# VEHICLE FRONTAL CRUSH STIFFNESS COEFFICIENTS TRENDS

By Sam Kodsi, Sarah Selesnic, Shady Attalla, and Avery Chakravarty

## INTRODUCTION

During a crash, kinetic energy is converted into crush damage. Crash severity can be assessed by measuring crush damage (permanent deformation) and using crash test data. A rudimentary form of this crush analysis method, based on Hooke's Law, was first developed by Emori[1] in 1968 (and corresponds to the well-known rule of thumb "one mile per hour for every inch of crush"). Contributions from others such as Mason, Campbell, and McHenry (who wrote the CRASH3 program) refined the theory into the method that is being used by crash reconstructionists today.[2,3,4]

The crush analysis method requires the crash reconstructionist to calculate the A and B crush stiffness coefficients for the particular vehicle involved. The A crush stiffness coefficient represents the damage threshold, i.e. the maximum force (per unit of width), that can be sustained without producing any permanent crush.[5] The B crush stiffness coefficient represents the relationship between the force and the amount of permanent crush - the ratio of the force per unit width (of the contact area) to the crush depth.[6] The A and B crush stiffness coefficients are then used along with the crush measurements of the vehicles to calculate the speed changes experienced by the vehicles (which is a measure of the severity of the collision). These speed changes are correspondingly used to determine the impact speeds of the vehicle(s), which is a variable typically sought after by crash reconstructionists.

Crash reconstructionists today typically use data from the National Highway Traffic Safety Administration (NHTSA) Vehicle Crash Test Database to calculate the A and B crush stiffness coefficients for a particular vehicle.[7] Jean[8] described the algorithms used to calculate the A and B crush stiffness coefficients in the CRASH3 program; they are reproduced below.

$$A\ (kg/cm) = (w\, b_0\, b_1) / (g\, L) \quad (1)$$

$$B\ (kg/cm^2) = (w\, b_1^2) / (g\, L) \quad (2)$$

where $$b_1\ (s^{-1}) = (\Delta V - b_0) / C_{avg} \quad (3)$$

and $$\Delta V\ (km/h) = V_i\,(e+1) \quad (4)$$

The NHTSA Vehicle Crash Test Database provides the weight (w), crush width (L), average crush (Cavg), and impact speed (Vi). The b0 value is the y-intercept of the graph of impact speed versus the average crush; previous research[10,11,12] has shown it to be approximately 5 to 11 km/h for frontal impacts (for vehicles made within the last 5 decades). Generally, for frontal barrier impact tests, the coefficient of restitution (e) is approximately 0.03 to 0.2 (depending on the impact speed), based on research.[13,14]

As stated in previous research,[15] sometimes there is no specific crash test data from which the A and B crush stiffness coefficients for a particular vehicle can be calculated. Therefore, it is useful to have generic trends to rely on when this situation arises. Siddall and Day[16] provided generic crush stiffness coefficients for 1983 to 1993 vehicles, classified by wheelbase. This paper relied on data from direct measurements, AAMA vehicle sheets, and published research to calculate the A and B crush stiffness coefficients. Osterholt[17] provided generic crush stiffness coefficients for vehicles produced between 1980 to 1989, 1990 to 1999, and 2000 to 2009, also classified by wheelbase (using the classifications established by Siddall and Day). Osterholt calculated the A and B crush stiffness coefficients by using data from the NHTSA Vehicle Crash Test Database.

Here, vehicles vehicles produced from 1973 to 2014 were classified by type, origin, and weight class, and correspondingly calculated the average A and B crush stiffness coefficients for each classification (as well as the standard deviation). We have also calculated the average A and B crush stiffness coefficients for several different year spans from 1973 to 2014, and have noted some trends.

## METHODOLOGY

We downloaded the crash test data for each tested vehicle from 1973 to 2014 from the NHTSA Vehicle Crash Test Database; we removed any test that was not a full frontal rigid barrier impact tests. This resulted in 2,072 crash tests in total. Five of the crash tests (tests #4671, 6655, 6732, 6860, and 6991) had negative values for the average crush - these were removed from the data set. The weights ranged from 824 to 3421 kg (with an average and standard deviation of 1722 kg and 413 kg, respectively), and the impact speeds ranged from 16 to 97 km/h (with an average and standard deviation of 52 km/h and 7 km/h, re-

