On the impact of the regulatory frontal crash test speed on optimal vehicle design and road traffic injuries

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Abstract: Many countries have instituted New Car Assessment Programs (NCAPs) to help consumers compare the crashworthiness of automobiles on the market. These typically involve four or five standardised tests, for which each new vehicle is rated on a 5-star scale. The ratings are available to customers and so, automakers strive for high scores by optimising their vehicle designs to the scenarios represented by the tests. The United States NCAP rates vehicles for frontal crashworthiness with a 56-kilometre-per-hour (35-mile-per-hour) full-engagement barrier collision, which is a relatively severe test, considering that over 98% of crashes on US roadways occur at slower speeds. This paper presents a methodology for understanding the impact of the NCAP crash test speed on vehicle design and the consequent on-road safety outcomes, using physics-based simulations and optimisation tools. The results suggest that lowering the test speed from the current level to 48 kilometres per hour (30 miles per hour) may decrease the rates of serious injuries to vehicle occupants in the US by up to 21%.
Keywords: automobile safety; crashworthiness; design optimisation; new car assessment program; vehicle design.


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1 Introduction

Road traffic injury and fatality rates have declined in developed nations over the past several decades due to systematic improvements in road design, vehicle design, traffic management and risk awareness (Peden et al., 2004). The National Highway Traffic Safety Administration (NHTSA) of the United States estimates that improvements to vehicle safety technology alone reduced US traffic fatalities by 43% in 2002 (Kahane, 2004). Many of these vehicle safety improvements have been supported by legislative requirements and published crash test ratings by governmental and private institutions, though they are typically first developed by
automakers and their suppliers. The first such motor vehicle safety legislation worldwide was the US National Traffic and Motor Vehicle Safety Act of 1966, through which the government established a mechanism for imposing safety requirements on automobile manufacturers. Europe and Australia followed shortly after with their own standards (O’Neill, 2009). The US Federal Motor Vehicle Safety Standards (FMVSS) promulgated by the NHTSA specify hundreds of design and performance requirements that vehicle manufacturers must certify that they meet. For example, vehicles are required to be equipped with steering wheels, seats, airbags and safety belts meeting certain performance requirements. The FMVSS describe procedures to be used to evaluate the standards. Dynamic performance requirements in FMVSS 208 (frontal crash protection) and 214 (side impact protection) specify a number of dynamic whole-vehicle crash tests that are performed using crash dummies to quantify occupant protection.

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

NCAP and other consumer-information testing have been effective in driving vehicle design improvements, based on the improving scores over the years. However, some researchers have concluded that the current NHTSA NCAP tests drive vehicle design that is not optimal in actual on-road crash scenarios. The IIHS has been a leader in assessing the effects of regulatory testing on vehicle design and the consequent effects on safety in the field. O’Neill (2009) discussed how neither the US nor the European NCAP side-impact tests address risks when vehicle intrusions strike the head of an occupant, which is a leading cause of fatal injuries in on-road side-impact crashes. These same tests also fail to address scenarios when vehicles with high front ends, such as Sport Utility Vehicles (SUVs) and pickup trucks, strike the sides of vehicles. However, IIHS testing focuses on these specific scenarios, although their results are not published on the window stickers of new vehicles with the NCAP star ratings.

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

The current study considers the US NHTSA NCAP frontal barrier crash test, which is a 56 kilometre-per-hour (kph), or 35 mile-per-hour (mph), full-engagement crash into a flat,
rigid barrier. Star ratings are assigned based on measurements taken from a mid-size-male Anthropomorphic Test Device (ATD) seated in the driver seat, with a small-female ATD in the passenger seat. Automakers consider this crash scenario when optimising the structures and restraint systems of their vehicles.

In developing this test, NHTSA has chosen an unusually severe frontal crash, considered on the basis of $\Delta v$, or change in velocity. The concern here is that the large majority of frontal crashes on US roadways have $\Delta v$-values lower than 56 kph; in fact, 98.8% of frontal, tow-away crashes reported in the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) between 1982 and 1991 were at slower speeds than this standard (Evans, 1994). A histogram of those crash speeds observed is shown in Figure 1. The IIHS and other worldwide NCAP tests are conducted at an even higher speed, 64 kph (40 mph), which is faster than 99.5% of the crashes shown in Figure 1, although IIHS uses an offset deformable barrier. The motivation for using high crash severities is that such crashes represent a large risk of death and injury. High speed tests drive improvements in vehicle strength and structural performance and result in restraint systems that can handle high loads. An underlying assumption is that systems that produce good performance in high-speed crashes will also perform well in lower-speed crashes, which are much more common.

