EVALUATION OF STIFFNESS MEASURES FROM THE U.S. NEW CAR ASSESSMENT PROGRAM

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ABSTRACT

Stiffness has been used to characterize a vehicle's crash behavior, and how it acts with collision partners and roadside structures. It also plays an important role in restraint design. This paper utilized crash test data from the 1982 to 2001 frontal U.S. New Car Assessment Program to evaluate three methods for computing vehicle stiffness. Test parameters, such as load cell force, dynamic displacement and measured crush, were used to compare stiffness trends in the passenger car fleet. Each method predicted a steady increase in passenger car stiffness.

Force-deflection profiles were averaged and examined historically for each passenger car class. Results were compared against light trucks, vans and sport utility vehicles (LTVs) to maintain fleet perspective. The initial stiffness method was then used to quantify stiffness of each passenger car and LTV class. Within some vehicle classes, there was a wide range of initial stiffness measures for a given test weight.

INTRODUCTION

Since 1979, the U.S. National Highway Traffic Safety Administration (NHTSA) has been providing consumers with comparative frontal crashworthiness information on new passenger vehicles through the New Car Assessment Program (NCAP). This, first of its kind, program was initiated in response to Title II of the Motor Vehicle Information and Cost Savings Act of 1973. In frontal NCAP, vehicles are evaluated based on the crash protection they provide in a 56 km/h full-frontal rigid barrier test. Accelerometers are mounted on the vehicle structure and belted 50th percentile Hybrid III dummies are positioned in the driver and right front passenger seats to evaluate occupant protection. In 1982, NHTSA added load cell instrumentation to the rigid barrier face to collect data on the forces vehicles apply to the barrier. In addition, supplemental post-test data collection measurements were made to study the structural characteristics of vehicles, including stiffness.

The need to understand front-end stiffness has been paramount in crashworthiness research studies for a number of reasons. First, stiffness is one of the main parameters studied in vehicle compatibility research to understand how vehicles behave when they interact with a collision partner. Stiffness, as well as other parameters, such as mass and geometry, play important roles in efforts to manage energy and improve structural engagement in vehicle-to-vehicle crashes. Second, stiffness is an important parameter for designing a vehicle's frontal restraint system to ensure that a vehicle provides sufficient protection to its occupants.

For many years, a number of research papers have been written discussing the role that stiffness plays in vehicle compatibility (Summers 2002, Nolan 2001, Hollowell 1999, Saul 1981). The significance arises in vehicle-to-vehicle crashes where there is an incompatibility in vehicle stiffness, the stiffer vehicle will absorb less of the crash energy and deform less than its collision partner. Depending on the degree of stiffness difference between the two vehicles, the less-stiff collision partner may be forced to absorb the bulk of the crash energy and reduce its occupant compartment integrity. This can result in an undesired disparity in the injury outcome between the occupants of the two vehicles. From a compatibility perspective, the preferred scenario would be for both vehicles to share the crash energy (Hollowell 1999). To do this, vehicles must have sufficiently stiff front ends to provide self-protection in crashes, but not have front ends so stiff that they cause harm when involved in a collision with a partner vehicle (Zobel 1999).

Vehicles with very stiff front-end structures require the crash energy management to rely heavily on the occupant restraint system (i.e., air bag, seat belts, pretensioners, etc.). By knowing a vehicle's stiffness characteristics during the design phase, optimization can be achieved through computer models (Deng 1994). This facilitates a restraint designer's ability to determine when and how to deploy frontal air bags and pretensioners.

Between vehicle compatibility, occupant restraint design, and overall vehicle crashworthiness, there is significant need for a better understanding of vehicle stiffness; however, there is not a single agreed-upon methodology for characterizing this measure. Traditionally, researchers have used a variety of load cell instrumentation, post-crush deformation, and accelerometers mounted on the vehicle under test, individually or in combination. Therefore, this paper attempts to explore and compare three proposed methodologies for calculating vehicle stiffness using a subset of NCAP frontal crash test data. The methods explored include: initial stiffness, static stiffness, and dynamic stiffness.

Passenger cars tested under the NCAP program were used to evaluate the three stiffness methodologies based on the hypothesis that passenger cars would show the most dramatic flux in vehicle stiffness during the 1982-2001 model year (MY) time frame. This hypothesis was based, in part, upon past studies that examined the NCAP crash test responses of 175 light trucks and vans (LTVs) distributed over MY 1983-1999 (Park 1999). The previous study found little change in LTV stiffness, as a group. Additionally, as discussed further in the paper, NHTSA has noticed little variation in the force-deflection characteristics of the LTV fleet. Therefore, MY 1982-2001 passenger cars were selected as the target group to explore the three methodologies.

DATA COLLECTION

For the majority of frontal NCAP tests, the load cell instrumentation attached to the fixed barrier consisted of 36 load cells in a 4 x 9 array. An example of how the load cells align with a vehicle is shown in Figure 1.

Figure 1: Example Load Cell Barrier (4x9 array).

The 36 force-time history data signals generated from the load cells were collected at 8,000 – 10,000 samples per second for the majority of the tests (depending upon the best-practices of the time). More recent NCAP crash tests collected the data at 10,000 samples per second. The data was then filtered according to the Society of Automotive Engineers Recommended Practice J211/1 rev. Mar 95, “Instrumentation for Impact Test – Part 1 – Electronic Instrumentation.” The load cell data traces were then summed to calculate the total force acting on the barrier over time. We note that a small number of NCAP tests used a load cell barrier with a coarser resolution (6 load cells in a 2 x 3 array). While the resolution of the force distribution may be slightly inferior to the 4 x 9 array, it is appropriate to use this data for the purposes of this study since it has no effect on the total force exerted on the barrier. Overall, NHTSA has collected load cell data for 792 frontal NCAP tests.

