Vehicle Frontal Stiffness and Female Vulnerability

Abstracted from Paper 2023 ESV 23 0232. "An NCAP Rating for Females," by Digges, K., and Dalmotas, D.

An earlier paper by UVa (Foreman 2019) reported that females were more likely than males to be injured in motor vehicle crashes. Researchers at IIHS published a further analysis of this issues (Jermaken 2021). The IIHS website provides the following summary from that paper:

"One explanation of the higher injury rates for women could be vehicle choice. Men and women crashed in minivans and SUVs in about equal proportions. However, around 70 percent of women crashed in cars, compared with about 60 percent of men. More than 20 percent of men crashed in pickups, compared with less than 5 percent of women. Within vehicle classes, men also tended to crash in heavier vehicles, which offer more protection in collisions."

In vehicle-to-vehicle crashes, the occupants of the lighter vehicle are more vulnerable to injury when there is a difference in vehicle weight. In many cases, the heavier vehicle also has a higher frontal stiffness. This higher stiffness further increases the severity of the crash to the lighter vehicle. One way to reduce the injury risks is to improve the stiffness compatibility of both heavier and lighter vehicles. EuroNCAP introduced a compatibility rating factor in January 2021 in order to better control the frontal stiffness of heavier vehicles. Current NHTSA tests provide measurements that could be used to control frontal stiffness.

NHTSA's frontal NCAP tests include the force measurements from 176 load cells mounted in a 1375 mm by 2000 mm array on the test barrier. Analysis of the barrier load cells permits the measurement of stiffness and force distribution for each vehicle tested. This test data allows an assessment of the stiffness and geometric compatibility of various vehicles.

Figure 1 shows a comparison of the force vs. displacement for the Ford Focus subcompact car and the Ford F 150 pickup. Based on the barrier results, a frontal deformation of 120 mm on the F 150 would produce 350 mm of deformation on the Focus in a head-on collision. These results are typical of stiffness differences that currently exist in the NCAP test database.

Additional compatibility tests of the Ford Focus crashed head-on into more aggressive vehicles can be found on-line in the NHTSA vehicle test database. The following test numbers in the NHTSA database are of the 2002 Ford Focus vs other more aggressive vehicles: Test 5448 – 2003 Chevrolet Silverado pickup; Test 5686 – 2006 Honda Ridgeline pickup; Test 5685 2005 Honda Odyssey MPV; Test 5542 – 2005 Chrysler Town and Country MPV. These tests illustrate the vulnerability of small car occupants in frontal collisions with more aggressive vehicles.

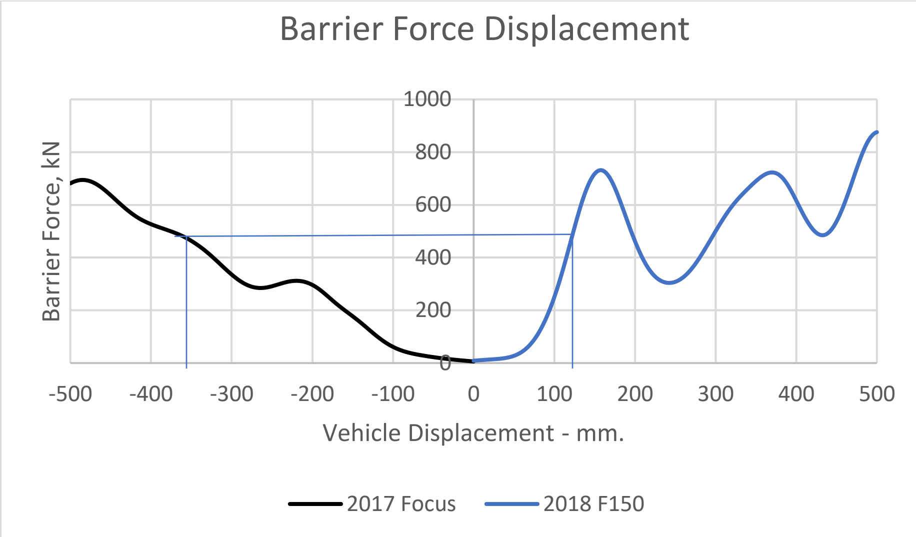

Figure 1. Stiffness comparison of the Focus vs F 150

In view of the expected increase in the population of electric vehicles in the fleet, it is essential to anticipate their influence on gender inequality. Like pickup trucks, electric vehicles have a weight advantage over most cars. Figure 2 and 3 show comparisons of the stiffness and weight of the F 150, the Tesla X, Polestar 2 and the Focus.

