Evaluating Vehicle Incompatibility Using Center of Velocity Change Methodology

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ABSTRACT

The concept of compatibility includes not only the safety of the occupants within the subject vehicle itself, but also the safety of occupants in other vehicles that are involved in the collision. The term self-protection describes the safety afforded to the occupants within a vehicle, while partner-protection describes the safety afforded to the occupants of the crash partner vehicle. Early research identified vehicle weight as having a critical but not exclusive role in defining crash outcomes. The geometry and vehicle stiffness or crush characteristics were also observed to play a significant role.

This study uses the New Car Assessment Program[1] (NCAP) frontal barrier test data to find a suitable metric to assess the effect of incompatibility in crashes involving light passenger vehicles. The number of drivers with AIS 3+ injuries in head on crashes between passenger car (PC) and light truck vehicle (LTV) is used to compute the effectiveness of the metric.

NCAP crash test data for 239 vehicles were used in calculating the value of "distance from ground to the center of velocity change". Ten years of National Automotive Sampling System /crashworthiness data systems[2] (NASS/CDS) data were used to demonstrate the metric. The crash compatibility metric developed can be used to compare the number of injuries that result in PCs - LTVs head on crashes.

Most safety benefits can be achieved by changes in the metric, specifically, adjusting for vehicle size (height) and the structural characteristics (stiffness). Hence the metric can be used as a measure of compatibility in crashes between vehicles.

This study is limited to investigation of incompatibility in full head-on crashes. This paper develops a new comprehensive metric that can quantify the compatibility disparity.

BACKGROUND

Throughout much of the 1980's and early 1990's National Highway Traffic Safety Administration's (NHTSA) compatibility research was focused on frontal and side impact safety and how the characteristics of the striking vehicle's front end affected the occupant survivability in the struck vehicle. The genesis of NHTSA's current program began in 1996 with studies investigating the changing vehicle mix in the US fleet and its effect on the vehicle compatibility problem. This problem is related to the introduction of a large number of sport utility, pick-ups (LTV) and minivans into the US fleet. This issue has a long history of research, but has recently received increased attention due to the changing mix of vehicles in the US fleet once again.

Over the last decade NHTSA has been vigorously pursuing some research activity to develop potential strategies to improve vehicle compatibility. Improving structural engagement characteristics in vehicle-to-vehicle crashes through establishment of an average height of force requirement energy management through front end stiffness and crush force parameter specifications, and even the development of a modified compatibility test barrier were all topics in NHTSA's research agenda that were pursued with some level of interest.

In December 2003, the Insurance Institute for Highway Safety[3] (IIHS) facilitated a voluntary commitment from the automobile manufacturers through their trade associations, the Alliance and AIAM, to begin designing vehicles to enhance vehicle-to-vehicle crash compatibility. The voluntary agreement included commitments to enhance occupant self protection in front-to-side crashes through improved head impact protection and design criteria to enhance partner protection in vehicles involved in front-to-front crashes by geometric matching of front structural components in cars and light trucks. This commitment required 100 percent of each participating manufacturers' vehicles to be designed according to the criteria specified for side impact protection and frontal impact protection by September 2009. The details of these commitments are available in a document originally submitted to the agency in December, 2003 and subsequently revised in November, 2005.

In 2006, IIHS completed an analysis of the safety benefits of the front-to-front Compatibility agreement. The Institute examined passenger-car driver death rates in two-vehicle crashes with light trucks. The light trucks were divided into two groups – those designs that met the front-to-front performance criteria and those that did not. The analyses used NHTSA's Fatality Analysis Reporting System (FARS) data for calendar years 2001-2004 involving model years 2000-2003 light trucks.

IIHS[4] found that in front-to-front crashes involving light trucks into passenger cars, the passenger car driver was 16 percent less likely to be killed if struck by a sport utility vehicle (SUV)with a front-end design that met the compatibility performance criteria specified under the voluntary agreement. Similarly, the passenger car driver was 20 percent less likely to be killed if struck by a pickup truck with a front-end design that met the compatibility performance criteria. The overall reduction in passenger car driver deaths in front-to-front crashes involving both SUVs and pickup trucks was 19 percent.

In front-to-side crashes involving light trucks into passenger cars, the passenger car driver was found to be 30 percent less likely to be killed if struck by a SUV with a front-end design that met the front-to-front compatibility performance criteria. The passenger car driver was 10 percent less likely to be killed if struck by a pickup truck with a front-end design that met the front-to-front compatibility performance criteria. The overall reduction in passenger car driver deaths in front-to-side crashes involving both SUVs and pickup trucks was 19 percent.

METHODS

The analytical effort described in this paper is an attempt to find a suitable metric that could be used to assess front-to-front structural compatibility in vehicle-to-vehicle frontal crashes as well as in front-to-side crashes. It was also important to determine the potential benefits if such a metric was used to make any or all vehicles in the fleet to be compatible.

NHTSA conducts 30 and 35mph frontal barrier impact tests under Federal Motor Vehicle Safety Standard (FMVSS) No.208, and the New Car Assessment Program (NCAP). These tests are assumed to represent NASS/CDS crash data where the principal direction of force, for the two vehicles involved, is in between 350 and 10 degrees. This study is an attempt to use the NCAP barrier test data to find a suitable metric to address the effect of incompatibility in crashes between passenger cars and light trucks. For this study crash test data for 239 passenger vehicles of model years 2000 - 2007 were used.