However, it is possible that vehicle designs optimised for these test conditions are not, in fact, optimal for protecting their occupants in more frequently-occurring lower crash speeds. Even though the risk of injury is lesser at lower speeds, the far greater number of lower-speed crashes creates the possibility that optimising for high crash speeds leads to more deaths and injuries than would be the case if a lower test speed were chosen. The objective of this paper is to use physics-based simulation tools to assess the effects of changing the US NCAP test speed on vehicle designs and on-road traffic safety. The next section introduces the problem formulation and the scientific approach used in the study, including the models used, the sampling technique and the optimisation approach. Section 3 presents the resulting vehicle designs and predicted societal impact. The results are then discussed in Section 4 and conclusions are offered in Section 5.

**Figure 1** Distribution of crash speeds from on-road data (see online version for colours)

*Source:* Adapted from Evans (1994)
2 Methodology

The system presented in this paper, describing the interactions among governments, manufacturers and society, is illustrated in Figure 2. A government regulatory agency sets a crash test standard with the hope of improving on-road safety as measured by societal statistics, e.g., the numbers of road traffic injuries or fatalities. Automobile manufacturers receive those NCAP standards and design vehicles to perform well on the tests, while also meeting the mandatory crash requirements of the region, which in the US are defined by Federal Motor Vehicle Safety Standards (FMVSS). While the government has control over these standards, they are treated in this study as fixed so as to understand the impact of solely changing the star rating tests; thus, the FMVSS requirements are constraints in the vehicle design optimisation formulation.

Figure 2  Framework of government, manufacture and societal interaction

Automakers optimise their vehicle designs with respect to the NCAP standards and in this study, vehicle design is simplified to five variables, as detailed in Table 1: the structural frontal stiffness of the frame defined by the yield strength and force-deflection characteristics of the metal (s); the elongation stiffness of the seat belt material as defined by a force-deflection curve (b); the belt retractor stiffness and load-limiting function, also defined by a force-deflection curve (r); the inflation rate of the airbag, prescribed as the total mass flow over a fixed time interval (a); and the deflation rate of the airbag modelled by the size of the vents (d). The two seat belt-related variables, b and r, act in series with a pretensioner to couple the occupant with the seat and vehicle body, where the material stiffness (b) provides more control of the pelvis through the lap belt and the load-limiting retractor (r) controls the upper torso through the shoulder belt. Other variables, including the stiffness of the steering column travel (c), the knee bolster (k) and the seat belt load-limiting webbing (w), were considered, but discarded as less important after conducting sensitivity analyses at the nominal crash condition.
Table 1  Design variables used in manufacturer’s optimisation

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Symbol</th>
<th>Domain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal rail stiffness</td>
<td>(s)</td>
<td>([0.125, 2])</td>
<td>Scale factor for frame rail material yield strength deformation function (stress vs. strain)</td>
</tr>
<tr>
<td>Seat belt stiffness</td>
<td>(b)</td>
<td>([0.25, 6])</td>
<td>Scale factor for shoulder and lap belt material loading function (stress vs. strain)</td>
</tr>
<tr>
<td>Loading-limiting belt retractor function</td>
<td>(r)</td>
<td>([0.25, 2])</td>
<td>Scale factor for belt retractor stiffness and load-limiting function (N vs. m)</td>
</tr>
<tr>
<td>Airbag inflation rate</td>
<td>(a)</td>
<td>([0.25, 2])</td>
<td>Scale factor for mass flow rate function (kg/s) vs. (s) and effective total mass flow</td>
</tr>
<tr>
<td>Airbag deflation rate</td>
<td>(d)</td>
<td>([0.72, 5.77])</td>
<td>Discharge coefficient for airbag vents</td>
</tr>
</tbody>
</table>

After finding the optimal designs, manufacturers sell vehicles to customers, who drive them and may crash them in a wide variety of scenarios. Here, random variables are introduced, as drivers come in a variety of statures or erect standing heights \((h)\), position their seats at varying distances back from the steering wheel \((p)\) and crash their vehicles at a range of speeds \((v)\); see Figure 1. Additional random variables exist in the field and other occupant positioning variables (e.g., torso angle of recline and neck angle) were also considered and discarded after sensitivity analyses. Accounting for these three random variables, predictions of injury probabilities for a given vehicle design are generated and extrapolated as road safety statistics, which were mentioned previously as the main driver of safety policy.

This article presents a parametric study of NCAP frontal crash speeds, examining the impact on vehicle design and occupant injury probability when the standard is lowered or raised by 8 kph. Thus, the interactions described above are modelled and computed for each of three scenarios: frontal crash test standard speeds of 48 kph, 56 kph and 64 kph.

2.1 Modelling and simulation

In the past decade, the design process for vehicle safety has come to rely heavily on virtual simulations to reduce time, cost and equipment requirements. The current study leverages previously developed and validated computational models of vehicles and occupant compartments to understand how a vehicle’s design and the crash scenario influence the occupant’s probability of sustaining an injury. The crash event is broken down into two separate models:

1. the motion response of the vehicle structure to the crash event
2. the injury response of the occupant and restraint system to the vehicle motion.

