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Frontal NCAP performance and field injury over 40 years

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ABSTRACT

Objectives: Vehicle and occupant responses in 35 mph NCAP tests were determined for small-midsize passenger cars grouped around model year (MY) 1980, 1990, 2000, 2010 and 2020. A baseline was established with 1980 vehicles not designed for NCAP. The results of four decades of vehicles designed for NCAP were compared to the baseline. The study also determined the risk for serious injury (MAIS 3+F) by vehicle model year (MY) using 1989–2015 NASS and 2017–2020 CISS. It explored safety trends in frontal crashes over 50 MYs of vehicles.

Methods: The 1980 baseline group was established with 10 1979–1983 MY passenger cars weighing <1,500 kg. Four decades of vehicle crash tests from five manufacturers established trends in vehicle dynamics and dummy responses over four decades of vehicles designed for NCAP. Triaxial acceleration of the head and chest were reanalyzed for each test to have a consistent set of responses over five decades. The risk for serious injury (MAIS 3+F) to the driver and front passenger was determined by vehicle MY using 1989–2015 NASS and 2017–2020 CISS with belted and unbelted drivers and right-front passengers. The data was sorted in four MY groups 1961–1989 MY, 1990–1999 MY, 2000–2009 MY and 2010 MY-2021 MY. The risk for MAIS 3+F injury was determined with standard errors using weighted data.

Results: The 1980 NCAP tests brought about changes in vehicle structures and occupant restraints by 1990; however, HIC_{15} and 3 ms chest acceleration have not changed much the past 20 years since the use of advanced airbags and seatbelts with pretensioner and load-limiters. For the driver, HIC_{15} dropped 40 ± 19% from the 1980 to 1990 NCAP tests and dropped further to 76 ± 32% in 2020. The percentage drops after 1990 were not statistically significant. The driver 3 ms chest acceleration dropped 18 ± 5% from 1980 to 1990 and plateaued with 22 ± 6% in 2020. For the front passenger, HIC_{15} dropped 68 ± 52% from the 1980 to 1990 NCAP tests and plateaued at 71 ± 49% in 2020. The passenger 3 ms chest acceleration dropped 13 ± 5% from 1980 to 1990 and has fluctuated with minimal change. Injury risks based on responses show the same initial drop in 1990 and have remained essentially constant. Nothing meaningful has changed in dummy responses in the past 20 years of NCAP testing. The field data found the belted driver MAIS 3+F risk was 1.66 ± 0.37% in 1961–1989 MY vehicles and 1.39 ± 0.33% in 2010–2021 MY vehicles. For belted right-front passengers, the risk was 1.52 ± 0.39% in 1961–1989 MY vehicles and 1.42 ± 0.46% in 2010–2021 MY vehicles. The field data shows no meaningful change in injury risk in 50 MYs of vehicles. NCAP involves 35–40 mph delta-V, which represents a small fraction, 0.33%, of belted occupant exposure and only 8.6% of severe injury based on 1994–2015 NASS.

Conclusions: The NCAP test lacks field relevance. Manufacturers are merely "tuning" the restraint systems for star ratings without meaningful changes in field injury risks the past 20 years. There are disbenefits of "tuning" safety for a single, high-severity crash when most of the severe injury occurs in lower severity crashes. NHTSA should reevaluate plans to change the dummy to Thor and add BrIC injury criteria to assess NCAP responses. These changes would cause manufacturers to further "tune" structures, restraints and interiors without meaningful effects in real-world crashes.

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Introduction

35 mph frontal NCAP

In 1979, NHTSA started NCAP (New Car Assessment Program) testing to address Title II of the Motor Vehicle Information and Cost Savings Act of 1972 (Hackney and Quarles 1982; Hackney et al. 1994). NCAP was intended to provide consumers with information on crash protection of different vehicles and assist in vehicle purchase decisions. Another goal was to motivate vehicle manufacturers to voluntarily improve vehicle crashworthiness without regulations. NCAP involved a 35 mph frontal crash into a rigid barrier, which was 36% more energy than the 30 mph barrier crash in FMVSS 208. The vehicle included an instrumented 50th Part 572 dummy belted in the driver and front passenger seat. Each dummy recorded head and chest acceleration and femur loads, which were compared to FMVSS 208 injury criteria.

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Viano (2024) analyzed the initial 13 NCAP tests conducted in 1979. Most vehicles had severe distortion of the occupant compartment during the crush of front structures. There was extensive rearward deformation of the firewall and displacement of the steering wheel toward the driver, often resulting in head impact on the rim and hub. The NCAP tests showed different performance for the driver and front passenger in the same vehicle and in vehicles of similar weight. There was a range of vehicle deformation, steering assembly displacement and lap-shoulder belt restraint. More than half of the dummy responses were above FMVSS 208 injury criteria.

NHTSA and its researchers regularly analyzed and reported on NCAP results. MacLaughlin and Saul (1982) and Hackney and Ellyson (1985) studied issues with the steering assembly and seatbelts on driver responses in NCAP tests. Jones et al. (1985) provided in-depth analyses of driver head kinematics and impact on the steering wheel rim and hub. Hackney and Ellyson (1985) extended the analysis of seatbelts, steering assembly and vehicle structures with more NCAP testing of front occupants. MacLaughlin and Saul (1982) studied issues with front passenger responses in NCAP tests. Cohen et al. (1989) conducted in-depth analysis of the front passenger performance in NCAP tests. Hackney et al. (1989, 1996) studied trends in driver and passenger performance in NCAP tests and discussed how newer models compared to older models. They showed downward trends in injury responses, but no standard deviations were provided to judge relevance.

The NCAP test caused vehicle manufacturers to change front structures by 1990 isolating deformation forward of the firewall and preventing components intruding into the occupant compartment. It caused manufacturers to change occupant restraint systems. Hackney (1991) compared trends in NCAP and FMVSS 208 crash tests from 1987 to 1991 MY vehicles and showed downward trend in injury criteria, again without showing standard deviations. Hackney et al. (1994) provided a historic review of NCAP and vehicle performance trends showing reductions in dummy responses with 1987–1993 MY compared to 1979–1985 MY vehicles, although no standard errors were provided. The addition of airbags in 1987 NCAP tests lowered injury criteria as lap-shoulder belts included pretensioners and load limiters balancing restraint of the upper torso by load sharing between the belts and airbag (Hackney and Kahane 1995).

Over 40 years, the dummies and injury criteria have changed in the 35 mph NCAP test. The 2020 tests involve a 50th Hybrid III driver and 5th Hybrid III front passenger. Each dummy has over 30 channels of instrumentation measuring responses of the head, upper neck, chest, femurs, tibias, ankles and feet. In comparison, the Part 572 dummy used in the 1979 tests had 8 channels of responses. Head injury risk was initially HIC, calculated with unlimited duration or HIC_{36} with a 36 ms duration. The HIC calculation was limited to 15 ms in the Hybrid III dummy, giving HIC_{15}. Chest injury risk was initially the 3 ms or peak resultant acceleration in the Part 572 dummy. It is now chest deflection in the Hybrid III dummy. The shifts in dummy and injury criteria make it difficult to understand the performance of 1990–2020 vehicles in perspective to what occurred in the initial NCAP tests.

Field relevance of the 35 mph NCAP

Grush et al. (1983) conducted a comprehensive study comparing NCAP dummy responses to fatalities in FARS. They restricted the field data to the NCAP-type crashes by selecting belted occupants in frontal crashes in vehicles matching the weight of the NCAP tests from 1979 to 1981. The NCAP injury criteria did not correlate with crash fatality rates computed using Polk data on registered vehicles. The fatality rate per million registered car years (mil yr) was similar for vehicles passing and failing FMVSS 208 injury criteria in NCAP. The driver fatality rate was 207/mil yr (range 73–341) for vehicles passing HIC criteria, compared to 217/mil yr (89–459) for those failing. The passenger fatality rate was 64/mil yr (31–115) for vehicles passing HIC and 77/mil yr (32–132) for those failing. The authors listed reasons for the lack of relationship including crash test variability, inadequate dummy responses and confounding variables.

Libertiny (1995) responded to a news release indicating NHTSA found a correlation between NCAP scores and fatality risks in field accidents. His analysis concluded that NCAP results did not provide a valid indication of occupant protection in a specific vehicle and consumers could make wrong decisions if they relied on NCAP scores. He showed that the differences between good and poor NCAP scores were small and not meaningful. Lavelle (2001) used 1995–1999 NASS-CDS to determine field injury rates while matching seating position, vehicle damage, impact direction and delta-V to NCAP conditions. He found only a small portion of occupants fit the NCAP condition and there was no correlation of dummy measurements to field injuries. Nirula et al. (2004) compared HIC and chest g in NCAP tests with field injuries in the 1994–1998 NASS-CDS while controlling for covariates. They concluded HIC and chest g were poor predictors of brain and thoracic injury in field accidents and that NCAP criteria were unable to differentiate vehicles of varying crashworthiness.

Understandably, NHTSA and its researchers reported the opposite conclusions. They showed improved occupant protection with the best performing vehicles in 35 mph NCAP tests. Jones et al. (1985) used Texas state data and reported 80–87% reduction in belted driver injury in the best performing vehicles in NCAP compared to the worst. They reported a 21–36% reduction for unbelted drivers. Jones and Whitfield (1988) found a significant relationship between NCAP results and serious injury or death in single-car frontal accidents also using Texas state data. They noted that chest acceleration was a better predictor than HIC for restrained drivers considering crash severity and driver age. Kahane (1994) and Kahane et al. (1994) studied head-on crashes in the 1978–1992 FARS involving 396 crashes similar to NCAP. They found a significant correlation between NCAP injury criteria and fatality risk for belted drivers with a 15–25% lower risk in cars with good NCAP scores. This was the study criticized by Libertiny (1995).

Increasing stiffness and weight of vehicles

Trends in vehicle structures were analyzed starting in 1982 with the addition of load-cells on the barrier to measure impact force. The force (F) and deformation (d) of front structures was used to estimate front stiffness in NCAP tests. Swanson et al. (2003), Patel et al. (2007), Saunder et al. (2008), Wu et al. (2020) studied changes in vehicle crash pulse and front stiffness by model year. Sahraei et al. (2013) found an increase in vehicle stiffness and weight in NCAP tests. They found front stiffness (k) correlated with vehicle MY. Stiffness was $k = 38.3(\text{MY-1974})$, $R^2 = 0.79$, slope se = 3.7 N/mm/MY for vehicles tested in 1982–2010. They found vehicle weight (W) correlated with vehicle MY. Weight was $W = 11.9(\text{MY-1853})$, $R^2 = 0.79$, slope se = 1.2 kg/MY.

There is a fundamental relationship in automotive safety between fatality risk and vehicle weight. Increasing the weight of a vehicle improves crash safety for its occupants (Evans 1991). Evans and Frick (1993) found car weight was a dominant factor in driver fatality rates in two-car crashes with higher risks in lighter vehicles. It seems clear the underlying relationships are that front stiffness correlates with vehicle weight, and the relationships with MY found by Sahraei et al. (2013) were associations, as vehicles have become heavier, stiffer and safer. The fundamental relationship was $k = 3.22(\text{W-1,440})$, valid for vehicle weight >1,500 kg. The increase in vehicle weight and stiffness was related to structural changes due, in part, to meeting the requirements of consumer information tests, such as the side impact NCAP, IIHS offset frontal and side impacts and revision to FMVSS 208.

The fundamental relationship between vehicle weight and safety is an issue in any field accident study of NCAP scores and occupant injury. In general, newer cars are stiffer, heavier and safer compared to older models. Heavier cars generally performed better in NCAP tests, even within a time period. For example, the 1979 NCAP vehicles passing FMVSS 208 injury criteria were 351 lb (160 kg) heavier than vehicles failing, although the difference was not statistically significant ($t = 0.78$, NS). Samaha et al. (2010) showed a steady increase in the weight of the Toyota Camry from at 3,049 lb (1,386 kg) for the 3rd generation (1992–1996 MY) to 3,296 lb (1,498 kg) for the 6th generation (2007–2010 MY) Camry.

The purpose of this study was to determine NCAP performance over four decades (1990, 2000, 2010 and 2020) of small-midsize passenger cars from five manufacturers that were designed for the NCAP test and to compare the results to a 1980 baseline group of small-midsize vehicles not developed for the 35 mph NCAP. The study reanalyzed dummy responses in each test to have a consistent set of injury criteria over five decades. The study also analyzed field accident data for belted drivers and front passengers using 1989–2015 NASS and 2017–2020 CISS to explore trends in risk for serious injury (MAIS 3+F) in frontal crashes with over 50 MYs of vehicles.

Methods

Vehicle dynamics in NCAP tests

In this study, 35 mph NCAP tests were selected for five manufactures of small-midsize passenger cars that were NCAP tested. They were grouped around model year (MY) 1980, 1990, 2000, 2010 and 2020. The 1980 and other decade notation is shorthand for vehicles built within ±4 years of the start of the decade. The tests represent four decades of development for the 35 mph frontal NCAP. The NCAP results were compared to vehicles designed before the 35 mph NCAP started in 1979. The 1980 baseline group was determined using a larger sample of 10 NCAP tests on passenger cars weighing ≤ 1,500 kg with 1979–1983 MY. The 1980 vehicles were not developed for the 35 mph frontal NCAP.

