Causal Influence of Car Mass and Size on Driver Fatality Risk

Leonard Evans, DPhil

ABSTRACT

Objectives. This study estimated how adding mass, in the form of a passenger, to a car crashing head-on into another car affects fatality risks to both drivers. The study distinguished the causal roles of mass and size.

Methods. Head-on crashes between 2 cars, one with a right-front passenger and the other with only a driver, were examined with Fatality Analysis Reporting System data.

Results. Adding a passenger to a car led to a 14.5% reduction in driver risk ratio (risk to one driver divided by risk to the other). To divide this effect between the individual drivers, the author developed equations that express each driver's risk as a function of causal contributions from the mass and size of both involved cars. Adding a passenger reduced a driver's frontal crash fatality risk by 7.5% but increased the risk to the other driver by 8.1%.

Conclusions. The presence of a passenger reduces a driver's frontal crash fatality risk but increases the risk to the driver of the other car. The findings are applicable to some single-car crashes, in which the driver risk decrease is not offset by any increase in harm to others. When all cars carry the same additional cargo, total population risk is reduced. (*Am J Public Health.* 2001;91:1076–1081)

More than 25 years ago, research established that drivers of larger, heavier cars have lower risks in crashes than drivers of smaller, lighter cars.[1–5] The question of how adding mass to an existing car affects safety, however, has remained unanswered. One common way to express this question is "Am I safer if I put bricks in my trunk?" Although kinematic considerations[6,7] suggest an answer, no empirical studies have been done. Data sets rarely contain information on cargo or on actual mass during crashes. Generally, only curb mass, identical for all cars of the same make and model, is coded. Information is available on occupants, however.

By interpreting the addition of a passenger to be equivalent to the addition of cargo, the present investigation estimated how adding mass to existing cars affects driver fatality risk. The investigation used 1975 to 1998 Fatality Analysis Reporting System data[8] to examine head-on crashes between 2 cars. One car contained only 1 occupant, a driver, whereas the other contained a right-front passenger also. If all other factors are the same, the masses of the cars differ only by the mass of the passenger.

The results contributed to the development of an equation that distinguishes between causal contributions from mass and size. The many relations that are reported between fatality risk and car mass[1–7,9–24] and between fatality risk and car size[3,9,10,17–26] cannot distinguish between such causal contributions, because mass and size are so highly correlated.[19] The equation derived expresses the risk to a driver as a function of the size and mass of both involved cars.

Methods

The method of deriving relative risk in 2-car crashes, from an earlier study,[11] is described briefly in this section. From a formal perspective, the cars involved in a 2-car crash can be considered to play symmetrical roles: they crash into each other.

For every crash between 2 cars of known mass—car$_a$ and car$_b$—we can define a mass ratio, μ, as

$$\mu = \frac{\text{mass of car}_b}{\text{mass of car}_a} \tag{1}$$

and a driver fatality risk ratio, R, as

$$R = \frac{\text{probability of driver fatality in car}_a}{\text{probability of driver fatality in car}_b}. \tag{2}$$

Earlier studies[10,12,19] found that

$$R = \mu^u \tag{3}$$

fitted well the data for many categories of 2-car crashes. For the case of interest here, cars crashing head-on into each other, the value of the parameter u is 3.58 (Figure 1). Equation 3 applies to cars that are not differentiated by any attribute other than mass, so, by definition, $R = 1$ when $\mu = 1$. The relation is thus constrained to pass through the point $\mu = 1$, $R = 1$. Fitting data to equation 3 yields only 1 parameter, u.

When cars of the same mass crash into each other, equation 3 provides no useful information. However, 5 sets of data[9,10] and a calculated relationship[7] support (Figure 2) that the relative driver risk, R_{MM}, when 2 cars of the same mass, M, crash into each other is given by

$$R_{MM} = \frac{c}{M}, \tag{4}$$

where c is a constant.

At the time of the study, the author was with the Vehicle Analysis and Dynamics Laboratory, General Motors Research and Development Center, Warren, Mich.

Requests for reprints should be sent to Leonard Evans, DPhil, President, Science Serving Society, 973 Satterlee Rd, Bloomfield Hills, MI 48304-3153 (e-mail: le@scienceservingsociety.com).

This article was accepted August 22, 2000.

Equations 3 and 4, and their associated applications in Figures 1 and 2, may be regarded as 2 “laws” of 2-car crashes; both refer only to relative risk. Later, they contribute to an equation to estimate risks to individual drivers.

If the cars are differentiated by an attribute other than mass (e.g., car_a is old, and car_b is new), then the value of R when $\mu=1$ in equation 3 measures the influence of car age on fatality risk. The earlier study[11] found that the relation

$$R = A\mu^{u} \tag{5}$$

fitted well such cases; the parameter A estimates the influence of the attribute when the masses are equal. In the present application, the cars differed in the attribute that car_a contained a passenger and car_b did not.