For each NCAP test, vehicle acceleration data and post-test crush measurements were also collected. Different locations on the vehicle structure were considered for analysis of vehicle acceleration. For the purposes of this study, accelerometers mounted in the occupant compartment closest to the driver were used to gather vehicle acceleration data. Post-test crush measurements were extracted from the NCAP final test reports by computing the difference between pre and post-test measurements of the vehicle length.

APPROACH

This study uses available NCAP data collected for MY 1982-2001 passenger car tests to evaluate three methodologies for calculating vehicle stiffness. In this study, no extrapolations were made to sales or registration volumes, so the data is not meant to represent fleet projections; rather it reports stiffness trends for NCAP-tested vehicles for the model years under study.

NCAP reporting classifies passenger cars into five categories based on their curb weight. These include: mini (680-907 kg), light (907-1134 kg), compact (1134-1360 kg), medium (1360-1587 kg) and heavy (1587 kg and over). However, for the purposes of this study, *test weight* was used instead of curb weight to group the passenger car classes, since the mass of the test vehicle is important in stiffness calculations. Test weight includes the weight of two Hybrid III 50th percentile dummies and the vehicle-rated cargo weight, so it is greater than the curb weight. Table 1 lists the passenger car classes and the respective test weights used in the paper. Effectively the test weight categories represent the standard NCAP categories + 159 kg cargo weight.

Since very few passenger cars fall into the *mini* class, no attempt was made to discuss stiffness trends for this particular vehicle class. However, the data for the mini class were included in the calculations made for "all passenger cars."

Table 1: Passenger Car Classes

Class	Test Weight (kg)
Mini	839 – 1065
Light	1066 – 1292
Compact	1293 – 1519
Medium	1520 – 1746
Heavy	1746 and over

The next three sections dicuss the methodologies for determining vehicle stiffness.

Method 1: Initial Stiffness

The first method computes, what we have termed, the *initial stiffness* of a vehicle. This method attempts to quantify a vehicle's stiffness characteristics from the early portion of the force-deflection profiles that result from NCAP tests. These force-deflection profiles are generated using force exerted on the barrier plotted against the dynamic deformation or crush that the vehicle experiences during the duration of the test. The dynamic deformation (or crush) was calculated by double-integrating the acceleration recorded by the vehicle accelerometers. This data was truncated at time zero and resampled in one-millimeter increments to facilitate the averaging of the force-deflection profiles. Figure 2 is an example force-deflection plot with an estimated linear stiffness range.

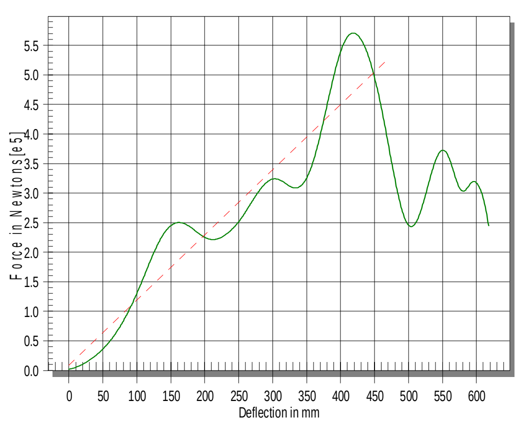

Figure 2: Example Force-Deflection Profile and Linear Fit.

For this study, force-deflection profiles were generated for 400 passenger vehicles tested in U.S. NCAP between 1982 and 2001. Even though NHTSA has collected load cell data for 543 passenger car NCAP tests, only 400 were suitable for analysis. The other 143 NCAP tests were disqualified due to errors in the load cell data collection. These were determined by reviewing the force-deflection profiles for each NCAP test by hand and analytically comparing the response characteristics to those from the vehicle's accelerometer data. Errors in the load cell data were notably more common in the older NCAP tests. Additionally, in 1998, NCAP did not collect load cell data, so this MY is not represented in the results.

Once the force-deflection profiles were created for the 400 qualifying NCAP tests, it was necessary to develop a systematic and repeatable approach to quantify the initial stiffness (or slope of the force-deflection curve). Several linear fit variations were evaluated. Desirable characteristics of the methodology included:

- A good correlation of linear fit (R^2 value).
- An emphasis on the initial deformation of the vehicle.
- A reflection of the overall slope (i.e., not limited to short regional behavior).
- An allowance for non-zero intercepts.

Further refinement of these characteristics, ultimately led NHTSA to the proposal that good correlation with initial stiffness would be a R^2 value greater than 0.95 (Summers 2002). It was also decided that the correlation should begin within the first 200 millimeters of deflection to emphasize the vehicle's initial deformation, and in order to reflect the overall slope, the linear stiffness had to correlate for a minimum distance of 150 millimeters. The longest correlation that met all of the criteria was chosen for the initial stiffness. Additionally, to compensate for small variations in time zero data collection, the linear fits were not constrained to zero force at zero deflection. For some tests, the curves did not fall through this point either because, the instrumentation did not start measuring the barrier force until the contact switches were fully engaged, or minor amounts of force were measured prior to the indicated time zero.

Out of the qualifying 400 passenger car NCAP tests with acceptable force-deflection profiles, 11 were further removed from the initial stiffness analysis because they did not have a suitable linear region. However, the remaining 389 tests predominantly met expectations, as shown in Figure 2.

Figure 3 depicts the initial stiffness values computed for NCAP tests of 1982 – 2001 passenger cars averaged in four model year clusters. (The data is provided in Table 1 of the Appendix). The graph shows a gradual increase of initial stiffness, starting with 1044 N/mm in the early 1980's to 1376 N/mm in current model years. This method estimates a 32 percent increase in vehicle stiffness over the past twenty years of NCAP data collection.

