

THE CRASH COMPATIBILITY OF CARS AND LIGHT TRUCKS

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ABSTRACT

This paper investigates the compatibility of cars, light trucks, and vans (LTVs) involved in traffic crashes. An analysis of U.S. crash statistics shows that, although LTVs currently account for approximately one-third of registered U.S. passenger vehicles, collisions between cars and LTVs account for over one half of all fatalities in light vehicle-to-vehicle crashes. In these crashes, 81 percent of the fatally injured are found to be occupants of the car. These statistics suggest that LTVs and passenger cars are incompatible in traffic crashes, and that LTVs are the more aggressive of the two vehicle classes. The fundamental incompatibility between cars and LTVs is observed even when the analysis is restricted to collisions between vehicles of model year 1990 or later -- indicating that, despite the availability of newer safety countermeasures, e.g., air bags, the incompatibility between cars and LTVs will persist in future fleets. Through examination of crash test results, field crash statistics, and vehicle measurements, the paper explores the

design imbalances between cars and LTVs, e.g., mass, stiffness, and geometry, which lead to these severe crash incompatibilities.

KEYWORDS

Crashworthiness, Aggressivity, Crash Compatibility, Passenger cars, Light trucks

INTRODUCTION

During the past decade, a profound shift in the composition of the passenger vehicle fleet has been realized in the United States. Fueled by the growing popularity of pickup trucks, minivans, and, more recently, by sports utility vehicles, the demographics of the U.S. fleet are characterized by a growing population of light trucks and vans (LTVs). As a group, LTVs are heavier, of more rugged construction, and have higher ground clearance than the passenger cars with which they share the road. The concern is that these design features, introduced to allow specialized functions, e.g. off-road driving, may make LTVs fundamentally incompatible with cars in highway crashes, and in some cases dangerous to the occupants of cars struck by LTVs.

The compatibility of a vehicle is a combination of its crashworthiness and its aggressivity when involved in crashes with other members of the vehicle fleet. While crashworthiness focuses on the capability of a vehicle to protect its occupants in a collision, aggressivity is measured in terms of the casualties to occupants of the other vehicle involved in the collision. Crashworthiness is sometimes referred to as self-protection while reduction in aggressivity is sometimes referred to as partner-protection.

Crash incompatibility is of concern in all vehicle-to-vehicle collisions including car-to-car, car-to-LTV, and LTV-to-LTV collisions. LTV-to-car collisions are one specific, but growing, aspect of this larger problem. This issue has been examined by Gabler and

Hollowell [1996, 1998a, 1998b] and the Insurance Institute for Highway Safety [1998] in earlier studies.

The goal of this paper is to examine the crash compatibility of cars and LTVs in vehicle-to-vehicle crashes. The specific objectives are to define the nature of the problem through examination of crash statistics, and to explore the relationships between crash aggressivity and vehicle design characteristics.

THE DEMOGRAPHICS OF LTV AGGRESSIVITY

Registrations of LTVs currently account for over 1/3 of all light vehicle registrations, and are a growing component of the U.S. fleet. Analysis of the R.L. Polk Vehicle Registration Database shows that LTV vehicle registrations increased from 20 percent to 35 percent from 1980 to 1997. Although LTVs only account for 1/3 of all registered vehicles, traffic crashes between an LTV and any other light vehicle now account for the majority of fatalities in vehicle-to-vehicle collisions. Analysis of the Fatality Analysis Reporting System (FARS), maintained by the National Highway Traffic Safety Administration (NHTSA), shows that in 1997 LTV-car crashes accounted for 5,373 fatalities. By contrast, car-car crashes led to 3,961 deaths and LTV-LTV crashes resulted in 1,306 fatalities.

A disproportionate number of the fatalities in LTV-car crashes are incurred by the car occupants. Of the 5,373 fatalities in LTV-car crashes in 1997, 81 percent of the fatally injured were occupants of the car. In 1997, side impacts in which an LTV was the bullet vehicle resulted in 2,536 deaths (or 57 percent) of the 4,415 fatalities in side struck vehicles. In the same year, frontal impacts in which an LTV was involved accounted for

2,765 deaths (or 62 percent) of the 4,459 fatalities in frontal impact in that year. These statistics suggest that LTVs and passenger cars are incompatible in traffic crashes, and that LTVs are the more aggressive of the two vehicle classes. In particular, crashes with an LTV cause a disproportionate number of vehicle-to-vehicle fatalities.

Fatalities and injuries that arise from the incompatibility of LTVs and cars are a growing problem. The LTV market share has risen steadily from 1980 to 1997 [Automotive News, 1980-97]. LTVs captured over 45 percent of all light vehicle sales in 1997 as compared with 20 percent in 1980. Comparison of LTV registrations and LTV-caused fatalities over the same period show that LTV impacts have always caused a disproportionate number of vehicle-to-vehicle fatalities. For example in 1980, when LTVs accounted for 20 percent of the registered light vehicle fleet, side impacts in which an LTV was the bullet vehicle led to 31 percent of all fatalities in side struck vehicles. The magnitude of this problem then is not only due to the aggressivity of LTVs in crashes, but also the result of the dramatic growth in the LTV fraction of the U.S. fleet.

PROBLEM DEFINITION

U.S. crash statistics were examined to determine the characteristics and extent of the vehicle compatibility problem. One obstacle to quantifying the compatibility of a vehicle is the lack of an accepted measure of aggressivity. To date, this research effort has developed two potential aggressivity metrics.

Option 1:

$$\text{Aggressivity} = \frac{\text{Fatalities in collision partners}}{\text{Registrations of subject vehicle}}$$

Option 2:

$$\text{Aggressivity} = \frac{\text{Fatalities in collision partners}}{\text{Number of Crashes of subject vehicle}}$$

Hollowell and Gabler [1996] developed the first metric for an early study of crash compatibility. For each vehicle make / model, this metric first measures the number of fatalities in the collision partner resulting from collisions with the subject vehicle. Only two-vehicle crashes in which both vehicles were either a car or an LTV are considered. The fatality count is normalized by the total number of registrations of the subject vehicle so that vehicles with large populations are not unfairly penalized. Using this metric, Hollowell and Gabler rank ordered all make / models in the U.S. fleet by aggressivity. This initial study indicated that LTVs as a group were twice as aggressive in crashes as passenger cars -- i.e., per vehicle, LTVs caused more than twice as many fatalities in their collision partners as do cars.

Gabler and Hollowell [1998a, 1998b] studied the second metric as a refinement to the earlier definition of aggressivity. This improved metric defines aggressivity to be the number of fatalities in the collision partner normalized by the number of vehicle-to-vehicle crash involvements of the subject vehicle. Only two-vehicle crashes in which both vehicles were either a car or an LTV are considered in computing the fatality count and the crash involvement count. One of the confounding factors in determining aggressive vehicle designs is aggressive driver behavior. Because aggressive drivers are involved in more crashes than less aggressive drivers, normalizing by the number of crashes rather than

vehicle registrations focuses the metric more on vehicle performance and less on driver behavior. Using the second metric and concentrating on driver fatalities alone, Gabler and Hollowell rank ordered all light vehicle categories in the U.S. fleet by aggressivity.

