EFFECTS OF GEOMETRY AND STIFFNESS ON THE FRONTAL COMPATIBILITY OF UTILITY VEHICLES

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Paper No. 91

ABSTRACT

The issue of vehicle incompatibility, especially between passenger cars and utility vehicles/pickup trucks, has received a lot of attention in recent years. Real-world crash data show that occupants of cars are much more likely to be injured in frontal crashes with utility vehicles and pickup trucks than with other passenger cars, even after controlling for vehicle mass. Factors in addition to mass that can influence compatibility are stiffness and geometry. In this paper, the effects of these factors on occupant injury measures and vehicle deformation patterns are examined. The Insurance Institute for Highway Safety conducted a series of car-to-utility-vehicle frontal offset tests with the Ford Taurus as a common collision partner. To vary stiffness, the Taurus collided with either a Mercedes ML320 or a relatively stiffer Isuzu Rodeo. To vary geometry, the test matrix included an ML320 at normal ride height, a Rodeo at normal ride height, an ML320 lowered 9 cm so the frame rails matched the ride height of the normal Rodeo, and a Rodeo raised 9 cm to match the ride height of the normal ML320. In each test, both vehicles were traveling at 48 km/h (30 mi/h). A Hybrid III 50th percentile male dummy was seated in the driver's seat of each vehicle. Vehicle deformation patterns, dummy injury measures, and vehicle accelerations were recorded and compared. Results indicated that, despite its lesser stiffness, the normally higher ride height of the ML320 produced a less 'compatible' crash than the Rodeo, whose front end is stiffer but normally lower. The benefits of lesser front-end stiffness were smaller and only apparent in comparisons of tests at a common ride height. These results indicate that there is little benefit of reduced utility vehicle stiffness without good geometrical alignment of vehicles' front structures.

INTRODUCTION

In the United States, the popularity of utility vehicles and pickup trucks has been growing over the years. From 1975 to 1997, registration of these vehicles has increased 35 percent (The Polk Company, 1997) and in 1998, they were 25 percent of all registered passenger vehicles. Coupled with their rising popularity, there has been growing concern with the aggressivity of these vehicles in crashes with other vehicles. Per registered vehicle, utility vehicles are four times as likely to kill occupants of the other vehicle in two-vehicle collisions as are cars (Insurance Institute for Highway Safety, 1998).

Much of this excess aggressiveness is due to increased mass—more than half of the utility vehicles and pickup trucks sold in 1999 (22 percent of total registered vehicles) weighed more than 1,815 kg (4,001 lb) while 87 percent of all cars sold in the same year (54 percent of total registered vehicles) weighed less than 1,590 kg (3,505 lb) (Lund et al., 2000). As shown in Figure 1, for cars, utility vehicles, and pickup trucks, the likelihood of deaths in other vehicles in two-vehicle collisions increases with their mass (Lund and Chapline, 1999). Thus, based solely on their greater average mass, utility vehicles would be expected to be more aggressive than cars in multiple-vehicle crashes.

Mass is clearly not the only factor. As figure 1 shows, at every weight category, utility vehicles and pickups account for more crash deaths in other vehicles than do cars (per registered utility vehicle, pickup, or car). Two other factors considered important in the incompatibility of vehicle-to-vehicle crashes are front-end stiffness and geometry. Some researchers believe stiffness to be the key factor (Klaner et al., 1998; Steyer et al, 1998). Conceptual models relating mass, stiffness, and front-end crush distance have been developed suggesting the need to soften the front ends of heavier vehicles and increase the stiffness of lighter ones (Zeidler et al., 1999; Zobel, 1999).

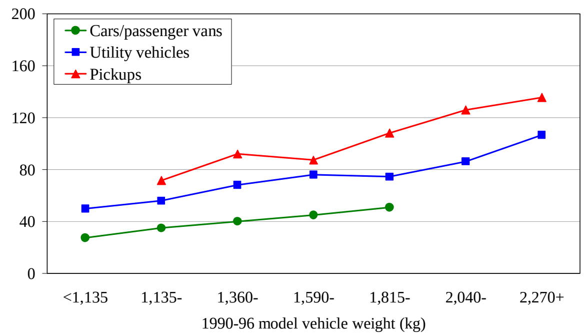

Figure 1. Occupant Death Rates for All Other Cars/ Passenger Vans in Two-Vehicle Crashes with 1990-96 Model Passenger Vehicles, Deaths per Million Vehicles per Year

Other researchers have argued that geometric effects may be even more important than stiffness (Faerber et al., 1998; Wykes et al., 1998). Research appears to support this position, at least with respect to side impacts. Early research at Transport Research Laboratory (Hobbs, 1989) and Renault (Provensal, 1981) suggested that the pattern of intrusion in side impacts was more important than the extent of intrusion in determining whether occupants would be injured. Front-end geometry, or the location of stiff structural elements, is more important in determining pattern of intrusion than is stiffness, which tends to affect the extent of intrusion.

