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

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ABSTRACT

Over the years, vehicle manufacturers may have implemented structural changes to light vehicles to comply with upgraded Federal Motor Vehicle Safety Standards (FMVSS) such as advanced air bags (FMVSS No. 208), side impact protection (FMVSS No. 214), and roof crush (FMVSS No. 216), as well as to improve performance in tests conducted by consumer information programs such as NHTSA's New Car Assessment Program (NCAP) and the Insurance Institute for Highway Safety (IIHS). Both programs have undergone changes in recent years. The NCAP was updated in 2010 to include advanced test dummies, new injury criteria, and a side pole test, and the IIHS adopted side impact, small overlap, and roof crush test protocols. Furthermore, as fuel economy requirements become more stringent, vehicle manufacturers may choose to light-weight vehicles and incorporate materials such as advanced high-strength steel and aluminum. This paper will investigate what effect, if any, these changes have had on vehicle crash pulses, as measured under NCAP. Although more stiffness metrics and crash pulse characteristics have been examined, this study mainly updates the analysis from the 2003 ESV paper, *Evaluation of Stiffness Measures from the U.S. NCAP*. [Swanson, 2003]

This paper utilizes data from model year (MY) 2002 to MY 2014 frontal NCAP crash tests to compute vehicle stiffness using four different methods: linear "initial" stiffness, energy equivalent stiffness, dynamic stiffness and static stiffness. The data are averaged and examined historically for three light duty vehicle classes (light duty pickup trucks (PUs), multi-purpose vehicles (MPVs), and passenger cars (PCs)) to provide a fleet perspective on changes to frontal crash characteristics. In addition, various crash pulse characteristics such as duration and peak acceleration are investigated. Collectively, these metrics have been traditionally used to characterize a vehicle's crash behavior and can subsequently influence restraint design.

The Swanson study found that not only were the average stiffnesses of PCs increasing from MY 1982 to 2001, but there was also a large disparity between the average stiffnesses of PCs and those of MPVs and PUs. The current study identified different trends. The average stiffnesses of PCs and MPVs appear to be converging, indicating that these two vehicle classes may have become more structurally homogenous in this respect. This is also evidenced by the changes observed for the crash pulse characteristics. In recent years, the crash pulse durations for both PCs and MPVs have decreased (though MPVs slightly more than PCs) such that the pulse duration is now essentially equal, on average, for both vehicle classes. The average peak accelerations for PCs and MPVs also increased during the years in this study. PU data is presented for completeness, but no extensive conclusions were made on this vehicle class because no statistically significant trends could be identified.

INTRODUCTION

Over the years, new or more stringent Federal Motor Vehicle Safety Standards (FMVSS) such as advanced air bags, side impact protection, and roof crush have been promulgated and implemented for the modern light vehicle fleet. In addition, NHTSA's NCAP consumer information program was updated in 2010 to include advanced test dummies, new injury criteria, and a side pole test, and the IIHS expanded its crash test information program to include not only a 40 percent frontal offset test, but also side impact, small overlap, and roof crush test protocols. As a result, vehicle manufacturers have implemented structural changes throughout their vehicles.

During a crash, the vehicle's front structure manages the crash forces by transferring the crash energy to structural elements throughout the vehicle. Intrusion and forces into the occupant compartment must be limited so that the restraints can manage the energy transferred to the occupant(s). Side impact and roof crush tests have driven vehicle manufacturers to make additional improvements to the occupant compartment structure in an attempt to limit door and roof intrusion, respectively.

Concurrently, as fuel economy requirements became more stringent, vehicle manufacturers may have chosen to light-weight vehicles by incorporating materials such as advanced high-strength steel and aluminum while continuing to comply with FMVSS requirements and perform well in consumer information programs. Being successful in such an approach most likely requires optimization of the vehicle structure while giving consideration to the special material properties for these higher strength and lightweighted materials. This paper will explore what impact these additional tests and regulations may have had on vehicle front stiffness as measured in MY 2002 to MY 2014 frontal NCAP tests.

Stiffness is one factor studied to understand how vehicles interact with their collision partners in the real world. Stiffness, as well as other factors such as mass and geometry, provides insight into how energy is managed in crashes. It is also an important factor in understanding the energy that the frontal restraint systems will have to manage in crashes in order to protect the occupants.

Swanson examined three methods of evaluating vehicle front-end stiffness using passenger car data from NCAP tests conducted between MY 1982 and MY 2001. The methods included: initial stiffness, static stiffness, and dynamic stiffness. Two of these methods, initial stiffness and dynamic stiffness, showed a steady increase for PCs over the model years analyzed (21 percent and 34 percent, respectively). The static stiffness method predicted much greater increases (61 percent) in stiffness due to its reliance on static crush data that does not account for the elasticity in front-end structures like dynamic stiffness does.

Average force-deflection plots generated in the Swanson paper for the various PC classes (compact, midsize, full-size) confirmed the increasing stiffness trends predicted by the initial stiffness and dynamic stiffness methods. Similar plots were generated for three other vehicle classes, light trucks, vans, and sport utility vehicles (SUVs), known collectively as LTVs. While stiffness values for the LTV classes tended to be much higher than those for the PC classes, their stiffness characteristics had not changed as much over the same time period.

A recent study using full-frontal rigid-barrier tests data from the NHTSA and Transport Canada crash test databases was conducted to analyze the vehicle crash pulse. [Caitlin, 2012] The paper grouped the data by vehicle type (PC, PU, minivan, and SUV) and size (small, midsize, and large) using the Highway Loss Data Institute classification based upon size and weight. The authors examined crash pulse characteristics, such as peak acceleration and crash pulse duration, for tested MY 2000–2010 vehicles. The paper showed an overall increasing trend in peak acceleration and a decrease in pulse duration, by year, for most vehicle classes. The authors concluded that the shorter, more severe pulse is consistent with stiffening vehicle structure for the current vehicles within the fleet. However, they also found that for later model year vehicles, the crash pulse characteristics were becoming more homogeneous for different vehicle classes.

As with Swanson, this paper will investigate initial stiffness (now termed linear “initial” stiffness), and static and dynamic stiffness. In addition, energy-equivalent stiffness will be calculated using the Kw400 methodology. [Patel, 2007] To expand upon the findings of Caitlin, this paper will also investigate various crash pulse characteristics for severity and duration as measured by time-to-zero velocity and peak acceleration, and will study the characteristics of force-deflection profiles seen in the modern fleet. Though the earlier papers divided their data based on vehicle type and size, since there is not a standard definition for vehicle size classification, this paper will utilize only vehicle type (as identified on the FMVSS certification label) in an effort to gain a fleet perspective on changes to frontal crash characteristics.

METHODOLOGY

Since 1979, NHTSA has been providing consumers with comparative frontal crashworthiness information on new passenger vehicles through NCAP. In the frontal NCAP test, vehicles are evaluated based on the crash protection they provide in a 56 km/h full-frontal rigid barrier crash. This is determined from injury readings recorded by Hybrid III test dummies positioned in the driver and right front passenger seats. Frontal NCAP test data can also be used to characterize a vehicle’s crash behavior.

In this study, available frontal NCAP data collected for MY 2002-2014 test vehicles was used to compute vehicle stiffness using four different methodologies – linear "initial" stiffness, energy-equivalent stiffness, dynamic stiffness, and static stiffness – each of which will be detailed in the next section.

For the first two of these methodologies, linear "initial" stiffness and energy-equivalent stiffness, stiffness is derived using data from (1) accelerometers that are mounted onto the vehicle structure near the driver or front passenger's seating location, and (2) load cells that have been added to the rigid barrier face to measure the total force the vehicle exerts on the barrier. The data from the vehicle accelerometer is double-integrated to obtain the vehicle's dynamic displacement, or crush, and the outputs from all of the individual load cells on a barrier are summed to obtain the total barrier force. (All accelerometer and load cell data were filtered according to the Society of Automotive Engineers Recommended Practice J211/1 rev. Mar 95, "Instrumentation for Impact Test – Part 1 – Electronic Instrumentation.") Although the sizes and numbersof load cells varied among NCAP testing laboratories over the years under study, this should have negligible effect on the total force exerted on a barrier; therefore, it is appropriate to use data from the various arrays for this study.

To compute dynamic stiffness and static stiffness, a vehicle's mass and veloctiy are used in combination with dynamic displacement data (again, derived from the vehicle accelerometers in the occupant compartments) and post-test vehicle crush measurements, respectively. For this study, crush measurements were calculated to be the difference between pre- and post-test measurements of the vehicle length, as recorded in the NCAP final test reports. It should also be noted that test weight, not curb weight, was used for these calculations since test weight includes the weight of the two Hybrid III test dummies and the vehicle-rated cargo weight, and best reflects the weight of the vehicle at impact and the resulting forces on the load cells on the barrier.

Although the original data set was comprised of 611 passenger vehicles, the data set for a given metric has been reduced because either the required data was lost, or because the available data was deemed invalid. The final data sets for each of the four stiffness metrics were divided into three vehicle class categories – PCs, MPVs (comprised of SUVs and vans), and light PUs. SUVs and vans were combined into one class, MPVs, because only a small number of vans were tested by NCAP over the years studied. The class category for a given vehicle was dictated by the classification noted on the vehicle's certification label – PC, MPV, or truck (PU).

