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Safer passenger car front shapes for pedestrians: A computational approach to reduce overall pedestrian injury risk in realistic impact scenarios

Guibing Li[a,b,*], Jikuang Yang[c,d], Ciaran Simms[b]

[a] School of Automobile and Mechanical Engineering, Changsha University of Science and Technology, Changsha, 410114, China
[b] Centre for Bioengineering, Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland
[c] Research Center of Vehicle and Traffic Safety (VTS), State Key Lab of Advanced Design and Manufacturing for Vehicle Body, Hunan University, China
[d] Vehicle Safety Division, Department of Applied Mechanics, Chalmers University of Technology, Sweden

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ABSTRACT

Vehicle front shape has a significant influence on pedestrian injuries and the optimal design for overall pedestrian protection remains an elusive goal, especially considering the variability of vehicle-to-pedestrian accident scenarios. Therefore this study aims to develop and evaluate an efficient framework for vehicle front shape optimization for pedestrian protection accounting for the broad range of real world impact scenarios and their distributions in recent accident data. Firstly, a framework for vehicle front shape optimization for pedestrian protection was developed based on coupling of multi-body simulations and a genetic algorithm. This framework was then applied for optimizing passenger car front shape for pedestrian protection, and its predictions were evaluated using accident data and kinematic analyses. The results indicate that the optimization shows a good convergence and predictions of the optimization framework are corroborated when compared to the available accident data, and the optimization framework can distinguish 'good' and 'poor' vehicle front shapes for pedestrian safety. Thus, it is feasible and reliable to use the optimization framework for vehicle front shape optimization for reducing overall pedestrian injury risk. The results also show the importance of considering the broad range of impact scenarios in vehicle front shape optimization. A safe passenger car for overall pedestrian protection should have a wide and flat bumper (covering pedestrians' legs from the lower leg up to the shaft of the upper leg with generally even contacts), a bonnet leading edge height around 750 mm, a short bonnet (<800 mm) with a shallow or steep angle (either >17° or <12°) and a shallow windscreen (≤30°). Sensitivity studies based on simulations at the population level indicate that the demands for a safe passenger car front shape for head and leg protection are generally consistent, but partially conflict with pelvis protection. In particular, both head and leg injury risk increase with increasing bumper lower height and depth, and decrease with increasing bonnet leading edge height, while pelvis injury risk increases with increasing bonnet leading edge height. However, the effects of bonnet leading edge height and windscreen design on head injury risk are complex and require further analysis.

1. Introduction

Accident data show that current vehicle designs still pose serious threats to pedestrians and the shape of a vehicle front has a significant influence on pedestrian injury risk (Liu et al., 2002; Longhitano et al., 2005; Peng et al., 2012). Even though much progress has been made in improving vehicle front design for pedestrian protection (Nie and Zhou, 2016; Schuster, 2006; Simms and Wood, 2009), an optimized vehicle front design remains an elusive goal. The broad range of vehicle-to-pedestrian accident scenarios implies that vehicle front optimization for pedestrian protection should consider the actual distribution of impact scenarios rather than one or two idealised collision configurations presently included in consumer and legislative tests (EEVC, 2002;

* Corresponding author at: School of Automobile and Mechanical Engineering, Changsha University of Science and Technology, 960, 2nd Section, Wanjiali South RD, Changsha 410114, China. Tel.: +86 (0)13667398086.
E-mail address: li8747@hotmail.com (G. Li).

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Euro-NCAP, 2013). Given the cost of physical testing and the increasing capacity of computational models to reproduce the results of physical tests and injury distributions in accidents (Elliott et al., 2012a; Li et al., 2016a), a computer-based vehicle front optimization approach which accounts for the broad range of actual pedestrian accident scenarios is now a realistic proposition.

Several researchers have focused on multibody model optimization of vehicle front shape for pedestrian protection. Carter et al. (2005) applied a Genetic Algorithm (GA) to optimize passenger car centre-line geometry to reduce pedestrian head and thorax injuries for three pedestrian sizes and two gait stances at 40 km/h. However, results did not show good convergence or a clear conclusion on improved shape. Kausalyah et al. (2014) used an adult and a child model struck at 40 km/h, response functions and a GA to optimize vehicle front shapes for head protection. However, injuries from other body regions and the effects of impact speed were not considered. Subramanian et al. (2012, 2016) proposed an injury cost objective for optimization which included injuries to the head, neck, thorax and leg (long bones) of different pedestrian sizes in simulations at 40 km/h. However, the effects of impact speed and pedestrian gait stance were not considered though these are important for pedestrian impacts (Elliott et al., 2012b; Li et al., 2015a; Peng et al., 2012; Simms and Wood, 2006). Moreover, their vehicle front models had some discontinuities between different structures (e.g. the bumper and bonnet), which caused some contact challenges (Subramanian et al., 2012, 2016) and they did not compare results to accident data.