Approach

The analysis presented here uses the second metric and includes both driver and passenger fatalities. Fatality counts are obtained from the Fatality Analysis Reporting System (FARS), and crash involvement counts are obtained from the General Estimates System (GES). FARS provides a comprehensive census of all U.S. traffic related fatalities. GES is a large sample of over 60,000 police reported crashes collected annually. The scope of the analysis was constrained to cars, light trucks, and vans under 10,000 pounds in Gross Vehicle Weight Rating (GVWR). The focus was further narrowed to two vehicle collisions in which the vehicles were either cars or LTVs.

Because GES is a sample of police-reported crashes, NHTSA [1998] notes that estimates from GES are subject to both sampling and nonsampling errors. Initial analysis of GES revealed that approximately half of the Vehicle Identification Numbers (VINs) in this database were listed as unknown. For those passenger cars in GES with a valid VIN, the curb weight was obtained by decoding the VIN following the procedure used by Kahane [1997]. As described below, curb weight was employed to categorize passenger car size. To account for the cars with unknown VINs, the number of crash involvements for all cars was weighted accordingly in order to preserve the total number of crashes. Although this strategy maintains the total count of crash involvements, this approach has

the disadvantage of preserving any reporting biases. An improved approach would be to explore the missing data as a function of vehicle body type and model year, and prorate unknown make-models within these categories if biases exist.

Overall Fleet Aggressivity Ranking

The second metric, hereafter referred to as the aggressivity metric (AM), was used to rank order all categories of passenger vehicles by their relative aggressivity using 1992-96 FARS and GES. The vehicles in the aggressivity ranking were aggregated by vehicle family into six categories of LTVs – full-sized pickups, small pickups, large sports utility vehicles (SUV), small sports utility vehicles, minivans, and full-sized vans – and five categories of passenger cars – large, midsize, compact, subcompact, and mini-car. The passenger car categories were assigned based upon curb weight using the NHTSA New Car Assessment Program car categories as shown in Table 1. For this analysis, both driver and passenger fatalities in the other car were included in the computation of the aggressivity metric.

Figure 1 suggests that LTVs as a group are more aggressive than passenger cars. With the exception of minivans, all categories of LTV were more aggressive than all categories of cars. Full-sized vans were found to be the most aggressive vehicle category with an AM = 4.3. This category was closely followed by Full-Size Pickups (AM=4.27), large SUVs (AM = 3.68), small SUVs (AM = 2.42), and compact pickups (AM = 1.65). Minivans were the least aggressive of all LTV groups with an average AM = 1.19. The AM of passenger cars was significantly lower and ranged from AM= 0.61 for subcompacts to AM=1.39 for large cars.

Vehicle weight is not always the overriding factor dictating aggressivity as clearly demonstrated by Figure 1. Mid-sized cars, e.g., the Ford Taurus, and the small pickups, e.g., the Ford Ranger, both have approximately the same curb weight of 1,400-kg. However, compact pickups (AM = 1.65) are approximately 50% more aggressive than mid-sized cars (AM = 1.12). The higher aggressivity of the compact pickup class may be due to its greater structural stiffness and its higher ride height.

Among cars, the Aggressivity Metric is a strong function of vehicle weight. AM for the large car category, e.g., the Ford Crown Victoria, is 1.39. This is two to three times higher than the AM for the mini-car category, e.g., the Geo Metro, which is 0.61. The conservation of momentum in a collision places smaller cars at a fundamental disadvantage when the collision partner is a heavier vehicle. Evans [1994], Kahane [1997], and Joksch et al [1998] have demonstrated the importance of car size in providing occupant protection in several studies of the U.S. crash statistics.

Aggressivity by Impact Mode

Having established that LTVs are incompatible with cars in traffic crashes, the next requirement was to determine the relationship between aggressivity and impact direction. The analysis computed the ratio of driver fatalities in the subject vehicle vs. driver fatalities in the collision partner for cars versus each of five LTV categories: full-size vans, minivans, utility vehicles, small pickup trucks and full-size pickup trucks. The counts of fatalities were obtained from 1992-96 FARS. All occupant restraint conditions, i.e., belts, air bags, and no restraints, were included.

As noted by Joksch et al [1998], driver age has a strong effect on the evaluation of crashworthiness and aggressivity. Younger drivers are more injury tolerant and, therefore,

less likely to die from their injuries. In contrast, older drivers are less injury tolerant, and are more likely to die from their injuries. Using the approach developed by Joksch, the results presented below were corrected for the bias which would be introduced by differences in age between the two colliding drivers by restricting the analysis to cases in which both drivers were of age 26-55.

It should be noted in the discussion that follows that this analysis was based on small numbers of fatal crashes (on the order of a hundred for each case), and the results should be regarded as preliminary. For example, in the case of minivans striking cars in side impact, the ratio of 16:1 was determined based upon 106 fatalities in the car versus 7 fatalities in the minivan. For this particular case, note that small changes in the number of minivan fatalities would make large differences in the fatality ratio.

The ratio of driver fatalities in the subject vehicle to driver fatalities in its collision partner driver resulting from frontal-frontal impacts is presented in Figure 2. In collisions between full-size vans and cars, 6 drivers died in the car for every driver who was killed in the van. In collisions between full-size pickup trucks and cars, 5.3 drivers died in the car for every driver who was killed in the pickup. In collisions between utility vehicles and cars, 4.1 drivers died in the car for every driver who was killed in the utility vehicle. Clearly, the drivers of passenger cars disproportionately shoulder the fatality toll in car-LTV frontal crashes.

The ratio of striking-to-struck driver fatalities resulting from side impacts are presented in Figure 3. This analysis includes both left and right side impacts. As a control configuration, note first that in car-to-car impacts approximately 6 side-struck drivers are fatally injured for every fatally injured driver in the bullet car. This imbalance is not unexpected as the side structure of passenger vehicles provides little protection for the

side-struck occupant when compared with the significantly greater protection afforded by the front structure to the bullet vehicle driver.

The analysis is even more startling for LTVs striking cars in side impact. As shown in Figure 3, 23 side-struck car drivers are fatally injured for every driver who dies in a striking full-size van. For every driver who dies in a striking utility vehicle, 20 side-struck car drivers are fatally injured. For every fatally injured driver of a striking full-size pickup truck, 17 side-struck car drivers are killed.