This early research was confirmed in a series of side impact tests conducted by the Insurance Institute for Highway Safety (IIHS). In this series, a large American car, the Mercury Grand Marquis, was struck in the side by a Lincoln Town car and several Ford F150 4x2 or 4x4 pickups that varied in mass, stiffness, and ride height (geometry). The results confirmed that mass, stiffness, and geometry each affected overall physical damage to the struck vehicle, but the effect of vehicle stiffness on injury measures clearly depended on front-end geometry. As a result, the stiffest striking vehicle, the Ford F150 4x4, did not cause the highest risk of occupant injury. These results suggest that, while vehicle stiffness may be an important issue in crash incompatibility, front-end geometry can greatly affect the aggressiveness of increased stiffness in side impacts.

The results for side impacts may not be applicable to frontal impacts. In side impacts, vehicle front ends are inherently much stiffer than the side structures they strike. The relative subordination of stiffness effects in side impacts may reflect this fact. Therefore, another series of tests was conducted to assess the importance of front-end stiffness and geometry in frontal impacts. In this research, a passenger car is involved in head-on offset collisions with utility vehicles that vary in front-end stiffness and geometry (location of stiff structural elements).

TEST METHODOLOGY

A series of four tests was conducted to evaluate the effects of stiffness and geometry of a utility vehicle when crashed into a passenger car. In each test, the utility vehicle, either a 1995-96 Isuzu Rodeo or a 1998-99 Mercedes ML320, was crashed into a common partner, a 1996 Ford Taurus, with an offset equal to 50 percent of the Taurus front-end width. The masses of both utility vehicles were kept constant and equal to each other. The mass of the Taurus was also kept constant.

Front-End Stiffness

The ML320 was touted by the manufacturer as the "first SUV designed with 'crash compatibility' with smaller cars and other SUVs in mind" (Mercedes-Benz, 1998). Examination of load cell barrier data from the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP), as well as testing conducted at Mercedes, indicated that the ML320 was indeed much less stiff than the Rodeo in the full-frontal rigid barrier crash test. Vehicle stiffness was assessed from force deflection curves derived from NCAP tests of these vehicles. In these flat, rigid barrier frontal crash tests, the barrier is fitted with load cells that measure the force exerted in 6 (in some cases 36) zones over time. Forces measured in the different zones were summed to obtain the total force at regular intervals during the crash. In addition, the vehicle's longitudinal acceleration measured at the B-pillars was integrated twice to estimate forward displacement of the vehicle's center of gravity at regular intervals after the crash began. Figure 2 gives a comparison of the force deflection curves for the ML320 (test conducted by Mercedes in 1995), the 1995 Isuzu Rodeo, and the 1996 Ford Taurus. It indicates that the Rodeo is considerably stiffer than the ML320, which in turn is stiffer than the Taurus. In 1998, Mercedes incorporated a structural change to strengthen the occupant compartment of the ML320. The ML320s that were tested by IIHS had these changes incorporated, while the vehicle tested in the NCAP-style rigid barrier test did not. To quantify the effects of the structural modifications, acceleration versus displacement plots from frontal offset deformable barrier tests, conducted by Mercedes, were compared (Figure 3). The figure shows that, due to structural changes, there was an increase in stiffness of the ML320 late in the crash event when the occupant compartment was beginning to be engaged. Because the ML320 occupant compartment was not as deformed in crashes with the Taurus as in the 64.4 km/h offset deformable barrier test, it was deemed appropriate to consider both the pre- and post-modification vehicles as having the same stiffness.