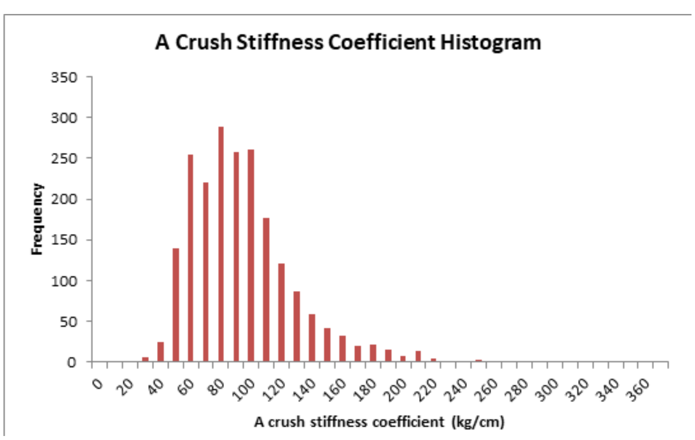


*Figure 1: Histogram of A crush stiffness coefficient.*

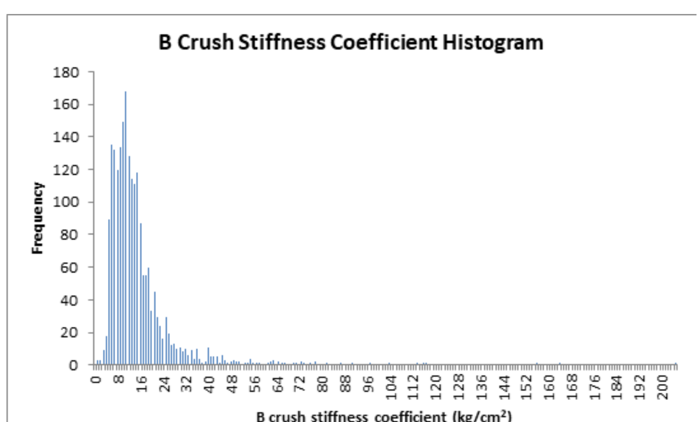


*Figure 2: Histogram of B crush stiffness coefficient.*

spectively). The weights followed an approximate normal distribution, whereas most of the crash tests were done at impact speeds of 56 to 57 km/h (approximately 59% of all crash tests). Crash tests done at impact speeds of 40 to 49 km/h also accounted for approximately 34% of all crash tests.

The A and B crush stiffness coefficients were then calculated for each vehicle by using the Equations 1 to 4, a $b_0$ value of 8 km/h, and a coefficient of restitution of 0.1, based on above noted published research. The histograms of the A and B crush stiffness coefficients for all of the vehicles were plotted, showing that the data sets followed an approximately normal distribution. (See Figures 1 and 2).

The histograms demonstrate that there were significant outliers (especially in the case of the B crush stiffness coefficients). As such, we then filtered the calculated A and B crush stiffness coefficients by applying the modified Z-score for a normal distribution (formulas shown below), and removing any values that were associated with a modified Z-score of greater than 3.5.[18,19]

$$M_i = |x_{i\text{-median}(x)}| \ / \ MAD \qquad (5)$$

where $$MAD = 1.4826 * \text{median}\,(|x_{i\text{-median}(x}|)) \qquad (6)$$

As a result of the filtering, a total of 123 tests were removed (out of 2,067 crash tests). The histograms of the filtered A and B crush stiffness coefficients are produced (from a total of 1944 crash tests). They are presented Figures 3 and 4.

The unfiltered crash tests were divided into four vehicle types (pick-up, sedan, SUV, and van), three vehicle origins (European, American, and Japanese-Korean), and five vehicle weight classes (800-1250 kg, 1250-1500 kg, 1500-1750 kg, 1750-2000 kg, and greater than 2000 kg). We again calculated the A and B crush stiffness coefficients for each vehicle by using Equations 1 to 4, a $b_0$ value of 8 km/h, and a coefficient of restitution of 0.1. We then applied the same filters to the A and B crush stiffness coefficients.

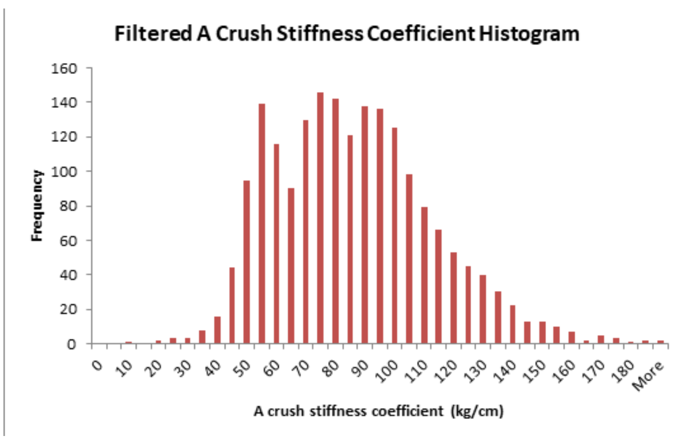


*Figure 3: Histogram of filtered A crush stiffness coefficient.*

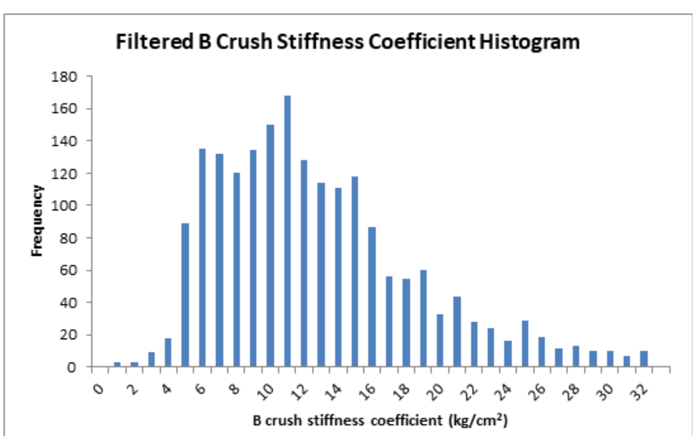


*Figure 4: Histogram of filtered B crush stiffness coefficient.*

Finally, we analyzed the A and B crush stiffness coefficients trends for all vehicles from 1973 to 2014, and we calculated the average and standard deviations of the A and B crush stiffness coefficients for each subdivision within vehicle type, vehicle origin, and vehicle weight class.

