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Assessing the Impact of Vehicle Weight on Road Safety

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16. Abstract Since 2009, pedestrian fatalities have risen by 80%, which mirrors the increase in the average weight of vehicles accompanying the rising popularity of SUVs and pickup trucks. Additionally, many modern safety and environmental technologies, including those in electric vehicles, contribute to increased vehicle weight. Heavier vehicles generate greater kinetic energy, which can lead to a higher risk of fatalities and serious injuries in crashes. This research synthesis examines the relationship between vehicle weight, design, and safety for road users, particularly pedestrians. However, not all studies find a statistically significant link between vehicle weight and pedestrian injuries, possibly because even lighter vehicles already weigh so much more than pedestrians. Existing research indicates that vehicle design is a more critical factor. For example, the higher front ends of light trucks are more likely to strike a pedestrian's upper body and abdomen, causing more severe injuries than the lower front ends of sedans, which typically impact the legs. Our findings suggest that design changes, such as lowering front-end heights and adding safety features, would be more effective in reducing risks to pedestrians from vehicle crashes.			
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Assessing the Impact of Vehicle Weight on Road Safety

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October 2026

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Executive Summary

Executive Summary

Since 2009, pedestrian fatalities have surged by 80%, a trend that coincides with significant increases in average vehicle weight associated with a shift in consumer preferences towards larger vehicles, such as sports utility vehicles (SUVs) and pickup trucks. Heavier vehicles, due to their greater mass, can cause more fatalities and serious injuries in crashes, particularly affecting vulnerable road users like pedestrians, bicyclists, and users of other micromobility modes. Additionally, the increased weight of these vehicles requires more braking power, making crash prevention more challenging for drivers.

Studies have shown that within a specific speed range, heavier vehicles pose a greater danger than lighter ones. However, some research does not find a statistically significant link between vehicle weight and fatalities among pedestrians and cyclists. This discrepancy may be due to the already substantial weight difference between them and road vehicles. While reducing vehicle weight is one possible solution, research also indicates that braking technology, and the presence or absence of onboard object detection features, are critical factors in vehicle safety and significantly affect crash outcomes. In addition, reducing weight could make vehicle occupants less safe in crashes with heavier vehicles, roadside objects, or in rollover crashes. Higher vehicle power-to-weight ratios, resulting from weight reductions, could encourage speeding, potentially negating safety benefits. Moreover, safety features and environmental technologies, such as those in electric vehicles, often increase vehicle weight, creating a trade-off between enhancing safety and environmental benefits. The relationship between vehicle size and weight further complicates the issue. Larger vehicles, which are typically heavier, have higher front ends that can cause serious injuries to pedestrians and cyclists by impacting the abdomen and upper body, whereas the lower front ends of sedans tend to impact the lower legs. Additionally, light trucks have more blind spots and are more likely to pull pedestrians underneath in a collision. Therefore, design changes that mitigate these safety problems, such as lowering vehicle front ends, shielding the vehicle underside, and incorporating features like windshield airbags, can significantly improve safety.

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Introduction

U.S. pedestrian deaths in road crashes have increased by 80% since reaching a low point in 2009; this pace has been more than twice that of any other country in the Organization for Economic Co-operation and Development (International Transport Forum, 2020). In 2021, pedestrian fatalities in the United States hit a forty-year high with 7,388 pedestrians killed in traffic crashes (National Highway Traffic Safety Administration's National Center for Statistics and Analysis, 2023). This amounts to a rate of more than 20 pedestrian fatalities per day. In addition to pedestrian fatalities, 961 bicyclists were killed in 2021, and around 60,000 pedestrians and 41,000 bicyclists injured in motor vehicle crashes on U.S. public roadways. Pedestrians comprised about 17% of all crash deaths, and bicyclists made up an additional 2% (IIHS HLDI, 2023b). One possible cause of this increase may be due to the increasing size and weight of vehicles on the roadway.

Figure 1 shows the correlation between fatal pedestrian crashes and the sales volume of light trucks, including vans, pickups, and SUVs, sold in the United States. Full-size SUVs are the heaviest class of personal vehicles and are 55% heavier than the average car. Pickups are also heavy — on average 51% heavier than cars (Tyndall, 2024). Although larger, heavier vehicles provide more protection to their occupants and thus have lower driver death rates per registered vehicle than smaller cars (IIHS HLDI, 2023a), research has found increased risk of serious injury or death to pedestrians from impacts with light trucks, which includes trucks, vans, and SUVs, compared with passenger cars (Lefler and Gabler, 2004; Roudsari et al., 2004, 2005).

The increase in pedestrian fatalities coincides with an increase in registrations of sports utility vehicles (SUVs) (Tyndall, 2021). The number of registered SUVs increased 37% between 2009 and 2016 while the number of other registered passenger vehicles decreased by about 1%. Correspondingly, there was an 82 percent rise in the number of SUVs involved in fatal pedestrian crashes, which was larger than the increase in cars, vans, pickups, or medium/heavy trucks involved in such crashes (Hu and Cicchino, 2018).

