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An Assessment of the Implications of "Smart Design" on Motor Vehicle Safety

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16. Abstract

This report describes research conducted at the Volpe National Transportation Systems Center which tries to assess the implications of "smart design" on motor vehicle safety. Analytical pairs of vehicle models were proposed which matched size or mass with the intent of determining whether lightweight vehicles of a given size were demonstrably safer. Statistical analyses of crash data were inconclusive due to the limited amount of comparable crash data for each vehicle pair. The overall conclusions of the report were that care should be taken to verify the feasibility that the vehicle will meet engineering and economic feasibility when it is suggested that "smart design" can produce comparable or increased safety at lower mass. Suggestions for associated further research were given.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F	=	y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

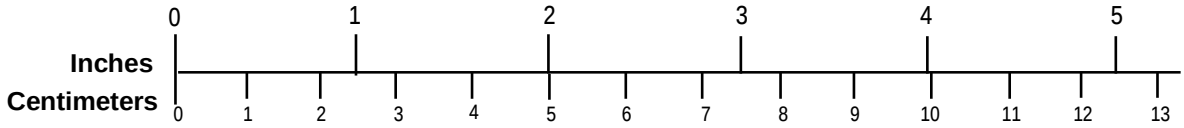
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

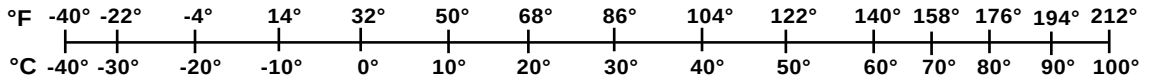
TEMPERATURE (EXACT)

[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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1. INTRODUCTION

In support of NHTSA's CAFE rulemaking, the Volpe National Transportation Systems Center (Volpe Center) conducted research into the implications of "Smart Design," a term intended to embody concurrent improvements in structural mass reduction and structural crashworthiness resulting from improved design technologies and advanced materials. This task included describing smart design, selecting analytical pairs of vehicles (substantially similar vehicles in which only one significant structural factor is varied), using appropriate crash databases (such as NASS-CDS and FARS) to analyze and correlate single-vehicle crash data and two-vehicle crash data (e.g., either against a common partner vehicle or simply as characterized by estimated change in velocity ["delta V"]), and providing guidance and suggestions for current and future research projects. This report documents these activities and provides conclusions and recommendations for the purposes of informing rulemaking decisions.

2. DATABASE ANALYSES OF SMART DESIGN

2.1 Working Definition of "Smart Design"

Any assessment of the benefit of smart design depends in large part on the definition of "smart design." In its broadest sense, a design which provides the same occupant protection at a lower mass and comparable cost could be considered "smart". In its narrowest sense, the term is often used to suggest an innovative use of advanced lightweight materials that accomplishes this goal. There is the inherent presumption that the size of the vehicle structure remains nominally the same or that, at a minimum, any change does not affect essential vehicle attributes such as vehicle class and passenger and cargo volume.

2.2 Selection of Analytical Vehicle Pairs

Vehicle attributes of current generation vehicles were used to propose pairs of vehicles for statistical analysis. A list of vehicle attributes related to preliminary sales figures in 2009 was used. Previous statistical analyses indicate that there is a correlation between a vehicle's size and/or mass and its protective capability [2.1, 2.2]. Therefore, the selection of proposed vehicle pairs has been governed by maintaining either mass (curb weight) or footprint (wheelbase times track width) and allowing the other to vary. The implication is that a design which is lighter for the same size or larger for the same mass is, in the generic sense, "smarter", so long as vehicle class and functionality are preserved.

One desirable feature in the pairs would be a more overt presence of "smart design" in one of the vehicles. One candidate vehicle that is often mentioned is the Audi A8 because of its advanced lightweight material structure. However, this vehicle has significant non-structural content and in fact weighs more than all other vehicles of comparable size. It would therefore be ambiguous as to whether any reduction in injury rate experienced by this vehicle is a consequence of the advanced design or the increased mass.

A family of popular vehicles which might be considered for this study is the group of Honda vehicles with Advanced Compatibility Engineering (ACE) structures. These vehicles have multiple load paths through the front end to strengthened A-pillars and occupant compartment floor. If this design feature could significantly reduce injury rates, it may be evident by comparing these vehicles with non-ACE vehicles of similar size or mass. Nonetheless, this strengthened structure is slightly heavier than comparable structures due to added cross-beams and additional material. Thus, the relative "smartness" of the overall vehicle design results in part from the reduction in mass of non-structural components.