Data

Two-car crashes satisfying the following criteria were extracted from Fatality Analysis Reporting System[8] data for 1975 through 1998:

- One car had a driver and a right-front passenger, whereas the other had only a driver.
- Cars were involved in frontal crashes only, defined as a principal impact point[8] at the 11-o’clock, 12-o’clock, or 1-o’clock position for both cars.
- At least 1 of the drivers was killed (crashes in which the passenger was the only fatality were excluded).
- All 3 occupants were coded as unbelted.

This filtering process produced a sample of 3118 crashes. Each of the 15 points plotted in Figure 3 uses at least 200 crashes.

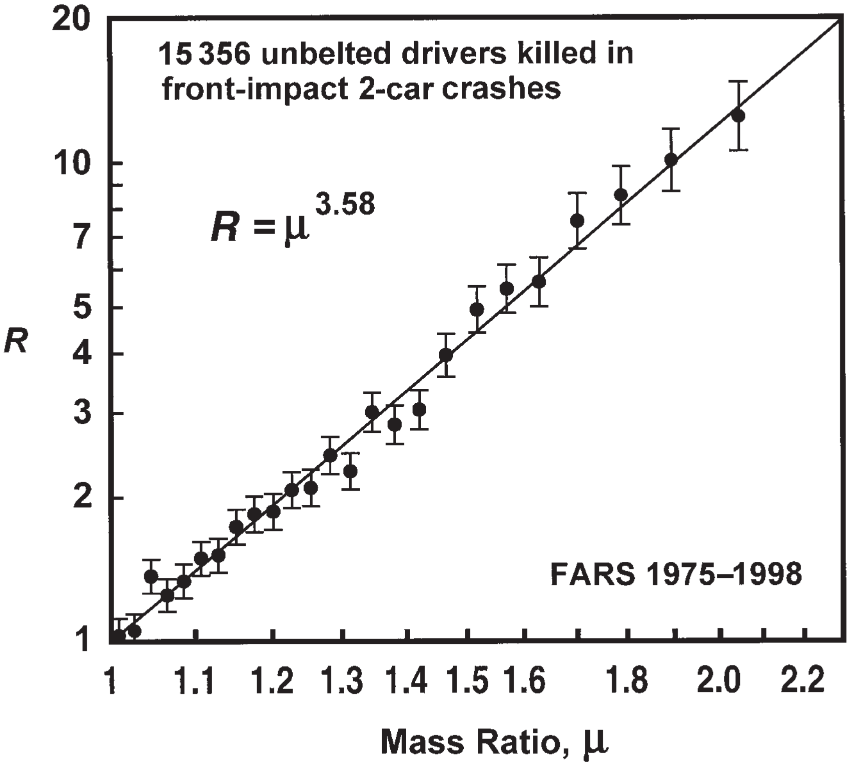
Results

The line in Figure 3 is a weighted least squares fit to

$$\text{Ln}(R) = \text{Ln}(A) + u\,\text{Ln}(\mu)\,, \tag{6}$$

the natural logarithm (logarithm to base e) transformation of equation 5.

The fit gives $u=3.36\pm0.10$ and, more central to the present study, $A=0.855\pm0.023$. It is convenient to discuss A in terms of $\Delta R=100(A-1)/R$, the percentage change from the $R=1$ value. The finding from Figure 3 is that the presence of a passenger gives $\Delta R=-(14.5\pm2.3)\%$. This effect arises from an undetermined decrease in the accompanied driver’s risk and an undetermined increase in the lone driver’s risk. None of the equations above apply to adding mass to existing cars. They are all based on data in which heavier cars are larger.



Note. The relation is the first of the 2 “laws” of 2-car crashes. FARS = Fatality Analysis Reporting System.[9]

FIGURE 1—The ratio, *R*, of driver fatalities in the lighter compared with the heavier car vs the ratio, μ, of the mass of the heavier to the mass of the lighter car for frontal crashes (both cars with principal impact point at 11, 12, or 1 o’clock).

Calculation of Intrinsic Mass and Size Effects

When 2 cars—car_1 and car_2—of curb masses m_1 and m_2 crash into each other, the first of the 2 “laws” (equation 3) gives

$$R = \left(\frac{m_2}{m_1}\right)^{u}, \tag{7}$$

where R=the risk in car_1 divided by the risk in car_2. In what follows, m_1 generally will be larger than m_2, so R will be less than 1.

Next, driver risks are compared in the following 2 crashes. The first crash is between 2 cars of equal mass m_1. The second is between 2 cars of equal mass m_2. The second “law” (equation 4) gives

$$\frac{\text{risk when 2 } m_1 \text{ cars crash into each other}}{\text{risk when 2 } m_2 \text{ cars crash into each other}} = \frac{m_2}{m_1} \tag{8}$$

When 2 bodies of the same mass crash into each other, Newtonian mechanics shows that the value of the mass does not affect their postcrash trajectories. Thus, although equation 8 is expressed in terms of mass, the causal effect is intrinsically one of size.