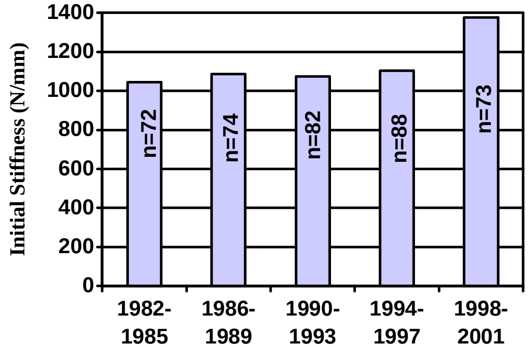

Figure 3: Average Initial Stiffness Measures for 1982-2001 MY Passenger Cars Tested in NCAP.

Figure 4 shows the trends for each individual passenger car class; however, vehicle classes that had less than 10 NCAP tests were omitted from the plot. Since the individual classes each have smaller sample sizes, more variance is evidenced in the trends. Light passenger cars show little change in initial stiffness while the other classes showed an increase.

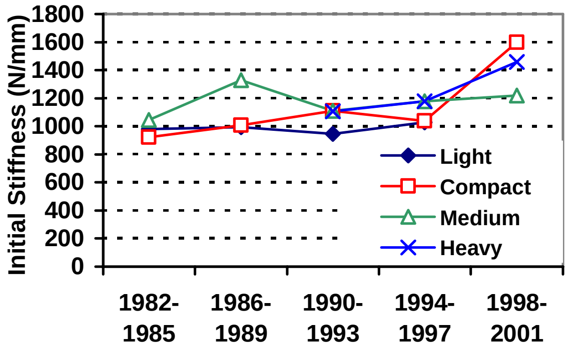

Figure 4: Average Initial Stiffness Measures for 1982-2001 MY Passenger Car Vehicle Classes Tested in NCAP.

Method 2: Static Stiffness

The second method computes a vehicle's static stiffness using only the post-crash static crush measurements. In terms of data collection, this is a relatively simpler approach and is often used in crash reconstruction programs, such as CRASH3. However, static stiffness does not account for vehicle rebound or the elastic behavior often found in the vehicle front-end structure.

Static stiffness is calculated from the following energy equation:

$$E = \frac{1}{2}MV^2 = \frac{1}{2}KX^2 \qquad (1.)$$

or solving for stiffness, K

$$K = \frac{MV^2}{X^2} \qquad (2.)$$

where M is the mass of the test vehicle, V is the closing speed of the test vehicle, and X is the maximum static crush of the vehicle. As previously discussed, the maximum crush is determined from the difference of pre and post-test measurements of the vehicle length.

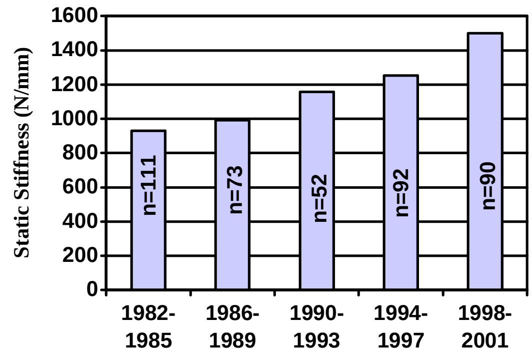

Figure 5: Average Static Stiffness Measures for 1982-2001 MY Passenger Cars Tested in NCAP.

A total of 418 passenger car NCAP tests were evaluated for static stiffness. Figure 5 shows the average static stiffness for passenger cars tested from 1982 to 2001, grouped in four model year clusters. Again, when considering all passenger cars NCAP has tested, an increasing trend in static stiffness is observed over the reported time period. The average static stiffness rose from 931 N/mm in the early 1980's to 1500 N/mm for

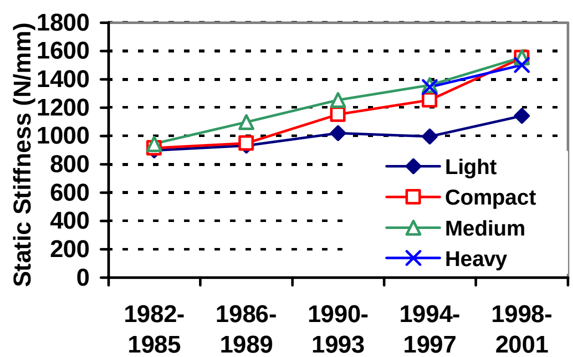

Figure 6: Average Static Stiffness Measures for 1982-2001 MY Passenger Car Vehicle Classes Tested in NCAP.

the present day vehicles. This is approximately a 61 percent increase in stiffness over the past twenty years of NCAP data collection.

Figure 6 shows the trends for each individual passenger car class; however, again, vehicle classes that had less than 10 NCAP tests were omitted from the plot. While the plot shows some deviation for the heavy and light vehicles in the 1990-1993 time period, overall there is very little difference of static stiffness between different passenger car classes. All passenger car classes show a significant increase in static stiffness between 1997 and 2001. Post-test crush measurements were also reduced on average from 615 mm in the early 1980's to 532 mm in the more recent model years. The average values are included in Table 2 of the Appendix.

Method 3: Dynamic Stiffness

The third method to approximate vehicle stiffness is termed dynamic stiffness. Dynamic stiffness is similar to static stiffness in that it uses Equation 2 from above; however, accelerometers mounted in the vehicle are used to estimate the maximum dynamic displacement. The dynamic displacement is calculated from the maximum of the double integral of the vehicle acceleration. Unlike static stiffness, vehicle rebound off the barrier is incorporated into the calculation of dynamic stiffness. Our experience has shown that the typical rebound for an NCAP test is 8-10 km/h.