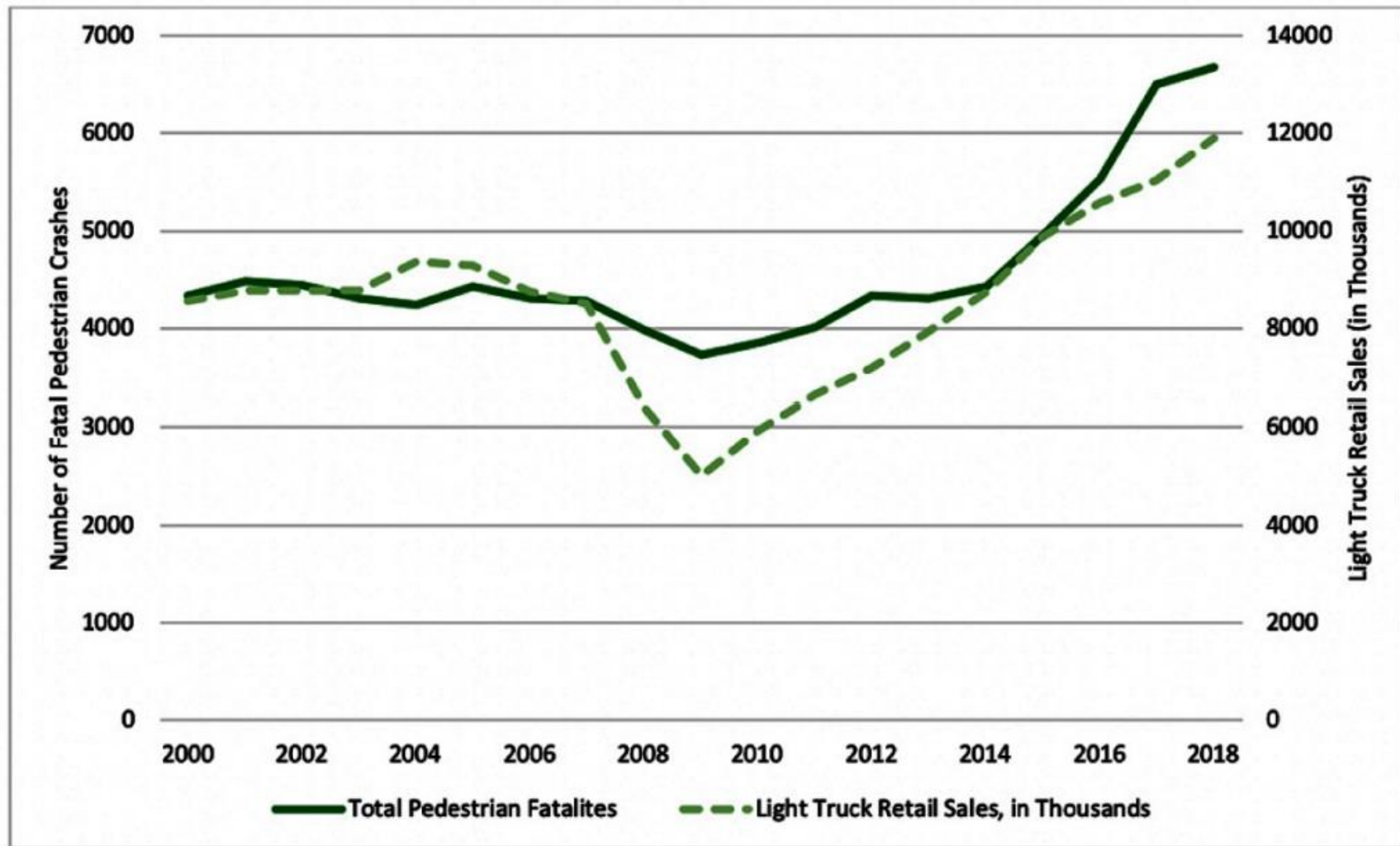


Figure 1. Fatal Pedestrian Crashes and Volume of Light Trucks Sold in the U.S., 2000-2008

Source: Sandt et al., 2020 (copied from Primer on Safe System Approach for Pedestrians and Bicyclists).

U.S. Vehicle Size Classification

In the United States, vehicle weights are governed by the American Automobile Labeling Act that defines a passenger motor vehicle as a vehicle that can carry no more than 12 people and has a gross vehicle weight rating (GVWR)¹ of 8,500 lbs. or less. This includes light-duty trucks and multipurpose passenger vehicles but not motorcycles or delivery trucks (NHTSA, n.d.-a).

The U.S. Environmental Protection Agency (EPA) uses GVWR to categorize vehicles for fuel economy and emissions certifications. Vehicles with a GVWR of less than 8,500 lbs. are considered light-duty while those that are 8501 lbs. and above are considered heavy-duty (Alternative Fuels Data Center, n.d.-a). The Federal Highway Administration (FHWA) classifies all vehicles less than 10,000 lbs. as light-duty with Class 1 vehicles being under 6,000 lbs., and Class 2 vehicles being in the range of 6,001 to 10,000 lbs.

NHTSA categorizes vehicles by curb weight.² Passenger cars are further subdivided into the following sub-categories (NHTSA, n.d.-2).

- Passenger cars mini (PC/Mi) (1,500–1,999 pounds)
- Passenger cars light (PC/L) (2,000–2,499 pounds)
- Passenger cars compact (PC/C) (2,500–2,999 pounds)
- Passenger cars medium (PC/Me) (3,000–3,499 pounds)
- Passenger cars heavy (PC/H) (3,500 pounds and over)
- Sport utility vehicles (SUV)
- Pickup trucks (PU)
- Vans (VAN)

Natural Gas Vehicles (NGVs) and Electric Vehicles (EVs) may exceed the federal maximum gross vehicle weight limit for comparable conventional fuel vehicles by up to 2000 lb. The NGV or EV must not exceed a maximum gross vehicle weight of 82,000 lbs. (Alternative Fuels Data Center, n.d.-b).

¹ Gross Vehicle Weight Rating (GVWR) or gross vehicle mass (GVM) is the maximum weight a vehicle can safely carry when fully loaded, including the vehicle's weight, passengers, cargo, fuel, and trailer tongue weight (*Gross Vehicle Weight Rating (GVWR) Labels* | *California Air Resources Board*, n.d.; Ministry of Transportation and Infrastructure, British Columbia, n.d.).

² Curb weight is the weight of a vehicle with standard equipment including the maximum capacity of fuel, oil, coolant, and air conditioning (NHTSA, n.d.-b).

While the United States defines vehicles as light-duty for weights up to 8,500 lbs. (EPA) or 10,000 lbs. (FHWA), Sweden's cut off for light vehicles (plus trailer, if any) is lower, 3.5 metric tons or 7,716 lbs. (Transport Styrelsen, n.d.) and Australia's is 4.5 metrics tons or 9,931 lbs. (Government of Australia, n.d.; VicRoads, 2024). In addition to defining light vehicles to include vehicles with more mass than in other countries, the United States lacks regulations limiting vehicle weights overall or controlling the proliferation of sports utility vehicles and pickups. Moreover, NHTSA rules focus on the safety of vehicle occupants more than on pedestrian safety; the agency is more proactive on the issue of rollovers in SUVs compared to crash compatibility with lighter vehicles or persons on the ground. Indeed, no federal or state rule governs crash compatibility. Instead, the current NHTSA rule allows major automakers to set their own voluntary standards to improve outcomes in light-duty truck-on-car collisions (Saylor, n.d.).

To summarize, federal control over increasing vehicle size has been lax so far, resulting in significant growth in vehicle weights. NHTSA could, however, regulate vehicle weights through its Federal Motor Vehicle Safety Standards and through the New Car Assessment Program (NCAP).

Vehicle Weight, Speed, and Kinetic Energy

Newton's laws of motion dictate that when two objects collide, the lighter object will bear the brunt of the force from the heavier object. In a pedestrian crash, the force experienced is a direct determinant of the extent of harm to the human body. As such, the vehicle's mass and speed are critical factors in determining the extent of harm caused in a crash. Moving vehicles carry kinetic energy that is transferred to another vehicle, individual, or object in a crash. When the transferred kinetic energy in a crash exceeds the human body's capacity, it will cause an injury. The higher the amount of energy transferred, the more severe the outcome of the crash. The kinetic energy at impact between a vehicle and an individual is primarily due to the vehicle and can be calculated using the equation:

$$KE = \frac{1}{2}mv^2 \quad (1)$$

in which KE is the kinetic energy of the vehicle at impact, m is the mass of the vehicle, and v is the impact speed of the vehicle. While the speed of the vehicle factors much more in the kinetic energy, the mass of the vehicle also clearly plays an important role.

Figure 2 shows the difference in kinetic energy generated at different speeds for vehicles of different weights. While at lower speeds the kinetic energy generated by each is similar, at higher speeds the kinetic energy generated by the heavier vehicle increases at a greater rate. Beyond 40 mph in this figure the forces generated exceed the tolerance of the human body and would be fatal. For individuals hit by a vehicle at speeds less than 40 mph, the minor difference in kinetic energy due to the weight of the striking vehicle makes a difference to the magnitude of injury and probability of death.

