CRASH COMPATIBILITY: THE U.S. PERSPECTIVE

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Introduction

Incompatibility between two vehicles involved in crashes has been recognized for a long time as an important factor in the injury risks for occupants. In recent years crash incompatibility has received renewed attention in both the United States and Europe. The U.S. focus has been driven by the growth in sales of relatively large sport utility vehicles (SUVs) and concerns about their "aggressivity" in collisions with cars. In Europe recent compatibility questions have been related to claims that consumer crash test programs, which compare the occupant protection capabilities of different vehicles, may lead to design changes that could make some vehicles less compatible.

Three vehicle design attributes have been identified as potential contributors to crash incompatibility: weight, geometry, and stiffness. Weight differences between vehicles in crashes have been well documented as a major crash incompatibility factor for a long time. The newer concerns in both the United States and Europe involve the roles of the other two potential incompatibility factors — geometry and stiffness. Assessing the influence of differences in vehicle geometry and stiffness on occupant injury risks in two-vehicle crashes is complex because of the strong interrelationships between these features and vehicle weight. Heavier cars typically are stiffer than lighter cars; in the U.S. fleet, in particular, many heavier SUVs and pickups are very stiff, and their geometry is quite different from that of most cars. This together with the fact that features such as geometry or stiffness are not easy to characterize complicates the assessment of their relative influence on compatibility.

This paper examines both real-world crash statistics and crash test results to begin to assess the role of geometry and front-end stiffness, after controlling for weight differences, in injury outcomes in two-vehicle crashes. The analyses focus particularly on crashes between cars and SUVs or pickups, because these are the kinds of crashes in which design features are likely to be most incompatible.

The U.S. Passenger Vehicle Fleet

The U.S. passenger vehicle fleet has long been more diverse than the European fleet. Large pickup trucks, for example, always have had a significant market share, and the weights and geometric characteristics of these vehicles are very similar to those of the newly popular SUVs. Pickups and SUVs typically have four-wheel drive, high ground clearance for off-road use, and relatively stiff body-on-frame designs.

Even though the U.S. media focus on the crash incompatibility between cars and SUVs is new, major design differences have existed in the U.S. fleet for more than 25 years (Table 1). What is new is the dramatic growth in sales of the heaviest SUVs and pickups; only 4 percent of new passenger vehicles registered in 1975 weighed more than 1,815 kg, while in 1999 this proportion had jumped to 22 percent. In 1999, 18 percent of new passenger vehicle registrations in the United States were SUVs, and more than half of these weighed more than 1,815 kg (4,000 lb.). At the other end of the passenger vehicle weight/size spectrum, 9 percent of new 1999 registrations were light/small cars weighing less than 1,135 kg (2,500 lb.).

Effect of Vehicle Weight

Weight so strongly influences occupant death and injury risk that it is necessary to isolate this effect before assessing the contributions of other compatibility factors. Data from the 1991-97 Fatality Analysis Reporting System (FARS) maintained by the U.S. Department of Transportation (DOT) clearly show that, as 1990-96 model passenger vehicles got lighter their occupant death rates (per million vehicles per year) in

two-vehicle crashes went up (Figure 1). These relationships hold for SUVs, pickups, and cars; the lighter they are, the higher their occupant death rates. In two-vehicle crashes, cars and pickups of similar weight tend to have similar occupant death rates, and these are somewhat higher than corresponding rates for SUVs.

Table 1
Percent of Passenger Vehicle Registrations by Vehicle Type, Weight, and Model Year

Vehicle type	Weight (kg)	1975	1985	1995	1999
Cars	<1,135	12	28	15	9
	1,135-	27	37	39	39
	1,590+	41	8	9	6
Passenger vans		0	2	8	8
	Total	**81**	**76**	**71**	**61**
Pickups	<1,590	1	12	4	4
	1,590-	9	2	5	3
	1,815+	3	2	6	12
	Total	**13**	**16**	**16**	**18**
Sport utility vehicles	<1,590	1	4	2	3
	1,590-	1	0	5	5
	1,815+	1	1	5	10
	Total	**2**	**5**	**11**	**18**

Figure 1
Occupant Death Rates in 1990-96 Model Passenger Vehicles in Two-Vehicle Crashes