Additionally, vehicle crash pulse data such as peak acceleration and time to zero velocity were grouped by vehicle class to observe any changes during the model years considered.

The trends in vehicle dynamic and static stiffness from MY 1982-2014 were examined. In doing so, the MY 2002-2014 data is added to that from Swanson. For the trend analysis spanning from MY 1982-2014, the data was subdivided into model year clusters, with each cluster spanning two model years, and the computed stiffness values for each cluster were then averaged. Three-year intervals were used to present force-deflection profiles for each vehicle class.

As this study is limited to only those vehicles selected for NCAP testing during the given model years, and data was not weighted based on vehicle sales or registration volumes, findings are not necessarily representative of the vehicle fleet as a whole. Trends observed can only be inferred for those vehicles tested by NCAP for the model years under study. Further, no effort was made to relate occupant injury values collected in these tests to the stiffness metrics explored.

RESULTS AND DISCUSSION

For each of the stiffness metrics and the vehicle parameter analysis, the data was primarily analyzed by grouping the first four MY of the study (2002-2005) and the last four MY of the study (2011-2014) and comparing the averages found for each interval. For ease of discussion, these intervals will be referred to as the "first four years" and the "last four years."

Linear "Initial" Stiffness

For this first method, vehicle stiffness was defined to be the slope of a linear regression line fit to the early portion of a vehicle's force-deflection profile. A force-deflection profile reflects the total force exerted on the load cell barrier versus the dynamic deformation, or crush, that a vehicle experiences during the duration of a crash test. As mentioned above, this crush is calculated by double-integrating the acceleration recorded by vehicle accelerometers in the occupant compartments.

Force-deflection profiles were generated for the 611 passenger vehicles subjected to frontal NCAP testing spanning model years 2002 through 2014; however, 89 tests were ultimately eliminated because of errors in accelerometer or load cell data collection or because a linear fit of the data could not be achieved. This resulted in a final data set of 522 vehicles for this metric. In the absence of a standard technique, the authors developed a method for resolving differences in the data collected by load cell barriers and vehicle accelerometers. The data collected from the load cell wall and vehicle accelerometers were verified for accuracy by analyzing the momentum balance. Data was considered acceptable if the vehicle velocity (calculated by integrating the vehicle accelerometer data): (1) shared a similar slope to the momentum curve (determined by the force measured at the load cell wall) for the first 400 mm of crush, which was generally 30 ms or less into the crash event, and (2) reflected the actual delta-V. The data was visually inspected to ensure the force on the load cell wall (i.e., momentum curve) led the velocity response and did not diverge from the velocity response prior to the first 400 mm of crush.

For the 522 qualifying tests, linear "initial" stiffness was determined by applying the following criteria: (1) good correlation of linear fit (R^2 value greater than 0.95), (2) correlation begins within the first 200 millimeters of deflection to emphasize what is considered the "initial" deformation of the vehicle, (3) correlation is maintained for a minimum distance of 150 millimeters in order to reflect the overall slope, and (4) linear fit is not constrained to zero force at zero deflection to compensate for small variations in time zero data collection. For a given vehicle, the longest linear correlation that met all four criteria was estimated to be indicative of the vehicle's linear stiffness. [Summers, 2002], [Swanson, 2003] If a linear fit meeting the preceding criteria could not be achieved for a particular force-deflection profile, linear "initial" stiffness was not quantified for the corresponding vehicle. Figure 1 depicts the results for the three vehicle classes studied. The associated data is provided in the Appendix.

The average linear "initial" stiffness was 1,678 N/mm for all vehicles tested since MY 2002. By class, the average was 2,448 N/mm for PUs, 1,895 N/mm for MPVs, and 1,336 N/mm for PCs during this time period. As shown in Figure 1, average linear "initial" stiffness decreased for MPVs and slightly increased for PCs over the years studied. The average linear "initial" stiffness for the first four years was 1,292 N/mm for PCs, whereas for the last four years, the average was 1,431 N/mm. This was an increase of 10.7 percent, which was found to be significant at the 95% confidence level. MPVs, however, have shown a clear decrease in linear "initial" stiffness since MY 2002. For the first four years, MPVs had an average linear "initial" stiffness of 2,054 N/mm, while for the last four years, this average dropped 14.4 percent to 1,759 N/mm. This result was also significant at the 95% confidence level. It appears that linear "initial" stiffness values for MPVs and PCs are converging. The difference in the average linear "initial" stiffness for the first four years between MPVs and PCs was 45.5 percent. This difference has dropped to 20.6 percent for the last four years. This is consistent with the trend to construct MPVs on more car-like, unibody platforms instead of truck-based, body-on-frame construction. There are more unibody-based MPV offerings than there were during the time period studied in Swanson. Figure 1 shows that average linear "initial" stiffness values for PUs remained higher than those for PCs and MPVs. No statistically significant trend in linear "initial" stiffness could be identified for PUs.

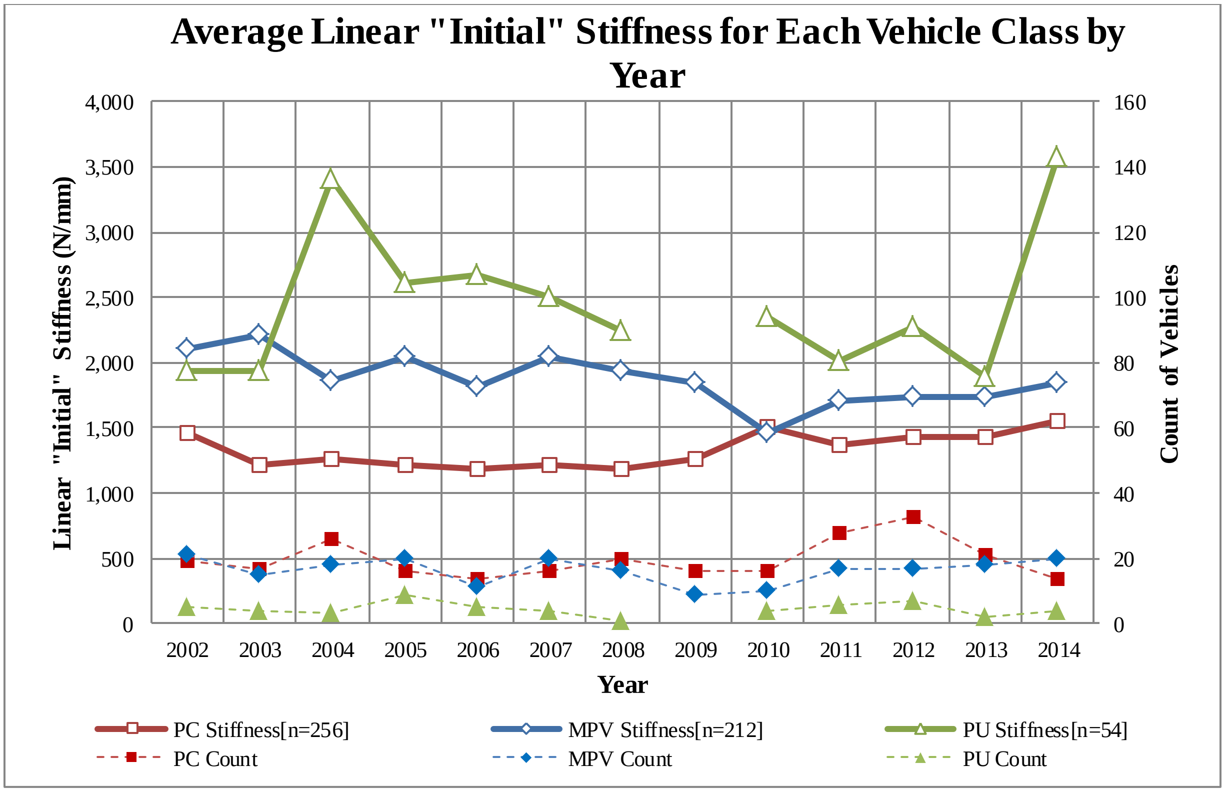

Figure 1: Average linear "initial" stiffness values computed for MY 2002-2014 NCAP test vehicles.

Energy-Equivalent Stiffness: Kw400

Like the linear "initial" stiffness method, this second method, energy-equivalent stiffness, is also designed to characterize a vehicle's stiffness based on its force-deflection profile. However, where the linear stiffness method approximates initial stiffness based on the slope of a line fit to the force-deflection curve over a given displacement range, this second method is based on the crash energy (or area under the force-deflection curve) over a given range.

One metric that can be used to approximate energy-equivalent stiffness is Kw400. Kw400 is derived from equating the energy stored in an ideal spring (½ Kx^2) to the work of crushing the front end of a vehicle ($\int Fdx$). Contrary to the linear "initial" stiffness method, in which the displacement range is variable, the displacement range for the energy-equivalent stiffness method, as defined by Kw400, is fixed. To calculate energy-equivalent stiffness, the integral of the area under the force-deflection curve is evaluated between 25 and 400 mm of vehicle frontal crush. The equation for Kw400 is shown below. [Patel, 2007]

$$\mathrm{Kw400} = \frac{2\int_{25mm}^{400mm} Fdx}{\left(400^2 - 25^2\right)}$$

This equation was used to calculate energy-equivalent stiffness for the same 522 qualifying tests discussed in the linear "initial" stiffness section.