The relations above suggest expressing the risk, r_1, faced by the driver of car_1 in collisions with car_2 as

$$r_1 = \frac{k}{(m_1 + m_2)} \times \left(\frac{m_2}{m_1}\right)^{t}, \tag{9}$$

where k is an arbitrary scaling constant and t is a parameter. Choosing k=2800 kg leads to the convenience of a driver risk of 1 for the base case of 2 cars of 1400 kg crashing into each other. The risk, r_2, to the driver of car_2 in this same crash is given by equation 9 with m_2 and m_1 interchanged.

The risk ratio $R=r_1/r_2$ reproduces the first “law” (equations 3 and 7), provided $t=u/2$ (= 1.79). If car_1 and car_2 have the same mass (e.g., m_1) and crash into each other, the risk to each driver is $k/(2\times m_1)$. If the cars have an identical mass m_2, then the risk is $k/(2\times m_2)$. The ratio of these reproduces the second “law” (equations 4 and 8).

From the above information, we decomposed equation 9 into 2 components, one reflecting intrinsic size effects and the other intrinsic mass effects.

$$r_1 = k \times \frac{1}{(m_1 + m_2)} \times \left(\frac{m_2}{m_1}\right)^t \qquad (10)$$

[net effect] = [intrinsic size] × [intrinsic mass]

The intrinsic mass effect is what happens if mass changes but size does not. The intrinsic size effect is what happens if size changes but mass does not.

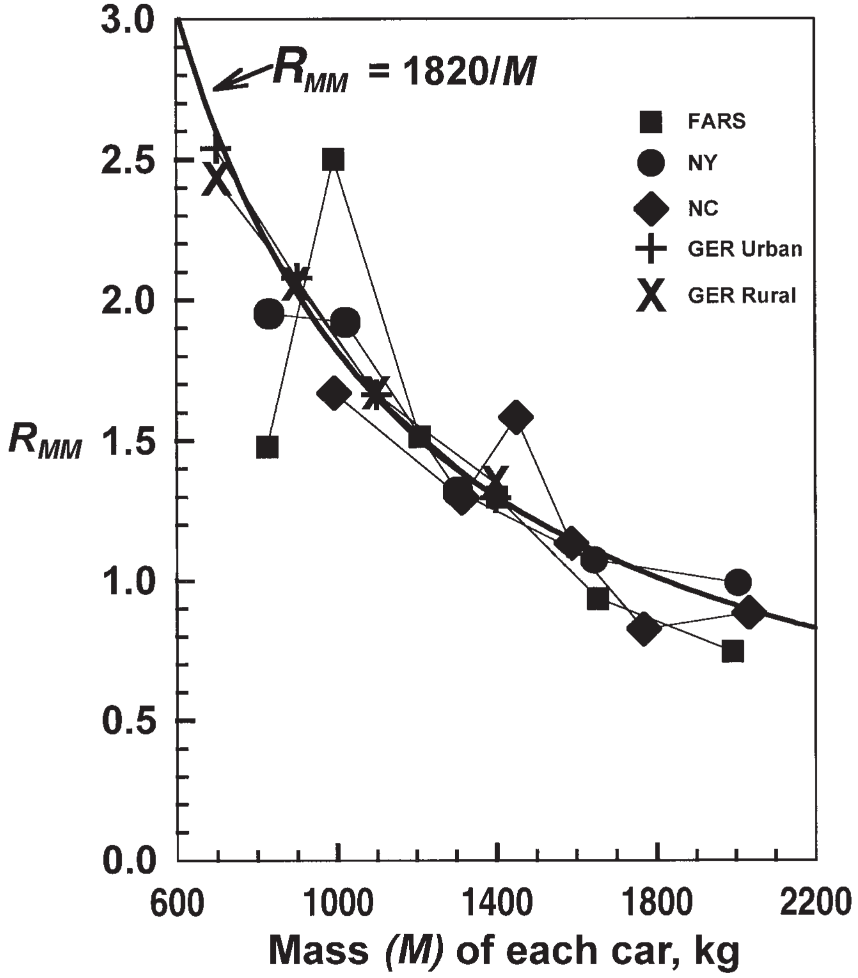
Although presented as a function of mass, the intrinsic size effect should be considered exclusively a function of the sizes of the cars associated with the indicated masses. For example, mass and wheelbase are approximately related by $m = 109\ W^{2.51}$, where m is mass in kilograms and W is wheelbase in meters.[18] Although it is formally superior to substitute wheelbase values into the intrinsic size component, we did not do this because of the resulting increase in equation complexity.