Thirty-one (31) NCAP tests were downloaded and analyzed. There were six NCAP tests representing 1990 small-midsize passenger cars with 1987–1992 MY. There were five tests representing 2000 with 1999–2004 MY, five tests representing 2010 with 2011–2015 MY and five tests representing 2020 with 2017–2020 MY. Wherever possible the same model was selected from the NCAP test library at NHTSA (www.nhtsa.gov/research-data/research-testing-databases#/vehicle) for 1980, 1990, 2000, 2010 and 2020. None of the manufactures used the same model name over the study period, so another platform was substituted to have at least five vehicles per decade with at least one vehicle per manufacture. The five manufacturers and models were:

Manufacturer	1980	1990	2000	2010	2020
Ford:	1984 Escort,	1987 Escort,	2000 Focus,	2015 Focus,	2017 Fusion.
General Motors:	1984 Cavalier,	1990 Cavalier,	2001 Malibu,	2011 Malibu,	2020 Malibu.
Honda:	1979 Civic,	1989 Civic,	1999 Civic,	2013 Civic,	2018 Accord.
Nissan:	1979 Datsun 210,	1989 Maxima,	2004 Maxima,	2012 Maxima,	2020 Maxima.
Toyota:	1979 Celica, others	1987, 1992 Camry,	2000 Camry,	2011 Camry,	2018 Camry.

Table A1 lists the NCAP tests used in the study. It provides the DOT test #, make, model, platform generation with MY run, VIN and test weight. The crash test results included the maximum front crush, interior intrusion and delta-V, where provided. Table A1 also lists the restraint system in the vehicle, which included:

1980:	8 manual belts, 2 passive belts.
1990:	2 manual belts, 4 passive belts and 1 vehicle with driver airbag.
2000:	5 manual belts, 4 advanced airbags, 1 1st generation airbag, 3 pretensioners with load limiters.
2010:	5 manual belts, 5 advanced airbags, 5 pretensioners with load limiters, 1 knee airbag.
2020:	5 manual belts, 5 advanced airbags, 5 pretensioners with load limiters, 4 knee airbags.

Driver and front passenger responses in NCAP tests

The NCAP tests included an instrumented driver and front passenger dummy. There was an evolution in dummies and injury criteria used in the 35 mph NCAP test over the past 40 year. The initial NCAP tests used the Part 572 dummy (Hybrid II) with 8 channels of instrumentation. The 50th Hybrid III was used in the early 1990s with 30 or more channels. The 50th Thor dummy with 34 or more channels has be used in research NCAP tests. The dummies and instrumentation included:

1980:	50th Part 572 dummy with 8 channels of data, triaxial head acceleration, triaxial chest acceleration and left and right femur load.
1990:	4 tests with the 50th Part 572 dummy with 8 channels of data and one test with the 50th Hybrid III with 30 channels of data, including triaxial pelvis acceleration, 6 channels of upper neck forces and moments, 1 channel of chest deflection, 6 channels of foot triaxial acceleration and 6 channels for the upper and lower tibia force (compression and moments).
2000:	50th Hybrid III with 30 channels of data as listed above.
2010:	50th Hybrid III driver and 5th Hybrid III passenger as listed above.
2020:	50th Hybrid III driver and 5th Hybrid III passenger with 36 channels of data reduction to 3 channels of upper neck (tension and fore-aft shear and flexion moment).
2020:	50th Thor dummy research tests with 34 channels of instrumentation, including triaxial head rotational acceleration, 3 neck channels (neck tension, fore-aft shear and flexion moment) and 4 channels of ankle rotation and moments.

The UDS data for the driver and front passenger was downloaded for each NCAP test. The triaxial head accelerations of the driver and front passenger were reanalyzed for HIC_{15}, HIC_{36} and HIC with unlimited duration. The reanalysis used the NHTSA HIC software (https://www.nhtsa.gov/databases-and-software/signal-analysis-software-windows). The triaxial chest accelerations were reanalyzed using the NHTSA Clip3ms software for the peak and 3 ms duration chest acceleration. The other responses summarized included the peak resultant head acceleration, 3 ms chest acceleration, left and right femur load, and where available Nij, neck tension and chest deflection in the Hybrid III dummy.

Variability in NCAP tests

Machey and Gauthier (1984) studied the variability and repeatability in the NCAP test. They conducted 14 repeat crash tests with a minimum of four impacts of 1982 Chevrolet Citations at three test sites. The test sites were Calspan Corporation, Buffalo, New York, Dynamic Science Inc., Phoenix Arizona and the Transportation Research Center, East Liberty, Ohio. The vehicles were manufactured consecutively by Chevrolet to achieve maximum uniformity.

The NCAP tests were downloaded from the NHTSA website, including the UDS data (Table B1 in the Appendix). The HIC_{15}, HIC_{36} and HIC with unlimited duration and triaxial chest acceleration resultant 3 ms and peak were recalculated using the method described above. The average, standard deviation (sd) and coefficient of variation (CV) was determined for HIC_{15}, HIC_{36} and HIC, peak resultant head acceleration and peak and 3 ms resultant chest acceleration for the driver and front passenger. The CV was the sd/average.

Table 1. Percent reduction in dummy responses by decade since the 1980 NCAP baseline.

MY[a]	Driver		Right-front passenger	
	HIC_{15}	3 ms g	HIC_{15}	3 ms g
1980	—NCAP baseline—[b]			
1990	40 ± 19%	18 ± 5%	68 ± 52%	13 ± 5%
2000	56 ± 31%	19 ± 6%	67 ± 47%	6 ± 2%
2010	76 ± 53%	23 ± 6%	75 ± 56%	−4 ± 1%
2020	76 ± 32%	22 ± 6%	71 ± 49%	6 ± 2%

[a]Vehicle MY within ±4 years of the start of decade. [b]Data is percent reduction from baseline with ± standard deviation.

Converting biomechanical responses to injury risk

Injury risk is not adequately described by a human tolerance with injury above an IARV (injury assessment reference value) and no injury below. There is a distribution of injury (and no injury) in tests with different biomechanical responses. For very low biomechanical responses, there is a very low injury risk. The tail of the risk function is close to zero. For very high biomechanical responses, there is essential 100% risk of injury at the other tail. Between the two tails, there is a transition zone where injury risk is proportional to the biomechanical response. Although the shapes and complexity of risk functions vary and there is never enough data to determine the precise risk function, the available biomechanical data is generally fit with a sigmoidal function, where injury involves a distribution of weak through strong subjects. Prasad and Mertz (1985) provided injury risk curves for skull fracture and brain injury using Weibull, linear and Mertz-Weber methods. Hertz (1993) reanalyzed the skull fracture data with different risk functions. Mertz et al. (1996) provided risk functions for forehead impacts. Prasad et al. (2010) compared the earlier risk functions to those used by NHTSA to evaluate NCAP tests. Wang et al. (2003) compared 8 different methods including Weibull, Logistic and Log Normal for HIC and chest compression. Petitjean and Trosseille (2011) added more analysis of injury risk functions.

Two risk functions were used to interpret head and chest responses in this study. The primary one was the Logist function, which has three distinct regions typical of injury distributions. Viano and Arepally (1990) used Logist and reported the parameters for head, chest and femur injury risk. The Logist function estimates the probability of injury p(x) for a response (x) using two parameters α and β that provide a best fit to the sigmoidal function $p(x) = [1+\exp(\alpha - \beta x)]^{-1}$. The 50% risk of injury is α/β. The goodness-of-fit was quantified by chi-squared (χ^2), p-value and correlation coefficient (R) from Viano (1991). The α and β parameters for HIC_{15} and chest acceleration used here were reported by Parenteau et al. (2022), Appendix D based on parameters in Viano and Arepally (1990) and scaling for the 5th Hybrid III.

The determination of injury risk for low biomechanical responses is important and needs careful interpretation. The Logist function does not converge to zero for low values of x and is invalid if $\beta x > \alpha$. With $x = 0$, $p(x) = [1+\exp(\alpha)]^{-1}$, which is non-zero risk. A valid interpretation of risk for low x is important because it represents risks in low-speed crashes that involve x often below the range of injury data used to determine the Logist fit, i.e., $HIC_{15} < 300$. In this case, a more complex risk function was used from NHTSA (Berkowitz 2001). The basis for the NHTSA function is unclear, but the function approximates the Logist for the known biomechanical data. For MAIS 4 + F head injury, the NHTSA risk function is $p(x) = [1+\exp((4.9+200/x) - 0.00351x)]^{-1}$, where x is HIC_{15}. This risk function converges to zero risk at $x = 0$, although the term 200/x approaches infinity. Figure C1 shows injury risks for $HIC_{15} < 200$ with three functions used in previous studies. For MAIS 4 + F chest injury, the NHTSA function is p(x) = [1 + exp

$(4.3425 - 0.063x)]^{-1}$, where x is chest acceleration (g). The NHTSA chest function has the form of the Logist function.

Statistical significance

The difference in NCAP responses was compared between decades using the t-test in Excel assuming unequal variance. The difference was considered significant with $p < 0.05$.

NASS-CDS field data on MAIS 4+F injury by crash delta-V

NASS-CDS is a crashworthiness data system available on the NHTSA website (www.nhtsa.gov/crash-data-systems/). Viano and Parenteau (2022) used the 1994–2015 NASS-CDS to determine the exposure and severe injury (MAIS 4+F) by crash direction and delta-V for occupants 15+ years old. In this study, only frontal impacts were analyzed. The following describes the selection criteria used in the sub-set from the larger study. Following Viano and Parenteau (2022), frontal crashes were selected using location (GAD1='F') without rollover (rollover ≤ 0). Crash severity was assessed with the DVTOTAL using 8 km/h (5 mph) increments starting at 16 km/h (10 mph) up to 72 km/h (45 mph). The data for crashes <16 km/h (<10 mph) and 72+ km/h (45+ mph) delta-V were grouped. This gave 9 increments of delta-V. Seatbelt use was defined by the NASS-CDS investigator's variables MANUSE = 4 (manual belt use) and ABELTUSE (automatic belt use). Occupants with known injury MAIS 0-6 or F were defined as the exposure group. The shorthand notation was MAIS 0+F. Occupants with severe injury were defined as MAIS 4-6 or F with the shorthand notation MAIS 4+F. All calculations were based on weighted values. Standard errors (se) were determined using the SAS procedure "SURVEYFREQ" accounting for PSU, PSUSTRAT and RATWGT factors. The weighted and unweighted data for lap-shoulder belted occupants in frontal crashes is in Viano and Parenteau (2022), Appendix C. In this study, field data on the risk of MAIS 4+F from Kahane (1994) with 1988–1991 NASS was compared to the risk in the 1994–2015 NASS by delta-V.

NASS-CDS and CISS field data on MAIS 3+F injury by vehicle model year (MY)

NASS-CDS and CISS are crashworthiness data system available on the NHTSA website (www.nhtsa.gov/crash-data-systems/). In this study, the 1994–2015 NASS-CDS and the 2017–2020 CISS were searched using SAS for serious injury (MAIS 3+F) to belted and unbelted drivers and right-front passengers in frontal crashes. The data was sorted in four model year (MY) groups, 1961–1989 MY, 1990–1999 MY, 2000–2009 MY and 2010 MY-2021 MY. The analysis followed methods previously reported on the searching and combining the two databases (Parenteau et al. 2022; Viano and Parenteau 2023). National estimates for the number of occupants and MAIS 3+F injuries were made using the Inflation Factor (named RATWGT in the NASS-CDS and CASEWGT in CISS). The sample included vehicles with frontal impact location (GAD1 = "F") and no rollover (rollover ≤ 0). Occupant age, seatbelt use and injury severity were searched using methods described in Viano and Parenteau (2022). All calculations were based on weighted values. Standard errors (se) were determined using the SAS procedure "SURVEYFREQ" accounting for PSU, PSUSTRAT and RATWGT factors.

Analyses of changes in field injury with different vehicle designs

Viano (1987) described a method to optimize rate-dependent padding for side impact protection that used the sigmoidal risk function with a biomechanical response over the range of impact velocity causing injury. The distribution of exposed occupants involves very high exposure in low-severity crashes with low risks and very low exposure in high-severity crashes with high risks. Fundamentally, the risk of injury increases with crash severity (impact velocity, delta-V). The product of risk times exposure at each delta-V gives the number injured. MAIS 4+F injuries are uniformly distribution of over a wide range of crash delta-V.

The key to an accurate interpretation of a design change is knowing the injury risks and associated biomechanical responses over the range of crashes causing injury. While there is very low risk of injury in crashes that occur very frequently, they cause as many injuries as occur in severe exposures that are infrequent, the modified design needs to lower risks over the range of crashes causing injury. This balances the safety design over the actual delta-V range field injuries to optimize injury prevention. Tuning at one high-severity exposure can lead to greater injuries at lower speed because of the necessity to stiffen components for the high-severity exposure.

Biomechanical responses need to be determined with the modified and baseline design over the range of crash severities involving MAIS 4+F injury in field accidents. The difference in risk at each delta-V increment was multiplied by the number of exposed occupants to estimate the distribution of reduced (or increased) injury with the modified design. Situation where the risk of injury was higher with the modified design compared to the baseline, would require changes in the design to lower risks below the baseline. This would prompt an analysis of reasons for the higher risk and cause modifications in the design to ensure uniform safety improvements over the range of crashes. Viano (1991) summarized each step in the method using an example of a modified steering wheel design compared to a production steering wheel in frontal crashes. Field data on the drivers exposed and seriously injured in frontal crashes established the baseline risk. A computer program was developed to calculate the effect of the modified design, showing the expected change in injuries by crash delta-V.

An additional finding of this type of analysis is that optimizing a design is best initially done at the average crash severity causing injury. This balances the design for the weak in the population and the strong. Tuning a design for a high-severity crash, often increases injuries to the weaker in the population in lower severity crashes. The average severity of frontal crashes was 26 mph (42 km/h) for MAIS 4 + F injury to lap-shoulder belted occupants using 1994–2015 NASS. The crashes involve airbag deployments, as occurred. Viano and Parenteau (2010) determined the percent airbag deployment by delta-V for frontal crashes in the 1996–2007 NASS-CDS. Overall, 49.0% of frontal crashes involved airbag deployment in NASS-CDS with 35.0% in < 10 mph, 62.8% in 10–15 mph, 77.4% in 15–20 mph up to 98.0% in 35–40 mph crashes for belted front occupants.

