Vehicle Design Parameters that Affect Partner Protection in Front-to-Front and Front-to-Side Crashes

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Abstract Improving passenger vehicle compatibility in a changing fleet requires identifying design parameters that contribute to partner protection and quantifying their relative importance. Many studies have identified one or more factors relevant to compatibility, but the few that have compared these factors' contribution to real-world crash outcomes have been restricted to specific vehicle types. This study was designed to provide effect estimates that can be compared to each other and applied across vehicle types and that are relevant to vehicles with modern levels of crashworthiness. Front-to-front and front-to-left crashes in which the lighter vehicle was the side-struck vehicle were analysed. Partner protection metrics (PPMs) were calculated for 497 vehicle designs using data from the US New Car Assessment Program full-width rigid barrier and/or IIHS offset deformable barrier test. These were matched to approximately 75,000 and 106,000 police-reported front-to-left and front-to-front crashes, respectively, and 3,200 fatal front-to-front crashes from 2000 to 2023. Logistic regression analyses identified that mass was the dominant vehicle design parameter affecting injury outcomes in all three crash datasets. Beyond mass, multiple stiffness-related PPMs had statistically significant effects on partner driver injury in both crash modes, while centre-of-gravity height was another predictive factor in front-to-front crashes.

Keywords Aggressivity, compatibility, crashworthiness, front impacts, side impacts.

I. INTRODUCTION

Minimising fatality and injury risks to passenger vehicle (PV) occupants in crashes requires vehicle designs that protect their own occupants without increasing the risks in partner vehicles. Despite its fundamental role in dictating crash outcomes, there are relatively few constraints on vehicle aggressivity. In the US, the only regulation directly addressing compatibility is the requirement that semi-trailers be equipped with rear underride guards. Worldwide, the only assessment of a passenger vehicle's partner protection is the mobile progressive deformable barrier (MPDB) test introduced by the European New Car Assessment Programme (Euro NCAP) in 2020 [1], and subsequently adopted by NCAPs in Australia, China and South Korea [2]. The effects of this test on real-world crash outcomes have yet to be quantified. Part of the challenge in doing so, and in developing future assessments in the US or elsewhere, is that the relative contribution of different factors affecting partner protection have not been well-established.

Literature Review

Vehicle crash compatibility is usually considered as three separate but related factors: mass; structural alignment; and structural stiffness. Vehicle curb weight is a well-publicised vehicle specification and its inclusion in many crash databases has facilitated its inclusion in crash analyses. There is a large body of research exploring the effect of mass on outcomes in two-vehicle crashes, e.g. [3-6]. Defining and evaluating structural alignment and stiffness is more difficult. Regulatory bumper requirements in the US [7] apply to cars but not to light trucks and vans (LTVs), resulting in bumper and longitudinal frame heights that are often misaligned [8]. Additionally, LTVs historically have had higher measures of stiffness in crash tests than cars of similar mass [9-10]. Without isolating the effects of geometry and stiffness, many field studies have shown that LTVs are more aggressive than cars while controlling for mass, e.g. [11-12].

While most prior studies of crash compatibility have been limited to evaluating the effect of vehicle mass or of mass combined with vehicle type, some researchers have included measures of structural geometry or stiffness. Most of these studies were associated with the compatibility research program begun by the National

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Highway Traffic Safety Administration (NHTSA) in the 1990s. One study [9] plotted design-specific partner-driver deaths per registered vehicle year against vehicle mass, stiffness and ride height. The authors observed that LTVs had higher partner-driver death rates than cars and were more aggressive according to all three vehicle design metrics, but they stated that they had not "attempted to assign what proportion of the aggressivity of LTVs is a function of each of these three separate sources of incompatibility".

A 2002 report funded by NHTSA did evaluate potential sources of LTV aggressivity [13]. Joksch studied two-vehicle crashes between an LTV and a car. He calculated the car driver fatality risk per crash occurrence, using the Fatality Analysis Reporting System (FARS) for fatality observations and the National Automotive Sampling System-General Estimates System (NASS-GES) weighted counts for crash exposure. In addition to LTV mass, the study evaluated the effects of structure parameters calculated from loadcell barrier tests of the LTVs. The average height of force (AHOF), peak force, dynamic stiffness, static stiffness, and peak power (the product of force and velocity) were all evaluated separately. Additional covariates included for each crash were the speed limit, LTV driver sex, LTV driver age, and calendar year, as well as two- and three-way interactions between several of these variables. There were no controls for any characteristics of the struck car or car driver, including belt use or airbag deployment. After controlling for LTV mass, Joksch reported that LTV AHOF was related to struck car driver fatality risk in front-to-left crashes. In front-to-front crashes, the stiffness of pickups (dynamic and static), but not of SUVs or vans, was related to partner-car driver fatality risk. He also found that peak power for all LTV types was inversely related to partner-car driver fatality risk in front-to-front crashes. Joksch stated that the lack of consistent findings for front-to-front crashes could have been related to insufficient data. The study included 12 unique pickup designs, 17 SUVs, and 11 vans from 1985 and later model years in calendar years 1991–1999.

The following year, NHTSA published its own report on vehicle mass that included an analysis of factors contributing to LTV aggressivity [14] and which differed from [13] in several respects: it evaluated 1991–1999 model year vehicles in calendar years 1995–2000, it calculated partner-driver fatality rates using estimated miles travelled instead of crash occurrence, it accounted for the mass of the struck car, and it included both AHOF and stiffness in the same regression models. The regression models also included many additional covariates: age and gender of both drivers; availability of airbags, ABS, and four-wheel drive for both vehicles; vehicle age; urban/rural crash environment; speed limit; day/night crash time; road surface condition; high/low state fatality rate; and calendar year. While controlling for these, [14] reported that LTV AHOF was associated with partner-car fatality rates in front-to-left crashes, and LTV stiffness was associated with car fatality rates in front-to-front crashes. However, when extending these analyses to crashes between two cars the results differed; both the stiffness and AHOF of the striking car had significant effects in front-to-left crashes, but neither factor was predictive of the outcome in front-to-front crashes. A secondary analysis found that, counterintuitively, increasing car stiffness was significantly associated with improved partner-car driver outcomes in front-to-front crashes. In addition, significant differences existed for striking LTV types (pickup, SUV, or minivan) in front-to-left crashes, even while controlling for AHOF and stiffness. The overall results indicated aggressivity differences among vehicle types were not fully explained by the measures used to quantify mass, stiffness and geometry. It is also possible that collinearity between these and other covariates masked their true effects or that the estimated mileage exposure variable (derived from odometer readings of crashed vehicles in another database) was inaccurate.

A 2005 study [15] was designed to validate results from [14] using more vehicles and a different methodology. It included 1985–2003 model year vehicles involved in two-vehicle crashes contained in seven state crash databases from 1998 to 2002. The effects of AHOF and stiffness on the risk of the partner-car driver sustaining a fatal or incapacitating injury in a front-to-left or front-to-front crash were estimated. For LTV vs. car crashes, the results of [15] were similar to [14]. LTV AHOF, but not stiffness, was a significant predictor of partner-car driver injury in front-to-left crashes, while LTV stiffness, but not AHOF, was somewhat predictive of injury in front-to-front crashes (p=0.10). Unlike [14], there was no attempt to investigate the influence of geometry or stiffness in crashes involving two vehicles of the same type, or to determine whether there were aggressivity differences between vehicle types that were not explained by mass, stiffness and AHOF.

Another study analysed the Japanese fleet using structural measures of self- and partner-protection calculated from Japanese NCAP tests [16]. These included energy-equivalent stiffness and maximum force calculated at different displacement levels, energy absorption at different maximum force levels, and toe pan intrusion, all measured in both offset deformable barrier (ODB) and full-width rigid barrier (FWRB) tests. The effect of each of these metrics on the risk of fatal or serious driver injury were estimated in two-vehicle crashes in Japan from 1998 to 2005, where both vehicles were sedans and had a mass of 2,500 kg or less. The authors reported that improved partner protection in front-to-left and front-to-front crashes was associated with lower FWRB maximum force measured within 200 mm. Unlike [13-15], this research was restricted to belted drivers.

Need for an Updated Fleet-Wide Analysis

Despite all the previous work, a new evaluation of vehicle compatibility and partner protection would be helpful for several reasons. None of the earlier studies was able to estimate effects of vehicle design parameters that held for all vehicle types. Several only considered LTV parameters, while [14] found LTV and car stiffness produced directionally opposite effects. There remains a need for partner protection estimates that hold across vehicle classification schemes. In the US, LTVs account for three-quarters of new PV sales [17], reducing the relevance of compatibility assessments restricted to LTV-vs.-car impacts. Furthermore, SUV construction now more often resembles cars than pickups, but SUV ground clearance remains higher than cars. Rather than create additional vehicle categories (e.g. “crossovers”) for purposes of assessing crash compatibility, it would be more meaningful to estimate the specific risks posed by individual vehicles based on their design parameters. This also could allow compatibility assessments in markets that have a different mix of vehicle types than the US, or where the classification scheme is not directly comparable.