Derivations From Relation Between Driver Risk and Both Car Masses

Equation 10 can be used to explore how changing the mass or size, or both, of cars affects the risk to drivers in each car, the total risk in the crash (the sum of the risks to both drivers), and the total risks in the population. Reducing total risk is generally a goal of safety policy. However, a reduction in total risk still may involve an increase in risk to some drivers. Some examples in which both cars are initially 1400 kg are presented in this section and summarized in Table 1.

Adding Cargo (or Passengers) to a Car. When 75 kg of cargo is added to car$_1$, the size term remains fixed at 1/(1400+1400), but the intrinsic mass term becomes $(1400/1475)^{1.79} = 0.911$ for one driver and $(1475/1400)^{1.79} = 1.098$ for the other. Thus, the cargo reduces the risk to driver$_1$ by 8.9% but increases the risk to driver$_2$ by 9.8%, leading to a total risk increase of 0.4%. For any added cargo, total risk exceeds the initial value of 2 (the horizontal line in Figure 4) by amounts that increase with cargo mass. This is true, however, only for cars that are initially the same mass. If the masses are not initially equal, there is always a range of cargo mass that when added to the lighter car reduces total risk.

The risk ratio associated with adding 75 kg of cargo is $R = 0.911/1.098 = (1400/1475)^{3.58} = 0.830$, or $\Delta R = -17\%$, compared with the observed (Figure 3) value associated with adding a passenger, $\Delta R = -14.5\%$. The −14.5% value can be divided between the 2 drivers by rescaling the individual risks to match the proportions for the calculated addition of 75 kg of cargo. This leads to the conclusion that adding a passenger reduces driver risk by 7.5% but increases risk to the other driver by 8.1%, for an increase in total risk of 0.3% (Table 1).



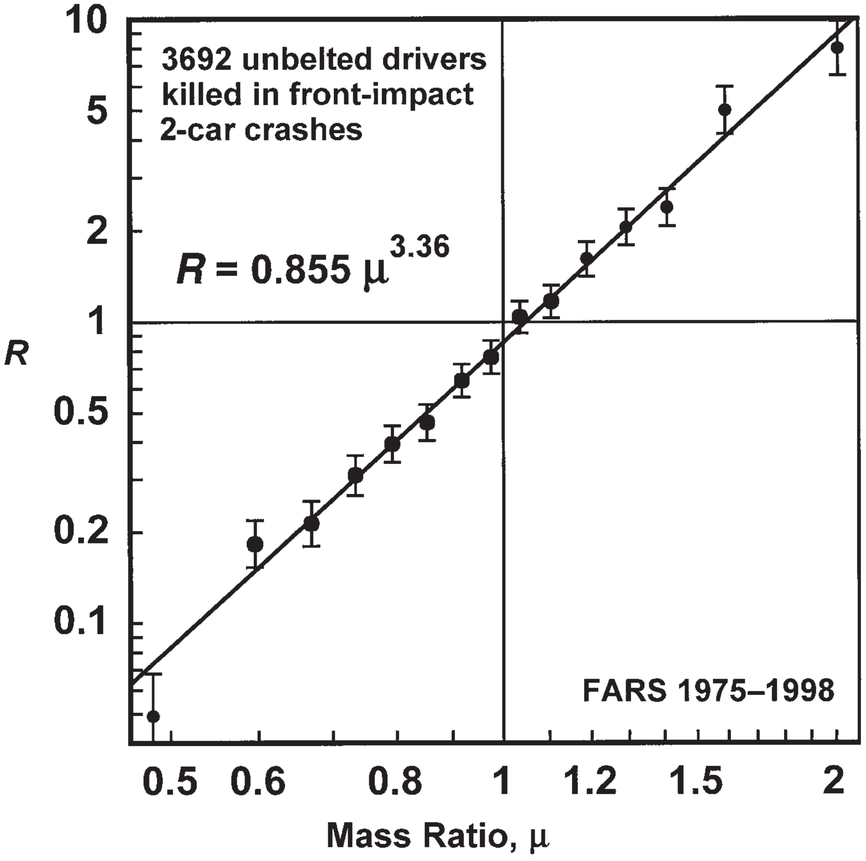
Note. In all cases, the data are scaled to assign a risk of 1.3 to $M = 1400$ kg. The relation is the second of the 2 "laws." FARS (Fatality Analysis Reporting System) = fatalities in the United States[9]; NC = injuries in North Carolina[9]; NY = injuries in New York State[9]; GER Rural = injuries on rural roads in Germany[10]; GER Urban = injuries on roads in built-up areas in Germany.[10] Analytic curve was computed from vehicle-structural considerations, etc.[7]

FIGURE 2—Relative risk, R_{MM}, of driver injury or fatality when cars of similar mass crash head-on into each other vs M, the mass of each car.