Aggressivity in Future Fleets

The previous analyses have examined crash compatibility in vehicle-to-vehicle collisions between cars, light trucks and vans in the current fleet, and included all model years. Recent model year cars and LTVs however have safety countermeasures, e.g., air bags and side impact protection, which were not available in earlier models, but will be a standard component of future fleets. To understand the crash compatibility of cars, light trucks, and vans in future fleets, the preceding analyses were repeated for vehicle-to-vehicle collisions in which both vehicles were of model year 1990 or later.

Because a filter of this type sharply restricts the number of cases available for analysis, sufficient numbers were not available to compute meaningful fatality ratios. However, sufficient counts were available for calculation of the Aggressivity Metric presented earlier. The analysis presented below were based on 1992-96 FARS and GES for vehicle-to-vehicle collisions in which both vehicles were either a car or LTV of model year 1990 or later.

Figure 4 presents aggressivity by vehicle category for all frontal-frontal collisions (no restriction on model year), and for frontal-frontal collisions in which both vehicles were

of model year 1990 or later. Note that by examining frontal impacts only, the analysis focuses on the effect of widespread air bag availability in future fleets. Comparing the two aggressivity rankings, with and without the model year restriction, the first observation is that, for the late model fleet, the aggressivity metric is lower for all vehicle categories. This is presumably due more to the availability of airbags in the struck vehicle than due to any reduction in aggressivity in the striking vehicle. The second observation is that, despite a reduction in the aggressivity metric in the later model fleet, in every case LTVs were more aggressive as a group than were cars. The conclusion is that, even with an airbag-equipped late model fleet, there persists a fundamental incompatibility between cars and LTVs in frontal impacts.

Figure 5 presents aggressivity by vehicle category for all frontal-side collisions (no restriction on model year), and for frontal-side collisions in which both vehicles were of model year 1990 or later. By focusing on side impacts only, the analysis explores the benefit of dynamic side impact protection in future fleets. As with the frontal-frontal aggressivity ranking, the late model fleet, the aggressivity metric for all vehicle categories is lower for the late model fleet than the metric when both new and older vehicles are included. This may be due to the improved side impact protection, which began to appear the fleet in response to the 1990 dynamic side impact protection revision to Federal Motor Vehicle Safety Standard No. 214. Despite a reduction in the aggressivity metric in the later model fleet, in every case LTVs were more aggressive as a group than were cars. The conclusion is that, even with improved side impact protection available to occupants of the late model car fleet, cars and LTVs remain incompatible in side impacts.

It should be noted that Kahane [1997] has observed that older vehicles, generally, have an underreporting of low-severity crashes, and are driven by higher-risk drivers.

Thus, the lower aggressivity metric observed for newer vehicles may, to an important extent, be due to the bias which the removal of older vehicles introduces into the metric.

WHY ARE LTVS MORE AGGRESSIVE?

The preceding analysis of crash statistics has clearly demonstrated the incompatibility between cars and LTVs in highway crashes. Still remaining to be determined however are the design characteristics of LTVs which lead to their incompatibility with cars. In general, crash incompatibility arises due to three factors:

- Mass Incompatibility.
- Stiffness Incompatibility
- Geometric Incompatibility.

The following section will examine the relationship between LTV-car compatibility and these sources of incompatibility based upon FARS (1990-94) and GES (1990-94) crash statistics.

Mass Incompatibility

Kahane [1997] has shown that LTVs are 900 pounds heavier than cars on average. The conservation of momentum in a collision places smaller vehicles at a fundamental disadvantage when the collision partner is a heavier vehicle. As shown in Figure 6, LTVs, as a group, tend to be heavier than passenger cars. Figure 6 crossplots AM as a function of vehicle weight, and demonstrates the relationship between mass and aggressivity.

Stiffness Incompatibility

As a group, LTV frontal structures are more stiff than passenger cars. LTVs frequently use a stiff frame-rail design as opposed to the softer unibody design favored for cars. Drawing on NHTSA New Car Assessment Program crash test results, the linear stiffness of a selection of LTVs and cars was estimated using the following relationship:

$$k = (mv^2) / x^2 \quad (1)$$

where m is the mass of the vehicle, v is the initial velocity of the vehicle, and x is the maximum dynamic crush of the vehicle. The relationship between linear stiffness and AM is shown in Figure 7. Figure 7 indicates that stiffness is a contributing factor to the aggressivity of a vehicle. Because the stiffness of a vehicle is also somewhat related to its mass, as shown in Figure 8, stiffness may not prove to be as dominant an aggressivity factor as mass. Although stiffness and mass are related in many cases, stiffness is not totally driven by the mass of the vehicle. Figure 8 shows that for any given mass, there is a wide distribution of linear stiffness values. For example for 1750-kg vehicles, the least stiff vehicles are passenger cars while the most stiff vehicles are LTVs. Figure 9 compares the frontal stiffness, as extracted from crash test results, for a Ford Taurus and a Ford Ranger pickup. Both vehicles had approximately the same crash test weight (1750-kg), but note that the Ranger pickup was significantly stiffer than the Taurus. In a frontal collision between the two, the bulk of the crash energy would be absorbed by the Taurus and the Taurus occupants. Far less energy would be absorbed by the Ranger. From a compatibility perspective, a more ideal scenario would be for the Taurus and Ranger structures to each

share the crash energy rather than forcing one of the collision partners to absorb the bulk of the crash.

Geometric Incompatibility

LTVs, especially four-wheel drive sport utility vehicles, ride higher than cars. This creates a mismatch in the structural load paths in frontal impacts, and may prevent proper interaction of the two vehicle structures in a collision. In a side impact, this imbalance in ride height allows the LTV structure to override the car door sill, and contributes to the intrusion of the side-impacted vehicle.

Ideally, the ride height used in an analysis of this type would be the height of the forward-most load bearing structural member of the vehicle. The location of this forward-most structural element however has no precise definition, and must be estimated from other measurements. Some analyses have used bumper height as the height of this load bearing member. However, because in the U.S., the bumper must only meet a 2-½ mile/hour bumper impact standard, and LTVs have no bumper standard, the belief is that, with respect to occupant protection, bumpers are largely ornamental, and their location provides little evidence of the location of load bearing members. The rocker panel, on the other hand, is a much more substantial structural member, and because the rocker panel is typically lower than the forward-most structure, serves as a superior lower bound on the location of the frame structure.

Figure 10 shows that ride height is related somewhat to vehicle mass. For this analysis, ride height is defined to be the ground clearance to the bottom trailing edge of the front wheel well. However, note that the rocker panel height across all masses of passenger cars is relatively consistent – perhaps due to the bumper standard with which all passenger cars

must comply. On the other hand, LTVs, which have no bumper standard, exhibit a wide variation in ride height and are in general much higher than passenger cars.

Figure 11 presents average ride height by vehicle category. Sport utility vehicles have the highest ride height with an average rocker panel height of 390 mm. Subcompact cars have the lowest ride height with an average rocker panel height of 175 mm. SUVs ride almost 200 mm higher than mid-sized cars – a geometric incompatibility that would readily permit the SUV to override any side structure in a car and directly strike the car occupant.