Another benefit of isolating the individual factors that contribute to vehicle-partner protection is the ability to compare the potential effects of different changes in the fleet. As a past example, LTV manufacturers voluntarily committed to align primary or secondary energy-absorbing structures with the US regulatory bumper test height for cars by the 2010 model year [18]. Studies of the effect on real-world crash outcomes produced mixed results [19-21], but it is likely that the redesigned LTVs also differed from earlier models in terms of mass and stiffness. More recently, vehicle electrification has resulted in combinations of mass, structural alignment and stiffness that have not previously been observed with internal combustion engine vehicles [22]. By isolating these factors, it may be possible to better estimate the compatibility effects of electrification and other future fleet changes. This would allow partner protection improvements to be incorporated into designs more quickly, potentially mitigating the greater risks heavier EVs present to their lighter crash partners, for example.

Determining whether a compatibility evaluation program will substantially reduce fatalities and injuries also relies on an accurate assessment of the relative contribution of each component factor. For example, it is unknown what effect could be expected from a future US evaluation of stiffness and alignment that does not also address the mass heterogeneity in the vehicle fleet. Similarly, a real-world analysis of fundamental compatibility measures could enable an estimate of the effects of the Euro NCAP evaluation, provided the design changes prompted by the test can be converted into the same fundamental measures.

There are other reasons an updated compatibility assessment would be beneficial. Vehicle designs have changed since 2003, the latest model year included in earlier US studies. Improvements in frontal and side-impact crashworthiness may have altered the underlying relationships between self- and partner-protection, both on the individual vehicle level and on the societal/fleet level. Restraint use rates also have increased. While the proportion of fatally injured drivers who are unbelted remains elevated in the US, it seems likely that the increasing belt use in the overall population [23] and the growing prevalence of technology in new vehicles to encourage use [24] means that even the fatally injured population will be predominantly belted in the future.

This study is designed to evaluate different partner protection metrics and identify those that are applicable to all vehicle types. It is restricted to belted drivers and vehicles with updated crashworthiness performance. To provide context, the study also includes an estimate of the number of US crash fatalities potentially related to vehicle incompatibility.

II. METHODS

The effects of vehicle mass, structural alignment and stiffness on the injury outcome of the driver of the lighter vehicle in two-PV crashes were studied. Front-to-front and front-to-left crashes in which the lighter vehicle was the side-struck vehicle were assessed separately. Mass was included as the ratio of the two vehicle masses in each crash. As discussed in detail below, structural alignment was represented by the height of the centre of gravity (h_{CG}) of the heavier vehicle or the difference between the two vehicles. Stiffness effects were evaluated using different partner protection metrics (PPMs). Two injury outcomes were studied for the driver of the lighter vehicle: the risk of fatal or incapacitating injury in a police-reported front-to-left or front-to-front crash; and the odds of fatality in a front-to-front crash in which exactly one driver was killed.

All analyses were limited to vehicles with good ratings in the IIHS moderate overlap frontal crash test (1994–2022 version). Previous research has found that results of this test are correlated with self-protection in front-to-front crashes [25]. While it is unknown how structural changes implemented to improve performance in this test may have affected partner protection, over 99% of tested 2012 and newer model year vehicles have been rated good. Any analysis of the potential for the current fleet to achieve improved partner protection should be limited to vehicles with modern levels of self-protection. Similarly, front-to-side crashes were further restricted to those involving struck vehicles with a good rating in the IIHS side-impact test (2002–2021 version), as ratings in this test have been shown to relate to injury risk [26].

Field Crash Data

Police-reported crash data from 2006 to 2023 were obtained from databases in 19 states using two different queries. Front-to-left side crashes were defined as two-vehicle crashes in which the damage location was coded as “front” for the heavier vehicle and “left” for the lighter vehicle. Front-to-front crashes were defined as two-vehicle crashes in which both vehicles had “front” impact locations. Cases were excluded if the driver of the lighter vehicle was coded as unbelted or if the police coded the lighter vehicle driver’s injury severity as “unknown”.

Data for fatal front-to-front crashes were obtained from FARS for calendar years 2000–2022. FARS is a census of all fatal motor vehicle crashes in the United States and is maintained by NHTSA using data submitted by each state. For this study, FARS was queried for all front-to-front crashes in which both drivers were coded as restrained by a lap and shoulder belt and one driver was killed. Front-to-front crashes were defined as those involving two vehicles with impact locations of 11, 12, or 1 o’clock in which the most harmful event was coded as an impact with another vehicle.

For both the state and the FARS data, vehicle mass was represented by the published curb weight obtained using the vehicle identification number (VIN) of the crash-involved vehicles. Vehicle model year was defined as the first model year of a structurally similar generation represented by the same IIHS moderate overlap test. Centre of gravity height measures were obtained from NHTSA static stability factor research [27] or rollover ratings.

Partner Protection Metrics

PPMs were obtained from static vehicle measures as well as data recorded during the IIHS ODB and NHTSA NCAP FWRB front tests. The IIHS ODB configuration entails a 64 km/h impact with a 40% overlap on the driver side [28]. The deformable barrier is 540 mm deep and is mounted to a rigid fixture. The NHTSA evaluation involves a 56 km/h impact into the FWRB, which is equipped with load cells to record the crash forces [29]. PPMs were based on the FWRB load cell data as well as measurements recorded by accelerometers attached to the vehicle’s occupant compartment in both tests. In the ODB test, acceleration is recorded at a single point on the floor near the vehicle centreline. In the FWRB test, occupant compartment acceleration is usually recorded at multiple locations on the left and right side of the occupant compartment. In tests with multiple valid measurements, data were averaged prior to calculating PPMs.

The metrics evaluated for this study are listed in Table I. To best isolate the effect of vehicle mass as a source of incompatibility, PPMs were evaluated only if they were not derived directly from vehicle mass. For example, maximum vehicle displacements (d_{max}) from both tests were included as candidates for the regression analyses, but dynamic stiffness ($k = mv_0^2/d_{max}^2$) was not included.

In addition to the PPMs listed in Table I, the average height of force (AHOF) was initially considered for inclusion. AHOF is calculated using the height from the ground of each row in the FWRB load cell wall, weighted by the total load on each row at each point in time. However, it has been shown that AHOF errors can exceed 10% in tests with a 4-row load cell wall [30-31], and the error would be substantially higher with fewer rows. Tests with 1–4 rows of load cells accounted for over 70% of the vehicles in the FARS sample. Since h_{CG} was available for nearly every vehicle, and because it was correlated with AHOF for tests with five or more load cell rows (Appendix, Fig. A1), h_{CG} was used instead of AHOF in the regression models. In theory, AHOF would be the preferred representation of a vehicle’s geometric compatibility. However, some previous analyses have indicated that AHOF measured in a FWRB test does not always detect important energy-absorbing structure [18][32].

An extensive data cleaning and processing procedure was required prior to calculating any of the PPMs derived from load cell wall data. Load cells were checked to ensure that they recorded valid data. In cases where data

TABLE I
PARTNER PROTECTION METRICS

Measurement	Symbol	Details
Static		
Bumper to firewall length (mm)	l_{BF}	Measured for NCAP and/or IIHS testing
NCAP FWRB test		
Energy-equivalent stiffness from 25 mm to 400 mm (kN/m)	Kw_{400}	Defined as: $2\int_{25\,mm}^{400mm} F\,dx \big/ (400^2 - 25^2)$, where F is total force on load cell wall, x is longitudinal displacement
Energy in centre 750 mm (%)	EA_{center}	Proportion of total energy absorption that was recorded in load cell wall columns within 325 mm of centreline; chosen based on most common load cell dimensions
Maximum displacement (mm)	d_{max}	Measured from vehicle longitudinal acceleration
Maximum force (kN)	F_{max}	Maximum total force on load cell wall
IIHS ODB test		
Maximum displacement (mm)	d_{max}	Measured from vehicle longitudinal acceleration

from individual load cells was missing or invalid, the force-time histories for the adjacent sensors (3 if the invalid sensor was on the edge of the load cell matrix, 4 if not) were averaged as a replacement for the missing data. Load cell wall dimensions were obtained from individual test reports in order to calculate AHOF and EA_{center}.

Even though a good rating in the IIHS moderate overlap test was an inclusion requirement, there were more vehicles with matching FWRB PPMs than with matching ODB d_{max}. This is because d_{max} is not reported by vehicle manufacturers who submit test data as part of the IIHS verification test programme. As a result, sample sizes for PPM analyses were larger for those based on NCAP tests or static vehicle measures.

