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Vehicle mass and injury risk in two-car crashes: A novel methodology

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ABSTRACT

This paper introduces a novel methodology based on disaggregate analysis of two-car crash data to estimate the partial effects of mass, through the velocity change, on absolute driver injury risk in each of the vehicles involved in the crash when absolute injury risk is defined as the probability of injury when the vehicle is involved in a two-car crash. The novel aspect of the introduced methodology is in providing a solution to the issue of lack of data on the speed of vehicles prior to the crash, which is required to calculate the velocity change, as well as a solution to the issue of lack of information on non-injury two-car crashes in national accident data. These issues have often led to focussing on relative measures of injury risk that are not independent of risk in the colliding cars. Furthermore, the introduced methodology is used to investigate whether there is any effect of vehicle size above and beyond that of mass ratio, and whether there are any effects associated with the gender and age of the drivers. The methodology was used to analyse two-car crashes to investigate the partial effects of vehicle mass and size on absolute driver injury risk. The results confirmed that in a two-car collision, vehicle mass has a protective effect on its own driver injury risk and an aggressive effect on the driver injury risk of the colliding vehicle. The results also confirmed that there is a protective effect of vehicle size above and beyond that of vehicle mass for frontal and front to side collisions.

1. Background

Amongst various vehicle design features, vehicle mass is a key variable from a policy perspective because of its effect on fuel consumption and emissions on the one hand, and its effect on safety performance of vehicles within the fleet on the other hand. A decrease in mass of the vehicles within the fleet is associated with a decrease in overall fuel consumption and emissions (Tolouei and Titheridge, 2009); however, the effect of vehicle mass on safety is more complicated. While it is generally accepted that decreasing the mass of a vehicle, all other factors being constant, imposes a greater risk of injury to its occupants when the vehicle is involved in a crash, it is not clear what effect a change in the distribution of vehicles' mass within a fleet has on the overall safety of the fleet. This is mainly due to the uncertainty on the combined effect of mass of a vehicle on the safety performance of that vehicle as well as that on the safety performance of the other vehicles with which the vehicle collides.

There are two distinct aspects of the safety performance of a vehicle in a fleet: *primary* safety performance, which is linked to the risk of crash involvement of the vehicle, and *secondary* safety performance, which is linked to the risk of occupant injury (to a specific level) when the vehicle is involved in a particular type of crash. While there is no evidence of any direct effect of vehicle mass on the primary safety performance of a vehicle, mass is a key variable that is directly related to the secondary safety performance of the vehicle. In a two-vehicle crash, the injury risk of occupants in the lighter vehicle tends to be higher than that in the heavier vehicle due to the greater velocity change during the collision. In the case of a frontal collision, for example, between two vehicles with masses m_1 and m_2 travelling with speeds v_1 and v_2, it can be easily shown using Newtonian mechanics that the velocity change of the first vehicle during the collision (Δv_1) depends on the proportion of the total mass contained by the other vehicle ($m_2/(m_1+m_2)$) and the closing speed (v_1+v_2):

$$\Delta v_1 = \left(\frac{m_2}{m_1+m_2}\right)(v_1+v_2). \quad (1)$$

There are therefore two aspects of the effects of mass of a subject vehicle on its secondary safety performance in a crash with another vehicle: a *protective* effect related to the injury risk (injury probability) of the occupants in the subject vehicle, and an *aggressive* effect related to the injury risk that mass imposes on the occupants of the other vehicles in collision with the subject vehicle. In order to

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investigate the relationship between vehicle mass and secondary safety performance, two-car crashes have been studied intensively in vehicle safety research. This is because they form a case for vehicle crashes where both protective and aggressive effects of mass are best represented since the closing speed is identical for both drivers in the crash. Two-car crashes can also provide insight into crashes between any pair of vehicles and also into single-vehicle crashes (Evans, 1994). However, there are certain disadvantages or shortcomings associated with the methodologies used so far.

In a two-car crash, Eq. (1) implies that the relative mass of the two cars directly influences the velocity change (Δv). Δv has been regarded and used in vehicle safety research as the best measure of crash severity contributing to the injury risk of vehicle occupants (Evans, 1994). The main difficulty in investigating the relationship between injury risk and Δv is lack of information on the speed of the vehicles prior to a crash, which is required together with mass of the vehicles to calculate Δv (see Eq. (1)).

Eq. (1) implies that in a two-car crash, the velocity change ratio is inversely related to the mass ratio of the cars ($\Delta v_1/\Delta v_2 = m_2/m_1$). As a result of this relationship and lack of data on vehicle speed, several studies have investigated the relative injury risk in two-car crashes as a function of mass ratio. Evans (2004) has intensively studied the effect of vehicle mass in two-car crashes using 1978–1998 US crash fatality data and he has shown empirically that in a crash between two cars of different masses, the fatality risk ratio (R) of the lighter to the heavier car increases as a power function of mass ratio ($\mu = m_2/m_1$) of the heavier to the lighter car (Evans and Frick, 1993):