It should be noted that the data for the preceding analysis was drawn from Vehicle Specification Sheets supplied by vehicle manufacturers, and collected in the NHTSA Vehicle Parameter Database developed by McCullough et al [1995]. While geometric data was available for most passenger car models, the Vehicle Specification sheets for LTVs were much more limited. The LTV data presented here was primarily obtained from foreign manufacturers, and contains no data on full-sized pickups or vans.

DISCUSSION

The study presented in this paper based its measure of aggressivity upon fatalities per 1000 police reported crashes. No effort was made to control for the severity of the crashes as this information was not available in the GES files. Some make-model vehicles, such as high performance sports cars, may have more severe crashes more because of the driver than because of the vehicle structure. Likewise, Kahane [1997] has noted that light trucks, which are used extensively in rural areas, tend to have a higher proportion of severe crashes in GES than do other members of the fleet. Normalizing fatalities by number of crash involvements removes much of this driver aggressivity effect but does not completely

eliminate this effect. Future work will explore refinements to the aggressivity metric which account for crash severity in addition to crash frequency.

The aggressivity metric used in this study assumes that all make-models strike the same cross-section of the vehicle population, i.e., the same proportion of small cars, large cars, minivans, pickups, and so forth. The influence of this assumption upon the aggressivity ranking will be explored in future work. Joksch et al [1998] has noted that the age distribution of struck drivers varies somewhat from make-model to make-model. As injury tolerance is a strong function of age, his analysis suggests an additional refinement to the aggressivity metric which corrects for any differences in age distribution from vehicle model to model.

The crash statistics presented in this paper demonstrate a clear incompatibility between cars and LTVs. A comparison of mass distribution, stiffness distribution, and ride height geometry confirm that these two categories of vehicles are incompatible from a design point-of-view. However, this study has not attempted to assign what proportion of the aggressivity of LTVs is a function of each of these three separate sources of incompatibility. Determination of the relationship between LTV design features and crash aggressivity will require the evaluation of LTV-to-car crash tests in conjunction with finite element simulations of LTV-to-car crash events.

CONCLUSIONS

This paper has examined the compatibility of LTVs and cars in vehicle-to-vehicle collisions. Using struck driver fatalities per crash involvement of the subject vehicle as an aggressivity metric, examination of U.S. crash statistics has clearly shown a serious incompatibility between cars and all categories of LTVs. LTVs now account for over one-

third of light vehicles on U.S. highways, but collisions between cars and LTVs lead to over 50% of all fatalities in light vehicle-to-vehicle collisions. Furthermore, a disproportionate number of the fatalities in LTV-car crashes are incurred by the car occupants. The availability of newer safety countermeasures, e.g., air bags, appears to improve crash compatibility indirectly by improving the crashworthiness of later model vehicles. However, the fundamental incompatibility between cars and LTVs is observed even when the analysis is restricted to collisions between vehicles of model year 1990 or later -- suggesting that the aggressivity of LTVs will persist even in future fleets. A comparison of LTVs and cars reveals that LTVs are more aggressive than cars for a number of reasons including their greater weight, stiffer structure, and higher ride height. This mismatch in design has serious consequences for crash safety as approximately one-half of all passenger vehicles sold in the U.S. are LTVs, and presents a growing source of crash incompatibility within the fleet.

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| Car Category | Curb Weight Range |
|---------------------|--------------------------|
| Mini-Car | < 2000 lbs. |
| Subcompact Car | 2000-2499 lbs. |
| Compact Car | 2500-2999 lbs. |
| Midsize Car | 3000-3499 lbs. |
| Large Car | ≥ 3500 lbs. |

Table 1. Passenger car categories

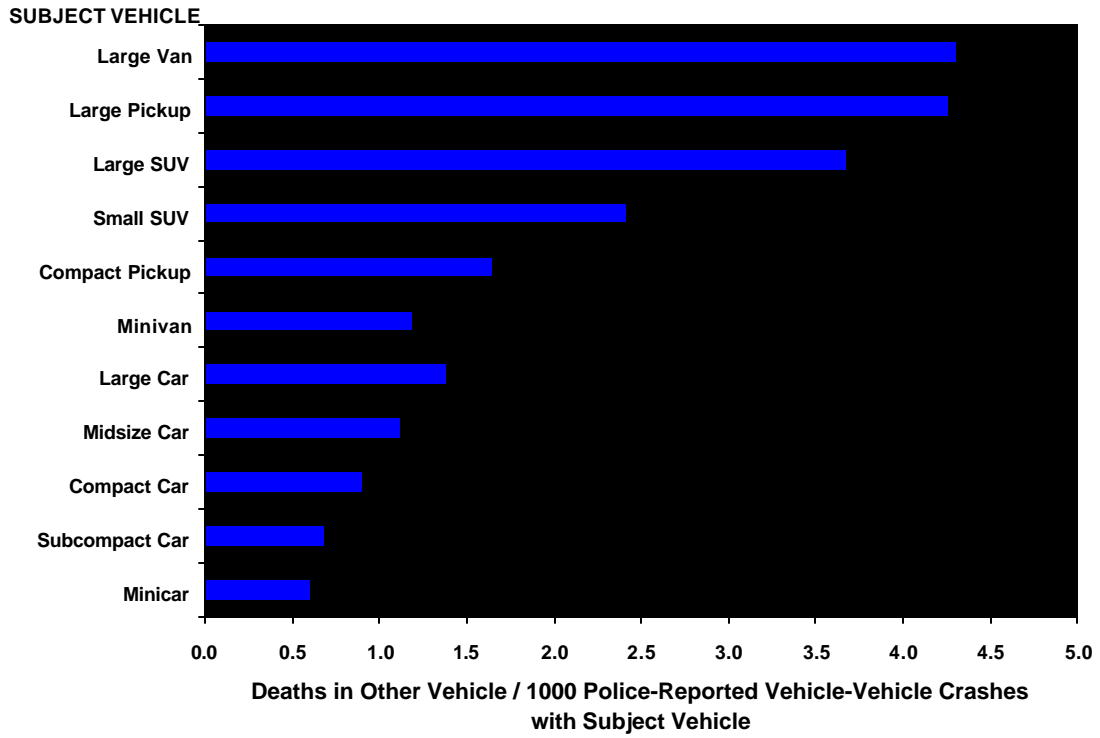


Figure 1. Vehicle aggressivity by vehicle category for all vehicle-vehicle crashes (FARS/GES 1992-96).

