

Relationship between Frontal Stiffness and Occupant Compartment Intrusion in Frontal Crash Tests

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ABSTRACT

In the United States, there are two leading frontal crash consumer information rating systems for light vehicles. The first is the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP). The second rating system comes from the Insurance Institute for Highway Safety (IIHS). For vehicle manufacturers, performing well in these rating systems has become an integral part of their safety program and the design of their vehicles. However, there has been much debate on the impact of these rating systems on vehicle design characteristics, specifically, their effects on frontal stiffness to improve these ratings.

Increased frontal stiffness in light trucks and vans (LTVs) has been shown to increase LTV aggressivity in LTV-car crashes, which is a concern. This paper focuses on how frontal stiffness relates to occupant compartment intrusion by vehicle type.

To investigate this issue, occupant compartment intrusion achieved in the IIHS offset crash test is compared to different vehicle frontal stiffness measured in a full frontal rigid wall NCAP test. The objective of this analysis is to determine if there is any relationship between these frontal stiffness measures and occupant compartment intrusion.

INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA) NCAP rating system uses a full frontal rigid barrier crash test at 56 kph with a Hybrid III (HIII) 50th dummy in the driver's seat. The star rating given to a vehicle is based on combination of injury probabilities for the head and chest. The IIHS rates a vehicle using a 64 kph, 40 percent frontal offset deformable barrier with a HIII 50th dummy in the driver's seat. IIHS calculates an overall rating based on the performance of the vehicle in the following categories: 1) Structure and safety cage, 2) Injury measures, and 3) Restraints and dummy kinematics.

Nolan and Lund (2001) found that the majority of vehicles (mainly passenger cars) whose structural performance improved in the IIHS frontal offset crash tests after being redesigned did so without significant alteration to the stiffness of the vehicle for the first half meter of deformation. However, General Motors Corporation (Verma, et al., 2003) found that the use of fixed barriers as a test device may lead to higher force levels for front ends of larger vehicles and could act to increase the incompatibility between large and small vehicles. Saunders, et al. (2005) reported on six pairs of vehicle-to-vehicle crash tests in which a redesigned vehicle in each pair obtained a better rating in the IIHS 40 percent offset deformable barrier ODB tests than its respective older model (the other vehicle in the pair). The redesigned vehicle models were found to be more aggressive in these crash tests than their older counterparts as demonstrated by the upper body injury measures of the dummies in the common target vehicles. However, Saunders could not establish a relationship between the increase in aggressivity of the redesigned vehicles and the corresponding increase in front end stiffness in the redesigned vehicle due to the confounding effects of vehicle mass and vehicle front end geometry of the redesigned vehicles.

The next section of this paper shows the methodology for calculating the vehicle's frontal stiffness and the occupant compartment intrusion for vehicle models tested by both NCAP and IIHS.

METHODOLOGY

This section describes the methodology used in selection and division of vehicle classes, in the calculation of frontal energy stiffness, and in the determination of occupant compartment intrusion. This section also describes the statistical methodology for determining the relationship between NCAP and IIHS measurements.

VEHICLE SELECTION AND DIVISION OF VEHICLE CLASSES

NHTSA's NCAP database was searched for vehicles that were also rated by IIHS, model years 1995-2006. Moreover, the NCAP tested vehicles selected for analysis had to fall within the valid range of model years provided by IIHS. In this analysis the vehicles tested by NCAP did not have to exactly match the vehicles tested by IIHS (e.g. engine size, body style, and options). Also, the average of the vehicle stiffness was used when more than one NCAP vehicle was in the valid model year range provided by IIHS for their intrusion data.

The vehicles were classified as either passenger cars (PCs) or light trucks and vans (LTVs). LTVs included pickups (PUs), sport utility vehicles (SUVs), and minivans (VANs). The weight classes for PCs are defined in Swanson, et al, 2003 and SUVs, Pickups (PUs), and Vans are defined in Saunders, et al, 2007. Table 1 shows the weight classes for PCs, Vans, PUs, and SUVs used. In this analysis, no extrapolations were made to sales or registration volumes. Therefore, this analysis only reports trends for NCAP and IIHS tested vehicles for the models and years under study.

Table 1. Weight classes for PCs, Vans, PUs, and SUVs.

