Analysis of Hyperthermia of Children in Enclosed Vehicle

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Abstract. Aiming at the problem of high temperature hazard in children stranded in cars, based on the thermal environment parameters of the enclosed vehicle during outdoor thermal soaking in summer, the predicted heat strain (PHS) model was used, combined with children's height, weight, clothing and other factors, to simulate the changes in physiological indicators such as core temperature, rectal temperature and water loss, and to scientifically determined the maximum allowable exposure time. It was predicted that the core temperature of human body exceeded 38℃ at 72 minutes, and then the body began to heat exhaustion.

1. Introduction
Child occupant safety is one of the important topics in the field of automobile safety. The current research work mainly focuses on the optimization design of the child restraint system and its safety evaluation. There is a lack of in-depth research on the safety of children stranded in the vehicle after parking. Kids and Cars.org conducted statistics and categorization of non-traffic accident injuries among children in the United States from 2001 to 2010. The results show that the death rate of heat suffocation among children stranded in cars accounted for 58%, much higher than other injury types, as shown in Figure 1 [1].

Figure 1. Statistics of child non-traffic accident injury types.
2. Thermal environment parameters of enclose vehicle

General Motors and Safe Kids Worldwide have investigated and researched that the temperature difference between the inside and outside of a car that stays outdoors is often as high as 7 to 10 degrees Celsius even if it is bathed in low-light sun [2]. Through a large number of interior temperature tests, Zhu Hang et al. from Tongji University obtained interior temperature change data under different ambient temperatures, and studied the effect of body color and interior color on the interior temperature. The test results show that: (1) The temperature inside the car will rise rapidly after closing the door at various ambient temperatures, and 75% of the temperature rise occurs within the first 15 minutes; after 40 minutes, the temperature tends to be flat, and its trend temperature is related to the ambient temperature. However, even at an ambient temperature of 22℃, which is suitable for the human body, the temperature inside the car reached 40℃ after 1 hour, exceeding the tolerance limit of human core temperature threshold of 39.4℃. (2) The interior color has a greater impact on the interior temperature. When the body color and interior color are both dark, the interior temperature rises most obviously [3]. Hou Shiliang of Beijing institute of industry and technology, through statistical analysis of the temperature changes inside the vehicle when parked in the open air in summer, drew the following conclusions: (1) Solar radiation has a great influence on the temperature change inside the vehicle. The temperature distribution inside the car is uneven, with obvious stratification in the vertical direction. The temperature rises gradually from the foot space upwards. (2) Car windows with dark film can suppress the increase in temperature in the car to a certain extent. The temperature rise of vehicles without film is significantly higher than that of vehicles with dark film. (3) The temperature rise in cars parked in open spaces under direct sunlight is significantly higher than that of cars under shade of trees [4].

In order to obtain the thermal environment parameters of the enclosed vehicle, an experiment of collecting the temperature inside the vehicle was carried out from 13:15 to 15:10 on August 12, 2020. The experimental vehicle is a white 2020 Mazda3 AXELA with a dark grey interior and no solar film. The vehicle is parked on an open field that can guarantee sunlight, with the front of the vehicle facing east. The ambient temperature fluctuates around 30℃, and the average solar light intensity is 847W/m². The real-time data is shown in Figure 2, which gradually decreases with the westward movement of the sun, with wind speed of 5m/s gust and humidity of 45%.

![Figure 2. Solar radiation intensity.](image2)

![Figure 3. Recorded interior temperature.](image3)

The temperature recorder probe is supported on the back seat of the vehicle at a distance of 380mm from the seat plane, and the refrigeration and air conditioning are turned on to make the temperature in the vehicle lower than the ambient temperature. After that, turn off the air conditioner, car windows and doors to keep the vehicle in a closed state, and start the experimental data collection. The
experiment data collection frequency is once a minute. Figure 3 shows the collected temperature data. As can be seen from the figure, the temperature in the car started at 25.8°C and then increased continuously, but the rate of increase gradually decreased. The highest temperature reached 45.9°C, that is, the maximum temperature rise was 20.1°C. The temperature rise reached half of the maximum temperature rise at 10min, reached more than 80% at 33min, and only increased by about 20% in the remaining time. The data conforms to the temperature change law of enclose vehicle, which is real, objective and effective, and lays a foundation for the next step of thermal stress prediction.

3. Predicted heat strain model

At present, the focus of the relevant research on children stranded in cars is the temperature change inside the car, and the physiological changes of children have not been investigated. As an organism, humans have the function of body temperature regulation, that is, when the ambient temperature changes, they can adjust their body temperature independently to maintain the body temperature within a certain boundary. The adjustment function is a dynamic and stable adjustment of the internal conditions of the body, not simply a thermal balance with the surrounding environment. With reference to the standard ISO 7933 (2018) of ergonomics of the thermal environment [5], a method was proposed to evaluate the health risk of children stranded in cars in summer by means of the predicted heat strain model. This method takes into account the human body thermal regulation model and the heat transfer mechanism between the outer surface of the body and the surrounding environment, and determines the maximum allowable exposure time for children in enclose vehicle by analyzing physiological indicators such as human core temperature and water loss in the thermal environment.