The average energy-equivalent stiffness was 1,362 N/mm for all vehicles tested from MY 2002 to MY 2014. By class, the average energy-equivalent stiffness was 1,720 N/mm for PUs, 1,502 N/mm for MPVs and 1,171 N/mm for PCs during this time period. More specifically, Figure 2 shows that PCs had an average energy-equivalent stiffness of 1,106 N/mm during the first four years, and 1,245 N/mm for the last four years – a 12.6 percent increase that was statistically significant at the 95% confidence level. Conversely, the average energy-equivalent stiffness for MPVs was 1,561 N/mm for the first four years, and decreased 7.8 percent to 1,439 N/mm for the last four years. Again, this difference was found to be statistically significant at the 95% confident level. The difference in energy-equivalent stiffness between MPVs and PCs was 34.2 percent for the first four years of the data set. This difference dropped to 14.5 percent for during the last four years. Directionally, the results are consistent with those found for linear "initial" stiffness; however, the energy-equivalent stiffness metric identified a smaller difference in stiffness between PCs and MPVs than the linear "initial" stiffness metric. No statistically significant changes were identified for the PU fleet. Similar to that mentioned for linear "initial" stiffness, the average energy-equivalent stiffness for PUs is higher than that for PCs and MPVs as shown in Figure 2.

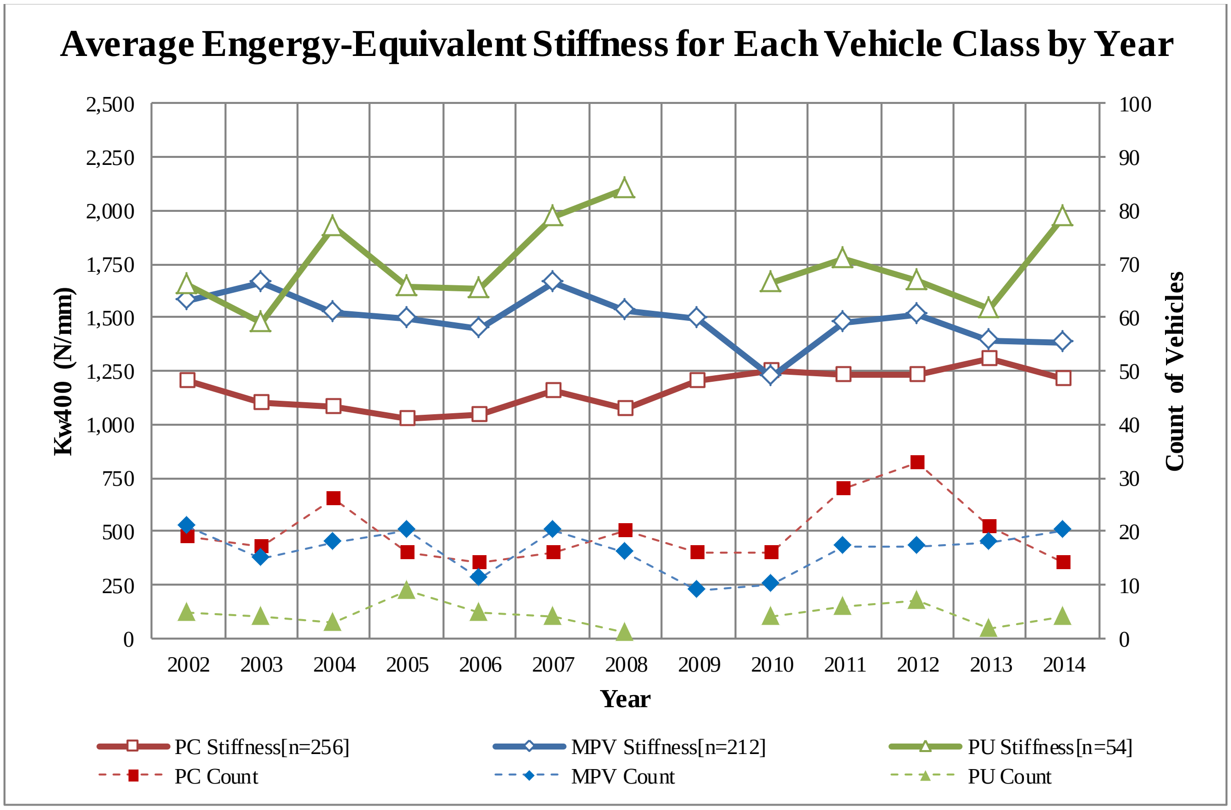

Figure 2: Average energy-equivalent stiffness values computed for MY 2002-2014 NCAP test vehicles.

Dynamic Stiffness

For the third method, dynamic stiffness, a vehicle's stiffness, K, is computed using the equation $K = mv^2/x^2$, where m is the test weight of the vehicle, v is the closing speed of the vehicle, and x is the maximum dynamic displacement. This equation was derived using the approximation of the conservation of total energy, $E = ½\ mv^2 = ½\ Kx^2$. As mentioned previously, the maximum dynamic displacement (or crush) for a vehicle is found by taking the maximum of the double integral of the vehicle acceleration in the front occupant compartment. Dynamic displacement accounts for the elastic behavior often found in the vehicle front-end structure. [Swanson, 2003]

There were 611 passenger vehicles subjected to frontal NCAP testing from MY 2002 through MY 2014; however, 10 of the tests were ultimately eliminated because of errors in accelerometer data, resulting in a final data set of 601 for dynamic stiffness, static stiffness and vehicle acceleration data. The average dynamic stiffness from MY 2002 to MY 2014 for all vehicles was 1,101 N/mm. By class, the average dynamic stiffness for the model years studied was 1,409 N/mm for PUs, 1,191 N/mm for MPVs, and 959 N/mm for PCs. During the first four years, the average dynamic stiffness for PCs was 916 N/mm. For the last four years, the average dynamic stiffness for PCs was 980 N/mm – an increase of 7.0 percent over the earlier interval. This increase was statistically significant at the 95% confidence interval. When examining the same intervals, dynamic stiffness values decreased for MPVs. In the first four years, the average dynamic stiffness for MPVs was 1,221 N/mm. This value decreased 6.7 percent to an average of 1,138 N/mm for the last four years. These results were also found to be statistically significant at the same level of confidence. The dynamic stiffness decrease for MPVs, again, likely corresponds to the trend of constructing MPVs on more car-like, unibody structures and not on pickup truck-based, body-on-frame structures. The difference in average dynamic stiffness between MPVs and PCs was 28.5 percent during the first four years. This difference dropped to 15.0 percent in the last four years. This converging trend is directionally consistent with the other stiffness metrics already discussed and very similar to the 14.5 percent difference found when using the Kw400 (energy-equivalent) approach. Again, although no significant differences could be identified for the PU data set, dynamic stiffness is higher, on average, for PUs than for PCs and MPVs.

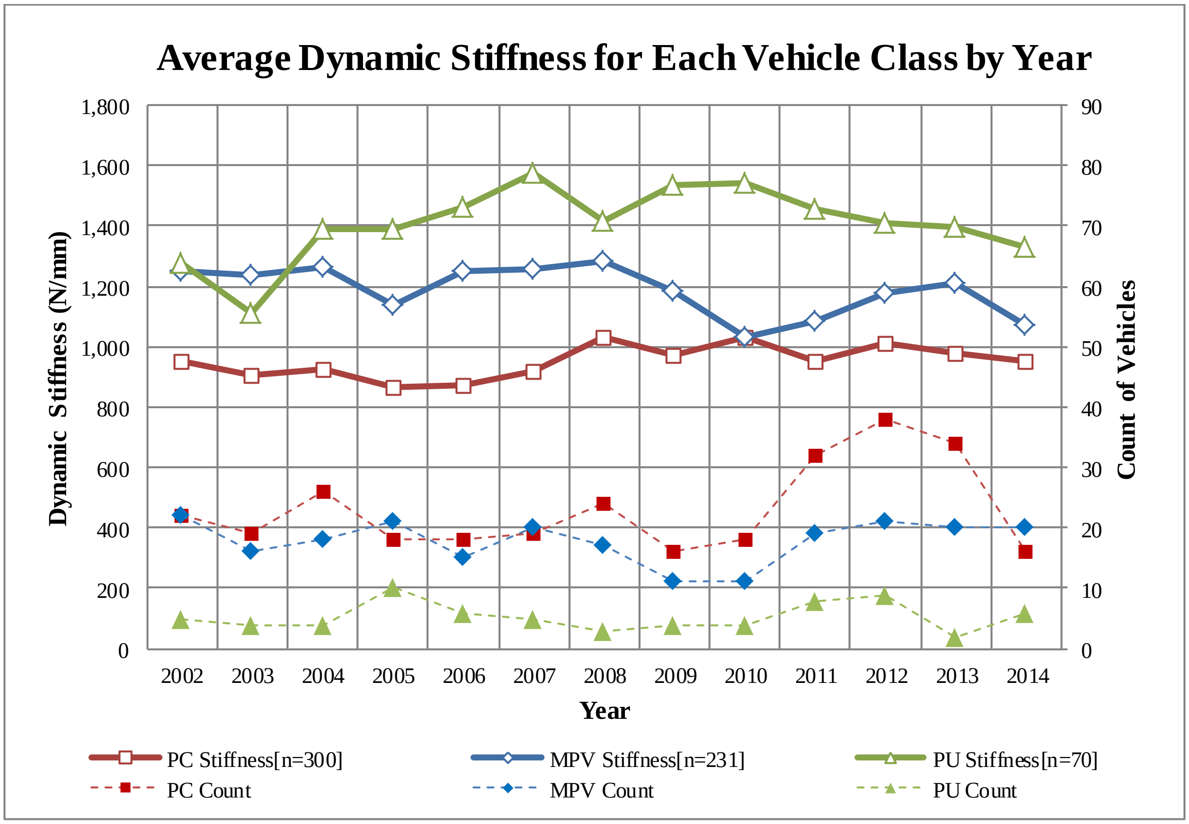

Figure 3: Average dynamic stiffness values computed for MY 2002-2014 NCAP test vehicles.