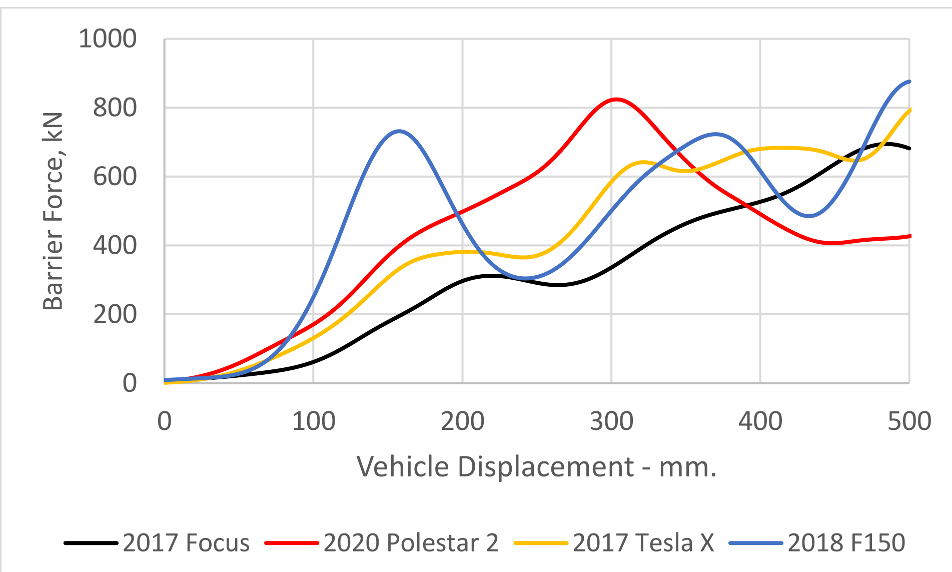

Figure 2. Frontal Stiffness of the F 150, Tesla X, Polestar 2, and Focus

The combination of weight and stiffness incompatibility makes it essential to encourage compatibility countermeasures to reduce the crash severity experienced by occupants of lighter vehicles that are more likely to have female occupants.

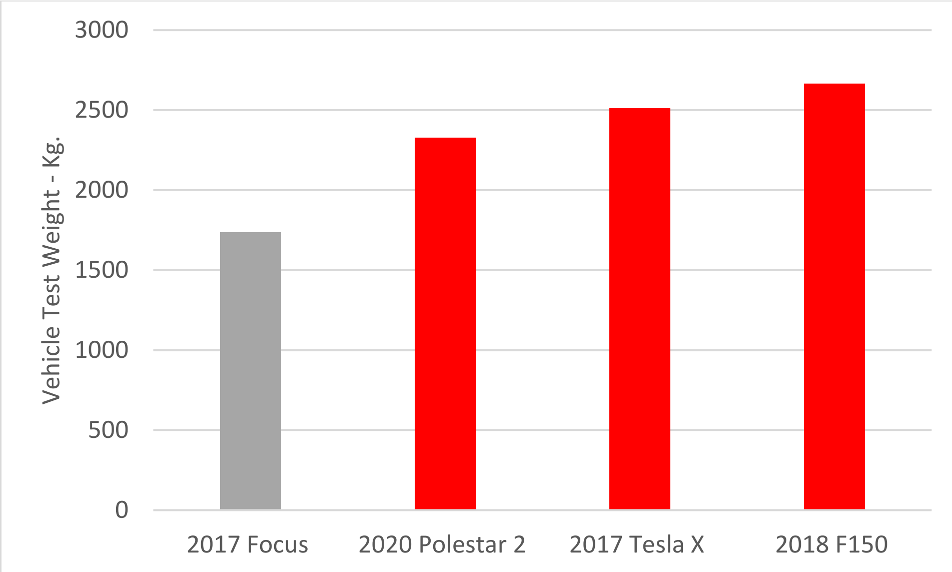

Figure 3. Vehicle NCAP Test Weight of 2017 Focus and Three Heavier Vehicles

Analysis of barrier force distribution has been reported in several papers (Digges, 1999, 2000, 2001, 2003). In a study for NHTSA, Digges, Eigen and Harrison analyzed barrier data to asses vehicle compatibility issues (Digges, 1999). They produced comparative barrier force distribution patterns for different classes of vehicles and proposed a geometric compatibility metric based on the Height of the Center of Force required to produce a restoring moment to the barrier forces. This metric, subsequently named the Average Height of Force (AHOF), was further applied in a paper that examined the aggressiveness of light trucks (Digges 2001). Figure 4 shows the AHOF for four vehicles.

