

Updated Evaluation of Size and Mass Effects in Front-to-Front Crashes Involving Light Vehicles

Vitaly Eyges and Jeya Padmanaban

JP Research, Inc.

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ABSTRACT

Studies used 1981-2006 FARS and state crash data to examine the relative importance of vehicular, driver, and environmental factors in influencing odds of driver fatality in two-vehicle (car-to-car, light truck-to-car, and light truck-to-light truck) frontal crashes for 1981-2003 model-year vehicles. It was found that all vehicle factors, including vehicle frontal stiffness, have a second order effect compared to vehicle weight. Most of the driver factors included were found to be highly significant. Assumptions and methodology used by other vehicle size/weight safety studies were also evaluated. Results show trends similar to those of other key studies, with one notable exception.

INTRODUCTION

The studies reported here concluded a long-term, field-data-based, vehicle size/mass effects research program. The primary goals of the overall project were to use field data to identify and separate the safety effects of size and mass on fatality odds. This paper contains an update to the logistic regression analyses reported earlier [Padmanaban, 2003; Padmanaban et al., 2004] and offers an additional evaluation of how the results of the present set of studies compare with those of other size/mass effects studies.

BACKGROUND – During the past 20 years, the relationships between vehicle size, vehicle mass, and occupant safety have been studied by numerous public and private auto safety research groups, including the Department of Transportation (DOT), the Office of Technology Assessment of the United States Congress, the Insurance Institute for Highway Safety, General

Motors Research Laboratories, the National Academy of Sciences, and other members of the highway safety research community.

Evans and Frick (1992) and Evans (2001) explored relationships between mass and size, but used wheelbase as the only size parameter. Evans, however, improved on the earlier report by estimating how adding mass, in the form of a passenger, to a car crashing head-on into another car affects fatality risks to both drivers, thereby distinguishing between the causal roles of mass and size.

Kahane (1997), in a National Highway Transportation Safety Administration (NHTSA) study, focused on exploring relationships between vehicle weight and safety by using logistic regression and generalized linear models to establish relationships between weight and other size parameters. The study analyzed weight-safety relationships for several crash modes to estimate the net effect of vehicle weight change on fatality risk. However, this study examined very few size variables. Jokschi (1998), using NHTSA crash files, attempted to evaluate the fatality rate per driver involved in collisions between two cars and between a car and a light truck for various collision configurations. These studies acknowledge that more sophisticated approaches are warranted to evaluate fatality risk as a function of combinations of several independent variables.

In recent studies, Evans (2003) addressed the difficulties involved in estimating changes to fatality risk resulting from Corporate Average Fuel Economy (CAFE) standards, and Ross and Wenzel (2002) estimated driver fatality risk by vehicle type and model using Fatality Analysis Reporting System (FARS) calendar year 2000 data for recent model year vehicles (1995-1999).

This latter study evaluated the fatality risk to the driver of the vehicle in question and fatality risk to the driver of other vehicles involved in crashes with the vehicle in question. The study acknowledged that separating the role of driver characteristics from vehicle design contribution is difficult. The authors updated their study [Ross and Wenzel, 2003] and concluded that some design factors, such as bumper height and stiffness of light trucks and sport utility vehicles (SUVs), could be better predictors of risk than vehicle mass.

In 2003, Kahane made a revision of his 1997 NHTSA report, and applied different analysis techniques to more recent crash data. The updated statistical analysis of 1991-1999 model year vehicles in 1995-2000 calendar year crashes superseded NHTSA's 1997 report. The new study expanded the analyses by separately estimating the effects of 100-pound reductions in four categories of light vehicles: heavier light trucks and vans (LTVs), lighter LTVs, heavier cars, and lighter cars. It compares the fatality rates of LTVs and cars to quantify differences between vehicle types, given drivers of the same age/gender, etc. In support of NHTSA's research on car-LTV compatibility, the 2003 Kahane study also analyzed fatality rates in two-vehicle crashes based on the mass and rigidity of each vehicle and the height mismatch between vehicles.