Static Stiffness

The fourth stiffness calculation method, static stiffness, is similar to dynamic stiffness in that it uses the same equation derived from the conservation of energy ($K = mv^2/x^2$); however, x instead reflects the maximum static crush measured for the vehicle post-test. Unlike dynamic stiffness, static stiffness does not account for the elastic deformation of the vehicle front-end. [Swanson, 2003]

Static stiffness was computed for the same 601-vehicle data set used to calculate dynamic stiffness. The average static stiffness for all vehicles from MY 2002 to MY 2014 was 2,035 N/mm. By class, the average stiffness was 2,149 N/mm for PUs, 2,160 N/mm for MPVs, and 1,913 N/mm for PCs over this time period. As shown in Figure 4, the static stiffness for PCs has generally been increasing since MY 2002. In the first four years, the average static stiffness for PCs was 1,691 N/mm, which increased 24.0 percent to 2,097 N/mm in the last four years. This was a statistically significant increase at the 95% confidence level. Conversely, in the first four years, the average static stiffness for MPVs was 2,183 N/mm, which decreased 3.6 percent in the last four years to 2,104 N/mm. This difference was not found to have statistical significance at the 95% confidence interval. The difference in static stiffness between MPVs and PCs was 25.4 percent during the first four years; this difference dropped to 0.3 percent in the last four model years. In general, it also yielded the highest average values among the methods. As with the other stiffness metrics discussed, there currently appears to be more homogeneity in stiffness between PCs and MPVs compared to earlier model years. As with the other stiffness metrics, no statistically significant changes could be identified for PUs. However, it should be noted that the magnitude of static stiffness values for PUs appears to be more comparable to those for MPVs and PCs when compared to results seen for the other three stiffness metrics.

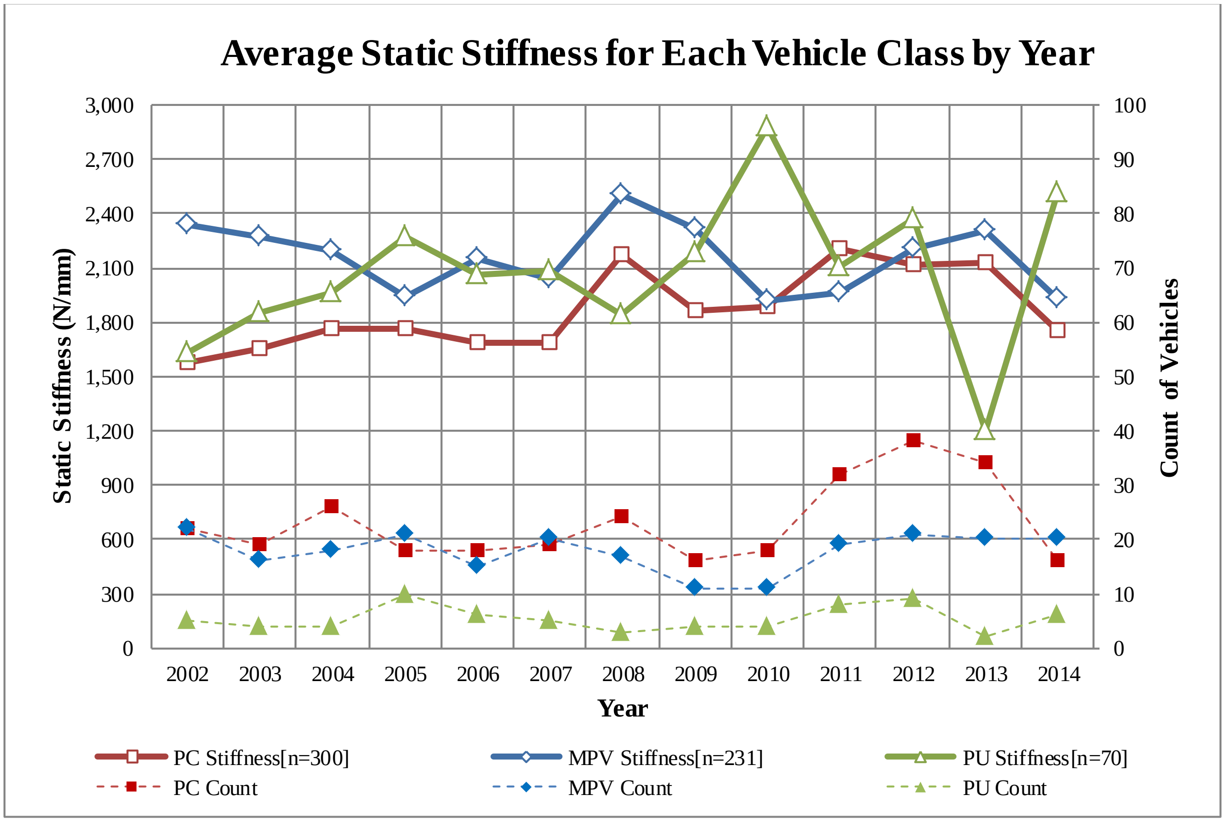

Figure 4: Average static stiffness values computed for MY 2002-2014 NCAP test vehicles.

Overall, the four methods of computing vehicle stiffness showed similar trends. They each showed a slight increasing trend in average stiffness for PCs, and a concurrent responding decreasing trend in average stiffness for MPVs, with both classes becoming more homogenous with respect to their front-end stiffnesses. When comparing the first four years to the last four, average percent increases in stiffnesses for PCs when compared to average percent decreases in stiffnesses for MPVs varied depending on the metric used. This is illustrated in Table 1. Table 2 shows, by stiffness metric, the percent difference between the average stiffnesses of PCs and MPVs when comparing the first four years to the last four. All of the metrics showed a decrease in the difference between PC average stiffnesses and MPV average stiffnesses, again supporting the notion that the two are converging. The metric that showed the least difference when comparing MPVs versus PCs for the first four years with the last four was static stiffness.

Table 1.
Differences in average stiffnesses for PCs and MPVs between the first and last four years.

	PCs	MPVs
Linear "Initial" Stiffness	10.7%	-14.4%
Energy-Equivalent Stiffness	12.6%	-7.8%
Dynamic Stiffness	7.0%	-6.7%
Static Stiffness	24.0%	-3.6%

Table 2.
Differences in average stiffnesses, MPVs versus PCs, for the first and last four years.

	MY 2002-2005	MY 2011-2014
Linear "Initial" Stiffness	45.5%	20.6%
Energy-Equivalent Stiffness	34.2%	14.5%
Dynamic Stiffness	28.5%	15.0%
Static Stiffness	25.4%	0.3%

Differences between static stiffness trends and the other three stiffness metrics may largely be due to the fact that the static stiffness metric relies upon post-test vehicle crush measurements for displacement rather than dynamic (accelerometer-based) measurements, which are used for the other three metrics. Unlike dynamic deformation, static post-test crush measurements cannot account for the elastic deformation that occurred during the crash. Instead, static measurements represent only the inelastic residual crush. As such, static crush measurements are inherently smaller than calculated values for dynamic displacement, and this translates into higher stiffness values for static stiffness compared to the other three metrics evaluated.

To better understand the role elastic vehicle components play in stiffness results for the metrics studied, it was of interest to compare static and dynamic stiffness results directly since the same equation is used to calculate both; the only difference between the two calculations is the source of displacement - either post-test vehicle measurements (for static stiffness) or vehicle accelerometer readings (for dynamic stiffness).

Figure 5 depicts the average calculated static stiffness and dynamic stiffness for PCs tested by NCAP since MY 1982. For this comparison, data from Swanson (MY 1982-2001) was added to that used for the current study (MY 2002-2014). The static and dynamic stiffness data was subdivided into two-year intervals and then averaged for each interval. This figure shows that there was a gradual upward trend in static and dynamic stiffness from MY 1982 to MY 2014. It is also of interest that the values for both seemed to stabilize just prior to the last four years in this study. It can also be seen that the difference between average dynamic and static stiffness values has grown larger over the years. This indicates an increase in elasticity of the front-end vehicle structure. Therefore, results using linear "initial" stiffness, energy-equivalent stiffness, and dynamic stiffness – the three methods that use dynamic displacement in their calculations – may more realistically approximate the stiffness of the current fleet, since dynamic deformation accounts for the elastic and energy-absorbing front-end components.