	Class Id	Test Weight (Kg)
PCs	Compact (PC/COM)	1292<w≤1519
	Medium (PC/MED)	1519<w≤1746
	Heavy (PC/HEAVY)	>1746
VANs	VAN	All
PUs	Compact (PU/COM)	≤2268
	Heavy (PU/HEAVY)	>2268
SUVs	Compact (SUV/COM)	≤1814
	Medium (SUV/MED)	1814<w≤2268
	Heavy (SUV/HEAVY)	>2268

ENERGY STIFFNESS

To characterize the frontal stiffness of vehicles, the energy stiffness over the crush of the vehicle was used and calculated according to Patel, et al. (2007). The equation for energy stiffness is listed below:

$$\text{Energy stiffness} = \frac{2F(X_f - X_i)}{X_f^2 - X_i^2}$$

The equation for energy stiffness comes from computing the work to crush the vehicle front (e.g., average total force exerted on a rigid wall barrier, F , times net crush $(X_f - X_i)$), and equating this to the energy stored in an

ideal spring of energy stiffness, K , with a crush, X , between initial and final values (e.g., $\frac{1}{2} K (X_f^2 - X_i^2)$).

Energy stiffness was calculated using the load cell wall data from NHTSA's NCAP 56 kph full frontal rigid wall crash test. Three different values of energy stiffness were calculated for this analysis:

$Kw400$ = energy stiffness from 25 mm of crush to 400 mm of crush.

$KwTotal$ = energy stiffness from 25 mm of crush to maximum crush.

$KwFinal$ = energy stiffness from 400 mm of crush to maximum crush.

OCCUPANT COMPARTMENT INTRUSION

The IIHS measures four intrusion points of the toepan before and after a 40 percent overlap 64 kph offset frontal deformable barrier crash test. These intrusion points include three intrusion points on the toepan and one intrusion point on the footrest. The maximum toepan intrusion from these four points was used for this analysis.

STATISTICAL ANALYSIS

This section describes the methodology used to evaluate the relationship between $Kw400$ and IIHS toepan intrusion for a vehicle class. For the relationship in a particular vehicle class, the data group of interest was compared to the relationship in the reference group using statistical hypothesis testing. The hypothesis tests were performed as follows. Let y_i be the NCAP $Kw400$ of vehicle i , let x_i be its IIHS Toepan Intrusion, and let D_i be 1 if the vehicle was in the group of interest or 0 otherwise. For the subpopulation of vehicles that consists of the group of interest and the reference group only, estimate the following statistical model:

$$y_i = \beta_1 + \beta_2 x_i + \beta_3 D_i + \beta_4 x_i D_i + \varepsilon_i$$

Then, consider the following hypothesis tests:

$$\text{Test 1: } H_0 : \beta_3 = 0, H_A : \beta_3 \neq 0$$

$$\text{Test 2: } H_0 : \beta_4 = 0, H_A : \beta_4 \neq 0$$

If the null hypothesis in the first test is rejected, it means that the group of interest probably has a different intercept than the reference group; if the null hypothesis is rejected in the second test, it means that the group of interest probably has a different slope than the reference group.

The next section shows the results of comparing frontal stiffness from full frontal crash tests to the occupant compartment intrusion from the offset deformable barrier tests for PCs and LTVs.

RESULTS

This section discusses the distribution of vehicles in each vehicle weight class and the results of the linear fit of stiffness values with respect to IIHS maximum toepan intrusion.

DISTRIBUTION OF VEHICLES IN THE STUDY

The number of vehicles in each vehicle weight class that were both rated by IIHS and had valid frontal energy stiffness is shown in Table 2. From this table it is seen that PUs had the fewest number of vehicles for this analysis, with the number of vehicles for PU/COM and PU/HEAVY at only 11 and 6, respectively. Also note that the number of SUV/COM and SUV/HEAVY vehicles was small at 12 and 14, respectively. Therefore, the reader must be careful about making any conclusions about the following results due to the small number of vehicles in these groups, and the results for these groups should only be considered as trends. All data for the vehicles considered in this study are shown in Appendix A.

Table 2. Number of vehicles in each vehicle weight class.

Vehicle Class	Number of vehicles
PC/COM	35
PC/MED	43
PC/HEAVY	35
Total PCs	113
Total VANs	19
SUV/COM	12
SUV/MED	33
SUV/HEAVY	14
Total SUVs	59
PU/COM	11
PU/HEAVY	6
Total PUs	17
Total LTVs	95

KW400 WITH RESPECT TO IIHS MAXIMUM TOEPAN INTRUSION

Table 3 shows results of the two hypothesis tests discussed above. Thus, for example, there is statistically significant evidence that passenger cars had a different intercept than LTVs. As another example, there is statistically significant evidence that PU's had a different slope than PCs, VANs, and SUVs combined.