Regression Analyses

Logistic regression was used to evaluate the effect of vehicle mass, height and stiffness on partner-vehicle driver injury risk while controlling for other covariates related to the crash, vehicles and drivers. For each of the three datasets described above, an initial model estimated the effect of vehicle type (car, SUV, pickup or minivan) on partner-driver injury outcome while controlling for vehicle mass. For consistency with the conservation of momentum, vehicle mass was represented as the logarithm of the ratio of the two vehicles' curb weights. Next, a model including h_{CG} was used to assess whether height differences could explain any vehicle type differences observed while controlling only for mass. Finally, the effect of vehicle stiffness was assessed using separate models for each of the PPMs in Table I, both for all vehicle types and while stratifying by vehicle type.

Models based on the state crash data estimated the odds of the partner driver sustaining a fatal or incapacitating injury (K or A on the KABCO scale) in a police-reported crash. In addition to the mass ratio and the heavier vehicle's h_{CG} and stiffness, a binary variable was included indicating whether the heavier vehicle's model year was 2010 or later, based on the voluntary commitment made by vehicle manufacturers to align LTV and car structures by this year [18]. Other covariates included the state where the crash occurred, the h_{CG} and model year of the lighter vehicle, the age of both drivers, and the sex of both drivers. Covariates that never produced estimates with $p<0.10$ were dropped from the final models. Statistical significance for the PPMs was assessed at the $\alpha = 0.05$ level.

Since FARS only includes crashes that produce at least one fatality, these were analysed using a different procedure. As described above, the FARS sample for this study consisted of two-PV front-to-front crashes that resulted in a fatality to exactly one of the two drivers. An initial conditional logistic regression model was used to estimate how differences between each pair of vehicles and drivers related to the odds of fatality. Covariates representing the logarithm of vehicle mass, h_{CG}, model year, driver age and driver sex were included.

Results of the conditional logistic regression were used to select driver and vehicle covariates to be included in unconditional logistic regression models estimating the effects of PPMs in Table I. PPMs for only the heavier vehicle in each crash pair were included, while the outcome variable was whether the observed driver fatality occurred in the lighter vehicle. While these model results cannot be used to calculate overall fatality risk, they reflect the potential for design changes in the heavier vehicle to mitigate the increased risk that the partner driver would experience based on mass alone.

Relevance Estimate

To provide context to the issue of vehicle compatibility in the US, FARS PV occupant fatalities in 2022 were categorised based on relevant crash and occupant factors. Because the regression analyses were focused on belted drivers, unbelted occupants and occupants in crashes involving more than two vehicles were not included in the relevant population, even though it is likely many would benefit from improved partner protection. After establishing the total number of belted PV occupant fatalities in side-struck or front-front crashes, the distribution of partner-vehicle curb weights above 1,750 kg were compared with the distribution of curb weights in the fleet on the basis of total registration data provided by S&P Global. The curb weight of 1,750 kg was selected as a minimum because it represents the median curb weight for the heavier partner in two-PV crashes producing a fatality. As with belt use, while it is likely that some occupants in crashes with vehicle partners lighter than 1,750 kg would benefit from improved partner protection, no benefit was assumed since the regression models only evaluated PPMs for the heavier partner. Total registrations were selected as an appropriate exposure variable after a comparison with FARS single-vehicle crash counts produced similar results.

III. RESULTS

Estimates of the relevance of vehicle compatibility in US fatal crashes in the year 2022 are shown in Fig. 1 and Fig. 2. After excluding unbelted occupants and configurations other than two-PV crashes, there were 2,056 fatalities in front-to-front crashes and 1,441 fatalities in the side-struck partner in front-to-side crashes (Fig. 1). Combined, this represents 13.8% of all PV occupant fatalities and 30.7% of belted PV occupant fatalities. Vehicle incompatibility as a function of mass is illustrated by the overrepresentation of heavy vehicle partners in these two-vehicle crashes (Fig. 2). Relative to their proportion of registrations, vehicles with curb weights greater than 1,750 kg accounted for 284 and 271 excess front- and side-impact fatalities, respectively.

There were 497 vehicle designs with FWRB and/or ODB test results representing the heavier vehicle in two-vehicle front-to-front or front-to-side crashes. The correlation coefficients between vehicle mass, centre of gravity height (h_{CG}), and all of the evaluated PPMs for these designs are shown in the Appendix (Fig. A2). Centre of gravity height had the strongest correlation with vehicle mass. Most of the PPMs had a low degree of collinearity; the strongest correlation was between the maximum displacement (d_{max}) measured in the two crash tests.

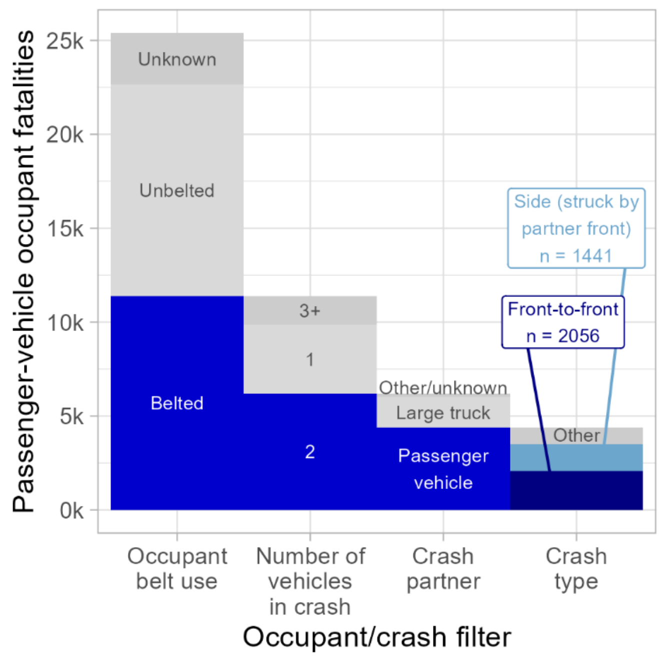

Fig. 1. US passenger-vehicle occupant fatalities in 2022, filtered by factors relevant to passenger-vehicle front partner protection.

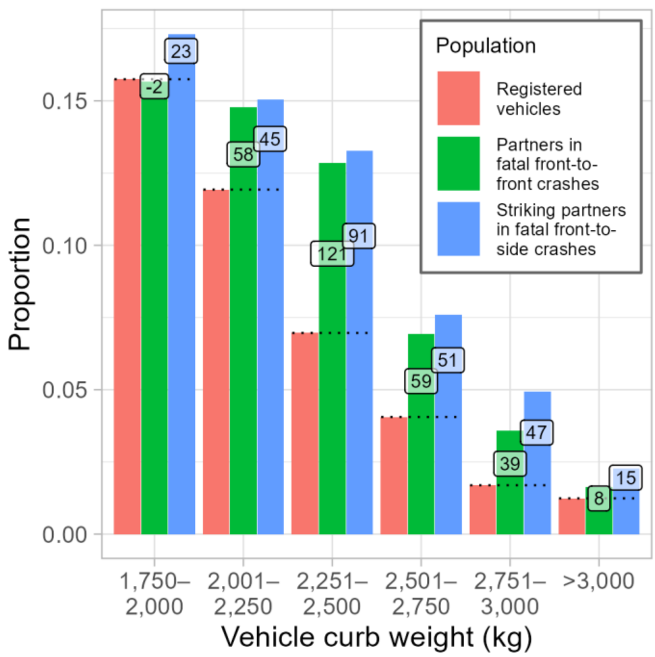

Fig. 2. Representation of passenger vehicles with curb weights ≥1,750 kg in US fleet and fatal crashes. Labels show excess fatalities relative to expected based on the fleet proportion.

Fig. A2 in the Appendix shows correlations for all vehicle types combined; it does not capture potential differences between cars, SUVs, minivans, and pickups. Fig. A3 in the Appendix shows the relationships between vehicle mass and h_{CG}, bumper-to-firewall length (l_{BF}), energy-equivalent stiffness (Kw_{400}), and FWRB d_{max} by vehicle type. Car h_{CG} values were lower than for other vehicle types and did not increase strongly with vehicle mass. By contrast, l_{BF} increased with mass for cars more than for other vehicle types and cars tended to have l_{BF} that was similar to much heavier SUVs and pickups. Despite this, the relationship between mass and Kw_{400} was similar for cars, SUVs and pickups, although the correlations were all fairly weak. The general trend of increasing stiffness with vehicle mass is also reflected in the lack of any consistent relationship between vehicle mass and d_{max}, whether stratifying by vehicle type (Fig. A3) or not (Fig. A2); maintaining a constant dynamic stiffness would require d_{max} to increase with the square-root of mass.