For cars of the same mass crashing into each other, adding identical cargo to each does not affect risk. However, for crashes in which crash mass is not identical, adding identical mass to each car reduces total risk. For example, a crash between 900-kg and 1800-kg cars gives driver crash risks of 3.95 and 0.34, for a total risk of 4.29. If 75 kg is added to each car, the risks become 3.68, 0.36, and 4.04. Adding 75 kg to both cars reduces total risk by 6%.

Items that can move within a car during the impact influence crash dynamics less than items fastened to the car structure. The somewhat smaller empirical effect for passengers compared with the predicted effect for increasing mass by 75 kg ($\Delta R = -14.5\%$ compared with −17.0%) is consistent with reduced dynamic effect due to passenger motion but too uncertain to justify specific conclusions. All occupants were unbelted because of insufficient belted cases.

Replacing a Car With a Different Car. When a given car is replaced by a different car, all quantities in equation 10 are replaced by the masses of the new car, reflecting that a heavier car also will be larger. Replacing a 1400-kg car with a 1475-kg car leads to lower risks to both drivers compared with adding



Note. When the cars are of equal mass, the presence of a passenger is associated with a change in R of –14.5%. FARS = Fatality Analysis Reporting System.

FIGURE 3—The ratio, *R*, defined as the number of accompanied drivers killed divided by the number of lone drivers killed in the same crashes, vs μ, the curb mass of the lone drivers' cars divided by the curb mass of the accompanied drivers' cars.

TABLE 1—Risk to Drivers in Car_1 and Car_2 When These Cars Crash Head-On Into Each Other, Calculated With Equation 10

Car_1 Description (Car_2 is 1400 kg)	r_1	r_2	r_{Total}	$R = r_1/r_2$
Add cargo to 1400-kg car				
1400-kg car (base case)	1.000	1.000	2.000	1.000
Change from base-case values	0%	0%	0%	0%
1400-kg car with 75-kg cargo added	0.911	1.098	2.009	0.830
Change from base-case values	–8.9%	9.8%	0.4%	–17.0%
1400-kg car with passenger (empirical result)	NA	NA	NA	0.855
Change from base-case values				–14.5%
Adjust 75-kg cargo case to make $R = 0.855$	0.925	1.081	2.006	0.855
Change from base-case values	–7.5%	8.1%	0.3%	–14.5%
Replace with a different car				
1475-kg car	0.887	1.069	1.956	0.830
Change from base-case values	–11.3%	6.9%	–2.2%	–17.0%
1670-kg car (largest reduction in total risk)	0.665	1.251	1.916	0.532
Change from base-case values	–33.5%	25.1%	–4.2%	–46.8%
2015-kg car (no effect on total risk)	0.427	1.573	2.000	0.272
Change from base-case values	–57.3%	57.3%	0.0%	–72.8%

Note. NA = not available.

75 kg of cargo (Table 1). In particular, the total risk declines by 2.2% compared with the 0.3% increase for adding cargo.

When the car is replaced by another, total risk continues to decline as car mass increases until reaching a maximum decrease of 4.2% at $m_1 = 1670$ kg (Figure 4, top). Total risk is reduced when a 1400-kg car is replaced by any car with a mass of less than 2015 kg. Only about 3% of the cars in the Fatality Analysis Reporting System are heavier than this, so replacing a 1400-kg car by almost any heavier car reduces total risk. Replacing any individual car with a heavier one will in the vast majority of cases reduce total population risk; quantitative estimates require detailed modeling incorporating equation 10 and the distribution of cars by mass.