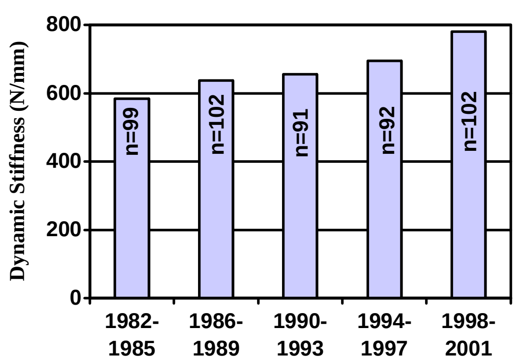

Figure 7: Average Dynamic Stiffness Measures for 1982-2001 MY Passenger Cars Tested in NCAP.

Figure 7 depicts the dynamic stiffness values computed for 486 NCAP tests of 1982 – 2001 passenger cars averaged in four model year clusters. The graph shows that the average dynamic stiffness has steadily increased, beginning at 584 N/mm in the early 1980's to 781 N/mm for present day vehicles. This method estimates a 34 percent increase in vehicle stiffness over the past twenty years of NCAP data collection.

Figure 8 shows the dynamic stiffness trends for each individual passenger car class (omitting classes that had less than 10 NCAP tests). Light passenger cars showed little change in dynamic stiffness, while other car classes show an increase in later model years. This is consistent with the calculated dynamic crush steadily decreasing for each vehicle class (Table 2 of Appendix).

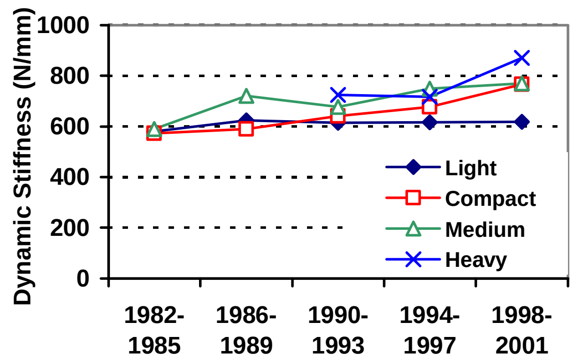

Figure 8: Average Dynamic Stiffness Measures for 1982-2001 MY Passenger Car Vehicle Classes Tested in NCAP.

ANALYSIS OF METHODS

Overall, the three methods of computing vehicle stiffness showed similar trends. They each showed that the average passenger car front-end stiffness steadily increased on average over the past twenty years of NCAP testing, with the greatest increase occurring in the mid-to-late 1990's. However, depending on the methodology, the stiffness increases ranged from 21 to 61 percent of the stiffness metric under investigation. Figure 9 is a plot comparing the three methods.

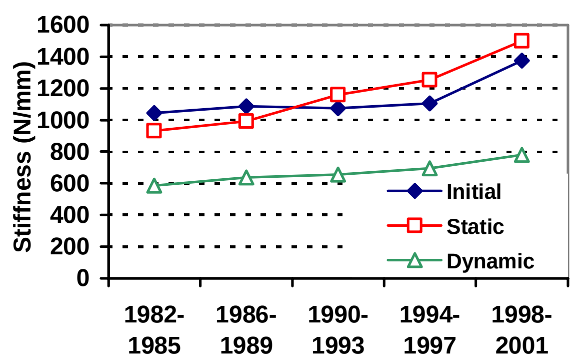

Figure 9: Comparison of Stiffness Methods for 1982-2001 MY Passenger Cars Vehicle Classes Tested in NCAP.

The initial stiffness and dynamic stiffness methods both show a relatively gradual increase in stiffness over the range of model years tested. The initial stiffness method predicted a 21 percent increase, whereas the dynamic stiffness method predicted a 34 percent increase. Both of these methods use the dynamic displacement calculated from the vehicle's accelerometers to compute stiffness.

The static stiffness method, however, shows two relatively large jumps in vehicle stiffness. The first was between the late 1980's and early 1990's and the second was between the late 1990's and 2001. This method also predicted a 61 percent increase in vehicle stiffness over the range of model years tested (two to three times what was predicted with the initial and dynamic stiffness methods, respectively). The difference may largely be due to the fact that the static stiffness method relies upon the post-test crush measurements for displacement, rather than the dynamic (accelerometer-based) measurements used in the other two methods. By only considering the post-crash crush measurements, some of the deformation that occurred during the crash, but rebounded back at the end of the crash (due to energy absorbing elements or materials) was not taken into account. Thus, less deformation used in the static stiffness calculation led to larger stiffness calculations for this method (see Equation 2).

Figure 10 compares the static crush measurements to the calculated dynamic displacement using the vehicle accelerometers. As expected, the dynamic displacement was typically 150-200 mm greater than the measured static crush. There is also a decrease in crush with newer model year vehicles. Figure 10 also shows that the average elastic crush occurring during the crash (that rebounded post-crash) has increased for passenger cars from 160 mm in the 1980's to 190 mm in the 1990's. Therefore, the two methods that use dynamic displacement in the stiffness calculations may be more realistic with present vehicle designs that include elastic composites and energy absorbing members.

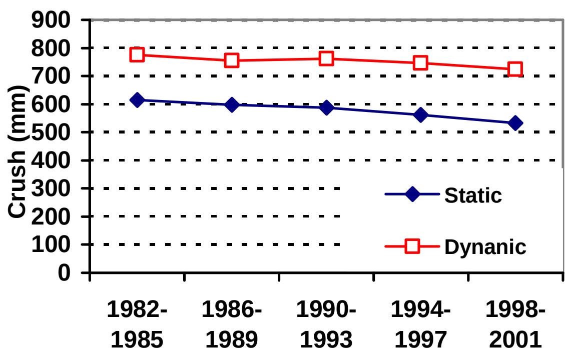

Figure 10: Comparison of Stiffness Methods for 1982-2001 MY Passenger Cars Vehicle Classes Tested in NCAP.