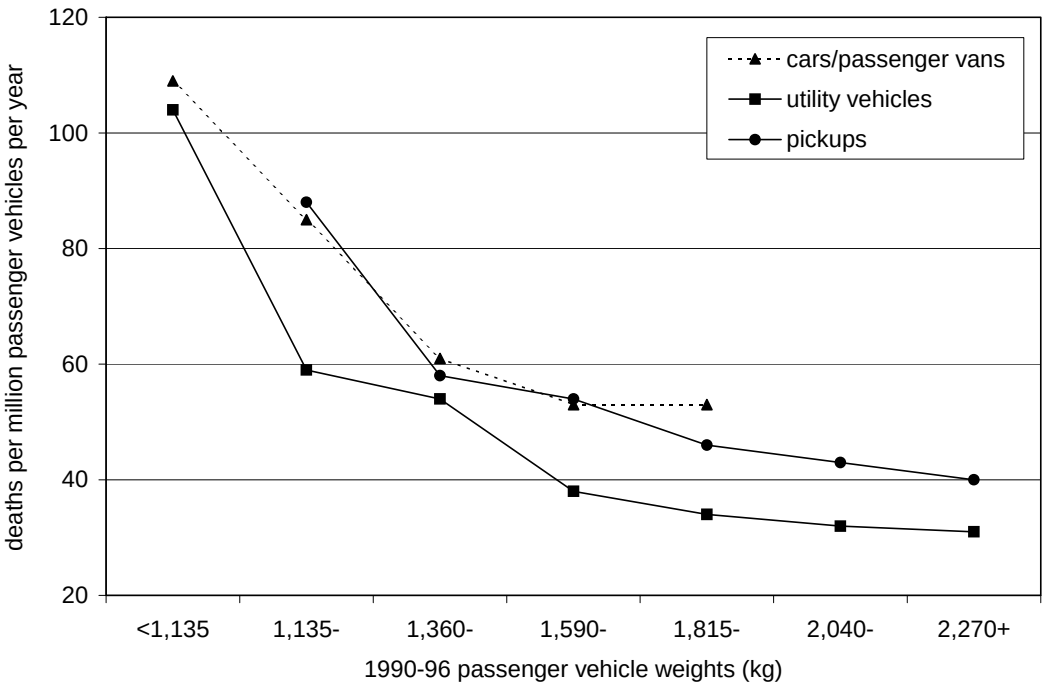


Figure 2 shows the rates of occupant deaths in other cars (all model years) in collisions with 1990-96 model cars, SUVs, or pickups. The denominators for these rates are the numbers of 1990-96 model cars, SUVs, or pickups registered. The results show that as the weights of the 1990-96 cars, SUVs, or pickups increased so did death rates in other cars with which they collided. In every weight class, however, the rates of occupant deaths in cars involved in collisions with pickups or SUVs were higher than when cars collided with cars. The highest rates of occupant deaths in cars (all model years) occurred in crashes with pickups. The differences in the rates between cars and SUVs are comparable to the effect of weight in car-to-car crashes, but the differences between cars and pickups are much greater than the effects of weight in car-to-car crashes.

Figure 2
Occupant Death Rates in Cars in Collisions with 1990-96 Model Passenger Vehicles

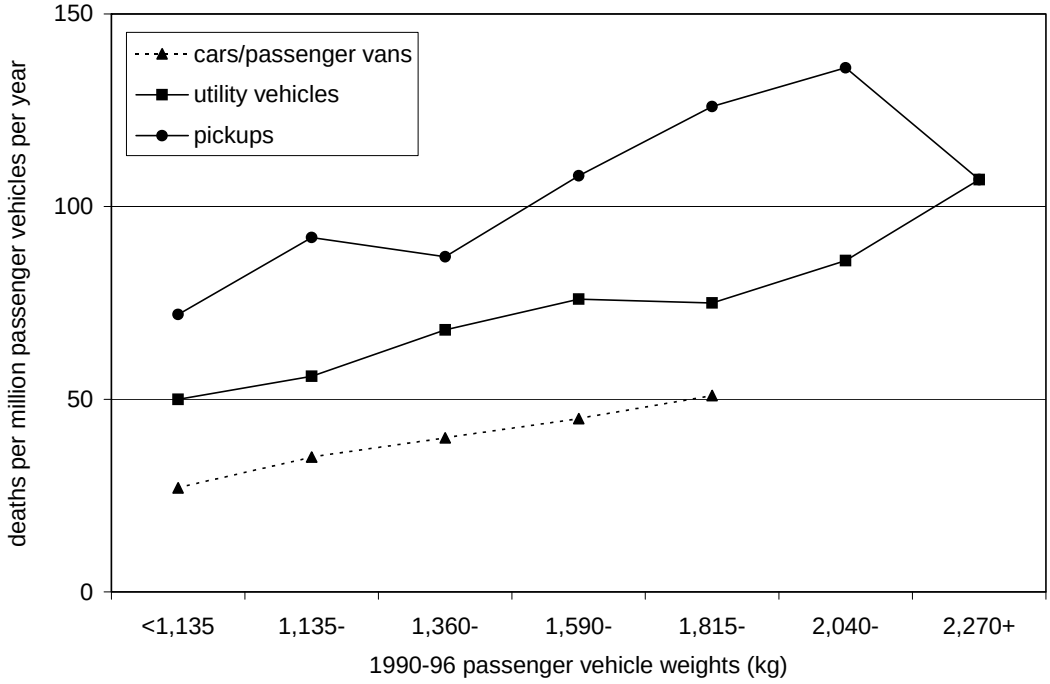


Figure 3 shows the death rates in other cars in collisions with 1990-96 model cars together with a breakdown of the rates for front-to-front and front-to-side (other car struck in side) crashes. In two-car crashes, the death rates for both crash types were almost identical. Figures 4-5 show the corresponding death rates in cars in collisions with SUVs or pickups. For crashes between cars and SUVs or pickups, the car occupant death rates were higher in front-to-side than in front-to-front crashes.