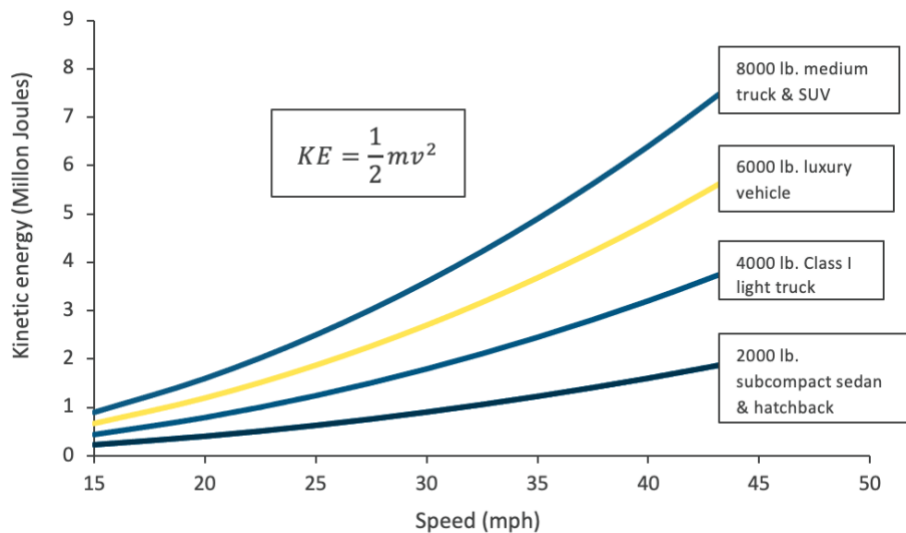


Figure 2. Kinetic Energy Generated at Different Speeds for Vehicles of Different Weights

Trends in Vehicle Sizes: Car Bloat and Weight Creep

Despite the danger posed by larger and heavier vehicles, over the past few decades, average vehicle size and weight have been increasing. Following the enactment of the U.S. Corporate Average Fuel Economy (CAFE) standards in 1975, automakers initially reduced the size and weight of their vehicles to help achieve the required fleetwide averages. However, innovations in technology have since enabled vehicle manufacturers to meet the increasingly stringent fuel economy standards even for their heavier vehicles. There is some evidence that this change has not been responsible for increasing fatalities, at least early in the 2000s. An international study on the effect of fuel economy, age cohorts, alcohol consumption, and quality of healthcare on total fatalities and pedestrian fatalities concluded that changes in vehicle efficiency were not associated with a change in traffic fatalities, suggesting that either the size and weight changes at that time did not have a strong effect on fatalities, or were not associated with fuel economy improvements (Noland, 2005). The author notes a 2002 National Research Council study concluding that many of the efficiency improvements since the 1980s came from improved engine design.

Even with tighter fuel standards, in response to the increasing popularity of larger and heavier passenger vehicles, manufacturers have progressively increased their size, weight and power leading to an “arm’s race” (M. L. Anderson and Auffhammer, 2014; Li, 2012; White, 2004). Over the past 30 years, the average U.S. passenger vehicle has become four inches wider, 10 inches longer, eight inches taller, and 1,000 pounds heavier (IIHS HLDI, 2023c).

In an analysis of vehicles sold between 2000–2007, the National Highway Traffic Safety Administration (NHTSA) found while some lighter makes and models were discontinued due to dwindling sales owing to changes in consumer preferences, many models were redesigned to be heavier and larger than their previous counterparts in 1991–1999, and consumers more often selected stretched versions such as crew cabs in their new vehicle purchases. Additionally, new heavier vehicle types such as crossover utility vehicles have also become prevalent. Improved gas mileage, along with the research showing that heavier vehicles are safer for occupants (Kahane, 1997, 2003, 2012) may have affected consumer preferences (Safety Experts, 2024). As a result, between 2000 and 2007, the average mass of passenger cars increased by 5% while that of pickup trucks increased by 19%. Other types of vehicles became heavier by intermediate amounts. The curb weight of one of the most popular four-door sedan increased by 43% from 1,939 pounds in model year 1985 to 2,766 pounds in model year 2007. A high sales mid-sized sedan grew 41% from 2,385 to 3,354 pounds. A best-selling pickup truck grew 40 percent from 3,390 to 4,740 pounds in the basic 2-door model with rear-wheel drive. A popular minivan grew 31 percent from 2,940 to 3,862 pounds (Kahane, 2012).

Between 2016 and 2021, the average size of vehicles striking pedestrians increased (Tyndall 2024). The median front-end height also increased by 5% (6 cm, 2.4 in.), the median weight grew by 3% (43 kg, 94.8lbs.), and the probability the vehicle was a light truck rather than a car rose by 11% (4.3 percentage points). These larger vehicles are tied to the increasing fatality rates.

Figure 3 shows the share of vehicles over 5,511.5 lbs (2,500 kg) in the United States involved in a fatal crash increased by 11 percentage points from 2000 to 2019. Over the same period, the prevalence of SUVs increased by 59%, and the share of vehicles more than 5,511.5 lbs. increased by 374% (Tyndall, 2021).

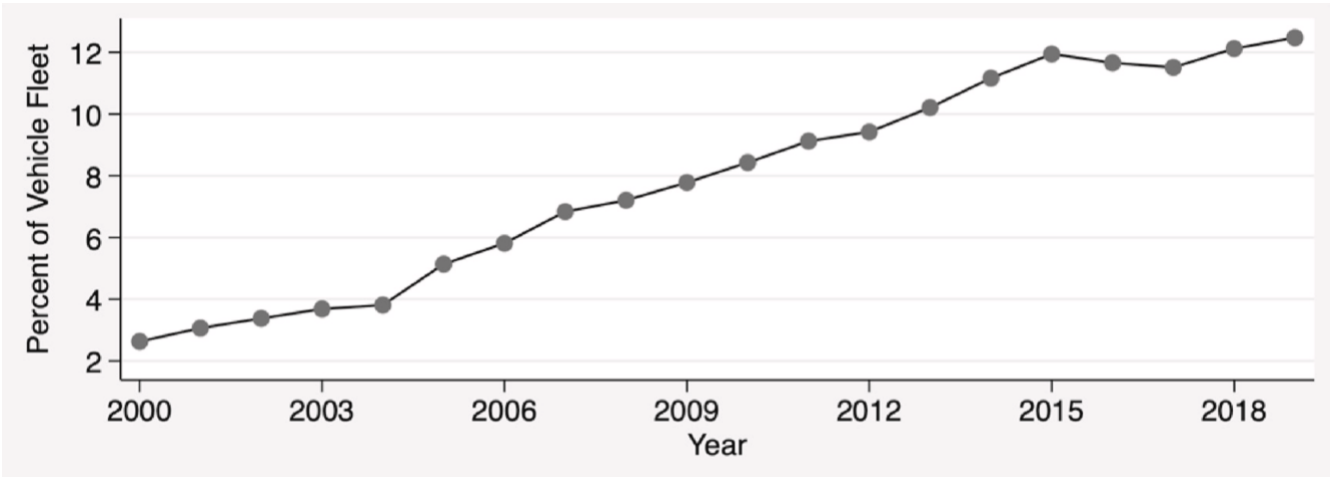


Figure 3. Share of Vehicle Fleet over 5,512 lbs. (2,500 kg)

Source: Tyndall, 2021.

Figure 4 shows the trends in new passenger car and light truck sales in the United States from 1990 to 2022. Passenger car sales have been on a downward trend since the 1990s with a small increase between 1998 and 2000, and from 2009 to 2012. Sales have fallen to almost one-third of the sales in 1990. In comparison, light truck sales have almost doubled since 1990 except for a sharp drop between 2005 and 2009, and a minor drop between 2019 and 2020.