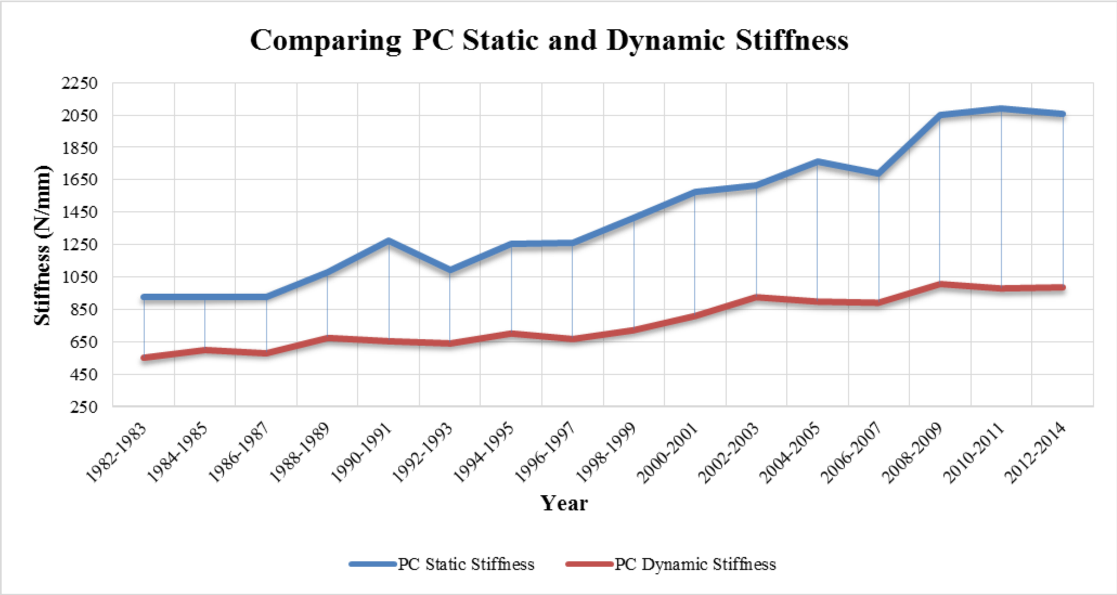

Figure 5. Comparing static and dynamic stiffnesses for NCAP-tested vehicles.

Considering the previous discussion, it is not surprising that a correlation was found between energy-equivalent and dynamic stiffness, which is shown in Figure 6. This is also demonstrated by a similar percent decrease in stiffness observed using the energy-equivalent and dynamic stiffness metrics. These metrics showed stiffness decreases of 14.5 percent and 15.0 percent, respectively, for the last four model year interval when compared to the first four model year interval. As both metrics rely on test instrumentation, and in particular, vehicle acceleration data, to calculate stiffness, both metrics may be more reliable than methods that do not take these into account. Although linear "initial" stiffness also relies on vehicle acceleration data to compute stiffness, a similar correlation to energy-equivalent stiffness and/or dynamic stiffness was not observed for this metric. This may be because of the potential error introduced by fitting a straight line to the force-deflection curve. Fitting a line slightly earlier or later in time along the curve, or over a longer stretch of time, could significantly influence the slope of the line, and therefore, the approximated stiffness.

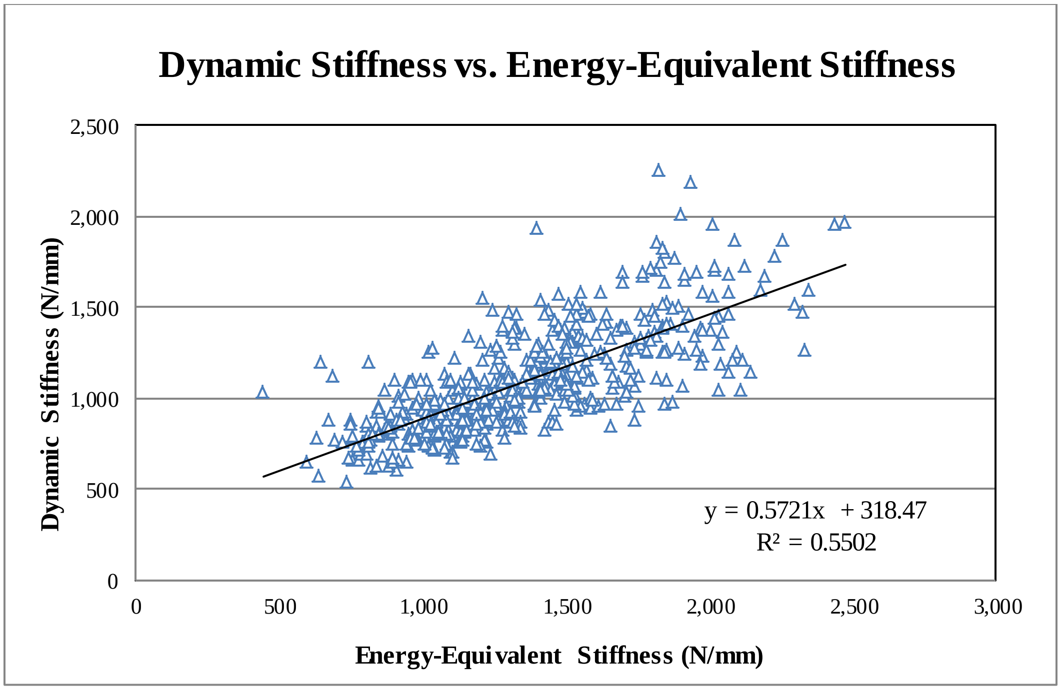

Figure 6. Comparing energy-equivalent stiffness and dynamic stiffness for NCAP-tested vehicles.

As an additional check, the force-deflection profiles used for the linear "initial" stiffness and energy-equivalent stiffness metrics were studied. Similar to that done for the comparison of static and dynamic stiffness, the force-deflection data was subdivided into three-year intervals and then averaged for each interval. The slope of each of the averaged force-deflection profiles was then examined for the first ~200 mm of deflection as an indicator of vehicle stiffness (i.e., the sharper the rise of the curve, the stiffer the vehicle front-end). Figure 7 illustrates the concept previously discussed, that the linear stiffnesses of PCs and MPVs are converging. This is shown by the similar amount of force required to crush each of these vehicle types 200 mm in the later model years. Furthermore, the stiffness of PUs, on average, is higher than that of both PCs and MPVs.

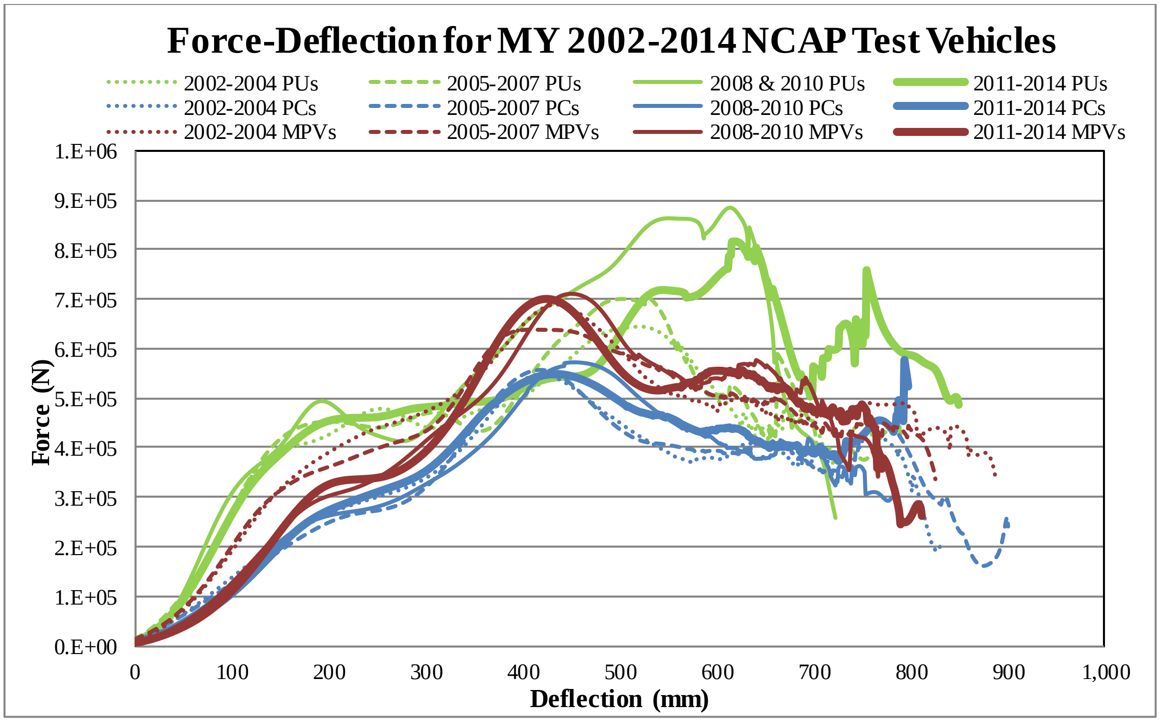

Figure 7. Force-Deflection Plot for MY2002-2014 NCAP Test Vehicles.