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

The first part of the simulation is conducted using the LS-DYNA finite-element package (LSTC, 2007) to simulate the US NCAP frontal barrier test for a 2003 Ford Explorer, using
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A model developed by the George Washington University National Crash Analysis Center. The model, shown in Figure 3a, was modified to allow different frontal stiffness ($s$) values by scaling the original values of the frame rail yield strength and force-deflection profile. Other researchers, such as Kamel et al. (2008), Liao et al. (2008) and Yang et al. (2005), have conducted optimisation studies and used the thickness of the rail instead of the yield strength to modify frontal stiffness. These techniques were both tested and found to have similar effects on the motion response and so the yield strength was chosen because it keeps the geometry of the model constant and eliminates computational problems that arise with changes to the geometry. In vehicle design practice, metal thickness, material substitutions, or other design changes may be adjusted to achieve the desired frontal stiffness. The output of interest from this vehicle model is the acceleration versus time profile for the first 120 milliseconds of the event, known as the crash pulse, at the location on the floorboard where the driver’s seat is mounted. As is common in design practice, the numerically-noisy 1200-point response curve is filtered with a 60-point moving average and an example of a filtered pulse is shown in Figure 4.

The crash pulse is next applied to the occupant compartment and the restraint system model shown in Figure 3b, which measures the impact of the prescribed motion on a seated mid-size male driver inside the vehicle. The model was developed by Ford Motor Company using the MADYMO multibody analysis and finite element software package (TASS, 2010) and represents a generic high-seat-height vehicle such as a SUV or a Crossover Utility Vehicle (CUV). The model was modified to explore the design space among the four restraint system
variables: seat belt stiffness ($b$), load-limiting retractor function ($r$), airbag inflation rate ($a$) and deflation rate ($d$). These parameters affect the coupling of the occupant to the vehicle during the crash and therefore, influence the probability of injury.

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

The US NCAP uses four criteria to assess restraint performance, all of which are concerned with a ‘serious’ injury, defined on the Abbreviated Injury Scale (AIS) as a level 3 injury or higher (AAAM, 1990). These criteria, which are extracted as outputs of the occupant and restraint system model, are the Head Injury Criteria ($HIC15$), the Neck Injury Criteria ($Nij$), chest compression in millimetres and femur axial compression in kilonewtons. Each of these has an associated injury curve that yields the probability of an AIS level 3 or higher ($AIS3^+$) injury in that body region as a function of the criterion, although the femur injury criterion considers moderate, or AIS2+, injuries. These curves have been derived from laboratory test data (NHTSA, 2008) and they are currently used to assess new vehicle star ratings in the US from physical ATD measurements. Plots of the four injury curves are shown in Figure 5; close inspection of the neck injury curve reveals that the minimum possible value is near 4%. This is problematic for predicting injury probability in low-speed crashes and so the curve was amended for this study by fitting a line from the origin that intersects the curve on a tangent, shown as a dotted line. Neck injury probability is then calculated as a piecewise function using the dotted line when the $Nij$ value is below the intersection and using the solid curve elsewhere.

**Figure 5** Injury curves representing probability of injury as a function of criteria in the (a) head, (b) neck, (c) chest and (d) leg regions
To combine these four curves and obtain a single probability of injury, Equation (1) is used, which yields the overall probability of sustaining an injury in at least one of the four locations. This single value is then used to assign star ratings and in this case, it is used as the objective function to optimise manufacturer design decisions.

\[ P_{\text{overall}} = 1 - (1 - P_{\text{head}})(1 - P_{\text{neck}})(1 - P_{\text{clav}})(1 - P_{\text{femur}}). \]  

(1)

2.2 Manufacturer’s optimisation

The process followed for manufacturer optimisation and societal impact assessment is outlined in Figure 6, beginning with the previously-discussed sensitivity analysis over the design variables. This process is then followed for each of the three test speed scenarios and includes several batches of simulations for each scenario, as well as separate simulations for the FMVSS requirements, which enter the optimisation formulation as constraints. The objective of this procedure is to obtain an expected probability of injury for the optimised vehicle design, given that a frontal crash occurs.

Due to the computational expense of the dynamic models of the vehicle and restraint system, design optimisation is conducted using response surfaces that are generated from computational Designs of Experiments (DOEs). An Optimal Latin Hypercube Sampling (OLHS) technique is employed (McKay et al., 1979) to improve the efficiency of the sampling over five design variables:

1. frontal rail stiffness \((s)\),
2. seat belt material stiffness \((b)\),
3. load-limiting retractor function \((r)\),
4. airbag inflation rate \((a)\)
5. airbag deflation rate \((d)\).