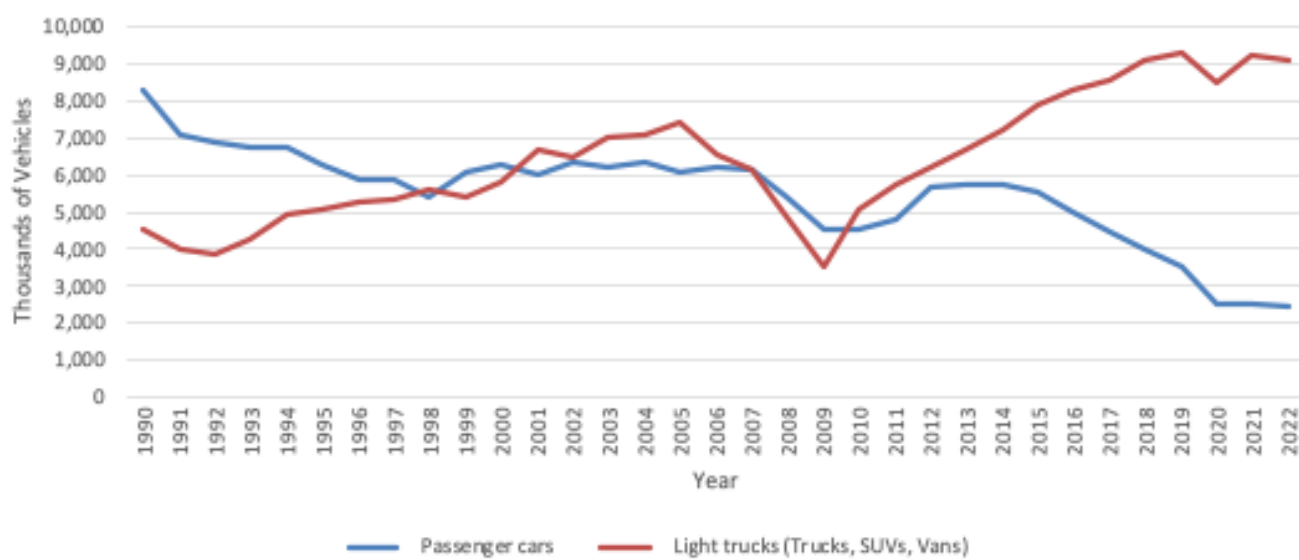


Figure 4. New Passenger Car and Light Truck Sales and Leases

Source: U.S. Department of Transportation, 2024.

Figure 5 shows the market share by vehicle type for the model years 1975 to 2020. SUVs have grown the most to capture two-thirds of the market share of cars and wagons. The share of pickups has remained roughly the same. While the popularity of vans increased between 1980 and 1994, it decreased between 1994 and 2009.

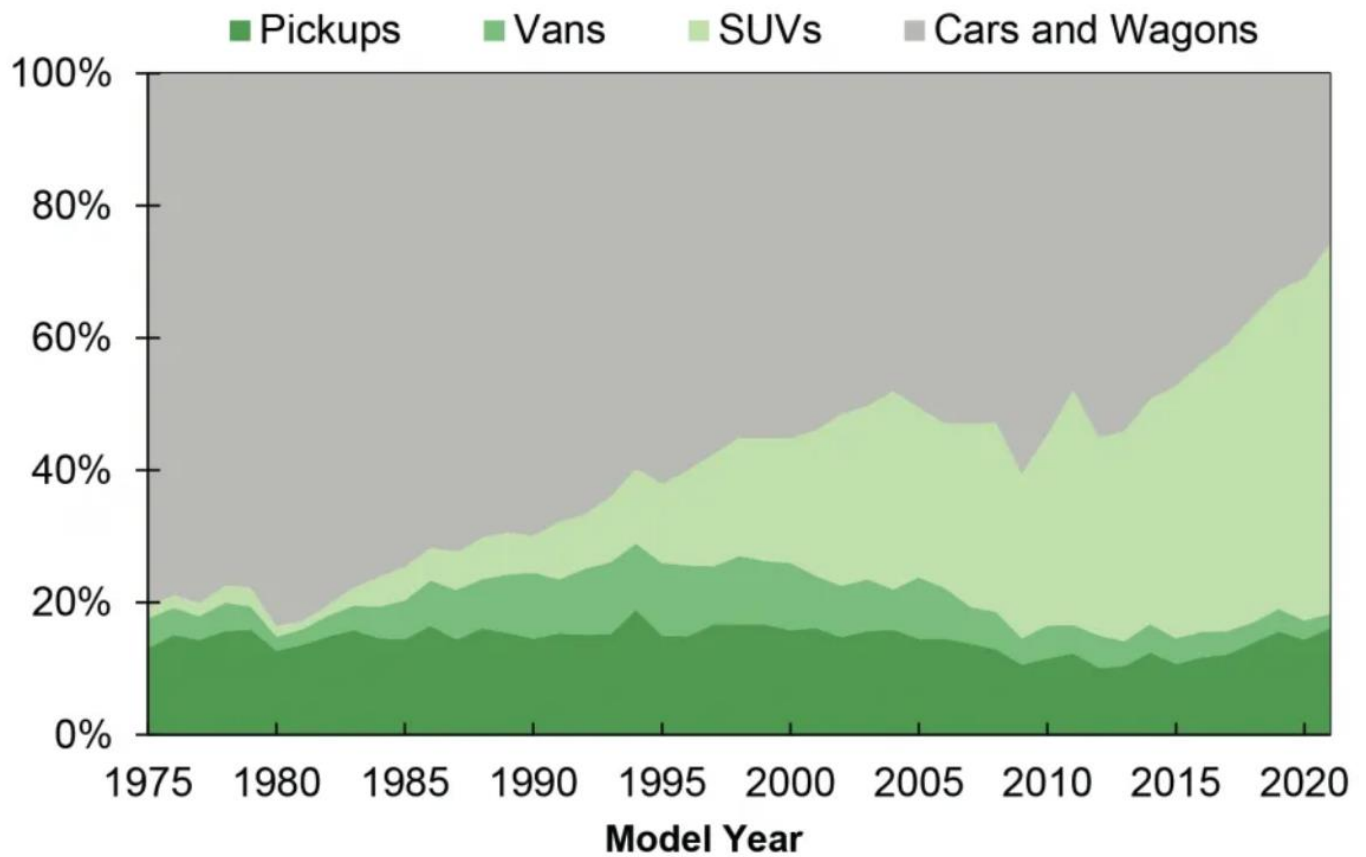


Figure 5. Market Share by Vehicle Type, 1975-2020.

Data source: U.S. Environmental Protection Agency, 2022.

Plot credit: Personal Transportation Factsheet, n.d.

Figure 3 through **Figure 5** summarize the growth in average vehicle weight as the combination of growth in weights of the individual vehicle categories and the share of the heavier vehicles in the market.

Vehicle Factors Associated with Pedestrian Safety

In this section, we discuss the various vehicle factors that are associated with pedestrian safety outcomes. Most researchers agree that all else being equal, reducing vehicle mass would be safer for pedestrians. However, isolating the effect of vehicle mass in studies is challenging as heavier vehicles are usually bigger, and have higher and often more rigid front ends, which increases the risk they pose. Compared to lighter cars, they need more engine power to move at high speeds, and as we discuss below, higher vehicle power-to-weight ratios pose a greater risk of crashes.

Weight and Speed

Some studies show that weight is a factor in pedestrian risk while others find speed to be determinative. For example, one study found that at comparable speeds vehicle curb weight was a significant factor in pedestrian fatalities and serious injuries. But this was true only at lower speeds, where pedestrians struck by sports utility vehicles, pickup trucks, and vans were approximately two times more likely to have traumatic brain, thoracic, and abdominal injuries than those struck by cars; at higher speeds there was no difference (Ballesteros et al. 2004). In another study, vehicle speed was shown to be overwhelmingly responsible for serious injuries to pedestrians in crashes while curb weight was not a statistically significant factor (Tefft, 2013).

