Safety performance optimization of front bumper system based on pedestrian lower leg protection

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Abstract. Taking the front bumper system of a passenger car as the research object, a finite element model of pedestrian lower leg collision was first established, and the tibial acceleration at Y400 was found to be high in the performance analysis. Second, the sensitivity analysis was performed on the main parameters of the bumper system to determine the skin Thickness and foam density are the main influencing variables. Finally, a performance improvement scheme is proposed, and the lower leg tibia acceleration is reduced by 47.71% after the improvement, indicating that the scheme is conducive to lower leg protection.

1. Introduction
In traffic accidents, pedestrians are the most vulnerable groups, and pedestrians' lower leg are the most vulnerable parts. The front bumper system first contacted the pedestrian's leg, causing tibia fractures, ligament tears, and knee injuries. The current research method is to reduce the damage to the lower leg by changing the thickness of the relevant materials, but less consideration is given to the overall collision performance, and it does not involve the development and design of new components. The optimization scheme proposed in this article satisfies various performances, provides a reference for the development of the front bumper system, saves development costs, and has certain research significance.

2. Pedestrian lower leg collision performance analysis

2.1. Establishment of finite element model for lower leg collision
The front bumper system mainly includes the front bumper skin, energy absorbing foam, and beams. The front bumper skin includes parts such as skin, upper grille, lower grille, left and right brackets, etc. In Hypermesh, it is divided according to a grid size of 5mm, foam and beams are divided according to a grid size of 8mm, and the skin and beam use thin shells. Foam uses solid units, as shown in Figure 1. In terms of material selection, the skin and beams were simulated using MTL24, and the energy-absorbing foam was MTL57[1]. A shell unit is covered on the outer surface of the energy-absorbing foam to prevent the occurrence of negative volume. The material parameters are shown in Table 1.
In terms of connection settings, this study uses rigidbody to simulate the connection between deformable locks; by creating a nodal rigid body, the bolt connection between parts is achieved\textsuperscript{[2]}. Set the center of mass coordinates and give the vehicle a mass of 1.595t.

This article uses a pedestrian protection test leg impactor developed by LSTC. This model is based on the physical structure of the lower limb module of EEVC, as shown in Figure 2.

The model contains 29 components, divided into upper leg and lower leg parts, and they are connected by ligaments. The pedestrian lower leg finite element model has passed the static and dynamic calibration tests required by European regulations (EC631 / 2009)\textsuperscript{[3]}.

The six degrees of freedom in the x, y, and z directions must be constrained on the bumper system. In addition, according to the requirements of pedestrian collision regulations, a leg impactor of 40km/h in the x direction is given. Bumper self contact, leg bumper self contact, and bumper and calf bumper contact must be set. The calculation time of the pedestrian leg collision model set in this paper is 30ms.

In terms of the collision area, the collision points Y0, Y100, Y200, Y300, and Y400 with distances...
from the center of symmetry of 0mm, 100mm, 200mm, 300mm, and 400mm were selected. According to EEVC regulations, pedestrian evaluation indicators are shown in Table 2 below.

Table 2 Pedestrian lower leg evaluation index target value

| Evaluation index | Tibia acceleration/g | Knee joint bending angle/° | Knee shear displacement/mm |
|------------------|----------------------|---------------------------|---------------------------|
| Target limit     | ≤ 150                | ≤ 15                       | ≤ 6                       |

Taking the Y0 collision point as an example. The total energy is basically unchanged, and the initial total energy is 825.25J. The hourglass energy is 12.02J, and the maximum slip energy is 23.39J. Both the hourglass energy and the slip energy are less than 5% of the total energy, and the curve is smooth and there is no abrupt phenomenon. Therefore, it can be shown that the calculation result of this model is more accurate.

2.2. Crash performance analysis

Simulate on each collision point, and finally get the tibial acceleration, knee bending angle, and knee shear displacement of the five collision points of Y0, Y100, Y200, Y300, Y400[4]. The lower leg injury index statistics of each collision point are shown in Table 3.

Table 3 Lower leg injury index statistics

| Collision point | Peak tibia acceleration/g | Peak knee joint bending angle/° | Peak knee shear displacement/mm |
|-----------------|---------------------------|---------------------------------|---------------------------------|
| Y0              | 103.92                    | 10.59                           | 1.31                            |
| Y100            | 88.72                     | 4.08                            | 0.98                            |
| Y200            | 75.72                     | 4.28                            | 0.96                            |
| Y300            | 87.19                     | 3.52                            | 0.98                            |
| Y400            | 189.60                    | 4.25                            | 1.30                            |

As can be seen from the table 3, the tibia acceleration at the collision point of Y400 exceeded the target value, and there was a huge risk to the protection of the lower leg, which needs to be optimized. Because Y400 is located in the collision angle area, there are components with high rigidity such as headlight mounting brackets. Compared with the middle position, the overall rigidity of the collision point is greater. In addition, the knee joint bending angle and knee shear displacement of the five collision points meet the requirements.

3. Parameter sensitivity analysis of front bumper system

The parameters that affect the lower leg injury value are skin thickness, upper grille thickness, foam density, beam material, beam thickness, and beam height. In order to effectively optimize the front bumper system of an automobile, it is necessary to analyze the degree of influence of six parameters[5]. Taking the above six parameters as input variables, each variable is set to 3 levels, and the table of input variable levels is shown in Table 4.

