for some higher speed; this is attributed to errors due to computational noise of the simulations and the fit of the linear regression model.

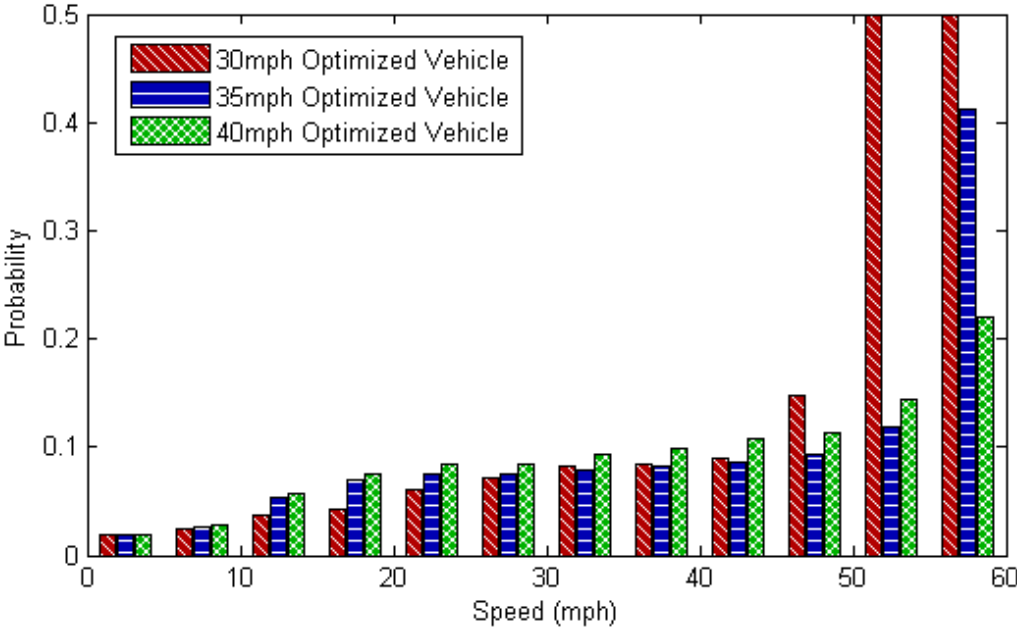


Figure 6. Probability of injury for three vehicles at varying crash speed

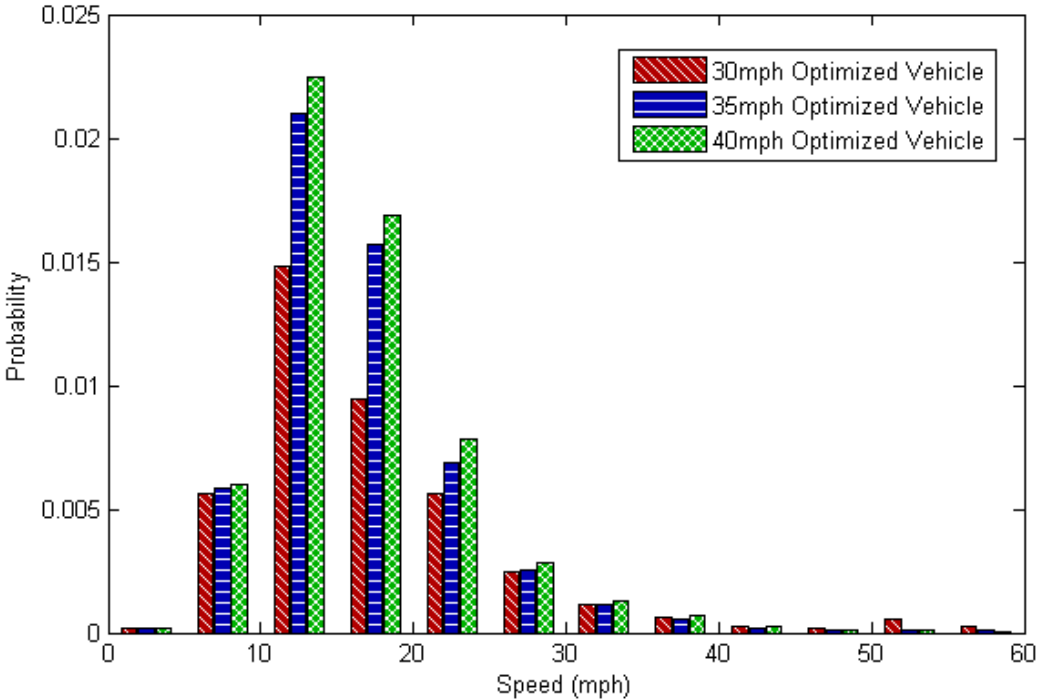


Figure 7. Weighted probability of injury at each speed given a reported frontal crash

Multiplying the data from Figures 5 and 6 together provides a weighted probability of injury, i.e., the probability of injury at each speed given a reported crash, and this is shown in Figure 7. Here, it is clear that the lower speeds have a much greater impact on this weighted probability than the higher speeds, suggesting that designing for lower speed crashes might improve overall driver welfare.