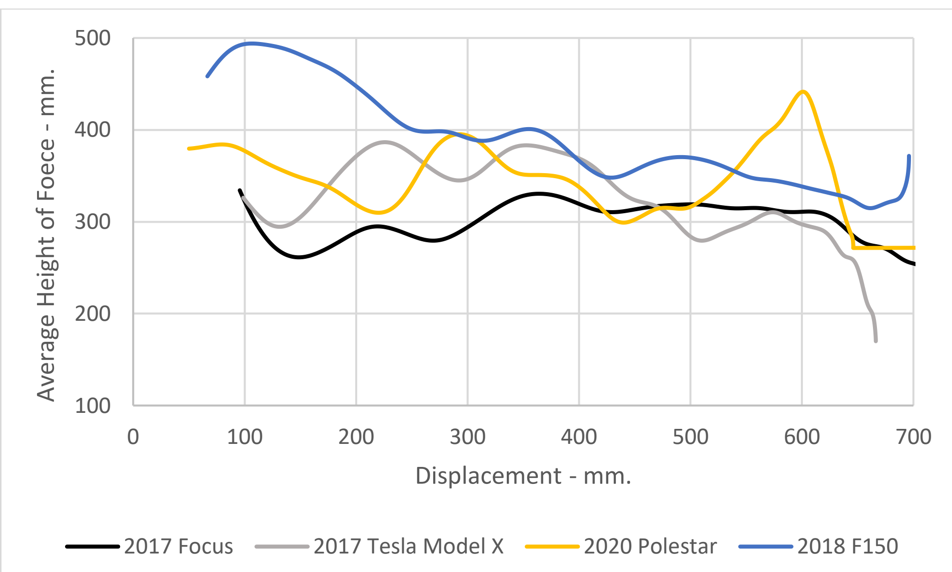

Figure 4. Average Height of Force Vs. Displacement for Focus, Polestar 2, Tesla X and F 150

Figure 5 shows the barrier force distribution for the Ford Focus, Tesla X and the Ford F 150 taken from NCAP test data on NHTSA website.

