Science Serving Society Devoted to adding reason and knowledge to public policy

Information about 2004 book **Traffic Safety** | More info on this subject in Ch. 4 of **Traffic Safety** | **SSS** HOME

Causal influence of car mass and size on driver fatality risk

Much more on this and related subjects more recently treated in Chapter 4 *Vehicle Mass and Size* in *Traffic Safety* by Leonard Evans (August 2004)

Return to Publications | Latest *Traffic Safety* You Tube

(This preprint is substantially the same as the final published paper)

President, *Science Serving Society*
973 Satterlee Road
Bloomfield Hills, MI 48304-3153
USA

LE@ScienceServingSociety.com
http://www.scienceservingsociety.com/

ABSTRACT

Objectives. To estimate how adding mass, in the form of a passenger, to a car crashing head-on into another car, affects fatality risks to both drivers, and thereby distinguish between the causal roles of mass and size.

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

Results. Adding a passenger to a car leads to a 14.5% reduction in driver risk ratio (risk to one driver divided by risk to the other). In order to divide this effect between the individual drivers, equations are developed which express each driver's risk as a function of causal contributions from the mass and size of both involved cars.

Conclusions. Adding a passenger reduces a driver's frontal crash fatality risk by 7.5%, but increases the risk to the other driver by 8.1%. The findings are applicable to some single-car crashes, where the driver risk decrease is not offset by any increase in harm to others. All cars carrying the same additional cargo reduces total population risk

Introduction

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]. However, the question of how adding mass to an existing car affects safety has remained unanswered. One common way to express this question is "Am I safer if I put bricks in my trunk?" While kinematic considerations [6,7] suggest an answer, there are no empirical studies. Data sets rarely contain information on cargo, or on actual mass during crashes. All that is generally coded is a curb mass that is identical for all cars of the same make and model. Information is, however, available on occupants.

The present investigation estimates how adding mass to existing cars affects driver fatality risk by interpreting the addition of a passenger to be equivalent to the addition of cargo . Head-on crashes between two cars are examined using 1975-1998 Fatality Analysis Reporting System (FARS) data [8]. One car contains only one occupant, a driver, while the other contains also a right-front passenger. If all other factors are the same, the masses of the cars differ by the mass of the passenger.

The results contribute to the development of an equation which distinguishes between causal contributions from mass and size. The many relationships 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.

Empirical Study

Method

The method, from an earlier study [11], is described briefly below. From a formal perspective, each car involved in a two-car crash can be considered to play a symmetrical role -- they crash into each other.

For every crash between two cars of known mass, car_a and car_b, we can define a mass ratio, μ, as

$$(1) \qquad \mu \quad = \quad \frac{\text{Mass of } car_b}{\text{Mass of } car_a}$$

and a driver fatality risk ratio, R, as

$$(2) \qquad R \ = \ \frac{\text{Probability of driver fatality in } car_a}{\text{Probability of driver fatality in } car_b} \quad .$$

Earlier studies [10, 12, 19] found that

$$(3) \qquad R \ = \ \mu^u$$

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

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

$$(4) \qquad R_{MM} = c/M,$$

where c is a constant.

Equations 3 and 4 and their associated Figures 1 and 2, may be regarded as two "laws"; both refer only to relative risk. Later they contribute to an equation to estimate risks to individual drivers.

If the cars are differentiated by some attribute other than mass, say car_a is old and car_b is new, then the value of R when μ=1 in Equation 3 measures the influence of car age on fatality risk. The earlier study [11] found that the relationship

$$(5) \qquad R \ = \ A\,\mu^u$$

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

Data

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

- One car carries a driver and a right-front passenger, whereas the other has only a driver.
- Frontal crashes only, defined as principal impact point [8] = 11, 12, or 1 o'clock for both cars.
- At least one of the drivers was killed (crashes in which the passenger was the only fatality were excluded).
- All three 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

(6) $Ln(R) = Ln(A) + u\, Ln\, (\mu)$,

the natural logarithm transformation of Equation 5.