However, this raises a problem by requiring that both the 10-hour vehicle and the 6-minute restraint system simulations be conducted for each sample, which is impractical. The crash pulse which links the two simulations is a 1200-point vector, where each point represents the acceleration at each tenth of a millisecond during the vehicle response simulation. Since the curves are observed to share some commonalities in general shape, a batch of simulations for each of the three NCAP speed scenarios was conducted across the one-dimensional design space varying frame rail stiffness and the curves were parameterised using Proper Orthogonal Decomposition (POD), sometimes referred to as principal component analysis or eigenvalue decomposition (Alexander et al., 2011). The POD results showed that five parameters represented over 95% of the cumulative percentage variance, i.e., 95% of the original 1200-point curves’ characteristics are captured by just five variables. To achieve a full 1200-point pulse from the five variables, the five-variable row vector is multiplied by a 5-by-1200 transformation matrix, which means that knowledge of the five parameters can generate a full curve.

Figure 7 shows an example of an original curve and corresponding velocity profile with its parameterised, or reduced, representation, where it can be seen that the reduced representation very closely matches that of the actual crash pulse. Thus, kriging surrogate models (Lophaven et al., 2002) were fit to find expressions for each of the five new parameters
Figure 6  Process flow diagram for manufacturer optimisation and societal modelling (see online version for colours)
as a function of vehicle frontal stiffness and these, combined with the transformation matrix, create a full crash pulse as a function of vehicle frontal stiffness. Samples of two curves produced using the kriging surrogate models and POD transformation are shown in Figure 8, where the dotted line represents a low-stiffness pulse and the solid line a high-stiffness pulse, both in a 56 kph crash scenario. The plot shows that the low-stiffness vehicle pulse has a slower initial rise in acceleration, but it has a higher peak later in the crash event than that of the higher-stiffness vehicle.

Figure 7  Original crash pulse and velocity profile compared with reduced representation from proper orthogonal decomposition

Figure 8  Comparison of low- and high-stiffness vehicle crash pulse and velocity profiles

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

Aside from maximising performance in NCAP tests, vehicle manufacturers must also consider regulatory constraints that influence design decisions. Three FMVSS requirements were accounted for and incorporated into the optimisation formulation as constraints. Each of these has injury thresholds that the ATD may not exceed, corresponding with a 30% probability of injury in several body regions. Two of these tests are full-engagement frontal barrier tests with mid-size male ATDs, one performed at 48 kph (30 mph) with a belted occupant and the other performed at 40 kph (25 mph) with an unbelted occupant. The third test is a static out-of-position test with a small, unbelted female ATD, where the dummy’s chin starts out on the rim of the steering wheel prior to
inflating the airbag. For each of these, DOE studies were conducted across the applicable design variables and surrogate functions were developed to be used in the constraints during optimisation.

With the objective and all constraints represented as numerical functions, the formulation can be represented mathematically as Equation (2).

\[
\begin{align*}
\text{minimize} & \quad P_{\text{injury}} = 1 - (1 - P_{\text{head}})(1 - P_{\text{neck}})(1 - P_{\text{chest}})(1 - P_{\text{femur}}) \\
\text{subject to} & \quad F_{48\text{kph},i} = g_1(s,b,r,a,d) \leq T_{50\text{th},i} ; \forall i \\
& \quad F_{40\text{kph},i} = g_2(a,d) \leq T_{50\text{th},i} ; \forall i \\
& \quad F_{\text{static},i} = g_3(a,d) \leq T_{5\text{th},i} ; \forall i \\
& \quad lb \leq s,b,r,a,d \leq ub
\end{align*}
\]

Here, the objective function is the overall probability of injury from Equation (1), where each of the four injury modes is a kriging surrogate function \( f \) of the five design variables. Further, the injury thresholds \( T_{50\text{th}} \) and \( T_{5\text{th}} \) are the four values for the mid-size male and the small female, respectively. These values are used in the three FMVSS constraints, which are functions of the design variables: the 48 kph crash with a belted mid-size male occupant \( (F_{48\text{kph}}) \); the 40 kph unbelted crash, which is not a function of the two belt-related variables, \( b \) and \( r \), \( (F_{40\text{kph}}) \); and the static out-of-position test \( (F_{\text{static}}) \), which uses a small female ATD and is not a function of \( s \), \( b \) or \( r \), since there is no vehicle motion or seat belt. Lastly, lower and upper bounds were required for the five design variables listed in Table 1, which were placed sufficiently far away in such a way that no bounds would be active. Optimisation was performed using the DIRECT global optimisation algorithm (Jones, 1999), which was chosen because all of the functions are fast to evaluate. This formulation was optimised for each of the three NCAP test speeds, resulting in an optimal vehicle design for each scenario.