Police-Reported Front-to-Left Crashes

There were 74,287 front-to-left crashes in the state databases that met the inclusion criteria. Results of logistic regression models estimating the fatal or incapacitating injury risk of the driver of the side-struck vehicle are shown in Fig. 3 and in the Appendix (Table AI). While controlling for vehicle mass, the initial model indicated a higher injury risk when the striking vehicle was a pickup compared with a car, SUV or minivan (Table AI, first column). Including h_{CG} as a covariate had a minimal effect on the magnitude of the vehicle type estimates, but did reduce their statistical significance (second column).

When comparing across striking vehicle types, five PPMs for the striking vehicle had statistically significant effects on partner-driver injury (Fig. 3). Injury risk decreased with increasing d_{max}, EA_{center}, and F_{max}, and with decreasing Kw_{400}, all measured in the FWRB test, and with decreasing l_{BF}. When stratifying by striking vehicle type, Kw_{400} and d_{max} remained significant predictors of driver injury outcome in the lighter vehicle. By contrast, the effects of l_{BF}, F_{max}, and EA_{center} were weaker and no longer significant, suggesting that some of their apparent effect may be related to systematic differences among vehicle types.

Other statistically significant effects in the front-to-side crashes were observed for vehicle mass ratio, the age of both drivers, the sex of both drivers, the model year of the struck vehicle, and crash state (not shown in Table AI). The magnitudes of most of these effects were consistent across the different regression models. One exception was the sex of the striking vehicle's driver. While still significant, this effect was weaker when stratifying by vehicle type, indicating that some of the elevated risk in crashes involving male drivers is explained by vehicle type differences. The h_{CG} of the struck vehicle and model year of the striking vehicle (<2010 vs. ≥2010) were not included in the final models since they were only associated with effects that had *p* values above 0.1.

Police-Reported Front-to-Front Crashes

There were 105,748 front-to-front crashes in the state databases that met the inclusion criteria. Results of logistic regression models estimating the fatal or incapacitating injury risk of the driver of the lighter vehicle are shown in Fig. 3 and in the Appendix (Table AII). While controlling for vehicle mass, the initial model indicated a higher risk when the heavier vehicle was a pickup compared with a car, SUV or minivan (Table AII, first column). However, this effect was not significant when accounting for differences in h_{CG} of the heavier vehicle (second column).

When comparing across vehicle types, two PPMs for the heavier vehicle had statistically significant effects on the odds of fatal or incapacitating driver injury in the lighter vehicle (Fig. 3). The risk of injury decreased with increasing EA_{center} and ODB d_{max}. When stratifying by striking vehicle type, the estimated effect of ODB d_{max} but not EA_{center} remained significant. In addition, increasing l_{BF} was associated with significant reductions in partner-driver injury risk when controlling for striking vehicle type.

Other statistically significant effects were observed for vehicle mass ratio, model year of both vehicles, age of the lighter vehicle driver, the sex of both drivers and crash state (not shown in Table AII). Covariates that never produced estimates with *p* values below 0.10 and were dropped from the final models were h_{CG} of the lighter vehicle, model year of the heavier vehicle (<2010 vs. ≥2010), and the heavier vehicle driver's age.

Fatal Front-to-Front Crashes

There were 3,178 front-to-front crashes in FARS involving two good-rated vehicles where both drivers were belted and one was killed. Prior to evaluating any PPMs, a conditional logistic regression model estimated that higher fatality odds were associated with lower vehicle curb weight, lower vehicle centre of gravity, older vehicle model year and higher driver age. The effect of driver sex was small and not statistically significant. Model results

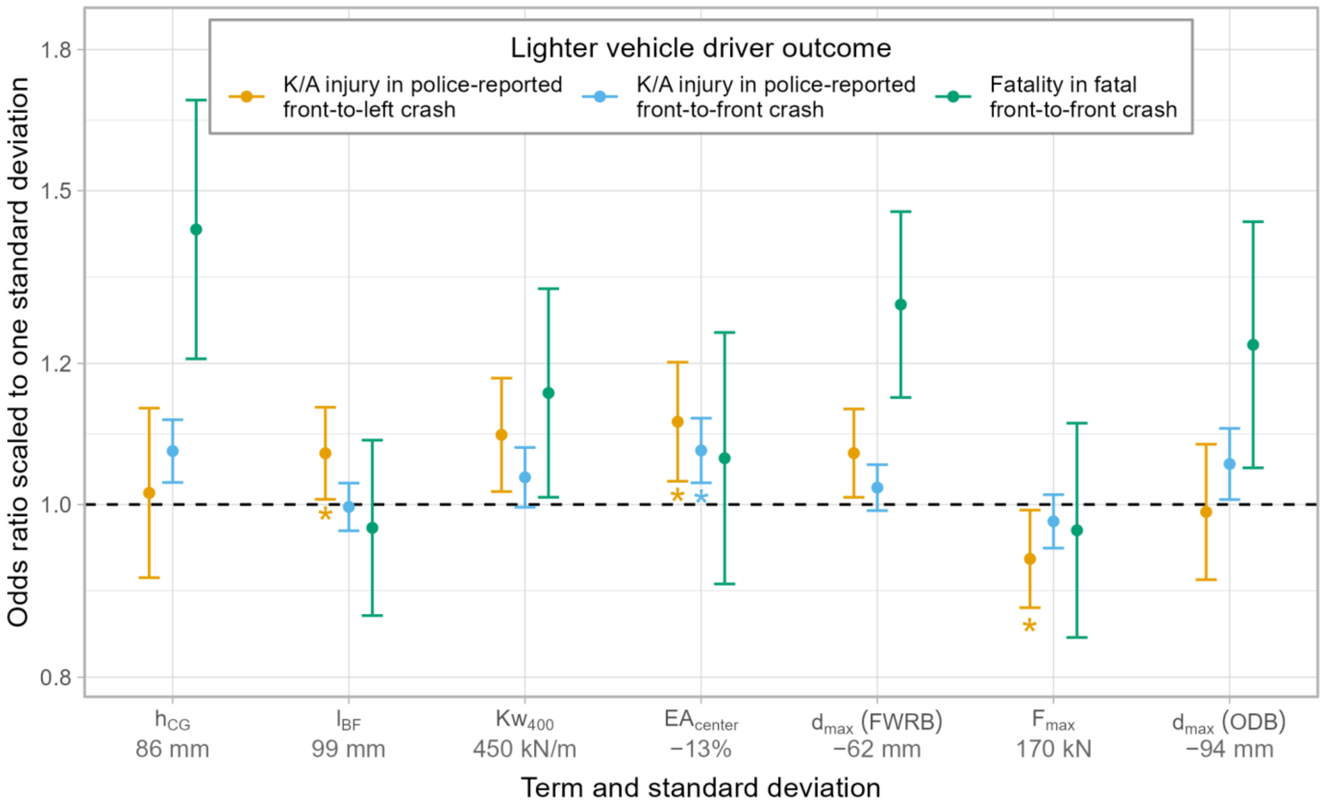

Fig. 3. Lighter vehicle driver injury odds ratios associated with centre of gravity height (h_{CG}) and PPM changes for the heavier vehicle while controlling for curb weight ratio. Odds ratios for EA_{center} and d_{max} have been inverted to facilitate comparison. The h_{CG} effects shown are the medians across all the PPM models. Effects that were not statistically significant when including vehicle type as a covariate are indicated by *.
Note: K/A injury = fatal or incapacitating injury.

are shown in Table AIII along with results of a conditional regression model that also included vehicle type. Drivers of pickups and SUVs had estimated fatality odds lower than drivers of cars, but these differences were not statistically significant. Minivan drivers had significantly greater estimated fatality odds than drivers of cars.

Based on the results of the conditional regression, covariates representing differences in vehicle mass, h_{CG}, model year and driver age for each vehicle/driver pair were included in unconditional regression models. The models estimated the effects of each PPM for the heavier vehicle on the odds that the driver fatality occurred in the lighter vehicle. Results are shown in Fig. 3 and Table AIV. The effects of curb weight ratio, h_{CG} difference, model year difference, and driver age difference were consistent with estimates obtained from the conditional logistic regression models. The apparent inversion of the effects is explained by the fact that the values for the lighter vehicle were always used as the baseline in the unconditional logistic regression. While the conditional logistic regression model estimated the fatality odds associated with a difference in the logarithms of the two vehicle's curb weights, this is equivalent to including the logarithm of the weight ratio in the unconditional model.

Pickups and SUVs were associated with significantly higher odds of partner-driver fatality than cars when controlling for vehicle mass, model year and driver age (Table AIV, first column). These differences were much smaller and not significant when h_{CG} differences were accounted for (second column), while minivan partners represented a significantly lower risk than cars. In addition, three PPMs for the heavier vehicle were associated with statistically significant effects on the fatality outcome (Fig. 3). Vehicles with lower Kw_{400}, greater FWRB d_{max}, or greater ODB d_{max} were associated with lower odds of partner-driver fatality, partially offsetting the elevated risk associated with the vehicle mass difference. All three of these PPMs still had significant estimated effects when the heavier vehicle type was included along with h_{CG} in regression models, while none of the other PPMs had significant effects. These results are not shown in Table AIV given their similarity to the models that did not include vehicle type.