The load cell barrier, currently used in the NCAP tests, has a 36 load cell array arranged as a 4 rows and 9 columns matrix as shown in Figure 1

D1	D2	D3	D4	D5	D6	D7	D8	D9
C1	C2	C3	C4	C5	C6	C7	C8	C9
B1	B2	B3	B4	B5	B6	B7	B8	B9
A1	A2	A3	A4	A5	A6	A7	A8	A9

Figure 1: Barrier with 36 load cells used in the front barrier test.

The width of all the cells in the load cell barrier is 9 inches (229mm). While height of the bottom two rows (A&B) is 9 inches (229mm) each, the height of the top two rows (C&D) is 10.2 inches (259mm) each. The bottom edge of the barrier is 2.62 inches (66.67mm) above the ground. The data used in this study is collected from the time of impact until the vehicle velocity reaches zero.

Derivation of Impulse Ratio

Time histories of forces acting on load cell rows A, B, C, and D during NCAP frontal barrier test for a compact car is shown in Figure 2. The area under the curve gives the impulse acting on each of the load cell rows A, B, C, and D (listed from bottom); their values are 2310.6, 17651.9, 4181.1, and 285.3 Newton second respectively. The sum of calculated impulses gives the total impulse acting on the barrier, for the selected example. The sum in this case is equal to 24429 Newton second.

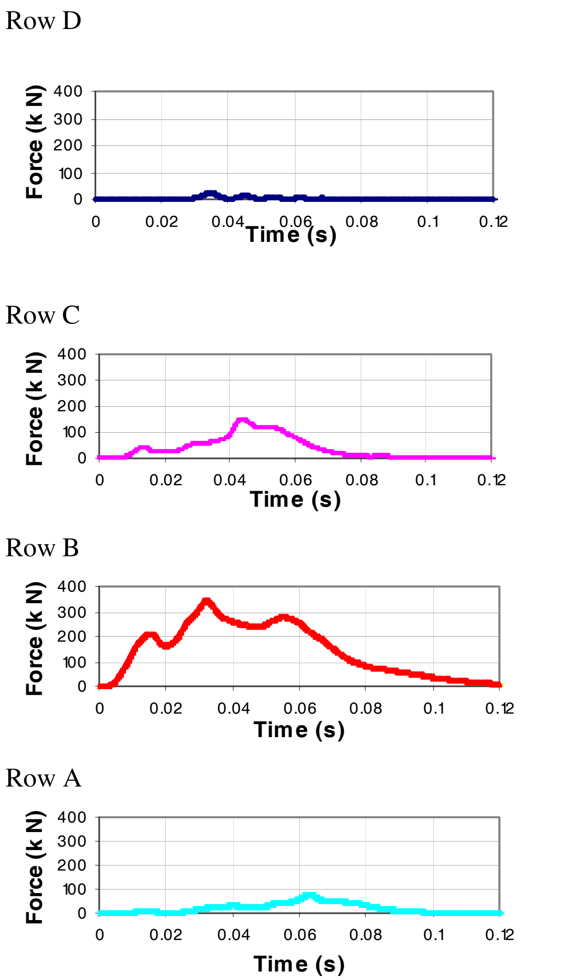

Figure 2: Force acting on the load cell rows from NCAP frontal barrier test for a compact passenger car

The row impulses are assumed to be acting on the center of each of the load cell rows A, B, C, and D. The distances from ground to the center of the load cell rows are 7.13 inches (181.2mm), 16.15 inches (410.2mm), 25.66 inches (651.7mm), and 35.66 inches (905.7mm), for load cell rows A, B, C, and D, respectively.

The ratio of impulse on load cell row A as a fraction of total impulse is given below:

$$F_A = \frac{2310.6}{24429} = 0.09 .$$

Similarly the ratio of impulse for each load cell row as a fraction of the total impulse for the compact passenger car example given above are 0.72, 0.17, and 0.01 for rows B, C, and D, respectively.

Similarly the ratio of impulse for each of the load cell rows as a fraction of the total impulse for each of the 239 NCAP barrier tested PCs and LTVs were calculated. The impulse ratios for the PCs and LTVs are grouped into three groups each by test weights for PCs and LTVs - less than 3000 lbs, 3000 to 4000 lbs and greater than 4000 lbs for PCs and less than 4000 lbs, 4000 to 5000 lbs and greater than 5000 lbs for LTVs. The distribution of the impulse ratios for each of the PC and LTV weight groups are shown in Figure 3. Impulse ratios are shown on the Y axis and the vehicles tested are shown on the X axis for each weight group.

The impulse data for each vehicle tested is presented row by row for the different weight groups in PCs and LTVs. In Figure 3 the blue region shows the impulse in load cell Row A as a fraction of the total impulse. Similarly the impulse ratios for Rows B, C, and D are given by the areas in green, red and dark red colors, respectively. The data in each graph is ordered by vehicle test weight. It can be inferred from the figure that a large portion of the impulse in PCs is in rows A and B (blue and green) compared to LTV's, especially in the heavier weight groups. But, the LTVs weighing greater than 4000 lbs show a significantly large area covered by red and dark red (rows C and D) in comparison to PCs, implying large and heavy LTVs have impulses acting on a higher plane from the ground relative to the PCs. This is not surprising because of the higher profile of the LTVs.