$$R = \mu^u. \tag{2}$$

The value of parameter u for a given set of two-car crashes is estimated by aggregating the crash data into categories associated with values of μ in given ranges and estimating a least square fit to $\log(R_k) = u \times \log(\mu_k)$ where R_k and μ_k for each crash category k are the ratio of driver fatalities of the lighter cars to the heavier cars and the average mass ratio, respectively. Eq. (2), which is regarded by Evans (2004) as the "first law of two-car crashes", has been commonly accepted and used by the researchers and practitioners in the area of vehicle safety. Different values of exponent u for various sets of US crash data are estimated ranging from 2.70 (crashes in all directions) to 3.80 (frontal crashes) (Evans and Frick, 1992, 1993, 1994; Evans, 1994, 2001, 2004). While Evans' relationship provides a simple approach to estimate injury and fatality risk ratio as a function of mass ratio in two-car crashes, it is associated with some disadvantages (see Tolouei, 2011 for details). For example, Evans (1994) shows that the underlying assumption behind Eq. (2) on the relationship between absolute driver injury and fatality risk (P) and vehicle velocity change (Δv) has the following form:

$$P = \left(\frac{\Delta v}{\propto}\right)^k. \tag{3}$$

where $\propto$ and k are parameters that are estimated from the crash data. As Evans (1994) points out, this relationship suffers from a major structural problem that results in values of risk greater than 1 when $\Delta v > \propto$. Besides, this does not provide the relationship between P and mass of vehicles in two-car crashes explicitly. A few other studies have investigated a similar relationship to that of Evans (Eq. (2)) between fatality and injury risk ratio and mass ratio in two-car crashes (e.g. Ernst et al., 1991; Ernvall et al., 1992; Joksch, 1993; Ross and Wenzel, 2001). These are all empirical studies based on aggregate analysis of crash data, which have used a similar approach to that of Evans and Frick (1993) as explained earlier.

Other studies have investigated the relationship between vehicle mass and driver risk of injury directly. For example, Broughton (1996a) discussed the effect of vehicle mass on injury risk in two-car crashes based on British crash data where injury risk is defined as the probability of driver injury when the vehicle is involved in a two-car crash in which at least one of the drivers is injured. He found that driver risk falls steadily with increasing mass according to a linear relationship and that mass could explain a high proportion of variation in the casualty data. This generally reflected the greater protection of drivers in the heavier cars compared to that of drivers in the lighter cars in fleet; however, this relationship alone does not provide any information on the aggressive effect of vehicle mass in fleet as it does not include the mass of the colliding vehicle. Besides, the measure of injury risk that he has used is not the ideal measure as it is a relative measure and hence is not independent of risk of injury in the colliding car (Broughton, 1996b). Wenzel and Ross (2005) defined risk as the driver deaths per year per million registered vehicles for a given car model and all types of crashes and found that mass alone is only a modestly effective predictor of risk. The difference between their results and those from previous studies on the effect of mass could arise because they used a different measure of vehicle safety; one which is a measure of both primary safety (crash involvement) and secondary safety (injury risk).

The ideal measure of secondary safety in two-car crashes is the absolute injury risk defined as the probability of driver injury when the vehicle is involved in a crash, whether or not the driver in the colliding vehicle is injured. However, the relationship between vehicles' mass and absolute driver injury risk in two-car crashes has remained unclear in the literature. The major issue is that absolute driver injury risk cannot be directly estimated from the crash data because data on non-injury crashes (crashes in which neither of the drivers are injured) is not normally available. Besides, data on the speed of the vehicles prior to the crash, which contribute to the injury risk through Δv (see Eq. (1)), is not available.

One other issue which has not been addressed properly in the analysis of injury risk in two-car crashes is the partial effects of vehicle mass and size. There is generally a high level of correlation between vehicle mass and size (vehicle length or wheelbase has been often used as a proxy for vehicle size in the literature). Many of the studies that have investigated the effect of mass on risk of injury and fatality have not controlled for the effect of vehicle size appropriately; therefore, their estimates could contain the effects of vehicle size as well. There is evidence in the literature suggesting different effects of mass and size on risk of injury and fatality given a crash; however, there are inconsistencies in the results of different studies (for example, see Grime and Hutchinson, 1982; Evans and Wasielewski, 1987; Broughton, 1999; Ross and Wenzel, 2001; Van Auken and Zellner, 2005). The main question, which has remained unclear in the literature, is whether there is any effect of vehicle size above and beyond that of mass ratio (Hutchinson and Anderson, 2009). This is of particular importance because there is the potential to reduce vehicle mass while maintaining its size through various mass-reduction technologies (Ross and Wenzel, 2001).

The study reported in this paper introduces a novel methodology based on a disaggregate analysis of two-car crash data to estimate partial effects of mass, through the velocity change, on absolute driver injury risk in each of the vehicles involved in the crash when absolute injury risk is defined as the probability of injury when the vehicle is involved in a two-car crash. The novel aspect of the introduced methodology is in providing a solution to the issue of the lack of data on the speed of vehicles prior to the crash as well as a solution to the issue of the lack of information on non-injury two-car crashes in national accident data, which has often led to focussing on relative measures of injury risk that are not independent of risk in the colliding cars. Furthermore, the introduced methodology is used to investigate whether there is any effect of vehicle size above and beyond that of mass ratio, and whether there are any effects associated with the gender and age