IV. DISCUSSION

Mass, stiffness and structural overlap all contribute to vehicle crash compatibility, but mass is by far the single greatest source of incompatibility when measured by increased injury risk for partner-vehicle occupants. In the police-reported front-to-side and front-to-front crashes, the median curb weight ratio was 1.2, which represents fatal/incapacitating injury risk increases of 29% and 17% for the driver of the lighter vehicle in a side or front crash, respectively. To fully offset just this median difference in curb weight, the heavier vehicle would require countermeasures equivalent to 3–4 standard deviations from the mean for most PPMs. This relationship is illustrated for one PPM in Fig. 4, where the uppermost line (labelled "1") defines the combinations of vehicle mass and crush distance that produce an equal estimated risk to the driver of a 1,500 kg partner vehicle in a front-to-front crash. In order to offset the mass-based risk, a 2,000 kg vehicle would need to crush around 137 cm in the IIHS test – 26% greater than the maximum observation of 109 cm, which was measured in a test of the 2003–2011 Ford Crown Victoria.

Rather than working to offset mass effects, height and stiffness often compound vehicle aggressivity as mass increases (Appendix, Fig. A2, Fig. A3). Bumper-to-firewall distance (l_{BF}) increases with mass are greater for cars than for LTVs. In fact, considering only vehicles heavier than the median 1,750 kg, there is no statistical relationship between mass and l_{BF} (r^2=0.004). In other words, as mass increases beyond the fleet median, the typical space available for energy-absorbing vehicle structure is essentially constant. This is reflected in dynamic crush values for the heaviest vehicles that often are similar to or even lower than much lighter vehicles (Fig. 4 and Appendix, Fig. A3) and energy-equivalent stiffness values that are higher (Appendix, Fig. A2 and Fig. A3). The increases in vehicle height with mass are even more clearly defined. For example, a typical 2,750 kg vehicle has an h_{CG} of 850 mm. Relative to an h_{CG} of 700 mm, this represents an estimated injury risk increase of 19% for a partner-vehicle driver in a front-to-front crash in addition to the elevated risk due to any mass difference.

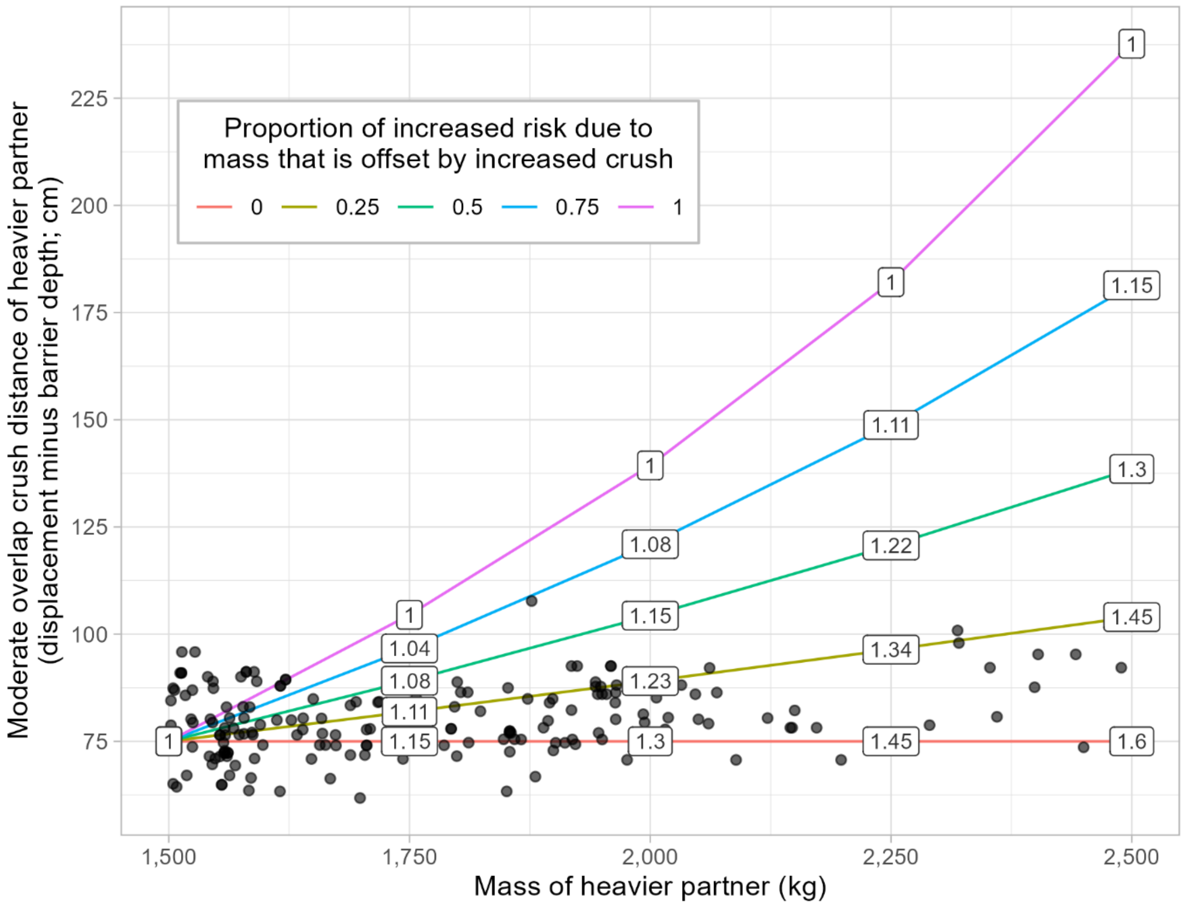

Fig. 4. Illustration of how both the mass and d_{max} (in ODB test, converted to crush distance) of the heavier partner vehicle affect driver injury risk in front-to-front police-reported crashes. The labels show the K/A injury risk for the driver of a 1,500 kg vehicle relative to the risk in a crash with another 1,500 kg vehicle with a 75 cm crush distance in the test. The lines show the crush distances necessary for the heavier vehicle in order to offset some or all of the increased risk posed by the vehicle mass. Dots represent actual vehicle designs included in the study.

These comparisons of the relative contributions of mass, stiffness, and vertical alignment highlight the compatibility challenges associated with vehicle electrification. EVs typically are over 300 kg heavier than conventional counterparts with similar external dimensions [22], and some electric SUVs and pickups have curb weights exceeding 3,000 kg [33]. EVs often have lower centres of gravity (e.g. the two lowest h_{CG} values in Fig. A3 are both EVs), and in frontal crashes this should benefit their crash partners. However, lower h_{CG} values are unlikely to fully compensate for the increased mass of EVs for several reasons: lower h_{CG} was not found to benefit side-struck partners, fully offsetting the risk in front-to-front crashes would require unrealistic h_{CG} reductions, and, as discussed below, h_{CG} itself has limitations as a measure of structural overlap. Not only is the proportion of fatalities related to incompatibility likely to increase alongside EV penetration into the fleet, but if a fully electrified future fleet has more mass heterogeneity, it could have a relatively larger incompatibility problem than the present fleet. (It is still too early to predict EV mass heterogeneity in the US given the predominance of a few models in the total registration counts.) While this study did not evaluate the presence of any tradeoffs in self-protection, [34] found no evidence that increasing mass above 1,800 kg improved self-protection in two-vehicle crashes for 2013–2021 model year vehicles. This may be related to the increased stiffness of heavier vehicles as discussed above. Whatever the cause, without changes in technology or design choices that reduce EV mass or new crashworthiness advancements, it is possible that typical two-vehicle crashes in the future will pose a greater overall injury risk than similar crashes today.

This study builds on the large body of existing research [35] in a few important ways. First, it estimates effects for crashes between vehicles with good front and side crash test ratings. This could help explain the difference in the side-impact results with [13-15]. All three of these studies found that increasing LTV AHOF was associated with higher driver injury risk in partner side-struck cars, while [14-15] found that LTV stiffness was not. In the current study the reverse was true: h_{CG} was not a significant predictor of partner-vehicle driver injury outcome in front-to-side crashes, but Kw_{400} and FWRB d_{max} were. Prior to improvements in side-impact crashworthiness, vehicle side structure may have been so weak that the variation in the front-end stiffness of the striking vehicle made little difference, while the lack of side airbags meant that striking vehicle height often determined whether there was direct head contact. With standard side airbags and stronger structure, side-impacted driver outcomes now appear more sensitive to the stiffness of the striking vehicle than to its height. In front-to-front crashes, the new results indicate that both the height and the stiffness of the heavier vehicle are factors in the partner-driver injury risk, whereas [14-15] only found significant effects for stiffness. However, it is possible that the inclusion of unbelted occupants in [14-15] contributed to this difference. Limiting estimates of partner-protection effects to belted drivers is another distinction of this study relative to previous work.