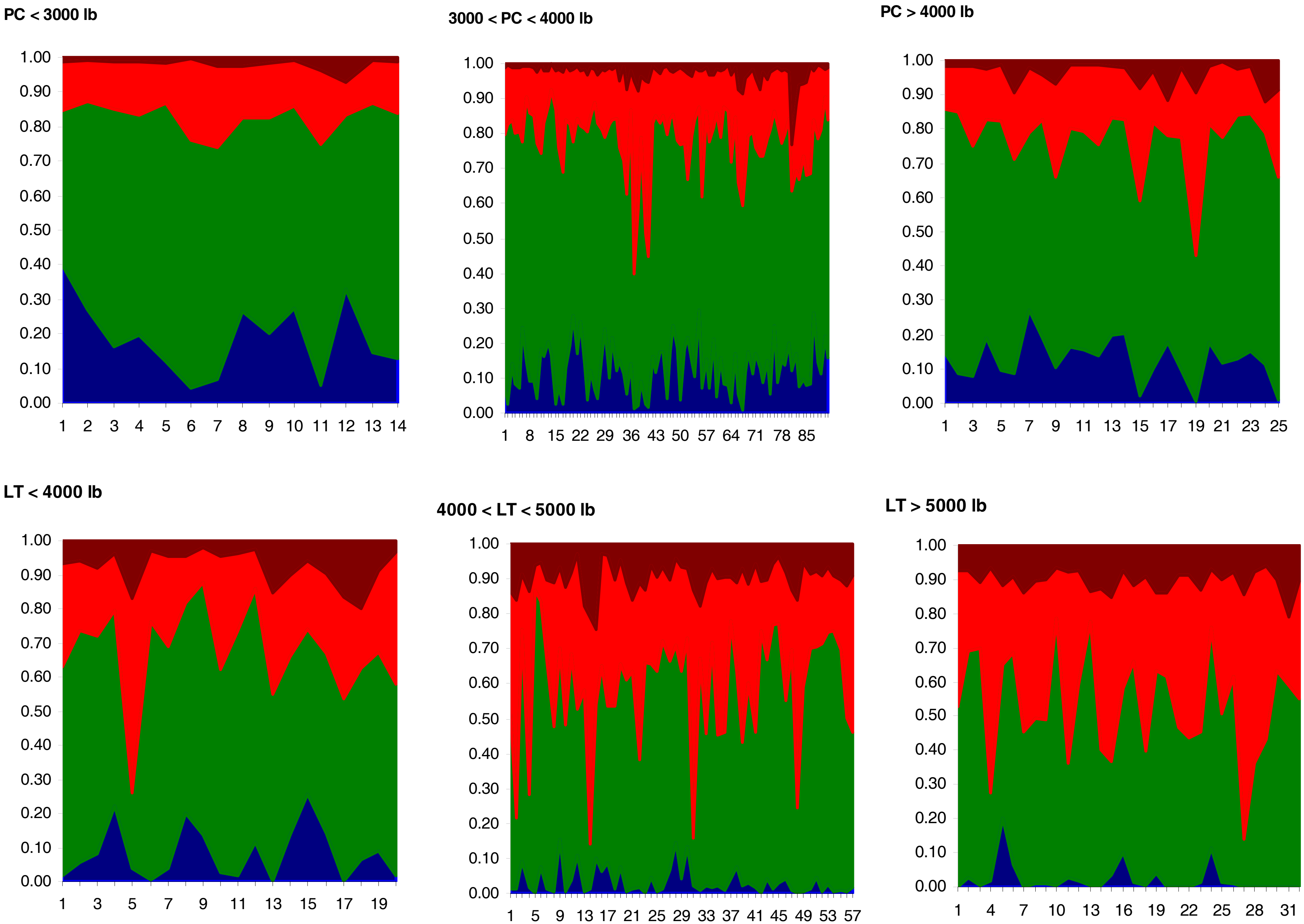

Figure 3, Distribution of Force during a Frontal Fixed Barrier Test

Derivation of a suitable metric from impulse to define compatibility

Impulse is defined as the integral of force with respect to time;

$$I = \int F.dt\,,$$

where, 'F' is force and 'dt' is the time increment. $I_{A,}$ the impulse on load cell row A is determined by $I_A = \int F_A.dt_A$, and is equal to the area below the Force-Time curve for load cell row A in Figure 2. Similarly values for I_B, I_C, and I_D are determined. The time duration dt for each test theoretically starts at the time the test vehicle contacts the load cell barrier (time zero) and ends when the test vehicle velocity crosses zero as the vehicle starts to rebound from the barrier.

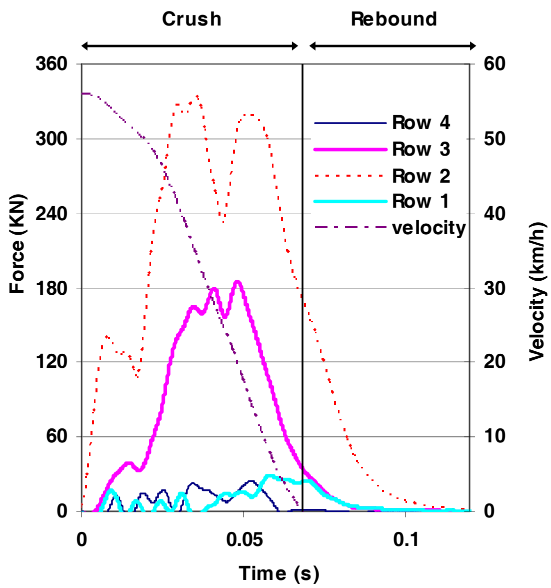

Figure 4, Forces acting on each load cell row along with vehicle velocity.