A Japanese study found pedestrian death rates linked to both vehicle class (a proxy for weight) and speed, with lighter vehicles at high speeds posing similar risks as heavier vehicles at lower speeds. The risk of death was as high as 5% at impact velocities below 30 km/h (18.6 mph) for light-duty trucks, box vans, and sedans, or at impact velocities under 20 km/h (12.4 mph) for medium-duty trucks, but as high as 10% for heavy-duty trucks at impact velocities of just 10 km/h or less (Matsui et al., 2016). Similar results were obtained in a study comparing passenger vehicles and heavy vehicles (Schubert et al. 2023). Another study concluded SUVs are disproportionately likely to injure and kill pedestrians at crash speeds between 19 to 39 mph (Monfort and Mueller, 2020). Above this range, injuries were likely to be fatal, regardless of the type of vehicle, and below this range, injuries were likely to be minor.

A recent study found that for pedestrian crashes involving a car, the average collision speed was 23.5 mph, while the average crash speed involving a light truck was 21.1 mph (Tyndall, 2024). The author postulated that drivers of larger vehicles might be choosing to drive more slowly to reduce their risk.

Vehicle Size

Larger vehicles tend to weigh more than smaller vehicles and thus vehicle size can serve as a proxy for assessing risk when data on vehicle weights are unavailable. Studies show that the increasing number of larger vehicles on the road poses a greater risk to pedestrians. Light trucks doubled their fleet size from 1980 to 2004. A U.S. study found that every one-percentage point increase in light truck shares raised annual traffic fatalities by 0.34% or 143 deaths per year. Approximately one-fifth of this increase was the light truck's own occupants, and the remaining four-fifths were occupants of other vehicles and pedestrians (Anderson 2008). U.S. crash data from 1995 to 2001 showed that larger vehicles were creating more dangerous road conditions; for every passenger life saved by an individual switching from a car to a light truck (due to it offering more protection), 4.3 fatalities occurred among other drivers, pedestrians, and cyclists (White 2004). Studies by Li (2012) and Anderson and Auffhammer (2014) also conclude that light trucks impose significant risks relative to passenger cars.

Other studies have shown that pedestrians have a two to three times greater likelihood of dying when struck by a light truck or van than when struck by a car (Lefler and Gabler 2004). These vehicles also posed a higher risk of serious head and thoracic injury. Another study comparing conventional cars to light trucks and vans in Maryland between 1995 and 1999 found that pedestrians hit by light trucks were more likely to have more severe injuries and to die of them (Ballesteros et al. 2004). Other studies have found that pedestrians were three times as likely to die when hit by a light truck than by a car (Roudsari et al. 2004), and 50% more likely to die (Desapriya et al. 2010). After adjusting for curb weight along with pedestrian age and impact speed, Roudsari (2004) found that the risk of death for pedestrians struck by light trucks and vans was four times higher, while greater curb weight did not increase the risk of death.

Studies of U.S. traffic fatalities estimated that replacing all light trucks with cars would have reduced annual pedestrian deaths by 460 during 2019 (Tyndall, 2021), and by 1,179 in 2021 (Tyndall, 2024). The later study found that compact SUVs increase the probability of death by 63%, pickups increase the probability by 68%, and full-size SUVs increase the probability by 99%. While it did not find a statistically significant difference in pedestrian deaths between cars and vans, it did find vans to be over-represented among minor crashes. Edward and Leonard (2022) examined crash and hospital record data in Chicago and found that while pickups were involved in 6% of pedestrian and pedalcyclist crashes combined, they were involved in 13% of fatalities. SUVs were involved in 15% of such crashes but 25% of fatalities.

Tamura et al. (2008) found that the average traction force produced in cervical spinal cord injuries exceeded 50 Newtons (N) in impacts involving SUVs and 25 N in impact involving a sedan in a 50th percentile American male pedestrian model, when the striking vehicle was traveling at 40 km/h.

Vehicle Manufacturing and Design

Vehicle manufacturing quality and design also plays a significant role in crashworthiness. Kahane (2003) studied the influence of the vehicle make (nameplate) and new vehicle price on the fatality rates of pedestrians, bicyclists, and motorcyclists involved in crashes and found some makes to be significantly more likely to be involved in fatal pedestrian crashes, without regard to vehicle weight. However, he postulates safer drivers selecting brands with a better image for safety, rather than superior manufacturing, was responsible.

Edwards and Leonard (2022) examined hospital records for fatal and non-fatal pedestrian crashes and found light trucks to be over-represented in fatal crashes by 69%. As shown in **Figure 6**, another found that except for minivans, larger vehicles with heavier masses had more pedestrian fatalities per 1000 reported single vehicle-pedestrian crashes (Lefler and Gabl, 2004).

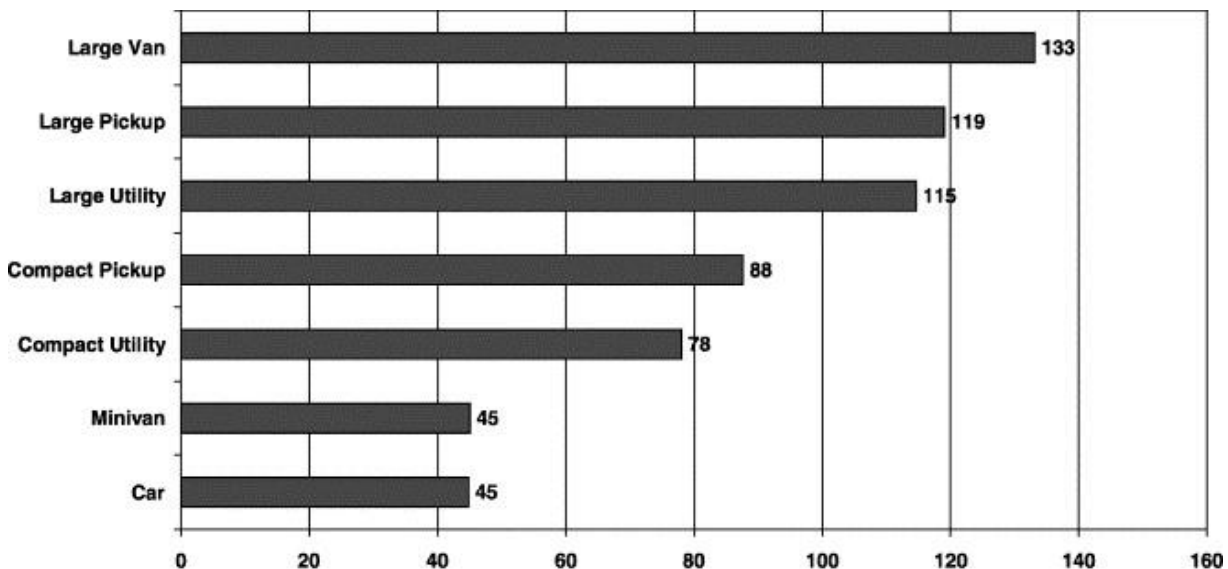


Figure 6. Pedestrian Fatalities/1000 Reported Single Vehicle-Pedestrian Impacts Fatality Analysis Reporting System/General Estimates System 1995-2000

Source: Lefler and Gabler, 2004.

However, the authors hypothesize that the differences in pedestrian fatalities may not be due to the mass of the striking vehicle even though some light trucks are much heavier than cars. Along with other researchers they theorize that because both cars and light trucks are much heavier than pedestrians, pedestrians are at a severe disadvantage in any vehicular crash regardless (Lefler & Gabler, 2004; Niebuhr et al., 2016; National Transportation Safety Board, 2018; Tyndall, 2024).