To study the real world significance of the various stiffness methods, NHTSA and other researchers (Joksch 2000) have conducted multi-variable regression analyses with crash data. Specifically, Joksch examined injury risk in vehicle-to-vehicle crashes and the influence of static and dynamic stiffness values, amongst others variables. While the study found no consistent relationship between injury risk increase and static or dynamic stiffness, the study did suggest other variables should be considered for future vehicle compatibility studies. One suggestion was to consider stiffness at various levels of deformation (instead of the overall deformation used in both the static and dynamic methods). The initial stiffness method discussed in this paper (Method 1) coincides with this suggestion. Initial stiffness, by definition, examines only the initial portion of crush. NHTSA has expanded the analysis, as suggested by Joksch, to include initial stiffness, and preliminary results appear to show better correlation than either static or dynamic stiffness methods.

DISCUSSION

Each of the three stiffness methodologies suggests that passenger cars tested in NCAP are becoming increasingly stiffer on average. As an additional check, the force-deflection profiles used in the initial stiffness calculations were averaged by vehicle class for three different time periods: 1982-1989, 1990-1995, 1996-2001. The slopes of the initial ~200 mm of deflection were examined as an indicator of vehicle stiffness (i.e., the sharper the rise of the curve, the stiffer the front-end characteristics were likely to be). Figures 11-14 plot the average force-deflection profiles for light, compact, medium, and heavy passenger cars, respectively. For

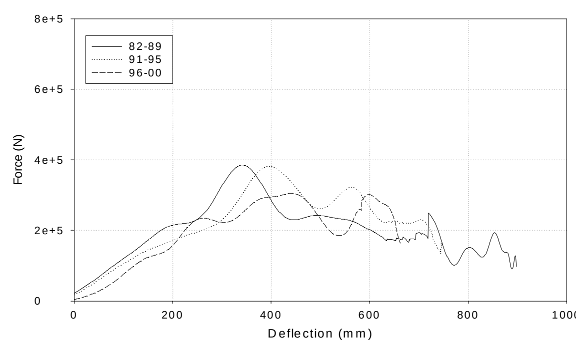

Figure 11: Average Force Deflection Curves for Light Passenger Cars Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

the light passenger car class, Figure 11 shows that over the first 200 mm of deflection, the initial stiffness has not changed substantially. The initial parts of the curves are approximately parallel to one another (or similar in slope).

However, for compact passenger cars, shown in Figure 12, there appears to be more of a shift in the stiffness characteristics for this vehicle class. The compact passenger vehicles tested between 1996-2001 exhibit a rapid rise of the force-deflection curve, indicative of a stiffer structure.

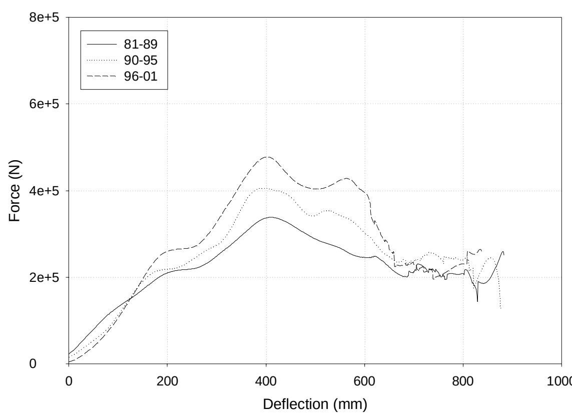

Figure 12: Average Force Deflection Curves for Compact Passenger Cars Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

A similar trend in increasing stiffness with later model years is evidenced in Figure 13 for medium passenger cars and Figure 14 for heavy passenger cars. For example, in Figure 13 the force required to crush the average medium passenger car 200 mm was

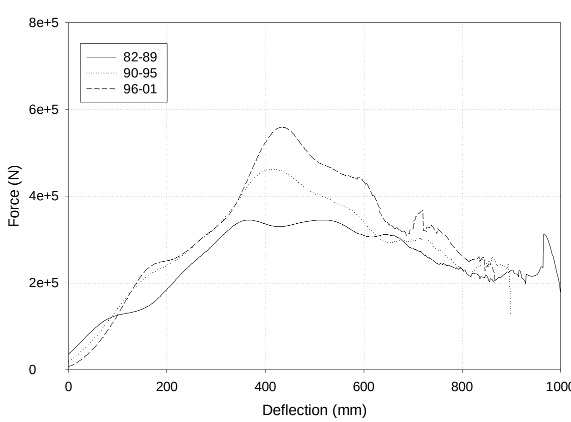

Figure 13: Average Force Deflection Curves for Medium Passenger Cars Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

approximately 190 kN for model year 1982-1989 vehicles. In later model years, this same required force increased to approximately 250 kN, thus demonstrating an increase in structural behavior.

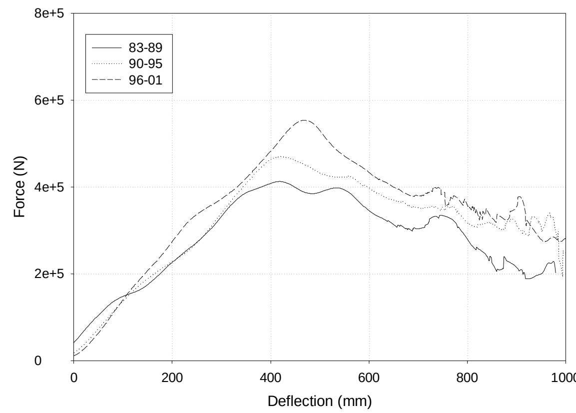

Figure 14: Average Force Deflection Curves for Heavy Passenger Cars Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

While the data shows an increasing trend in passenger car stiffness with later model years, this conclusion must be placed in perspective when considering the full spectrum of light vehicles in the fleet. On average, passenger cars still tend to be much less stiff than LTVs. Figure 15 is a plot comparing the average force deflection profiles for four passenger car classes with three LTV classes (sport utility vehicles (SUVs), vans, and trucks). This data represents the average of NCAP tests from 1982-2001.