Changes to the fleet in response to things such as new regulatory requirements, revisions to consumer information programs, and shifting consumer preferences do not occur all at once and are generally phased in over time. This is evidenced by the steady increase in offerings of unibody-based MPVs compared to the prior (Swanson) study. However, the analysis of vehicle stiffness appears to support the notion that just prior to the last four years of this data set, a change affecting the front-end design of PCs and MPVs may have occurred in the fleet. To expand upon this finding, and build upon the Caitlin study, an additional analysis that focused on crash pulse characteristics was conducted. Specifically, peak acceleration and crash pulse duration for the vehicles tested during the model years under study were examined. With this analysis, there was a desire to see how vehicles designed to the latest regulatory and consumer information programs are managing crash forces. It was of particular interest to note any change in the amount of force translated to the occupant compartment over the years studied. It was also hoped that the trends observed for the stiffness metrics would correspond, in time, to any observations made for the crash pulse characteristics. To be consistent with the stiffness analysis, the same model year intervals were used for this analysis.

Peak Acceleration

The first crash pulse characteristic reviewed was the peak x-axis acceleration, measured in G's. Once again, this measurement is recorded by accelerometers that are mounted onto the vehicle structure near the driver or front passenger's seating location. Peak acceleration is typically indicative of the crash severity and correlates, in combination with the occupant's mass, to the amount of force the restraint system would need to manage during the crash. Effectively, this metric reflects how much of the crash forces are translated to the occupant compartment during the crash.

The average peak acceleration for all vehicles tested during the model years under study was 43G. By vehicle class, the average peak acceleration was 41G for PUs, 44G for MPVs, and 43G for PCs over this same time period. Averages for each model year by vehicle type are shown in Figure 8. Of interest is the relatively narrow range of average peak acceleration values calculated for the model years under study. The peak acceleration range for PUs was 36G to 49G; for MPVs, the range was 39G to 51G, and for PCs, the range was 39G to 48G. For the first four years, the average peak acceleration for PCs was 41G, and for the last four years, it increased 10.0 percent to 45G. This was a statistically significant increase at the 95% confidence interval. The average peak acceleration for MPVs from these same intervals increased 16.3 percent from 40 G to 47 G. This was also a significant finding at the 95% confidence level. Furthermore, for both PCs and MPVs, average peak accelerations have increased in the most recent years, even though, when comparing the first four years to the last four years, the average stiffnesses of PCs were increasing while the average stiffnesses of MPVs were decreasing. A statistically significant trend was not identified for PUs.

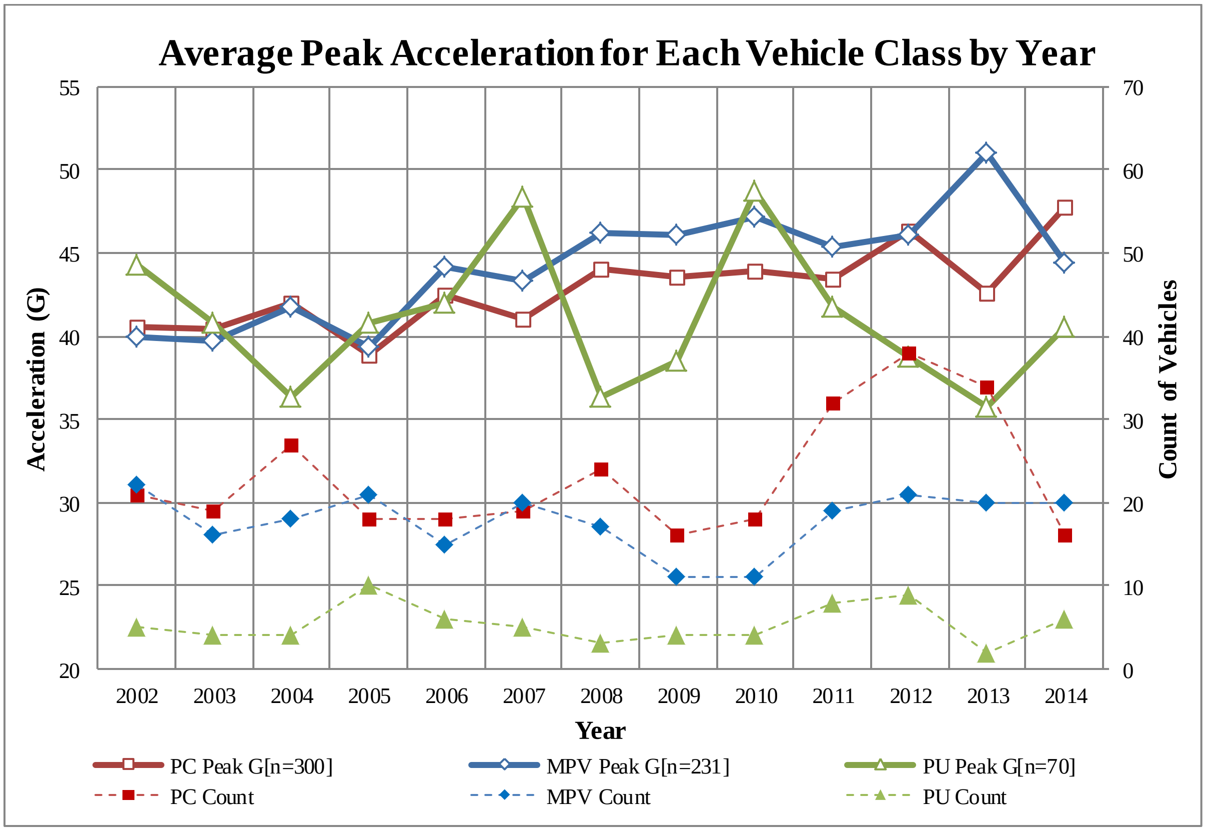

Figure 8. Average peak acceleration.

Time-to-Zero Velocity

The second pulse characteristic analyzed was the crash pulse duration, which is measured in milliseconds. This measurement is determined from single integration of the vehicle's x-axis acceleration and spans from the point of impact (t=0) until barrier separation, or when the vehicle velocity is equal to zero. Like peak acceleration, the crash pulse duration is also indicative of crash severity. If the duration of the crash event is shorter, the occupant and the restraint system may have to absorb the crash energy over a shorter period of time, which could make the event more severe.

For all MY 2002-2014 vehicles tested, the average time-to-zero velocity was 72 ms. By vehicle class, the time-to-zero velocity was 74 ms for PUs, 73 ms for MPVs, and 71 ms for PCs over this same time period. Figure 9 shows that there do not appear to be any significant trends overall; however, the results for PCs for the first four years show an average crash duration of 72 ms, which decreased by 3.8 percent to 70ms for the last four years. For MPVs, the average pulse duration for the first four years was 75 ms, and this decreased 5.7 percent to 71 ms during the last four years. For all practical purposes, on average the crash duration for both PCs and MPVs is now nearly the same.

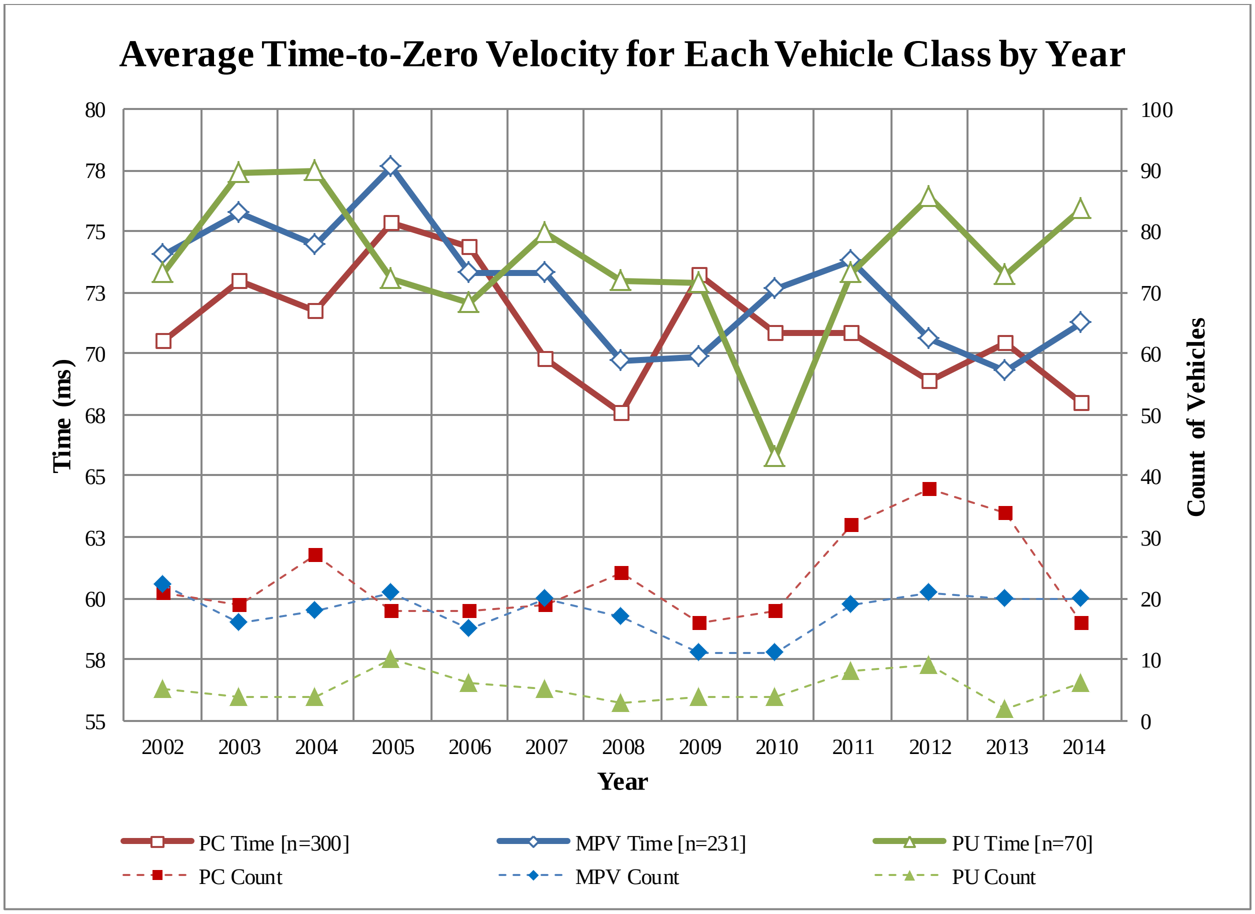

Figure 9. Average time-to-zero velocity.