Table 4 Bumper system parameter input variable level table

| Input variable          | Level 1 | Level 2 | Level 3 |
|------------------------|---------|---------|---------|
| A Skin thickness/mm    | 2       | 2.6     | 3       |
| B Upper grid thickness/mm | 2     | 2.5     | 3       |
| C Foam density/kg m^-3 | 50      | 90      | 110     |
| D Beam material        | Steel M414 | Steel M1000 | Aluminum alloy |
| E Beam thickness/mm    | 2       | 2.5     | 3       |
| F Beam height/ mm      | 145.6   | 155.6   | 165.6   |
In the pedestrian lower leg collision at the Y400 collision point, the maximum tibial acceleration, the maximum knee bending angle, the maximum knee shear displacement, and the front bumper system mass were used as output variables. The test results were imported into Hyperstudy for DOE analysis, and the results were analyzed and processed from the experimental index average and range respectively. Recorded as the average of the corresponding levels of each impact factor, R is the range of the mean. The magnitude of the range reflects the influence of each factor on the output response. The larger R is, the greater the influence of this factor on the output response, and the more critical the factor [6, 7].

Table 5 shows the corresponding range of the influence factors of the peak acceleration of tibia. Among them, the degree of influence of the factors on the peak acceleration of the tibia is ranked as A > C > F > E > D > B, which shows the thickness of the skin and the density of the foam have a greater impact on the acceleration of the tibia. Figure 3 shows the main effect of the peak acceleration of the tibia. It can be seen that as the thickness of the skin increases, the acceleration of the tibia decreases sharply; as the density of the energy-absorbing foam increases, the acceleration of the tibia also decreases sharply. Therefore, consider increasing the thickness of the skin and the density of the foam, which is conducive to reducing the peak acceleration of the tibia.

![Figure 3 The main effect of tibia acceleration](image)

| Evaluation index | Impact factor |
|------------------|---------------|
| Peak tibia acceleration | A | B | C | D | E | F |
| $K_1$ | 172.13 | 145.73 | 172.77 | 144.38 | 140.93 | 164.37 |
| $K_2$ | 158.16 | 142.26 | 148.90 | 159.09 | 138.28 | 133.20 |
| $K_3$ | 111.43 | 153.72 | 120.04 | 138.25 | 162.51 | 144.14 |
| $R$ | 60.70 | 11.46 | 52.73 | 20.84 | 24.23 | 31.17 |

4. Optimization of front bumper safety performance parameters
According to the sensitivity analysis, among the six parameter variables, the most sensitive variables to the collision point Y400 are the skin thickness and foam density. The optimization scheme is proposed. The design variable values of the optimization scheme and the original scheme are shown in Table 6.

| Scheme | A/mm | B/mm | C/kg mm$^2$ | D | E/mm | F/mm |
|--------|------|------|-------------|---|------|------|
| Original | 2.6 | 2.5 | Steel M414 | 2.5 | 145.6 |
| Optimal | 3.0 | 2.5 | Steel M414 | 2.5 | 145.6 |

The five collision points of Y0, Y100, Y200, Y300, and Y400 in the lower leg collision area are analyzed. Table 7 shows the comparison of the tibia acceleration before and after the optimization of
each collision point, which below the legal limit of 150g and meets the design requirements. Among them, the simulation values at the three collision points of Y0, Y100, and Y200 have increased. This is due to the increase in the thickness of the skin and the density of the foam, resulting in an increase in the overall stiffness. The acceleration front end is reduced by 47.71%, which is due to the skin and foam can not play a good role in energy absorption. Increasing the stiffness can reduce the energy transmitted to the beam and other parts of the stiffness height, and reduce peak tibia acceleration.

Table 7 Comparison of peak initial value and optimal value of tibial acceleration

| Collision point | Y0       | Y100      | Y200      | Y300      | Y400      |
|-----------------|----------|-----------|-----------|-----------|-----------|
| initial tibia acceleration/g | 103.92   | 88.72     | 75.72     | 87.19     | 189.60    |
| optimal tibia acceleration/g   | 120.34   | 103.65    | 95.30     | 83.91     | 99.14     |
| Rate of change/%               | 15.80    | 16.83     | 25.86     | -3.76     | -47.71    |

5. Conclusion
In this article, the front bumper of a passenger car is taken as the research object to establish an accurate and reliable crash simulation model. Through safety performance analysis, it is found that the acceleration of the tibia at the collision point Y400 is high, which is not conducive to pedestrian lower leg protection. Through the sensitivity analysis, it can be seen that the thickness of the skin and the density of the energy-absorbing foam have a greater impact on the tibia acceleration, and its parameters need to be optimized. The skin thickness of the initial scheme was changed from 2.6mm to 3mm, and the foam density was changed from 90 kg·mm$^{-3}$ to 110 kg·mm$^{-3}$. The tibia acceleration at the collision point Y400 was reduced by 47.71% after optimization, and all other collision points could meet the limit conditions. The optimization methods have certain guiding significance for future research.

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