Results

Trends in vehicle dynamics in NCAP tests

Figure 1 shows an increase in vehicle weight with newer-model small-midsize passenger cars. The black line represents the average of the vehicles by decade and the dashed lines show the average ± 1 standard deviation. The 2020 vehicle weight of 1,727 ± 118 kg was significantly greater than the 1,292 ± 181 kg for passenger cars in 1980 ($t = 5.60$, $p < 0.001$) and 1,409 ± 235 kg in 1990 ($t = 2.90$, $p < 0.05$).

Figure 2 shows a reduction in front crush in the 35 mph NCAP with newer passenger cars. The front crush was about 500 ± 50 mm from about 2000 to 2020. Figure 3 shows the progression of front crush for the 1979 Datsun 210 (left) followed by the 3rd generation Maxima, 6th generation Maxima, 7th generation Maxima and 8th generation Maxima (right). The images at the top are time zero followed by 40, 80 and 100 ms (bottom). The 1979 Datsun had manual belts and the 1989 Maxima had passive belts without an airbag (Table A1). The 2004 and 2012 Maxima had advanced airbags, manual belts with pretensioners and load limiters. The 2020 Maxima added knee airbags. The four decades of Maxima had good vehicle dynamics and occupant kinematics. The 1989 NCAP test used the 50th Part 572 dummy. The 2004, 2012 and 2020 NCAP tests used the 50th Hybrid III dummies with the 5th Hybrid III used on the passenger side in 2012 and 2020 tests.

Figure 3 lists the maximum front crush and firewall intrusion at the bottom for each test. The Datsun 210 performed poorly in the NCAP test. The eight generations of Maxima had reasonable performance with controlled front crush and minimal firewall intrusion. The 2020 Maxima had 17% lower front crush than the 1979 Datsun 210. The firewall (plenum) intrusion was 96% lower. The addition of the passenger airbag and refined seatbelts maintained the passenger upright during restraint in the 2020 test compared to the 1989 Maxima kinematics. The 2020 Maxima had minimal pitch during front crush and the rearward edge of the passenger airbag was greater, indicating a deeper airbag. The refinements in the seatbelt included pretensioning and load limiting to improve load-sharing with the airbag.

Figure 4 shows a dramatic reduction in firewall (plenum) intrusion with newer passenger cars. The 2020 intrusion was 16.6 ± 17.5 mm, which was significantly lower than the intrusion in 1980 vehicles ($t = 5.73$, p, 0.001) and 1990 vehicles ($t = 3.02$, $p < 0.05$).

Variability in NCAP tests

Table B1 summarizes the results of the reanalysis of the NHTSA repeatability NCAP tests by Machey and Gauthier (1984). For the driver, HIC_{15} was 445 ± 117 ($n = 14$) with a coefficient of variation (CV) of 26%. The 3 ms chest acceleration was 41.6 ± 4.4 g with a CV of 10%. For the front passenger, the HIC_{15} was 372 ± 118 ($n = 13$) with a CV of 32%. The 3 ms chest acceleration was 33.7 ± 2.2 g with a CV of 7%.

Trends in driver responses in NCAP tests

Table A2 summarizes the driver responses in the NCAP tests, including the HIC_{15}, HIC_{36} and HIC with unlimited duration. The other responses include the peak resultant head acceleration chest 3 ms acceleration, left and right femur load, and where available Nij, neck tension and chest deflection in the Hybrid III dummy.

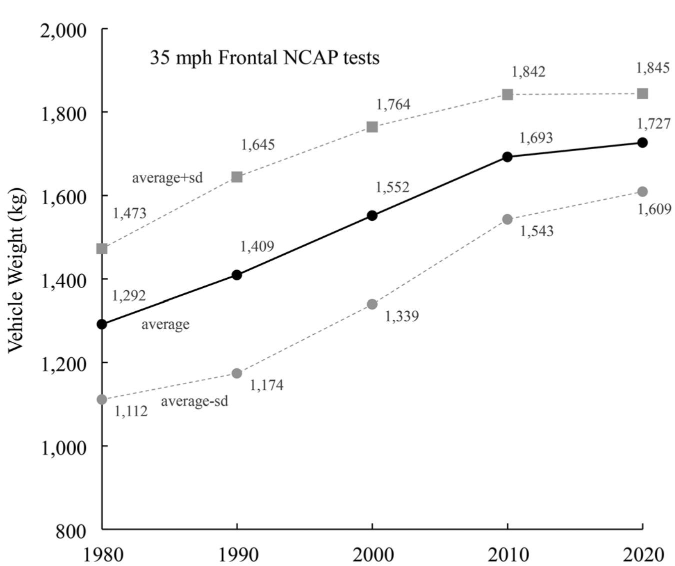

Figure 1. Vehicle weight by decade for selected NCAP tests.

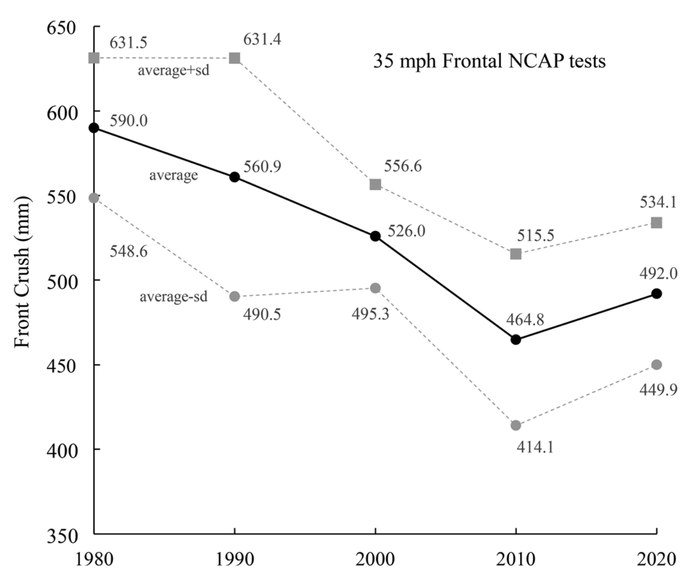

Figure 2. Front crush by decade for selected NCAP tests.

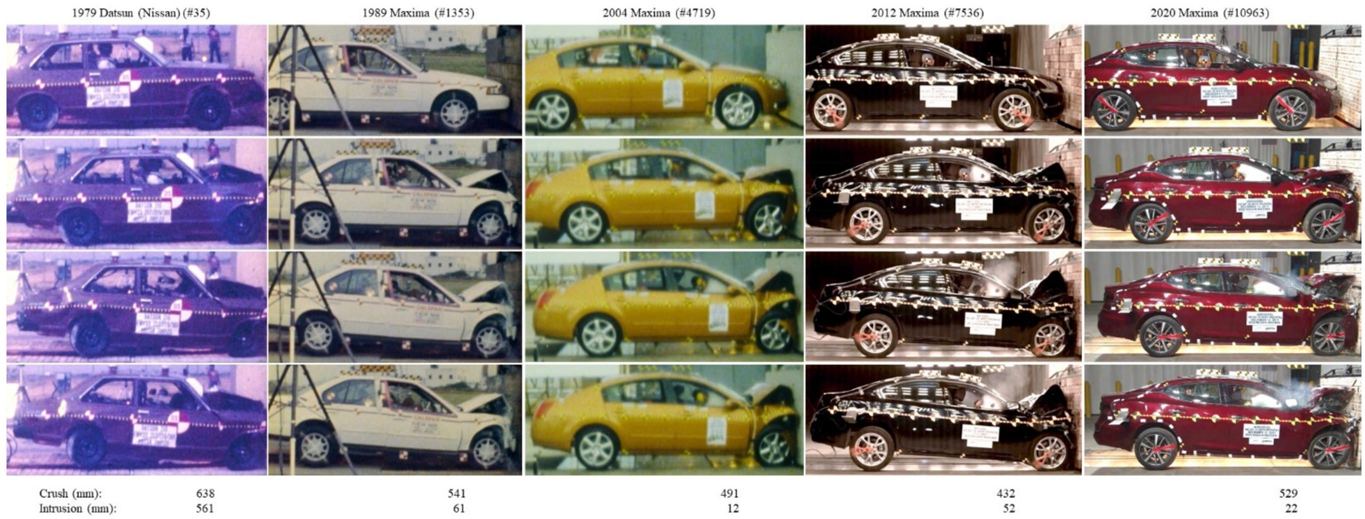

Figure 3. Vehicle dynamics in NCAP tests with eight generations of Nissan Maxima and the early Datsun 210.

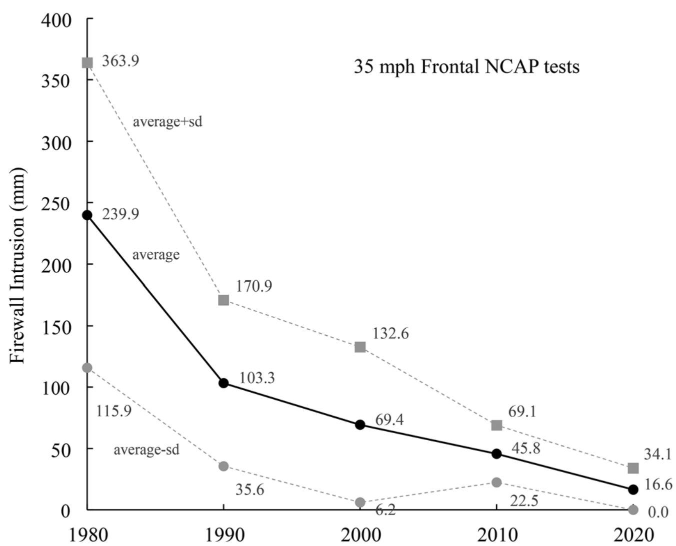

Figure 4. Intrusion of the firewall (plenum) by decade for selected NCAP tests.

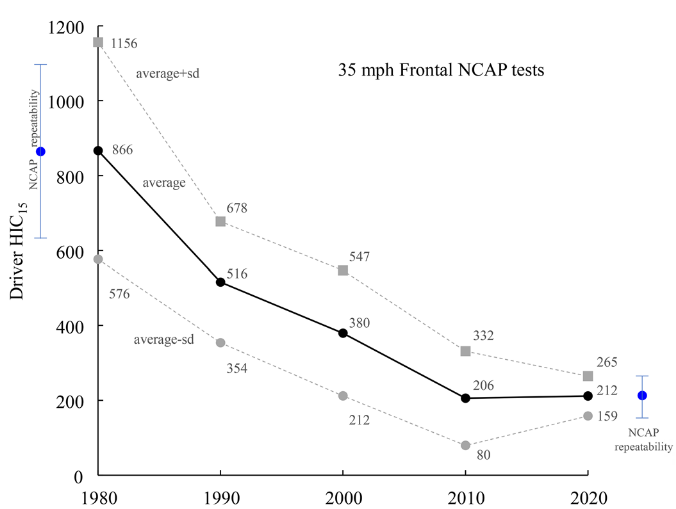

Figure 5. Driver HIC_{15} by decade for selected NCAP tests.

Figure 5 shows the driver HIC_{15} by decade in NCAP tests. By 2000, most passenger cars were equipped with advance airbags and manual seatbelts with pretensioners and load limiters. The advanced airbag and seatbelts resulted in significantly lower HIC_{15} in the 2000 vehicles compared to the 1980 vehicles ($t = 4.11$, $p < 0.001$). The 2020 vehicles had significantly lower HIC_{15} than the 1980 vehicles ($t = 6.91$, $p < 0.0001$); however, the 2000 vehicles had statistically similar HIC_{15} to the 2020 vehicles ($t = 2.14$, NS). In terms of HIC_{15}, the transition to advance airbags with seatbelts was sufficient to control HIC_{15}. Figure 5 includes the variability in HIC_{15} from the repeatability tests conducted by NHTSA (Machey and Gauthier 1984). The CV was 26% for HIC_{15}, which resulted in a sd (standard deviation) of 225 using the average HIC_{15} of 866. The test-to-test variability is plotted in blue next to the 1980 NCAP results. The variability for the 2020 NCAP HIC15 is also plotted with a sd of 112. The repeatability of the NCAP tests is about as large as the standard deviation in the tests with different vehicles.

Figure 6 shows the driver chest acceleration by decade. There was an initial drop in chest acceleration with seatbelts and vehicle structural changes in 1990 vehicles; however, the reduction from 1980 to 1990 was not statistically significant ($t = 1.93$, NS). From 1990 to 2020, the chest acceleration remained constant even with the addition of dual pretensioners, load limiters and knee airbags in the most recent vehicles.

Table 1 shows the driver HIC_{15} dropped $40 \pm 19\%$ from 1980 to 1990 NCAP tests and dropped further to $76 \pm 32\%$ in 2020. The drop since 1990 was not statistically significant. The driver 3 ms chest acceleration dropped $18 \pm 5\%$ from 1980 to 1990 tests and plateaued to $22 \pm 6\%$ in 2020.

Trends in driver risk estimations in NCAP tests

Figure 7 shows the driver head injury risk based on HIC_{15}. The 1980 vehicles had an average risk of 9.99% (3.90–23.3%). The risk dropped to less than 2%, on average, with vehicles

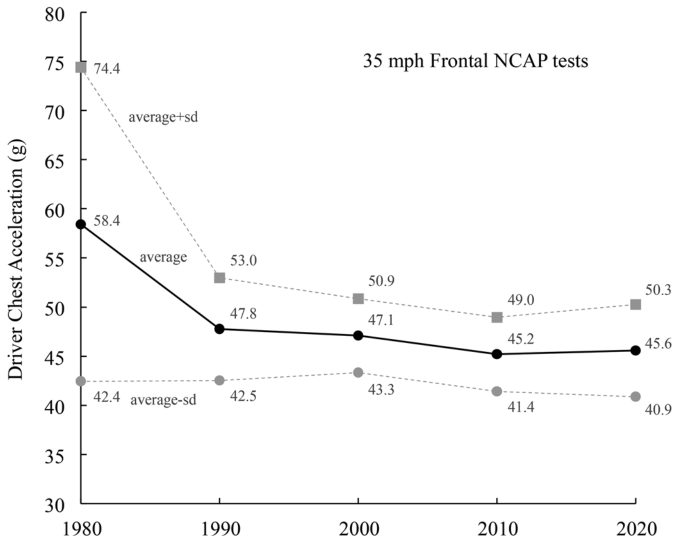

Figure 6. Driver chest acceleration by decade for selected NCAP tests.