Table 3. Results of statistical hypothesis testing.

	Different intercept (Test 1)	Different slope (Test 2)
SUV/HEAVY vs SUV/COM and SUV/MED		
SUV/MED vs SUV/COM and SUV/HEAVY		
SUV/COM vs SUV/MED and SUV/HEAVY		
PU/COM vs PU/HEAVY	x	
PCs vs VANs, SUVs, PUs	x	
VANs vs PCs, SUVs, PUs		
SUVs vs PCs, VANs, PUs		
PUs vs PCs, VANs, SUVs	x	x

Note: Items that were statistically significant at the 0.05 level are marked with an "x".

All vehicles classes showed no relationship between Kw400 and IIHS maximum toepan intrusion, except for PUs (Figure 1 and Figure 2). For the PUs, the data relationship showed that as IIHS maximum toepan intrusion decreased in the offset test, the Kw400 increased in the full frontal test for comparable vehicles. This difference between PUs and all other vehicles was statistically significant when compared to other vehicle classes, as shown in the last line of Table 3, but was only correlated ($R^2 = 0.3965$) for the data analyzed.

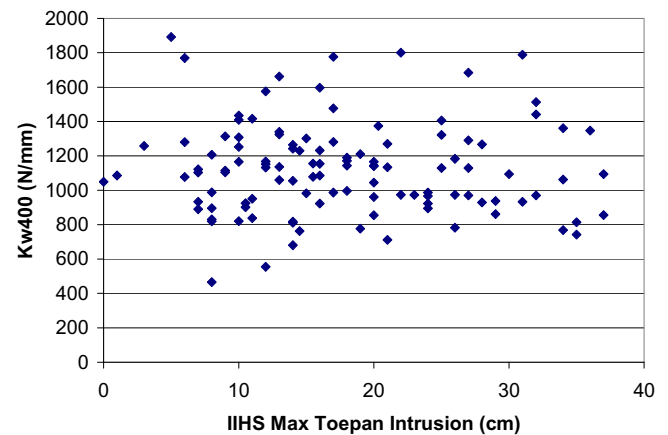


Figure 1. Kw400 versus IIHS max toepan intrusion for PCs.

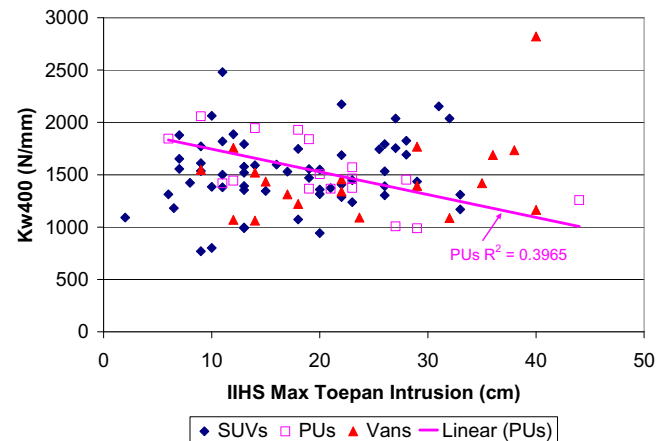


Figure 2. Kw400 versus IIHS max toepan intrusion for LTVs with the linear fit for PUs.

THE ROLE OF WEIGHT IN VEHICLE CLASSES

It can be seen from Figure 3 and Figure 4 that there is no relationship between Kw400 and IIHS maximum toepan intrusion for any weight group of PCs and SUVs. However, the weight group PU/HEAVY showed a relationship between Kw400 and IIHS maximum toepan intrusion ($R^2=0.7617$) and the weight group PU/COM showed a slight relationship between Kw400 and IIHS maximum toepan intrusion ($R^2=0.4018$) (Figure 5). This difference between PU/COM and PU/HEAVY is statistically and significantly different when compared to all other weight classes. It should be noted that this relationship is based on only 6 data points for PU/HEAVY and 11 data points for PU/COM. This relationship is different if all PUs are considered together, as discussed earlier.

