Influencing factors investigation of passenger head injury in subway collisions

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Abstract—With the development of the subway and the pressing demand of environmentally friendly transportation, more and more people travel by subway. In recent decades, the issues about passenger passive safety on the train have received extensive attention. In this research, the head injury of a standing passenger in the subway is investigated. Three MADYMO models of the different standing passenger postures, defined as baseline scenarios, are numerically set up. HIC15 values of passengers with different postures are gained by systematic parametric studies. The injury numerical simulation results of various scenarios with different friction coefficients, collision acceleration, standing angle, horizontal handrail height, and ring handrail height are analyzed. Results show that the horizontal handrail provides better protection in the three different standing passenger postures. Different friction coefficients and the standing angle have great impact on the head injuries of passengers in three different scenarios. The handrail height also has some effects on head injury of passengers with different standing postures, so it is necessary to be considered when designing the interior layout of the subway. This study may provide guidance for the safety design of the subway and some advices for standing subway passengers.

Key words: subway collisions; head injury; standing postures; MADYMO simulation

THE INTRODUCTION

In July, a 13-year-old boy was also killed and 28 people injured two seriously when an escalator malfunctioned at a Beijing subway station. That disaster killed 40 people, injured 177 and sparked an outpouring of public anger and unusually bold reporting by Chinese media.[1][7][9] Reuters said it was unable to reach anyone at the company for comment.

Tuesday's collision was the most popular topic on Weibo.

"Another accident what a joke. So much money has been spent, all they've built is crap," wrote one user. "The alarm bells are ringing again, telling us that in economic development we cannot ignore safety and must not blindly try to follow developed western countries. We must go one step at a time," said another.
Shen Jun, 23, who was in the first coach of one train, said "blood was everywhere". "Many people were hurt. Look at the blood on me, on my arm," he said, pointing at patches on his shirt." I was stunned, not knowing what happened. We tried to open doors and windows but couldn't. I felt smoke in the car," another passenger told Xinhua. A third said: "The train braked suddenly … some people fell and some cried, then the automatic alarm sounded."[2][20]

Xinhua said subway staff had been directing trains by telephone after a signal failure, with services running at slower speeds. The Shanghai Shen Tong Metro Group, which operates the services, twice apologized via the popular Weibo microblog service – only to delete each message shortly after it appeared.

### THE BACKGROUND

In general, many countries have focused on the crashworthiness of rail vehicle in the 80s of last century. In the United Kingdom, Railway Safety and Standards Committee (RSSC) revised the GM/RT 2100Iss4. It contained detailed requirements of the interior of the train, such as interior trim and seat spacing. Subsequently, the UK put forward the crashworthiness standards AV/ST 9001 and started to research how to reduce the occupant secondary collision injury by changing the interior design.[3][17]

In the United States, there have been multiple studies addressing rail crashworthiness and occupant safety. The Federal Railroad Administration (FRA) sponsored studies on the vehicle collision response and crashworthiness performance of vehicles by computer analysis and experiments. The US Volpe National Transportation Systems Center carried out a series of real-vehicle crash tests and occupant secondary collision tests. They made some measures to reduce occupant secondary collision injury. Simons and Kirkpatrick used the vehicle crash response to calculate the acceleration environment of the car interior in mathematical simulation. Separately, they applied this acceleration environment to simulate the response and injury of passengers in seated configurations. On bus collisions, vehicle compatibility issues were proposed during typical mass transit bus collisions with sedans, light trucks, and heavy trucks through the use of numerical finite element simulations.

China's cosmopolitan business hub is in the midst of an ambitious subway expansion plan. Shanghai now has 11 lines running on more than 400 km of track, as well as a magnetic levitation, or maglev, link to its main international airport.

In one case, a train appears briefly to have gone in the wrong direction. Caixin, a well-respected business magazine, said the signal system for the subway was made by the China Railway Signal and Communication Corporation – which also made the signals blamed by some officials for contributing to this summer's high-speed rail crash in Wenzhou, Zhejiang.

It should be noted that before drawing the final conclusion about the head injuries of standing passengers during a crash, more researches need to be extended in the future, due to the limitations in this paper. Firstly, balance of human body requires closed loop control to generate a complex sway movement using neural signals to activate muscles. We do not take balance loss into consideration.[4][8][14] It is inaccurate under the emergency braking conditions. Secondly, head injury is just one of the factors which may result in the standing subway passenger injury. Other lethal injuries are not considered in this paper, such as abdominal injury and serious thoracic trauma. Thirdly, only the standing subway passenger was considered, while the sitting subway passenger was uninformed. Finally, the FE impact simulations with only the FE head model (non-FE human body model) may have some limitations, so a pedestrian FE model (e.g., GHBMC model or THIMS model) will be considered in the future.