The total crash duration is made up of crush period, between time zero and the time when the velocity crosses zero and the rebound period as the vehicle bounces off of the barrier (Figure 4). In this study, the impulse is calculated only for the period up to the point of rebound because the load cell readings during the rebound are not consistent and the impulse contribution during rebound as a percent of the total is not significant as seen in Figure 4..

Since the time dt for each load cell row is influenced by the effective stiffness (geometric stiffness distribution) characteristic of the vehicle structure, it can be concluded that the calculated metric for compatibility using the impulse also reflects the effect of stiffness.

A suitable metric can now be derived using the impulse that could define the distinguishing compatibility characteristics of PCs and LTVs during a full frontal head-on crash. For the purpose of deriving this metric, a point located on the vehicle is defined as the center of velocity change. This point is assumed to be the point at which the total impulse I is concentrated as the vehicle contacts the load cell barrier. This point is projected on to the crash foot print on the barrier. It is located at a height X from the ground. The distance to this point defined as the "Center of Velocity Change", can now be calculated as shown below:

$$I = \int F.dt = \int d(mV) = m\int dv$$

Distance from the ground to the center of velocity change is:

$$X = \frac{I_A \cdot Z_A + I_B \cdot Z_B + I_C \cdot Z_C + I_D \cdot Z_D}{I_A + I_B + I_C + I_D}$$

Where:
F = crash forces transferred to the barrier
m = mass of the vehicle
$I_{A, .etc.}$ = impulse acting on load cell row A, etc.
$Z_{A, etc.}$= distance from ground to the midpoint of the row A, etc.

The ratio of impulse on each load cell row to the total impulse normalizes the effect of mass.

Substituting the values for impulse and its respective distances from the ground for each load cell row in the above equation, the value for X - "the distance from the ground to the center of velocity change", is determined. The metric "X" is a single measure of height (distance from the ground) at which the net impulse of a vehicle will act during a fixed rigid load cell barrier crash. It can be considered to be the impulse ratio weighted average of the heights $Z_{1,}$ $Z_{2.......}$etc. for each row.

For the example using the compact car data that was previously presented, the value X, is calculated to be 435.66 mm or 17.15 inches.

Ideally for compatible vehicle crashes involving passenger cars and LTVs, the value of X for light trucks should be similar to the value of X for passenger cars. This can be achieved by controlling one or both of the following variables: distance from the ground represented by Z_i and the impulse ratios. Since duration of force and level of force constitute the impulse, they can be varied to attain an optimum value for X by appropriate vehicle structural design.

Analysis based on breakdown of vehicle class by test weight

The distance, X, was calculated for all the 239 vehicles that were tested in frontal New Car Assessment Program (NCAP) barrier tests. The correlation between median vehicle test weights and Xs, for all the vehicles tested in NCAP frontal barrier tests were determined.

In this analysis, it was observed that there is a strong correlation between the calculated values of X and the test weights, even though the weights themselves do not enter directly into the calculation of X both in PCs and in the LTVs. However, it is also noted that the vehicles tested in NCAP are not designed for optimal value of X and therefore, the correlation noted above is only because the weights and size are the two most dominant parameters that are well correlated for the vehicles in the current fleet.

The calculated value of X is a reflection of parameters including stiffens and size, that exist in the fleet. However, vehicles that are optimized for the values of X may have better correlation not only to vehicle weights and size, but also to stiffness since other design variables such as the stiffness and geometry could be modified within certain limits to get the desired value of X in future fleets.

The following are the six steps involved in this analysis to obtain estimates of the potential benefits of optimizing the value of X. The first three steps relate to the computation of the compatibility metric X from NCAP data for relevant vehicle classes and calculation of relative injury risk for drivers in real world vehicle-to-vehicle frontal crashes. Steps four through six explain how the relative risks change as the value of X is varied. Step four provides a means to directly compare the relative risk in one class of vehicle as it interacts with all the other vehicle classes in real world crashes.

Step 1

The value of X was computed from 239 NCAP tests that belonged to different vehicle test weight groups. The weight groups in the NCAP data are used in the analysis of real world data.

Crash database NASS/CDS includes the variable, vehicle curb weight. Those weights were used to match the vehicle classes in the real world against the classes in the NCAP data. Ten years of real world crash data in NASS/CDS 1997- 2006, were used in this analysis to determine the injury risk based on the number of injured drivers in head-on crashes of different vehicle classes. The median values and the average values of X along with the standard deviation are given in Table 1. Both are found to be close and using either of these values would be satisfactory.

Table 1 NCAP front barrier test vehicle classes and X values

Vehicle Class	Test weight range (lbs)	Estimated			Symbol
		Average X (in)	Standard Deviation	Median	
Compact Passenger Car	Less than 3,500	16.9	1.3	16.6	CPC
Full size Passenger Car	Greater than 3,500	17.7	1.6	17.2	FPC
Compact Light Truck vehicle	Less than 4500	20.1	2.4	19.8	CLTV
Large Light Truck Vehicle	Greater than 4500	20.9	1.7	20.7	LLTV

However, the median values of X determined for each vehicle class based on weights were used in this analysis. Since there were only a limited number of crash cases in the NASS/CDS data, the vehicle classes were collapsed into four classes as stated before - two classes of PCs and two of LTVs.