### 2.3 Societal uncertainty

Each of these optimised vehicle designs was then placed in a simulated crash across the distributed range of the three random variables: occupant height \( (h) \), seating position \( (p) \) and crash change in velocity \( (v) \). In a similar manner to the previous DOE studies, the variable associated with the full vehicle model, \( v \), was first simulated and parameterised for each of the three optimal vehicle designs. A POD analysis was again conducted to parameterise the 1200-point pulses to five parameters, again capturing at least 95% of the cumulative percentage variance. Using this, kriging surrogate models were developed so that a crash pulse for each of the optimal vehicle designs could be mathematically constructed for a given crash speed. Next, a 200-point OLHS DOE study of the restraint system model was conducted across the three continuous random variables and linear regression was applied to the results to obtain polynomial functions for injury probabilities as a function of the three random variables, \( P_{\text{rand}} \).
Height distribution data for American men from the National Health Statistics Reports were fit to a normal distribution (McDowell et al., 2008), shown in Equation (3), where $h$ is measured in centimetres. To modify occupant height in the restraint system simulation model, a MADYMO feature called ‘madyscale’ was invoked to generate ATD models of continuously varying sizes. Heights were specified according to the distribution in Equation (3) and other body size parameters were scaled in proportion to the height for an occupant with an average Body Mass Index (BMI).

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

Humans of different sizes typically have different thresholds of forces and moments that can be withstood prior to injury. To account for this, the injury criteria outlined in Figure 5 were scaled in accordance with the conclusions found by Eppinger et al. (2000), which provide separate neck criteria critical intercept values, chest deflection thresholds and femur compression thresholds for the three standard ATD sizes (small female, mid-size male and large male). The head injury criterion is identical for each of the three ATDs and so no scaling was necessary for the head injury probability. For the other three injury locations, the reported numbers were interpolated and extrapolated to find specific threshold values for any given percentile of human size ($z$) between 0 and 100, as determined in this model by the appropriate quantile from within the height ($h$) distribution. The neck injury criterion ($N_{ij}$) is calculated based on critical intercept values for tension ($T_{int}$), compression ($C_{int}$), flexion ($F_{int}$) and extension ($E_{int}$); these intercept values, provided by Eppinger et al. were fit to linear regression models, which are provided as Equations (4)–(7).

$$T_{int} = 43.66z + 4254$$

$$C_{int} = 39.56z + 3849$$

$$F_{int} = 2.889z + 148.9$$

$$E_{int} = 1.244z + 64.78$$

For the chest deflection and femur compression injury mechanisms, values are given which correspond with a 10% probability of injury (Eppinger et al., 2000). To incorporate this into the same injury probability curves from Figure 5, the numbers measured from the range of human size models are scaled to ‘mid-size male equivalent’ values. The scaling factors depend on the corresponding 10% probability thresholds and least-squares regression on the values for the three standard ATDs provided Equation (8) for the chest deflection threshold ($D_{chest,threshold}$) in millimetres and Equation (9) for the femur compression force threshold ($F_{femur,threshold}$) in kilonewtons.

$$D_{chest,threshold} = -0.001z^2 + 0.2988z + 50.53$$

$$F_{femur,threshold} = 0.0656z + 6.556$$

Manary et al. (1998) conducted a study with human subjects to investigate how driver stature influences seat position in the fore-aft direction. Subjects were chosen that resemble the
sizes of the three main dummies (small female, mid-size male, large male) and the mean seat position was recorded for each dummy size. These numbers were fit with second-order polynomial curves to estimate the impact of height on mean seat position, shown in Equation (10). An estimate of the standard deviation of the seating position ($\sigma_p$) is taken from Flannagan et al. (1998) to be 30 millimetres. Thus, with a given height $h$, a normal distribution was constructed using Equation (11), where $p$, $\mu_p$, and $\sigma_p$ are measured in metres. The data have been adapted to coincide with the coordinates of the occupant and restraint system simulation and they represent MADYMO model adjustments to the positioning of the entire seat and seat belt system along with the occupant.

$$\mu_p = -0.15h^2 + 0.88h - 0.93$$ (10)

$$f(p) = \frac{1}{\sqrt{2\pi\sigma_p^2}} e^{-\frac{(p-p_0)^2}{2\sigma_p^2}}$$ (11)

