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Crash protectiveness to occupant injury and vehicle damage: An investigation on major car brands

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ABSTRACT

This study sets out to investigate vehicles' crash protectiveness on occupant injury and vehicle damage, which can be deemed as an extension of the traditional crash worthiness. A Bayesian bivariate hierarchical ordered logistic (BVHOL) model is developed to estimate the occupant protectiveness (OP) and vehicle protectiveness (VP) of 23 major car brands in Florida, with considering vehicles' crash aggressivity and controlling external factors. The proposed model not only takes over the strength of the existing hierarchical ordered logistic (HOL) model, i.e. specifying the order characteristics of crash outcomes and cross-crash heterogeneities, but also accounts for the correlation between the two crash responses, driver injury and vehicle damage. A total of 7335 two-vehicle-crash records with 14,670 cars involved in Florida are used for the investigation. From the estimation results, it's found that most of the luxury cars such as Cadillac, Volvo and Lexus possess excellent OP and VP while some brands such as KIA and Saturn perform very badly in both aspects. The ranks of the estimated safety performance indices are even compared to the counterparts in Huang et al. study [Huang, H., Hu, S., Abdel-Aty, M., 2014. Indexing crash worthiness and crash aggressivity by major car brands. Safety Science 62, 339–347]. The results show that the rank of occupant protectiveness index (OPI) is relatively coherent with that of crash worthiness index, but the ranks of crash aggressivity index in both studies is more different from each other. Meanwhile, a great discrepancy between the OPI rank and that of vehicle protectiveness index is found. What's more, the results of control variables and hyper-parameters estimation as well as comparison to HOL models with separate or identical threshold errors, demonstrate the validity and advancement of the proposed model and the robustness of the estimated OP and VP.

1. Introduction

For a long time, both safety researchers and vehicle designers have made great efforts on exploring the safety characteristics of various motor vehicles (Evans, 2004). Generally, there are two groups of methods on quantifying the impacts of these characteristics on safety (Wenzel and Ross, 2005). The first is based on laboratory experiments for testing the ability of a vehicle to avoid a crash at the pre-crash stage (crash avoidance), and to protect its occupants at the post-crash stage (crash worthiness). However, these tests are rather costly and thus are usually conducted on a single vehicle. What's worse, they cannot replicate the varieties of crash scenes in the reality, such as crashes at different angles with different kinds of vehicles or roadside objects. The second group is to use historical data from real-world crashes to empirically investigate vehicle safety, which has been extensively conducted around the world (Broughton, 1996; Cameron et al., 1999; Gustafsson et al., 1989; Huttula et al., 1997; Subramanian, 2006; Wenzel and Ross, 2005). In the earlier studies, fatalities per distance traveled (Kahane, 2003) and per million vehicles registered (Subramanian, 2006; Wenzel and Ross, 2005), are utilized as the criteria for safety evaluation. Despite of simpleness, these population-averaged approaches cannot control various external factors nor adequately make use of crash severity data with merely considering fatality or non-fatality, and thereby may result in biased analysis. To avoid the shortcoming of population-averaged approaches, crash-specific approaches are adopted in recent research (Fredette et al., 2008; Huang et al., 2011, 2014a,b; Toy and Hammitt, 2003). With more detailed crash information collected and the development of analysis methods, the safety effects of vehicles have been estimated more accurately and precisely.

Specifically, a vehicle's safety performance is mainly evaluated by its crash incompatibility, which is the combination of its crash worthiness, the self-protective capacity, and crash aggressivity, the hazardousness that it imposes on the other vehicle(s) involved

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in the same collision (Fredette et al., 2008; Huang et al., 2014a). These two indices, along with other external factors with regard to driver behavior and collision circumstances etc., are found significantly affecting crash severity when a crash occurs. In the previous studies (Fredette et al., 2008; Huang et al., 2011, 2014a,b; Toy and Hammitt, 2003), only the severities of occupant injury (especially driver injury) are considered as crash severity outcomes. Although vehicle damage is seldom used as the dependent variable when modeling crash severity, several studies indicated that those mentioned-above factors may have significant effects on it as well (Broyles et al., 2001; Zwerling et al., 2005). Moreover, no injury (or property damage only, PDO) crashes usually account for the largest portion of the whole crash population. That is, vehicle damage is the only cost in most collisions. Therefore, someone may also want to know how a vehicle shields itself in a collision, particularly for the users of luxury cars.

In current study, we divide the conventional crash worthiness into two separate components: occupant protectiveness (OP), i.e. protective capacity of a vehicle on its occupants, and vehicle protectiveness (VP), i.e. protective capacity of a vehicle on itself. Accordingly, both occupant injury and vehicle damage are employed as response variables in the model for rating the two indices with taking vehicles' crash aggressivity into consideration and other external factors controlled. Given that a collision occurs, the correlation between the responses of the same vehicle may exist for possibly sharing some unobserved or unobservable factors that may have significant influence on the both responses, such as the time of collision, weather condition and light condition. Thus, we modify the state-of-the-art method, Bayesian hierarchical ordered logistic (HOL) model, proposed by Huang et al. (2011) for indexing vehicles' crash aggressivity and worthiness, into a Bayesian bivariate hierarchical ordered logistic (BVHOL) model. It accounts for the potential correlation between the severities of damage sustained by a vehicle and its occupants, while retains the HOL model's original advantages over the other subject-specific methods, including reasonably taking the order nature of crash severity and cross-crash heterogeneities into account (Huang and Abdel-Aty, 2010). Although the BVHOL model is suitable for evaluating safety performance of any vehicle type, model or other properties, herein we only demonstrate the proposed model by an example of comprehensively investigating the OP and VP of 23 major passenger car brands in Florida.