The PHS model is based on the thermal energy balance of the body which may be written as:

\[ M - W = C_{res} + E_{res} + K + C + R + E + S \]  

This equation expresses that the internal heat production of the body, which corresponds to the metabolic rate, \( M \), minus the effective mechanical power, \( W \), are balanced by the heat exchanges in the respiratory tract by convection, \( C_{res} \), and evaporation, \( E_{res} \), as well as by the heat exchanges on the skin by conduction, \( K \), convection, \( C \), radiation, \( R \), and evaporation, \( E \). If the balance is not satisfied, some energy is stored in the body, \( S \).

Heat exchanges are computed at time, \( t_i \), from the body conditions existing at the previous computation time, \( t_{i-1} \), and as a function of the current climatic, metabolic and clothing conditions during the time increment. The steps are:

1. The required evaporative heat flow, \( E_{req} \), skin wettedness, \( W_{req} \), and sweat rate, \( Sw_{req} \), are first computed;
2. The predicted evaporative heat flow, \( E_p \), skin wettedness, \( w_p \), and sweat rate, \( Sw_p \), are then computed considering the stress criteria (\( E_{max} \), \( W_{max} \) and \( Sw_{max} \)) as well as the exponential response of the sweating system;
3. The rate of heat storage is estimated by the difference between the required and predicted evaporative heat flow; The stored heat contributes to the increase or decrease in the body temperatures;
4. From these values, the heat exchanges during the next time increment are computed.

4. Prediction of thermal stress of children trapped in vehicles

4.1. PHS simulation initial value setting

The initial values of the physiological indicators in PHS model were set as: skin temperature 34.1°C, core temperature 36.8°C, rectal temperature 36.8°C, steady-state core temperature 36.8°C, and total water loss rate 0W/m². The value of children's height and weight refers to the "WHO Child Growth Standards" issued by World Health Organization [6]. Table 1 shows the standard height and weight for
different ages and genders of 1-5 years old. The standard height and weight of boys of 3 years old were taken for simulation.

Table 1. Standard height and weight tables.

| Age | Boys Height (m) | Boys Weight (kg) | Girls Height (cm) | Girls Weight (kg) |
|-----|-----------------|------------------|-------------------|------------------|
| 1   | 0.757           | 9.6              | 0.740             | 8.9              |
| 2   | 0.878           | 12.2             | 0.864             | 11.5             |
| 3   | 0.961           | 14.3             | 0.951             | 13.9             |
| 4   | 1.033           | 16.3             | 1.027             | 16.1             |
| 5   | 1.100           | 18.3             | 1.094             | 18.2             |

4.2. Prediction results of thermal stress in children

Combining the collected thermal environment parameters, the PHS model was used to predict the thermal stress of a 3-year-old boy stranded in the vehicle. The results are shown in Figures 4 to 7.

Figure 4 shows the prediction results of human core temperature and rectal temperature. From the figure, it can be seen that the core temperature and rectal temperature are almost equal. Due to the effect of body temperature regulation, the early temperature rise is relatively gentle. According to the occupational health standard GBZ41 (2019) "Diagnosis of Occupational Heat Stroke" [7], when the body temperature exceeds 38℃, it is diagnosed as heat exhaustion. The core temperature exceeds 38℃ at 72 minutes, indicating that when the child is left in the vehicle with the air-conditioning turned off in summer, the child's body will reach a state that cannot withstand the heat of the external environment after 72 minutes. Figure 5 shows the amount of water loss. The total water loss was 171g at 72 minutes, accounting for 1.19% of its body weight, without excessive water loss.
Figure 6 shows the change of heat flow between children and the interior of the vehicle. Positive is heat dissipation, while negative is heat absorption. In the first 8 minutes, due to the low temperature of the air in the car, children can dissipate heat through convection, radiation, respiration and evaporation. However, as the air temperature gradually rises, children’s heat dissipation through convection, radiation, and respiratory convection decreases and gradually evolves into endothermic. In a high temperature environment, children can only lose heat through skin evaporation and breathing evaporation. During the whole heat exchange process, the heat exchange effect of respiratory convection and respiratory evaporation is very small, close to zero. At 34 min, since the skin surface moisture has reached the maximum, the evaporative heat transfer has a downward trend. On the other hand, the heat absorption through convection and radiation continues to increase, causing children's body heat storage to be positive every minute, and the core and rectal temperature continue to rise. Figure 7 shows the body heat storage per minute.

5. Conclusions
By analyzing the temperature change in enclosed vehicle during outdoor thermal soaking in summer, the law of change over time is obtained. The experiment shows that 60% of the temperature rise is mainly concentrated in the first 15 minutes, and the highest temperature rise is related to the regional environment. Combined with the measured parameters of the thermal environment in enclosed car, the PHS model predicts that the core temperature of the human body will exceed 38°C when the child stays in the car for 72 minutes, reaching the maximum acceptable exposure time. The analysis of hyperthermia of children in enclosed vehicle is helpful to give a set of scientific solutions to reduce the risk of children stranded in the car.

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