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Have pedestrian subsystem tests improved passenger car front shape?

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ABSTRACT

Subsystem impactor tests are the main approaches for evaluation of safety performance of vehicle front design for pedestrian protection in legislative regulations. However, the main aspects of vehicle safety for pedestrians are shape and stiffness, and though it is clear that subsystem impact tests encourage lower vehicle front stiffness, it is unclear whether they promote improved vehicle front shapes for pedestrian protection. The purpose of this paper is therefore to investigate the effects of European pedestrian safety regulations on passenger car front shape and pedestrian injury risk using recent German In-Depth Accident Study (GIDAS) pedestrian collision data and numerical simulations. Firstly, a sample of 579 pedestrian collision cases involving 190 different car models between 2000–2015 extracted from the GIDAS was used to compare front-end shapes of passenger cars manufactured before and after the legislative pedestrian safety regulations were introduced in Europe. The focus was on changes in passenger car front shape and differences in pedestrian AIS2+ (Abbreviated Injury Scale at least level 2) leg, pelvis/femur and head injury risk observed in collisions. Multi-body simulations were also used to assess changes in vehicle aggressivity due to the observed changes in vehicle shape. The results show that newer passenger cars tend to have a flatter and wider bumper, higher bonnet leading edge, shorter and steeper bonnet and a shallower windscreen. Both the collision data and the numerical simulations indicate that newer passenger car front bumper designs are significantly safer for pedestrians' legs. However, the results also show that the higher bonnet leading edge in newer passenger cars is poor for pedestrian pelvis/femur protection, even though newer cars show an obviously lower AIS2+ injury risk to younger pedestrians in collisions. Newer cars have a lower AIS2+ head injury risk for pedestrians in collisions, but the numerical analysis indicate that this is not likely due to shape changes in passenger car fronts. Overall, the introduction of pedestrian safety regulations has resulted in reductions in pedestrian injury risk, but further benefits would accrue from tests which promote a lower bonnet leading edge. The influence of vehicle shape on pedestrian head injury risk remains unclear.

1. Background

Pedestrian protection is a major concern in vehicle safety due to the high frequency of occurrence and high injury/fatality risk in these collisions (World Health Organization, 2013). Many studies have focused on understanding pedestrian injuries and kinematics and developing pedestrian protection technologies based on real world collision data (Lefler and Gabler, 2004; Li et al., 2012, 2017a; Otte, 1994), physical impact tests (Kajzer and Schroeder, 1992; Kerrigan et al., 2003, 2008) and numerical simulations (Elliott et al., 2012; Han et al., 2012; Li et al., 2015, 2017b). These studies have provided useful information to improve vehicle design for pedestrian protection and it is now well understood that variations in pedestrian injuries for a collision at a given speed and pedestrian age arise primarily from a combination of vehicle shape and stiffness (Liu et al., 2002; Matsui et al., 1999; Simms and Wood, 2009).

Moreover safety regulations and consumer tests, such as the EU Directive on pedestrian safety and New Car Assessment Programs (NCAPs) in different countries and regions also include pedestrian subsystem test procedures to evaluate new car safety performance using isolated impactors considering leg-to-front bumper impacts, pelvis-to-bonnet leading edge and head-to-bonnet/windshield area impacts (C-NCAP, 2018; Euro-NCAP, 2017; J-NCAP, 2014). With a decade of continuing development, the current car fleets show significantly higher score in Euro-NCAP tests than cars assessed in the early 2000s (Strandroth et al., 2014).

Many studies have focused on this topic. Delaney and Cameron (2006) analysed the potential relationships between Euro-NCAP

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pedestrian star rating and pedestrian injury severity using collision data reported by police from Great Britain, France and Germany. However, no significant relationship was found in this study. Liers and Hannawald (2011) investigated how well the pedestrian rating system matches the expected real world benefit based on GIDAS collision data, and found a correlation between the Euro-NCAP score and moderate pedestrian injuries, but reported significant injury ranges within a single Euro-NCAP score. A study of the correlation between pedestrian injury severity in real world crashes and Euro NCAP pedestrian scores in Sweden showed a reduction of injury severity when comparing tow star cars with one-star cars (Strandroth et al., 2011). However, cars with a high Euro-NCAP score and the effect on separate body regions could not be analysed in this study due lack of cases. Pastor (2013) used pedestrian collision data with 7576 Euro-NCAP rated vehicles collected in the German National Collision Records during 2009–2011 and found significant correlations between pedestrian injury severity in real-life crashes and Euro-NCAP pedestrian test results. In particular, the fatality risk was reduced by 35% and the risk of a serious injury by 16% when comparing a vehicle scoring 5 points with a vehicle scoring 22 points in Euro-NCAP (Pastor, 2013). But the impact speed and pedestrian age which are highly correlated with pedestrian injury severity have not been controlled and the effects on different body regions have not been considered in this paper. Strandroth et al. (2014) studied 1184 real world pedestrian collision cases recorded by police and hospitals in Sweden between January 2003 and January 2014 and found that low scoring cars in Euro-NCAP pedestrian test have a 20–56% higher AIS2+/AIS3+ (Abbreviated Injury Scale at least level 2/3) injury proportion and RPMI1+/RPMI10+ (Risk of Permanent Medical Impairment at least 1%/10%) risk than high scoring cars, and this difference is significant for all body regions, especially for the head. However, in their study the injuries in the pelvis and leg were combined together even though the vehicle structures involved are generally different. Recently, Nie and Zhou (2016) used a numerical assessment approach to compare the front shape between vehicles with model year before 2003 and between 2008–2011, and found that newer cars have flatter front-end designs which tend to reduce pedestrian knee ligament injury risk. However, no evidence from collision data was available and the injury risk of other body regions were not analysed.