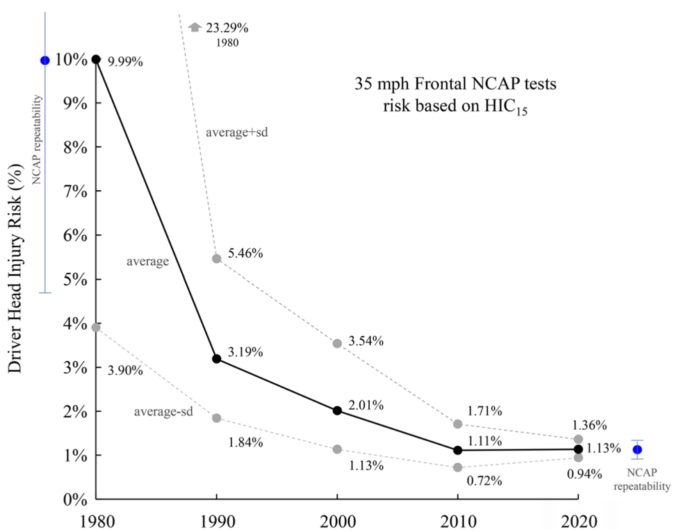

Figure 7. Driver head injury risk based on HIC_{15} by decade for selected NCAP tests.

from 2000 to 2020 vehicles. The 1980 head injury risk was not statistically different from the 1990 ($t = 1.44$, NS), 2000 ($t = 1.12$, NS) or 2020 risks ($t = 1.72$, NS) because of the wide variability in HIC_{15} in the initial NCAP tests.

Figure 7 also includes the variability in HIC_{15} risk about the average using the 26% CV from the reanalysis of the NCAP repeatability tests. For the 1980 NCAP tests, the test variability involves a wide range in risk with 9.99% (4.78–19.7%). For the 2020 NCAP tests the variability leads to an injury risk of 1.13% (0.94–1.37%). The variability is plotted in blue next to the 1980 and 2020 risks. Figure 8 shows the driver chest injury risk based on chest acceleration. There was an initial drop in risk from 1980 to 1990 vehicles, but the lower risk was not statistically significant for any decade compared to the 1980 risk.

By 2000, the NCAP test used the 50th Hybrid III dummy, which added measurements of chest deflection. The deflection was 29.3 ± 7.7 mm. By 2010, the chest deflection was 21.7 ± 5.8 mm, not significantly different from 2000 vehicles ($t = 1.77$, NS). By 2020, the deflection was 19.8 ± 3.7 mm, which was significantly lower than the 2000 deflection

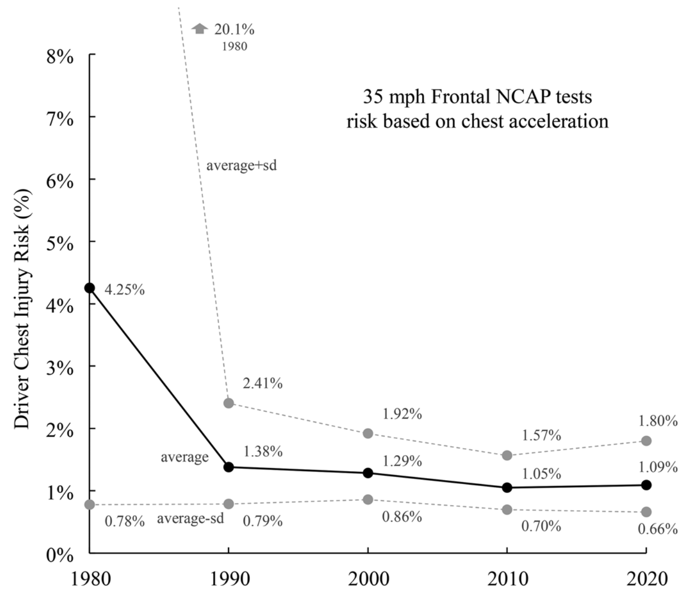

Figure 8. Driver chest injury risk based on chest acceleration by decade for selected NCAP tests.

($t = 1.94$, $p < 0.05$). The difference between the 2010 and 2020 responses was not significant ($t = 1.91$, NS).

Trends in passenger responses in NCAP tests

Table A3 summarizes the front passenger responses in the NCAP tests. Figure 9 shows the passenger head HIC_{15} by decade. By 1990, most passenger cars modified vehicle structures to control front crush and intrusion, and the lap-shoulder belts were sufficient to control HIC_{15}. There was little difference in HIC_{15} with the addition of advance airbags, pretensioners, load limiters and knee airbags in the 2020 NCAP results, although the 2020 results were significantly lower than the 1980 HIC_{15} ($t = 3.12$, $p < 0.05$). The 1980 and 1990 NCAP tests used the 50th Part 572 dummy. The 2000 NCAP used the 50th Hybrid III dummy. The 2010 and 2020 tests used a 5th Hybrid III dummy.

Figure 10 shows the passenger chest acceleration by decade. Chest acceleration was consistently managed with seatbelts as newer model vehicles incorporated sophisticated restraint systems. By 2000, the NCAP test used the 50th Hybrid III dummy, which added measurements of chest deflection. The deflection was 29.7 ± 4.5 mm. By 2010, NCAP used the 5th Hybrid III in the passenger seat. The chest deflection was 18.7 ± 4.3 in 2010 and 14.1 ± 3.0 mm in 2020. The difference between the 2010 and 2020 responses was not significant ($t = 1.91$, NS). Table 1 shows the front passenger, HIC_{15} dropped 68 ± 52% from the 1980 to 1990 NCAP tests and plateaued to 71 ± 49% in 2020. The passenger 3 ms chest acceleration dropped 13 ± 5% from 1980 to 1990 and has fluctuated with minimal change over 30 years.

Trends in passenger risk estimations in NCAP tests

Figure 11 shows the passenger head injury risk based on HIC_{15}. The 1980 vehicles had an injury risk of 17.9%

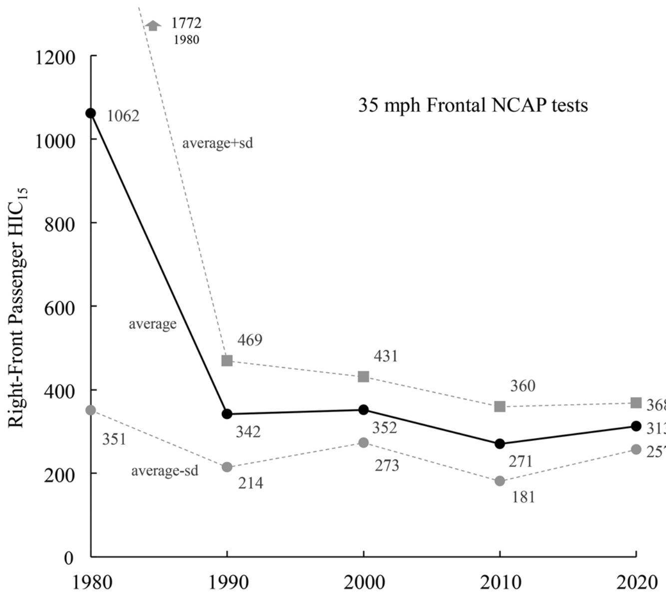

Figure 9. Passenger HIC_{15} by decade for selected NCAP tests.

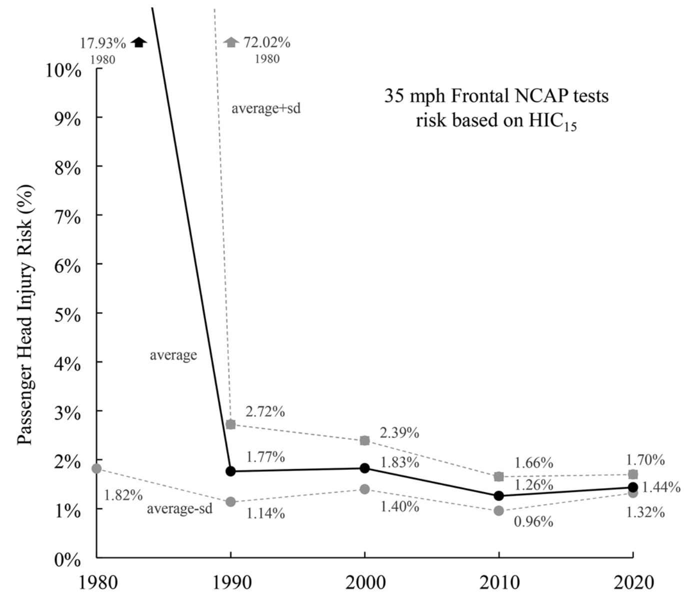

Figure 11. Passenger head injury risk based on HIC_{15} by decade for selected NCAP tests.

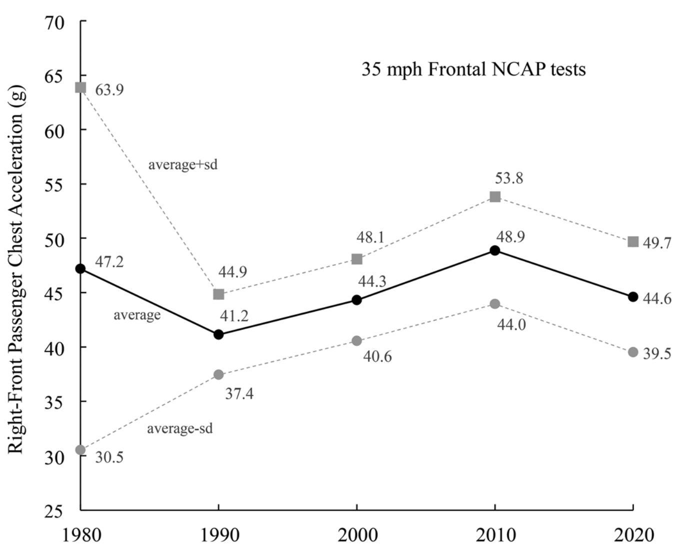

Figure 10. Passenger chest acceleration by decade for selected NCAP tests.

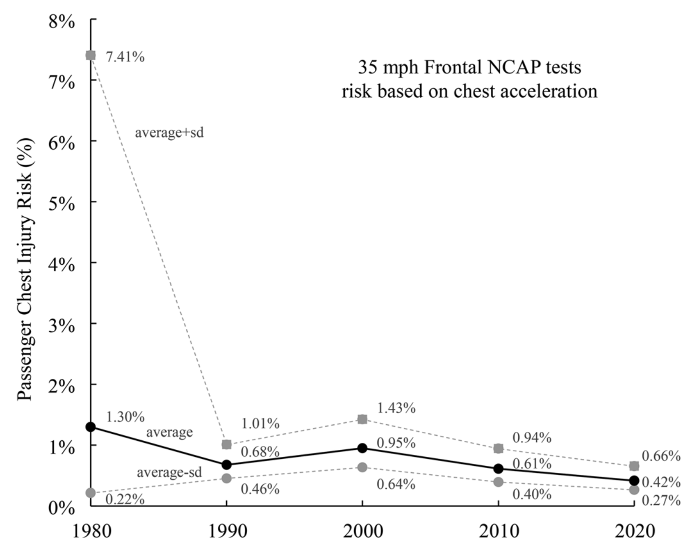

Figure 12. Passenger chest injury risk based on chest acceleration by decade for selected NCAP tests.

(1.82–72.0%). The risk dropped below 2%, on average, with vehicles from 1990 to 2020. The 1980 head injury risk was not significantly different from the 1990 risk ($t = 2.23$, NS). Figure 12 shows the passenger chest injury risk based on chest acceleration. There was large variability in chest acceleration in the 1980 NCAP tests. The responses were controlled in the 1990–2020 vehicles. The average risk was similar over the past four decades based on chest acceleration. There was no statistical difference in passenger chest acceleration from 1980 to 2020 NCAP tests ($t = 0.44$, NS) or 2000 to 2020 NCAP tests ($t = 0.17$, NS).

Field data for frontal crashes

Figure 13 shows the risk for severe-to-fatal injury (MAIS 4 + F) from NASS-CDS. The data from Kahane (1994) is for MAIS 4 + F risk to belted drivers using the 1988–1991 NASS. The risks were 14.1% in 35–40 mph, 31.0% in 40–45 mph and 57.3% in 45+ mph delta-V crashes. The data from Viano and Parenteau (2022) is for belted occupants using 1994–2015 NASS. This includes mostly vehicles with airbags and manual seatbelts with pretensioners and load limiters. The risks were lower in high-severity crashes in the 1994–2015 NASS. The risks were 7.3 ± 3.2% in 35–40 mph, 15.1 ± 4.1% in 40–45 mph and 28.2 ± 4.8% in 45+ mph frontal crashes. The lower risk in the high-severity crashes is consistent with improved front-structures, lower firewall intrusion and refinements in the airbags, triggering and restraint systems in 1990+ MY NCAP test vehicles, although a causal relationship has not been determined. Figure 13 shows similar risks for MAIS 4 + F in 30–35 mph frontal crash in the 1988–1991 and 1994–2015 NASS. For

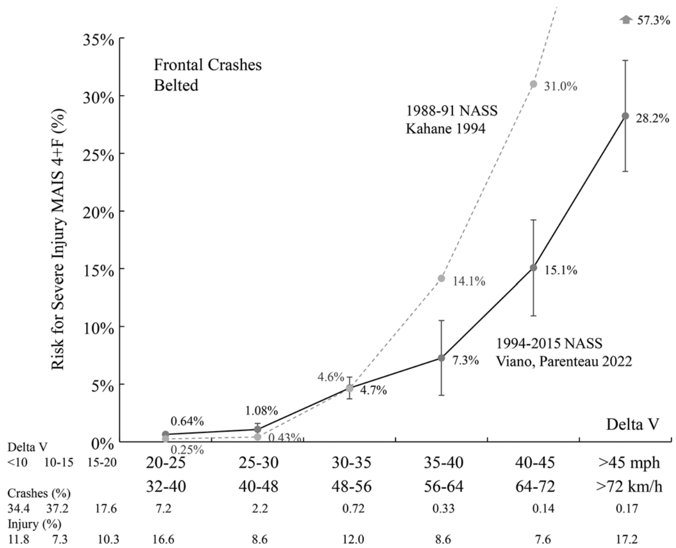

Figure 13. Risk for severe injury with belt use in frontal crashes by delta-V.

