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The necessity of evaluating child neck injury in frontal collision of school bus for transportation safety

Zhigang Li *, Hao Ge [1], Jinhuan Zhang [1], Yonghua Zhu [1]

Tsinghua University, No. 1 Tsinghua Yuan, Haidian District, Beijing 10084, China

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ABSTRACT

The frequent school bus accidents and resulting injuries accelerated the formulation and revision of the school bus regulations. In the school bus regulations, the injury criteria and evaluation procedures of head, chest, and femur were included, however, neck injury evaluation has not been incorporated. Thus, the neck protection was often ignored and no relevant studies were found to specially focus on this topic. In this study, the child body region injuries, especially the neck under compartmentalization (without seatbelt), lap belt, and lap/shoulder belt restraint strategies in school bus frontal impact were particularly evaluated through a series of sled tests in laboratory environment. Results showed that most of the injury metrics of head, chest, and femur were below their threshold limits, but, on the contrary, most neck injury metrics did not meet the requirement of the regulations, which indicated that neck was one of the most easily injured regions in frontal impact. This study also pointed out that the lap/shoulder belt can provide good protections for all the body regions involved in this study, whereas traditional compartmentalization and only lap belt can protect head, chest, and femur well, but cannot effectively protect the neck, thus some countermeasures on redesigning the traditional seatback were proposed. According to the conclusions drawn in this study, neck injury evaluation are strongly recommended to incorporate into the regulations, meanwhile, lap/shoulder belt is also suggested to equip with the current school bus seats.

1. Introduction

There are 450,000 school buses travelling 4.3 billion miles for 23.5 million children in USA every year (Hinch et al., 2002). Although school bus travel was considered one of the safest transportation in USA (Bolte et al., 2000), National Highway Transportation Safety Administration (NHTSA) estimates that there are 8500 school bus related injuries per year, of which 86% are minor, 10% are moderate, and 4% are severe and most of the nonfatal injuries often occur to the children riding in the school bus (McGeehan et al., 2006). School bus accidents are more serious in the developing countries. In China, the incomplete statistics showed that over 40 children died at the school bus due to accidents only in 2011 (Zhao, 2012).

The frequent accidents and resulting injuries accelerated the formulation and revision of the school bus regulations, such as US's FMVSS No. 220, 221, 222 (FMVSS, 1998a,b,c), and China's GB24406, GB24407 (AQSIQ, 2012a,b) and Europe's ECE R80 (UNECE, 1998). The dynamic sled test can mimic the real school bus crash accident and evaluate the restraint system protective capability. It has been incorporated in the regulations GB24406/ECE R80. In FMVSS 222, equivalent impacting tests were incorporated to impact the specified zone of the seatback and the restraining barrier with a head and a leg form from any direction at 6.7 m/s and 4.9 m/s respectively. The dynamic responses of the head and leg forms should be met the requirement in the regulation. Although no dynamic sled tests were included in the US school bus regulation, some whole school bus crashes and sled tests have already been conducted in USA and other countries to investigate the protective capabilities of different restraint systems. Transport Canada conducted three school bus crash tests to determine the effectiveness of the compartmentalization (without belt) versus seatbelts in 1984 (Farr, 1985). National Transportation Safety Board investigated 43 serious school bus crash accidents in 1987, obtaining that deaths or serious injuries were mainly due to direct impact with some objects (NTSB, 1987). Bolte et al. (2000) reconstructed several school bus accidents by computer modeling in 2000, suggesting that compartmentalization may not function well in lateral impacts, rollovers, etc. Elias et al. (2001, 2003) conducted two full-scale crash tests and some sled tests in 2001 and 2003 to compare the effectiveness of compartmentalization, lap belt and lap/shoulder belt in frontal crashes. The existing school bus accidents, full school bus and sled tests were reviewed by Hinch

* Corresponding author. Tel.: +86 01062781639 18; fax: +86 01062786828.
E-mail addresses: lizhigang504@163.com (Z. Li), thugeh@gmail.com (H. Ge), zhjh@mail.tsinghua.edu.cn (J. Zhang), jzhu2002@126.com (Y. Zhu).
[1] Tel.: +86 01062781639 18; fax: +86 01062786828.

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et al. (2002). Tanov et al. built a school bus FE model and carried out simulations on school bus crashes in 2003 (Tanov et al., 2003). Yutong Bus Co., one of the school bus manufacturing companies in China, conducted China's first school bus frontal crash test recently (Anon., 2012), but the test data is unveiled. Although some of above studies collected the dummy neck injury metrics during sled tests (Elias et al., 2001, 2003), no study comprehensively focused on the neck injury evaluation in frontal crash.