Recently, we proposed a Simulation Test Sample (*STS*) approach and an Injury Weighting System (*IWS*) which can account for the broad range of pedestrian impact scenarios and their distributions in accidents and predict similar injury distributions as published accident data (Li et al., 2016a,c). Based on these approaches a fitness function for vehicle front optimization was further defined using the injury cost system proposed by ISO: 13232-5 (2005) in Li et al. (2015b). The purpose of the present study is therefore to assemble these earlier approaches as an efficient framework for vehicle front shape optimization for pedestrian protection accounting for the broad range of real world impact scenarios observed in recent accident data and to evaluate this framework by applying it to optimize passenger car front shapes for overall pedestrian protection. Passenger cars are our focus since they account for about 90% of pedestrian cases in the German In-Depth Accident Study (GIDAS) data (Li et al., 2016b). The key approaches used in the current study are summarized as follows:

- A Simulation Test Sample (STS) consisting of 60 weighted impact scenarios based on the GIDAS data (Li et al., 2016c) is used to represent the range of pedestrian collision configurations based on multi-body simulations via MADYMO software (MADYMO, 2013b).
- A novel dimension chain is used to generate and control continuous vehicle front shapes in the optimization process.
- A fitness function to weight the predicted pedestrian injuries is based on the distribution of impact scenarios in GIDAS data using the ISO: 13232-5 injury costs (ISO: 13232-5, 2005; Li et al., 2015b).
- A Genetic Algorithm (GA) defined using the MATLAB Global Optimization Box (MathWorks-GA, 2016) is used to optimize passenger car front shape for overall pedestrian protection.
- GIDAS pedestrian accident data and sensitivity studies are used to evaluate and understand the predictions of the optimization framework.

2. Methods

2.1. Optimization framework

2.1.1. Simulation test sample (STS)

We previously proposed a Simulation Test Sample (*STS*) approach to assess the threat of a vehicle front design to pedestrians in accidents (Li et al., 2016a,c). This *STS* accounts for the broad range of impact speeds, pedestrian heights and gait stances and including injuries from ground contacts for low impact speed collisions (<40 km/h) (Li et al., 2016a,c). The size of the *STS* can be varied to control overall predictive capacity, but an *STS* including sixty different impact scenarios (Li et al., 2016c) was selected for assessing the aggressivity of a vehicle front design in the optimization. In this *STS* impact speeds of 16–75 km/h, which cover nearly 90% of AIS2+ injury accidents in GIDAS (Li et al., 2016b), were divided into six discrete groups with an interval of 10 km/h, see Table A1. Pedestrian heights were divided into five groups according to the GIDAS data and the availability of MADYMO pedestrian models (MADYMO, 2013a) to meet the average height of the corresponding group (Li et al., 2016a), Table A1 and Fig. A1. In particular, the 6 years old (6YOC), 5th% female (5th%F), 5th% male (5th%M), 50th% male (50th%M) and 90th% male (90th%M) pedestrian models were used, where all other models were scaled from the 50th%M model via MADYMO/SCALER. According to previous studies the 50th%M model and scaled adult male models of different sizes are generally reliable to predict pedestrian head kinematics in vehicle-to-pedestrian collisions (Elliott et al., 2012a; Lyons and Simms, 2012), when compared to cadaver and dummy test data published by Kerrigan et al. (2005, 2009a) and Subit et al. (2008). Unfortunately, no direct validation data for the 5th%F and the 6YOC models are available yet. Two of the ten pedestrian gait stances proposed by Untaroiu et al. (2009) were included (struck leg forward or backward with a straight knee, see Fig. A2) since these two cases have more potential to lead to a high injury risk to pedestrians' legs and heads compared to other stances (Elliott et al., 2012b; Li et al., 2015a). In total sixty impact scenarios (six vehicle impact speeds × five pedestrian heights × two gait stances) were included in the *STS* which shows good predictive capability for pedestrian injury distribution compared to real world accident data (Li et al., 2016c).

2.1.2. Vehicle-to-pedestrian impact simulation

To facilitate efficient assessment of thousands of different vehicle front shapes, a simplified and automated process to ensure continuous front shapes is needed. As this work was a largescale and conceptual analysis the detailed curvature of the vehicle front was not considered. Accordingly, a geometric dimension chain defined by the centres of six ellipsoids was developed as a string of numerical parameters in MATLAB (MathWorks-GA, 2016) to describe the vehicle centre-line geometry, see Fig. 1(a). This chain is controlled by bumper lower height (#1) and depth (#2), bumper height (#3), bumper upper height (#4), bonnet leading edge height (BLEH, #5) and depth (#6), bonnet angle (#7) and length (#8) and windscreen angle (#9), and each combination forms a unique vehicle front shape. The dimensions for bumper and bonnet leading edge were defined according to the EuroNCAP protocol (Euro-NCAP, 2013). The geometric dimension chain is thus able to define a vehicle front model automatically by coupling MATLAB and MADYMO.

The crash scenario with a pedestrian being hit laterally (Fig. 1(b)) accounts for about 80% of accidents in GIDAS and was considered as the baseline simulation condition for varying vehicle speed and pedestrian size, gait stance and walking speed. The pedestrian was offset by 400 mm from the vehicle centre line (opposite to the pedestrian walking direction, see Fig. 1(b)) since a specific walking