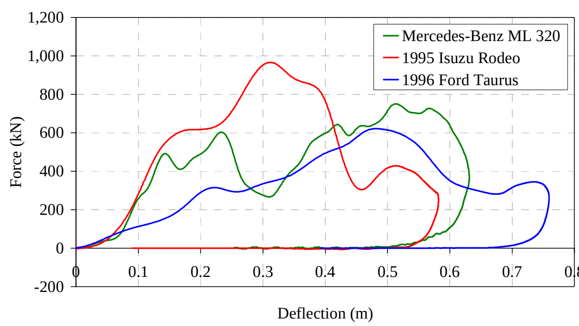

Figure 2. Force-Deflection Characteristics Frontal Compatibility Test Vehicles From NCAP Vehicle Acceleration and Load Cell Barrier Data

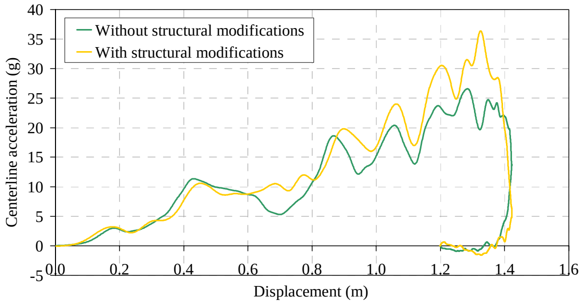

Figure 3. Comparison of Vehicle Acceleration of ML320 in Offset Deformable Barrier Tests Before and After Structural Modifications

Front-End Geometry

Although the side-view profiles of the two utility vehicles are very similar, the heights of the structural elements of the two vehicles are considerably different (Figure 4). The frame rails of the Rodeo are 9 cm lower than the frame rails of the ML320. The bumper element of the Rodeo is attached to the frame rails by weak brackets, thus suggesting that the primary load path to the frame rails is not through the bumper. Although the Rodeo appears more aggressive due to the location of this bumper element, its structural elements align more closely with those of the Ford Taurus. The horizontal centerline of the frame rails of the Rodeo is aligned with the lower edge of the Taurus front longitudinals, while the centerline of the ML320 frame rails is aligned with the upper edge of the Taurus front longitudinals. The first two crash tests were conducted with the utility vehicles in their normal configuration. To evaluate the effect of geometry, two additional tests were conducted; one with the ML320 lowered 9 cm to match the frame rail height of the Rodeo and one with the Rodeo raised 9 cm to match the height of the ML320. The test matrix is shown in Table 1.

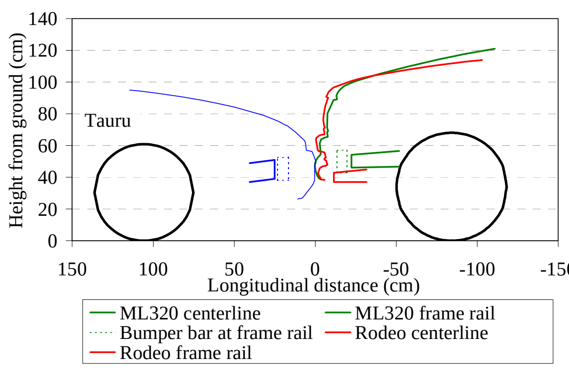

Figure 4. Comparison of Front Contours of the 1996 Ford Taurus to the 1999 Mercedes ML320 and 1995 Isuzu Rodeo

Table 1.
Test Matrix

	Low Ride Height	**High Ride Height**
Lesser Stiffness	Lowered ML 320	Normal ML 320
Greater Stiffness	Normal Rodeo	Raised Rodeo

TEST PROCEDURES

The frontal offset tests were conducted with both vehicles moving at 48-49 km/h (30 mi/h), resulting in a 96 km/h closing speed. The frontal overlap was on the left side of the vehicles and was 49-50 percent for the Taurus, 55 percent for the Rodeo, and 50-51 percent for the ML320. The 50 percent offset for the Taurus was chosen to best replicate the loading condition seen in the 40 percent frontal offset deformable barrier test. Due to concerns about overwhelming the Taurus front structure, a 96 km/h closing speed was chosen for these tests, resulting in a slightly lower delta-V for the Taurus than seen in the 64 km/h offset deformable barrier test.

The mass of the Taurus was kept constant at 1660 kg (3660 lbs) and the masses of both utility vehicles were kept constant at 2180 kg (4806 lbs), which was the test weight of the first ML320 tested. The ML320 weighs approximately 164 kg more than its measured curb weight and the Rodeo weighs approximately 368 kg more than its measured curb weight. To achieve these weights, nonstructural components were removed from the rear of the vehicle or ballast was added in the floorpan of the passenger compartment.