Size factors, as distinct from mass, were also discussed in NHTSA testimony before the Senate Committee on Commerce, Science, and Transportation. Speaking on the safety of SUVs, NHTSA Administrator J.W. Runge (2003) addressed the problem of size incompatibility in vehicle-to-vehicle crashes:

In the fleet of 20 years ago, the primary incompatibility was one of weight. However, the arrival of SUVs and increased numbers of pickups has made other incompatibilities important as well — incompatibility in vehicle height and in the alignment of interacting vehicle structures, such as bumpers and chassis frame rails.

In response to the Kahane studies, researchers at the Dynamic Research Institute (DRI) conducted several analyses to test the assumption that vehicle weight could be used as a proxy for other vehicle attributes (vehicle size or height) [Van Auken and Zellner, 2002; 2003; 2005a; and 2005b]. DRI included two size variables in addition to weight in their regression analyses. The size variables were track width (the width of the vehicle between the two tires) and wheelbase (the length of the vehicle between the two axles). The Van Auken/Zellner studies came to the conclusion that these size variables are equally as important as vehicle weight in predicting the odds of driver fatality in a frontal crash.

PRESENT STUDIES – All of these previous studies examine the relative contribution of size variables, mass, and other non-vehicular factors influencing fatality odds in two-vehicle crashes. The present studies expanded upon these analyses by including massive amounts of historic and recent state and FARS accident data, and by

providing additional insight into the roles of vehicle mass, size, and stiffness in frontal impacts. Comparison of the results with estimates from other analyses shows trends similar to those of other key studies, with the notable exception of those by Van Auken and Zellner. The approach employed in the Van Auken/Zellner analyses is evaluated in this paper, as is the significant multicollinearity effect created due to the simultaneous presence of vehicle weight and size parameters in their logistic fit.

METHODOLOGY

This paper presents the results of three interrelated studies. The first study was a statistical overview of crash statistics by crash type and configuration. The second was a logistic analysis of the relationship between vehicle speed, stiffness, mass ratio, and odds of driver fatality, including an estimate of the societal effect of weight reduction in frontal crashes. The final study was a detailed evaluation of statistical studies that purport to examine the relationship between vehicle mass, stiffness, and odds of driver fatality in a frontal crash. The methodology for each study and data used are presented below.

VEHICLE DATA – Vehicles used for the studies of vehicle mass, size, and odds of driver fatality included 1981-2003 model year light vehicles (passenger cars, pickups, SUVs, and vans) with curb weights not exceeding 9000 lbs. and wheelbases greater than 75 inches. These restrictions ensured vehicles were no older than 1981 and did not exceed size/weight norms for passenger vehicles. Information on vehicle parameters such as vehicle mass, wheelbase, stiffness, and FAW (distance between frontal axle and windshield) were obtained from previous studies [Padmanaban, 2003; Padmanaban et al., 2004] performed as part of the larger research program. Discussion of the sources used to obtain parameter data and the importance of these parameters to the model are provided in the referenced papers.

ACCIDENT DATA – The FARS database, maintained by NHTSA, was used to examine two-vehicle, non-rollover, fatal frontal crashes occurring on US roadways in calendar years 1981 through 2006. FARS is a census of motor vehicle traffic crashes occurring on US public trafficways that result in at least one fatality within 30 days of the crash.

In addition to FARS data, police-reported motor vehicle accident data files for 1981-2006 from selected states were examined. The state accident data files examined included Florida (1986-2005), Idaho (1990-2006), Maryland (1989-2006), Missouri (1993-2005), Nebraska (2000-2006), and North Carolina (1981-2005). States (and years) used for this study were selected based on availability of data files and of specific data collected, such as VINs; crash type (e.g., frontal, side); driver factors (e.g., age, gender, belt use, alcohol); and injury severity (fatality). Table 1 provides the number of observations used in the logistic regression analyses.