The fit gives $u = 3.36 \pm 0.10$, and, more central to the present study, $A = 0.855 \pm 0.023$. It is convenient to discuss A in terms of $?R = 100*(A-1)/R$, the percent change from the $R = 1$ value. The finding from Figure 3 is that the presence of a passenger gives $?R = -(14.5 \pm 2.3)\%$. 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.

Calculation of intrinsic mass and size effects

When two cars, car_1 and car_2, of curb masses m_1 and m_2, crash into each other, the first of the two "laws" (Equation 3) gives

(7) $R = (m_2/m_1)^u$

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

Now compare driver risks in the following two crashes. The first crash is between two cars each of equal mass m_1. The second is between two cars each of equal mass m_2. The second "law" (Equation 4) gives

(8) $$\frac{\text{Risk when two } m_1 \text{ cars crash into each other}}{\text{Risk when two } m_2 \text{ cars crash into each other}} = m_2/m_1 \qquad .$$

When two bodies of the same mass crash into each other, Newtonian Mechanics shows that the value of the mass does not affect their post-crash trajectories. So, although Equation 8 is expressed in terms of mass, the causal effect is intrinsically size.

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

$$(9) \qquad r_1 \quad = \quad \frac{k}{m_1 + m_2} \quad x \quad (m_2/m_1)^t$$

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 one for the base case of two 1400 kg cars 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 3,7) provided t = u/2 (= 1.79). If car_1 and car_2 have the same mass, say m_1, and crash into each other, the risk to each driver is $k/(2\, m_1)$. If the cars have identical mass m_2, then the risk is $k/(2\, m_2)$. The ratio of these reproduces the second "law" (Equations 4,8).

Based on the above, we decompose Equation 9 into two components, one reflecting intrinsic size effects, and the other intrinsic mass effects.

$$(10) \qquad r_1 \quad = \quad k \quad x \quad 1/(m_1 + m_2) \quad x \quad (m_2/m_1)^t$$

$$\text{[net effect]} \quad = \qquad \text{[intrinsic size]} \quad x \quad \text{[intrinsic mass]}$$

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 kg and W is wheelbase in meters[18]. While it is formally superior to substitute wheelbase values into the intrinsic size component, we do 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 and/or size 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 populations. Reducing total risk is generally a goal of safety policy. However, a reduction in total risk may still involve an increase in risk to some drivers. Some examples in which both cars are initially 1400 kg, are presented below and summarized in Table 1.

Adding cargo (or passengers) to a car

When 75 kg cargo is added to a 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. However, this is for the cases of 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 cargo is $R = 0.911/1.098 = (1400/1475)^{3.58} = 0.830$, or $?R = -17\%$, compared to the observed (Figure 3) value associated with adding a passenger, $?R = -14.5\%$. The -14.5% value can be divided between the two drivers by rescaling the individual risks to match the proportions for the calculated addition of 75 kg 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).

For cars of the same crash 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 k 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 a 6%.

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

Replacing a car by a different car

When a car is replaced by a different car, all quantities in Equation 10 are replaced by the masses of the new car, reflecting that if it is heavier, it will also be larger. Replacing a 1400 kg car with a 1475 kg car leads to lower risks to both drivers compared to when 75 kg of cargo is added (Table 1). In particular, the total risk declines by 2.2% compared to the 0.3% increase for adding cargo.