To lower the ML320, the front torsion bars were let out all the way and the front shocks, which were already fully compressed, were unbolted at the lower end. In the rear, portions of the suspension springs were removed and the rear tires were replaced with smaller tires (from size 225/65 R16 to 225/555 R16). To raise the Rodeo, the torsion bars in the front of the vehicle were adjusted and the spring shackles in the rear were extended.

A Denton IDDAS was used for all dummy data acquisition. During the crash, all measurements were recorded at a sample rate of 10 kHz in accordance with SAE Recommended Practice J211/1 – Instrumentation for Impact Test – Part 1, Electronic Instrumentation MAR95. All filtering and subsequent calculations were executed using DSP Development Corporation's DADiSP Ver. 4.1 NI NK B07 (DSP Development Corporation, 1997). In addition to summary metrics for each of the recorded data channels, the vector resultant of the head acceleration, the head injury criterion (HIC), vector bending in legs, and tibia indices were calculated. All calculations comply with SAE Information Report J1727 – Injury Calculation Guidelines AUG96 (SAE, 1998).

RESULTS

Front-End Geometry

The height of the Rodeo frame rails is lower than that of most utility vehicles, including the ML320, and slightly lower than the frame rails of the Ford Taurus (Figure 5). The effect of this height difference is apparent upon examination of the structural crush of the Taurus after impact. In the test with the normal Rodeo, the Rodeo completely engages the frame rails of the Taurus, while in the test of the normal ML320, the front longitudinals of the Taurus are completely overridden. When the ML320 is lowered to the height of the normal Rodeo, the crash deformation of the Taurus is similar to that caused by the normal Rodeo. When the Rodeo is raised to the height of the normal ML320, the crash deformation to the Taurus is similar to that caused by the normal ML320 (Figures 6a-d and Figure 7).