## RESULTS & DISCUSSION

### General Trends

Figure 5 shows the A and B crush stiffness coefficients over time. Table 1 presents the overall range, average, and standard deviation of the A and B crush stiffness coefficients). Overall, the data indicated that the front end of vehicles in general are becoming stiffer over the years, however, the trend also appears to be currently stabilizing.

In order to find additional trends, we further analyzed the trend of A and B crush stiffness coefficients for each 10 year span from 1973 to 2014. Figures 6 through 9 show the A and B crush stiffness coefficients over each 10 year span are shown below, while Tables 2 and 3 summarize the ranges and the slope of the linear model fit for each graph.

As can be seen from these graphs and tables, the A and B crush stiffness coefficients did not significantly increase in the 1970's or the early 1980's (in fact, the linear fit model showed that they decreased slightly). The A and B crush stiffness coefficients then increased significantly from 1985 to 2004 (almost doubled), after which they continued to increase, but at a lower rate (indicating that the trend is stabilizing). Interestingly, these trends correspond well with the development of government regulations regarding vehicle safety, and the corresponding advancements in crashworthiness and automotive engineering.

The first Federal Motor Vehicle Safety Standards (FMVSS) re-

**TABLE 1: A and B crush stiffness coefficients overall statistics (from 1973 to 2014).**

| Covariate | Range | Average | Std Dev |
|---|---|---|---|
| A (kg/cm) | 8.7 to 188.4 | 83.8 | 27 |
| B (kg/cm²) | 0.1 to 32 | 12.2 | 5.9 |

**TABLE 2: Average A crush stiffness coefficients for each division.**

| Model Year | Number of Tests | A (kg/cm) | | | |
|---|---|---|---|---|---|
| | | Range | Average | Std Dev | Slope |
| 1973 - 1984 | 275 | 30 - 157 | 56.7 | 16.7 | -0.60 |
| 1985 - 1994 | 425 | 9 - 188 | 69.2 | 24.6 | 1.8 |
| 1995 - 2004 | 664 | 37 - 187 | 87.4 | 21.5 | 1.6 |
| 2005 - 2014 | 580 | 51 - 175 | 103.2 | 21.0 | 0.84 |

**TABLE 3: Average B crush stiffness coefficients for each division.**

| Model Year | Number of Tests | B (kg/cm²) | | | |
|---|---|---|---|---|---|
| | | Range | Average | Std Dev | Slope |
| 1973 - 1984 | 275 | 3 - 30 | 7.0 | 3.5 | -0.17 |
| 1985 - 1994 | 425 | 0.14 - 29 | 8.9 | 4.2 | 0.36 |
| 1995 - 2004 | 664 | 4 - 32 | 13.2 | 5.3 | 0.26 |
| 2005 - 2014 | 580 | 4 - 32 | 16.1 | 5.5 | 0.19 |

garding crash worthiness and occupant compartment safety were passed in the late 1960's and early 1970's (Canada Motor Vehicle Safety Standards, or CMVSS, is the Canadian version).[20] In the early 1990's, the Insurance Institute for Highway Safety (IIHS) opened their crash testing facility, where many vehicles that were initially tested earned less than good ratings.[21] The National Highway Traffic Safety Administration also established the 5-Star Safety Ratings Program, to provide vehicle owners information regarding the safety ratings of particular vehicles.[22] The ratings of new vehicles increased over the years, indicating that automobile manufacturers were improving on vehicle design in terms of safety. The developments discussed above are most probably the reason for the significant increase in the A and B crush stiffness coefficients from 1985 to 2004, after a period of no apparent change in the 1970's and early 1980's.

By the late 1990's, most new vehicles were earning good crash worthiness ratings in terms of vehicle design. As such, the focus shifted to other ways of improving crash worthiness and occupant safety; for example, in 1998, the United States federal government mandated the installation of frontal airbags in all new vehicles, and in 2000, the 5-Star Safety Ratings Program was expanded to include rollover safety. Therefore, as auto manufacturers focused on new areas to improve, we would expect the A and B crush stiffness coefficients to begin stabilizing, as seen in the graphs/table above.

The "current" A and B crush stiffness coefficients from 1997 to 2013 were further analyzed. The average age of vehicles as of the end of 2016 was approximately 12 years (and taking into account a standard deviation of 8 years).[23] The statistics of the A and B crush stiffness coefficients for these years appear in Figure 10.