As the car is substituted by another, total risk continues to decline as car mass increases until reaching a maximum decrease of 4.2% at m_l = 1670 kg (Figure 4, top). Total risk is reduced when a 1400 kg is replaced by any car with mass less than 2015 kg. As only about 3% of cars in FARS are heavier than this, replacing a 1400 kg car by almost any heavier car reduces total risk. Replacing any individual car by 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 two-car crash, replacing both cars by others heavier by a fixed percent, or by a fixed amount, always reduces risk. It follows that replacing all the cars in a population by 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 prior to impact. The time for the cars to complete their (unchanged) speed changes will 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, say, 40 km/h. Each will undergo a speed change of 40 km/h (using some simplifying assumptions). As one of the cars becomes heavier and heavier, its speed change approaches zero and the lighter car's approaches 80 km/h. A relationship (Figure 3 of Reference 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 by multiplying by a correction multiplier to give

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

The correction multiplier is very close to 1 unless m_2/m_1 or m_1/m_2 become large. For the range of masses in this paper, differences between estimates using Equation 11 and Equation 10 generally agree to within about the thickness of the lines plotted in Figure 4. As mass differences increase, difference between the estimates from the two equations increase. 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 paper were computed using Equation 10. In no case was the value materially different from that computed from Equation 11. Equation 11 is preferable because it not only satisfies the two "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 [28,29].

Comments

As the study is confined to frontal crashes, the passenger is 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 was also performed with a more restrictive definition of frontal crash (12 o'clock principal impact point) with similar results (?R = -13.7% compared to -14.5%). For crashes in all directions, ?R = -8%. This lower magnitude may reflect that the role of passengers in non-frontal 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 addresses only how the presence of a passenger affects outcome, given that a crash occurs. Passengers may exercise larger influences on crash-involvement rates by, on the one hand, providing an extra pair of look-out eyes, but on the other hand, by distracting drivers. Accompanied drivers are observed to choose longer following headways [30], perhaps because a portion of their total attention is transferred from the driving task to the passenger.

Conclusions

Empirically, it is found that adding a passenger to one of two identical cars involved in a two-car crash reduces the driver fatality risk ratio (risk to the accompanied driver divided by the risk to the lone driver) by $(14.5 \pm 2.3)\%$.

In order to allocate this effect to the drivers individually, an equation was developed which reflects well-established empirical findings relating to two-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 using this equation are given below.

Conclusions relating to adding cargo

- A driver with a passenger is 7.5% less likely to die when two 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.

-

Conclusions relating to replacing a car by one of different mass

- Increasing the size of one car decreases the risk to both drivers

- Replacing all cars by others lighter by a fixed amount (or percent) increases total risk in every crash, and therefore must increase total risk for any population.

While two-car crashes provide 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 [20,31]. 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 cars. The addition of cargo increases damage to the struck object, but with no corresponding increase in human harm. When all crashes are considered, adding mass in the form of passengers reduces total driver deaths.

The finding that everyone carrying extra cargo generates a safer traffic system is clearly a technical finding and not a policy recommendation; likewise, the much greater reduction in risk resulting from replacing all cars by heavier ones. Such changes impose extra costs on drivers, resources and environment, and, for adding cargo, reduce the room, useful life, and acceleration and braking capabilities of the car (if not properly restrained, cargo can increase risk). However, when policies are expected to influence the mix of cars , effects on safety should not be ignored.

Return to SSS home page

References

1. Severy, DM; Harrison, MB; Blaisdell DM   Smaller vehicle versus larger vehicle collisions. SAE Transactions, (paper number 710861). 1971;80:2929-58

2. Campbell, BJ; Reinfurt, DW.   The relationship between driver crash injury and passenger car weight. Chapel Hill, NC: 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. Proceedings of the Fifth International Technical Conference on Experimental Safety Vehicles, London, UK, p 362-368. Washington, DC: National Highway Traffic Safety Administration, 4-7 June 1974.

4. Joksch, HC   Analysis of the future effects of the fuel shortage and increased small car usage upon traffic deaths and injuries. Report DOT-TSC-OST-75-21; January 1976.

5. Grime G, Hutchinson TP.   Vehicle mass and driver injury. *Ergonomics.* 1979;22:93-104; 1979.

6. Evans L. Driver injury and fatality risk in two-car crashes versus mass ratio inferred using Newtonian Mechanics. *Accident Analysis Prev.* 1994;26:609-616.