Figure 3
Occupant Death Rates in Cars in Collisions with 1990-96 Model Cars

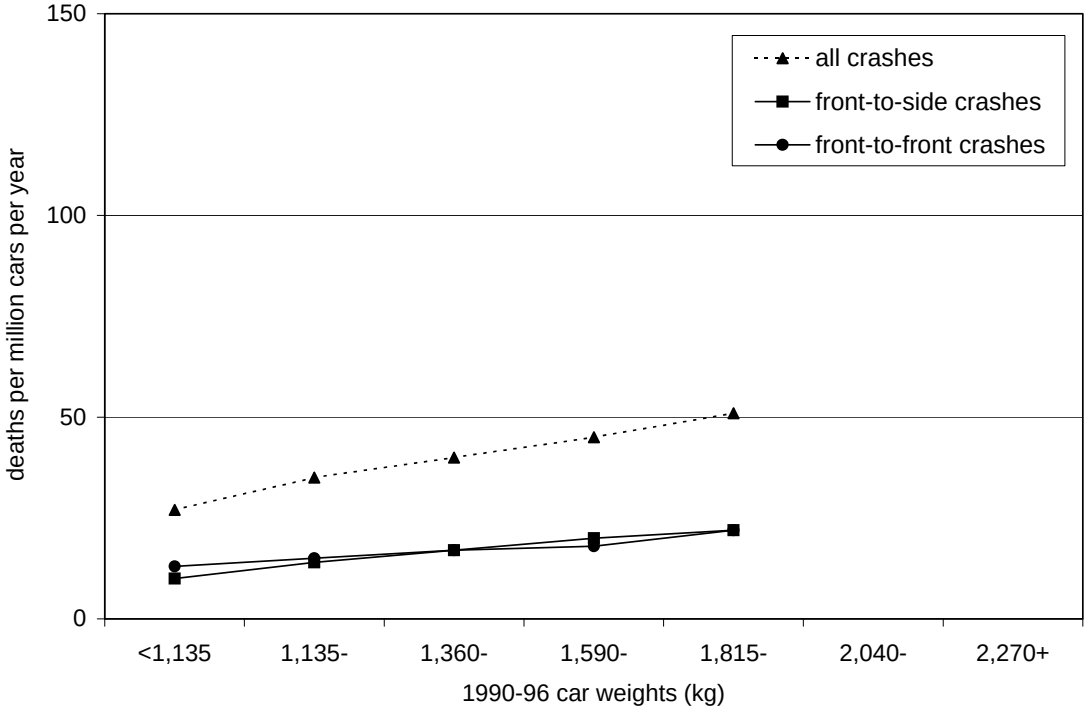


Figure 4
Occupant Death Rates in Cars in Collisions with 1990-96 Model Sport Utility Vehicles

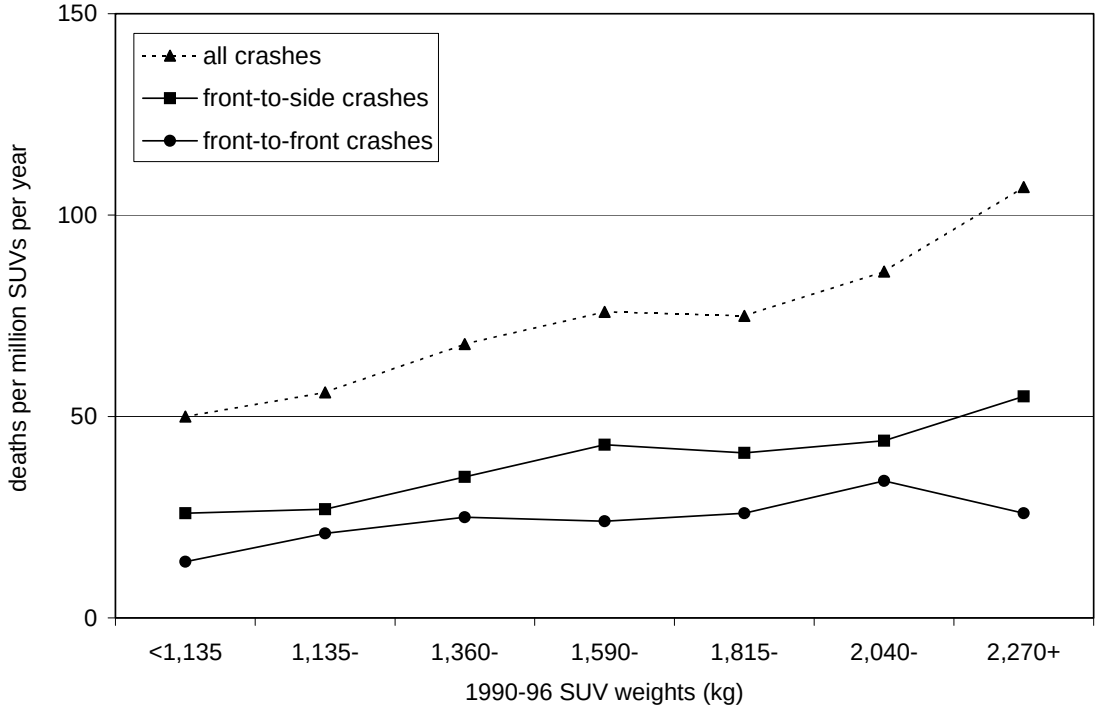
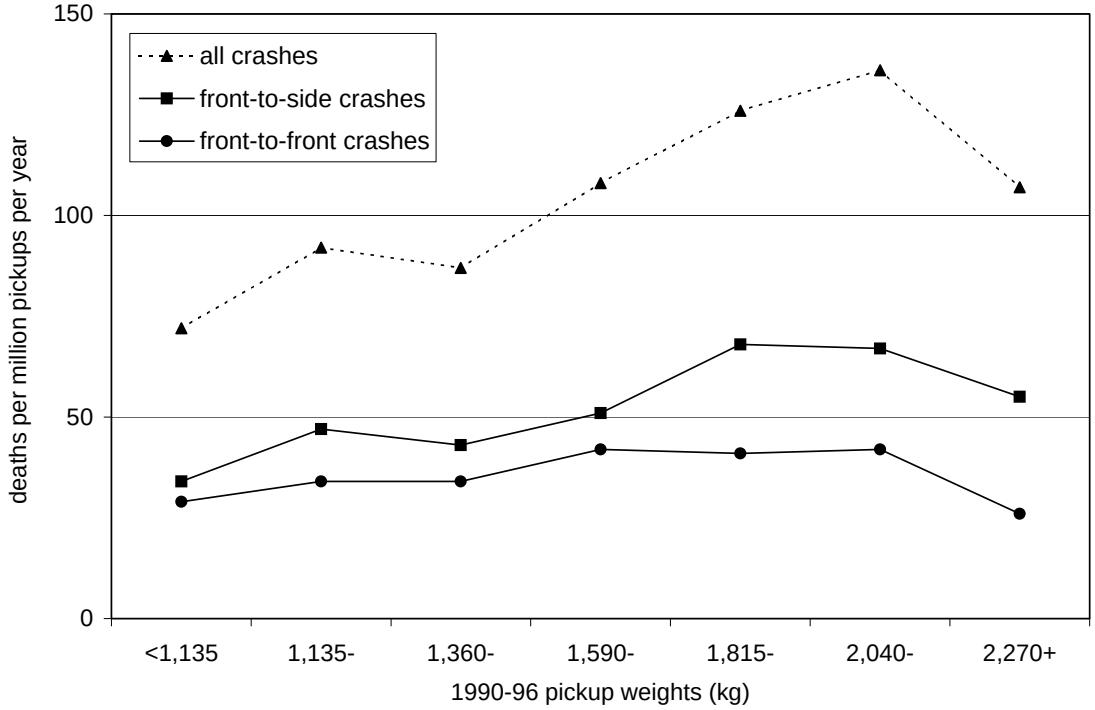