The increase of the A and B crush stiffness coefficients over this year span is significant, as such, it is important for the crash reconstructionist to use appropriate A and B crush stiffness coefficients for crush analysis.

### Crush Stiffness Coefficients by Type, Origin, and Weight Class

As mentioned earlier, we additionally calculated the A and B crush stiffness coefficients for vehicle types, origins, and weight classes (over all the years, from 1973 to 2014). The average and standard deviations of the A and B crush stiffness coefficients for each subdivision within vehicle type, origin, and weight class are given in Table 4. The average A and B crush stiffness coefficients are also illustrated graphically for each division (type, origin, and weight class in Figures 11 through 13.

As can be seen from the above table and graphs, the stiffest vehicles are typically SUVs,

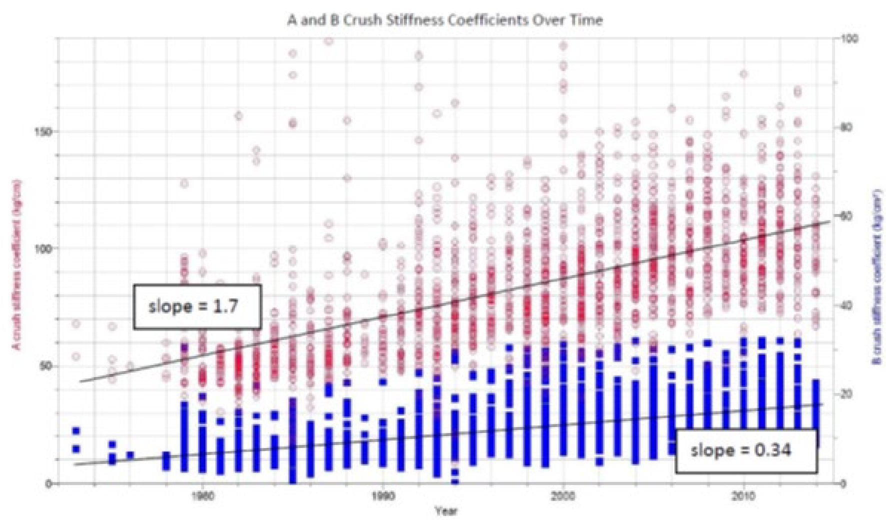


*Figure 5: A and B crush stiffness coefficients plotted over time.*

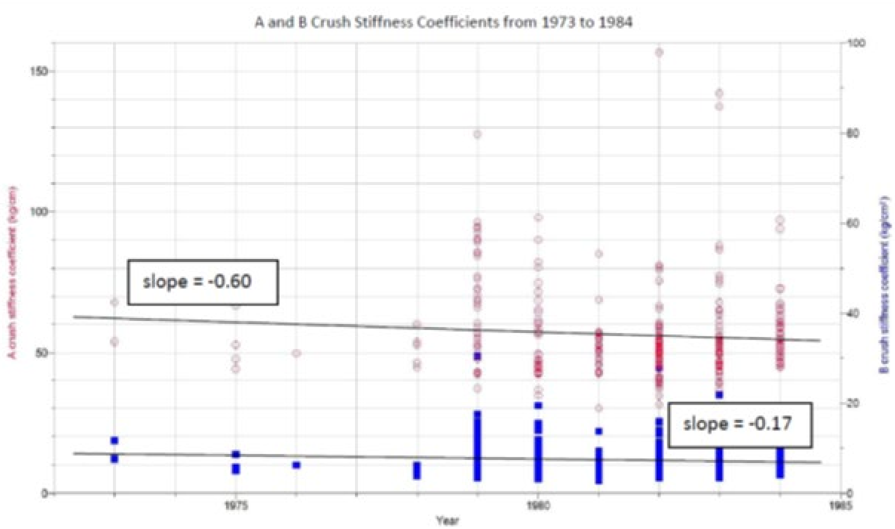


*Figure 6: A and B crush stiffness coefficients plotted from 1973 to 1984.*

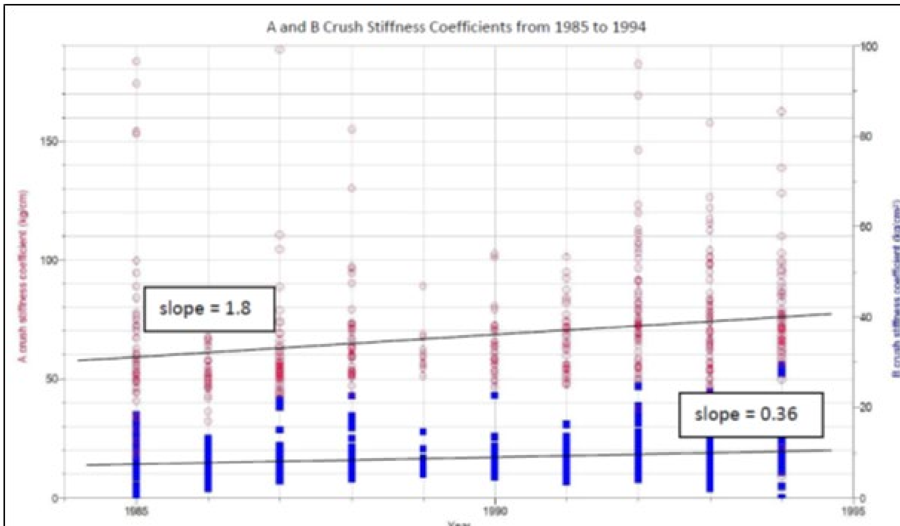


*Figure 7: A and B crush stiffness coefficients plotted from 1985 to 1994.*

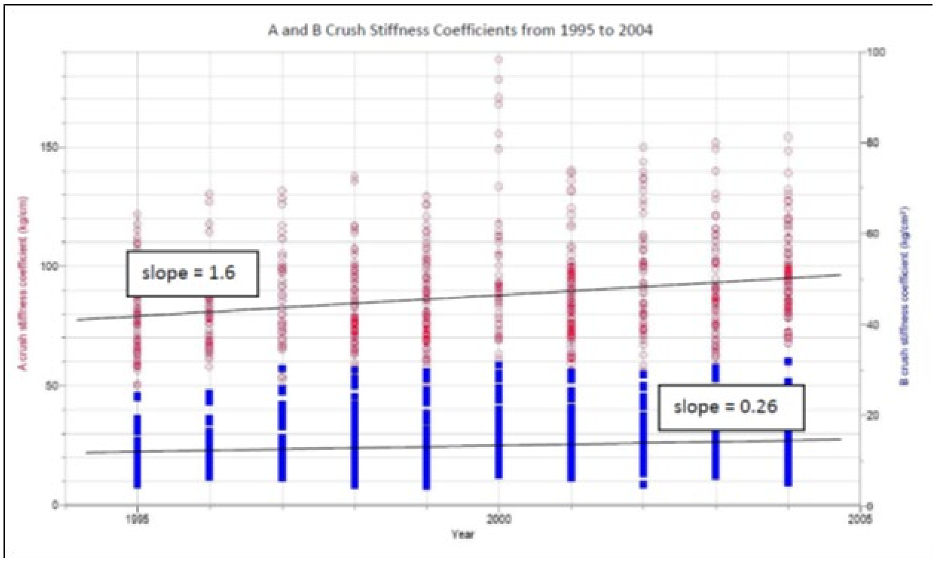


*Figure 8: A and B crush stiffness coefficients plotted from 1995 to 2004.*

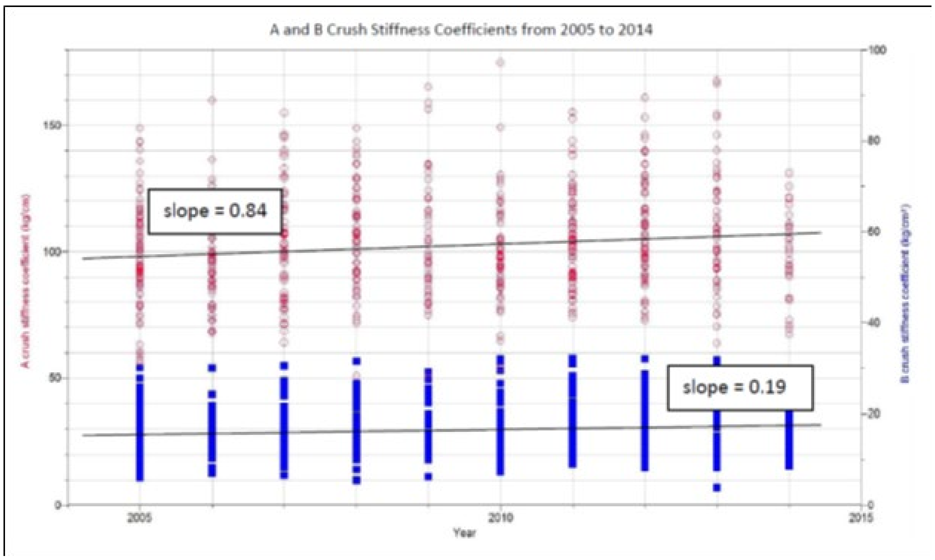


*Figure 9: A and B crush stiffness coefficients plotted from 2005 to 2014.*

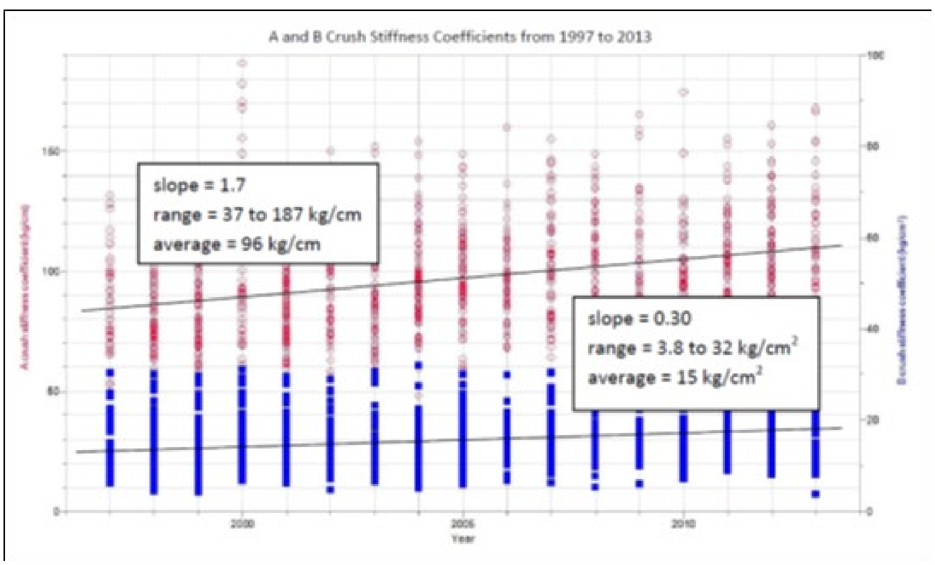


*Figure 10: A and B crush stiffness coefficients plotted from 1997 to 2013.*

European, and heavy. On the other hand, the least stiff vehicles are typically sedans, American/Japanese-Korean, and light. With regards to the weight classes, the A and B crush stiffness coefficients trends present no surprises. The weight distributions of vehicles are usually similar, regardless of type, origin, or weight class. As such, we would expect heavier vehicles to be stiffer. We would also expect smaller vehicles (such as sedans) to be on average less stiff than larger vehicles such as