Finally, the frontal crash speed distribution shown previously in Figure 1 was fit to a log-normal distribution and is represented as Equation (12), where $v$ is in kilometres per hour. However, it is important to recognise that in multi-vehicle crashes and in crashes with non-rigid objects, a heavier vehicle will have a lower $\Delta v$. To account for this phenomenon, the speed distribution was adjusted according to the conservation of momentum equation, assuming contact with a vehicle of average US fleet mass, approximated at 1650 kilograms; the adjustment factor used is shown in Equation (13). According to data from the NASS General Estimates System (GES), approximately 75% of frontal crashes in 2009 involved more than one vehicle and thus, the adjustment factor of Equation (13) was applied to the crash distribution curve of Equation (12) for only 75% of the distribution, as given by Equation (14). Therefore, if the vehicle is heavier than the average fleet vehicle, the lower adjusted speed will shift the probability distribution function $f_{\text{adjusted}}(v)$ to the left, as shown in Figure 9. Because the data used do not categorise the crash distribution information by single- and multiple-vehicle events, this study assumes that the crash speed distributions can be treated as identical.

$$v_{\text{adjusted}} = \frac{2 \times 1650}{m + 1650}$$ (13)

$$f_{\text{adjusted}}(v) = 0.75 \times f\left(v_{\text{adjusted}}\right) + 0.25 \times f\left(v_{\text{original}}\right)$$ (14)

To account for all three random variable distributions, the injury probability function was multiplied by the distributions from Equations (3), (11) and (12) and integrated across the appropriate ranges of each variable. The triple integral function given by Equation (15) was evaluated, yielding a single expected probability of injury $E[P]$, given that a frontal crash occurred at some random speed with some random driver inside. This is the value that regulatory agencies should seek to minimise, as it corresponds to an expected total number of on-road injuries.
Another option for calculating the expected injury probability without integration is to run large Monte Carlo simulations on the surrogate models, where the distributions of sampled points are representative of the random variable distributions previously described. The expected injury probability was calculated using both the integral and the Monte Carlo techniques, where the definite integral was computed using a quadrature function and the weighted Monte Carlo method included 100,000 samples; the results exhibited the same trends using both methods. The results presented in the next section were derived using the integration approach described by Equation (15).

\[ E[P] = \int_0^{120} \int_0^{19} \int_{-50}^{50} P_{\text{rand}}(h, p, v) f(h) f(p) f(v) dh dp dv. \tag{15} \]

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3 Results

Using the physics-based simulation tools in the manner described in Section 2, an optimal vehicle design for the 2003 Ford Explorer was obtained for each of the three NCAP scenarios: 48 kph, 56 kph and 64 kph frontal barrier tests. These three optimal designs were then simulated across a range of uncertain societal variables and an expected probability of injury was calculated, given that a crash occurred.
3.1 Optimal vehicle designs

The domain of each design variable was determined using sequential approximate optimisation, where the computational DOE studies and subsequent optimisation were iteratively conducted three times. Each iteration used information on the previous optimisers to determine the appropriate upper and lower bounds for each variable and in the third iteration, interior solutions were found. The final variable domains are presented in the upper section of Table 2, along with the optimal vehicle designs from the manufacturer’s formulation, where the first four values are scaling factors from the original simulation models described in Table 1. For variables that represent curves, a scaling factor of two indicates that all of the dependent values in the curve were doubled. None of the three regulatory constraints were active at the optimal solutions, indicating that for this particular vehicle, minimising injury for NCAP is sufficient for meeting the FMVSS requirements.

Some of the variable trends are clear and result in injury trends for the mid-size male dummy, shown in the lower section of Table 2: as test speed increases, the optimal retractor stiffness and the load-limiting function \( r \) increase, exerting higher belt forces on the occupant and resulting in higher measured chest compressions. The computations show that this effect causes the peak belt force to occur while the occupant is in contact with the airbag, such that the retractor and airbag absorb the energy of the occupant simultaneously. It is also evident that both the optimal airbag inflation rate \( a \) and deflation rate \( d \) decrease as test speed increases, which curbs the increase in the head injury criterion. The slower deflation rate at higher speeds allows the occupant to ‘ride down’ the impact for a longer duration and the slower inflation rate balances out the total pressure inside the airbag that would otherwise be higher due to the lower deflation rate.

### Table 2

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Variable domain</th>
<th>48 kph</th>
<th>56 kph (baseline)</th>
<th>64 kph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal frame stiffness, ( s )</td>
<td>[0.125, 2]</td>
<td>0.80</td>
<td>1.79</td>
<td>1.62</td>
</tr>
<tr>
<td>Seat belt material stiffness, ( b )</td>
<td>[0.25, 6]</td>
<td>3.81</td>
<td>2.63</td>
<td>3.01</td>
</tr>
<tr>
<td>Retractor stiffness function, ( r )</td>
<td>[0.25, 2]</td>
<td>0.72</td>
<td>1.05</td>
<td>1.23</td>
</tr>
<tr>
<td>Airbag inflation rate, ( a )</td>
<td>[0.25, 2]</td>
<td>1.12</td>
<td>0.88</td>
<td>0.82</td>
</tr>
<tr>
<td>Airbag deflation rate, ( d )</td>
<td>[0.72, 5.77]</td>
<td>4.76</td>
<td>4.47</td>
<td>4.24</td>
</tr>
<tr>
<td>Head injury criterion, ( HIC_{15} )</td>
<td>–</td>
<td>147</td>
<td>163</td>
<td>239</td>
</tr>
<tr>
<td>Neck injury criterion, ( N_{ij} )</td>
<td>–</td>
<td>0.244</td>
<td>0.202</td>
<td>0.259</td>
</tr>
<tr>
<td>Chest compression (mm)</td>
<td>–</td>
<td>27.8</td>
<td>31.7</td>
<td>34.0</td>
</tr>
<tr>
<td>Femur axial force (kN)</td>
<td>–</td>
<td>1.93</td>
<td>2.02</td>
<td>1.94</td>
</tr>
<tr>
<td>Serious injury probability, ( P_{ass} )</td>
<td>–</td>
<td>8.9%</td>
<td>10.1%</td>
<td>12.7%</td>
</tr>
</tbody>
</table>