7. Wood DP.   Safety and the car size effect: a fundamental explanation. *Accident Analysis Prev.* 1997;29:139-151.

8. Fatality Analysis Reporting System, formatted fatal injury traffic data; 1990-1996.   National Highway Traffic Safety Administration, Washington DC, 1998. <http://www.nhtsa.dot.gov/people/ncsa/fars.html>

9. Evans L, Wasielewski P.   Serious or fatal driver injury rate versus car mass in head-on crashes between cars of similar mass. *Accident Analysis 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 to the 13th International Technical Conference on Experimental Safety Vehicles, Paris, 4-11 November 1991.

11. Evans L, Frick MC.   Mass ratio and relative driver fatality risk in two-vehicle crashes. *Accident Analysis 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. *Accident Analysis Prev.* 1984;16:19-36.

14. Hertz E. The effect of decrease in vehicle weight on injury crash rates. US DOT HS 808 575. NHTSA Technical report, Washington D.C., 1997.

15. Klein TM, Hertz E, Borener S. A collection of recent analyses of vehicle weight and safety. Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles, Paris, France, 4-7 November 1991, Document DOT HS 807 990, Washington DC, Vol. 1, p 94-103, July 1993.

16. Partyka SC; Boehly WA. Passenger car weight and injury severity in single vehicle nonrollover crashes. Proceedings of the 12th International Technical Conference on Experimental Safety Vehicles, Vol. 1, p 507-519, Gothenburg, Sweden; 29 May-1 June 1989.

17. Buzeman, D, Viano DC, Lovsund P. Car occupant safety in frontal crashes: influence of vehicle mass, impact speed, and inherent vehicle protection. *Accident Analysis 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. Proceedings of the 14th Enhanced Safety of Vehicles Conference, Munich, Germany, 23-26 May 1994, US Government Printing Office:1995-381-067, Vol. 1, p 721-733, 1995.

20. Evans L. Small cars, big cars: what is the safety difference? Chance -- New Directions for Statistics and Computing, a journal of the American Statistical Association. 1994;7(No. 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. Rep. No. DOT HS 808 570, National Highway Traffic Safety Administration, Washington, DC, 1997.

23. Mizuno K; Umeda U, Yonezawa H. The relationship between car size and occupant injury in traffic accidents in Japan. Proc. of SAE Conf. Occupant protection and injury assessment in the automotive crash environment, SP-1231, Detroit: 45-59. Paper no. 970123. Warrendale, PA 1997.

24. Thomas, P, Frampton, R. Large and small cars in real-world crashes - patterns of use, collision types and injury outcomes. Proceedings of the 43rd annual meeting of the Association for the Advancement of Automotive Medicine, Barcelona (Sitges), Spain, 20-21 September 1999, p. 101-118.

25. Insurance Institute for Highway Safety. Fatality Facts, published annually, Arlington, Virginia. (http://www.highwaysafety.org/safety_facts/fatality_facts/passveh.htm).

26. Insurance Institute for Highway Safety. Small passenger vehicles a problem. Status Report 22(2), February 28 1987.

27. Natonal Center for Health Statistics. Anthtropometric reference data and prevalence of overweight, United States, 1976-1980, DHHS Publication No. PHS 87-1688, Series 11, 239, Washington, DC,1987.

28. Evans L; Frick, MC. Driver fatality risk in two-car crashes -- dependence on masses of driven and striking car. Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles, Paris, France, 4-7 November 1991, Document DOT HS 807 990, Washington DC, Vol. 1, p 83-93, July 1993.

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 .Injury 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. Accident Analysis Prev. 1983;l5:l2l-l36.