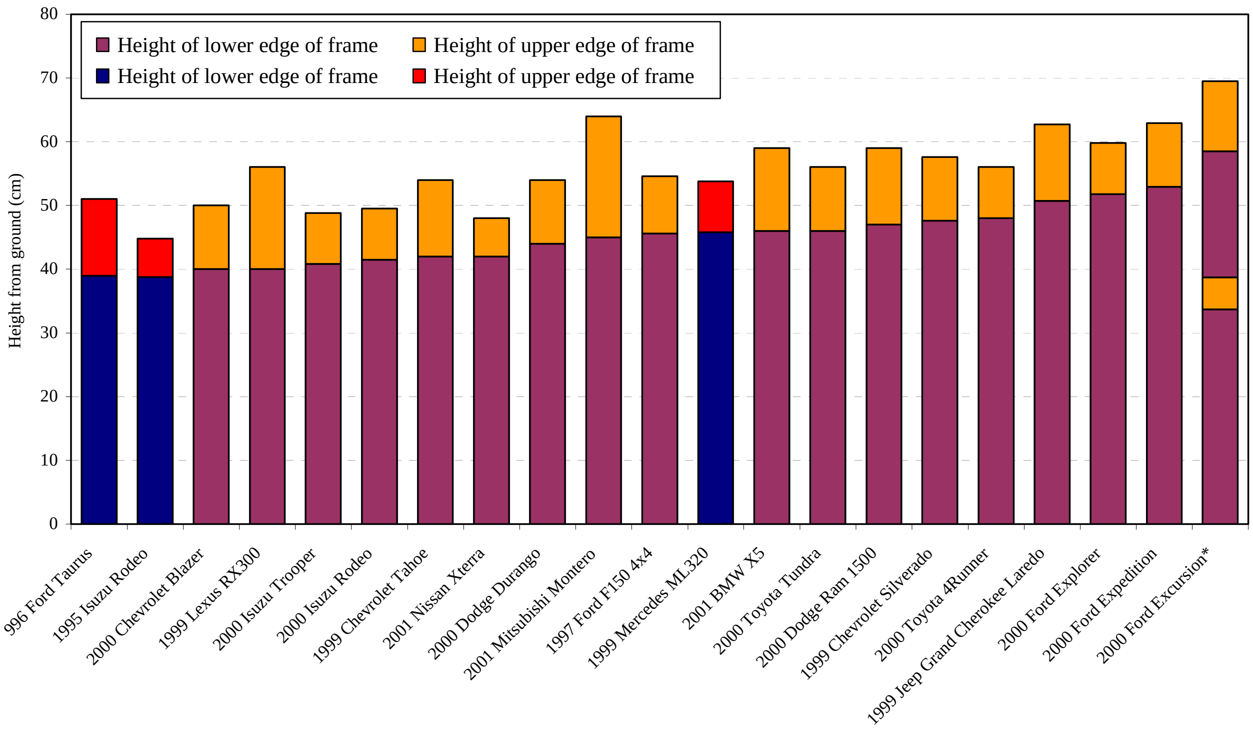

Figure 5. Comparison of Heights of SUV Frame Rails and Blocker Bars
*Lower orange section is BlockerBeam™, upper orange section is frame rail

Figure 6a. Crush caused by Normal Rodeo

Figure 6b. Crush caused by Normal ML320

Figure 6c. Crush caused by Raised Rodeo

Figure 6d. Crush caused by Lowered ML320

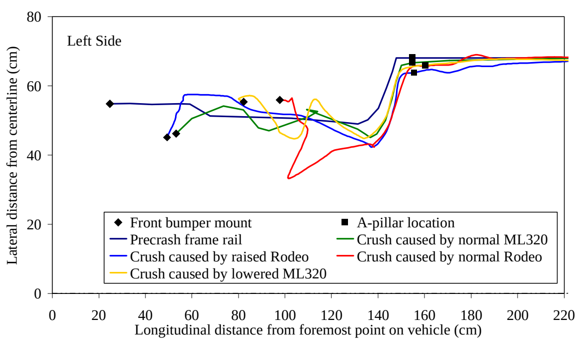

Figure 7. Underbody View of Taurus Left Frame Rail

The effects of the height differences can also be seen in the intrusion measures (Figure 8, Table 2). The normal Rodeo (low and stiff) causes the most intrusion in the Taurus footwell and some of the least intrusion at the instrument panel level (knee bolster, steering column, door aperture closure). When the Rodeo is raised and overrides the Taurus front longitudinal, the footwell intrusion decreases and there is an increase in intrusion at the instrument panel level. The same pattern exists, to a much lesser extent, for the ML320 crashes. The normal ML320 (high and soft) caused more intrusion at the instrument panel level than the lowered ML320.

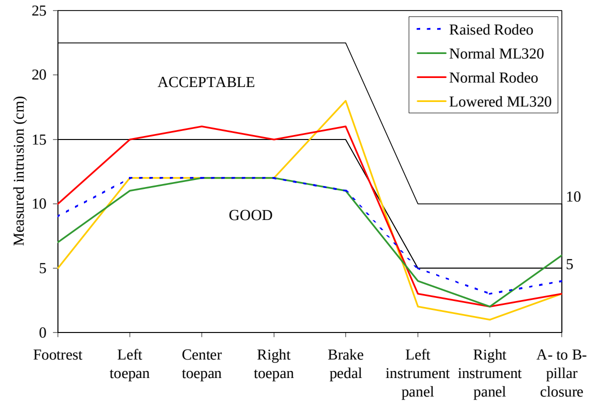

Figure 8. Intrusion Results - 1996 Ford Taurus

Table 2.
Upper Vehicle Intrusion in Ford Taurus

Vehicle Struck	Steering Column Rearward Movement (cm)	Steering Column Upward Movement (cm)	Door Aperture Closure (cm)
Normal Rodeo	2	8	3
Lowered ML320	0	5	3
Raised Rodeo	6	6	4
Normal ML320	3	6	6

Injury Values

Injury results for the Taurus are shown in Figures 9 and 10. Injury measures for the dummies in all vehicles tested were below injury assessment reference values. In normal conditions, the ML320 causes greater upper body (head, neck, chest, and femur) injury measures than the Rodeo. At the same ride height, the upper body injury values are similar for both vehicles, although the ML320 generally produced slightly greater injury measures than the Rodeo.