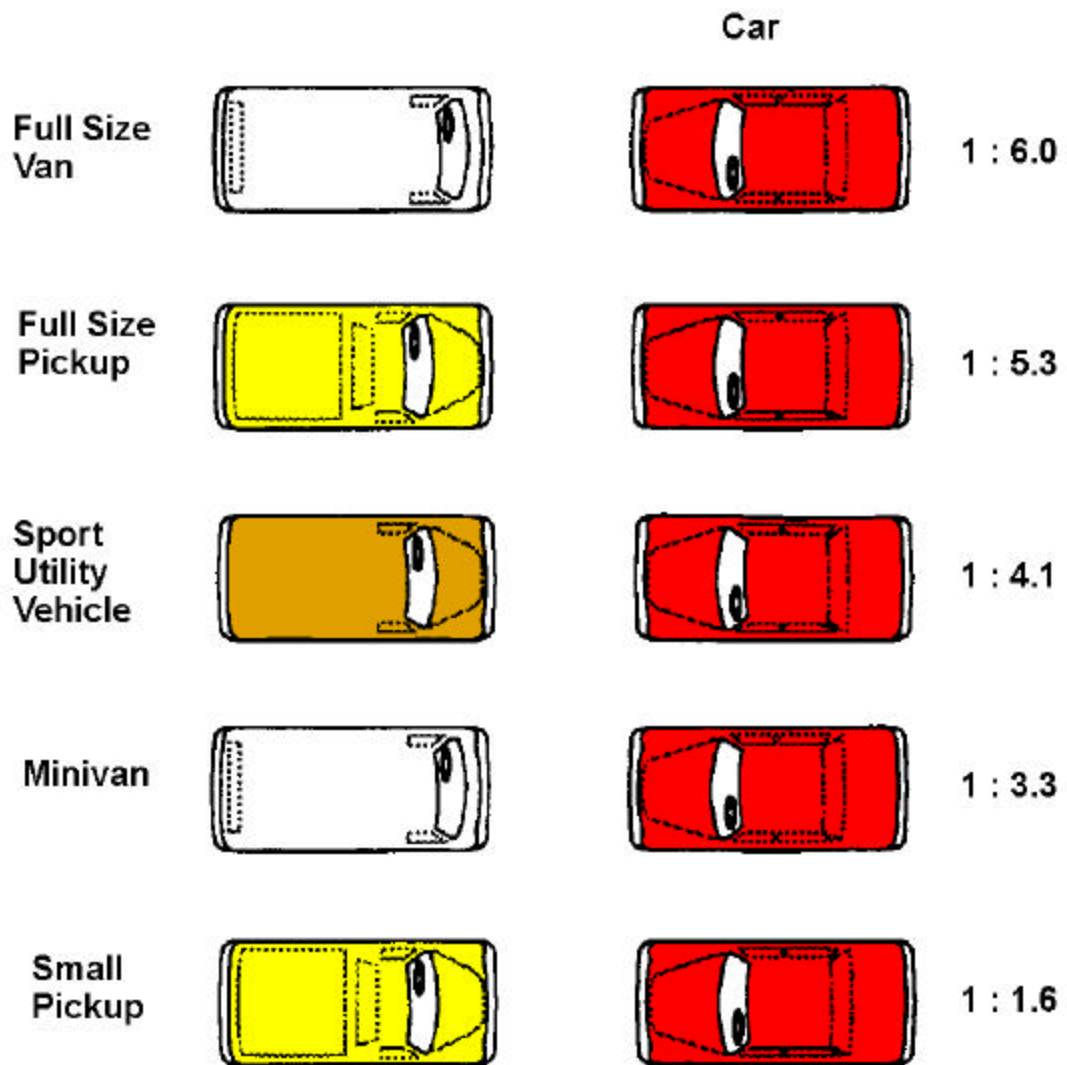


Figure 2. Ratio of fatally injured drivers in LTV-to-car frontal collisions (FARS 1992-96).

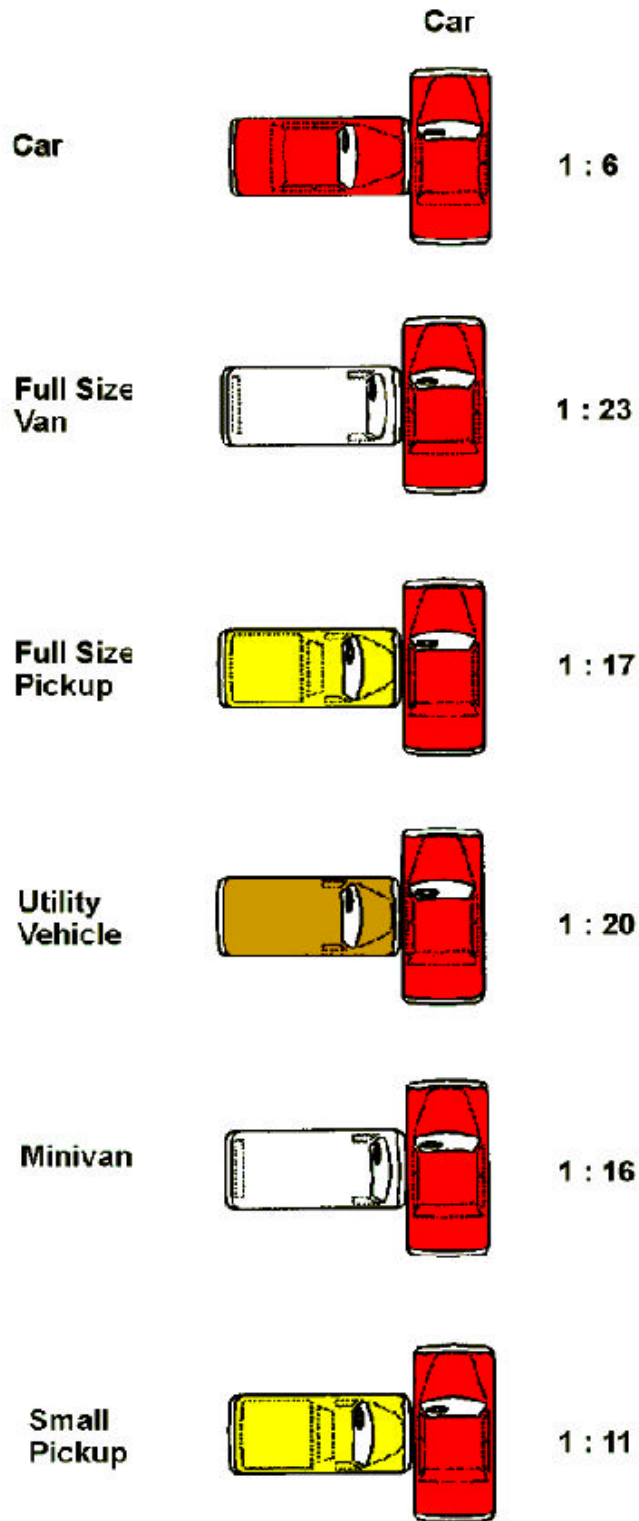


Figure 3. Ratio of fatally injured drivers in LTV-to-car side impacts (FARS 1992-96).