pickups, vans, and SUVs (as sedans are typically lighter). It is interesting to note that the stiffest vehicle type are SUVs, followed by vans, and then followed by pickups (with sedans holding last place). It is also interesting to note that European vehicles are significantly stiffer than American and Japanese-Korean vehicles. There were no significant differences in weights among the vehicle types (specifically SUVs, vans, and pickups), and among vehicle origins. As such, these trends are most likely due to the differences in how the vehicles are built, and the materials/components that are used to build the vehicles. For example, isolators/pistons at the front bumper are usually found among European vehicles; this may be a factor that increases the A and B crush stiffness coefficients.

We also compared our results to the results presented in the Osterholt paper. Osterholt had 5 subdivisions for passenger vehicles (which we compared to our sedan results), 2 subdivisions for pickups, and 2 subdivisions for vans. We took the overall average for each subdivision, and took the average of the overall averages, and compared these numbers to ours. (See Table 5).

In general, our calculated A and B crush stiffness coefficients are higher than those calculated by Osterholt. There are likely several reasons for this; listed below are the differences between our methodology and Osterholt's methodology:

- Our A and B crush stiffness coefficients encompass vehicles from 1973 to 2014; Osterholt's encompasses vehicles from 1980 to 2009.
- We used a coefficient of restitution of 0.1; Osterholt appears to have used a restitution of 0.
- We used a b0 value of 8 km/h for all vehicles; Osterholt calculated the b0 value for each subdivision (by graphing the impact speeds versus average crush and finding the y-intercept) - these values ranged from 6.0 to 7.4 km/h for passenger vehicles, 7.2 to 7.7 km/h for pickups, and 7.4 to 7.7 km/h for vans.
- We applied a filter to our data; Osterholt did not mention any filtering of the data.