Finally, summing these probabilities for each vehicle design equates to the overall probability of injury given that the vehicle is in a reported frontal crash. For the 30 mile-per-hour optimized design, this total probability is 4.1 percent, compared to 5.5 percent and 5.9 percent for the 35 and 40-mile-per-hour optimized vehicles, respectively. This suggests that, despite the aforementioned bias that undervalues low crash speeds, optimizing for a 30-mile-per-hour crash is predicted to reduce serious injuries by 24 percent over the current standard, and a 40-mile-per-hour standard is expected to increase serious injuries by 8 percent.

3.2 Impact of Injury Severity

One of the other specifications of the NHTSA NCAP frontal barrier test is that only serious injury probability is calculated (with the exception of femur loads, which only represent moderate injuries), as quantified on the Abbreviated Injury Scale (AIS), and therefore vehicle designers optimize only for this particular severity of injury. Serious, or level 3 injuries, include but are not limited to base skull fractures, unilateral lung contusions, or injuries causing amputation below the knee. The AIS, however, includes other injury severities, ranging from minor (AIS level 1) to critical (AIS level 5). Since minor injuries typically don't pose significant costs to individuals or society, this study examines the impact of optimizing the barrier crash for occupant injuries of AIS levels 2 through 5. Some examples of moderate (AIS level 2) injuries include cranial nerve lacerations or contusions, herniated discs and muscle lacerations; severe (AIS level 4) injuries include complex base skull fractures, open chest wounds and injuries resulting in amputation above the knee; and critical (AIS level 5) injuries include brain stem injuries and quadriplegia [7].

The regression models developed in Section 2 were used to calculate the four injury criteria, and different equations were used to calculate the probability of each injury severity in each body region. The NCAP specifications include only AIS3 injury curves [10], and so a different set of curves from expanded Prasad/Mertz data were used to calculate injury probability for the four severities of interest [15,16]. Femur injuries were calculated for AIS level 2, but more severe injuries in the lower extremities are rare and were excluded from the analysis under the assumption that these would be accompanied by severe injuries to the head or chest [7]. Using these formulas, optimization was conducted to find the combination of design variables that minimize each level of injury.