Table 4 shows all the correlation coefficients and slopes for all the weight classes. The rate of change in Kw400 per centimeter of IIHS maximum toepan intrusion was higher for PU/HEAVY (34 (N/mm/cm) compared to PU/COM (15(N/mm/cm). This trend demonstrates that the stiffness increased at a higher rate as IIHS toepan intrusion decreased for PU/HEAVY. Again, this trend between different sized PUs could also be from how PU/COM and PU/HEAVY are designed to be used in the real world (e.g., with towing packages).

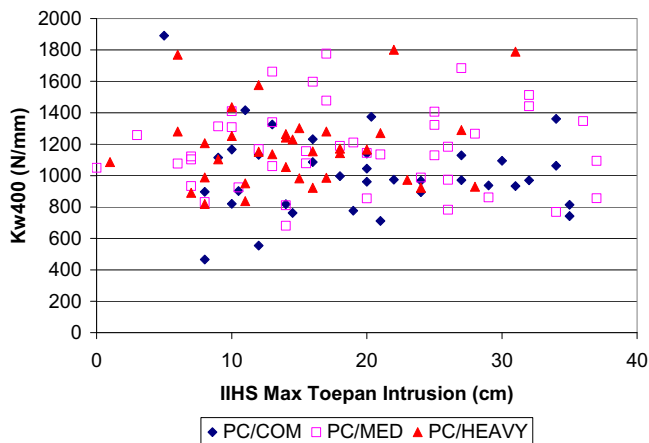


Figure 3. Kw400 versus IIHS max toepan intrusion for different size PCs.

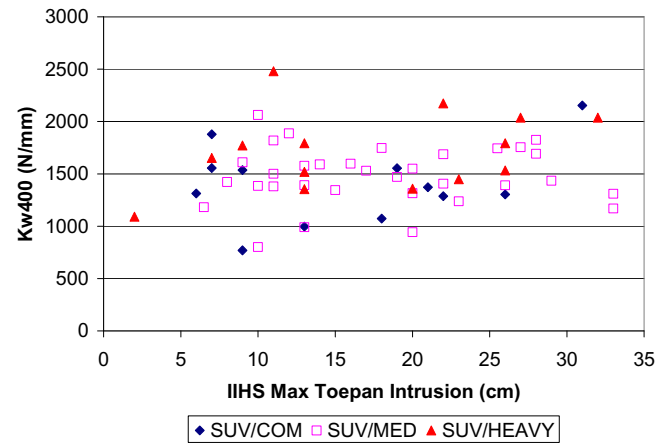


Figure 4. Kw400 versus IIHS max toepan intrusion for different size SUVs.

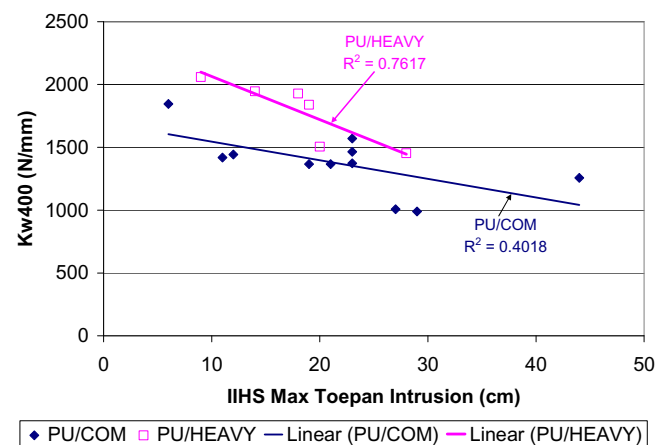


Figure 5. Kw400 versus IIHS max toepan intrusion for different size PUs.

Table 4. The slope and R^2 values for linear fit of Kw400 versus IIHS maximum toepan intrusion for different vehicle weight classes.

	Slope	R^2
PC/COM	-3.5	0.014
PC/MED	0.5	0.000
PC/HEAVY	5.9	0.025
SUV/COM	12.0	0.070
SUV/MED	1.0	0.001
SUV/HEAVY	13.2	0.099
PU/COM	-14.8	0.402
PU/HEAVY	-34.4	0.762

KWTOTAL, KWFINAL, AND STIFFNESS RATIO WITH RESPECT TO IIHS MAXIMUM TOEPAN INTRUSION

KwTotal showed similar results as Kw400 (Table 5). PUs were the only LTVs to show a relationship between KwTotal and IIHS maximum toepan intrusion and, again, PU/HEAVY had a higher rate of change in KwTotal per centimeter of IIHS maximum toepan intrusion.