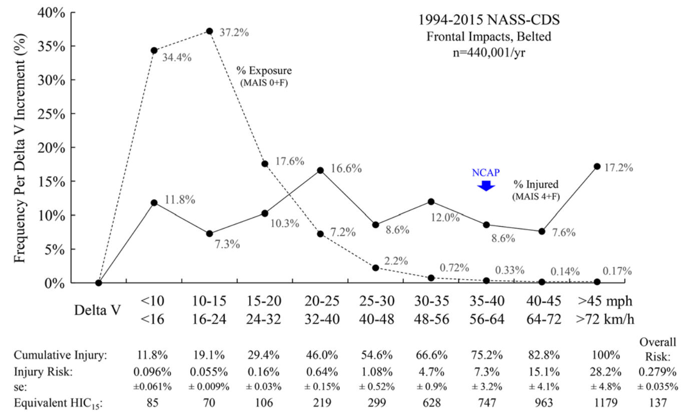

Figure 14. Frequency of frontal crash exposure and severe injury (MAIS 4+F) with injury risk and se and equivalent HIC_{15}.

lower severity crashes, the risks cross. The risk in the 1988–1991 NASS was lower than in the 1994–2015 NASS for 20–25 mph and 25-30 mph delta-V crashes.

Figure 14 shows the frequency of frontal crash exposure and severe injury (MAIS 4 + F) by delta-V increment. It complements the injury risks in Figure 13 and shows there are variations in the rate of serious injury. Table 2 provides the 1994–2015 NASS data in the left columns by delta-V in 5 mph increments. The number of occupants with known injury (MAIS 0 + F) provides the exposure and the number severely injured (MAIS 4 + F) gives the risk of injury by dividing the number injured by the number exposed. The weighted sample had an exposure of 9,680,020 wearing lap-shoulder belts with 27,045 severely injured MAIS 4 + F in the 1994–2015 NASS. The MAIS 4 + F risks in the 1994–2015 and 1988–1991 NASS are listed, where available.

Figure 14 shows the fraction of severely injured is uniformly distributed from 10 to 15 mph to 40–45 mph frontal crashes. The number injured is the result of decreasing exposure and increasing risk in frontal crash crashes with increasing delta-V. The severity of the NCAP test is shown at 35–40 mph delta-V. 66.6% of severe injury occurred in frontal crashes <35 mph delta-V. 46.0% occurred <25 mph and 29.4% occurred <20 mph delta-V. Frontal crashes <26 mph involve about half of all severe injury (MAIS 4 + F) to belted occupants in field accidents.

Figure 15 shows the risk for serious-to-fatal injury (MAIS 3 + F) to belted and unbelted drivers (top) and front passengers (bottom) by vehicle model year (MY). The risks are grouped by 1961–1989 MY, 1990–1999 MY, 2000–2009 MY and 2010–2021 MY vehicles. The risk for MAIS 3 + F injury is shown with the average ± one standard error based on weighted data. The percent belted in the exposure and injured occupants is shown at the bottom. For example, 30% of severely injured drivers were belted in 1961–1989 MY vehicles; whereas, 65% were belted in 2010–2021 MY vehicles.

For belted drivers, the risk for MAIS 3 + F was 1.66 ± 0.37% in 1961–1989 MY vehicles. It was 1.39 ± 0.33% in 2010–2021 MY vehicles. For belted front passengers, the risk was 1.52 ± 0.39% in 1961–1989 MY vehicles. It was 1.42 ± 0.46% in 2010–2021 MY vehicles. The field data does not show consistent trends in risk with newer vehicles despite design changes for 35 mph NCAP performance, other crash tests and the progression in occupant restraints. There are fluctuations in risk but the average risk is within ± one standard error indicating no statistical difference in risk by MY. There are several reasons for this finding.

Why field injury risks are not lower in newer MY vehicles

The following analysis was performed to demonstrate the effect of changes in field injury risk as vehicles were modified for better performance in the 35 mph NCAP. Table 2 and Figure 13 show the risk of severe injury in 35–45+ mph delta-V crashes was 1.94–2.06 times greater in the 1988–1991 NASS than in the 1994–2015 NASS. The risk was similar (0.94 times) in 30–35 mph crashes. However, the injury risk was lower (0.39–0.40) in the 1988–1991 NASS than in the 1994–2015 NASS for crashes <30 mph delta-V. The adjusted injury risks match the 1988–1991 NASS from Kahane (1994). For crashes <20 mph delta-V, the risk adjustment was assume 0.40.

If the adjusted risk is multiplied by the 1994–2015 NASS exposure, an adjusted injured count is provided for the 1988–1991 NASS. This hypothetical assumes the same exposure. It shows the number of injured was slightly higher in the 1988–1991 NASS. The overall risk was 0.281% in the adjusted 1988–1991 NASS compared to 0.279% in 1994–2015 NASS. The numbers of injured are close because there were 9,144 more injuries in high-speed crashes, but 8,959 fewer in low-speed crashes, giving only 185 more injuries in the adjusted 1988–1991 NASS, only 0.68% higher. This demonstrates that with large reductions in risk in high-speed crashes, like the 35 mph NCAP, it is possible to not realize large injury reductions when there are higher risks in low-speed crashes.

Table 2. 1994–2015 NASS field data for frontal crashes with belted use and adjustment to 1988–1991 NASS data from Kahane (1994).

Delta-V		1994–2015 NASS[a]			1988–1991 NASS				HIC$_{15}$ at field risk	
mph	km/h	MAIS 0+F	MAIS 4+F	Risk	Risk[b]	94–15 Adjusted to '88–91			'94–'15	'88–'91
				(%)	(%)	Risk	Injured	Difference		
<10	<16	3,326,077	3,193	0.096%	–	0.40	1,277	−1,916	85	63
10–15	16–24	3,602,537	1,972	0.055%	–	0.40	789	−1,183	70	54
15–20	24–32	1,702,959	2,779	0.163%	–	0.40	1,112	−1,667	106	74
20–25	32–40	700,966	4,493	0.641%	0.25%	0.39	1,752	−2,741	219	130
25–30	40–48	216,125	2,328	1.077%	0.43%	0.40	929	−1,399	299	173
30–35	48–56	69,244	3,239	4.677%	4.60%	0.98	3,186	−53	628	624
35–40	56–64	31,963	2,327	7.279%	14.1%	1.94	4,508	2,181	747	942
40–45	64–72	13,678	2,063	15.083%	31.0%	2.06	4,240	2,177	963	1215
>45	>72	16,471	4,651	28.240%	57.3%	2.03	9,437	4,786	1179	1517
	Overall	9,680,020	27,045	0.279%			27,230 0.281%[c]	185	137	138

[a]Viano, Parenteau (2022), [b]Kahane (1994) for crashes above 20 mph delta-V, [c]adjusted overall risk in 1988–1991 NASS.

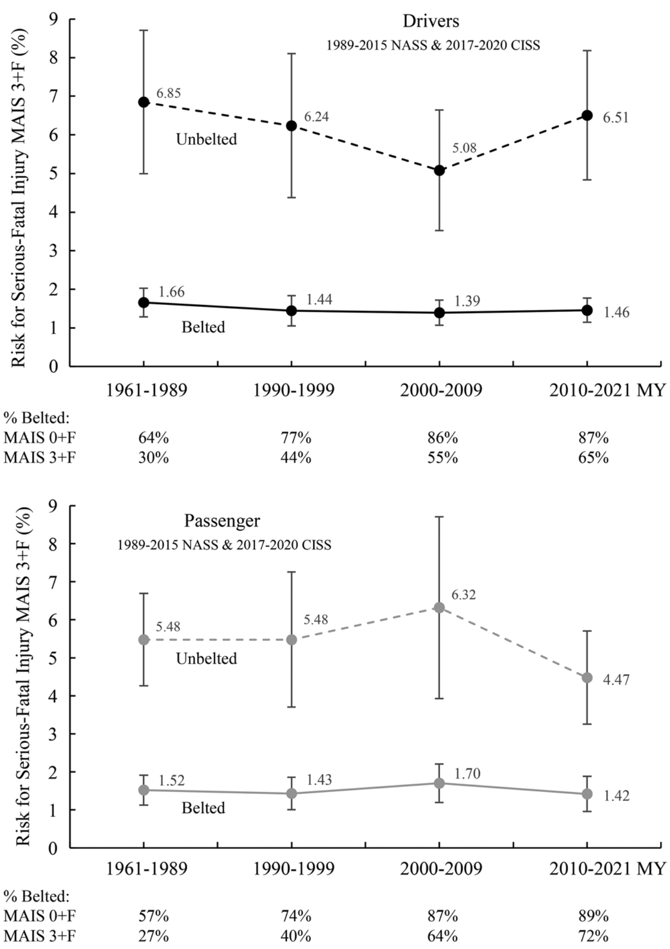

Figure 15. Risk for serious injury (MAIS 3+F) in belted and unbelted drivers (top) and passengers (bottom) by vehicle MY.

Discussion

Trends in vehicle dynamics in NCAP tests

The weight of small-midsize passenger cars has steadily increased since 1980. Figure 1 shows an increase of 435 kg (956 lb) from 1,290 ± 181 kg in 1980 to 1,727 ± 118 kg in 2020. This is, in part, related to the 35 mph NCAP, other consumer tests and regulations over the past 40 years. There were rapid changes in front structures of vehicles from the initial 1979–1983 NCAP tests with about 500 ± 50 mm of crush since 1990. There was better management of engine displacement to reduce firewall deformations. Intrusion of the firewall showed the most dramatic reduction with a steady decrease from 235.0 ± 117.9 mm in 1980 to 16.6 ± 17.5 mm in 2020 (Figure 4). Today, the occupant compartment is minimally deformed in NCAP tests because of modifications to frame elements, pillars and rails.

Trends in injury responses in NCAP tests

Figures 5 and 6 show the five decade trend in driver HIC$_{15}$ and chest acceleration in frontal NCAP tests. Table 1 shows the percent reduction in responses by decade. There was an initial drop in the 1990 responses and tightening in the variability among the vehicles, which were designed for the 35 mph NCAP tests. However, the responses have been constant from 1990 to 2020 without significant reductions. Figures 9 and 10 show plateauing of the injury responses from 1990 to 2020. The same plateauing is seen the risks of injury when the injury responses are converted to risk. Figures 7 and 8 show injury risk dropping for the driver HIC$_{15}$ and plateauing with the introduction of airbags and belt features. The risk of chest injury plateaued from 1990 to 2020 after an initial drop. The plateauing in risk is seen when the passenger HIC$_{15}$ and chest acceleration were converted to risk. The past four decades of NCAP testing merely has the manufacturers "tuning" the restraint system to achieve star ratings with only small changes in risk in the 39 mph delta-V NCAP-type crash.

Risk of serious injury in frontal crashes

Figure 15 shows the risk of MAIS 3+F for belted and unbelted drivers and front passengers by MY of the vehicle using 1989–2015 NASS-CDS and 2017–2021 CISS. Several studies have shown the 35 mph NCAP tests represents a very small fraction of frontal crashes. Lavelle (2001) used the 1995–1999 NASS and determined the 35 mph NCAP represented only 0.2% of frontal crashes and only 1.3% of HARM. This was for 55.0 ± 2.5 km/h (34.2 ± 1.5 mph) delta-V crashes. Since the NCAP delta-V is about 39 mph (63 km/h), a higher delta-V group 60.0 ± 2.5 km/h (37.3 ± 1.5 mph) should have been used by Lavelle (2001). The frequency and % Harm was about half that in the 55.0 km/h crashes.

Figure 14 shows the NCAP test represents a very small fraction of the exposure to frontal crashes. The 1994–2015 NASS field data shows that 35–40 mph delta-V crashes represent only 0.33% of exposed and 8.6% of severely injured occupants. Only 0.64% of frontal crashes are more severe than 35 mph delta-V. This means 99.34% of frontal crashes involve less than 35 mph delta-V with 96.4% less than 25 mph delta-V. The overall risk was 0.279 ± 0.035% for frontal crashes with seatbelt use. The overall risk is heavily weighted by crashes less than 39 mph with half of the MAIS 4 + F injuries occurring up to 26 mph delta-V.

Why injury risks are not lower in newer MY vehicles

The lack of meaningful change in injury risks in 50 MYs of vehicles with belted drivers and front passengers is a conundrum given the refinements in vehicle structures and restraints. The 1980 NCAP tests brought about vehicle changes leading to advanced airbags and sophisticated belt systems restraining the occupant in a reinforced occupant compartment during controlled front crush in a crash. Front crush typically occurs in structures forward of the firewall and the pillars and rails of the occupant compartment have been strengthened to reduce compartment deformation while reducing rearward displacement of the steering system and other components into the interior. These changes were obvious in the 1990–2000 NCAP tests resulting in more control of occupant responses with less variability among vehicles. However, field data on the risk for MAIS 3 + F injury in frontal crashes shows essentially no difference for belted or unbelted occupants in 50 MYs of vehicles.