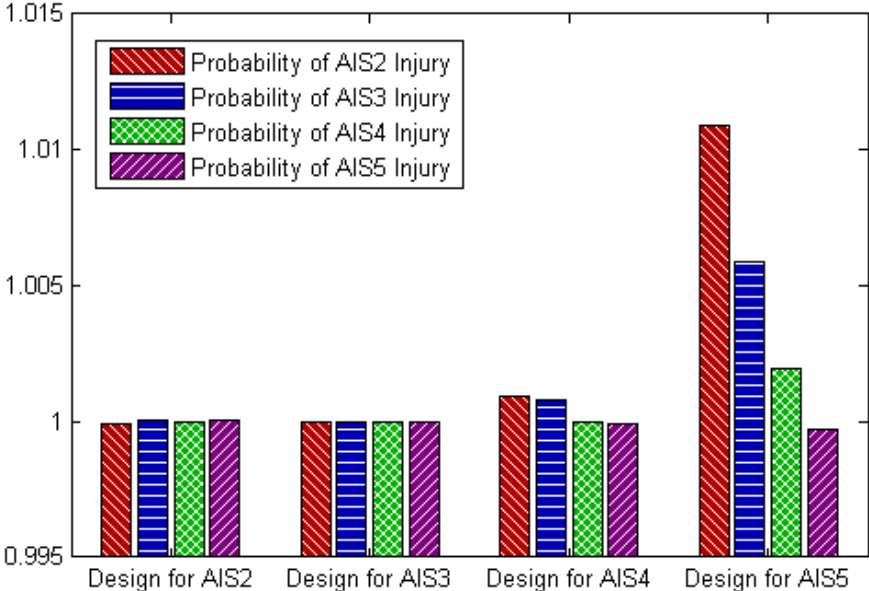


Figure 8. Probability of different injury severities for four optimal designs

The optima for each scenario corresponded to similar designs, with the exception of the AIS5 design, which had a noticeably stiffer front end. The results are plotted in Figure 8 shown as percentage changes from the AIS3 baseline scenario. These data show very little change between designing for moderate, serious, and severe injuries, while designing for critical injuries exhibits a relatively large increase in lower severity injury rates. As expected, designing for AIS2 injuries results in slightly lower injury rates at that level, yet slightly higher injury rates at the other levels. It is difficult to compare across these lower injury levels, and so strong conclusions cannot be drawn. The authors

postulate that the minor decrease in AIS5 injuries with its respective design is not worth the larger increases in other injury modes, and thus lower-severity injury standards are supported.

3.3 Impact of Rating Scale

The scale used by the NHTSA NCAP for assigning star values is based on injury probability, and for simplicity of interpretation, the probabilities are grouped into five categories of injury probability. A rating of five stars indicates a 10-percent or lower probability of injury, four stars between 11 and 20 percent, three stars between 21 and 35 percent, two stars between 36 and 45 and one star for 46-percent probability or greater. With these groupings, it is reasonable to believe that some vehicle manufacturers will not differentiate between an 11-percent and a 20-percent probability of injury when designing a vehicle, which will produce quite different safety performance outcomes. In this section, we examine the difference that would be experienced if the ratings system were based on a 100-point scale rather than a five-point scale, where each percentage would count for design optimization. While designers aim to produce the safest car possible, the vehicle must also meet other objectives, such as fuel economy or acceleration performance. The analysis here assumes that the secondary design objective is to minimize vehicle weight, which is positively correlated with improving both fuel economy and acceleration.

Table 1. Rating scale data

| Objective | Mass | Frontal Stiffness | Seatbelt Stiffness | Airbag Flow Rate | $P_{overall}$ (AIS3) |
|-------------------------|----------|-------------------|--------------------|------------------|----------------------|
| minimize $P_{overall}$ | 3,680 kg | 0.98 | 1.60 | 0.47 | 9 % |
| $P_{overall} \leq 0.10$ | 2,700 kg | 0.92 | 1.60 | 0.59 | 10 % |

Data from minimizing probability of injury and for minimizing weight while injury probability is constrained at 10 percent are shown in Table 1. Here, the stiffness values and airbag inflation rate are shown as scaling factors, where 1.00 is the baseline. Under the current U.S. NCAP rating system, both of these vehicles would receive the identical mark of five stars. It is clear that this rating system, which does not reward designing for lower than 10 percent, may result in a 27 percent lighter vehicle with an injury probability 10 percent higher. While this gives automakers more freedom to meet safety goals while considering other objectives, it does not adequately reward designers who optimize for safety. A rating scale based on percentages would give the former case a 91 out of 100 points and the latter case a 90. Market studies can explore the consumer sensitivity with respect to such ratings and provide further guidance for design decisions. Note that this scenario presents a very conservative situation, where the optimized design is already near the 10 percent limit. One can postulate that an optimized vehicle with an 11-percent injury probability being reduced to 20 percent for meeting other objectives would exhibit more dramatic consequences in market perception and on-road safety.

4. CONCLUDING REMARKS

The findings of this study show how the National Highway Traffic Safety Administration’s New Car Assessment Program (NHTSA NCAP) frontal barrier crash test specifications impact vehicle design by considering alternate test standards and their implications. Three case studies were conducted, and the results were presented in Section 3, showing how changes to the test speed, injury severity measured, and ratings system are predicted to impact design and, in some cases, on-road performance. From the first two case studies, it is evident that the standard should strive to represent the scenarios that occur most frequently, such as lower crash speeds and lower injury severities. From the third case study, it is shown that a more precise ratings system might affect market perception of safety relative to star ratings in use worldwide. The authors recognize that NHTSA’s new standards effective late 2010 have shown some improvements to the testing procedures, including the use of a 5th percentile female in the passenger seat for the frontal barrier test, but additional revisions may be more representative of real injury-inducing crash scenarios.

Further work is proposed to evaluate the impact of additional parameters that are specified in the frontal barrier test, such as the occupant size and positioning, as well as the specifications of other crash tests and standards. It is also suggested that the parameters be examined jointly to observe the multivariate behavior of these factors.

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