32. Evans L, Gerrish PH, Taheri B. Epidemiology of the older driver -- some preliminary findings from data through 1996. Proceedings of the 16th International Conference on the Enhanced Safety of Vehicles, Windsor, Canada, 1-4 June 1998, Report No. DOT HS 808 759, Vol. 2, 1496-1507, National Highway Traffic Administration, Washington DC, October 1988.

Table 1.   Risk to drivers in car_1 and car_2 when these cars crash head-on into each other, calculated from Equation 10.

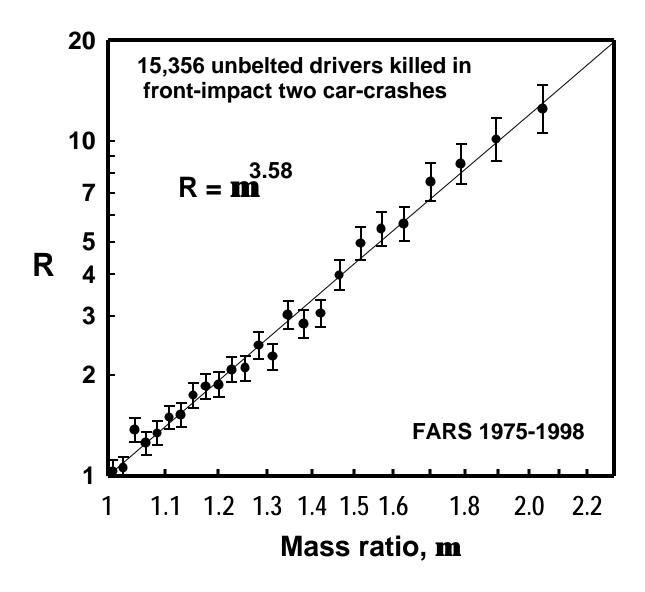| Car_1 description (car$_2$ is a 1400 kg car)	r_1	r_2	r_{Total}	$R=\dfrac{r_1}{r_2}$
Add cargo to 1400 kg car				
1400 kg car (base case)	1.000	1.000	2.000	1.000
	0%	*0%*	*0%*	*0%*
1400 kg car with 75 kg cargo added	0.911	1.098	2.009	**0.830**
	-8.9%	*9.8%*	*0.4%*	***-17.0%***
1400 kg car with passenger (empirical result)	na	na	na	**0.855**
				-14.5%
Adjust 75 kg cargo case to make R = 0.855	0.925	1.081	2.006	**0.855**
	-7.5%	*8.1%*	*0.3%*	***-14.5%***
Replace by a different car				
1475 kg car	0.887	1.069	1.956	0.830
	-11.3%	*6.9%*	*-2.2%*	*-17.0%*
1670 kg car -- largest reduction in total risk	0.665	1.251	1.916	0.532
	-33.5%	***25.1%***	*-4.2%*	*-46.8%*
2015 kg car -- no effect on total risk	0.427	1.573	2.000	0.272
	-57.3%	*57.3%*	*0.0%*	*-72.8%*

FIGURE 1   The ratio, R, of driver fatalities in the lighter compared to in the heavier car versus

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). The

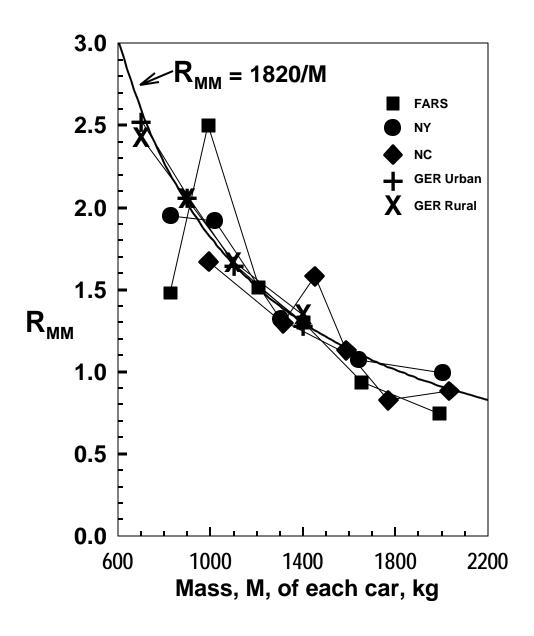relationship is the first of the two "laws" of two-car crashes.