Horsch (1987) noted that real world injuries are distributed uniformly across a wide range of crash severities. He pointed out that safety evaluations for the NCAP test involve a high severity crash, which has high risks for injury but low exposure frequency. Little or no evaluation was directed toward low-to-moderate severity crashes, which have low risk of injury but high exposure frequency. Low-to moderate severity crashes resulted in a large fraction of the total injury. For example, Figure 14 shows 46.0% of serious injury occurs below 25 mph delta-V, 54.6% occurs below 30 mph and 75.2% occurs below 35 mph delta-V. Most of the occupant injury occurred in lower speed crashes than the 35 mph NCAP, which results in about a 39 mph delta-V.

Horsch (1987) laid out a method to evaluate occupant protection using an injury risk function to interpret responses and consider exposure frequency producing an expected injury distribution over a range of crash severities that mimic real-world crashes. Viano (1991) further developed the method by compare the performance of baseline and modified safety systems over the range in crashes to balance a system design for very strong and very weak tolerances in the population. This approach is necessary to achieve a meaningful reductions in injury in field accidents.

The hypothetical analysis in Table 2 demonstrates why there may be no significant change in risk of MAIS 3 + F injury in frontal crashes for more than 20 years. While there were reductions in injury related to 35 mph NCAP performance improvements, the changes are only effective in 0.64% of frontal crashes > 35 mph delta-V. The reductions were offset by increased injury in lower-speed crashes. Even modest increases in risk in lower-speed crashes have an effect, because they apply to 99.36% of frontal crashes.

Figures 13 and 14 and Table 2 show injury risks are low in low-speed frontal impacts. The risk for MAIS 4 + F with seatbelt use was 0.163 ± 0.030% in 15–20 mph, 0.641 ± 0.147% in 20–25 mph, 1.077 ± 0.518% in 25–30 mph and 4.677 ± 0.931% in 30–35 mph delta-V frontal crashes. The low risk is consistent with many occupants not being severely injured with belt use in low delta-V crashes. For example, the risk of 0.641% in 20–25 mph crashes means one severely injured occupant out of 156 (127–202 range) exposed. It is possible to assign a HIC_{15} value to the field injury risks by delta-V. The last two columns in Table 2 show the equivalent HIC_{15} for the risks in the 1988–1991 NASS and 1994–2015 NASS. The risks were calculated using the more complex risk function for HIC_{15} that converges to zero risk (Berkowitz 2001). It shows that most field injuries occur with an equivalent HIC_{15} <300. The average risk in a frontal crashes has an equivalent HIC_{15} of only 137. This is in an area of HIC_{15} with minimal to no biomechanical data on injury. Prasad and Mertz (1985) and Mertz et al. (1996) had only three head impact tests with HIC_{15} <300 without brain injury or skull fracture.

"Tuning" designs for 35 mph NCAP performance

There are implications of focusing on a single, high-speed crash test that can reduce injuries in a narrow range of crashes but cause more injuries in lower-speed crashes because of stiffening structures and restraints. In the case of front impact, as structures are stiffened there is less intrusion and less risk of injury from intruding structures or components. The crash pulse stiffens with a shorter duration and higher deceleration. The amount and rate of energy transferred to the occupant increases. For crashes in the NCAP velocity range, there is a tradeoff between injury from intrusion and injury from crash pulse severity. However, stiffening the vehicle increases the severity of the crash and increases the risk for injury at lower velocities. Given the results in this paper, the tradeoff should not be considered for a single velocity but across the full spectrum of crash severities.

The 35 mph NCAP involves one test severity, one sized dummy in the front seats, one adjusted position of the seat and one seating position. NCAP involves a very small fraction of the real-world conditions in 35–40 mph delta-V crashes. Bean (2009) showed the complexity of fatalities in frontal crashes with belts and airbags in 2000–2007 MY vehicles. The circumstances did not mimic the 35 mph NCAP. There is also the known limitation that revising the methods and criteria cause manufacturers to "re-tune" the restraints for the new criteria. This type of "re-tuning" does not change the overall injury risk in frontal crashes based on the analysis here. NHTSA achieved almost everything it could for driver and front passenger safety in the first years of the 35 mph NCAP. The test drove modifications in vehicle structures and restraints with advanced airbags and sophisticated seatbelt systems by 2000; however, nothing meaningful has changed the past 20 years, except "tuning" the restraints for star ratings that lack field relevance.

Possible changes in NCAP

The lack of meaningful change in NCAP responses over the past 20 years makes it obvious that NHTSA should reevaluate how it upgrades NCAP. Efforts to refine injury criteria with Bric and use the Thor dummy in the driver or front passenger seat seem to follow the same process as in the past and is most likely to produce the same lack of relevant results in field accidents. Their proposed changes and additions are misguided. Switching to Thor and adding Bric will have no effect, or degrade safety in field accidents (Brumbelow et al. 2022; Prasad et al. 2024). Vehicles are already highly "tuned" to the 35 mph NCAP test with dual pretensioners, load-limiting shoulder belt and airbag inflation optimized for the NCAP test.

It is inappropriate to make changes to NCAP without a meaningful benefit to motor-vehicle safety. It is unlikely changing to Thor and BrIC could have valid support in a cost-benefit calculation. From what has been published recently, the change may lead to disbenefits in safety (Brumbelow et al. 2022; Prasad et al. 2024). In addition, it is illogical for a rotational head injury criterion not to include a time duration component. BrIC is related to the weighted sum of three peak rotational velocities that occur at different times in orthogonal axes of the head. At least, the Nij tracks the different components in time before giving a peak response.

The concept of BrIC is nonsensical, irrespective of the tolerances proposed (Prasad et al. 2024). NHTSA has provided no theoretical foundation or biomechanical principle for the BrIC formula (Appendix E). Since HIC is related to head translational acceleration raised to the 2.5 power multiplied by duration, it is likely one type of rotational injury criterion is related to head rotational acceleration raised to the 2.5 power multiplied by duration for short < 15 ms duration head impacts. This would take into consideration that head impacts involve a moment arm (radius) about the neck. Viano et al. (2005) found boxers delivered punches with proportionately more rotational than translational head acceleration than head impacts in football. Boxing punches had a 65 mm effective radius from the head cg, which was almost double the 34 mm in football. This type of calculation is based on the strong correlation between translational and rotational acceleration in head impacts. A valid rotational head injury criterion for long duration accelerations (50–65+ ms) is unclear.

One area where NHTSA should consider adding responses is in the lumbar spine. Field accident studies have identified an increase in lumbar and thoracic spine fractures in belt restrained occupants in frontal crashes (Richards et al. 2006, Kaufman et al. 2013). Tang et al. (2020) found the anti-submarining ramp and seat structures were a significant factor causing force in the lumbar spine. No one has studied how compressive loads and moments have changed as the restraint system and seat designs have changed the past 20 years.

Another area is the reporting of HIC_{15}, which lacks a basis to assess head injury risks with belt and airbag restrained occupants in frontal NCAP tests. The duration of head acceleration in 2000, 2010 and 2020 NCAP tests is more than 50–65 ms. HIC_{15} addresses head impacts with short duration less than 15 ms; it does not address long duration head accelerations. The average HIC_{15} was 266 ± 143, HIC_{36} was 415 ± 159 and the peak head acceleration was 53.9 ± 10.0 g for the 15 NCAP tests from 2000–2020 (Table A2). Prasad and Mertz (1985) reported the HIC, duration and peak acceleration for the head impacts used to develop skull fracture risk functions. The HIC was 1142 ± 706, duration was 4.0 ± 2.3 ms and average head acceleration was 158 ± 52 g. They summarized the Nahum and Smith (1976), Nahum et al. (1976) tests, which had HIC of 942 ± 801, duration of 2.4 ± 1.1 ms and average acceleration of 173 ± 62 g. There were no brain injuries in the Nahum, Smith tests. They also summarized the APR head impact tests, which had HIC of 1208 ± 440, duration of 6.7 ± 2.7 ms and average acceleration of 132 ± 37 g. Twelve of the 25 tests had AIS 3+ brain injury. The lowest brain injury had HIC of 516, 10.1 ms duration and 76 g average acceleration. The biomechanical data used to develop head injury risk functions and IARV had durations typically <10 ms (3 tests had duration of ≥ 10 ms with the longest 13.7 ms). NCAP tests over the past 20 years have involved > 50–65 ms durations of head acceleration. There is no database of head injury research with accelerations > 50 ms in duration.

In conclusion, the NCAP test lacks field relevance and manufacturers have merely tuned the restraint systems for star ratings without meaningful changes in occupant responses or field injury over the past 20 years. There can be disbenefits of tuning safety for a single, high-severity crash when most of the severe injury occurs at lower severities. NCAP represents only 0.64% of exposed occupants with >35 mph delta-V in frontal crashes. The test has unknown effects in 99.34% of crashes at lower severities. NHTSA should reevaluate the planned change to the Thor dummy and addition of the BrIC injury criteria to assess NCAP responses. The changes would cause manufacturers to further fine-tune the restraints without meaningful effects in real-world crashes.

Limitations

There are limitations to the study of NCAP tests and field accident injury. First, there is variability in the measurement of vehicle crush and firewall intrusion among the test facilities and from test-to-test. Based on the Mackey and Gauthier (1984), the variability (CV) in HIC_{15} was 26% for the driver and 32% for the front passenger. The variability in 3 ms chest acceleration was 10% for the driver and 7% for the passenger. The variabilities are large in comparison to response differences each decade.

Second, the statistical comparisons involve the t-test in Excel assuming unequal variance. The unequal variance was used because the F-test between NCAP responses from different decades had $p<0.05$. For example, the driver HIC_{15} in 1980 was compared to 2020 giving $F=29.9$, $p<0.005$. The variability between tests and test facilities needs to be considered in the comparison of NCAP responses by decade. It makes comparisons between decades difficult and is a factor in the significance of differences in responses and relevance to field injuries.

Third, there are other measurements of intrusion, such as displacement of the footwell, pedals etc. that were not included. They might add insights on vehicle deformation trends not reported here.

Fourth, there were changes in the dummy used in NCAP tests. The initial tests used the 50th Part 572. NCAP shifted to the 50th Hybrid III and eventually used the 5th Hybrid III in the passenger seat. The dummy influences NCAP response comparisons that are not accounted for in this study. Prasad (1990) conducted matched tests with the Part 572 and Hybrid III. The initial sled tests involved an inertially locking lap-shoulder belt. He found the Hybrid III had higher HIC_{36} and chest acceleration than the Part 572 dummy, and the CV was lower with the Hybrid III than the Part 572 dummy. Sled tests with belts and airbag resulted in comparable responses. HIC_{15} was not reported.

Fifth, the early studies published by NHTSA showed drops in NCAP responses between 1980 and 1990 tests, but none of the studies included standard deviations in the response comparisons. For example, Figure 4 in Hackney et al. (1994) showed percent reductions in driver HIC between 1979–1986 MY and 1987–1993 MY passenger cars in NCAP tests by manufacturers. They reported a 9.5% reduction in HIC for GM vehicles with a drop from 897 to 812. No standard deviations were reported. If the 26% test variability in NCAP tests for the driver HIC is used, the difference was 897 ± 233 to 812 ± 211. The 85 unit drop in HIC is within the test-to-test variability.

Sixth, the sample size of 31 NCAP tests spanned five decades and involved a minimum of five vehicles per decade, one for each of five manufacturers of small-midsize passenger cars. A larger sample was possible, but the focus on a vehicle model from five manufactures was believed to give ample perspective on trends in NCAP responses.

Seventh, NHTSA collects field data in NASS-CDS by a prospective selection of crashes, which are weighted to a nationally representative sample of towaway crashes in the U.S. The data is useful because injury severity is documented by body region and severity using the AIS classification. There have been changes in the collection methods and AIS classification. NASS-CDS no longer investigates vehicles over 10 year old limiting a full understanding of crashes and injuries in America (Viano 2024). For this study, all belted or unbelted drivers and front passengers were selected with known injury status to determine the risk for serious injury (MAIS 3+F). There was no effort to select a subset of small-midsized passenger cars.

Eight, the 1980 baseline tests involved passenger cars weighing < 1,500 kg. The term small-midsize was used. The designation of passengers cars by weight has varied. McLaughlin and Saul (1982) defined sub-compacts as weighing 977–1,205 kg and intermediate weighing 1,205–1,522 kg with standard weighing >1,522 kg. The small-midsize was meant to exclude large passenger cars in the 1980s.

Ninth, the delta-V reported in NASS-CDS comes from accident reconstruction software. Funk et al. (2008) found NASS underestimated delta-V when injury risks are estimated, but it overestimated delta-V when scatter was corrected. Hampton and Gabler (2009) evaluated the new version of WinSmash used in NASS-CDS and determined it increased delta-V by 7.9%. Gabler et al. (2004) compared delta-V from WinSmash and vehicle EDR. They found WinSmash underestimated longitudinal delta-V by 20% in single-event collisions of GM vehicles with airbag deployment. The delta-V in NASS was used to sort injuries. No effort was made to adjust the delta-V.

Tenth, MAIS 4+F injury was used to determine injury risks by delta-V because it focuses on life-threatening injury. Viano and Parenteau (2018) found the risk of belted driver death was $17.4 \pm 3.4\%$ with MAIS 4, $39.6 \pm 9.5\%$ with MAIS 5 and $99.7 \pm 16.3\%$ with MAIS 6 injury. The fatality risk was only $2.99 \pm 0.50\%$ with MAIS 3 injury, which includes many musculoskeletal injuries to the extremities that are important but not life-threatening.