Step 2

Only two-vehicle, head-on crashes were selected as the target crash type from the NASS/CDS crash data as it is similar to the full frontal NCAP barrier tests. The head-on crash data include the crashes in which the frontal area of one vehicle impacts the frontal area of another. The vehicle body types selected are PCs, compact and large utility vehicles, and compact and large pick up trucks. NCAP crash test data for MY 2000-2007 were used in calculating the value of X that provided a direct measure of compatibility characteristics. In order to increase the number of cases available in the NASS/CDS database, all vehicle model years in the NASS/CDS database for ten years were included in the analysis. However, it is noted that the NCAP data used are for newer vehicles tested.

The number of injured drivers with AIS 3+ injuries is used as the outcome measure to calculate the effect of changes in the value of X. Only driver injuries are considered in this analysis to eliminate the errors that could result because of the varying occupancy rates in the vehicles involved.

Table 2 shows number of (un-weighted) drivers with and without AIS 3+ injuries in two vehicle head-on crashes. The numbers in the upper half of each cell in Table 2 represents the number of injured or uninjured drivers of the subject vehicle, while the numbers in the lower half of each cell represents the number of injured or uninjured drivers in other vehicle. The other vehicle represents the principal other vehicle involved in two vehicle full head on crash with the subject vehicle.

For example, comparing crashes between full size passenger cars (FPC) and compact light truck vehicles (CLTV), it is seen in the un-weighted data (shown in bold for this example) that there are 43 AIS 3+ injured drivers in full size passenger cars. There are also 99 un-injured drivers in FPCs (subject vehicle) in towed vehicles in the database. In the same manner, there are 36 AIS 3+ injured and 108 uninjured drivers in CLTVs (other vehicle).

The uninjured data from Table 2 are not used in any further calculations because odds ratio comparisons could not be made with out knowing the exact count of uninjured drivers in each vehicle class.

Table 2: AIS 3+ Drivers injured in two vehicle head-on crashes in subject vehicles and other vehicles, NASS/CDS 1997 to 2006 (un-weighted).

Subject Vehicle / Other Vehicle	Compact Passenger Car (CPC)		Full Size Passenger Car (FPC)		Compact Light Truck Vehicle (CLTV)		Large Light Truck Vehicle (LLTV)	
	Injured	Un-Injured	Injured	Un-Injured	Injured	Un-Injured	Injured	Un-Injured
Compact Passenger Car (CPC)	67 / 67	186 / 186						
Full Size Passenger Car (FPC)	96 / 59	224 / 262	23 / 23	61 / 61				
Compact Light Truck Vehicle (CLTV)	77 / 30	94 / 141	**43** / **36**	**99** / **108**	9 / 9	24 / 24		
Large Light Truck Vehicle (LLTV)	87 / 22	85 / 149	56 / 23	65 / 97	25 / 14	38 / 48	10 / 10	21 / 21

Table 3 gives the weighted number of injured drivers from the same data shown in Table 2, giving the number of injured drivers only.

Table 3 AIS 3+ Drivers Injured in two vehicle head-on crashes, CDS 1997 to 2006 weighted data.

Subject vehicle / Other vehicle	Compact Passenger Car (CPC)	Full size Passenger Car (FPC)	Compact Light Truck Vehicle (CLTV)	Large Light Truck Vehicle (LLTV)
Compact Passenger Car (CPC)	5212 / 5212			
Full size Passenger Car (FPC)	4908 / 3126	1625 / 1625		
Compact Light Truck Vehicle (CLTV)	7203 / 2470	5696 / 3178	1149 / 1149	
Large Light Truck Vehicle (LLTV)	6904 / 1452	3667 / 2275	2222 / 653	959 / 959

Step 3

This step calculates relative driver injury risk in two vehicle full head on crash. From Table 2 it is seen that the number of drivers injured in certain vehicle class interactions are small in the ten years of un-weighted NASS/CDS data. In the case of the small number of injured drivers in Table 2, the affect of weighting on calculations of weighted data shown in Table 3 is not well understood. Hence, using weighted data in this analysis is likely to cause larger errors because of the discrepancy in certain weights and, therefore, it was considered desirable to use the un-weighted data. Therefore, the relative risk for drivers is calculated from the un-weighted data. However, for the purpose of estimating benefits, the target populations available from the weighted data were used.

The relative risk of AIS 3+ injuries to the driver using the un-weighted data in each of the above four vehicle groups is calculated and shown in Table 4. Table 4 gives the relative risk of driver injuries in the vehicles classified as the subject vehicle when involved in two vehicle head-on crashes with a vehicle type shown as the other vehicle.

The relative risk for a specific vehicle class is determined by calculating the ratio of number of drivers injured in subject vehicles to those injured in other classes. For example, the relative risk of AIS 3+ driver injury in a CLTV, when involved in a head-on crash with a CPC is 0.39. This is obtained by dividing the number of drivers injured in CLTV by the number injured in CPC (30/77). The inverse of this number shows the relative risk of AIS 3+ driver injury in CPC when involved in a head-on crash with a CLTV (2.57). The relative risk is equal to 1 along the diagonal of the matrix in vehicle-vehicle interactions that involve vehicles belonging to the same class.