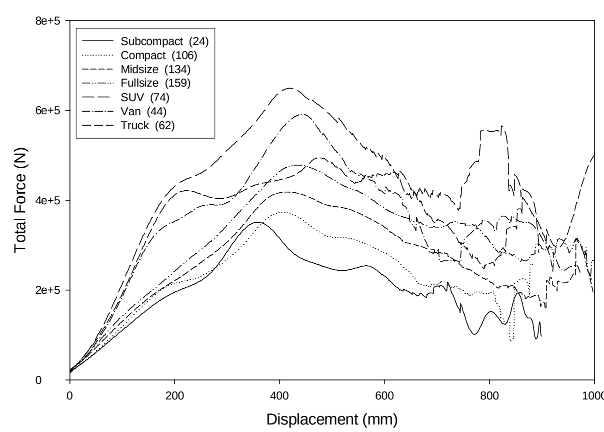

Figure 15: Average Force Deflection Curves for Seven Vehicle Classes in NCAP (1982-2001).

The four passenger car classes have relatively similar force-deflection characteristics with subcompact (or light) passenger vehicles being the less stiff and full-size (or heavy) being the stiffest of the four. Each of the three LTV classes is considerably stiffer than each of the passenger car classes. The LTVs range from vans to trucks to SUVs in order of increasing stiffness.

However, when considering trends in LTV force-deflection characteristics over the twenty-year NCAP data collection, the average force deflection profile has been relatively steady. Figures 16-18 are the average force-deflection profiles for light trucks, SUVs and vans, respectively, for the same three time periods. When considering the first 200 mm of crush, light trucks, SUVs and vans have not changed much in their force-deflection characteristics, particularly between 1990-2001. However, the vans tested in the 1996-2001 time frame appear to have become less stiff on average.

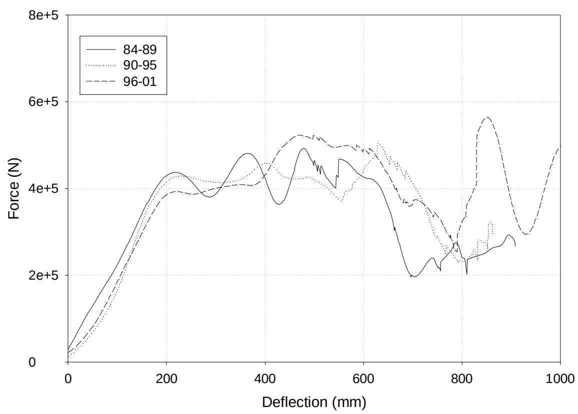

Figure 16: Average Force Deflection Curves for Light Trucks Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

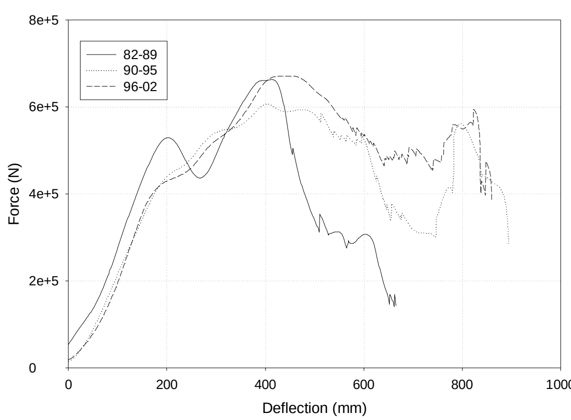

Figure 17: Average Force Deflection Curves for SUVs Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

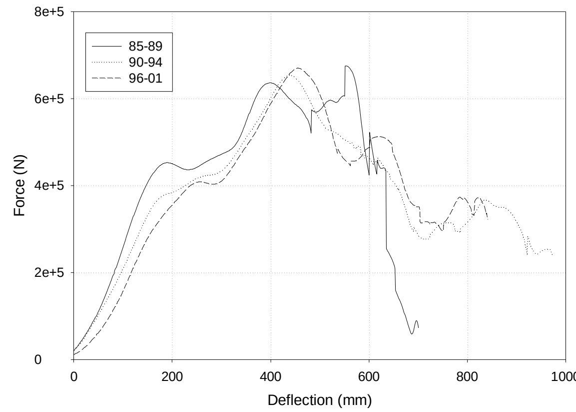

Figure 18: Average Force Deflection Curves for Vans Tested in NCAP (1982-1989, 1990-1995, and 1996-2001).

To better quantify LTV stiffness in comparison to passenger cars, the initial stiffness (Method 1) was computed for the LTV data. Figure 19 illustrates the average initial stiffness measurements and first standard deviation bars for seven vehicle categories of NCAP data collected between 1982-2001. This figure shows that initial stiffness generally increases with test weight and substantially higher initial stiffness measurements result from the SUV and truck categories.

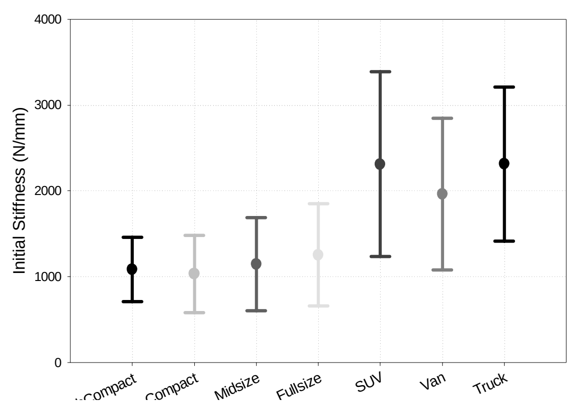

Figure 19: Average Initial Stiffness Measurements and First Standard Deviation Bars for Seven Vehicle Classes Tested in NCAP (1982-2001).