Table 1. Summary of Crashes/Fatalities in Study Data Set, by Crash Configuration

Crash Type	Number of Drivers in Crashes	Number of Driver Fatalities
Car-to-Car	447,722	11,500
Truck-to-Car	235,643	10,090
Truck-to-Truck	54,935	3,431

The police reports, code occupant injury on a five-point scale known as KABCO, where K = killed, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, and O = no injury. To determine where an injury falls on the KABCO scale, police officers rely on the definitions provided by the 1976 National Safety Council manual on Classification of Motor Vehicle Traffic Accidents.

To update the methodology used in previous phases of the study [Padmanaban, 2003; Padmanaban et al., 2004], steps were taken to adjust the model to better reflect the kinematics of front-to-front light vehicle collisions. The kinematic parameters of the frontal crash and their influence on the odds of driver fatality are discussed below. The mass term in the logistic model was transformed to account for the relation between the weights of the colliding vehicles and changes in their velocities during the crash.

VEHICLE SPEED AND ODDS OF DRIVER FATALITY IN A FRONTAL CRASH – In a frontal crash, crash severity plays an important role in influencing injury outcome. A related kinematic parameter—the change in vehicle velocity during the crash (or delta-V, also written as ΔV)—is typically used by researchers to identify crash severity. Higher ΔV , everything else being equal, implies higher deceleration. It is therefore a commonly accepted method to approximate the dependence of the fatality odds on the multitude of kinematic parameters by considering a function based on ΔV .

If two vehicles are colliding head on, the momentum conservation dictates that ΔV of the first vehicle in the crash is:

$$\Delta V_1 = \frac{m_2}{m_1 + m_2} \times (v_1 + v_2) \quad (1)$$

where m_1 , m_2 are the masses of the colliding vehicles and v_1 , v_2 are their velocities directed towards each other. Similar expression can be written for the second vehicle, with an appropriate change of the indices in equation (1). The assumption behind equation (1) is that vehicles lock after the initial phase of the crash. It is correct to about 5-10% accuracy, which is a typical range for the ratio of rebound and initial collision energies.

The odds of fatality are proportional to $(\Delta V)^a$; i.e., if p is a fatality risk, then:

$$\frac{p}{1-p} \sim \left[\frac{m_2}{m_1 + m_2} \right]^a \times (v_1 + v_2)^a \quad (2)$$

where a is a parameter determined by fitting the model to the data. The reason for using odds $p/(1-p)$ on the left side of equation (2), rather than risk p , is that risk is limited by the interval (0,1) while the right side of equation (2) could possibly take any value from 0 to infinity, as can the odds. For instance, if the right side of the equation evaluates to 3 (provided that the proportionality coefficient is taken into account), then the odds are equal to 3, and the risk is 0.75.

When analyzing the state and FARS data, the closing velocity of the crash $v_1 + v_2$ is typically not available and, therefore, only the mass term from equation (1) can be used to explain the fatality odds. The risks of each driver in the frontal crash p_1 and p_2 are then modeled by applying equation (2) to each driver independently. Integrating over the closing velocity term (i.e., dropping it from the equation), the logistic model for the odds of driver fatality in a frontal crash becomes:

$$\log\left(\frac{p_1}{1-p_1}\right) = a \times \log\left(\frac{m_2}{m_1 + m_2}\right) + \text{other parameters} \quad (3a)$$

$$\log\left(\frac{p_2}{1-p_2}\right) = a \times \log\left(\frac{m_1}{m_1 + m_2}\right) + \text{other parameters} \quad (3b)$$

Equations (3a) and (3b) define the updated mass term in the logistic model. An obvious implication of this functional dependence is that, everything else being equal, the fatality odds of the two drivers in a two-vehicle frontal crash are related as:

$$\frac{\text{odds}_1}{\text{odds}_2} = \left(\frac{m_2}{m_1}\right)^a \quad (4)$$

which is in agreement with the observations made by Evans (2004) and confirmed by other authors [Wenzel and Ross, 2006] using recent FARS data.

VERIFICATION OF LOGISTIC FIT – Before applying model (3) to the state and FARS data, the logistic fit was validated using a simulated accident dataset. In particular, it was important to demonstrate that omitting the collision velocity term ($v_1 + v_2$) from equation (2) does not compromise the estimate of the mass term coefficient by the logistic regression fit.