Under these constraints, analytical vehicle pairs are proposed in Table 2.1. The vehicles with ACE structures are shown in bold. The average values of footprint and curb weight are averages based on preliminary 2009 sales figures. For the purposes of defining these vehicle pairs, "similar" was defined as a difference of less than one percent.

Table 2.1: Proposed Vehicle Pairs

	Model	Footprint	Curb Weight	Model	Footprint	Curb Weight	Footprint Ratio	Mass Ratio
Similar Size, Different Mass	TOYOTA YARIS	39.1	2335	SCION XD	39.4	2665	99.2%	87.6%
	KIA RIO	41.3	2418	HYUNDAI ACCENT	41.4	2418	99.8%	100.0%
	KIA RIO	41.3	2418	FORD FOCUS	41.7	2622	99.1%	92.2%
	HYUNDAI ACCENT	41.4	2418	FORD FOCUS	41.7	2622	99.3%	92.2%
	VOLKSWAGEN JETTA	42.4	3308	SCION XB	42.4	3086	99.9%	107.2%
	VOLKSWAGEN JETTA	42.4	3308	TOYOTA COROLLA	42.5	2543	99.7%	130.1%
	SCION XB	42.4	3086	TOYOTA COROLLA	42.5	2543	99.8%	121.4%
	AUDI A4 (not 4WD Quattro)	43.1	3627	**HONDA CIVIC**	43.2	2586	99.8%	140.3%
	AUDI A4 (not 4WD Quattro)	43.1	3627	MAZDA MAZDA3	43.3	3053	99.7%	118.8%
	HONDA CIVIC	43.2	2586	MAZDA MAZDA3	43.3	3053	99.9%	84.7%
	CHEVROLET CLASSIC	44.0	3174	HYUNDAI ELANTRA	44.0	2723	100.0%	116.6%
	KIA SPECTRA	44.5	2778	NISSAN SENTRA	44.7	2995	99.6%	92.8%
	KIA SPECTRA	44.5	2778	CHEVROLET COBALT	44.8	3064	99.3%	90.7%
	NISSAN SENTRA	44.7	2995	CHEVROLET COBALT	44.8	3064	99.8%	97.7%
	HYUNDAI SONATA	46.0	3253	FORD FUSION	46.1	3329	99.8%	97.7%

	FORD FUSION	46.1	3329	NISSAN ALTIMA	46.2	3230	99.8%	103.1%
	NISSAN ALTIMA	46.2	3230	**HONDA ACCORD**	46.6	3243	99.1%	99.6%
	HONDA ACCORD	46.6	3243	CHRYSLER SEBRING	46.7	3399	99.7%	95.4%
	HONDA ACCORD	46.6	3243	TOYOTA CAMRY	46.9	3312	99.4%	97.9%
	HONDA ACCORD	46.6	3243	CHEVROLET MALIBU	46.9	3446	99.4%	94.1%
	CHRYSLER SEBRING	46.7	3399	TOYOTA CAMRY	46.9	3312	99.7%	102.6%
	CHRYSLER SEBRING	46.7	3399	CHEVROLET MALIBU	46.9	3446	99.7%	98.6%
	CHRYSLER SEBRING	46.7	3399	CHEVROLET IMPALA	47.1	3731	99.2%	91.1%
	TOYOTA CAMRY	46.9	3312	CHEVROLET MALIBU	46.9	3446	100.0%	96.1%
	TOYOTA CAMRY	46.9	3312	CHEVROLET IMPALA	47.1	3731	99.6%	88.8%
	CHEVROLET MALIBU	46.9	3446	CHEVROLET IMPALA	47.1	3731	99.6%	92.3%
Sim. Mass, Diff. Size	TOYOTA COROLLA	42.5	2608	FORD FOCUS	41.7	2622	102.0%	99.5%
	HONDA ACCORD	46.6	3243	HYUNDAI SONATA	46.0	3253	101.3%	99.7%
	TOYOTA CAMRY	46.9	3312	FORD FUSION	46.1	3329	101.7%	99.5%

2.3 Statistical Crash Analysis

The purpose of this analysis was not to assess the likelihood of crash, injury, or fatality as a function of vehicle miles traveled (VMT) or any similar proxy. The exposure metric in this analysis was crashes experienced by the vehicle model. Vehicles of a given model of consecutive model years were considered together (as a single "generation") so long as no significant structural changes occurred.