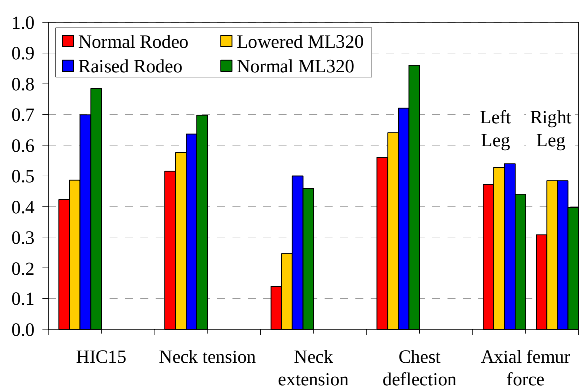

Figure 9. Frontal Compatibility Testing 1996 Ford Taurus - Upper Body Injury Measures

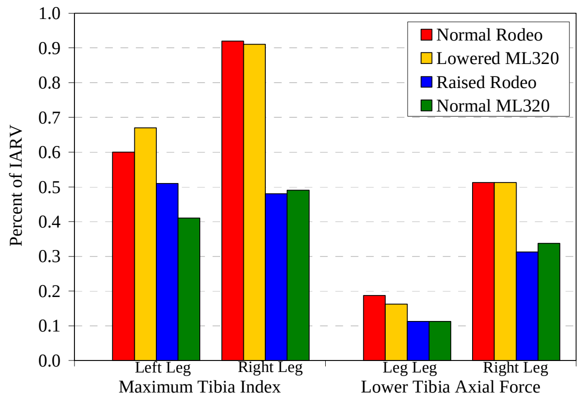

Figure 10. Frontal Compatibility Testing 1996 Ford Taurus - Lower Body Injury Measures

The results of the lower leg injuries in the Taurus indicate the opposite trend. The lower leg injury risk (maximum tibia index and tibia axial force) is greater in the low-ride height tests and is less in the high-ride height tests when the front longitudinal was overridden.

Front-End Stiffness

Initial assessments of the Rodeo and ML320 stiffnesses were confirmed by observations of bumper deformation in these tests. Figure 11 shows a top view of the bumper deformation of the utility vehicles. When compared at the same ride heights, the ML320 exhibited more crush than the Rodeo.

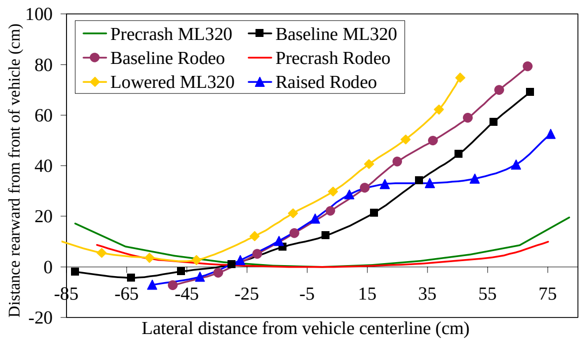

Figure 11. Bumper Crush Comparison of the 1999 ML320 and 1996 Isuzu Rodeo (Both Crashed into a 1996 Ford Taurus)

Results from the frame rail crush sustained by the Taurus (Figure 7) show similar results. The crush caused by the lowered ML320 is considerably less than the crush caused by the normal Rodeo. The crush caused by the vehicles at the raised ride heights cannot be compared, since the frame rails were overridden.

DISCUSSION

Results from this testing show that when the masses of vehicles are equal, frontal geometry, rather than stiffness, plays the greater role in vehicle compatibility. Although the ML320 is considerably less stiff than the Rodeo, this reduced the damage to the Ford Taurus only when the stiff structures of the cars and utility vehicles were geometrically matched. When the utility vehicles were in the higher configuration, the normal ML320 caused just as much upper vehicle intrusion to the Taurus as the stiffer Rodeo. More importantly, injury measures were clearly dependent on the ride height of the striking utility vehicle, while there was no consistent effect of vehicle stiffness on either upper or lower body injury risk.

Clearly the measured differences in Taurus intrusion patterns and injury measures are the result of the front longitudinal override that occurs with the high-ride height vehicles. The normal ML320 and raised Rodeo override the frame rail of the Taurus and therefore the crush is located higher on the Taurus than that caused by the lowered ML320 and normal Rodeo. The upper body injury measures, steering column intrusion, and door closure also were greater due to crush from these higher vehicles. Interestingly, the measures of upper body injury and door closure caused by the ML320 are slightly greater than those caused by the stiffer raised Rodeo.

In contrast, the normal Rodeo and lowered ML320 cause greater lower leg injury risk in the Taurus, because the frame rails of the utility vehicles interact with the frame rails of the Taurus and cause slightly greater intrusion in the toepan area. This result was also noted by Zobel.