The first two differences in the above list are likely the most significant. Vehicles from 1973 to 1979, and vehicles from 2010 to 2014 were not included in Osterholt's analysis.

As seen earlier in this article, vehicles have generally become stiffer over the years. This trend was not as significant for vehicles made in the 1970's (the A and B crush stiffness coefficients actually decreased slightly). As such, our inclusion of vehicles from 2010 to 2014 (which corresponded to 281 crash tests, approximately 14% of the overall crash tests used) would have increased the overall A and B crush stiffness coefficients averages. Additionally, increasing the coefficient of restitution from 0 to 0.1 would also have increased the overall A and B crush stiffness coefficients averages, as both the A and B crush stiffness coefficients are directly proportional to the coefficient of restitution (see Equations 1-4).

## SUMMATION

The trends of the A and B crush stiffness coefficients over the years (from 1973 to 2014) have been analyzed within this article. In addition to a general knowledge of how the A and B crush stiffness coefficients have changed over the years, and how vehicle type, origin, and weight influences the A and B crush stiffness coefficients, this article also presents the average and standard deviations of the A and B crush stiffness coefficients for four vehicle types (pick-up, sedan, SUV, and van), three vehicle origins (European, American, and Japanese-Korean), and five vehicle weight classes (800-1250 kg, 1250-1500 kg, 1500-1750 kg, 1750-2000 kg, and greater than 2000 kg).

As mentioned at the beginning of this article, the severity of a crash can be assessed based on energy that is converted into crush damage. Also, crush analysis can be used as a validation tool. Using accurate A and B crush stiffness coefficients and crush damage measurements of at least one vehicle in a two vehicle collision allows the crash reconstructionist to compare the calculated speed changes against speed changes determined by other methods (i.e. conservation of linear momentum, computer simulations, analysis of black box data, etc.).