Figure 5
Occupant Death Rates in Cars in Collisions with 1990-96 Model Pickups



The results in Figures 2-5 show that, in two-vehicle crashes, for any given weight class SUVs and pickups pose greater risks to occupants of cars than do other cars. The risks from SUVs and pickups are highest when the cars are struck in the side. Thus crashes between cars and SUVs or pickups exhibit more incompatible outcomes than crashes between cars. This raises the question, what are the characteristics of SUVs and pickups that increase the risks to car occupants, especially when the cars are struck in the side?

Front-to-Side Crash Test Results

It is not possible from real-world crash data to separately identify the contributions that geometric or stiffness differences may make to increased incompatibility. To begin to address this question, the Insurance Institute for Highway Safety conducted a series of six 90-degree front-to-side crash tests with both vehicles moving [1]. In each test, the side-struck vehicle was a Mercury Grand Marquis moving at 24 km/h with a BioSID (biofidelic side impact dummy) in the driver position. The striking vehicles, all moving at 48 km/h, were a Lincoln Town Car and five Ford F-150 pickups. The baseline pickup — a normal F-150 4x2 — had a much stiffer front end than the Lincoln Town Car but was of comparable mass. Its front structural elements were about the same height as the Town Car's. Four other F-150 pickups were systematically varied with respect to weight, front-end stiffness, and ride height (Table 2).

Table 2
Test Matrix to Assess the Effects of Mass, Ride Height, and Stiffness

		Mass	
Height	**Stiffness**	**Low (~2,080 kg)**	**High (~2,400 kg)**
Low	Low	Lincoln Town Car	No test
	High	Normal F-150 4x2	Heavy F-150 4x2
High	High	Raised F-150 4x2	Raised-heavy F-150 4x2
	Highest	No test	F-150 4x4

Increased mass, stiffness, and ride height each had the predicted effect of increasing the extent of damage to the side-struck car. However, injury risk for the driver dummy in the car was not so predictable (Table 3). Increased ride height clearly affected injury risk in terms of both the likelihood of the head being contacted by the striking vehicle and thoracic injury likelihood as measured by thoracic trauma index (TTI), thoracic deflection, and thoracic viscous criterion. Increased mass further increased the risk of a head strike but affected only the TTI measure of thoracic injury.