It is also interesting to note how large the stiffness ranges are for the SUV, van, and truck categories (illustrated by the first standard deviation bars). For instance, the average SUV initial stiffness ± one standard deviation spans a stiffness range of approximately 2000 N/mm. This is approximately twice as large as those reported for the three passenger car categories. The stiffness ranges for the three LTV categories also demonstrate some overlap with the passenger car stiffness ranges in the 1200-1800 N/mm region. This suggests that compatible vehicle designs between passenger cars and LTVs may exist in the fleet.

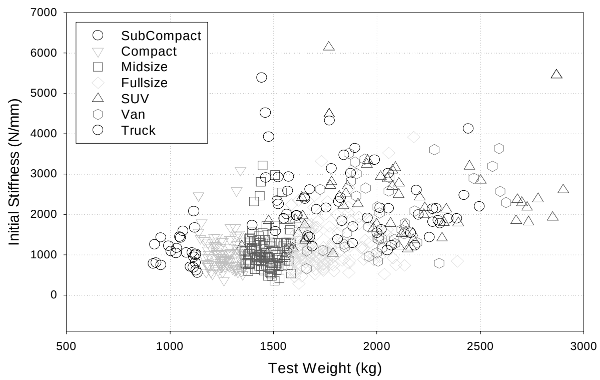

Figure 20: Initial Stiffness Values for Seven Vehicle Classes Tested in NCAP (1982-2001).

Finally, Figure 20 is a scatter plot of the initial stiffness metric computed from vehicle NCAP tests from 1982 to 2002 compared to their respective test weights. The purpose of this plot is to illustrate that within some vehicle classes, there is a wide range of initial stiffness values for a given test weight. For example, SUVs with a test weight of 1800 kg can have an initial stiffness value as low as 1000 N/mm or as high as 6000 N/mm.

CONCLUSIONS

There are multiple methods for calculating a vehicle's front-end stiffness. This study examined three methods using passenger car data from NCAP tests conducted between 1982-2001. The methods included: initial stiffness, static stiffness, and dynamic stiffness. Two of the methods, initial stiffness and dynamic stiffness, showed a steady increase in passenger car stiffness over the model years under study (21 percent and 30 percent, respectively). The static stiffness method predicted much greater increases in stiffness due to its reliance on static crush data that cannot account for elastic front-end structures rebounding back after the crash. The findings also showed that the average elastic crush occurring during the crash (that rebounded post-crash) has increased for passenger cars from 160 mm in the 1980's to 190 mm in the 1990's.

To study the real world significance of the various stiffness methods, NHTSA and other researchers have conducted multi-variable regression analyses with crash data. However, these studies found no consistent relationship between injury risk increase and static or dynamic stiffness methods. NHTSA has expanded the analysis conducted by Joksch, to include initial stiffness, and preliminary results appear to show better correlation than either static or dynamic stiffness methods.

Average force-deflection plots were generated for the various passenger car classes and confirmed increasing stiffness trends predicted by the previous two methods. Similar plots were generated for three LTV classes. While LTVs tended to be much stiffer than the passenger car classes, their stiffness characteristics have not changed as much over the same time period.

Finally, passenger car and LTV classes were compared using the initial stiffness method. The study found that initial stiffness generally increases with test weight and substantially higher initial stiffness measurements result from the SUV and truck categories. Furthermore, within some vehicle classes, there is a wide range of initial stiffness values for a given test weight.

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Appendix - Table 1.
Average Initial Stiffness Measures from Passenger Car NCAP Tests

Initial Stiffness												
	All		*Mini*		*Light*		*Compact*		*Medium*		*Heavy*	
Year	*n*	*Stiffness (N/mm)*	*n*	*Stiffness (N/mm)*	*n*	*Stiffness (N/mm)*	*n*	*Stiffness (N/mm)*	*n*	*Stiffness (N/mm)*	*n*	*Stiffness (N/mm)*
1982	13	997	0		2	669	8	1023	3	1146	0	
1983	14	795	0		4	785	6	670	3	707	1	1853
1984	24	1159	1	1439	9	1115	7	979	5	908	2	2475
1985	21	1107	2	1416	2	1066	9	950	8	1216	0	
1982-1985	72	1044	3	1423	17	979	30	920	19	1043	3	2267
1986	9	917	0		5	873	2	872	2	1073	0	
1987	22	1074	2	1422	8	943	9	977	3	1486	0	
1988	22	1232	2	1149	4	1265	6	1174	8	1400	2	744
1989	21	1021	2	770	3	965	8	950	3	1153	5	1190
1986-1989	74	1087	6	1113	20	993	25	1007	16	1329	7	1063
1990	22	1102	0		3	717	7	1314	7	1066	5	1087
1991	20	1070	0		6	968	7	1168	5	880	2	1509
1992	20	1014	2	967	2	791	6	930	6	1269	4	893
1993	20	1105	0		5	1119	7	999	7	1180	1	1250
1990-1993	82	1073	2	967	16	946	27	1109	25	1109	12	1106
1994	21	1142	0		1	1367	10	1130	6	1236	4	976
1995	33	1177	0		8	1036	9	1061	12	1330	4	1265
1996	18	1100	0		5	974	3	1052	3	963	7	1269
1997	16	908	0		2	965	7	870	4	789	3	1118
1994-1997	88	1104	0		16	1028	29	1038	25	1177	18	1178
1998	2	2025	0		0		0		1	531	1	3519
1999	13	1041	0		3	786	2	1149	4	1034	4	1185
2000	20	1237	1	1041	1	697	4	1127	8	1248	6	1418
2001	38	1530	0		3	1906	9	1910	13	1308	13	1402
1998-2001	73	1376	1	1041	7	1254	15	1600	26	1218	24	1458