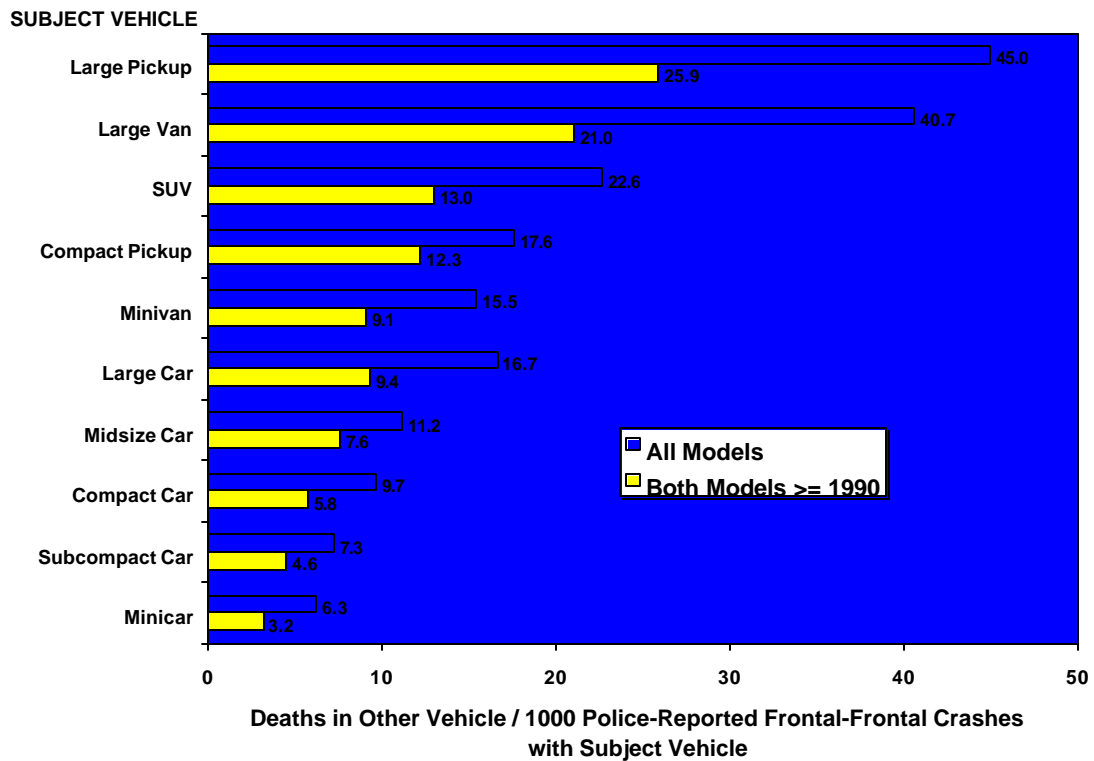


Figure 4. Aggressivity by vehicle category in frontal-frontal impacts (FARS/GES 1992-1996).

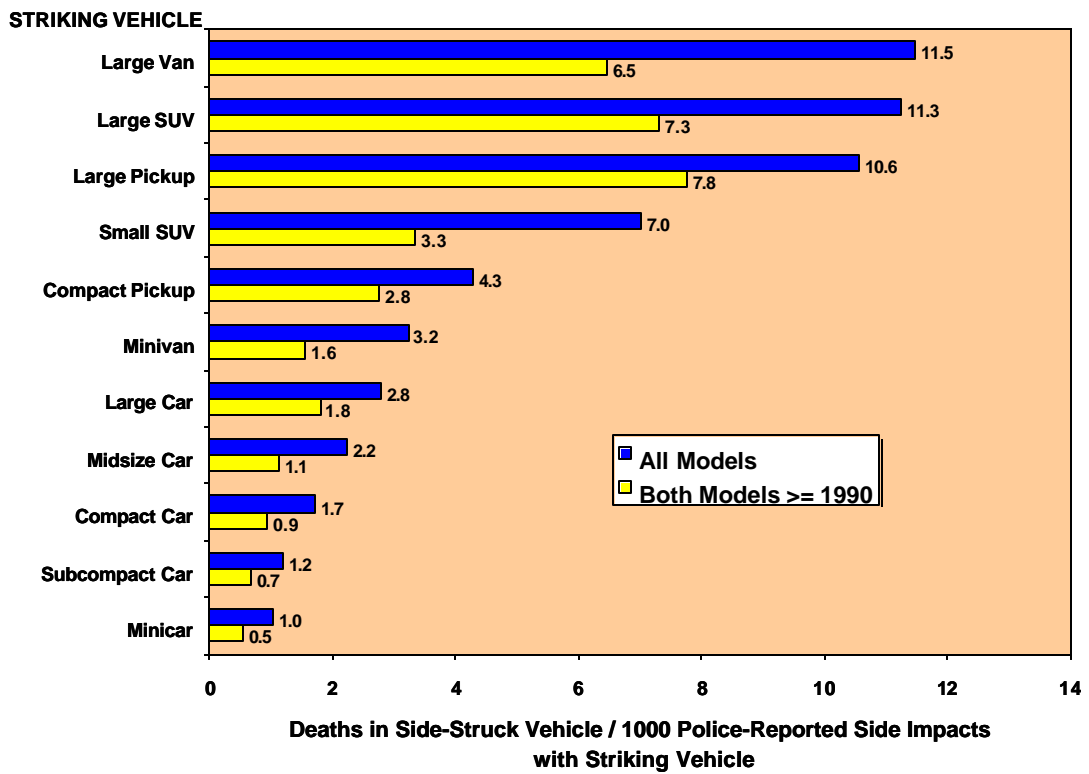


Figure 5. Aggressivity by vehicle category in side impacts (FARS/GES 1992-96).