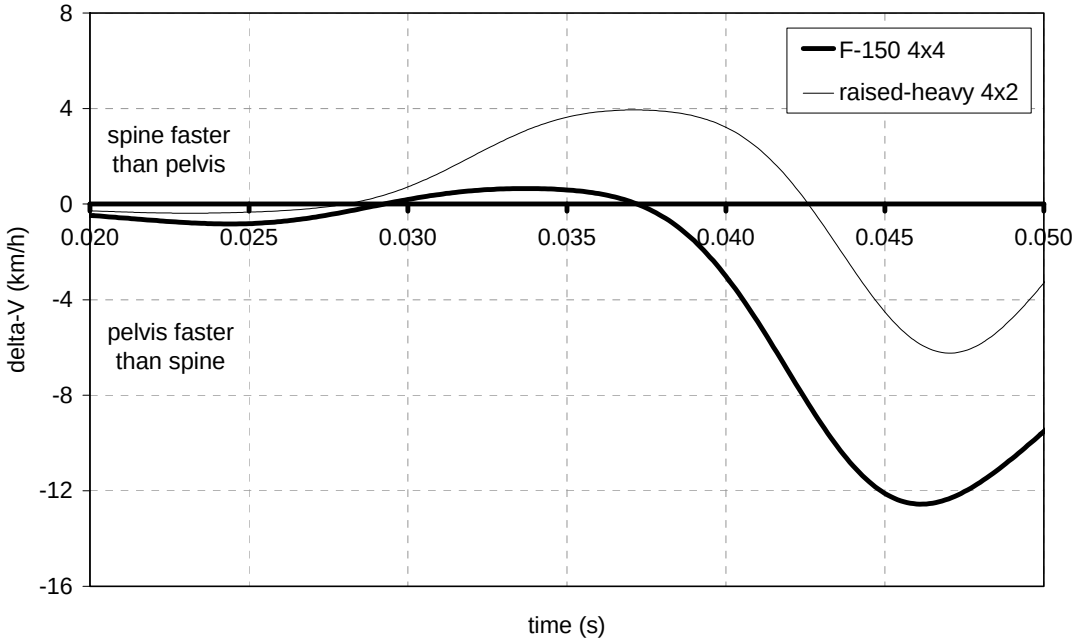
Table 3
Mercury Grand Marquis BioSID Injury Measures

Striking vehicle				Head injury criterion	Thoracic trauma index	Thoracic deflection (mm)	Thoracic viscous criterion (m/s)	Pelvis acceleration (g)
Type	**Height**	**Stiffness**	**Mass**					
Town Car	Low	Low	Low	75	50	41	0.40	48
F-150	Low	High	Low	182	68	37	0.40	105
F-150	High	High	Low	227	**86**	**60**	**1.51**	105
F-150	Low	High	High	249	**101**	32	0.37	103
F-150	High	High	High	no data	**111**	**62**	**1.54**	114
F-150	High	Highest	High	717	**87**	**48**	**0.44**	109
Injury reference values				1000	85	42	1.00	130

Most surprising was the unclear effect of vehicle stiffness. Dummy injury measures were lower in the test involving the relatively soft Town Car than in the test with the stiffer F-150 of the same weight and ride height. The stiffest vehicle (the 4x4 version of the pickup) did not produce the highest injury measures. In fact, thoracic injury risk was lower in this test than when the target car was struck by a 4x2 pickup of similar weight and height but less stiffness.

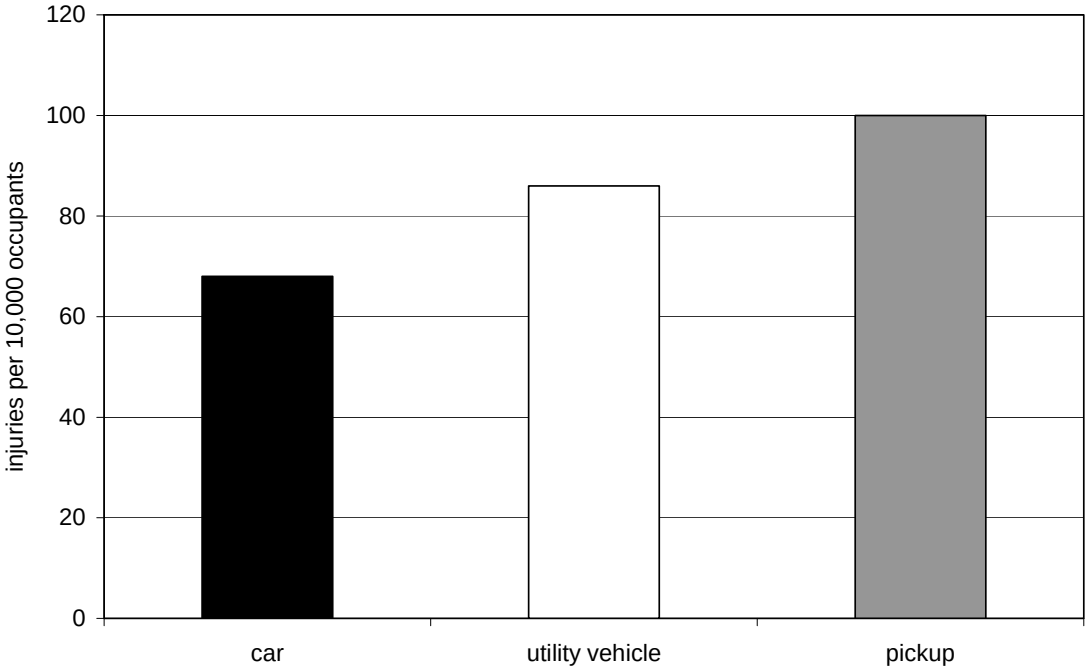
The explanation appears to be that the degree to which some areas of a vehicle's front end are stiffer than others — and where the stiffer areas are located — can affect incompatibility in side impacts. In the case of the 4x4 pickup, a pair of tow hooks happened to be located where they contacted the side of the struck car at a low level. This very stiff but low engagement with the car's side structure resulted in an intrusion profile of the struck car that accelerated the dummy's pelvis earlier than its thorax (Figure 6). The benefits of such a vertical intrusion profile have been discussed by Hobbs [2]. Thus, homogeneity of stiffness may be more important than overall stiffness in improving vehicle compatibility. The inherently incompatible features of front ends in side impacts may be mitigated by designs that spread the loads of striking vehicles both horizontally and vertically.