### RESEARCH ANALYSIS

1. Methods

To assess the head injuries of standing passengers during a crash, three different standing passenger postures, that is, horizontal handrail passenger, ring handrail passenger, and vertical handrail passenger, are considered. Almost all standing subway passenger scenes are covered. Numerical simulation scenes are set up based on MADYMO (MADYMO 7.5, Netherlands Organization for Applied Science Research, Delft, Netherlands) platform. The MADYMO platform is used to study the vehicle crash safety. In the analyses, the impact condition specified in EN15227 standard is applied. The wet weather conditions in this area and subway model referred are taken into consideration. Therefore, the baseline scenario of three different standing passenger postures is set with lower limit acceleration in 5.67 g, the static coefficient friction between shoes and floor with 0.49, and standing angle with 0°, and the heights of the
horizontal handrail and the ring handrail are 1850 mm and 2000 mm, respectively. [5][10][15]

Collision acceleration curve as defined in AV/ST 9001 vehicle interior crashworthiness. To further quantify the collision scenarios, numerical simulations are conducted at various collision acceleration, coefficient friction (between foot and floor), standing angle, and handrail height (from handrail to floor) with a total of 270 numerical simulations (shown in Table 1). Numerical collision conditions are simulated with the collision acceleration changed every 0.5 g range from 2 g to 10 g. The different gradients of the coefficient friction are set from 0.49 (baseline scenarios) to 0.85 with the interval of 0.05. The standing angle is set as dominant variables, that is, 0, π/4, π/2, 3π/4, π, 5π/4, 3π/2, and 7π/4. The heights of the horizontal handrail and the ring handrail are set from 1830 mm to 1950 mm and 1950 mm to 2050 mm with the interval of 10 mm, respectively.

In consideration of the head injury importance, we take finite element head models to analysis by simulating boundary conditions in the baseline scenario, individually. The results of MADYMO simulations for the baseline scenario with three different standing passenger postures are used as the boundary conditions for finite element simulations later. The head impact boundary conditions include linear velocity, angular velocity, head position, and head linear acceleration.

1. Accident Scenarios

Three standing models in the baseline scenario are shown. The relevant design parameters of the subway handrails correspond to actual designs in service in China. The standing models and standing angle to describe horizontal handrail, ring handrail, and vertical handrail.

1.2. Human Model

The 50th percentile male pedestrian model (1.74 m, 75.7 kg) incorporated within MADYMO is chosen to represent the standing subway passenger. This model is widely accepted for accident analysis and reconstruction studies to assess human body kinematics and injury potential. The pedestrian model consists of 52 rigid bodies, with an outer surface described by 69 ellipsoids, and there are 52 joints within the human model.

1.3. Hand Model

Between the hand model and the handrail, we define a contact with failure to simulate the hand grip force. The average grip strength for males aged 20–59 is 450 N in China. When the hand grip force reaches 450 N, the contact between the hand model and the handrail becomes invalid.

1.4. Injury Evaluation Index

HIC is widely accepted for assessing the severity of head injuries. HIC15 is well correlated with averaged angular acceleration and can avoid some of the potential errors. Consequently, HIC15 is chosen during the secondary impact.

1.5. Finite Element (FE) Head-Ground Impact Model

The HBM-head model is adopted to build the FE head-ground model. The HBM-head model has been validated and widely used in the field of skull and brain injury research. The subway aluminum honeycomb ground FE model is constructed. The FE head-ground impact model. The head-ground impact process is reconstructed by using three coordinate points to get the relative position of the HBM-head with ground. The linear velocities, angular velocities, and linear acceleration are used as the boundary condition. This method has been adopted to study the influence of head mass on temporoparietal skull impact. Open in a separate window

2. Results

From the dynamic point of view, the standing subway passenger accident could be divided into three phases, that is, hand-handrail contact phase (I), hand-handrail separation phase (II), and head-floor contact phase (III). In phase I, three kinds of standing subway passengers hold the handrail in three different ways. In phase II, the hand grip force of the passenger reaches 450 N. The contact between the hand model and the handrail becomes invalid. In phase III, the standing subway passenger falls down and the head and floor make contact. The kinematic mechanisms of the standing subway passenger in three postures are demonstrated by MADYMO. Open in a separate window, Dynamic responses of three passengers with different standing postures in the baseline scenario.