Another goal of this research was to identify vehicle design factors that account for incompatibility across vehicle types so that estimates can be applied to the entire fleet. This was partially achieved. In each of the three crash scenarios considered, there were stiffness PPMs that remained significant in models, including vehicle type, indicating these metrics were not simply proxies for vehicle type effects. However, vehicle mass, stiffness and h_{CG} did not fully capture the differences between vehicle types; pickups, in particular, often posed higher risks to partner drivers even while controlling for these factors. It is possible that typical impact velocities for pickup crashes are greater and that these differences were not fully controlled by covariates such as driver sex and age. However, it also seems likely that h_{CG} is an insufficient measure of vertical structural alignment for a variety of reasons. Most obviously, the location of heavy vehicle components, such as the engine and transmission, will affect h_{CG} but may not engage with the partner vehicle in some crashes. Less clear is the effect that changes made by individual pickup owners may have on their vehicle's aggressivity. In NHTSA's Crash Investigation Sampling System (CISS), 23% of pickups involved in 2017–2023 crashes were flagged as having post-manufacturer modifications, compared with 7–8% each for cars, SUVs and minivans. The specific modifications are not coded, but suspension lift kits are the first example listed in the CISS user manual [36].

While their unique driver demographics [37], body-on-frame construction, and high rates of customisation all make pickups more difficult to evaluate, it is clear that their mass, stiffness and height make them the most aggressive vehicle type overall (Appendix, Fig. A3). At least in the US, any meaningful improvement in vehicle compatibility needs to address the greater risks that pickups pose to partner-vehicle occupants. While previous studies have reported benefits of the automakers' voluntary height-matching agreement, the current study did not find that 2010 and newer model vehicles had better partner outcomes after controlling for vehicle mass, h_{CG}, and stiffness. There are a few possible explanations for this difference: most LTVs in this study were 2010 or later models, many of those built earlier may already have had lower structures [18], the good-rated partner vehicles in this study had better self-protection than those in earlier studies, and the changing fleet mix means an increasing number of the lighter partner vehicles are now SUVs rather than cars. Whatever the full explanation, further improvements in pickup compatibility require steps beyond the height-matching changes already applied.

One possible means of improving compatibility for all vehicle types would be a partner-protection evaluation that encourages increasing crush distance with mass, whether to maintain a similar stiffness across the fleet or even to allow stiffness reductions that offset some portion of the mass-related risk. The Euro NCAP evaluation rates vehicle compatibility using the occupant load criterion (OLC) calculated from the trolley acceleration and on the uniformity of the crush of the MPDB face [38]. While this study cannot directly address the effectiveness of the Euro NCAP ratings, it does support the concept of using OLC since it is affected by both the vehicle mass and the overall stiffness. The relevance of the crush uniformity metric is more difficult to address with the available data. EA_{center} was included in this study as an attempt to quantify the lateral force distribution in the FWRB condition, but this appeared mainly to distinguish pickups from other vehicle types. More fundamentally, the differences in the FWRB and MPDB reaction forces may preclude direct comparison of PPMs calculated from these two conditions [32][39]. This will be the subject of future research. It is possible that reanalysis of the FWRB load cell data could allow the calculation of a theoretical MPDB response, which would enable a real-world assessment of the benefits of the Euro NCAP test. Even if that proves infeasible, the current study suggests that even a rudimentary evaluation based on ODB d_{max} could promote vehicle designs with improved compatibility.

In 2022, 3,497 belted PV occupant fatalities in the US occurred in a front-to-front crash with another PV or in the side-struck partner in a front-to-side crash with a striking PV. This represents nearly one-third of the total number of belted PV occupant deaths. Improved partner protection has the potential to reduce fatality risk in all of these crashes. However, only 555 of these fatalities (16%) can be attributed to aggressivity beyond the baseline level represented by a vehicle with the median mass of the heavier partner (and, by extension, the stiffness and height typical of a vehicle with this mass). This implies that the majority of the existing compatibility problem is due not to a small number of designs with excessive partner risk, but to the baseline risk itself. A compatibility evaluation, or any other effort to address the issue, is more likely to be effective if it encourages relatively small design changes for a larger number of vehicles than vice versa. Of course, as discussed above, electrification could increase the number of "excessively" aggressive vehicles and their relative contribution to the problem.

Limitations

Vehicle compatibility is a complex subject, and there are many contributing factors that are difficult or impossible to quantify with the available data. Several of these are mentioned above, including the stiffness distribution in both the lateral and vertical directions. Even an accurate measure of stiffness homogeneity may be an incomplete characterisation of compatibility since two similarly homogeneous designs could have different degrees of load-sharing between alternative load paths [40], with the most influential factors varying by the specific crash conditions [41]. This study evaluates only a few of the factors potentially relevant to compatibility and includes no control for crash configuration other than front-to-front vs. front-to-side. Additionally, crash severity could not be directly controlled. This is less likely an issue in the FARS analysis, where the outcome variable was the vehicle in which the fatality occurred rather than the existence of a fatality/injury. While it seems unlikely given the large sample size, for the police-reported crashes it is possible that differences in severity remain after controlling for driver sex and age, and that these obscure the true relationship between PPMs and injury outcome.

V. CONCLUSION

Several measures of partner protection measured from front crash tests have significant effects on the risk of partner-driver injury or fatality in front-to-front and/or front-to-side crashes. Additionally, vehicles with higher centres of gravity pose greater risks to partner drivers in front-to-front crashes. However, the magnitudes of all stiffness and height effects are dwarfed by the effect of the mass differential that is typical of a two-vehicle crash in the US. While improved compatibility has the potential to mitigate crashes that currently result in around one-third of belted passenger-vehicle occupant fatalities, meaningful changes will require a comprehensive approach that includes greater emphasis on the role of vehicle mass in partner protection. Without this focus, the transition to electric vehicles seems likely to increase the proportion of fatalities and injuries that result from crashes between two passenger vehicles.

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VII. APPENDIX

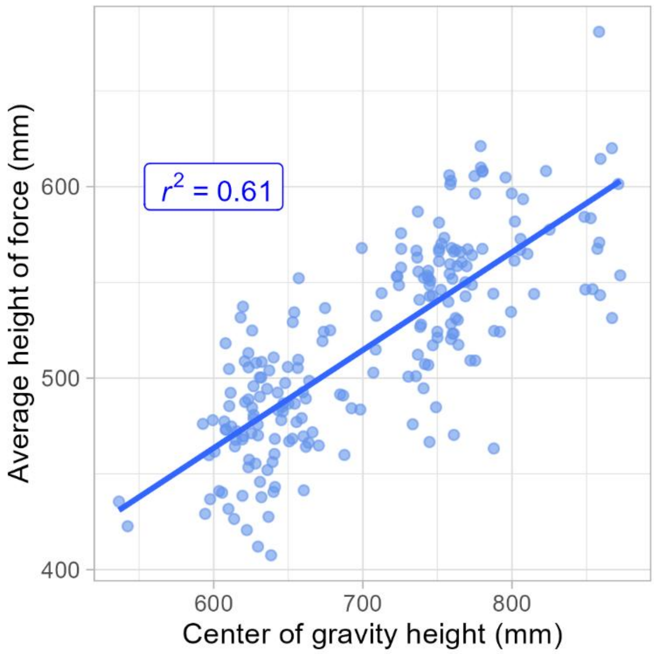

Fig. A1. Centre-of-gravity height vs. AHOF for FWRB tests with 5 or more load cell rows.

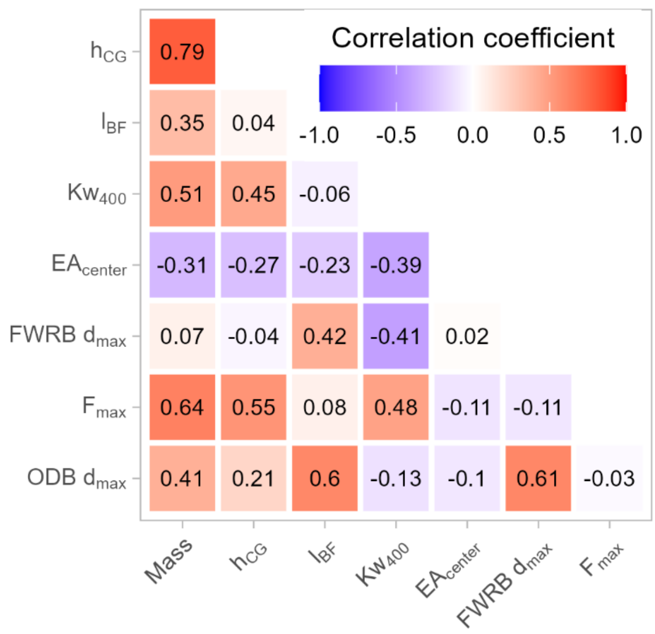

Fig. A2. Pearson correlation coefficients for partner protection metrics shown in Table I.