Mizuno and Kajzer (1999a) studied the rate of pedestrian fatalities in Japan for different sizes of cars striking pedestrians at different velocities and found that vehicle weight for *bonnet-type* cars (in which the vehicle front projects out substantially from the main body off the vehicle) weighing up to 1400 kg (3000 lbs.) did not affect

the outcome but deaths rose rapidly for heavier vehicles especially at higher speeds as shown in **Figure 7**. Both Lefler and Gabler (2004) and Mizuno and Kajzer (1999a) attribute the differences in pedestrian fatality rates to differences in the design of the heavier vehicle's front ends, primarily SUVs. In their study of crashes in Japan, Mizuno and Kajzer (1999a) examined the characteristics of *one-box* vehicles (in which the front end does not project out from the main body of the vehicle) and bonnet-type vehicles. They concluded that the one-box vehicles become “dangerous” at slower speeds (23.7 km/h) than bonnet-type sedans (26.2 km/h). In addition, the probability of a pedestrian dying when struck by a one-box (4.76%) is higher than with a bonnet-type car (3.91%). A later study in Japan also finds that despite their lighter weight, box vans impact pedestrians with just as much force as heavier vehicles such as light-duty, medium-duty, and heavy-duty trucks. However, the study does not differentiate between the effects of the mass of the vehicle and its greater stiffness or structural rigidity (Matsui et al., 2016).

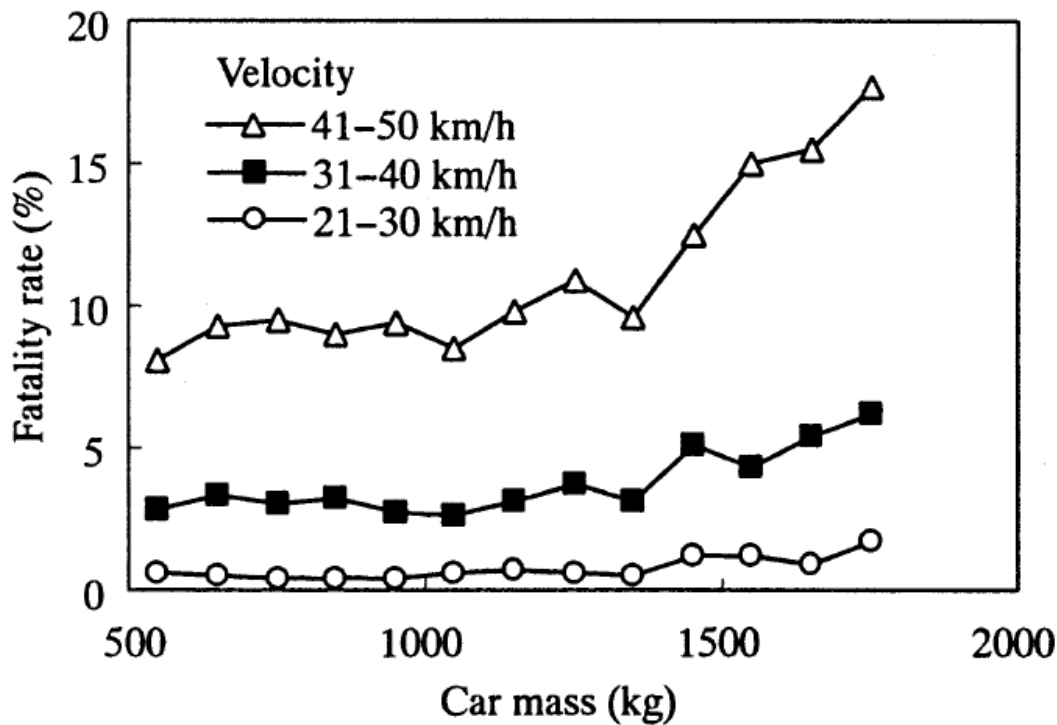


Figure 7. Pedestrian Fatality Rate and Car Mass Classified by the Velocity Recognized to be Dangerous for Bonnet Type Cars

Source: Mizuno and Kajzer, 1999b.

Insurance Institute for Highway Safety Highway researchers have determined that tall and blunt vehicles primarily inflicted torso injuries with their front ends rather than with the tops of their hoods. They were more likely to injure pedestrians by throwing them forward, while tall and sloped vehicles usually rolled them onto the hood of the vehicle first. In its 2018 study on pedestrian safety, the National Transportation Safety Board recommends changes in vehicle design and features, but it does not mention weight reduction (National Transportation Safety Board, 2018).

Focusing on the height of the vehicle front, Tyndall (2024) finds a highly significant relationship between vehicle weight and pedestrian death risk: a 100 kg increase in vehicle weight leads to a 6.6% increase in the probability that the pedestrian will die. Moving from the 25th percentile (1,452 kg) to the 75th percentile (1,981 kg) in average vehicle weight increases the pedestrian death risk by 35%. However, controlling for body type reduces the estimated effect of weight by 20% and the effect is no longer significant at the 5% level. However, differences in front-end height remained a significant risk factor.

A simulation study of various vehicle types by Simms and Wood (2006) based on real world crash data concluded that the difference in mass between cars and SUVs was *not* a significant factor in causing pedestrian injuries, but the height of the bumper and hood was. The shape of SUVs resulted in higher pedestrian injuries to the mid-body regions compared to passenger cars. Due to the higher front profile of SUVs, pedestrians are more likely to be struck in the body's center of mass, causing significant abdominal and internal injuries. The authors found head injuries from being hit by SUVs to be the same or slightly less likely as from cars. However, their data showed that the secondary impact with the ground is more severe in SUV impacts compared to cars. In their study on head injuries caused by ground impact, Yin et.al. (2017) note that not considering vehicle weight was not a limitation of their study as it does not play a role in pedestrian kinematics (the study of how objects move independent of the forces causing the motion).

Vehicle Power

While the discussion has mostly centered around the significance of vehicle weight and the effect of other factors such as vehicle height, in this section, we discuss how increased engine power for the same vehicle weight vastly increases the kinetic energy involved in crashes and results in more fatalities. McCartt and Hu (2017) found that the increases in vehicle power-to-weight ratios were associated with increased speeds and odds of speeding, and the relation between speeding and injury is well established (Leaf et al., 1999; Lubbe et al., 2022; Tefft, 2013). Hu and Cicchino (2018) found that the power of passenger vehicles involved in fatal pedestrian crashes increased during 2009-2016, with vehicle makes having the most power to begin with recording larger increases in vehicle power. Kahane's (2012) finding that smaller and lighter vehicles are driven "less well" than heavier ones also suggests that vehicles with high power-to-weight ratios may be susceptible to greater instances of speeding.

Figure 8 shows the trends in vehicle weight, horsepower, fuel economy, and footprint (the total area between where the tires contact the ground) between model years 1975 and 2022. As the CAFE standards were rolled out, car makers had to boost fuel efficiency by almost 50 percent in a very short time period. They achieved this mostly by making their vehicles smaller and lighter. As noted above, following that initial reduction in vehicle weight and horsepower between 1975 and the early 1980s, both have been increasing along with improved vehicle fuel economy. Technological innovation and changing market trends have resulted in the average new vehicle fuel economy growing 35% even while horsepower has risen 23% and weight increased 5% since model year 2004. The average vehicle footprint has also increased 8% since the EPA began tracking it in model year 2008.