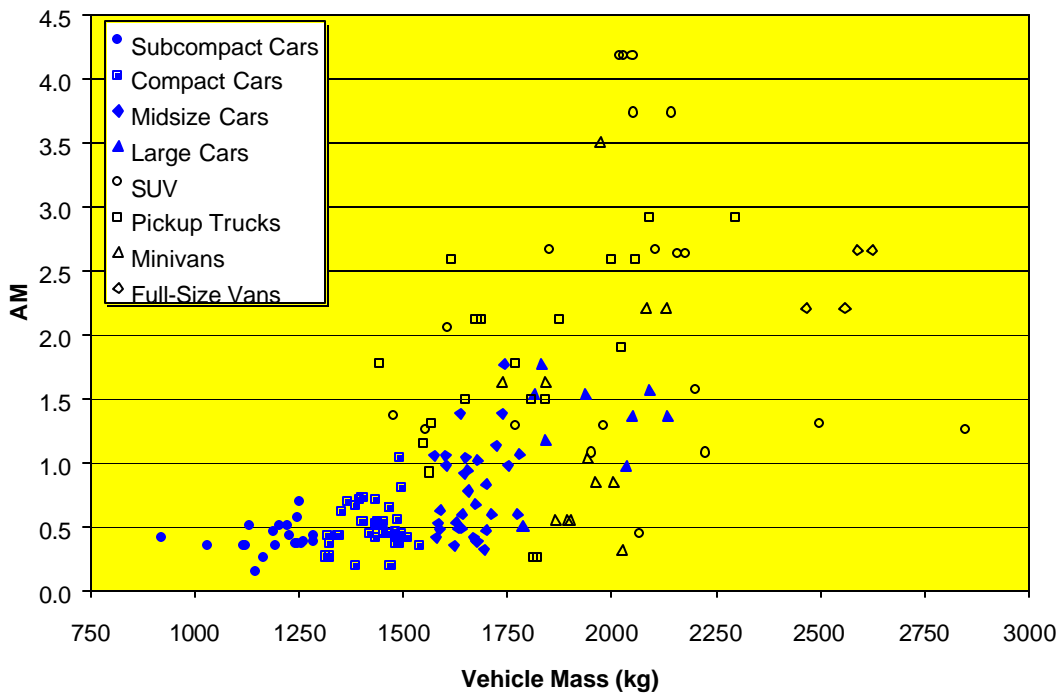


Figure 6. Aggressivity as a function of vehicle mass.

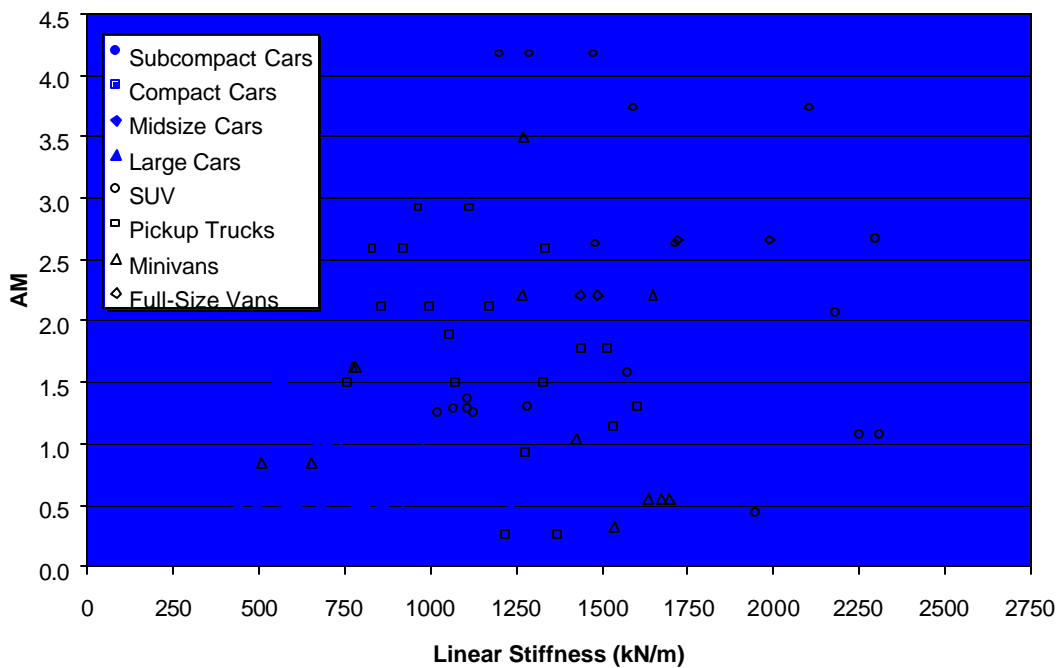


Figure 7. Aggressivity as a function of linear stiffness as computed from NHTSA NCAP crash test results.

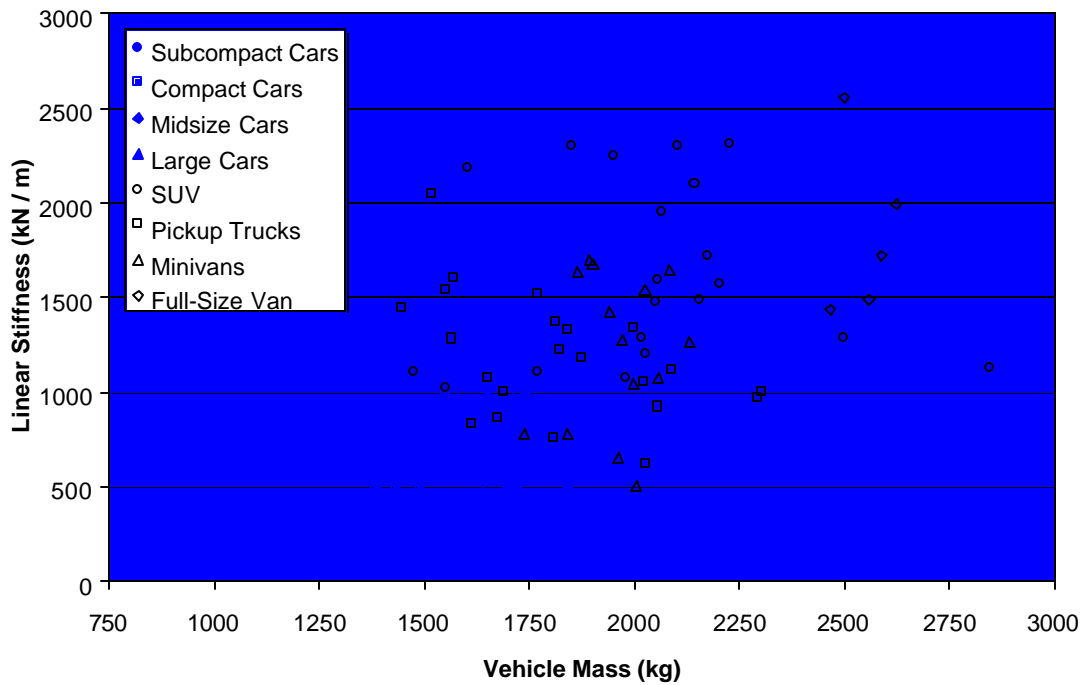


Figure 8. Relationship between frontal stiffness and vehicle mass as determined from NHTSA NCAP crash tests.