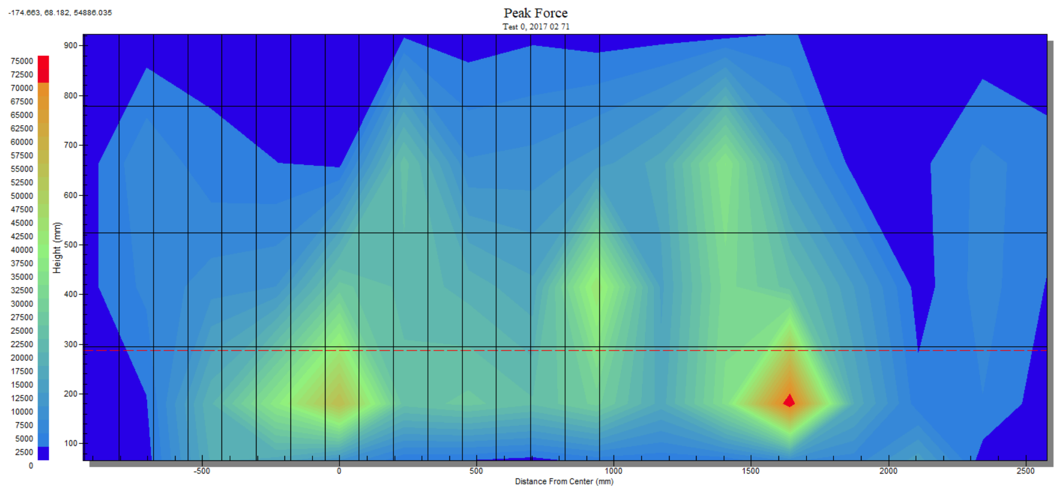

Figure 5a. 2017 Focus 10068 Barrier Force Distribution

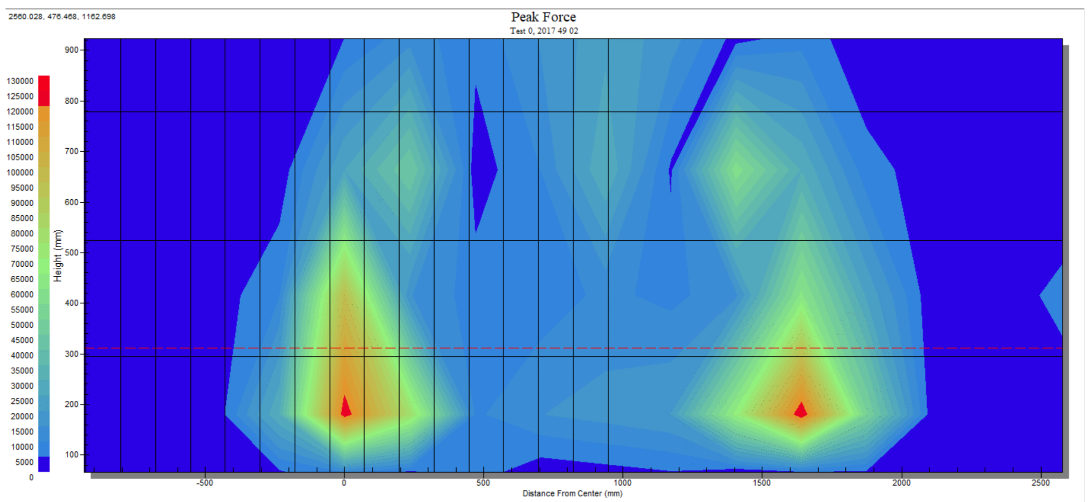

Figure 5b. 2017 Tesla X 10076 Barrier Force Distribution

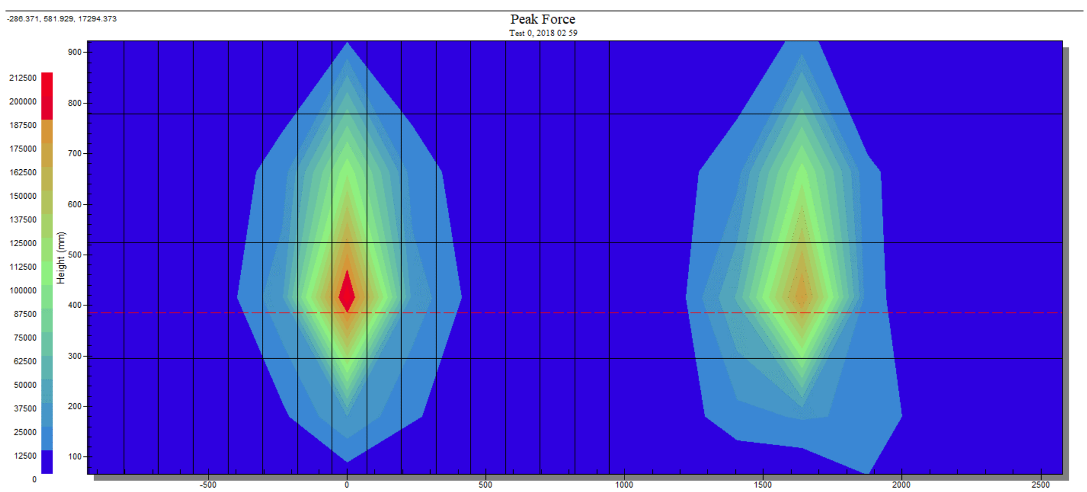

Figure 5c. 2018 Ford F 150 10310 Barrier Force Distribution

DISCUSSION: COMPATIBILITY

While females in lighter vehicles are expected to be the largest benefactors, even heavier vehicle occupants could benefit during collisions with fixed objects and other heavier vehicles. In addition, the occupants of vehicles involved in side impacts would benefit from bullet vehicles with more compatible front structures.

Figure 2 compares the stiffness of a compact car with a pickup and two electric vehicles. The initial stiffness of the electric Tesla X is a closer match to the small car than the electric Polestar 2. However, after the initial 350 mm the Tesla X is stiffer than Polestar 2. The higher stiffness of the heavier vehicles suggests that making electric vehicles stiffness compatible is not a design priority. Requiring stiffness compatibility in a Female NCAP would incentivize this compatibility improvement.