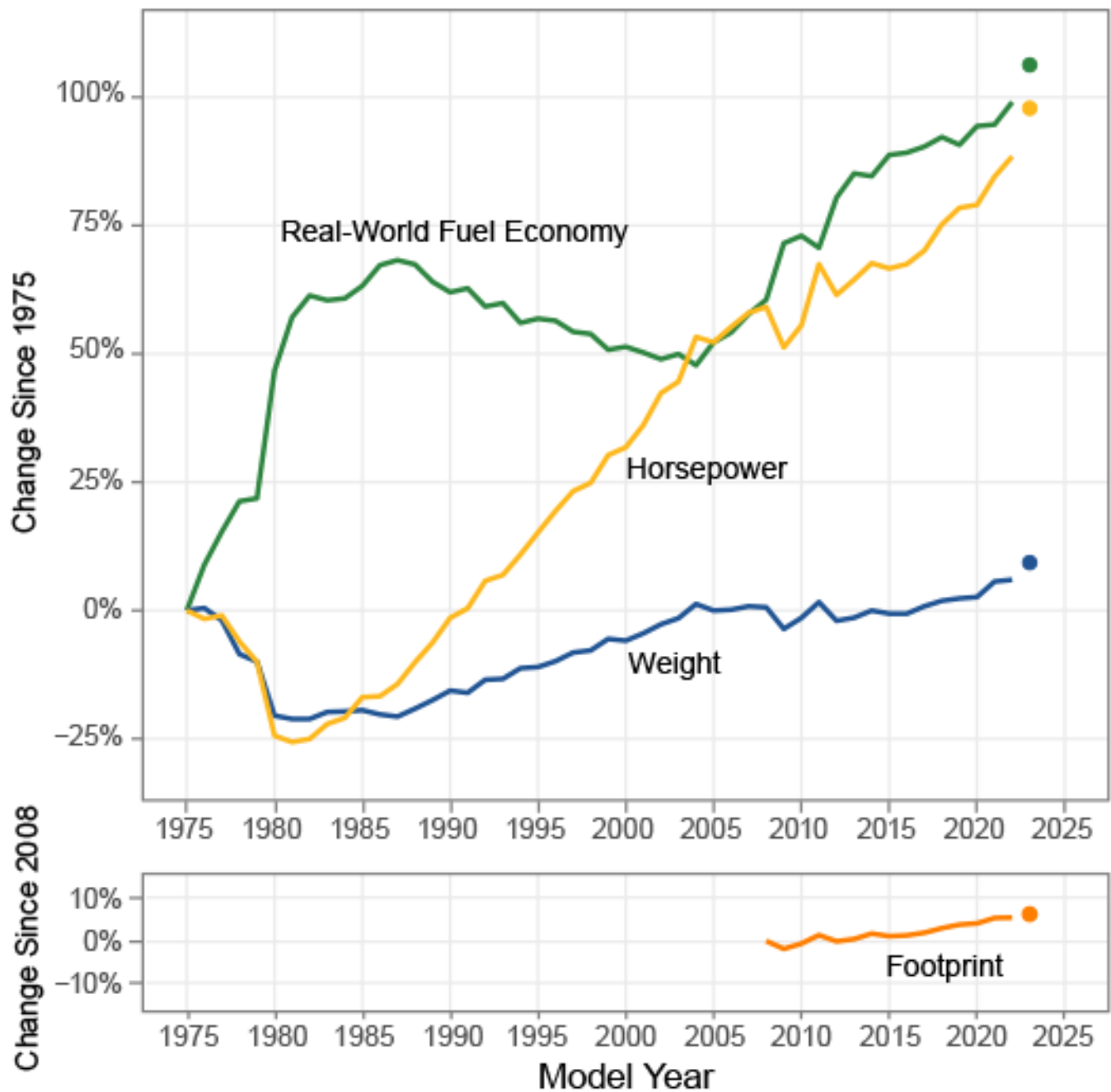


Figure 8. Trends in Vehicle Weight, Horsepower, Fuel Economy, and Footprint

Source: U.S. EPA, 2016.

Consequences for Vulnerable Road Users and Others

In this section, we discuss how the factors identified above, vehicle size, weight, design, power and speed affect crash victims. First, we look how the size and shape of vehicles may lead to more serious injuries. Then we consider the impact on crashes involving motorcyclists. We then look at the risks to vehicle occupants, and finally the potential for damage to road infrastructure and their impact on risky driving behavior.

Serious Injuries

Roudsari et al. (2004) find that taller vehicles are more likely to cause serious head injuries. Edward and Leonard (2022) find evidence that those struck by larger vehicles had more serious injuries resulting in higher hospital bills. Monfort and Mueller (2020) find that crashes involving an SUV were more likely to result in serious injury than those involving cars. While their study proposes that SUVs can cause more harm to pedestrians because of their greater weight and larger profile, in a subsequent review of a report by the Insurance Institute for Highway Safety (IIHS) examining 71 vehicle-cyclist crashes the authors argue that the injuries were most likely due to the higher front-end design of SUVs compared to cars (Monfort and Mueller, 2023). White (2004) finds that if a light truck rather than a car hits a pedestrian or bicyclist, the probability of fatality rises by 82%, but the probability of serious injury only rises by 12%. On the other hand, Tyndall (2024) finds no evidence that larger vehicles result in more serious injuries among crash survivors despite higher rates of pedestrian hospitalization in contrast to research showing that vehicle size has more impact on the chances of pedestrian survival than the severity of injury.

Effect on Cyclists

Researchers have also studied the outcome of crashes between larger and smaller vehicles and cyclists (Kahane, 1997, 2003; White, 2004; Kahane, 2012; Edwards and Leonard, 2022). White (2004) finds the probability of a cyclist fatality rising by 125% on being hit by a light truck rather than a passenger car, and the probability of serious injury rising by 12%. The IIHS study mentioned in the preceding section concluded that crashes involving an SUV were more likely to result in serious injury than those involving cars. The report argued that results were likely driven by the higher front-end design of SUVs relative to cars (Monfort and Mueller, 2023). Tyndall (2024) finds that larger vehicles may present similar dangers to cyclists as to pedestrians — a cyclist hit by a light truck is 99% more likely to die than when hit by a car — but cyclist survival rates are much higher. Additionally, he finds that pickup trucks have the largest effect, with cyclists 291% more likely to die when struck by a pickup rather than a car. In contrast to pedestrian crashes, he finds the effect of increased weight to be more significant than the increase in vehicle front height— a 100 kg increase in vehicle weight increased the cyclist death rate by 7.4% but a 10 cm increase in vehicle front height did not have a

statistically significant effect. He concludes that his estimates suggest that larger vehicles are perilous for cyclists, but that the limited range of the data means that the results should be interpreted with caution.

Implications for Vehicle Occupants

While the focus of this synthesis is the effect of vehicle weight on pedestrians and other vulnerable road users, in this section we conduct a preliminary review of the effect of vehicle weight in two-vehicle, rollover, and vehicle-object crashes. Since car occupants comprise 60% or more of fatalities due to car crashes in the United States, policies for improving pedestrian safety must also be beneficial or neutral to the safety of car occupants. Also, as noted previously, despite mass being an important component of kinetic energy, few studies find the mass or weight of the vehicle to be a significant determinant of the crash outcome because of the magnitude of the difference between the weight of the vehicle compared to the weight of the those struck. This makes an additional case for investigating the effect of vehicle weight in crashes that do not involve vulnerable road users.

Size and Weight

Studies find the mass of the vehicle is the main cause of driver fatalities in two-car crashes regardless of the length of the vehicles' wheelbases. As the speed change each vehicle would undergo following a crash is inversely proportional to its mass, it follows that the heavier vehicle provides more protection to its occupants when it strikes another vehicle, or any other object irrespective of its size or shape (Evans and Frick, 1992; IIHS, 2023a). However, Evans and Frick also find that a 4% larger wheelbase would generate about a 10% lower driver fatality risk. This finding is corroborated by other authors who noted that: "For vehicles using the same roads ... suggest a crashworthiness design concept for intervehicular crashes that regards increases in vehicle sizes as primarily protective and increases in vehicle weight as primarily hostile increases indicating the desirability of relatively sizeable but not heavy vehicles" (O'Neill, Joks, and Haddon, 1974 as cited in Evans and Frick, 1992). Joks finds that in a two-vehicle collision, the controlled fatality risk for the car driver increases with the weight of the striking vehicle, the height of its center of force, and the stiffness of its front end, as measured in crash tests (Joks, Hans C., 2000). Other studies corroborate this result (Van Aken and Zellner, 2005).