At this crash energy level, the mismatch in frame rail and front longitudinal heights resulted only in slightly greater intrusion and injury risk. Despite good injury results for the Taurus in all tests, the exterior deformation suggests a problem. In the crashes where there was good interaction of frame rails, the Taurus had more structure available to absorb energy than in those crashes with poor frame rail interaction. This means the Taurus could absorb more energy in crashes with good frame rail interaction before catastrophic failure occurs.

CONCLUSION

When the ML320 debuted, Mercedes touted it as “the first SUV designed with ‘crash compatibility’ with smaller cars and other SUVs in mind,” citing the height of the structure as an important factor. These test results confirm the importance of height, although Mercedes’ marketing claim is placed in doubt. The height of the ML320 frame rails was found to be average compared with other utility vehicles. Since the differences in crash results due to geometry (frame rail/front longitudinal mismatch) are so dramatic, this would imply that most utility vehicles on the market would act similarly to the ML320 and completely override the Taurus under the same test conditions. Interestingly, when Isuzu changed the design of the new Rodeo in the 1998 model year, the frame rail height was raised several centimeters.

The results from side impact testing found that front-end geometry of the striking vehicle had a significant role in how the struck vehicle crushed and that the effects of stiffness were secondary to the geometry. These results, in conjunction with the offset frontal impact testing results discussed here, greatly strengthen the argument that the frontal geometry of vehicles needs to be equalized before any potential benefits from decreasing the stiffness of larger vehicles can be realized.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

REFERENCES

Faerber, E. et al. 1998. Improvement of crash compatibility between cars. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 650-61. Washington, DC: National Highway Traffic Safety Administration.

Hobbs, C.A. 1989. The influence of car structures and padding on side impact injuries. *Proceedings of the 12th International Technical Conference on the Experimental Safety Vehicles*, 954-62. Washington, DC: National Highway Traffic Safety Administration.

Insurance Institute for Highway Safety. 1998. *Status Report Special Issue: Crash Compatibility*. 33(1). Arlington, VA. Available: http://www.highwaysafety.org/srpdfs/sr3301.pdf.

Klaner, W.; Felsch, B.; and van West, F. 1998. Evaluation of occupant protection and compatibility out of frontal crash tests against the deformable barrier. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 693-702. Washington, DC: National Highway Traffic Safety Administration.

Lund, A.K. and Chapline, J.F. 1999. Potential strategies for improving crash compatibility in the U.S. vehicle fleet (SAE 1999-01-0066). Vehicle Aggressivity and Compatibility in Automotive Crashes (SP-1442), 33-44. Warrendale, PA: Society of Automotive Engineers

Lund, A.K.; O'Neill, B.; Nolan, J.M.; and Chapline, J.F. 2000. Crash compatibility issue in perspective (SAE 2000-01-1378). *Vehicle Aggressivity and Compatibility in Automotive Crashes 2000* (SP-1525). Warrendale, PA: Society of Automotive Engineers.

Mercedes-Benz of North America, Inc. 1998. 1999 Mercedes-Benz brochure. Montvale, NJ.

Provensal, J. and Stcherbatcheff, G. 1981. Identification of compatibility factors in side collisions. *Proceedings of the 8th International Technical Conference on the Experimental Safety Vehicles*, 587-99. Washington, DC: National Highway Traffic Safety Administration.

Steyer, C.; Delhommeau, M.; and Delannoy, P. 1998. Proposal to improve compatibility in head-on collisions. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 682-92. Washington, DC: National Highway Traffic Safety Administration.

The Polk Company. 1997. National vehicle population profile 1997. Detroit, MI.

Wykes, N.; Edwards, M.; and Hobbs, A. 1998. Compatibility requirements for cars in frontal and side impacts. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 667-81. Washington, DC: National Highway Traffic Safety Administration.

Zeidler, F.; Knöchelmann, F.; and Scheunert, D. 1999. Possibilities and limits in the design of compatible cars for real world accidents. SAE Technical Paper Series 1999-01-0068. Warrendale, PA: Society of Automotive Engineers.

Zobel, R. 1999. Accident analysis and measures to establish compatibility. SAE Technical Paper Series 1999-01-0065. Warrendale, PA: Society of Automotive Engineers.