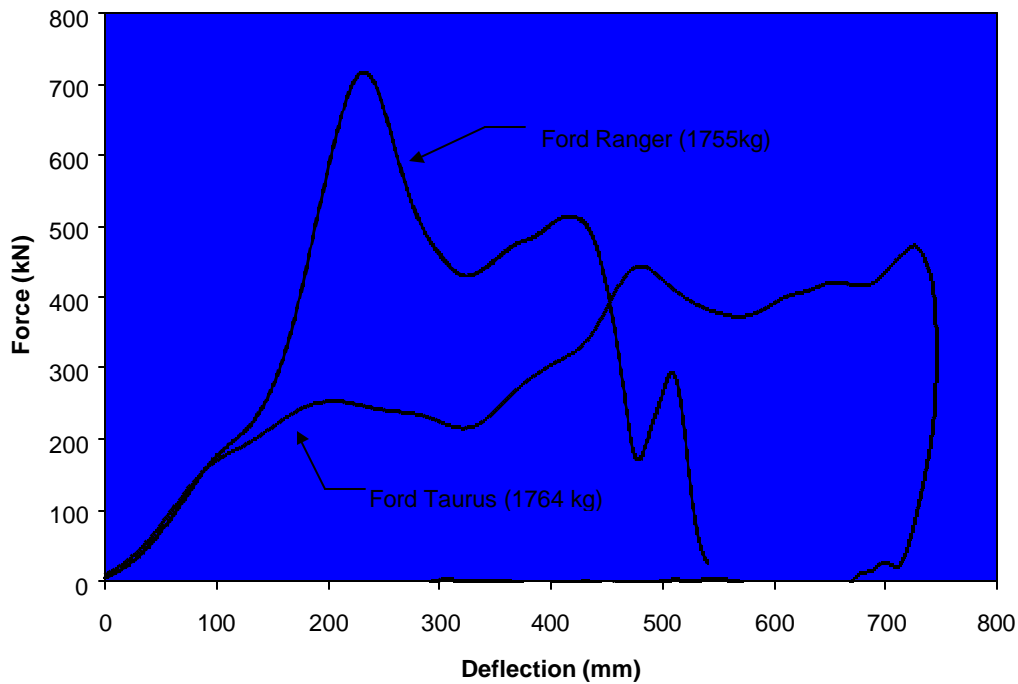


Figure 9. Frontal stiffness: small pickup truck (Ford Ranger) vs. midsize car (Ford Taurus).

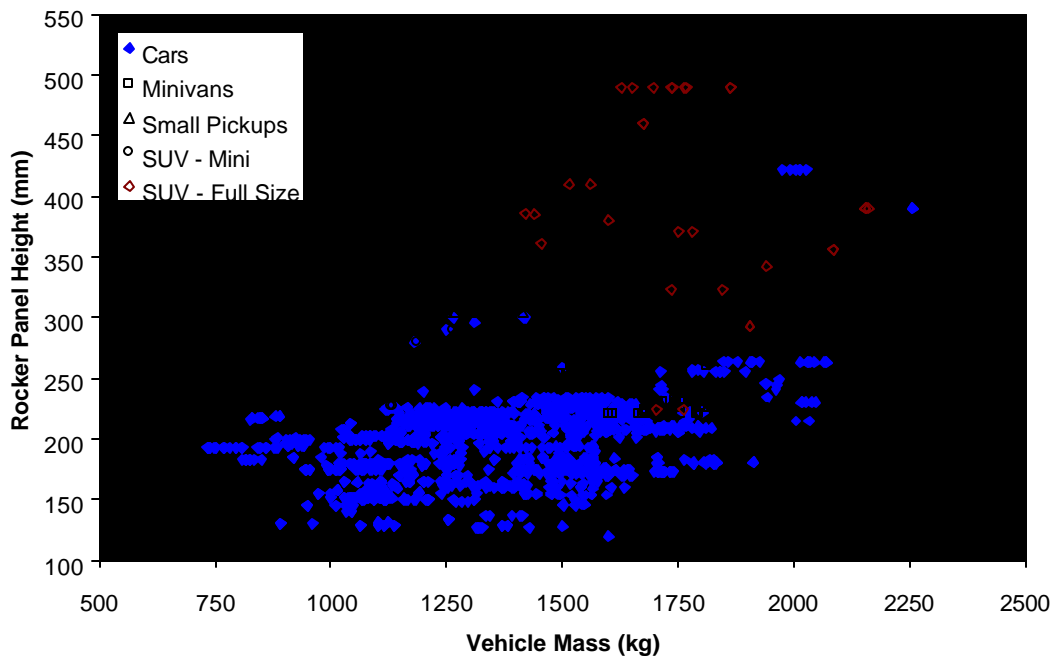


Figure 10. Relationship between vehicle mass and ride height as estimated by rocker panel height (NHTSA Vehicle Parameter Database, 1990-97).

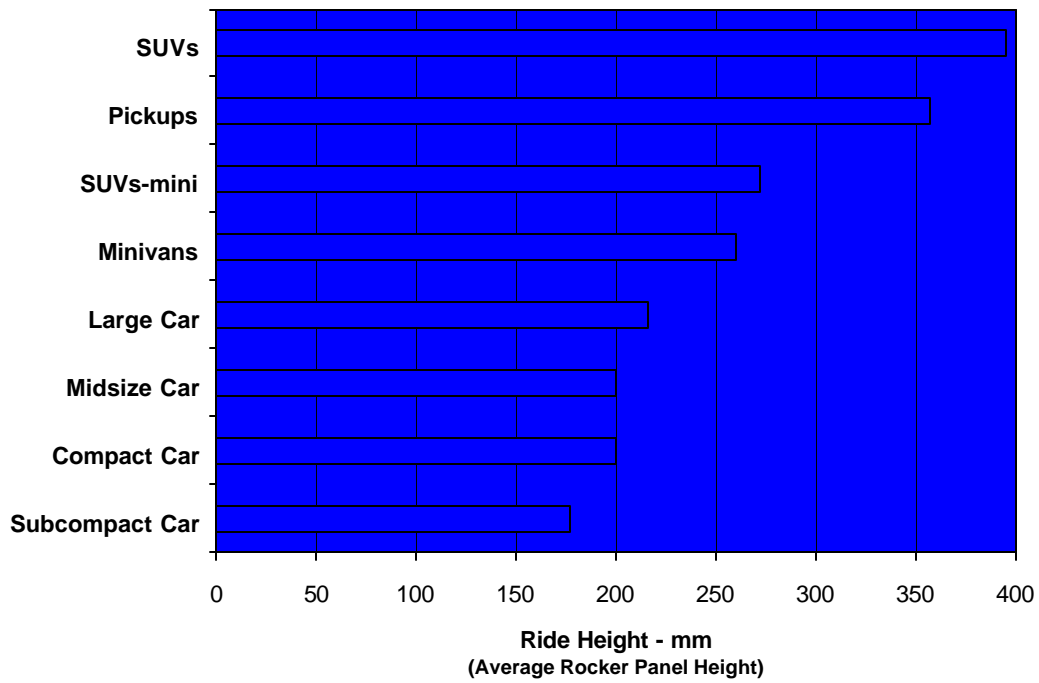


Figure 11. Geometric compatibility: average ride height vs. vehicle category (NHTSA Vehicle Parameter Database, 1990-97).