Multiple studies have considered the effect of reducing vehicle size and weight to conform to CAFE standards. NHTSA conducted research on vehicle mass, safety, and fatality risk to both pedestrians and vehicle occupants for vehicles ranging between model year 1985 to 2010. The analysis, conducted by Kahane (1997) and reported by the National Academy of Sciences, determined that in 1993, between 1,300 and 2,600 additional fatalities could be attributed to the downsizing and down weighting respectively since the 1970s. These findings were challenged by several studies. A 2003 analysis conducted with model years 1991 to 1999 passenger cars and calendar year 1995 to 2000 crash data revealed that, holding vehicle size (measured by footprint) constant, reducing vehicle mass in lighter cars would significantly increase fatality risk while the same decrease in heavier vehicles would significantly reduce fatalities by lowering the risk to the occupants of

the lighter cars (Kahane, 2003). Research published between 2003 and 2005 by Dynamic Research, Inc. concluded that while reducing vehicle mass improved safety and shortening the wheelbase and track length (distance between the wheels on the same axle) reduced safety, the two cancelled each other out (Van Auken and Zellner, 2005). Both studies found significant harmful effects of reducing vehicle size.

The principal limitation of Kahane's analysis is that it does not deal separately with size and weight. It also is based on old crash data (1985–93). For example, trends in the mid- and late-1990s show that the tendency for the lightest cars to be unsafe in rollovers declined sharply (see below). We also note that Kahane did not account for whether restraints (seat belts and/or airbags) were used. Subsequent analysis with data for model year 2000–2007 cars, light trucks and vans in calendar year 2002–2008 crashes revealed that, again while holding vehicle footprint constant, reducing mass by 100 pounds would cause a 1.56% increase in fatalities for cars weighing less than 3,106 pounds, which was statistically significant, but that the same weight reduction in heavier vehicle categories were insignificant (Kahane, 2012). Kahane concludes that the results of this analysis do not raise a red flag against reducing vehicle mass.

Ross and Wenzel (2001) demonstrate that in a crash between vehicles, heavier vehicles may provide additional protection to their own occupants, but this comes at the expense of the occupants of the vehicles with which they collide. Evans and Frick (1992) find that car mass and not car size, represented by wheelbase, has greater influence on fatality risk to car occupants. Jehle et al. (2021) find that in crashes between SUVs and passenger cars, the occupants of the passenger car fare worse regardless of the relative safety rating of the two vehicles due to differences in weight and bumper height.

Some studies find that reducing weights of the heaviest vehicles would increase safety. Noland (2004) finds that variance in vehicle weights may be more important than absolute weight of a vehicle. This finding is supported by NRC (2002) which suggests that the adverse safety effects of reducing vehicles weights, or producing more small cars would be minimized or even reversed if weight and size reductions were limited to heavier vehicles, particularly those over 4000 lbs. as that would eliminate the most damaging vehicles from the fleet.

Rollovers

Since the mid-and late 1990s, the tendency of the lightest cars to be unsafe in rollovers has declined sharply with improved design resulting in lower center of mass, wider track width, and stiffer suspension. Some small traditional SUVs, such as the Ford Explorer Sport have high rollover propensity and low rollover crashworthiness, and as such, are less safe compared to passenger cars. Yet small car-based light-trucks such as the PT Cruiser (classified as a light truck for fuel economy purposes, discontinued since 2010) were considerably safer than any traditional SUV, regardless of the impact of ground clearance requirements on the vehicle's center of gravity. Additionally, electronic stability control has further prevented rollovers in vehicles.

Safety Impacts on Road Infrastructure and Driving Behavior: Braking, Visual Effect, Reckless Driving

Besides the detrimental effect of heavier vehicles in two-vehicle crashes and crashes with pedestrians and cyclists, they are also detrimental to road safety infrastructure. The Midwest Roadside Safety Facility at the University of Nebraska-Lincoln conducted crash tests on guardrails using EV cars and trucks. They found that guardrails and barriers previously tested with internal combustion engine cars and pickup trucks might not be adequate for some heavier EVs (Nebraska Today, n.d.). Emerging technologies such as pedestrian crash prevention systems are more effective at mitigating pedestrian crash severity or in preventing crashes for lighter vehicles as it is possible to decelerate with less braking force (Mahdinia et al., 2022). Moradloo et.al. (2024) found, in an analysis of California Department of Motor Vehicles automated vehicle disengagement data, that disengagements happen more in automated SUVs and vans than in passenger cars. This could possibly be an effect of greater vehicle weight in automated vehicles.

Two studies observed that heavy goods vehicles appear to travel more slowly, and as such vulnerable road users might make riskier decisions around them (Petzoldt, 2016; Fabricius et.al., 2022). On the other hand, another study found that these vehicles also look more threatening, causing pedestrians and cyclists to leave more space for crossing in front of them (Petzoldt, 2017). Further research could determine if these observations could be extrapolated to light trucks and vans.

Tyndall (2023) hypothesizes that full-size SUVs marketed for their ruggedness match driver behavior or are selected by drivers who seek such an image. He also found that males are involved in a much larger percentage of crashes (Tyndall, 2024). The association of the size and weight of a vehicle with greater power could be a factor in promoting reckless driving.

Conclusion

Kinetic energy, a product of mass and speed, plays a critical role in vehicular safety and the severity of collisions. As a result, research indicates that even light trucks are more damaging in crashes involving vulnerable road users than automobiles. However, most studies attribute this increased severity to the design and the height of the front end of the vehicle rather than simply to its greater weight. On the other hand, heavier trucks are not necessarily likely to pose proportionately greater risks. This complexity arises because the mass of the vehicles substantially exceeds that of the crash victims, meaning that differences in vehicle weight alone are not indicative of the potential severity of injuries.

In crashes involving two vehicles, the difference in weight *does* emerge as a statistically significant factor alongside other size variables such as the relative height of the bumper. The consensus among the studies we reviewed is that reducing the weight of the heaviest vehicles in the fleet could enhance overall safety by decreasing weight variance. Furthermore, advancements in vehicle design, such as wider tracks and the implementation of Electronic Stability Control have mitigated the rollover propensity of the lightest cars, addressing previous safety concerns over reducing the weight of vehicles.

The power-to-weight ratio influences a driver's propensity to speed, with lighter vehicles potentially being more hazardous due to their quick acceleration. The impact of vehicle weight on vulnerable road users is particularly pronounced within specific speed ranges for different types of vehicles. Above this range, crashes tend to be fatal regardless of the vehicle's weight, while at slower speeds, crashes usually result in minor injuries. Within this critical speed range, heavier vehicles pose a greater danger.

The advent of electric vehicles, which are generally heavier than their gasoline counterparts due to the weight of batteries and additional electronic safety features, introduces new challenges. Ongoing research into advanced materials and technologies aims to reduce vehicle weight while maintaining safety and sustainability. This area of study holds promise for improving the overall safety profile of future vehicles without compromising their ecological benefits.

In conclusion, while mass and speed together determine kinetic energy and consequently the severity of collisions, the design and structural elements of vehicles also play crucial roles. Future research and development should focus on optimizing these factors to enhance safety for all road users, particularly in the evolving landscape of vehicle technology.

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