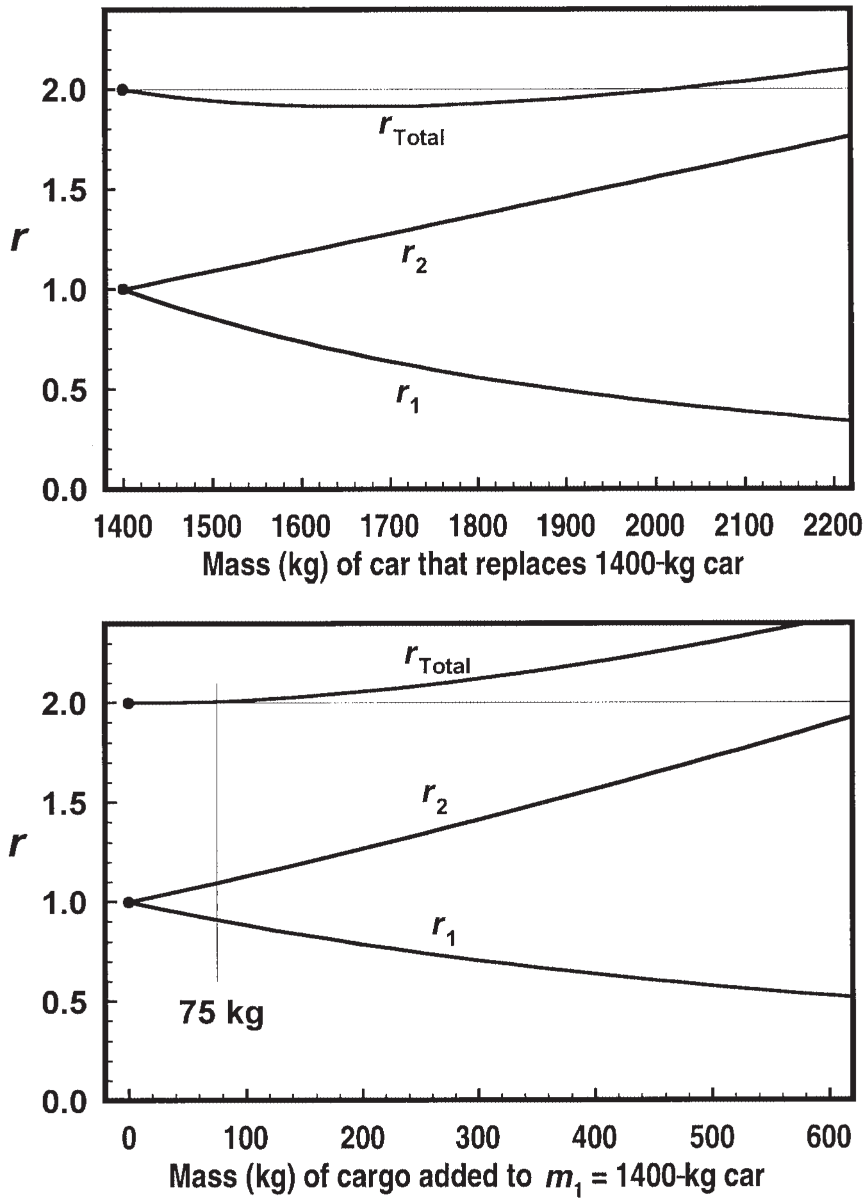
For any 2-car crash, replacing both cars with other cars heavier by a fixed percentage, or by a fixed amount, always reduces risk. Therefore, replacing all the cars in a population with cars lighter by a fixed amount or percentage will necessarily increase population risk.

Equation 10 shows that when the size of either car increases (with masses kept constant), risk decreases for both drivers. The plausibility of this can be illustrated by considering what would happen if a deformable object (think of a very stiff mattress) were placed between the cars just before impact. The time for the cars to complete their (unchanged) speed changes would be increased, approximately, by the time taken to crush the object, thereby reducing forces on both drivers. The risk reduction is similarly available if the deformable object is transported to the crash scene in the form of increased size of either of the cars.

Correction When One Mass Becomes Very Large. Equation 10 predicts that as mass increases indefinitely, risks increase without limit. This cannot happen. Consider cars of equal mass crashing head-on into each other at, for instance, 40 km/h. Each will undergo a speed change of 40 km/h (if some simplifying assumptions are used). As one of the cars becomes heavier and heavier, its speed change approaches zero, and the lighter car's speed change approaches 80 km/h. A relationship (Figure 3 of Evans[19]) indicates that doubling the speed change increases fatality risk by (at most) a factor of 23. Estimated driver risk can be constrained to never exceed 23 times the base case through use of a correction multiplier to give

$$(11)\ r_1 = \frac{k}{m_1 + m_2} \times \left(\frac{m_2}{m_1}\right)^t \times \frac{11.5}{9.5 + \left(\frac{m_1}{m_2}\right)^{t-1} + \left(\frac{m_2}{m_1}\right)^{t-1}}$$

The correction multiplier is very close to 1 unless m_2/m_1 or m_1/m_2 becomes large. For



Note. Initially, the mass of each car is 1400 kg. The top graph uses the net mass relationship to estimate how risks change when the first car is replaced by a different, heavier car (which will be larger). The bottom graph uses the intrinsic mass relationship to estimate how risks change when cargo is added to the first car. This increases the mass of the first car without changing its size.

FIGURE 4—Risks, *r*, to each driver when 2 cars crash head-on into each other calculated with equation 10 (see text).

the range of masses in this article, differences between estimates computed with equation 11 and equation 10 generally agree to within about the thickness of the lines plotted in Figure 4. As mass differences increase, the difference between the estimates from the 2 equations increases. For $m_1=600$ kg and $m_2=2400$ kg, equation 10 predicts $r_1=11.16$, whereas equation 11 predicts 10.01 (as above, $k=2800$ kg and $t=u/2=1.79$). For expository clarity, all values presented in this article were computed with equation 10. In no case was the value materially different from that computed with equation 11. Equation 11 is preferable because it not only satisfies the 2 "laws" but also has unobjectionable asymptotic behavior. Satisfying all these conditions does not guarantee its accuracy. However, inferences using equations that do not satisfy these conditions are necessarily deficient.[27,28]

Discussion

Because the study was confined to frontal crashes, the passenger was unlikely to affect the driver's trajectory during the crash. This supports the interpretation that the mechanism leading to the observed effect is the passenger's mass. The analysis also was performed with a more restrictive definition of frontal crash (12-o'clock principal impact point) with similar results ($\Delta R=-13.7\%$ compared with -14.5%). For crashes in all directions, $\Delta R=-8.0\%$. This lower magnitude may reflect that the role of passengers in nonfrontal crashes is less clear than in frontal crashes. In a left-side impact, an unbelted passenger can become a missile, which increases driver risk.