The list of the vehicles and the relevant model years of the same generation are given in Table 2.2. A NASS-CDS query was run for each of the 25 vehicle types for single- and two-vehicle crashes involving that vehicle in model years in which the structure is unchanged.

Table 2.2: Proposed Vehicles with Model Years of Design Generation

Vehicle	Model Years of Design Generation
AUDI A4 (not 4WD Quattro)	2009-2011
CHEVROLET MALIBU CLASSIC	2004-2008
CHEVROLET COBALT	2005-2010
CHEVROLET IMPALA	2006-2011
CHEVROLET MALIBU	2008-2011
CHRYSLER SEBRING	2007-2010
FORD FOCUS	2008-2011
FORD FUSION	2006-2009
HONDA ACCORD	2008-2011
HONDA CIVIC	2006-2011
HYUNDAI ACCENT	2006-2011
HYUNDAI ELANTRA	2007-2010
HYUNDAI SONATA	2006-2010
KIA RIO	2006-2011
KIA SPECTRA	2004-2009
MAZDA MAZDA3	2004-2009
NISSAN ALTIMA SEDAN	2008-2011
NISSAN SENTRA	2007-2011
SCION XB	2008-2011
SCION XD	2008-2011
TOYOTA CAMRY	2007-2011
TOYOTA COROLLA	2009-2011
TOYOTA YARIS	2007-2011
VOLKSWAGEN JETTA	2006-2010
VOLKSWAGEN NEW BEETLE	2006-2011

The crashes were segmented into frontal crashes (Principal Direction of Force [PDOF] = 11, 12, or 1), Left Side (PDOF = 8, 9, or 10), or Right Side (PDOF = 2, 3, or 4). Rear crashes (PDOF = 5, 6, or 7) and rollovers were not considered. The driver injury level (as measured by Maximum AIS injury level [MAIS]) was determined.

As the distribution of crash severity (as measured by ΔV) varied substantially across the datasets, a maximum likelihood analysis was planned for each injury level as a function of ΔV. For example, for all of the frontal single-vehicle crashes of a particular model, the crashes could be divided into those with a driver MAIS of 2 or above (MAIS2+) and those with a driver MAIS 1 or less (MAIS1-). With a properly chosen formulation and sufficient data, an estimate could be made for the likelihood that driver injury will be MAIS2+ as a function of ΔV.

Unfortunately, when all the crashes of a particular vehicle type were considered, the data available was generally insufficient. This is a byproduct of the nature of NASS-CDS; it is a

sampled database and provides details about a limited number of crash events with the same general distribution as the national distribution of crashes. Therefore, serious injuries are relatively rare. There were relatively few side and rear crash cases for any particular vehicle model. None of the data entries had specific floor pan intrusion values, so no quantitative assessment of self-protection or aggressiveness could be made based on that metric. In fact, when an initial query was done for these vehicles in the available years of the NASS-CDS database, only 17 had data from ten or more frontal crashes that could be used in a maximum likelihood analysis. These vehicles are listed in Table 2.3. No vehicle had ten data points for non-frontal crashes. As most Maximum AIS (MAIS) values were 0 (uninjured) or 1, only boundaries for MAIS0/MAIS1+ and MAIS1-/MAIS2+ could be generated. In nine of the 17 cases, the number of MAIS0 or MAIS2+ data points was insufficient (three or fewer) to generate a meaningful MAIS0/MAIS1+ or MAIS1-/MAIS2+ boundary. The eight vehicles with potentially meaningful curves at both boundaries are highlighted in bold in Table 2.3.

