Establishment of regression model for predicting pedestrian head injury based on vehicle front-end structural parameters

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I. INTRODUCTION

In China, 17,286 pedestrians died in road traffic accidents in 2017, 84.25% of whom died from head injuries [1]. In vehicle-to-pedestrian impacts, the vehicle front structural parameters are considered one of the most important factors affecting pedestrian head injury outcomes and as such have been studied extensively [2-3]. However, most studies focus on the relationship between the vehicle front-end structural parameters and pedestrian head injury caused by either (1) the pedestrian-to-vehicle impact (primary impact), or (2) the pedestrian-to-ground impact (secondary impact) [4]. There are very few studies that have performed a comprehensive analysis of both primary and secondary impacts. Regression analysis, which is a common analysis method used to analyse the relationship between the significant influencing factors of vehicle front-end structures and head injury risk, has been widely studied, but there is a lack of studies on comprehensive and quantitative analysis of all parameters and head injury risk.

Therefore, in this study we establish the regression model for pedestrian head injury risk in both primary and secondary impacts, and then quantitatively describe the relationship between all vehicle front structural parameters and the head injury risk.

II. METHODS

There are three key steps to establish head injury prediction regression equations based on the vehicle front structural parameters, as shown in Fig. 1. First, a total of 300 simulation sample sets was generated using the Latin Hypercube Design Test while considering five vehicle front structural parameters and three impact configurations. Secondly, the pedestrian kinematics were performed using the MADYMO code, and head injury criterion (HIC₁₅) values statistical analysis was undertaken for both primary and secondary impacts. Finally, multiple regression equations were established, accounting for both primary and secondary impacts based on the multiple regression analysis method.



Fig. 1. Analysis flowchart.

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Step 1. Building the simulation matrix

In this study, the multi-body vehicle model was established based on a real and verified vehicle model [5]. In this model, the front-end structure included the bumper centre height (BCH), bonnet leading edge height (BLEH), bonnet length (BL), bonnet angle (BA), and windshield angle (WA) (see Fig. 2). The upper and lower limits for the vehicle front-end structural parameters (see Fig. 1) were obtained from the literature [6].



Fig. 2. Parametric vehicle model.

Fig. 3. Parametric pedestrian model.

As pedestrians have different heights and weights, three different sizes of multi-body pedestrian model were selected in order to make the simulations closer to real-world accidents. These include a 5th percentile adult female and a 50th and a 95th percentile adult male (Fig. 3). In this study, two types of pedestrian gait were selected based on the classification of gait by Untaroiu [7]. The pedestrian walking speed is 1.54 m/s, based on the different age groups by Kong [8]. A total of 300 simulation sample sets was generated as prescribed based on the optimal Latin Hypercube method.

Step 2. Kinematics simulation in MADYMO

In real-world traffic accidents, the vehicle-to-pedestrian side impact is the most common collision scenario [9]. Therefore, for this study we chose the pedestrian side and the vehicle frontal centre as the contact area. A friction coefficient as 0.3 was selected between the vehicle-to-pedestrian impacts and of 0.6 between the pedestrian-to-ground impacts [10]. In order to simulate the pedestrian whole kinematic response and obtain HIC₁₅ in both the primary and secondary impacts, the calculation duration was carried out to 2,500 ms for each simulation model.

Step 3. Establish regression model for both primary and secondary impacts

Multiple regression analysis is a statistical analysis method based on sample sets to establish the relationship between the dependent variable and multiple independent variables [14]. The equation was as follows:

$$\mathbf{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \varepsilon \tag{1}$$

where y is the dependent variable, $x_1 \cdots x_n$ are the independent variables, $\beta_0 \cdots \beta_n$ are the constant coefficients, and ε is an error that is expected to be zero, which follows a normal distribution. Generally, the R-square value represents the degree to which the regression equation explains the original data and the F-value represents the relationship between independent variables and the dependent variable.

III. INITIAL FINDINGS

Establishment of regression equation

The multiple regression equation between the vehicle front structural parameters and pedestrian head injury in primary impact was obtained as shown below in Eq. 2:

$$HIC_{15} = -3.2 \times BA - 0.23 \times BCH - 0.28 \times BL - 0.204 \times BLEH + 1.01 \times WA + 28.5 \times V + 30.7 \times G + 58.1 \times S + 216.5$$
(2)

where R-square is 0.53 and F-value is 39.11.