Acknowledgments

The author was a proponent of the 35 mph NCAP test. Vehicle manufacturers reacted to the poor performance in the 1980 NCAP tests and improved vehicle structures and restraints, leading to sophisticated manual lap-shoulder belts and airbags. He felt NCAP was the crown jewel of Joan Claybrook's tenure as NHTSA Administrator. This study came about because he wanted to look at what happened the past 40 years in NCAP tests. The study provides his perspective; others may have different views. While the initial ambitions of the 35 mph NCAP were laudable, some recent proposed changes in methods seem self-serving efforts that have no real-world safety benefit. The agency has failed to reach consensus on the need for Thor and BrIC and ignores scientific criticism. Virtually none of the NHTSA papers address the criticisms of others. The author avoided the topic of Thor and BrIC in his research, but he has tracked the exchanges. His views are as a bystander, although an Editor publishing research on traffic injury prevention. Appendix E summarizes issues with BrIC. The NASS-CDS and CISS data run was conducted by Dr. Chantal Parenteau for MAIS 3+F injury in frontal crashes.

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Data availability statement

The crash test movies, data and reports are available from the NHTSA website (https://www.nhtsa.gov/research-data/research-testing-databases#/) using the test number (#) as a guide. Additional information on the data analysis can be requested of the author at dviano@comcast.net.

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Appendix A

Table A1: NCAP crash tests with selected small-to-midsize passenger cars.

DOT #	Date	MY	Vehicle	Gen	Model Run	Restraints	VIN	Weight kg	Impact km/h	Crush mm	Intrusion mm	Delta V km/h
5	6/12/79	1980	Chevrolet Citation	1st	80-85	MB	1X687AT117457	1,482	56.3	543.6	205.7	--
7	7/10/79	1979	VW Rabbit	1st	74-82	PB	1793857442	1,182	56.0	576.6	243.8	--
27	7/16/79	1979	Toyota Celica	2nd	77-81	MB	RA42-203271	1,375	56.0	614.7	175.3	--
35	5/24/79	1979	Datsun 210	4th	79-82	MB	HLB310219271	1,102	56.7	637.5	561.3	--
64	9/7/79	1979	Chevrolet Monza	1st	75-80	MB	IM07V97242698	1,473	56.4	647.7	210.8	--
73	9/17/79	1979	Chevrolet Chevette	1st	76-87	PB	lB68E9Y169671	1,235	56.0	556.3	182.9	--
92	9/12/79	1979	Ford Fairmont	1st	78-83	MB	9X92T264838	1,500	57.0	635.0	231.1	--
94	10/15/79	1979	Honda Civic	2nd	79-83	MB	SBA-7089830	985	55.9	530.9	200.7	--
452	6/15/82	1984	Ford Escort	1st,a	81-84	MB	1FABP0623CW146915	1,175	55.6	579.1	190.5	61.1
661	12/2/83	1984	Cavalier Convertible	1st	82-87	MB	1G1AE67P7E7102611	1,414	56.3	579.1	147.3	62.7
							average	1,292	56.2	590.0	235.0	
							sd	181	0.4	41.4	117.9	
997	3/4/87	1987	Ford Escort	1st,b	85-90	PB	1FAPP2095HT140209	1,245	55.9	553.7	106.7	61.9
1013	4/9/87	1987	Toyota Camry	V20	86-92	PB	JT2SV21E4H3057983	1,477	56.3	487.7	127.0	66.8
1288	3/14/89	1989	Honda Civic	3rd	88-93	MB	JHMED8361KS00849	1,047	55.7	495.3	94.0	--
1353	6/27/89	1989	Nissan Maxima	3rd	88-93	PB	JN1HJO1P2KT236374	1,659	55.5	541.0	61.0	60.0
1440	5/4/90	1990	Chevrolet Cavalier	2nd	88-94	PB	1G1JC54GXL7101163	1,391	56.3	665.5	215.9	61.1
1690	2/13/92	1992	Toyota Camry	V30	90-94	MB, DA	4T1SK12E3NU030378	1,636	56.0	622.3	15.2	60.3
							average	1,409	56.0	560.9	103.3	62.0
							sd	235	0.3	70.5	67.7	2.8
2993	12/18/98	1999	Honda Civic	6th	96-00	MB, AA	1HGEJ6124XL005430	1,259	56.6	552.0	146.0	65.3
3251	1/14/00	2000	Toyota Camry	XV20	96-02	MB, A, PT	4TlBG22K9YU922698	1,656	56.5	518.9	12.1	--
3295	3/22/00	2000	Ford Focus	1st	98-06	MB, AA, PT	1FAFP33P6YW269330	1,429	56.3	505.0	51.0	61.0
3566	12/18/98	2001	Chevrolet Malibu	1st	98-06	MB, AA	1G1ND52J716184616	1,608	55.6	563.0	126.0	61.0
4719	9/3/03	2004	Nissan Maxima	6th	04-08	MB, AA, PT	1N4BA41E44C841028	1,808	55.8	491.0	12.0	66.5
							average	1,552	56.2	526.0	69.4	63.5
							sd	212	0.4	30.7	63.2	2.8
6953	6/24/10	2011	Toyota Camry	XV50	11-19	MB, AA, PT*	4T4BF3EKXBR112045	1,693	56.0	507.0	50.0	63.0
6998	8/25/10	2011	Chevrolet Malibu	7th	08-12	MB, AA, PT	1G1ZB5E10BF110751	1,760	56.5	509.0	79.0	65.6
7536	11/30/11	2012	Nissan Maxima	7th	09-15	MB, AA, PT	1NA445AP0CC808948	1,815	56.3	432.0	52.0	60.6
8156	2/27/13	2013	Honda Civic	9th	12-15	MB, AA, PT	2HGFG3B58DH500796	1,437	56.2	483.0	30.0	68.5
9086	2/13/15	2015	Ford Focus	3rd	10-17	MB, AA, PT, K	1FADP3F27FL200555	1,760	56.6	393.0	18.0	--
							average	1,693	56.3	464.8	45.8	64.4
							sd	150	0.3	50.7	23.3	3.4
9763	6/15/16	2017	Ford Fusion	4th	17-	MB, AA, PT, K	3FA6P0T93HR104516	1,865	56.2	441.0	0.0	65.3
10146	10/3/17	2018	Toyota Camry	XV70	17-24	MB, AA, PT	JTNB11HK8J3028996	1,719	56.3	535.0	13.0	66.8
10191	12/14/17	2018	Honda Accord	10th	18-22	MB, AA, PT, K	1HGCV1F12JA010000	1,600	56.3	498.0	44.0	64.9
10914	11/18/19	2020	Chevrolet Malibu	9th	16-	MB, AA, PT, K	1G1ZB5STXLF009126	1,625	56.2	457.0	4.0	65.2
10963	12/12/19	2020	Nissan Maxima	8th	16-	MB, AA, PT, K	1N4AA6BV9LC361538	1,826	56.3	529.0	22.0	66.7
							average	1,727	56.3	492.0	16.6	65.8
							sd	118	0.0	42.1	17.5	0.9

*passenger pretensioner did not fire

Notation: MB-manual belts, PB-passive belts, DA-driver airbag only, AA-advance airbags, PT-pretensioner(s), K-knee airbag.

Table A2: Driver Responses in selected NCAP crash tests.

DOT #		Driver HIC	HIC36	HIC15	Head g	Nij	Tension	Chest 3ms	Defl	L Femur	R Femur
					g		N	g	mm	N	N
5	Part 572	846	846	539	79.0	--	--	48.0	--	560	760
7	Part 572	1024	1024	963	90.0	--	--	67.0	--	1,170	630
27	Part 572	849	849	506	94.0	--	--	61.0	--	2,920	435
35	Part 572	1312	1306	971	92.0	--	--	76.0	--		536
64	Part 572	1107	1094	1063	103.0	--	--	42.0	--	580	400
73	Part 572	872	868	868	118.0	--	--	47.0	--	1,280	1,600
92	Part 572	941	941	677	102.0	--	--	54.0	--	825	1,155
94	Part 572	2029	2029	1476	116.0	--	--	92.6	--	1,080	838
452	Part 572	950	950	950	234.0	--	--	50.8	--	5,560	5,560
661	Part 572	884	884	651	152.0	--	--	45.9	--	3,781	3,470
	average	1081	1079	866	118.0			58.4		1,973	1,538
	sd	363	363	290	45.5			16.0		1740	1683
997	Part 572	553	552	466	104.0	--	--	44.0	--	4,893	4,493
1013	Part 572	910	871	546	76.0	--	--	50.8	--	5,338	6,139
1288	Part 572	753	750	713	128.3	--	--	39.0	--	1,606	4,017
1353	Part 572	889	808	426	70.8	--	--	51.1	--	2,718	2,952
1440	Part 572	770	770	669	141.1	--	--	49.1	--	3,447	7,780
1690	50th H3	403	390	277	55.6	--	--	52.6	27.9	2,900	2,729
	average	713	690	516	96.0			47.8		3,484	4,685
	sd	198	182	162	34.1			5.2		1,406	1,950
2993	50th H3	431	428	282	53.6	--	1628	47.1	34.5	4,788	4,092
3251	50th H3	525	525	387	63.5	--	1121	46.6	24.1	3,038	3,281
3295	50th H3	725	725	539	69.3	--	1221	44.3	39.4	4,770	3,165
3566	50th H3	725	725	539	72.2	--	1977	53.4	28.1	4,292	3,717
4719	50th H3	300	272	152	44.6	--	899	44.1	20.5	1,228	926
	average	541	535	380	60.6		1,369	47.1	29.3	3,623	3,036
	sd	186	196	167	11.4		430	3.8	7.7	1,517	1,236
6953	50th H3	521	521	405	63.8	0.40	1714	40.5	23.6	1,923	2,520
6998	50th H3	393	385	223	50.8	0.20	842	44.5	22.8	255	2,363
7536	50th H3	390	295	127	45.4	0.30	1133	47.0	25.0	3,802	3,962
8156	50th H3	244	151	74	39.4	0.37	1540	43.5	25.7	2,353	1,563
9086	50th H3	357	357	201	48.2	0.31	1065	50.5	11.7	745	1,111
	average	381	342	206	49.5	0.32	1,259	45.2	21.7	1,816	2,304
	sd	99	135	126	9.0	0.08	358	3.8	5.8	1,399	1,092
9763	50th H3	377	373	234	51.2	0.32	875	40.8	17.5	1,032	1,574
10146	50th H3	303	268	140	45.8	0.20	1167	41.3	23.2	1,923	2,345
10191	50th H3	427	421	261	59.8	0.23	819	50.4	18.0	1,027	1,503
10914	50th H3	356	342	172	43.6	0.18	963	50.4	24.3	1,123	1,362
10963	50th H3	457	439	252	57.6	0.25	1286	45.0	16.0	1,597	1,058
	average	384	369	212	51.6	0.24	1,022	45.6	19.8	1,340	1,568
	sd	60	68	53	7.1	0.05	198	4.7	3.7	402	477

Table A3: Front passenger responses in selected NCAP crash tests.

		Right-Front Passenger									
DOT #		**HIC**	**HIC36**	**HIC15**	**Head g**	**Nij**	**Tension**	**Chest 3ms**	**Defl**	**L Femur**	**R Femur**
					g		N	g	mm	N	N
5	Part 572	623	560	375	64.0	--	--	34.5	--	1,040	350
7	Part 572	429	328	199	47.0	--	--	33.0	--	937	1,460
27	Part 572	1864	1864	1864	158.0	--	--	59.0	--	400	520
35	Part 572	1847	1847	1847	88.0	--	--	59.4	--	791	218
64	Part 572	1030	998	814	87.0	--	--	41.0	--	600	325
73	Part 572	859	719	716	88.0	--	--	45.0	--	690	1,400
92	Part 572	1585	1585	1428	94.0	--	--	85.0	--	1,245	600
94	Part 572	2095	2095	2095	142.0	--	--	46.0	--	1,520	1,460
452	Part 572	1070	1070	1046	96.0	--	--	39.8	--	6,708	6,690
661	Part 572	401	316	231	125.0	--	--	29.3	--	1,957	1,690
	average	1180	1138	1062	98.9			47.2		1,589	1,471
	sd	627	668	711	33.9			16.7		1857	1918
997	Part 572	550	418	221	48.5	--	--	43.0	--	2,002	2,669
1013	Part 572	1128	**973**	550	71.0	--	--	46.0	--	5,191	5,160
1288	Part 572	629	520	288	56.6	--	--	36.8	--	3,519	1,668
1353	Part 572	877	736	408	70.3	--	--	43.8	--	6,268	4,638
1440	Part 572	641	485	218	51.9	--	--	37.4	--	2,360	3,960
1690	50th H3	810	650	366	60.8	--	601.0	39.9	35.6	1,210	1,335
	average	773	630	342	59.9			41.2		3,425	3,238
	sd	213	204	127	9.3			3.7		1,963	1,586
2993	50th H3	709	696	470	68.1	--	2218	46.9	36.8	3,485	4,125
3251	50th H3	429	429	282	56.8	--	1109	37.8	28.1	2,681	1,765
3295	50th H3	507	501	306	48.1	--	1341	45.9	30.0	5,271	5,758
3566	50th H3	507	501	306	57.9	--	1641	46.5	29.0	4,540	1,587
4719	50th H3	640	637	396	45.7	--	1095	44.5	24.6	2,294	362
	average	558	553	352	55.3		1,481	44.3	29.7	3,654	2,719
	sd	113	110	79	8.9		468	3.8	4.5	1,247	2,177
6953	5th H3	476	475	378	64.7	0.65	953	45.6	25.0	2,261	2,274
6998	5th H3	338	304	172	45.0	0.67	1005	45.9	21.1	1,412	1,320
7536	5th H3	490	490	348	60.2	0.77	3413	48.0	17.0	3,413	2,957
8156	5th H3	399	395	248	52.8	0.41	705	47.4	14.5	2,906	2,082
9086	5th H3	329	329	207	48.0	0.40	769	57.5	15.8	1,798	1,009
	average	406	399	271	54.1	0.58	1,369	48.9	18.7	2,358	1,928
	sd	75	84	89	8.2	0.17	1,149	4.9	4.3	811	777
9763	5th H3	528	528	400	63.6	0.65	1024	51.5	11.3	1,058	910
10146	5th H3	548	548	335	58.6	0.21	606	41.7	17.7	1,182	1,378
10191	5th H3	442	435	266	53.3	0.34	621	44.6	11.0	1,681	963
10914	5th H3	482	481	272	53.1	0.36	751	38.2	16.6	720	1,033
10963	5th H3	495	494	290	56.2	0.31	551	47.0	14.0	1,993	1,385
	average	499	497	313	57.0	0.37	711	44.6	14.1	1,327	1,134
	sd	41	44	56	4.3	0.16	190	5.1	3.0	508	230

Appendix B

Table B1: NCAP variability and repeatability tests

referred to in Machey, Gauthier (1984).