Table 2.3: Vehicles with Ten or More Frontal Crash Data Points

Vehicle	MAIS 0 (uninjured)	MAIS 1	MAIS2+	Total	Potentially Sufficient?
CHRYSLER SEBRING	2	5	4	11	No
FORD FOCUS	3	13	1	17	No
FORD FUSION	**6**	**17**	**12**	**35**	**Yes**
HONDA ACCORD	2	10	1	13	No
HONDA CIVIC	**21**	**23**	**17**	**61**	**Yes**
HYUNDAI ACCENT	**5**	**2**	**4**	**11**	**Yes**
HYUNDAI ELANTRA	5	6	3	14	No
HYUNDAI SONATA	**9**	**11**	**4**	**24**	**Yes**
KIA RIO	3	5	2	10	No
KIA SPECTRA	**12**	**25**	**8**	**45**	**Yes**
MAZDA MAZDA3	**15**	**10**	**6**	**31**	**Yes**
NISSAN ALTIMA SEDAN	7	3	3	13	No
NISSAN SENTRA	3	6	2	11	No
TOYOTA CAMRY	**15**	**12**	**6**	**33**	**Yes**
TOYOTA COROLLA	6	4	0	10	No
TOYOTA YARIS	3	7	2	12	No
VOLKSWAGEN JETTA	**8**	**16**	**6**	**30**	**Yes**

Bold = At least four MAIS0 and four MAIS2+ data points

Maximum likelihood analyses were used to estimate injury probability curves for each of the eight vehicles. The data points in the calculations were weighted by the factors provided in the NASS-CDS database. The parameters describing these curves are given in Appendix 1.

The Weibull formulation generally produces an S-shaped curve that approaches 100% for large values of ΔV. Unfortunately, with the limited number of data points, the data can produce curves that more closely resemble a curve approaching an asymptote over the range of interest.

This can occur when the distribution of injury events remains fairly consistent over a wide range of ΔV.

The curves do not seem reasonably consistent for the general data set. For example, half of the eight vehicles exhibit a probability of injury (i.e., MAIS1+) of nearly 100% for a ΔV of 60 kph, but the others approach apparent asymptotes between 35% and 70%. In fact, a quirk in the distribution of MAIS1 events for the Honda Civic generates the result that the probability of MAIS2+ at a ΔV of 60 kph of nearly twice the probability of MAIS1+ (see Figure 2.1), which is of course impossible by definition. The MAIS1+ curve would normally be expected to have a shape similar to (and slightly above) the MAIS2+ curve. As the Civic has the highest number of data points of all 25 vehicles, this failure to produce a viable result casts significant doubt on the applicability of the process to the entire dataset. Therefore, even though the curves from the eight vehicles could be used to estimate an injury distribution for a given ΔV, there would be little confidence in the result. Comparisons between vehicles in the same vehicle pair would be more suspect. Hence, the attempt to use NASS-CDS data to generate maximum likelihood curves for the purpose of evaluating analytical vehicle pairs was inconclusive.