This study addressed only how the presence of a passenger affects outcome in a crash. Passengers may exercise larger influences on crash-involvement rates, on the one hand, by providing an extra pair of lookout eyes or, on the other hand, by distracting drivers. Accompanied drivers are observed to choose longer following headways (essentially greater following distances between their vehicles and the vehicles they are following),[29] perhaps because a portion of their total attention is transferred from the driving task to the passenger.

Conclusions

Empirical findings indicate that adding a passenger to 1 of 2 identical cars involved in a 2-car crash reduces the driver fatality risk ratio (risk to the accompanied driver divided by risk to the lone driver) by 14.5% ±2.3%.

To allocate this effect to the drivers individually, we developed an equation that reflects well-established empirical findings relating to 2-car crashes. The equation expresses each driver's risk as a function of causal contributions from the mass and size of both involved cars. Some examples from use of this equation are given below.

Adding Cargo

- A driver with a passenger is 7.5% less likely to die when 2 otherwise identical 1400-kg cars crash into each other.
- The risk to the other driver increases by 8.1%, with total risk increasing by 0.3%.
- If the cars differ in mass by more than a passenger's mass, adding a passenger to the lighter car reduces total risk.
- The answer to the question "Am I safer if I put bricks in my trunk?" is "Yes, provided that the added mass does not move relative to the car

structure during the crash and is not large enough to adversely affect braking, handling, or stability."

- Adding equal cargo to all cars reduces total risk.

Replacing a Car With One of Different Mass

- Increasing the size of one car decreases the risk to both drivers.
- Replacing both cars with others lighter by a fixed amount (or percentage) increases total risk in every crash and therefore must increase total risk for any population.

Although 2-car crashes provided the data for this study, the results are expected to apply to other types of crashes. This is particularly important because more than 40% of car occupants killed are killed in single-car crashes.[20,30] The risk reduction due to the presence of a passenger or other cargo is expected to apply to single-car frontal crashes into objects that deform in ways not too different from the ways cars deform. The addition of cargo increases damage to the struck object without a corresponding increase in human harm. When all crashes are considered, adding mass in the form of passengers reduces total driver deaths.

The finding that having all cars carry extra cargo generates a safer traffic system is clearly a technical finding and not a policy recommendation. The same is true of the finding that replacing all cars with heavier ones results in an even greater reduction in risk. Such changes impose extra costs on drivers, resources, and environment; adding cargo reduces the room, useful life, and acceleration and braking capabilities of the car (if not properly restrained, cargo can increase risk). When policies are expected to influence the mix of cars, however, effects on safety should not be ignored. ☐