The remainder of this paper is organized as follows. The next section explicitly describes and preprocesses the crash data collected from Florida to index the OP and VP of major passenger car brands. The structure of the developed BVHOL model is illustrated specifically in Section 3. Section 4 introduces the detailed implementation of the proposed model and discusses the estimation results. Finally, conclusions and recommendations for future research are presented in Section 5.

2. Crash data preparation

2.1. Data screening

The historical crash dataset in Florida in 2007, which is maintained by the Florida Department of Highway Safety and Motor Vehicles (DHSMV), is used in this analysis. Five criteria are employed to screen the data: (1) Two-vehicle crash. As we aim to study the crash aggressivity of the striking vehicle and the VP and OP of the struck vehicle, records of crashes involved with two vehicles are suitable. (2) Passenger cars only. Since injury severity is significantly dependent on the incompatibility between different types of vehicle (Huang et al., 2011), vehicle type need to be controlled when studying occupant injury and vehicle damage of passenger cars. (3) Driver injury representing occupant injury. In the collected crash data, driver injury records are more complete than those of passenger injury. Moreover, drivers often suffer severer injury and their seating position is fixed compared to passengers'. (4) Head-on, rear-end and angle crash type. These three crash types could accurately reflect the effects of colliding vehicles on crash severity, which excludes other major impacts on collision outcomes, such as driver injury caused by hitting roadside objects. Meanwhile, the crash types facilitate the estimation of relative speed, an important control variable, according to the recorded speeds of individual vehicles at the collision instant. (5) Cars made in 2000–2007. Vehicle age is also found having an important effect on crash severity (Zeng and Huang, 2014b), thus, we only select cars made in 2000–2007 to ensure these relatively new cars with similar safety devices and features. Moreover, 23 popular car brands in Florida are involved, including Acura, Benz, BMW, Buick, Cadillac, Chevrolet, Chrysler, Dodge, Ford, Honda, Hyundai, Infiniti, Kia, Lexus, Lincoln, Mazda, Mitsubishi, Nissan, Pontiac, Saturn, Toyota, Volkswagen and Volvo. With the above mentioned criteria, the data filtering yields a total of 7335 two-car crashes with 14,670 cars involved. The percentages of these car brands are summarized in Table 1.

2.2. Response and control variables

The response and control variables used for evaluating the OP and VP of the popular car brands are listed in Table 2, together with their description and statistics. Following the original definition in crash reports of Florida, the severity of driver injury is divided into five ordered categories, which is a very popular division in US: Category 1 – no injury (O); Category 2 – possible injury (C); Category 3 – non-incapacitating injury (B); Category 4 – incapacitating injury (A) and Category 5 – fatality (K). Similarly, the degree of vehicle damage is categorized into three ordered levels: Level 1 – no damage; Level 2 – functional damage; Level 3 – disabling damage. In the dataset, about 70% of drivers are not injured while over 60% of cars are damaged functionally in crashes.

The control variables in Table 2 are just the external factors controlled in the previous studies for indexing the crash aggressivity and worthiness by vehicle type (Huang et al., 2011) and make (Huang et al., 2014a) and rating cars' total secondary safety performance (Huang et al., 2014b), which cover most of the important characteristics of drivers and collisions.

In addition to the research on vehicle incompatibility, a great number of studies for analyzing crash severity have confirmed that both driver age and gender significantly influence the damage imposed on drivers and vehicles presumably for their behavioral and physiological differences (Farmer et al., 1997; Ulfarsson and Mannering, 2004; Zeng and Huang, 2014b). We partition drivers' ages into three groups: <25, 25–65, >65 years, representing young, middle-aged and elderly people respectively, and the young group is set as the reference one.

As we all know, using seat belts is able to prevent occupants' ejection. Actually, both 'seat belt used or not' and 'driver ejected or not' are included in Florida crash reports, but the latter is preferred as a control variable than the former, since most ejected drivers are found not wearing seat belts and 'driver ejected or not' is more strongly correlated with crash severity.

Undoubtedly, there is a close relationship between colliding velocity and crash severity degree. Suppose a two-vehicle crash happens, generally, the higher the relative speed of the two vehicles, the greater cost it may bring about. The estimated speeds of the two cars involved in the same crash are used to calculate the relative speed: if it is a head-on crash, the relative speed is the sum of the two estimated speed; if it is a rear-end crash, the relative speed is the absolute value of their difference; else it is an angle crash,