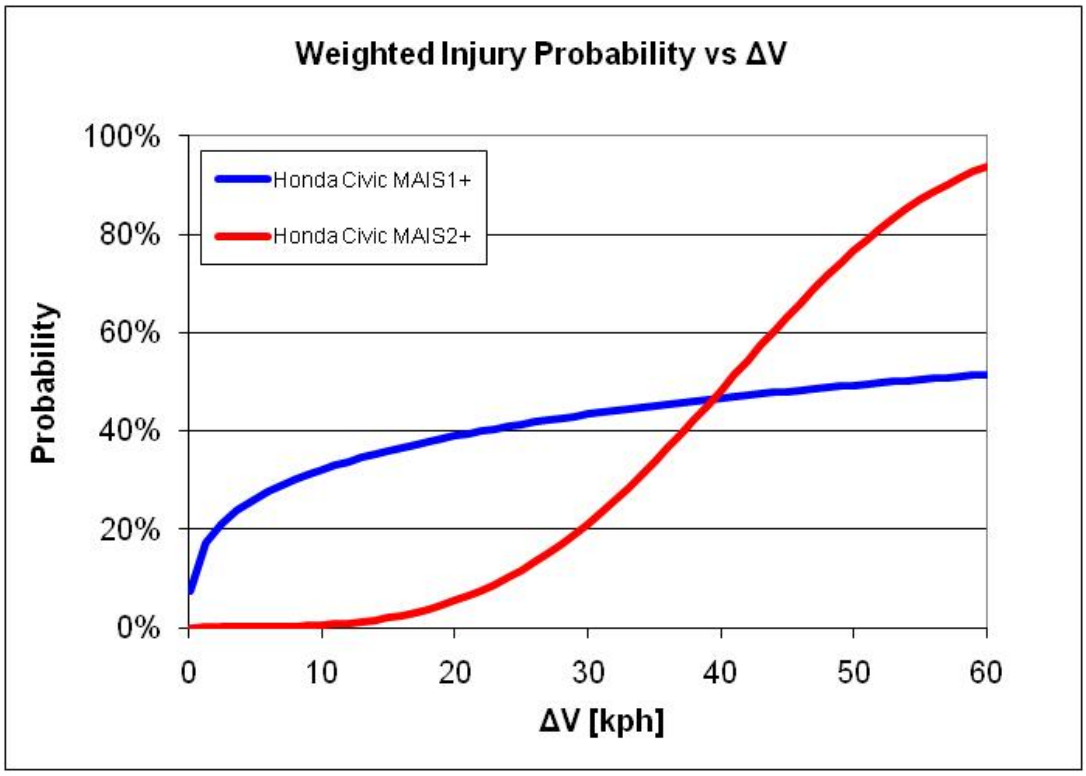

Figure 2.1: MAIS Injury Boundaries for Honda Civic

2.4 Fatality Analysis Reporting System (FARS) Case Analysis

The vehicle models considered in the statistical analysis were considered for case analysis through queries made to identify and retrieve data from the Fatality Analysis Reporting System

(FARS). The first FARS analysis considered two-vehicle crashes in which a "standard other vehicle" was taken as the crash partner for each vehicle in a vehicle pair. A crash was considered if the driver of the standard other vehicle were a fatality. With that prerequisite, non-fatalities of the subject vehicle driver could be considered.

The standard other vehicle would need to be a high volume model to increase the likelihood of sufficient data. Data showed the most common passenger vehicle in FARS not in Table 2.2 was the Ford Taurus/Mercury Sable. A preliminary query using the Ford Taurus as the standard other vehicle did not produce any vehicle pair case studies in which the known closing speeds were comparable. In fact, there were only three fatal crashes in FARS that involved a Ford Taurus/Mercury Sable and one of the vehicles listed in Table 2.2 (in the appropriate design generation) with a closing speed less than 80 mph. Pertinent data from those crashes is given in Table 2.4. Unfortunately, the three vehicles were not in any defined pair in Table 2.1, so no comparison could be made.

Table 2.4: FARS Crash Data for Crashes with a Driver Fatality in a Standard Other Vehicle

Crash Year	2007	2005	2008
State Case Number	450836	121739	121884
Combined Closing Speed [mph]	55	70	70
Standard Other Vehicle			
Model	Ford Taurus	Ford Taurus	Mercury Sable
Driver Injury	Fatal Injury	Fatal Injury	Fatal Injury
Travel Speed [mph]	10	30	45
Case Vehicle			
Model	2006 Chevrolet Impala	2005 Chevrolet Cobalt	2006 Hyundai Sonata
Driver Injury	None	Possible	Non-Incapacitating
Travel Speed [mph]	45	40	25

An alternative approach looked at FARS single vehicle crashes. In a sense, once non-occupant (e.g., pedestrian fatality) and rollover cases were excluded, this is equivalent to choosing a fixed object as a "standard other vehicle". Unfortunately, as there is the requirement that FARS cases must have at least one fatality, the selection of these cases does involve some potential bias in that the crashes are, by definition, severe enough to cause at least one fatality in the case vehicle. It might have been preferable to select cases on a more objective measure of crash severity (e.g., ΔV), but this was not possible when using FARS.

Relevant comparisons have to be made between vehicles in the same analytical pair in crashes with similar changes in velocity (say, ΔV within 5 mph). Since extreme velocities were rare and would be harder to compare, cases were considered in which the changes in velocity were in the range 20 mph to 40 mph. This yielded 17 cases involving 11 different vehicle models. Four

separate vehicle pairs (eight of the 11 vehicle models) were represented by these cases. They are listed in Table 2.5.