Table 4 Driver injury relative risks in two-vehicle head-on crashes (CDS 1997 - 2006 un-weighted data – Ratios of Injured)

Subject Vehicle / Other vehicle	Compact Passenger Car (CPC)	Full size Passenger Car (FPC)	Compact Light Truck Vehicle (CLTV)	Large Light Truck Vehicle (LLTV)
Compact Passenger Car (CPC)	1.00	0.61	0.39	0.25
Full size Passenger Car (FPC)	1.63	1.00	0.84	0.41
Compact Light Truck Vehicle (CLTV)	2.57	1.19	1.00	0.56
Large Light Truck Vehicle (LLTV)	3.95	2.43	1.79	1.00

Step 4

The calculated relative risk, from step 3, for the interactions of each vehicle type is then plotted against the height of the center of velocity change X for each of the four vehicle classes. Figure 5 is a plot of the relative risk and the height of the center of velocity change, X in inches. Median value of X for each vehicle class is used in developing the curves.

These plots are the best fit curves based on the four data points that represent the relative risk of driver injuries in each vehicle class in its interaction with all the other vehicle classes. Exponential fit yielded the best correlations and hence is used in generating the curves given in Figure 5. The range of values of X for each class is different. The curves in Figure 5 are plotted using the full range of X and the relative risks as one class of vehicle interacts with other classes of vehicles including its own class. i.e., different curves for each vehicle class indicate the risks of various vehicle class interactions and its relationship to X.

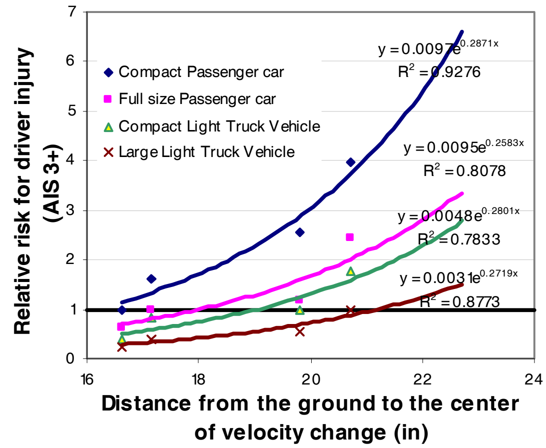

Figure 5: Relative risk vs distance X from the ground to the center of velocity change

Each of the curves for a specific vehicle class above shows the potential risk associated with frontal crashes involving a specific vehicle class and all the other vehicle classes.

For example, the top curve shows the risk of AIS 3+ injuries to compact passenger car drivers as they collide with vehicles in all the other classes. The values of X for the vehicle classes involved fall in a range of approximate 14 to 26 inches. The horizontal line showing a risk of 1.0 is the risk as a vehicle in a specific class collides with another vehicle of the same class. As expected, the curves plotted for each vehicle class is well correlated with the values of X as indicated by the R^2 values.

Step 5

The risk relationship between the subject vehicle and the other vehicle for PCs is shown in Figures 6 and 7. Figures 6 and 7 shows the change in risk with respect to X for CPC and FPC vehicle classes when they interact with all the other vehicle classes. As seen, when X for the other vehicle class increases, the risk of driver injury in subject vehicle increases. At the same time, the risk to drivers in the other vehicle class decreases. The intersection of the two curves indicates a risk of one. This point represents the risk to drivers in a specific vehicle class as they crash in to another vehicle class having same value for X.

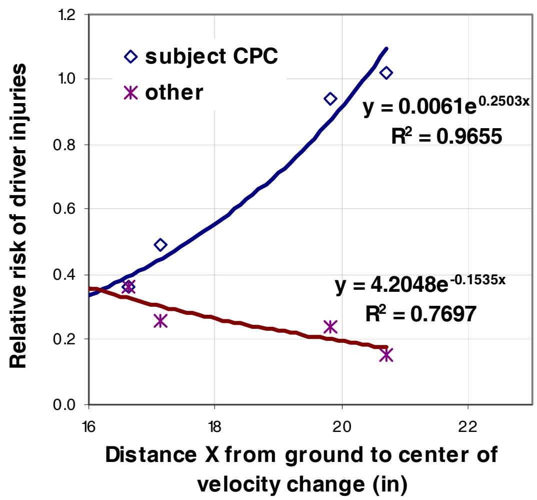

Figure 6 Relative risk for subject vehicle CPC (Using ratios of drivers injured)

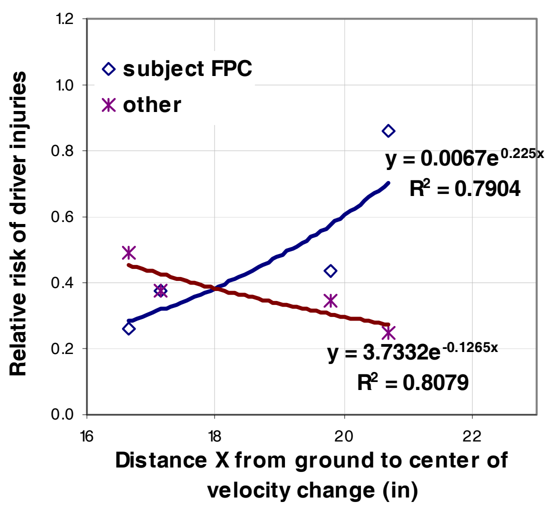

Figure 7 Relative risk for subject vehicle FPC (Using ratios of drivers injured)

Figures 8 and 9 are the same as described above, but, for CLTV and LLTV classes. From Figures 6 -9, it is clear that for PCs and LTVs, as the value of X for the other vehicles is increased, the risk to drivers in the subject vehicle increases, while the risk to drivers in the other vehicle decreases. These curves were generated based on risk calculations using the ratios of the number of injured drivers in pairs of interacting vehicle classes.