It may be noted in Figure 3 that the location of the maximum force for the Tesla X electric vehicle is close to the height of the max force of the Focus. The pickup tends to exert the max force at a higher level on the barrier. Figure 4 shows how the Average Height of Force varies with displacement for the three vehicles. The difference in Average Height of Force suggest that the pickup would tend to override the smaller vehicle more than the electric vehicles. The better alignment of electric vehicle crash forces should result in added structural engagement and increase the benefit to be expected from control of the stiffness of the heavier electric vehicles.

In order to improve stiffness compatibility, it would be desirable to design all vehicles so that their initial frontal stiffness is limited. Figure 6 shows the stiffness plot for a fixed barrier crash of a concept vehicle designed for stiffness compatibility. Either vehicle acceleration or barrier force are candidates for use in controlling initial vehicle stiffness. For an initial 400 mm of vehicle crush, there is a structural force or acceleration plateau that provides for structural stiffness compatibility. This structural force plateau will limit the force transmitted to both vehicles in lower severity vehicle-to-vehicle collisions. Consequently, occupants of both vehicles would benefit from the lower vehicle accelerations. Lower accelerations would also benefit compatible vehicle occupants in low severity single vehicle collisions with fixed objects.

Two different acceleration plateaus are shown in Figure 6 – the lower one for compatibility and the higher one for self-protection. The optimum vehicle crush and acceleration levels for these plateaus will require added research and analysis to determine.

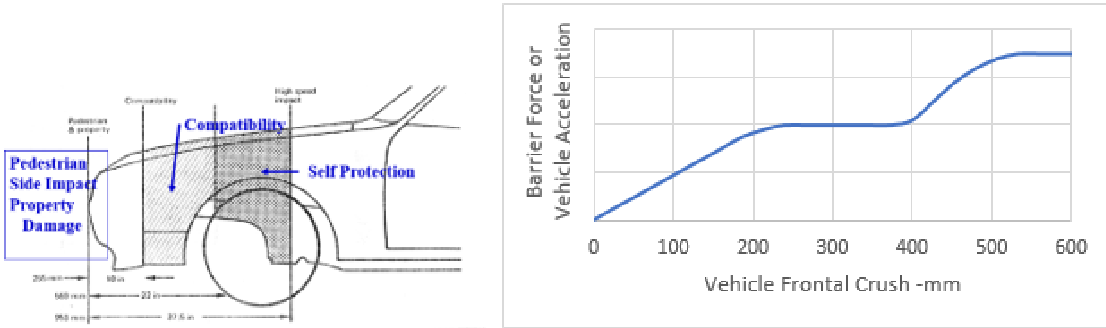

Figure 6. Vehicle Frontal Stiffness Compatibility Concept

CONCLUSIONS

Because females have increased presence in lighter vehicles they are more frequently exposed to crashes with heavier vehicles and could benefit most from improved front structure compatibility. Figure 3 shows the mass difference between a small car, a pickup and two electric vehicles. The higher mass of the electric vehicles and the increasing presence of these vehicles in the fleet suggest an urgent need to limit the stiffness aggressiveness of these vehicles. Research by Sahraei (2013) and Samaha (2010) indicates that much of the benefits of force-limited and pretensioned belts has been offset by the increased stiffness of vehicle front structures. This increase in stiffness increases the vehicle acceleration for each added increment of vehicle deformation during collisions, thereby increasing the crash severity. Figure 1 illustrates the structure deformation difference between two current on-the-road vehicles. Small deformation increments of the heavier vehicle structure cause much larger deformation increments in the lighter vehicle. This relationship contributes to the high fatality rates when car drivers collide with heavier vehicles as has been reported by Gabler (1998) and Joksch (1998).

Figure 2 shows that stiffness incompatibility exists not only in pickups, but also in some electric vehicles such as Tesla X and Polestar 2. It may be observed in Figures 4 and 5 that the geometric compatibility of the Tesla electric vehicle is a closer match with the small car than the pickup. This geometric match of the structures will tend to increase the vehicle acceleration for a given deltaV. In view of the large number of heavier electric vehicles expected to enter the fleet, it is imperative that Female NCAP address the resulting stiffness incompatibility issue that could result.

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