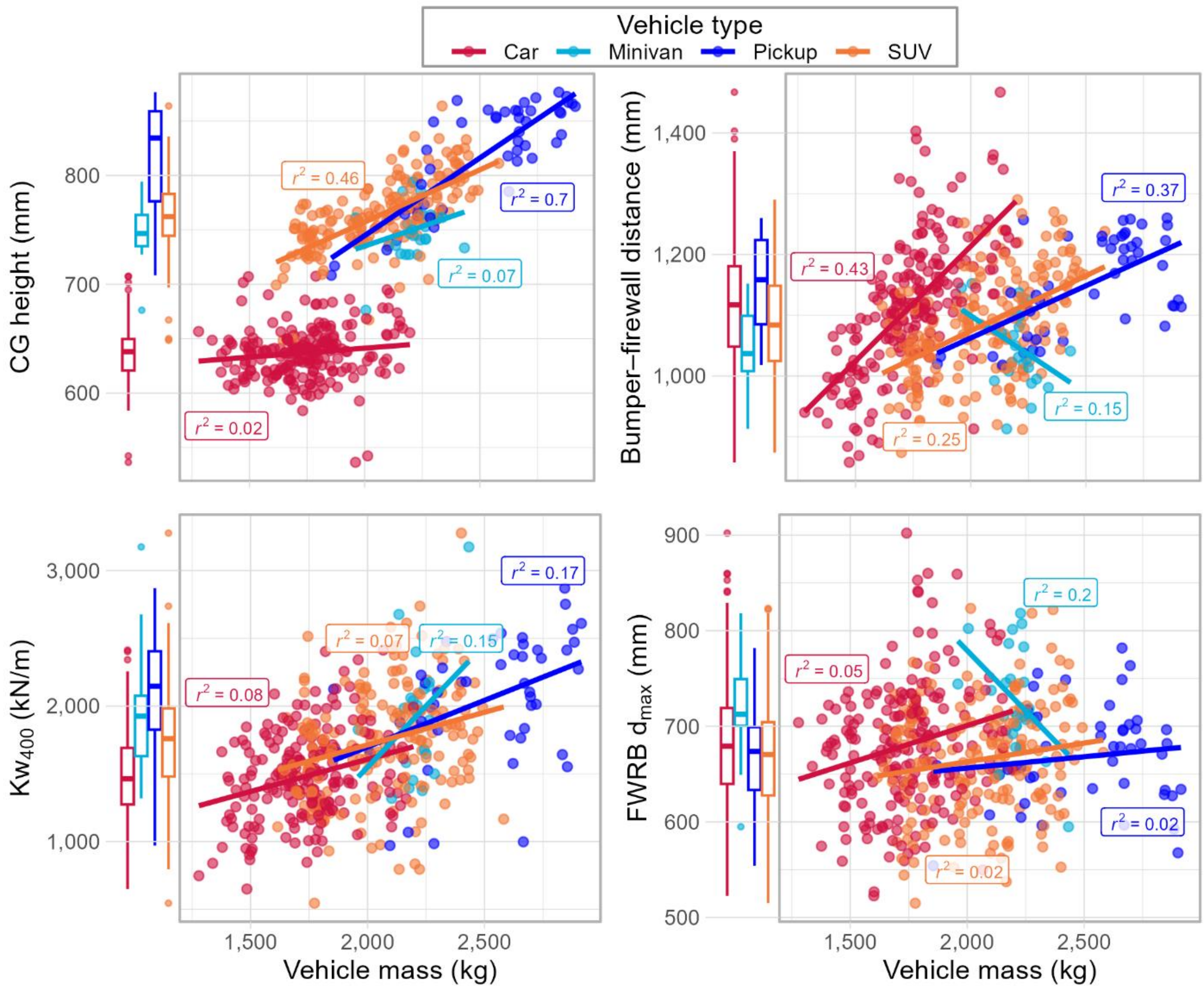

Fig. A3. Relationship between vehicle mass and other metrics by vehicle type.

TABLE AI

RESULTS OF LOGISTIC REGRESSION MODELS ESTIMATING ODDS OF SIDE-STRUCK VEHICLE DRIVER FATAL OR INCAPACITATING (K/A) INJURY IN FRONT-TO-LEFT CRASHES WHEN SIDE-STRUCK VEHICLE WAS LIGHTER PARTNER

	Model (striking vehicle partner-protection metric and/or vehicle type)													
	VT (without h_{CG})	VT (with h_{CG})	I_{BF}	Kw_{400}	EA_{center}	d_{max} (FWRB)	F_{max}	d_{max} (ODB)	I_{BF} + VT	Kw_{400} + VT	EA_{center} + VT	d_{max} (FWRB) + VT	F_{max} + VT	d_{max} (ODB) + VT
Crashes	74,342	74,287	74,287	72,575	60,197	74,287	72,877	38,738	74,287	72,575	60,197	74,287	72,877	38,738
K/A injuries	1,216	1,216	1,216	1,185	963	1,216	1,188	655	1,216	1,185	963	1,216	1,188	655
PPM sd	NA	NA	100 mm	420 kN/m	12%	64 mm	170 kN	89 mm	100 mm	420 kN/m	12%	64 mm	170 kN	89mm
Term	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value
Struck vehicle model year (+1)	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.94 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.95 <0.001**	**0.94 <0.001**
Struck driver male (ref: female)	**0.77 <0.001**	**0.77 <0.001**	**0.77 <0.001**	**0.76 <0.001**	**0.75 <0.001**	**0.77 <0.001**	**0.77 <0.001**	**0.75 <0.001**	**0.77 <0.001**	**0.76 <0.001**	**0.76 <0.001**	**0.77 <0.001**	**0.77 <0.001**	**0.75 <0.001**
Struck driver age (+10)	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.29 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.27 <0.001**	**1.29 <0.001**
Striking driver male (ref: female)	**1.18 0.01**	**1.18 0.01**	**1.24 <0.001**	**1.27 <0.001**	**1.28 <0.001**	**1.27 <0.001**	**1.25 <0.001**	**1.31 0.001**	**1.18 0.01**	**1.18 0.01**	**1.22 0.004**	**1.18 0.01**	**1.18 0.01**	**1.25 0.01**
Striking driver age (+10)	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.91 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.9 <0.001**	**0.91 <0.001**
Curb weight ratio (log heavier / lighter; +0.1)	**1.15 <0.001**	**1.15 <0.001**	**1.15 <0.001**	**1.16 <0.001**	**1.16 <0.001**	**1.17 <0.001**	**1.16 <0.001**	**1.14 <0.001**	**1.14 <0.001**	**1.14 <0.001**	**1.15 <0.001**	**1.15 <0.001**	**1.14 <0.001**	**1.13 <0.001**
Striking vehicle CG height (+50 mm)	NA	1 0.95	1.03 0.26	1 0.90	1 0.89	1.01 0.71	1.05 0.08	1.01 0.79	0.98 0.74	0.97 0.58	1.06 0.36	1 0.97	1 0.96	1 0.95
Partner protection metric (+1 sd)	NA	NA	**1.07 0.03**	**1.09 0.02**	**0.91 0.01**	**0.93 0.02**	**0.93 0.03**	1.01 0.83	1.03 0.37	**1.08 0.02**	0.96 0.28	**0.92 0.01**	0.96 0.23	0.97 0.50
Striking vehicle pickup (ref: car)	**1.3 0.01**	1.32 0.16	NA	NA	NA	NA	NA	NA	1.39 0.11	1.32 0.18	0.96 0.86	1.26 0.25	1.38 0.11	1.29 0.30
Striking vehicle SUV (ref: car)	0.94* 0.45	0.95* 0.74	NA	NA	NA	NA	NA	NA	1.02* 0.92	0.95* 0.72	0.8 0.19	0.89* 0.42	0.99* 0.95	0.96* 0.81
Striking vehicle minivan (ref: car)	0.85* 0.19	0.86* 0.36	NA	NA	NA	NA	NA	NA	0.93* 0.68	0.84* 0.31	0.72 0.10	0.86* 0.36	0.9* 0.56	0.86* 0.48

*$p \le 0.05$ for difference relative to pickups; estimates with $p \le 0.05$ are shown in **bold**.

Note: OR = odds ratio, PPM = partner protection metric, sd = standard deviation, VT = vehicle type. PPM abbreviations are shown in Table I.