The pair of curves, shown in each of the Figures, 6, 7, 8, and 9, is the inverse of the other curve. Comparison of Figures 6 and 7, shows that the rate of increase of risk for subject vehicle CPC class is higher than increase in FPC for PCs. Similarly, for CLTV and LLTV (Figures 8 and 9), the rate of increase in risk is smaller in comparison to the PCs (Figures 6 and 7).

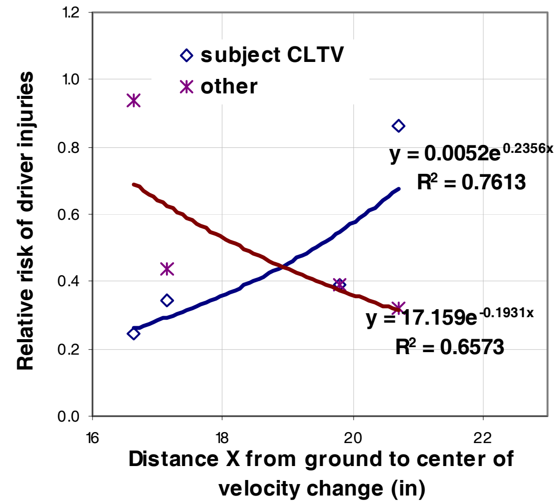

Figure 8 Relative risk for subject vehicle CLTV (Using ratios of drivers injured)

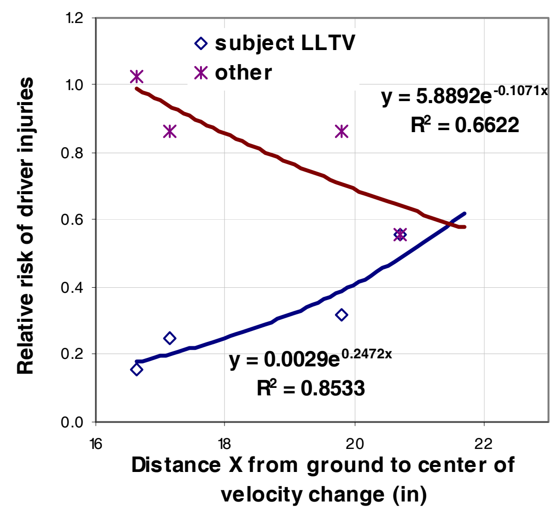

Figure 9 Relative risk for subject vehicle LLTV (Using ratios of drivers injured)

Step 6

In order understand the influence of X on injury risk a new curve for the subject vehicle could be plotted by changing the proportionality constant and the value of X in the exponent. This new curve will intersect with the curve representing the other vehicle classes. The point of intersection of the two curves defines the new risk and also specifies the value of X for the subject vehicle to make them more compatible with the other classes. Rather than changing the constants, it is easier to visualize the curve for other vehicles remaining constant while the subject vehicle curve is allowed to intersect the curve for the other vehicles as X for the other vehicle class is varied. The risk associated with the intersection points for each value of X can now be compared to the original risk to compute the change in risk.

The change in risk at the new intersection point can now be computed as a fraction of the original risk. This fraction represents the effectiveness for making the subject vehicle class meet a specific value of X. This effectiveness when multiplied by the target population of the total number of injuries that occur in crashes involving a specific subject vehicle class and all other classes will approximate the potential benefits in the specific subject vehicle class.

It is noted that in this analysis, the target population used is all AIS 3+ injuries in a specific vehicle class. These include the injuries that are due to mass disparities as well as differences, possibly in the values of X. Since the target population cannot be split up to separately account for the effect of each variable on the injury outcome in crashes, the estimated benefits are likely to be higher than what may result from changing the value of X.

These steps can now be repeated for each vehicle class to approximate the benefits in each class for the subject vehicles and the other vehicles. As can be seen, when X is varied for one class of vehicles, the benefits that may result in one class may be negated by the negative-benefits for the other. The combined benefits when all vehicle classes are made to comply with specific values of X can be approximated by summing up the benefits and negative benefits obtained class by class.

It is noted that, in this methodology each vehicle class interaction is treated as unique and the benefits calculated are upper bounds, because of the few benefits that result from the double counting involved each time the benefits are computed for interactions of one class of vehicles with all the other classes. Correcting for this discrepancy was not attempted each time. Since only the net benefits are of interest, an estimate of the over prediction is made and the net benefits are expressed as a range.

Assumptions used in the benefit calculations

1. The vehicle classifications developed from the NCAP data are equivalent to the classifications obtained from the NASS/CDS data.
2. The X values computed from the newer vehicles in NCAP data are similar to those vehicles including the older models in the fleet.
3. Relative risks derived from driver injury data in head-on crashes are only influenced by the compatibility metric X. However, in the current analysis, vehicle designs have not taken in to account X as a metric, the injuries that are seen in the fleet as it currently exists may be influenced by other factors such as mass and geometric disparities.
4. When the functional relationship between the risk for the drivers in subject vehicles and X for other vehicle classes is changed, it is assumed that the functional relationship between X and the risk for the other vehicle classes remain unchanged.
5. The benefits determined on the basis of AIS 3+ injuries reduced will equally apply to lesser injuries and fatal injuries irrespective of the crash conditions of speed and other variables.
6. The target population used for above includes the effect of all the variables that affect the injury outcome. Use of these numbers in estimating the benefits is likely to result in higher estimates than can be realized in actuality by changing the value of X
7. The head-on crashes selected from the NASS/CDS crash data have principal direction of force acting between 350 and 10 degrees for both the vehicles and are assumed to be similar to NCAP FMVSS No 208 crash tests.
8. As part of this study no case review (review of the accident case file) was conducted to verify whether the target population used in the benefit calculation would benefit from center of velocity change methodology.