FIGURE 2 Relative risk, R_{MM}, of driver injury or fatality when cars of similar mass crash head-on into each other versus M, the mass of each car. In all cases the data are scaled to assign a risk of 1.3 to M=1400 kg. The relationship is the second of the two "laws".

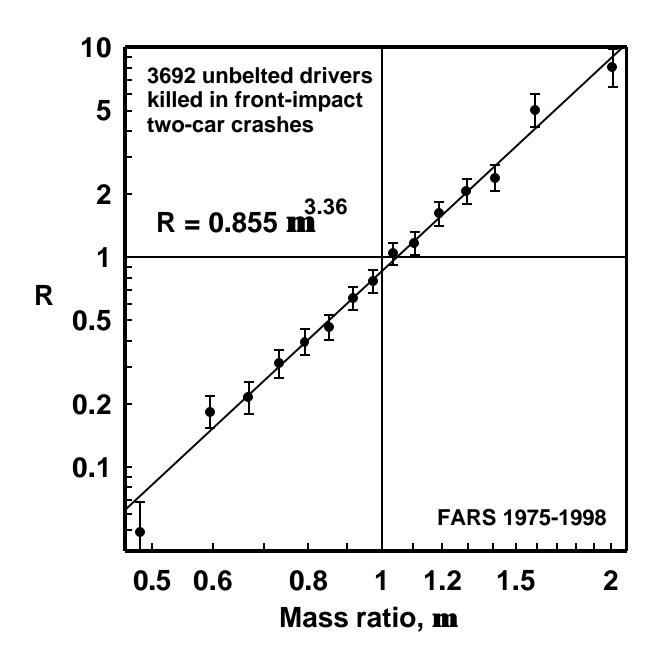|	
FARS	Fatalities in US[9]
NC	Injuries in North Carolina [9]
NY	Injuries in New York State [9]
GER Rural	Injuries on rural roads in Germany [10]
GER Urban	Injuries on roads in built-up areas in Germany [10]
Analytical curve	Computed from structural considerations, etc. [7]

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, versus μ, the curb mass of the lone drivers' cars divided by the curb mass of the accompanied drivers' cars. When the cars are of equal mass, the presence of a passenger is associated with a change in R of -14.5%.
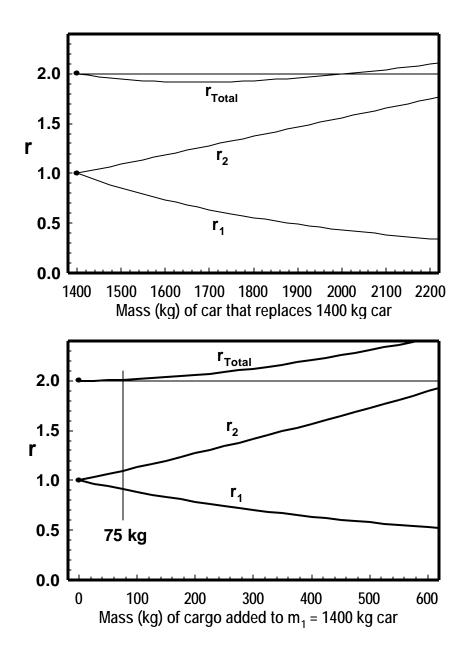
FIGURE 4. Risks to each driver when two cars crash head-on into each other calculated using Equation 10. Initially, the mass of each car is 1400 kg. The top graph uses the net mass relationship to estimate how risks change when the first car is replaced by a different heavier car (which will be larger). 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.