2.1. The Resultant Hand Grip Force

The hand grip force reflects directly the time when the hand and the handrail separate. As shown, the hand grip force of the horizontal handrail passenger, the ring handrail passenger, and the vertical handrail passenger reaches 450 N in 142 m/s, 94 m/s, and 78 m/s, respectively. The horizontal handrail has the greatest effect on the overall passenger response (integrating the force-time history), and the ring handrail has the least effect. It can be observed in the behaviors. For the horizontal handrail, the hand postures of a standing passenger change from 0 m/s to 142 m/s, while it keeps the same from 0 m/s to 94 m/s for the ring handrail. There are some fluctuations in

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the horizontal handrail curve and the vertical handrail curve before reaching the peak. It can be explained that the hand does not touch the ring handrail in the beginning. Open in a separate window. Resultant head-handrail forces of three different standing passenger postures in the baseline scenario. Open in a separate window.[12][16] The dynamic behaviors to the hand grip force.

2.2. The Resultant Head Acceleration

For the same impact scenarios selected in the previous section, three baseline scenarios in three postures present the representative simulation results. As shown, for the horizontal handrail and the ring handrail during the head-floor contact, there are several small peaks in head acceleration curve, while a peak in the vertical handrail. The reason is that the arm plays a buffer role when the standing subway passenger in the vertical handrail falls down. The head acceleration reaches the peak when the head and floor make contact for the first time. The peak in the horizontal handrail and ring handrail arrives late, compared with that in the vertical handrail. The peak value maximum in the vertical handrail is the smallest in three standing postures. It can be explained that the arm-floor contact mitigates a part of impact energy. For the standing subway passenger in the ring handrail, the time for head-floor contact is longer than the time in the horizontal handrail. This leads to the greater value of HIC15. Resultant head accelerations of three passengers with different standing postures in the baseline scenario.

2.3. The Head Center of Gravity (CG) Displacement

The displacement of the head center of gravity (CG) reflects directly the kinematic movement of the standing subway passenger in three standing postures. The head displacement is the horizontal displacement along the collision direction of the car body from falling over. The displacement is relative to a reference frame defined by a fixed position on the floor on the car body. The head displacement increases almost linearly at first. This indicates that the head velocity keeps constant. An abrupt gradient change can be observed in the displacement-time history curve in the three standing postures. The constraint of head movement is the head-floor contact. The gradient happens at about 620 m/s, and the three postures of the standing subway passenger head contact the floor, that is, 634.6 m/s, 621.5 m/s, and 618.6 m/s, respectively. Head CG displacement-time curves of three passenger standing postures in the baseline scenario.[13][18]

2.4. The Head Center of Gravity (CG) Speed

The speed-time history curves of the standing subway passenger head center of gravity in three standing postures are indicated. The general trends of the curves are ascending with some little fluctuations before the peak appears, due to the hand force of the standing subway passenger. The speed of head CG reaches the peak when the abdomen-vehicle contact happens, caused by a sudden drop. Later, there is a wave of the speed after the head-vehicle contact appears. Subsequently, the head center of gravity speed tends to be relatively steady. Head CG speed-time history of three passengers with different standing postures in the baseline scenario.

2.5. The Head Injury Analysis in FE Model

Three baseline scenarios are selected in three different standing passenger postures to assess the head injury by FE head-ground impact model. Head injury with coup pressure and skull von Mises stress is analyzed and the result is showed. The maximum coup pressure (362.8 kPa) and the minimum coup pressure (~246.3 kPa) happen in the ring handrail scenario. And the maximum skull von Mises stress (31.36 MPa) happens in the vertical handrail scenarios. All the coup pressures are graded distribution. The maximum skull von Mises stress concentrates on the zygoma. Relation of three passengers with different standing postures and FE head-ground impact model analysis results in the baseline scenario.

The coefficient friction between the passenger and the ground has a significant effect during collisions. The relation between the head injury HIC15 value and the coefficient friction is illustrated. Different impact acceleration conditions are considered: the lower limit acceleration (5.67 g), the middle acceleration (6.85 g), and the upper limit acceleration (8.0 g), respectively. The other parameters are kept the same as those in the baseline case. The results show that HIC15 of the standing subway passenger in the horizontal handrail and the vertical handrail increases with the increasing of friction coefficient, while HIC15 of the ring handrail decreases with the increasing of friction coefficient. This indicates the friction coefficient has a huge effect in different standing postures.