While conducting crush analysis, a general knowledge of how vehicle type, origin, and weight influences the A and B crush stiffness

**TABLE 4: Average A and B crush stiffness coefficients for each division.**

| | Number of Tests | A (kg/cm$^2$) | | B (kg/cm$^2$) | |
|---|---|---|---|---|---|
| | | Avg | Std Dev | Avg | Std Dev |
| **Type** | | | | | |
| Sedan | 1235 | 75.65 | 24.37 | 11.07 | 5.7 |
| Pickup | 198 | 86.36 | 23.87 | 11.72 | 4.9 |
| Van | 127 | 94.15 | 21.83 | 13.54 | 4.89 |
| SUV | 341 | 103.91 | 21.68 | 15.58 | 5.45 |
| **Origin** | | | | | |
| American | 949 | 83.19 | 28.20 | 11.73 | 6.11 |
| Japanese-Korean | 824 | 83.59 | 24.21 | 12.52 | 5.26 |
| European | 176 | 91.92 | 34.3 | 15.47 | 9.61 |
| **Weight** | | | | | |
| 800-1250 kg | 191 | 53.15 | 11.12 | 7.11 | 2.49 |
| 1250-1500 kg | 413 | 69.04 | 17.63 | 10.16 | 4.65 |
| 1500-1750 kg | 473 | 80.75 | 20.83 | 12.01 | 5.5 |
| 1750-2000 kg | 352 | 90.97 | 23.92 | 13.2 | 5.73 |
| greater than 2000 kg | 491 | 104.73 | 25.57 | 15.32 | 6.42 |

**TABLE 5: Comparison of results to the Osterholt results.**

| | Number of Tests | | Avg A (kg/cm) [Std Dev] | | Avg B (kg/cm$^2$) [Std Dev] | |
|---|---|---|---|---|---|---|
| | Kodsi | Osterholt | Kodsi | Osterholt | Kodsi | Osterholt |
| Pickup | 198 | 96 | 86.36 [23.87] | 61.72 [8.00] | 11.72 [4.9] | 8.46 [2.09] |
| Sedan | 1235 | 795 | 75.65 [24.37] | 53.34 [7.77] | 11.07 [5.7] | 8.40 [2.49] |
| Van | 127 | 52 | 94.15 [21.83] | 64.92 [6.56] | 13.54 [4.89] | 8.39 [1.56] |

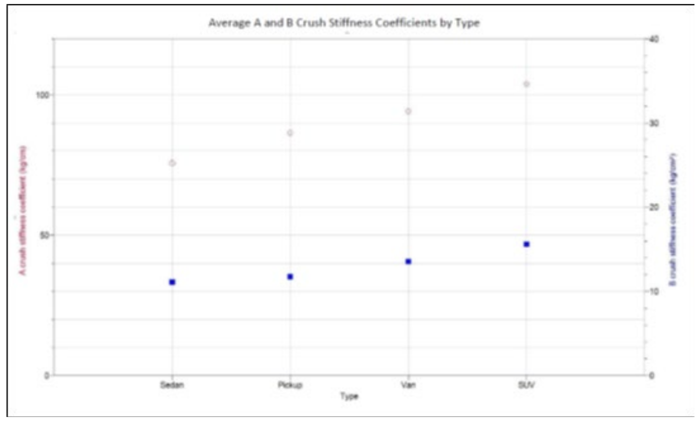


*Figure 11: Average A and B crush stiffness coefficients plotted by type.*

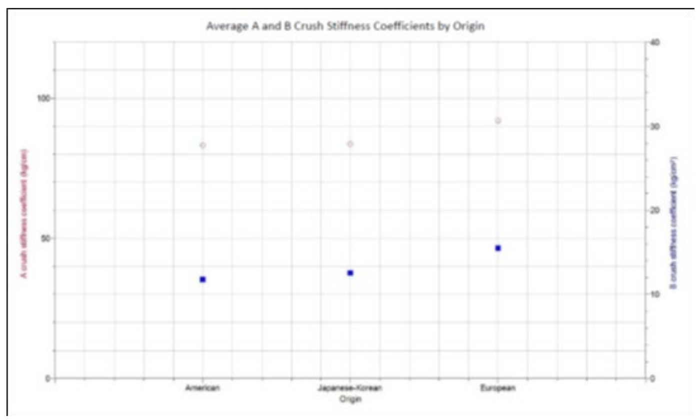


*Figure 12: Average A and B crush stiffness coefficients plotted by origin.*

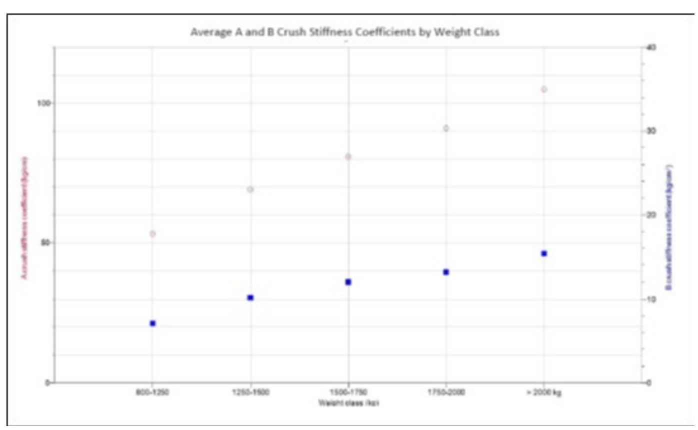


*Figure 13: Average A and B crush stiffness coefficients plotted by weight class.*