Thus it is clear that bumper shape and stiffness has evolved to reduce pedestrian injury risk however, it remains unclear whether the subsystem impactor approach has also improved vehicle front *shape* for femur/pelvis and head protection. Therefore, the purpose of this study is to investigate detailed changes in passenger car front shape and in accompanying pedestrian injury risk before and after subsystem impactor tests were introduced for pedestrian protection in Europe. The focuses of the current study are as follows:

1 How passenger car front shape, including bumper, bonnet leading edge, bonnet and windscreen, has changed since the introduction of pedestrian safety regulations and consumer tests in Europe?
2 Whether pedestrian head, pelvis/femur and leg injury risk has improved following the introduction of pedestrian safety regulations in Europe?
3 Whether the observed changes in passenger car front shape since the introduction of pedestrian safety regulations in Europe have benefitted pedestrian protection (separate to considering stiffness changes)?

2. Methods

2.1. Collision data and sampling

Pedestrian collision data from GIDAS were analysed, with the following inclusion criteria: 1) GIDAS pedestrian collision cases collected between 2000–2015, 2) collisions involving passenger cars (accounting for about 90% of GIDAS pedestrian cases) which stopped production before 2000 or started production after 2005, 3) both pedestrian and vehicle information are available, 4) the pedestrian was upright (not lying or sitting), 5) pedestrians were hit only once by the vehicle front. Based on these criteria, 579 cases were extracted from an original sample of 1258 pedestrian cases as the analysis sample, where in total 190 passenger car models were included.

Table 1
Groups for passenger car models according to the executing time of regulations for pedestrian protection in Europe.

Group	Production year	No. of car models	No. of collision cases
Old	Before 2000	144	518
New	After 2005	46	61

The inclusion criterion for car model year was defined to consider the effect of pedestrian protection regulations on car front design. The 2003 European Directive (EC, 2003) included the EEVC subsystem tests (EEVC, 2002) to promote improvement of vehicle front design for pedestrian protection since 2005. This cut-off date for vehicle model year is similar to a previous study from Shang et al. (2017). Table 1 summarises the vehicle data, where the group ***Old*** includes passenger car models that stopped production before 2000 (i.e. before the regulations for pedestrian protection were introduced) while the group ***New*** includes passenger car models starting production since 2005 (i.e. after the introduction of subsystem impactor tests). Passenger car models manufactured during 2000–2005 were not included since this may be regarded as a transitional period for changes in car front design. This sampling approach was defined to study the correlation between the introduction of subsystem impactor tests and car front shape change, even though other factors might also affect car front design.

2.2. Comparisons of shape between Old and New passenger car fronts

The main parameters defined to describe the passenger car front shape are shown in Fig. 1. These were measured parameters for each car model (brand, model and year in GIDAS) from the corresponding vehicle blueprint (The-Blueprints, 2015) and scaled accordingly. The bumper and bonnet leading edge dimensions were measured using the EEVC WG17 (EEVC, 2002) protocol by the defined reference lines (BLR, BUR and BLER in Fig.1), similar to previous studies (Li et al., 2017a; Shang et al., 2017).

The Mann-Whitney U test was applied to evaluate the difference in passenger car front shape parameters defined in Fig. 1 (measurements in red) between the ***Old*** and ***New*** passenger car fronts (the data is not normally distributed), similar to a previous collision analysis (Matsui, 2005). A p-value lower than 0.05 was used to indicate a significant difference between the two groups.

2.3. Comparisons of pedestrian injury risk between Old and New passenger car fronts

In the GIDAS database pedestrian's leg (including knee and lower leg), pelvis/femur and head injuries account for about 60% of AIS2+ injuries (Li et al., 2016a) and these body regions are considered in the pedestrian subsystem impactor test procedure (EEVC, 2002). Therefore, this section focuses on analysing the differences in injury risk for these body regions between the ***Old*** and ***New*** passenger car fronts. To build a comprehensive understanding, both observations from collision data and predictions from numeric simulations were analysed.

2.3.1. Observations from collision data

AIS2+ injury risk for pedestrians' leg, pelvis/femur and head were considered as the index for assessing the safety performance between the ***Old*** and ***New*** passenger car fronts. Firstly, the injury outcome was defined as a binary variable and coded as 1/0 for the cases with/