3. Parametric Study for Various Standing Angles

The standing angle is considered as a variable. Three postures of the standing subway passenger with different standing angles under the lower limit acceleration (5.67 g), the middle acceleration (6.85 g), and the upper limit acceleration (8.0 g), respectively. The relation of the standing angle and HIC15 values
of three passengers with different standing postures in three collision acceleration conditions. The varying trends of HIC15 at various standing angles are somewhat irregular. For the horizontal handrail of the standing subway passenger, the HIC15 is smaller when the standing angle is π/4. The HIC15 is quite bigger, when the standing angles are 0 and 7π/4. For the ring handrail of the standing subway passenger, the HIC15 reaches the biggest, when the standing angle is 0. The smallest HIC15 happens in the 3π/4 or π/4. As for the vertical handrail of the standing subway passenger, the standing angle of π/4 causes the smallest HIC15, while the biggest HIC15 happens in 0 and 3π/2. In general, the maximum HIC15 appears at both ends of the curve. It can be explained by the head-floor contact directly. To figure out detail contact behaviors in the collision, the head acceleration curves are extracted along with three postures. It can be observed that the HIC15 is higher when the time of head contact becomes earlier. The reason is that the hand plays a protective role, which means hand-floor contact comes first compared with head-floor contact and the HIC15 is smaller at the same time. This finding provides some guidance for the standing direction to subway passengers. Head acceleration-time history of three passengers with different standing postures in the lower limit acceleration (5.67 g).

Previous research and design indicated that the height of the handrail might bring different consequences to the injuries of the subway passenger during the collisions. It is also interesting to discuss the influence caused by various heights of the handrail in the standing subway passenger head injuries. The standard heights of the horizontal handrail and the ring handrail are 1850 mm and 2000 mm, respectively. The relationship between the HIC15 values and heights of the horizontal handrail and the ring handrail in three collision conditions. From the curves, the 6.85 g and 8.00 g scenarios in the ring handrail at 2000 mm height have high injury values but they are much lower at both the 1990 mm and 2010 mm heights. For the horizontal handrail, the standard height 1850 mm is on the middle level. The HIC15 values are sensitive to the height of the handrail. This finding is helpful to the handrail design, besides thinking about ergonomics.

### CONCLUSION

In this paper, numerical collision condition was set up to investigate the head injuries of standing passengers during a crash with three standing postures, that is, the horizontal handrail, the ring handrail, and the vertical handrail. Three baseline scenarios were set with three different standing subway passenger postures. The head finite element model was studied to emphasize the head injury importance in the three baseline scenarios. Then, parametric studies were carried out in the baseline scenarios, such as coefficient friction, collision acceleration, standing angle, and handrail heights. Based on the analysis, the following changes or suggestions were proposed for the subway and the standing subway passenger. A lower stiffness of the rubber used for the floor and the appropriate handrail height should be considered. Results showed that the bigger acceleration was likely to result in more serious head injuries in the standing subway passenger. Therefore, driver training should be included to brake faster when the collision occurs. The standing subway passenger should be discouraged from standing in a certain angle toward the subway moving direction. According to 195 numerical simulations of this paper (besides 75 numerical simulations in the study for various heights), the number of cases that the horizontal handrail obtains the lowest HIC15 values accounts for 61.5% (40 out of 65) of all simulations. The horizontal handrail is safer, compared with the ring handrail and the vertical handrail. It should be noted that before drawing the final conclusion about the head injuries of standing passengers during a crash, more researches need to be extended in the future, due to the limitations in this paper. Firstly, balance of human body requires closed loop control to generate a complex sway movement using neural signals to activate muscles. We do not take balance loss into consideration. It is inaccurate under the emergency braking conditions. Secondly, head injury is just one of the factors which may result in the standing subway passenger injury. Other lethal injuries are not considered in this paper, such as abdominal injury and serious thoracic trauma. Thirdly, only the standing subway passenger was considered, while the sitting subway passenger was uninformed. Finally, the FE impact simulations with only the FE head model (non-FE human body model) may have some limitations, so a pedestrian FE model (e.g., GHBMC model or THIMS model) will be considered in the future.

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