The results for the pulse characteristics suggest that an increase in pulse severity (i.e., an increase in peak acceleration and/or a decrease in duration) does not necessarily equate to an increase in vehicle stiffness. This is evident from the stiffness trends previously discussed for MPVs during recent model years. Although average peak accelerations increased when comparing the last four years to the first four years, average MPV stiffness was shown to have decreased. The same phenomenon exists when looking at pulse durations: average MPV pulse durations decreased during the same time period in which a decrease in stiffness was observed. In sum, average traditional vehicle pulse characteristics may be in contrast to these front-end stiffness findings. This finding is also supported by Figure 10, which compares peak acceleration values to stiffness values computed using the energy-equivalent stiffness method. As shown, there is no correlation between peak acceleration and energy-equivalent stiffness. Comparisons of linear "initial," dynamic, and static stiffness to peak acceleration showed similar results..

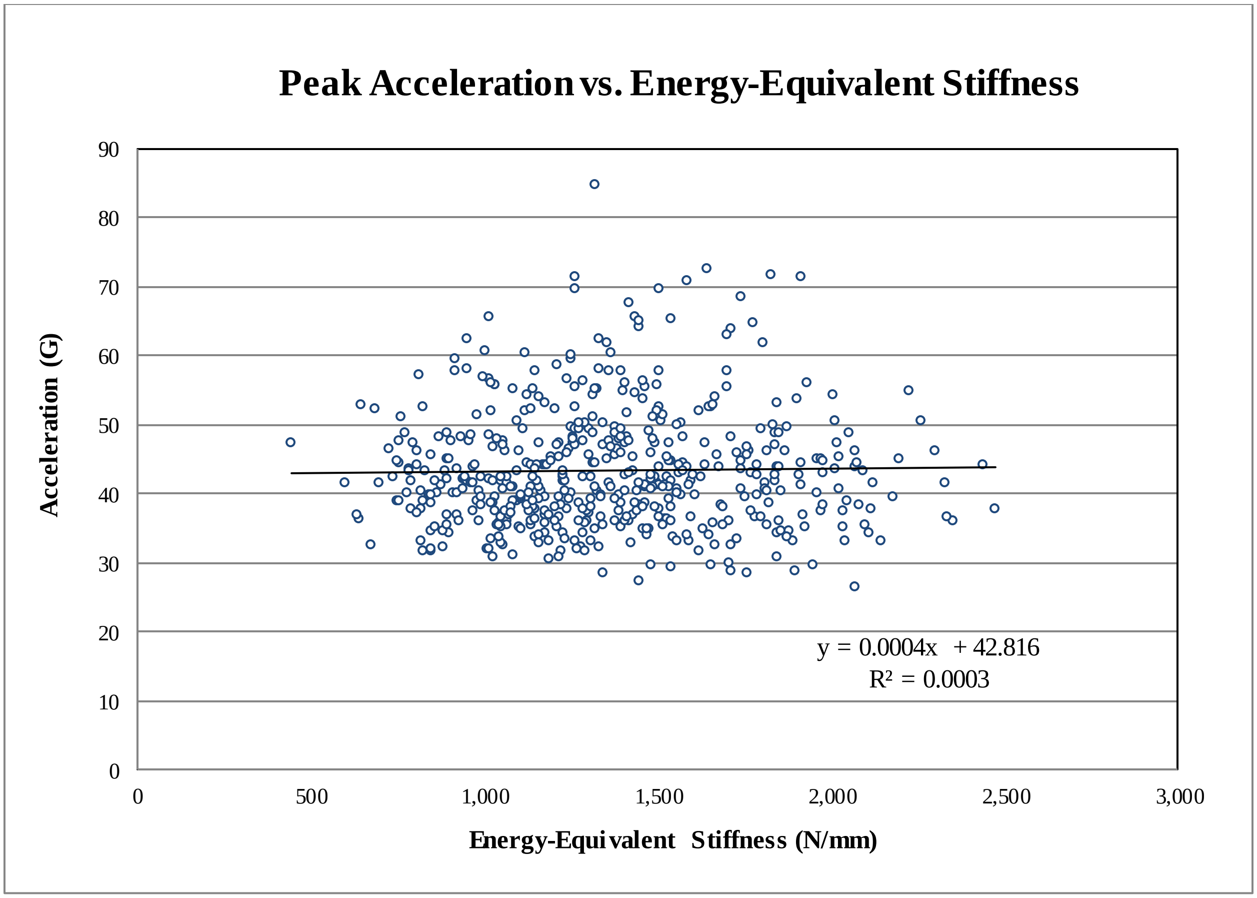

Figure 10. Comparing peak acceleration and energy-equivalent stiffness for NCAP-tested vehicles.

CONCLUSIONS

This study examined four methods of calculating front-end stiffness using vehicle crash data collected from NCAP tests conducted from MY 2002 through 2014. These methods included linear "initial" stiffness, energy-equivalent stiffness, dynamic stiffness, and static stiffness. This approach was similar to a study conducted by Swanson et al. that examined the MY 1982-2001 fleet. The Swanson study, which also used frontal NCAP data, found that not only were the average stiffnesses of PCs increasing over time, but there was also a large disparity between the average stiffnesses of PCs and that of MPVs and PUs. The results presented herein identified different trends. Generally, PCs continued to increase in average stiffness until stabilizing just prior to the last four years of this study, while MPVs decreased in average stiffness when considering the same time period. The average stiffnesses for PCs and MPVs appear to be converging, indicating that the fleet has become more homogenous with respect to these two vehicle classes. This is supported by the increase in MPV offerings utilizing unibody construction rather than traditional body-on-frame techniques. This study also examined the changes in crash pulse characteristics. While average peak accelerations generally increased for MPVs and PCs and pulse duration slightly decreased when comparing the first four years to the last four years of data, these findings do not appear to correlate to any of the stiffness metrics discussed. This analysis also further confirms the findings in Caitlin, which identified a slightly more severe, but homogeneous, crash pulse in the fleet.

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Appendix

Linear "Initial" Stiffness (N/mm)															
Year	***MPV***				***PC***				***PU***				***Avg of 3 Classes***	***Total Count***
	Stiffness	***Min***	***Max***	***Count***	***Stiffness***	***Min***	***Max***	***Count***	***Stiffness***	***Min***	***Max***	***Count***		
2002	*2,111*	*1,053*	*3,375*	*21*	*1,468*	*985*	*2,848*	*19*	*1,936*	*1,473*	*2,732*	*5*	*1,820*	*45*
2003	*2,207*	*894*	*3,578*	*15*	*1,221*	*769*	*1,702*	*17*	*1,929*	*1,613*	*2,505*	*4*	*1,711*	*36*
2004	*1,866*	*962*	*3,601*	*18*	*1,261*	*803*	*1,761*	*26*	*3,402*	*2,828*	*4,456*	*3*	*1,630*	*47*
2005	*2,049*	*1,045*	*4,289*	*20*	*1,210*	*759*	*1,700*	*16*	*2,613*	*1,929*	*3,809*	*9*	*1,863*	*45*
2006	*1,806*	*952*	*4,276*	*11*	*1,189*	*723*	*1,608*	*14*	*2,673*	*1,921*	*3,444*	*5*	*1,663*	*30*
2007	*2,050*	*819*	*3,951*	*20*	*1,208*	*440*	*1,667*	*16*	*2,504*	*2,374*	*2,811*	*4*	*1,759*	*40*
2008	*1,939*	*857*	*3,041*	*16*	*1,188*	*577*	*2,439*	*20*	*2,240*	*2,240*	*2,240*	*1*	*1,541*	*37*
2009	*1,843*	*1,258*	*2,857*	*9*	*1,261*	*655*	*1,955*	*16*	-	-	-	-	*1,471*	*25*
2010	*1,457*	*838*	*2,683*	*10*	*1,506*	*599*	*2,308*	*16*	*2,344*	*916*	*3,039*	*4*	*1,602*	*30*
2011	*1,713*	*866*	*3,387*	*17*	*1,366*	*489*	*2,059*	*28*	*2,016*	*1,684*	*2,486*	*6*	*1,558*	*51*
2012	*1,741*	*942*	*3,373*	*17*	*1,426*	*761*	*2,631*	*33*	*2,277*	*1,041*	*3,206*	*7*	*1,624*	*57*
2013	*1,733*	*731*	*3,044*	*18*	*1,437*	*723*	*2,286*	*21*	*1,892*	*1,572*	*2,212*	*2*	*1,589*	*41*
2014	*1,836*	*816*	*2,745*	*20*	*1,560*	*943*	*2,774*	*14*	*3,570*	*1,520*	*5,381*	*4*	*1,917*	*38*
Avg/Total	*1,895*	*731*	*4,289*	*212*	*1,336*	*440*	*2,848*	*256*	*2,448*	*916*	*5,381*	*54*	*1,678*	*522*