Figure 6
Dummy Loading Sequence, F-150 4x4 and Raised-Heavy F-150 4x2



Results of the crash tests also suggest that a major incompatibility factor associated with pickups — and by inference SUVs — is their high hoods. Because of their height, the hoods are more likely than the hoods of cars to strike car occupants' heads in side impacts. This is consistent with 1992-97 data from the U.S. DOT's National Automotive Sampling System (NASS) indicating that the likelihood of serious or worse head or face injury (Abbreviated Injury Scale 3+) increases sharply for occupants in side-struck cars (passenger vans not included) when the striking vehicle is an SUV or pickup compared with another car (Figure 7).

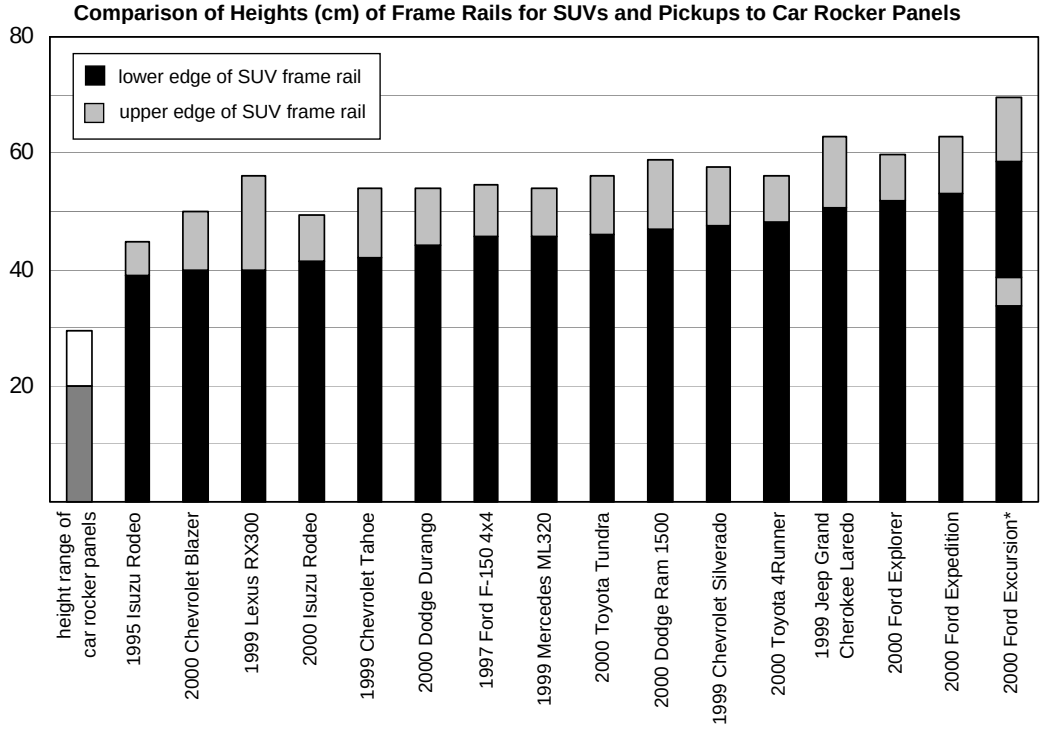
Figure 7
Occupant Head or Face Injuries (AIS 3+) in Side-Struck Cars in Two-Vehicle Crashes by Type of Striking Vehicle



Potential Compatibility Countermeasures

The test results clearly show that higher ride heights contribute to increased thoracic injury risk and increased likelihood of head contact with striking vehicle hoods when pickups hit the sides of cars; by inference the same conclusions would apply to SUVs. Measurements taken from the frame rail heights of a group of SUVs and pickups show considerable variation, but all are significantly higher than the stronger parts of cars' side structures (Figure 8). One countermeasure that has been proposed — and already implemented for some SUVs — is the addition of a strong beam across the front end mounted below the frame rails. Ford has added such a feature to its largest SUV and plans to add a similar beam (referred to as BlockerBeam™) to other large Ford SUVs. The beam added to the Ford Expedition, however, still is higher than car rocker panels (Figure 8). The effectiveness of this compatibility countermeasure in front-to-front or front-to-side crashes is not known at this time.