The frontal frame stiffness \( s \) increases sharply between 48 and 56 kph, followed by a slight decrease as the test speed is raised to 64 kph. It is expected that frontal stiffness should increase as speed of impact increases, seeing that more energy will need to be absorbed over the same crush distance. The decrease between 56 and 64 kph is unexpected, but upon further inspection, it is evident that increasing the frontal stiffness of the frame elements above a 1.6 scaling factor does not significantly affect the crash pulse. Therefore, this
decrease is an artifact of the model’s insensitivity to high stiffness values. Finally, seat belt stiffness ($b$) shows non-monotonic behaviour, which indicates that either the belt variable is responding to changes in other variables, or the response is simply not very sensitive to small changes at the high seat belt stiffness values shown. It should again be noted that this variable acts in series with a pretensioner and the load-limiting retractor and the interactions among these parameters and variables are likely affecting the optimal designs. As a result of the interactions among the various injury criteria, the neck and femur injury values also change non-monotonically.

3.2 Injury probabilities

The three vehicle designs from Table 2 were next simulated across the range of the three random variables, so that an expected probability of injury given a crash is computed for each vehicle using Equation (15). For the baseline scenario, where the NCAP frontal test speed is 56 kph, the expected probability of serious injury is approximately 5.4%. Decreasing the NCAP speed by 8 kph yields an expected probability of injury of 4.3%, a 21% decrease in injury probability, increasing the speed by the same amount yields an expected injury probability of 6.0%, an 11% increase from the baseline scenario. These results are shown in the leftmost bar grouping in Figure 10. Therefore, if reducing serious injuries measured by the NCAP injury curves from Figure 5 is the only objective of policymakers, this analysis suggests that the frontal crash test should be conducted at a lower speed, closer to the speeds at which the majority of on-road crashes occur.

Figure 10 Expected probability of injury for three NCAP scenarios using (left) NCAP serious injury probability curves and (right) Prasad-Mertz injury severity curves for moderate, serious, severe and critical injuries

One possible concern arising from these results is the impact on more severe injuries. While serious injuries may occur frequently at relatively low crash speeds, fatal injuries are rare at these low speeds and much more likely at high, less frequently occurring crash speeds. For
the same three vehicles, the four rightward bar groupings in Figure 10 show the expected probability of four different injury severities from the AIS:

1. moderate (level 2),
2. serious (level 3),
3. severe (level 4),
4. critical (level 5),

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

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

4 Discussion

4.1 Manufacturer vehicle design

The values presented in Table 2 may not be the true optimisers for occupant safety in these vehicle simulations. This is because surrogate models were used for optimisation and the results depend on the model architectures chosen and their goodness-of-fit; the kriging surrogates used are not an exact match for the simulation behaviour and therefore, different surrogates yield different optima. To ensure that the solutions found are reasonable, the authors conducted full simulations for each of the three designs in each of the three speed scenarios. The results, shown in Table 3, clearly show that the stated optimal vehicle designs performed better in their respective frontal barrier tests than the other two; i.e., of the three vehicles crashed at 48 kph, the design optimised to 48 kph in Table 2 had the lowest occupant injury probability and the same was true for the other two crash speeds.

It is interesting and perhaps counterintuitive, to note that in Table 3 the vehicle optimised for the high test speed performed worse in the lowest crash speed scenario than at the two
higher crash speeds. Further inspection of the simulation output revealed that the stiff belt retractor function combined with the lower crash energy of the 48 kph test caused the majority of the occupant deceleration to occur prior to contact with the airbag, which resulted in more abrupt chest deceleration and neck moments inflicted by the seat belt acting alone. This is also evident, though to a lesser extent, with the vehicle optimised to 56 kph at the slower crash speed. Another notable figure is the exceptionally poor performance of the vehicle optimised for the low test speed in the highest crash speed scenario, with a 68% probability of serious injury. This is a result of the softer belt retractor function and faster-deflating airbags causing hard contact of the head and chest with the rim of the steering wheel.