Analytical methodology for evaluating benefits

Potential benefits of changing the value of X for various vehicle classes in the fleet were calculated from the target injuries that occur in all head-on frontal crashes between the subject vehicle class and the other classes including itself. For example, it is seen from Table 3 that there are a total of 24,227 AIS 3+ driver injuries in compact passenger cars in crashes involving all other passenger vehicle classes including other compact vehicles. Similarly, 12,260 AIS 3+ injuries occur in the other vehicle classes also in the ten year period in the NASS database (weighted) involving compact vehicles. Similarly, there are a total of 14,114 AIS 3+ driver injuries in FPC and 11,986 in other classes, 9019 in CLTV and 14,701 in others and 5,339 in LLTVs and 13,752 in other classes, respectively. Since the vehicles in the fleet are not designed by optimizing X , the injuries used in the target population include effect of all variables including mass differences

The relative risk of CPC in crashes involving all other classes were first calculated by varying the values of X in the range of 16.0 to 21.5 inches in increments of 0.5 inch and then in the same range in increments of 0.1 inch. The original relative risk for CPC as indicated by the point of intersection of the two curves seen in Figure 6 is 1.0 (at a value of X = 16.14 inches). Similarly, for each of the other subject vehicle classes FPC, CLTV and LLTV and the other classes, the intersection point and the associated value of X for each class is different. Figure 6 presents the curves for PCs and Figure 6 presents the data for LTVs.

These effectiveness fractions for subject vehicle and other vehicle classes are multiplied by their respective target populations to determine the potential benefits in each class interaction. The net benefits are then determined by adding up the potential benefits for each subject vehicle class and all other classes at a specific value of X.

Based on this analysis, it is concluded that there is no advantage in driving changes in the value of X in FPC and CLTV. On the other hand, there are potential safety benefits to be gained by changes in small passenger cars (CPC) and large light trucks and vans (LLTV) using this metric. As expected, the methodology used in the benefit calculations result in different total benefits as values of X are varied. True relative risks can only be determined if the number of injured and uninjured drivers in each vehicle class is known.

The NASS data provide the uninjured numbers for only the tow-away crashes. In two-vehicle crashes, the uninjured numbers do not include the uninjured in non-tow-away vehicles. Therefore, calculating the relative risk as an odds ratio may exaggerate the potential benefits and is not considered. On the other hand, when the relative risks are calculated on the basis of the injured drivers only, it is assumed that the number of uninjured drivers in the subject vehicles and the other vehicles are the same.

Performance scheme and rationale

While the analysis described is based on head-on crashes only, many other frontal crashes that are not strictly defined as head-on crashes may also derive benefits from the changes in the compatibility metric X. For example, even though the data did not include many other types of frontal crashes that are not included under head-on type, it is reasonable to assume that those crashes would also be helped when vehicles comply with this compatibility metric.

The value of X can be increased by changes in geometry and stiffness characteristics. For example, for small passenger cars, it is not practical to change geometry significantly. However, stiffness of such vehicles may be increased substantially to increase X. Beyond limits, this may require redesign of the restraint systems. Some small cars in today's fleet are already stiffening up their structures and therefore, the compatibility metric X for those vehicles may already be high even though they have a low front-end profile.

Based on the front NCAP test data for vehicles, a value of X can be computed for each vehicle. If those nominal values fall with in the prescribed metric +- a tolerance value, an enhanced rating for such vehicles in the smallest and largest vehicle class could drive compatibility with out adding a new test or incurring additional cost for compliance evaluations. The full size passenger cars and the crossover vehicles could be left alone as they do not appear to provide any appreciable benefits when the value of X is changed for those classes.

Conclusion

Using the methodology described the overall safety benefits can be estimated by calculating the reduction in the number of drivers with AIS 3+ injuries in all frontal crashes as well as in side crashes by making the vehicles in the fleet comply with selected values of X. However, initially the benefits are estimated for head-on crashes only after validating the methodology described in this paper.

Additional estimates for side crashes can only be attempted once the necessary data related to side crashes and H-point heights in struck vehicles are obtained. It must be noted that, the relevant metric for side crashes is not likely to be just the value of X for striking vehicles, but also the difference between X for the striking vehicles and the height from the ground to the H-point (h) in struck vehicles. It is assumed that the relative risk of injuries in side crashes will be influenced by the new metric, (X - h). This new metric has to be derived from side NCAP data and a functional relationship between this metric and side crash injuries will have to be developed before applying the methodology for the benefits calculation. Absence of relevant H-point data for various vehicle classes prevented the development of a preliminary benefit estimate for side crashes. However, it is noted that at least for passenger cars, the H-point heights are close to each other, irrespective of the size of the vehicle. Therefore, it is reasonable to assume h to be a constant for passenger cars. Based on this assumption, available side

NCAP data for passenger cars could be used to develop the relationship between (X-h) and the real world relative risks in side crashes as various classes of vehicles strike the sides of passenger cars. Using this methodology, it can be attempted in the future as H-point data become available for light trucks as well.

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