Figure 8
Comparison of Heights (cm) of Frame Rails for SUVs and Pickups to Car Rocker Panels



*Lower gray section is BlockerBeam™, upper gray section is frame rail

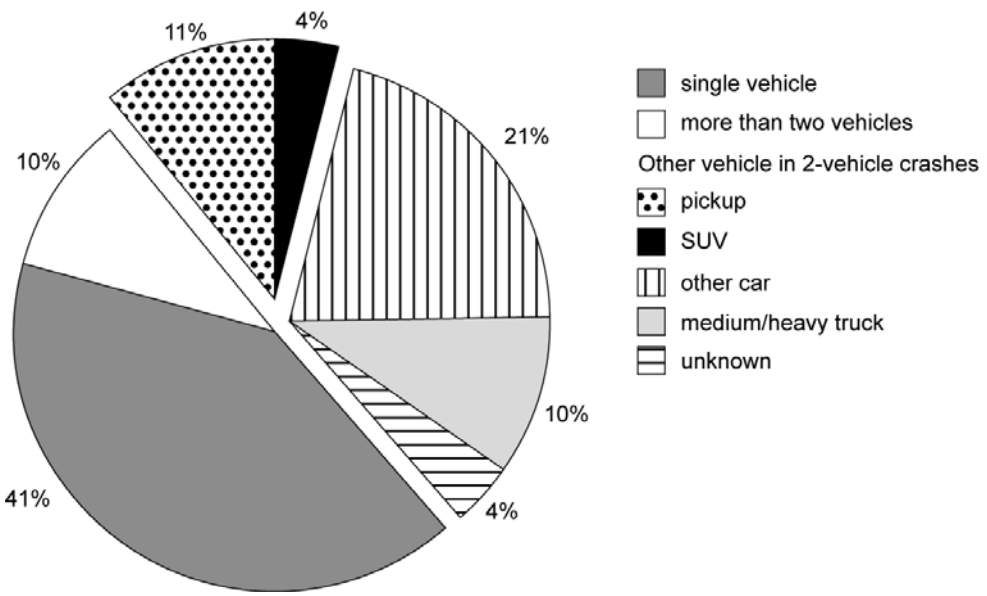
Countermeasures to reduce the risk of car occupants' heads being struck by the hoods of pickups or SUVs in front-to-side crashes would be desirable, if they are feasible. But how likely is it that practical modifications to the front ends of SUVs and pickups can achieve this? In every one of the crash tests involving a striking pickup, there was a threat to the struck driver's head. It is far more likely that meaningful reductions in head injury risk in such crashes would be achieved by adding side airbags that deploy between the head and any intruding striking vehicle. Moreover, such airbags would benefit car occupants in single-vehicle side impacts in which there is head injury risk from contact with external objects.

This points to two basic conclusions. First, crash incompatibility is not just about what have been called the aggressive features of one vehicle but also about the vulnerability, or crashworthiness, of the other vehicle. Crash incompatibility can be reduced either by changing an aggressive characteristic (mass or stiffness, for example) or by improving crashworthiness (adding a head airbag for side impacts or increasing the mass of the lightest vehicles, for example). Second, improving crashworthiness is likely to be more beneficial than reducing vehicle aggressivity because it addresses injury risk in single-vehicle as well as two-vehicle crashes.

Real-world crash data are necessary to put incompatibility issues in perspective. Crashes involving two passenger vehicles where compatibility differences are at issue do not cause most occupant deaths. According to FARS data, about 15 percent of occupant deaths in 1990-96 model cars during calendar years 1991-97

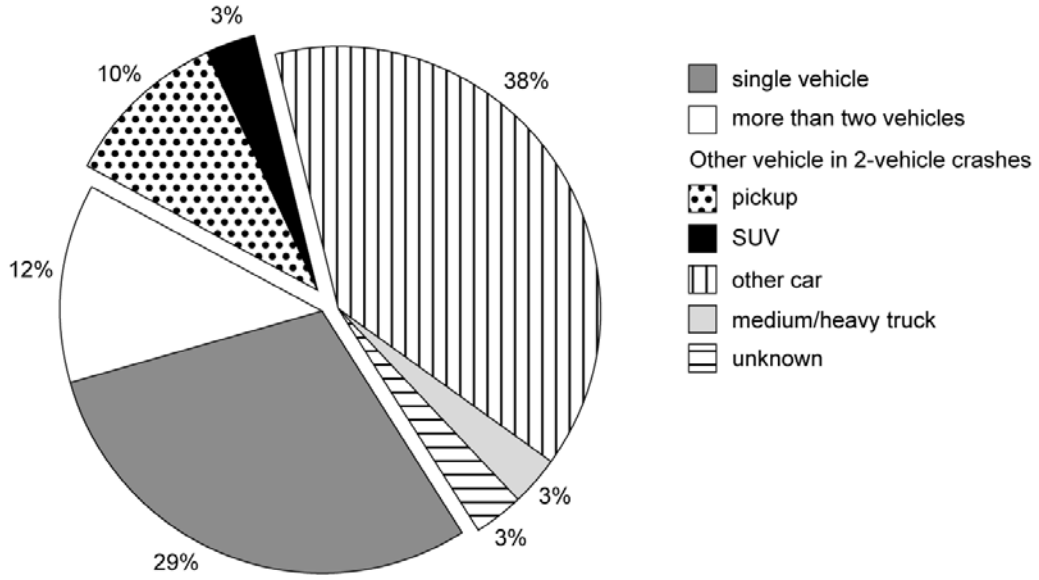
occurred in crashes with SUVs or pickups (Figure 9). Another 21 percent occurred in crashes with other cars; most of these were not crashes between heavy and light cars but involved cars without great mass differences. Even occupant deaths in light cars (less than 1,135 kg), in which crash incompatibility is most likely, follow a similar pattern; 15 percent of these deaths occurred in crashes with pickups and SUVs, 23 percent in crashes with other cars. Single-vehicle crashes are the leading cause of car occupant deaths, even in the lightest cars.