4.2 Societal injury probability

The serious level injuries computed with the Prasad-Mertz injury probability curves have about twice the probability of injury as those from the NCAP curves, with the baseline at 9% rather than 5%, as shown in Figure 10; further, the impact of changing the test standard is about half of that obtained with the NCAP formulas. These result discrepancies are a consequence of the differences in the injury probability curves, which stresses the importance of the accuracy of these curves. For each of the four injury severities measured by the Prasad-Mertz criteria, with the exception of level 5, the probability of injury decreases with a lower NCAP test speed and increases with a higher NCAP test speed, supporting the results using the NCAP level 3 criteria. However, critical (AIS level 5) injuries increase slightly when the test speed is reduced and they also increase when the test speed is raised. Thus, lowering the test speed is predicted to noticeably reduce moderate, serious and severe injuries, at the cost of slight increases to critical injury rates and possibly, fatalities.

Repeating these calculations with different crash speed distributions from those presented in Figure 9 showed that the results are highly dependent on this input data. When the probability distribution function is shifted to the left, the results more strongly suggest a slower regulatory test speed, while shifting the curve to the right advises keeping the current standard or raising the speed. Further analysis could show how advances in technology, such as pre-crash braking and forward collision warning systems, could potentially lower this speed distribution and therefore, affect probable injuries and optimal regulations.

4.3 Broader implications

While this study presents preliminary results for one specific crash scenario, motor vehicles on the road crash with a wide variety of directions, speeds and occupants. To generate reliable recommendations for regulatory agencies, this process should be expanded to broaden the scope of the present study. Two potential areas to achieve more meaningful results are to incorporate tests for different crash modes and to include a wide sample of vehicles.

<table>
<thead>
<tr>
<th>Crash Speed</th>
<th>48 kph-optimal vehicle</th>
<th>56 kph-optimal vehicle</th>
<th>64 kph-optimal vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 kph</td>
<td>8.90%</td>
<td>10.05%</td>
<td>13.06%</td>
</tr>
<tr>
<td>56 kph</td>
<td>17.50%</td>
<td>10.07%</td>
<td>11.99%</td>
</tr>
<tr>
<td>64 kph</td>
<td>68.07%</td>
<td>13.18%</td>
<td>12.73%</td>
</tr>
</tbody>
</table>
Simulating vehicles from different segments (e.g., compact, mid-size, SUV, pickup truck), particularly those that are smaller than the average on-road vehicle, may reveal different trends and conclusions than those derived with the large vehicle used in this study. Thus, to build a stronger understanding of the impact of the NCAP standards on the vehicle fleet as a whole, a range of models representative of different vehicle segments and manufacturers should be simulated and analysed in the manner prescribed in this paper.

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

One emerging technology with the potential to improve crash safety is the use of adaptive vehicle structures and restraint systems. By incorporating sensors and smart materials in vehicles that can change characteristics depending on an applied signal, different properties such as stiffness could be achieved in a single material by simply changing the electronic signal. This would effectively allow one vehicle to achieve the characteristics of all three optimal designs presented in Table 2, as well as the optimal designs for any other crash scenario and occupant combination. The method presented in this paper could be used to evaluate the benefit of implementing adaptive materials and different regulatory policies could be assessed to determine the best way to encourage the adoption of these technologies.

5 Conclusions

A quantitative approach to examining the impact of NCAP standardised tests on road traffic injuries has been introduced with preliminary counterfactual policy results. While this study considers only frontal crash modes and a single vehicle type and model, the methodology outlined in this paper could be extrapolated with a wider range of scenarios to draw more conclusive results. Although the procedure followed per Figure 6 is already computationally expensive, computer processing power and capabilities are continually improving over time and will make this type of large simulation-based analysis more practical.

For the single crash mode and vehicle used here, the results suggest that lowering the current 56-kph NCAP frontal crash test speed would drive vehicle design changes that improve overall occupant safety for non-critical injuries. An 8-kph decrease in the test speed is predicted to reduce occupant serious injury probability by as much as 21%, although this simulation-based analysis has important limitations. Additionally, since the optimal design for the 48-kph (lower-speed) test has a softer frontal frame, it would likely result in a less aggressive front end and be safer for occupants in vehicles with which it may crash, an added societal benefit that is not captured by the current analyses.

Further analysis with different types of standardised tests may show that optimal tests may be designed by considering the frequency of occurrence and the severity or importance of the possible scenarios. The authors suggest that policy should be driven by these types
of computational tools and scientific analyses, which would potentially yield significant improvements in social welfare.

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References


Association for the Advancement of Automotive Medicine (AAAM) (1990) The Abbreviated Injury Scale, revision, Des Plaines, IL.