coefficients is useful to the crash reconstructionist, as it provides a mental check when finding the A and B crush stiffness coefficients for a particular vehicle. Additionally, the average A and B crush stiffness coefficients for a particular vehicle type, origin, or weight class is also useful in cases where a specific crash test cannot be found for a particular vehicle, or when very little is known about one of the involved vehicles.

We have analyzed the A and B crush stiffness coefficients trends for vehicles up to 2014, however, vehicles are currently undergoing significant changes. In the next decade, the rise in electric and autonomous vehicles will affect vehicle design, engineering structure and, correspondingly, how vehicles behave during crashes. With a significantly reduced chance of a crash, government regulations regarding crashworthiness may become less strict. Further work may include assessing the force-deformation characteristics of new structures and hybrid systems.

## REFERENCES

1. Emori, Richard I. "Analytical Approach to Automobile Collisions", Society of Automotive Engineers, Paper number 680016.

2. Campbell, Kenneth L. "Energy Basis for Collision Severity", Society of Automotive Engineers, Paper number 740565.

3. Neptune, James A., Blair, George Y., and Flynn, James E. "A Method for Quantifying Vehicle Crush Stiffness Coefficients", Society of Automotive Engineers, Paper number 920607.

4. Stother, Charles E. et al, "Crush Energy in Accident Reconstruction", Society of Automotive Engineers, Paper number 860371.

5. Neptune, James A., Blair, George Y., and Flynn, James E. "A Method for Quantifying Vehicle Crush Stiffness Coefficients", Society of Automotive Engineers, Paper number 920607.

6. Neptune, James A., Blair, George Y., and Flynn, James E. "A Method for Quantifying Vehicle Crush Stiffness Coefficients", Society of Automotive Engineers, Paper number 920607.

7. National Highway Traffic Safety Administration, https://www-nrd.nhtsa.dot.gov/database/veh/veh.htm.

8. Jean, B., "Calculating Stiffness Coefficients From Barrier Test Data", Accident Reconstruction Journal, September-October 1992.

9. Campbell, Kenneth L. "Energy Basis for Collision Severity", Society of Automotive Engineers, Paper number 740565.

10. Neptune, James A., Blair, George Y., and Flynn, James E. "A Method for Quantifying Vehicle Crush Stiffness Coefficients", Society of Automotive Engineers, Paper number 920607.

11. Stother, Charles E. et al, "Crush Energy in Accident Reconstruction", Society of Automotive Engineers, Paper number 860371.

12. Osterholt, Gary et al., "Updating Generic Crush Stiffness Coefficients for Accident Reconstruction", Society of Automotive Engineers, Paper number 2010-01-1581.

13. Schmidt, B., Haight, W.R., et al., "System-Based Energy and Momentum Analysis of Collisions," Society of Automotive Engineers, Paper number 980026.

14. Kerkhoff, John F. et al., "An Investigation into Vehicle Frontal Impact Stiffness, BEV and Repeated Testing for Reconstruction, Society of Automotive Engineers, Paper number 930899.

15. Osterholt, Gary et al., "Updating Generic Crush Stiffness Coefficients for Accident Reconstruction", Society of Automotive Engineers, Paper number 2010-01-1581.

16. Siddall, Donald E. and Day, Terry D., "Updating the Vehicle Class Categories", SAE Technical Paper Series 960897, February 1996.

17. Osterholt, Gary et al., "Updating Generic Crush Stiffness Coefficients for Accident Reconstruction", Society of Automotive Engineers, Paper number 2010-01-1581.

18. Rosenmai, P. "Using the Median Absolute Deviation to Find Outliers", <https://eurekastatistics.com/using-the-median-absolute-deviation-to-find-outliers/>.

19. "Detection of Outliers", <http://www.itl.nist.gov/div898/handbook/eda/section3/eda35h.htm>.

20. "Federal Motor Vehicle Safety Standards and Regulations", <https://icsw.nhtsa.gov/cars/rules/import/FMVSS/#SN201>.

21. "About the Institutes", <http://www.iihs.org/iihs/about-us>.

22. NHTSA Timeline, <https://one.nhtsa.gov/nhtsa/timeline/index.html>.

23. "Vehicles Getting Older: Average Age of Light Cars and Trucks in U.S. Rises Again in 2016 to 11.6 Years, IHS Markit Says", <http://news.ihsmarkit.com/press-release/automotive/vehicles-getting-older-average-age-light-cars-and-trucks-us-rises-again-201>.