Through a comprehensive consideration of the upper and lower limits of the vehicle front-end structural parameters and the regression coefficients, we found the sensitivity of each of the front-end parameters to be:

BL > BLEH > BA > BCH > WA. In addition, based on the symbol for each coefficient, the relationship between the vehicle front-end parameters and the head injury risk can be obtained. Figure 4 provides the fitting results of the regression equation to original data, of which the red points represent the original data and the blue points represent the predicted values from the regression equation. In general, the fitting results indicated that the multiple regression equation has a good explanatory capability for predicting the original data.



Fig. 4. Fitting results of regression equation to original data in primary impact.

In addition, the multiple regression equations in secondary impact were also established, as shown in Eq. 3: $HIC_{15} = 28.6 \times BA + 0.58 \times BCH - 0.31 \times BL + 0.99 \times BLEH - 7.89 \times WA + 17.87 \times V + 139.7 \times G$ $- 431.5 \times S + 225.3$ (3)

where R-square and F-value are 0.41 and 8.56, respectively.

The sensitivity analysis results show that BA and BLEH are the most sensitive parameters for the pedestrian head injury risk in secondary impacts, followed by BL and WA; while BCH is the least sensitive parameter. Figure 5 provides the fitting results of the regression equation to the original data for the secondary impacts. Compared to the original data, the results of regression equation are more concentrated in the middle area, and the fitting results indicate that the secondary impact is worse than the primary impact.



Fig. 5. Fitting results of regression equation to original data in secondary impact.

The predictive capability of multiple regression equations

In order to obtain the predictive capability of multiple regression equations, the following steps were taken. First, we used the relationship between the HIC value and the AIS injury level to convert the HIC value in the simulation to the corresponding AIS injury level. Then, for each simulation we determined two AIS injury levels – AIS_a and AIS_b – where AIS_a is obtained by the MADYMO simulation and AIS_b is obtained based on the regression equation. Finally, the AIS level deviations were obtained in primary and secondary impacts through subtracting AIS_a and AIS_b . The results are shown in Fig. 6 and Fig. 7.





Fig. 6. AIS level deviation in primary impact.



An AIS level deviation that is close to zero means that the equation's predictive capability is better. From Figure 6, it is observed that an AIS level deviation of zero accounts for 42% of the values and that an AIS level deviation that does not exceed ±1 level reached 88.67%. From Figure 7, it is observed that an AIS level deviation of zero accounts for only 26% of the values, and that for 61.33% of the data the AIS level deviation does not exceed ±1 level.

IV. DISCUSSION

In this study, there are some inconsistencies in the parameter sensitivity analysis between the primary and secondary impacts as determined through comparing Eq. 2 and Eq. 3. In the primary impact, the most sensitive parameters are BL and BLEH, and there was an increase in pedestrian head injury risk through a decrease in BL and BLEH. In the secondary impact, however, the most sensitive parameters are BA and BLEH, and there was an increase in the BA and BLEH parameters. As a result of these findings, it is clear that it is necessary to consider *both* primary and secondary impacts in vehicle safety design, because a vehicle front-end structural design that is good for pedestrian head injury protection in a primary impact may lead to more serious head injury in a secondary impact.

In addition, we used the AIS level deviation instead of R-square to evaluate the predicted capability of the derived regression equations determined in this study. R-square means the HIC₁₅ deviation between the original data and the calculated value by the equations. In fact, the level of pedestrian head injury severity is similar when HIC₁₅ is equal to 100 or equal to 200, but the result will likely lead to R-square being unsatisfactory. Although it is more persuasive to use R-square as the basis for judging the quality of regression equation, as only 300 sample sets were simulated in this study it is difficult to get a satisfactory R-square value. There are some limitations in this study that must be noted. First, we used only 300 simulation sample sets to evaluate the prediction capability of the regression equations, and a lack of real-world accident cases meant there could be no further evaluation carried out. Secondly, only 61.33% of the data can be predicted when the AIS level deviation does not exceed ±1 level in the secondary impact.

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