Appendix - Table 2.
Average Static Stiffness and Static Displacement Measures from Passenger Car NCAP Tests

Static Stiffness																		
	All			***Mini***			***Light***			***Compact***			***Medium***			***Heavy***		
Year	*n*	*Stiffness (N/mm)*	*Displacement (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*
1982	35	938	599	1	1955	356	8	813	604	23	939	599	2	888	655	1	991	688
1983	21	914	640	0			5	879	590	7	789	660	7	992	658	2	1162	629
1984	31	944	612	2	806	569	10	954	557	9	1016	582	7	805	702	3	1110	699
1985	24	919	620	2	711	594	4	946	573	10	858	633	8	1033	632	0		
1982-1985	111	931	615	5	998	536	27	897	579	49	915	611	24	943	662	6	1108	674
1986	23	938	615	1	1125	480	8	849	596	6	944	610	8	998	654	0		
1987	23	943	598	2	1076	480	6	922	568	11	922	623	4	964	631	0		
1988	27	1082	585	2	969	516	7	1037	541	5	1009	600	10	1233	583	3	883	718
1989	0			0			0			0			0			0		
1986-1989	73	993	598	5	1043	494	21	932	570	22	948	614	22	1099	617	3	883	718
1990	7	1700	500	0			0			3	1053	563	2	2782	387	2	1587	519
1991	12	1022	620	0			6	1106	603	3	897	628	3	978	644	0		
1992	11	1070	595	1	877	536	1	809	602	5	1283	520	2	1041	640	2	796	764
1993	22	1103	593	0			5	961	558	7	1210	540	8	1031	665	2	1370	583
1990-1993	52	1158	587	1	877	536	12	1021	584	18	1152	553	15	1255	620	6	1251	622
1994	22	1211	576	0			1	758	637	12	1286	541	6	1218	586	3	1051	674
1995	33	1279	551	0			8	988	561	9	1246	536	12	1470	537	4	1362	607
1996	19	1257	565	0			5	1065	531	3	1213	533	4	1193	593	7	1451	586
1997	18	1259	561	0			3	979	545	7	1228	547	4	1413	557	4	1366	603
1994-1997	92	1254	562	0			17	995	554	31	1254	540	26	1360	560	18	1346	609
1998	27	1427	538	0			3	1007	560	6	1639	478	15	1452	539	3	1296	629
1999	15	1389	545	0			3	1102	537	2	1619	464	6	1560	532	4	1233	611
2000	21	1677	508	1	2024	349	1	971	564	4	1593	480	8	1917	485	7	1502	566
2001	27	1496	537	0			3	1377	458	6	1417	495	7	1363	561	11	1657	565
1998-2001	90	1500	532	1	2024	349	10	1143	523	18	1552	482	36	1556	530	25	1502	580

Appendix – Table 3.
Average Dynamic Stiffness and Dynamic Displacement Measures from Passenger Car NCAP Tests

Dynamic Stiffness																		
	All			***Mini***			***Light***			***Compact***			***Medium***			***Heavy***		
Year	*n*	*Stiffness (N/mm)*	*Displacement (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*	*n*	*Stiffness (N/mm)*	*Disp (mm)*
1982	26	539	796	0			9	528	772	12	545	788	4	539	840	1	549	925
1983	21	577	805	0			5	552	745	7	494	836	7	587	838	2	890	729
1984	29	605	754	2	617	652	10	633	684	9	643	735	6	523	868	2	533	944
1985	23	617	753	2	507	692	3	615	700	10	599	758	8	668	782	0		
1982-1985	99	584	775	4	562	672	27	581	726	38	573	776	25	590	828	5	679	854
1986	23	554	827	1	226	1070	8	546	762	6	528	848	8	623	845	0		
1987	26	625	738	2	630	622	8	656	676	12	590	789	4	664	767	0		
1988	28	704	718	2	590	650	7	665	670	6	632	753	10	800	715	3	689	815
1989	25	651	747	3	495	694	3	660	678	10	600	774	4	771	722	5	748	787
1986-1989	102	637	755	8	519	712	26	625	701	34	589	789	26	720	764	8	726	797
1990	22	705	750	0			3	627	690	7	690	705	7	722	772	5	748	819
1991	25	623	767	0			9	644	691	9	586	791	5	615	840	2	723	811
1992	22	642	771	2	506	694	2	519	743	7	633	749	7	739	758	4	620	883
1993	22	656	758	0			5	596	715	7	674	724	8	623	822	2	877	728
1990-1993	91	656	762	2	506	694	19	615	703	30	641	746	27	677	796	13	725	823
1994	22	707	753	0			1	721	653	11	654	751	6	823	715	4	676	840
1995	33	709	729	0			8	602	710	9	699	713	12	777	730	4	740	803
1996	19	660	778	0			5	604	703	3	712	698	4	653	826	7	682	837
1997	18	690	741	0			3	641	672	7	669	728	4	650	779	4	801	776
1994-1997	92	695	747	0			17	616	698	30	677	729	26	749	749	19	718	818
1998	27	737	733	0			3	623	724	6	706	703	15	761	736	3	797	789
1999	15	718	741	0			3	555	758	2	773	666	6	742	747	4	779	756
2000	21	791	719	1	725	583	1	439	839	4	768	675	8	831	707	7	819	761
2001	39	831	713	0			3	734	627	9	806	654	13	755	735	14	938	747
1998-2001	102	781	724	1	725	583	10	618	717	21	767	673	42	770	732	28	870	757