DOT #	Driver Reported values				Driver Recalculated			RFP Reported values				RFP Recalculated		
	HIC	Pk head (g)	Pk chest (g)	chest 3 ms (g)	HIC	HIC36	HIC15	HIC	Pk head (g)	Pk chest (g)	chest 3 ms (g)	HIC	HIC36	HIC15
474	748	234.0	47.1	40.6	748	748	563	--	200.3	--	--	--	--	--
475	672	288.5	53.4	50.5	673	672	517	715	89.5	32.5	31.3	715	686	511
477*	522	204.0	37.7	36.3	522	505	295	542	60.0	36.0	32.6	543	481	315
479	583	153.0	38.2	36.2	583	583	401	677	68.0	40.2	35.0	677	585	393
480*	851	158.0	42.4	38.7	543	481	315	767	56.0	38.4	36.4	767	648	307
481	954	259.0	53.3	47.1	954	954	525	950	68.2	38.7	37.1	950	805	478
482	619	178.5	47.7	44.1	619	619	495	696	94.3	32.4	31.0	696	548	317
483	789	154.6	46.0	42.4	789	789	607	630	61.2	34.0	32.7	630	552	278
486	593	293.1	49.8	43.8	593	564	406	793	148.7	36.0	34.2	793	739	496
492*	495	172.0	45.4	44.1	495	495	266	570	116.0	33.2	31.1	615	567	434
494**	618	219.1	42.8	41.6	618	618	507	770	218.1	33.6	32.5	770	665	572
495	771	223.0	40.7	38.1	771	771	592	722	61.2	34.8	33.1	722	560	310
545	--	--	--	--	546	546	457	--	--	--	--	484	336	173
552	567	206.5	48.4	36.9	567	547	289	644	147.7	39.8	36.9	644	533	253
Average	676	211.0	45.6	41.6	644	635	445	706	106.9	35.8	33.7	693	593	372
sd	137	48.1	5.1	4.4	129	137	117	109	55.5	2.8	2.2	118	119	118
CoV (%)	20%	23%	11%	10%	20%	21%	26%	15%	52%	8%	7%	17%	20%	32%

Notes: *noise on the head accelerations, **spike in head acceleration on rebound.

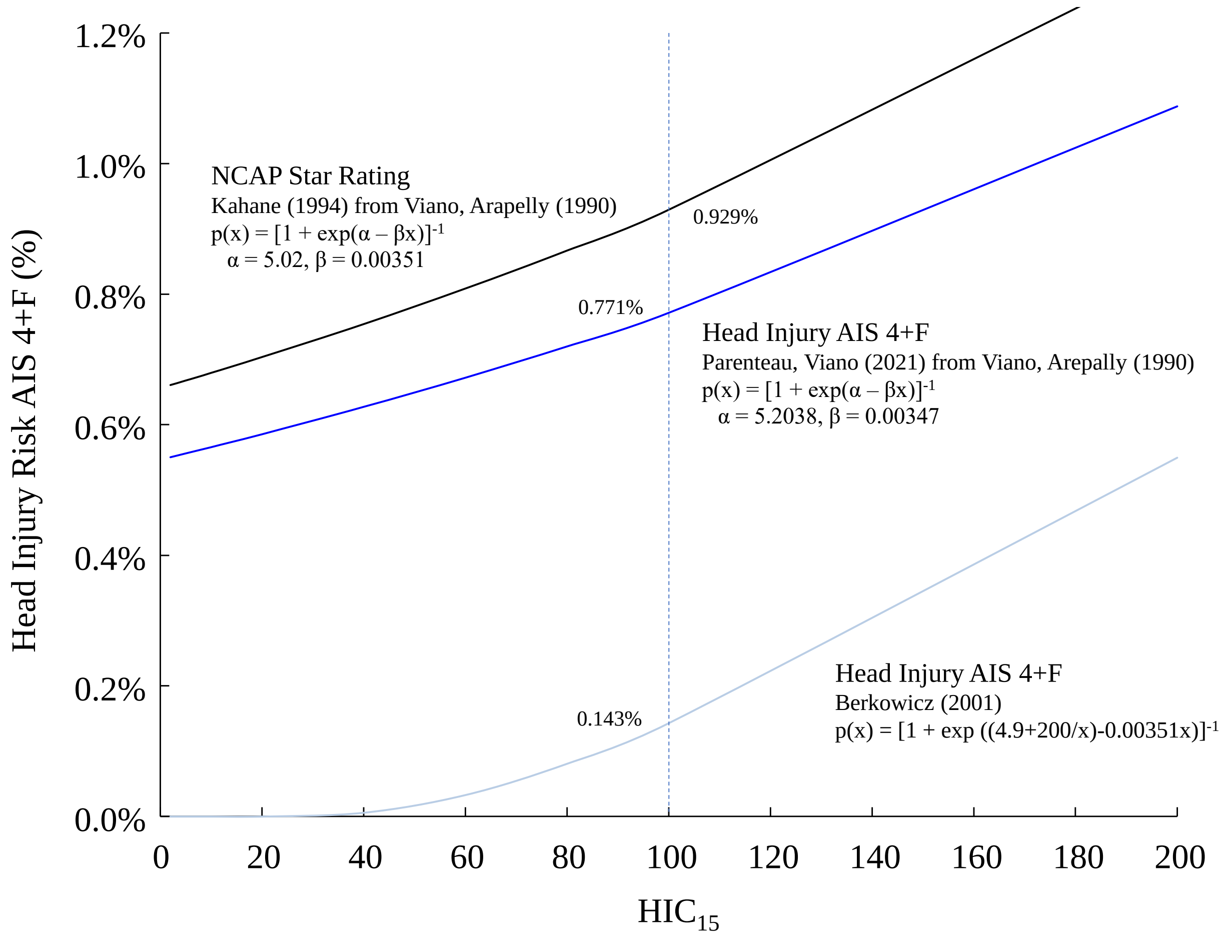

Figure C1: Head injury risk with $HIC_{15} < 200$ for three risk function for AIS 4+ injury. One Logist function was used by NHTSA to interpret risks (Kahane 1994, Libertiny 1995). It used the α and β parameters published by Viano, Arepally (1990). The other Logist function was an update by Parenteau et al. (2021) also based on the earlier study by Viano, Arepally (1990). The last function is from Berkowicz (2001). It is a modified Logist function with the parameter α replaced by $\alpha = (4.9 + 200/HIC_{15})$ with $\beta = 0.00351$, which is the β from Viano, Arepally (1990). The Berkowicz (2001) function approaches zero with HIC_{15} approaching zero. The other function approach a risk of 0.656% and 0.547%.

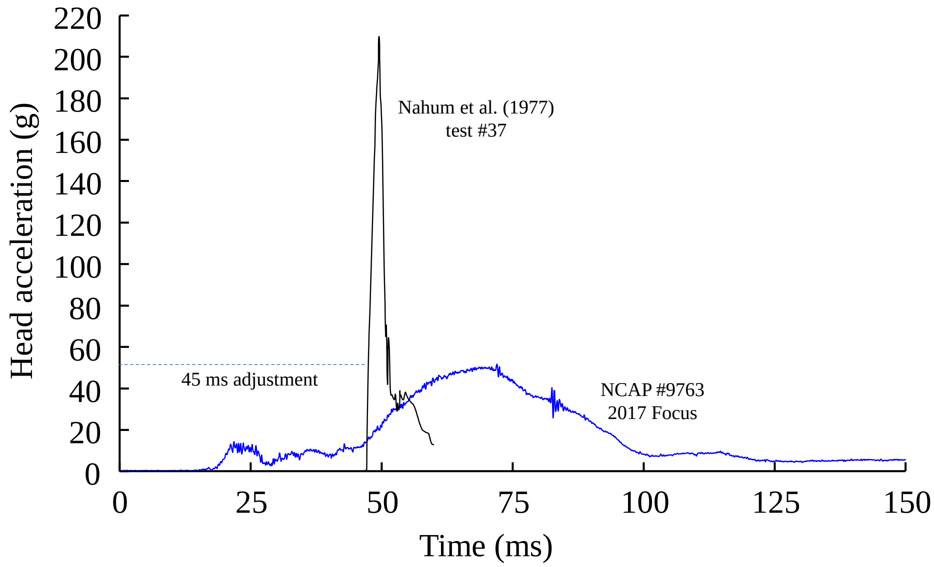

Figure D1: Head acceleration in test #37 from Nahum et al. (1977) and NCAP #9763 with the 2017 Ford Focus. Nahum test shifted 45 ms to the right for visualization.

Appendix E

Issues with BrIC: The author reviewed NHTSA papers on BrIC (Takhounts et al. 2003, 2008, 2011, 2013, 2019). The following is a short analysis. The NHTSA papers do not include sufficient detail, lack rigor in the formulation of the criterion and lack specific details on the validation of the FE models used to establish tolerances. NHTSA has provided no theoretical or biomechanical basis that uses principles of mechanics for the formulation of BrIC. The formula for BrIC has changed 4 or more times without an explanation by NHTSA why the earlier formulas were abandoned or why the newer one was needed.

The most recent NHTSA papers state the FE models of head impact are valid and refer to earlier studies for the validation. The earlier studies refer to yet earlier papers. They eventually trace back to earlier papers that claim validation; but, there is no clear description of the input conditions and output responses considered or what constitutes validation. In some cases, Figures are provided but graphs comparing results often show large difference without an explanation what validation means. As I understand, pressures in the brain FE model matched experiments by Nahum et al. (1977) and Trosseille et al. (1992) by adjusting material properties in the FE model. However, only one experiment by Nahum et al. (1977) has complete data and none of the Trosseille et al. (1992) tests are clear, because the stiffness of the padding on the face of the impactor was not described.

Nahum et al. (1977) test #37 is the test that shows impact force, head acceleration and pressures in the front, occiput and other regions of the brain during the forehead impact. Test #37 involved a 5.59 kg unpadded, rigid mass impacting the forehead at 9.94 m/s. The peak force was 7.9 kN resulting in 204 g head acceleration with 141 kPa in the frontal and -46.9 kPa in the occipital brain. Figure D1 shows the head acceleration in the forehead impact.

The Nahum (1977) tests are inconsistent with the type of head accelerations in NCAP tests. Figure D1 shows an example of the driver head acceleration in NCAP test #9763 with a 2017 Ford Focus. The acceleration in the NCAP test had a peak of 51.2 g with a duration >65 ms and HIC_{15} of 234 and HIC_{36} of 373. For vehicles tested in 2000, 2010 and 2020, the average HIC_{15} was 266 ± 143, HIC_{36} was 415 ± 159 and the peak head acceleration was 53.9 ± 10.0 g. In contrast, experiment #37 involved a peak head acceleration of 202 g with a duration of 4 ms and HIC of 744. The head impact caused no brain injury or skull fracture.

Other experiments involving neutral density targets that track brain displacements were used during the development of BrIC. For example, Hardy et al. (2001) tests involved HIC_{15} of 42 ± 46 and peak rotational velocity of 17.3 ± 5.5 r/s, below the risk for brain injury. Guettler et al. (2018) discussed other neutral density target tests. The head loading was 40 rad/s with 30 ms duration, below injury levels. Finally, NHTSA discussed using animal head impact data to determine BrIC tolerances. Scaling animal responses is fraught with uncertainty and lacks a means to verify accuracy. Animal data may guide understanding but should not be used to establish human tolerances, unless there is a broad consensus.

During the development of a tolerance for BrIC, NHTSA relied on instrumented helmet impacts using HIT telemetry. They did not inform the reader that independent testing of HIT showed it was inaccurate and invalid. Importantly, most of the studies claiming HIT accuracy involved co-authors connected to the company selling HIT. Jadischke et al. (2013) were independent of the HIT product, and they compared HIT to Hybrid III head responses. They found 55% of the tests had an absolute error >15%. The root mean error was 59.1%. They conclude that a head impact measured by HIT cannot be assumed accurate. People connected to the HIT product wrote a letter to the Editor. Jadischke et al. (2014) responded with broader criticisms of the technology. They refuted the Duma, Rawson claim of independence, since their co-authors were inventors, employees or owners of HIT, Simbex or later Riddell. Anyone interested in

BrIC should be aware of the flaws in the helmet impact database used by NHTSA, and they should not rely on tolerances linked to HIT data.

This author would argue that the FE models used by NHTSA are not valid for predicting brain injury risks with head accelerations typical of NCAP tests. BrIC does not provide meaningful risks for serious brain injury (Prasad et al. 2023). BrIC is not ready for use in assessing human protection. NHTSA needs a firmer foundation for adding a rotational head injury criterion, or they need a consensus among researchers, not only those dependent on NHTSA funding, that the addition is reasonable.

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