Energy-Equivalent Stiffness (Kw400) (N/mm)														
Year	**MPV**				**PC**				**PU**				**Avg of 3 Classes**	**Total Count**
	Stiffness	**Min**	**Max**	**Count**	**Stiffness**	**Min**	**Max**	**Count**	**Stiffness**	**Min**	**Max**	**Count**		
2002	1,582	1,044	2,257	21	1,203	805	1,870	19	1,650	1,408	2,022	5	1,429	45
2003	1,667	752	2,441	15	1,104	639	1,635	17	1,474	1,395	1,619	4	1,380	36
2004	1,527	644	2,472	18	1,085	754	1,787	26	1,928	1,769	2,038	3	1,308	47
2005	1,491	1,008	2,181	20	1,024	747	1,376	16	1,645	1,336	1,913	9	1,356	45
2006	1,447	882	2,334	11	1,047	736	1,295	14	1,633	1,430	1,961	5	1,291	30
2007	1,660	859	2,331	20	1,158	756	1,566	16	1,973	1,901	2,051	4	1,490	40
2008	1,533	688	2,302	16	1,072	444	1,816	20	2,098	2,098	2,098	1	1,299	37
2009	1,492	1,101	1,851	9	1,204	597	1,909	16	0	0	0	0	1,307	25
2010	1,221	848	1,640	10	1,250	698	1,766	16	1,666	1,027	2,228	4	1,296	30
2011	1,478	760	2,084	17	1,231	727	2,072	28	1,771	1,413	1,917	6	1,377	51
2012	1,513	1,139	2,067	17	1,233	674	1,825	33	1,676	1,020	1,969	7	1,371	57
2013	1,396	917	1,712	18	1,305	895	1,753	21	1,542	1,539	1,544	2	1,356	41
2014	1,382	969	1,853	20	1,214	805	1,588	14	1,974	1,590	2,143	4	1,382	38
Avg/Total	1,502	644	2,472	212	1,171	444	2,072	256	1,720	1,020	2,228	54	1,362	522

Static Stiffness (N/mm)

Year	MPV				PC				PU				Avg of 3 Classes	Total Count
	Stiffness	Min	Max	Count	Stiffness	Min	Max	Count	Stiffness	Min	Max	Count		
2002	2,341	1,104	7,762	22	1,578	1,051	2,758	22	1,635	1,312	2,065	5	1,926	49
2003	2,267	1,585	4,927	16	1,657	1,035	4,230	19	1,850	1,359	2,615	4	1,927	39
2004	2,194	1,477	3,602	18	1,762	926	3,597	26	1,967	1,827	2,111	4	1,941	48
2005	1,944	1,156	3,041	21	1,762	979	4,113	18	2,271	1,330	3,474	10	1,944	49
2006	2,152	1,226	3,910	15	1,688	899	2,746	18	2,060	1,721	2,306	6	1,924	39
2007	2,045	1,294	3,252	20	1,687	1,024	2,477	19	2,081	1,439	3,143	5	1,895	44
2008	2,509	1,511	5,434	17	2,178	1,093	5,883	24	1,844	1,507	2,035	3	2,283	44
2009	2,312	1,259	5,689	11	1,864	1,108	3,613	16	2,189	1,693	3,144	4	2,065	31
2010	1,923	1,224	3,977	11	1,887	1,258	3,039	18	2,881	1,224	4,638	4	2,020	33
2011	1,960	1,304	2,941	19	2,203	912	9,679	32	2,103	1,588	3,039	8	2,111	59
2012	2,209	1,244	3,797	21	2,120	1,015	4,612	38	2,373	1,180	4,692	9	2,181	68
2013	2,305	1,392	4,567	20	2,133	1,027	4,617	34	1,199	562	1,835	2	2,161	56
2014	1,931	1,015	4,765	20	1,754	1,257	2,620	16	2,515	1,506	4,453	6	1,947	42
Avg/Total	2,160	1,015	7,762	231	1,913	899	9,679	300	2,149	562	4,692	70	2,035	601

Dynamic Stiffness (N/mm)

Year	MPV				PC				PU				Avg of 3 Classes	Total Count
	Stiffness	Min	Max	Count	Stiffness	Min	Max	Count	Stiffness	Min	Max	Count		
2002	1,253	798	1,867	22	953	731	1,407	22	1,277	1,027	1,704	5	1,121	49
2003	1,238	840	1,949	16	905	565	1,358	19	1,112	954	1,193	4	1,063	39
2004	1,263	799	1,965	18	926	624	1,380	26	1,391	1,224	1,672	4	1,091	48
2005	1,138	743	1,827	21	868	616	1,289	18	1,389	1,035	1,795	10	1,090	49
2006	1,250	755	1,746	15	871	537	1,304	18	1,460	1,016	1,715	6	1,107	39
2007	1,260	868	1,668	20	922	748	1,295	19	1,577	1,109	2,009	5	1,150	44
2008	1,282	832	1,851	17	1,033	672	1,706	24	1,418	1,250	1,568	3	1,156	44
2009	1,186	881	1,563	11	975	648	1,342	16	1,539	1,463	1,581	4	1,123	31
2010	1,031	812	1,576	11	1,034	732	1,479	18	1,541	889	1,933	4	1,094	33
2011	1,085	727	1,680	19	954	662	1,681	32	1,457	1,240	1,745	8	1,064	59
2012	1,180	870	1,638	21	1,012	605	2,250	38	1,409	915	2,184	9	1,117	68
2013	1,209	871	1,566	20	982	668	1,481	34	1,397	1,339	1,454	2	1,078	56
2014	1,075	858	1,397	20	951	650	1,219	16	1,333	939	1,771	6	1,065	42
Avg/Total	1,191	727	1,965	231	959	537	2,250	300	1,409	889	2,184	70	1,101	601

Peak Acceleration (G's)														
Year	MPV				PC				PU					
	Accl.	Min	Max	Count	Accel.	Min	Max	Count	Accel.	Min	Max	Count	Avg of 3 Classes	Total Count
2002	40	58	30	22	41	55	29	21	44	54	40	5	41	48
2003	40	49	29	16	40	60	30	19	41	55	32	4	40	39
2004	42	55	28	18	42	62	32	27	36	43	32	4	41	49
2005	39	54	29	21	39	55	31	18	41	50	27	10	39	49
2006	44	65	32	15	42	70	32	18	42	49	35	6	43	39
2007	43	58	32	20	41	61	32	19	48	54	35	5	43	44
2008	46	58	33	17	44	71	32	24	36	38	36	3	44	44
2009	46	61	36	11	44	62	34	16	39	45	34	4	44	31
2010	47	56	34	11	44	68	29	18	49	58	39	4	46	33
2011	45	71	33	19	43	66	31	32	42	52	33	8	44	59
2012	46	60	26	21	46	72	32	38	39	56	27	9	45	68
2013	51	85	30	20	43	67	30	34	36	38	34	2	45	56
2014	44	63	35	20	48	71	33	16	41	51	33	6	45	42
Avg/Total	44	85	26	231	43	72	29	300	41	58	27	70	43	601

Time to Zero Velocity (ms)														
Year	MPV				PC				PU					
	Time	Min	Max	Count	Time	Min	Max	Count	Time	Min	Max	Count	Avg of 3 Classes	Total Count
2002	74	63	98	22	70	58	84	21	73	69	79	5	72	48
2003	76	61	96	16	73	61	91	19	77	70	91	4	75	39
2004	74	62	91	18	72	61	91	27	78	70	85	4	73	49
2005	78	60	95	21	75	61	93	18	73	63	87	10	76	49
2006	73	64	97	15	74	60	93	18	72	62	82	6	74	39
2007	73	63	98	20	70	62	78	19	75	57	106	5	72	44
2008	70	59	80	17	68	46	84	24	73	68	78	3	69	44
2009	70	58	76	11	73	64	89	16	73	69	77	4	72	31
2010	73	60	84	11	71	60	82	18	66	56	79	4	71	33
2011	74	64	85	19	71	57	86	32	73	62	81	8	72	59
2012	71	61	96	21	69	42	85	38	76	57	98	9	70	68
2013	69	55	79	20	70	47	87	34	73	69	78	2	70	56
2014	71	60	79	20	68	61	78	16	76	62	92	6	71	42
Avg/Total	73	55	98	231	71	42	93	300	74	56	106	70	72	601