Figure 9
Distribution of Car Occupant Deaths by Crash Type, 1990-96 Model Cars



Two-vehicle crashes are somewhat more important when nonfatal injuries are considered. In Germany it is reported that more than half of nonfatal car occupant injuries occur in two-vehicle crashes [3]. The same is true in the United States, where two-vehicle crashes account for almost 60 percent of moderate and more serious nonfatal car occupant injuries (1991-97 NASS data) (Figure 10). However, as with fatalities, collisions with other cars, not SUVs or pickups, account for most of the nonfatal injuries (38 percent). Only 13 percent of the injuries to car occupants occur in collisions with SUVs or pickups.

Figure 10
Distribution of Car Occupant Injuries (MAIS 2+) by Crash Type, 1990-96 Model Cars



Car-to-car crashes become more important for occupants in light cars, accounting for almost half of all injuries (47 percent). This is largely because the small size and light weight of these vehicles increase the vulnerability of their occupants in collisions with any other object, even vehicles as light as themselves. The influence of weight is particularly great; in comparison with light cars, heavy cars (1,590-1,814 kg) experience only 28 percent of their injuries in collisions with other cars.

Implications for Insurance

In addition to compatibility issues related to occupant injury risk, the growth in sales of large SUVs has raised questions about the effect these vehicles may have on insurance losses and, in turn, on insurance premiums. In U.S. insurance systems, first party and liability (third party) coverages for vehicle damage and injury losses are sold separately. The only vehicle-specific loss information is published by the Highway Loss Data Institute (HLDI), and this information currently includes only results for first and third party damage losses plus first party injury losses; it does not include information on injury liability losses.

The two damage coverages are collision and property damage liability. Collision coverage provides first party insurance for damage to an insured vehicle, and property damage liability provides third party insurance for damage inflicted by the insured person's vehicle on another vehicle or other property in a collision when the insured driver or vehicle is deemed at fault. Table 4 shows that overall collision losses are almost 3 times greater than property damage losses. Among cars, collision losses range from 20 percent above average for small cars to 26 percent below for large cars. Cars' property damage losses are all about or below average. Passenger vans have below average collision and property damage liability losses.

Table 4
Collision and Property Damage Liability Insurance Losses by Vehicle Type and Size Class, 1995-97 Models, Average Loss Payment per Insured Vehicle Year

Vehicle type and size		Collision	Property Damage Liability	Total Damage Losses
Cars	Small	$268	$79	$347
	Midsize	250	73	323
	Large	206	62	268
Passenger vans		165	64	229
Pickups	Small	200	101	301
	Standard	168	95	263
Utility vehicles	Small	211	94	305
	Midsize	212	98	310
	Large	135	107	242
	All passenger vehicles	**$224**	**$81**	**$305**

The largest utility vehicles have the lowest collision coverage losses and the highest property damage liability losses, but their combined loss total is lower than for all vehicle groups except passenger vans.

Conclusions

Results of real-world crashes as well as crash tests show the important contributions of both vehicle weight and ride height differences to injury risks for car occupants in two-vehicle crashes, especially collisions with SUVs and pickups. The contribution of front-end stiffness, at least in front-to-side crashes, is not so clear-cut.

What can be done to reduce the increased injury risks resulting from known incompatibility factors? The current U.S. passenger vehicle fleet includes a wide range of vehicle weights, and this fleet will not turn over quickly. Plus large weight spreads continue among new passenger vehicles. This means weight mismatches in two-vehicle crashes will continue into the foreseeable future. Ride height differences also seem likely to continue, especially if the popularity of larger SUVs continues. The addition of beams below the frame rails of SUVs does promise to somewhat reduce the override and underride of stiff structures in crashes between SUVs and cars. However, the hood heights of SUVs and many pickups will continue to pose risks to the unprotected heads of occupants of cars struck in the side by these high-riding vehicles.

Even if further research shows stiffness differences to be important, mismatches will always exist for cars struck in the side, because even the "softest" front end of a car is much stiffer than car sides. It is not clear that stiffer car front ends would make matters worse in side impacts. The role of stiffness, separate from ride height, in the aggressivity of pickups and SUVs is not clear. On the other hand, the higher ride heights of SUVs and pickups mean their occupants should be less vulnerable when struck in the side by cars because the stiffer structures on the cars' front ends will hit the stiffer rocker panels of the SUVs and pickups.

The results of these analyses strongly suggest that, although efforts should continue to reduce incompatibilities among passenger vehicles, any payoff is likely to be small compared with the benefits from improving the occupant protection afforded by all passenger vehicles in all crash modes.

References

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