Table 2.5: Single Vehicle FARS Cases by Vehicle Pairs
(Occupant Fatality, Non-Rollover)

Crash Year	State Case Number	Vehicle Model	Travel Speed
2009	122083	2006 Chevrolet Malibu	40 mph
2008	420027	2007 Hyundai Elantra	40 mph
2007	121286	2007 Ford Fusion	40 mph
2007	371270	2008 Nissan Altima	40 mph
2009	61474	2009 Kia Spectra	40 mph
2008	40795	2008 Nissan Sentra	40 mph
2008	390891	2008 Nissan Sentra	40 mph
2008	420986	2008 Nissan Sentra	40 mph
2006	390389	2006 Honda Civic	35 mph
2007	390877	2007 Honda Civic	35 mph
2009	390948	2006 Honda Civic	35 mph
2007	121837	2007 Mazda Mazda3	35 mph

While the number of cases found is not negligible, the statistics in the publicly available FARS summaries are insufficient for a detailed case study analysis that allows for examination of details such as crash configuration and vehicle kinematics. More detail is found in a typical NASS-CDS case, but only one case (case 2007-41-117, Mazda3) was documented in the CDS database as well. Thus, while general similarities can be identified by the analysis, complete case studies comparing fatal crashes in the same vehicle pair were not possible.

3. CONCLUSIONS

The statistical and engineering analyses presented in this report have uncovered no irrefutable evidence that “smart design” is a distinct discernible design concept which can generate vehicle designs which are both lower in mass and materially superior in occupant protection. The current crash databases do not have sufficient population to provide a significant number of detailed cases in which the injuries sustained in a so-called smart design vehicle can be directly compared to those in a nominal vehicle under substantially the same crash conditions. It is therefore prudent to exercise caution when purely statistical design models predict large mass reduction potential without confirmation by supporting engineering analysis. It would be

inadvisable to presume the feasibility of arbitrarily large mass reductions in the rulemaking process unless they were verified.

Analyses indicate that automotive technology is continuing to progress in a manner in which improvements in vehicle mass reduction and fuel economy are carefully traded off against each other as well as the numerous design constraints on performance, durability, and safety, and economic and technological feasibility. Specific options and innovations may occasionally provide both increased fuel economy and increased safety for specific models under certain conditions, but these will usually be applicable only to a particular model which has an amenable baseline design.

It can therefore be misleading to promote a non-specific concept of "smart design" as a means to universally reduce mass and improve safety when the applicability of any technology to any vehicle design may vary markedly under its particular economic and manufacturing constraints. Furthermore, indiscriminately adding more safety devices (e.g., airbags) without due consideration of the underlying physical limitations on their effectiveness may be of limited value.

To be meaningful in the context of regulatory analysis, proposals for application of advanced technologies should be specific to particular groups of similarly designed and marketed vehicle models and carefully evaluated for feasibility.

4. RECOMMENDATIONS FOR FURTHER RESEARCH

NHTSA should remain vigilant for opportunities to verify the effect of smart design. If the appropriate circumstances arose of a vehicle model with an advanced structural front end that was found to be of similar size as and lower mass than a similar conventional vehicle, NHTSA might consider a Special Crash Investigation that compared similar crashes of the two vehicles.

5. REFERENCES

2.1 Kahane, C., Relationships Between Fatality Risk, Mass, and Footprint in Model Year 1991-1999 and Other Passenger Cars and LTVs, National Center for Statistics and Analysis (NCSA), National Highway Traffic Safety Administration (NHTSA), March 2010.

2.2 Van Auken, R.M., Zellner, J.W., Supplemental results on the independent effects of curb weight, wheelbase, and track on fatality risk in 1985-1998 model year passenger cars and 1986-1997 model year LTVs. DRI-TR05-01. Dynamic Research, Inc., Torrance, California. 2005.

Appendix 1:

TABLE OF MAXIMUM LIKELIHOOD PARAMETERS

Vehicle	MAIS0/MAIS1+		MAIS1-/MAIS2+	
	A	B	A	B
Ford Fusion	13.4	0.97	400	0.53
Honda Civic/CRX	151	0.35	45	3.55
Hyundai Accent	358	0.48	140	0.34
Hyundai Sonata	26.3	1.62	40.8	4.42
Kia Spectra	19	1.33	46.8	3.14
Mazda Mazda3	23.2	1.65	650	0.78
Toyota Camry	344	0.38	289	1.09
Volkswagen Jetta	3	0.04	1000	0.5

Weighted data from NASS-CDS

Weibull format for probability that driver injury is below the boundary

$$Probability(\Delta V) = 1 - \exp\left(-\left(\frac{\Delta V}{A}\right)^{B}\right)$$

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