TABLE AII

RESULTS OF LOGISTIC REGRESSION MODELS ESTIMATING ODDS OF LIGHTER-VEHICLE DRIVER FATAL OR INCAPACITATING (K/A) INJURY IN FRONT-TO-FRONT CRASHES

	Model (heavier vehicle type and/or partner protection metric)													
	VT (without h_{CG})	VT (with h_{CG})	I_{BF}	Kw_{400}	EA_{center}	d_{max} (FWRB)	F_{max}	d_{max} (ODB)	I_{BF} + VT	Kw_{400} + VT	EA_{center} + VT	d_{max} (FWRB) + VT	F_{max} + VT	d_{max} (ODB) + VT
Crashes	105,837	105,748	105,748	103,184	84,483	105,748	103,581	57,268	105,748	103,184	84,483	105,748	103,581	57,268
K/A injuries	4,526	4,522	4,522	4,389	3,590	4,522	4,401	2,430	4,522	4,389	3,590	4,522	4,401	2,430
PPM sd	NA	NA	100 mm	420 kN/m	11%	65 mm	160 kN	90 mm	100 mm	420 kN/m	11%	65 mm	160 kN	90 mm
Term	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value
Lighter vehicle model year (+1)	**0.99** **0.001**	**0.99** **0.001**	**0.99** **0.001**	**0.99** **0.003**	**0.99** **0.001**	**0.99** **<0.001**	**0.99** **0.003**	**0.99** **0.01**	**0.99** **0.001**	**0.99** **0.003**	**0.99** **0.002**	**0.99** **0.001**	**0.99** **0.003**	**0.99** **0.01**
Lighter vehicle driver male (ref: female)	**0.91** **0.002**	**0.91** **0.002**	**0.91** **0.002**	**0.91** **0.004**	**0.92** **0.02**	**0.91** **0.002**	**0.91** **0.004**	**0.91** **0.02**	**0.91** **0.002**	**0.91** **0.004**	**0.92** **0.02**	**0.91** **0.002**	**0.91** **0.004**	**0.91** **0.02**
Lighter vehicle driver age (+10)	**1.15** **<0.001**	**1.15** **<0.001**	**1.15** **<0.001**	**1.15** **<0.001**	**1.16** **<0.001**	**1.15** **<0.001**	**1.15** **<0.001**	**1.16** **<0.001**	**1.15** **<0.001**	**1.15** **<0.001**	**1.16** **<0.001**	**1.15** **<0.001**	**1.15** **<0.001**	**1.16** **<0.001**
Heavier vehicle driver male (ref: female)	**1.28** **<0.001**	**1.27** **<0.001**	**1.32** **<0.001**	**1.32** **<0.001**	**1.31** **<0.001**	**1.32** **<0.001**	**1.32** **<0.001**	**1.32** **<0.001**	**1.28** **<0.001**	**1.28** **<0.001**	**1.27** **<0.001**	**1.27** **<0.001**	**1.28** **<0.001**	**1.3** **<0.001**
Curb weight ratio (log heavier / lighter; +0.1)	**1.09** **<0.001**	**1.08** **<0.001**	**1.09** **<0.001**	**1.08** **<0.001**	**1.09** **<0.001**	**1.09** **<0.001**	**1.09** **<0.001**	**1.1** **<0.001**	**1.09** **<0.001**	**1.08** **<0.001**	**1.08** **<0.001**	**1.08** **<0.001**	**1.08** **<0.001**	**1.09** **<0.001**
Heavier vehicle CG height (+50 mm)	NA	**1.06** **0.03**	**1.04** **<0.001**	**1.03** **0.05**	1.01 0.45	**1.04** **0.003**	**1.04** **<0.001**	**1.04** **0.01**	**1.08** **0.01**	1.04 0.21	1.04 0.18	**1.06** **0.03**	1.04 0.12	**1.07** **0.03**
Partner protection metric (+1 sd)	NA	NA	1.00 0.84	1.03 0.07	**0.94** **0.001**	0.98 0.15	0.98 0.22	**0.95** **0.03**	**0.96** **0.03**	1.03 0.07	0.98 0.25	0.97 0.07	1.00 0.84	**0.93** **0.004**
Heavier vehicle pickup (ref: car)	**1.24** **<0.001**	1.02 0.85	NA	NA	NA	NA	NA	NA	0.96 0.68	1.06 0.58	1.01 0.95	1.00 1.00	1.09 0.45	0.99 0.93
Heavier vehicle SUV (ref: car)	1.03* 0.39	0.9* 0.15	NA	NA	NA	NA	NA	NA	**0.83*** **0.03**	0.91* 0.23	0.87* 0.11	0.87* 0.08	0.92* 0.30	0.88 0.18
Heavier vehicle minivan (ref: car)	0.97* 0.63	0.85* 0.06	NA	NA	NA	NA	NA	NA	**0.77*** **0.01**	0.88* 0.15	**0.82*** **0.04**	0.85* 0.06	0.89* 0.19	0.83* 0.09

p* ≤ 0.05 for difference relative to pickups; estimates with *p*≤0.05 are shown in **bold.

Note: OR = odds ratio, PPM = partner protection metric, sd = standard deviation, VT = vehicle type. PPM abbreviations are shown in Table I.

TABLE AIII

RESULTS OF CONDITIONAL LOGISTIC REGRESSION MODEL ESTIMATING ODDS OF DRIVER FATALITY IN FARS FRONT-TO-FRONT CRASHES RESULTING IN A SINGLE DRIVER FATALITY

	Without vehicle type covariate		**With vehicle type covariate**	
Covariate	**Estimate**	***p* value**	**Estimate**	***p* value**
Curb weight (log; +0.1)	−0.674	<0.001	−0.688	<0.001
CG height (+50 mm)	−0.218	<0.001	−0.029	0.07
Model year (+1)	−0.091	<0.001	−0.088	<0.001
Age (+10)	0.627	<0.001	0.623	<0.001
Male (ref: female)	0.030	0.73	0.055	0.53
Pickup (ref: car)	N/A	N/A	−0.399	0.17
SUV (ref: car)	N/A	N/A	−0.241	0.21
Minivan (ref: car)	N/A	N/A	0.522	0.05

TABLE AIV

RESULTS OF LOGISTIC REGRESSION MODELS ESTIMATING ODDS OF LIGHTER VEHICLE DRIVER FATALITY IN FARS FRONT-TO-FRONT CRASHES RESULTING IN A SINGLE DRIVER FATALITY

	Model (heavier vehicle type or partner protection metric)							
	VT (without h_{CG})	VT (with h_{CG})	I_{BF}	Kw_{400}	EA_{center}	d_{max} (FWRB)	F_{max}	d_{max} (ODB)
Crashes	3,178	3,178	3,178	2,918	2,400	2,984	2,990	1,653
Lighter veh. fatalities	2,446	2,446	2,446	2,249	1,868	2,306	2,304	1,213
PPM sd	NA	NA	99 mm	450 kN/m	13%	62 mm	170 kN	94 mm
Term	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value	OR *p* value
Driver age diff. (heavier − lighter veh.; +10)	**0.54** **<0.001**	**0.54** **<0.001**	**0.53** **<0.001**	**0.53** **<0.001**	**0.53** **<0.001**	**0.53** **<0.001**	**0.54** **<0.001**	**0.54** **<0.001**
Model year difference (heavier − lighter veh.; +1)	**1.1** **<0.001**	**1.09** **<0.001**	**1.1** **<0.001**	**1.1** **<0.001**	**1.1** **<0.001**	**1.1** **<0.001**	**1.1** **<0.001**	**1.08** **<0.001**
Curb weight ratio (log heavier / lighter; +0.1)	**2.23** **<0.001**	**2.05** **<0.001**	**2.04** **<0.001**	**2.00** **<0.001**	**2.14** **<0.001**	**2.08** **<0.001**	**2.03** **<0.001**	**1.98** **<0.001**
CG height diff. (heavier − lighter veh.; +50 mm)	NA	**1.25** **<0.001**	**1.24** **<0.001**	**1.18** **<0.001**	**1.19** **0.001**	**1.17** **0.001**	**1.23** **<0.001**	**1.29** **<0.001**
Partner protection metric (+1 sd)	NA	NA	0.97 0.60	**1.15** **0.04**	0.94 0.47	**0.77** **<0.001**	0.97 0.64	**0.81** **0.01**
Heavier vehicle pickup (ref: car)	**1.62** **0.01**	1.11 0.61	NA	NA	NA	NA	NA	NA
Heavier vehicle SUV (ref: car)	**1.46** **0.01**	1.02 0.92	NA	NA	NA	NA	NA	NA
Heavier vehicle minivan (ref: car)	0.69 0.11	**0.51** **0.01**	NA	NA	NA	NA	NA	NA

Note: OR = odds ratio, PPM = partner protection metric, sd = standard deviation, veh. = vehicle, VT = vehicle type. PPM abbreviations are shown in Table I. Estimates with $p \leq 0.05$ are shown in **bold**.