References

1. Severy DM, Harrison MB, Blaisdell DM. Smaller vehicle versus larger vehicle collisions. *SAE Trans.* 1971;80:2929–2958.
2. Campbell BJ, Reinfurt DW. *The Relationship Between Driver Crash Injury and Passenger Car Weight.* Chapel Hill: Highway Safety Research Center, University of North Carolina; 1973.
3. O'Neill B, Joksch H, Haddon W Jr. Empirical relationships between car size, car weight and crash injuries in car-to-car crashes. In: *Proceedings of the Fifth International Technical Conference on Experimental Safety Vehicles, London, England, 4–7 June 1974.* Washington, DC: National Highway Traffic Safety Administration;1974:362–368.
4. Joksch HC. *Analysis of the Future Effects of the Fuel Shortage and Increased Small Car Usage Upon Traffic Deaths and Injuries.* Washington, DC: US Dept of Transportation; January 1976. Report DOT TSC OST 75 21.
5. Grime G, Hutchinson TP. Vehicle mass and driver injury. *Ergonomics.* 1979;22:93–104.
6. Evans L. Driver injury and fatality risk in two-car crashes versus mass ratio inferred using Newtonian mechanics. *Accid Anal Prev.* 1994; 26:609–616.
7. Wood DP. Safety and the car size effect: a fundamental explanation. *Accid Anal Prev.* 1997; 29:139–151.
8. Fatality Analysis Reporting System resources page. National Center for Statistics and Analysis Web site. Available at: http://www.nhtsa.dot.gov/people/ncsa/fars.html. Accessed January, 2000.
9. Evans L, Wasielewski P. Serious or fatal driver injury rate versus car mass in head-on crashes between cars of similar mass. *Accid Anal Prev.* 1987;19:119–131.
10. Ernst E, Bruhning E, Glaeser KP, Schmidt M. Compatibility problems of small and large passenger cars in head-on collisions. Paper presented at: 13th International Technical Conference on Experimental Safety Vehicles; November 4–11, 1991; Paris, France.
11. Evans L, Frick MC. Mass ratio and relative driver fatality risk in two-vehicle crashes. *Accid Anal Prev.* 1993;25:213–224.
12. Evans L, Frick MC. Car mass and fatality risk—has the relationship changed? *Am J Public Health.* 1994;84:33–36.
13. Evans L. Driver fatalities versus car mass using a new exposure approach. *Accid Anal Prev.* 1984;16:19–36.
14. Hertz E. *The Effect of Decrease in Vehicle Weight on Injury Crash Rates.* Washington, DC: US Dept of Transportation, National Highway Traffic Safety Administration; 1997. NHTSA Technical Report US DOT HS 808 575.
15. Klein TM, Hertz E, Borener S. A collection of recent analyses of vehicle weight and safety. In: *Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles, Paris, France, 4–7 November 1991.* Vol 1. Washington, DC: National Highway Traffic Safety Administration; 1993:94–103. Document DOT HS 807 990.
16. Partyka SC, Boehly WA. Passenger car weight and injury severity in single vehicle nonrollover crashes. In: *Proceedings of the 12th International Technical Conference on Experimental Safety Vehicles, Gothenburg, Sweden, 29 May–1 June 1989.* Vol 1. Washington, DC: National Highway Traffic Safety Administration;1989:507–519.
17. Buzeman D, Viano DC, Lovsund P. Car occupant safety in frontal crashes: influence of vehicle mass, impact speed, and inherent vehicle protection. *Accid Anal Prev.* 1998;30:713–722.
18. Evans L, Frick MC. Car size or car mass—which has greater influence on fatality risk? *Am J Public Health.* 1992;82:1009–1112.
19. Evans L. Car size and safety—a review focused on identifying causative factors. In: *Proceedings of the 14th Enhanced Safety of Vehicles Conference, Munich, Germany, 23–26 May 1994.* Vol 1. Washington, DC: US Government Printing Office; 1995:721–733.
20. Evans L. Small cars, big cars: what is the safety difference? *Chance—N Dir Stat Comput.* 1994; 7(3):9–16.
21. Evans L. *Traffic Safety and the Driver.* New York, NY: Van Nostrand Reinhold; 1991.
22. Kahane CJ. *Relationships Between Vehicle Size and Fatality Risk in Model Year 1985–1993 Passenger Cars and Light Trucks.* Washington, DC: National Highway Traffic Safety Administration; 1997. Report DOT HS 808 570.
23. Mizuno K, Umeda U, Yonezawa H. The relationship between car size and occupant injury in traffic accidents in Japan. In: *Proceedings of SAE Conference on Occupant Protection and Injury Assessment in the Automotive Crash Environment, Detroit, Mich, 24–28 February 1997* [SP-1231]. Warrendale, Pa: Society of Automotive Engineers; 1997:45–59. Paper 970123.
24. Thomas P, Frampton R. Large and small cars in real-world crashes—patterns of use, collision types and injury outcomes. In: *Proceedings of the 43rd Annual Meeting of the Association for the Advancement of Automotive Medicine, Barcelona (Sitges), Spain, 20–21 September 1999.* Des Plains, Ill: Association for the Advancement of Automotive Medicine; 1999: 101–118.
25. Insurance Institute for Highway Safety. Fatality facts: passenger vehicles. Available at: http://www.highwaysafety.org/safety_facts/fatality_facts/passveh.htm. Accessed January, 2000.
26. Insurance Institute for Highway Safety. Small passenger vehicles a problem. *Status Report.* February 28, 1987;22.
27. *Anthropometric Reference Data and Prevalence of Overweight, United States, 1976–1980.* Washington, DC: National Center for Health Statistics; 1987. DHHS publication PHS 87-1688, Series 11, 239.
28. Evans L, Frick MC. Driver fatality risk in two-car crashes—dependence on masses of driven and striking car. In: *Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles, Paris, France, 4–7 November 1991.* Vol 1. Washington, DC: National Highway Traffic Safety Administration; 1993: 83–93. Document DOT HS 807 990.
29. Buzeman-Jewkes D, Viano DC, Lovsund P. Occupant risk, partner risk and fatality rate in frontal crashes: estimated effects of changing vehicle fleet mass in 15 years. *J Crash Prev Inj Control.* 2000;2:1–10.
30. Evans L, Frick MC. Seating position in cars and fatality risk. *Am J Public Health.* 1988;78: 1456–1458.
31. Evans L, Wasielewski P. Risky driving related to driver and vehicle characteristics. *Accid Anal Prev.* 1983;15:121–136.