The injury criteria and evaluation procedure of the dummy head, chest, and femur were proposed in GB24406/ECE R80, however, the neck injury assessment were not incorporated into these school bus regulations. Therefore, the neck injury was usually ignored when evaluate the performance of restraints. For example, researchers concluding that compartmentalization provided good protection for children is on the premise of without considering the neck injury during crash (Bolte et al., 2000). Statistics have already shown that neck injury, such as strain and sprains, occurred frequently related with the child riding in the school bus (McGeehan et al., 2006; Lapner et al., 2003). Therefore, the purpose of this study is to primarily evaluate the potential risk of neck injury in the school bus through series laboratory sled tests according to GB24406/ECE R80; and also to compare the protective capabilities of compartmentalization, lap belt, and lap/shoulder belt restraint systems on different dummy body regions, especially the neck.

2. Materials and methods

2.1. Instruments and sled test procedure

Series of sled tests were carried out according to GB24406/ECE R80 in Automobile Crash Laboratory of Tsinghua University in China. The specific procedures and requirements for the tests are as followings:

- *Student seat installation*. School bus seat bucks are firmly mounted on the sled in a forward-facing mode.
- *Dummy calibration and preparation.* Three different size standard dummies were used: Hybrid III6-year-old child dummy (HIII-6C), Hybrid III 5th female dummy (HIII-5F) representing an 12-year-old child and P-series 3-year-old child dummy (P-3C). The first two dummies were instrumented with load cells on the head, neck, chest and femur, while the P-3C dummy was not instrumented. All the dummies were calibrated prior to the tests.
- *Crash pulse generation*. The crash pulses were generated as the sled impacted with a crash pulse generator (custom-designed hydraulic equipment) at the speed of 30 km/h with the crash pulse and the corresponding corridor in GB24406/ECE R80 as shown in Fig. 1.

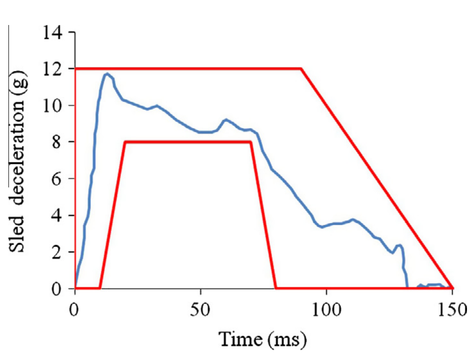

Fig. 1. The crash test deceleration pulses at the velocity of 30 km/h.

- *Stationary and high-speed video cameras arrangement.* Stationary and high-speed video cameras which were used to document the pre-and post-dummy positions and dummy kinematical trajectory respectively were located at suitable places.
- *Calculation of dummy injury metrics.* Injury metrics of different body regions, including head acceleration, HIC, neck force and moment, chest acceleration, femur (left and right) forces are collected and calculated.

2.2. Sled test matrix and data analysis

Two types of seat bucks were used to conduct sled tests in this study. The first seat buck (type-I) was provided by a school bus manufacture company of USA, including two rows of seats and frontal barriers on both sides of the aisle. The second seat buck (type-II) was provided by a school bus company of China, including two rows of seats. The type-I and type-II seat bucks are shown in Fig. 2.

Five sled tests were run on type-I and type-II sled bucks with all the crash pulse meeting the corridor in Fig. 1, of which 3 tests were run on type-I and 2 tests on type-II. The specific configurations of dummy position and restrained types are shown in Fig. 3. For the type-I seat buck, three dummies, HIII-6C, HIII-5F, and P-3C (uninstrumented) were used. For type-II seat bucks, two HIII-5F dummies and a HIII-6C dummy were adopted. The lap belt, compartmentalization (without belt), and lap/shoulder belt restraint strategies were involved in these five tests.

Based on above 5 sled tests, the dummy kinematic trajectory and injury metrics of child head, chest, femur, especially the neck under above mentioned three types of different restraint strategies were analyzed.

3. Results

3.1. Dummy kinematic trajectory analysis

The dummy kinematic trajectories are similar under the same restraint conditions for type-I and type-II seat bucks. For clarity, only dummy trajectories for type-I seat buck are shown in Fig. 4. At beginning, all the dummies were in similar upright sitting positions. During the impact tests, the dummy kinematic trajectories varied a lot with restraint strategy changing.

For the lap belt restraint (Fig. 4a), the dummy slid forward before the slack between the dummy and belt was removed. After the dummy pelvis was restrained, due to the inertia, the dummy upper torso continued to forward and then rotated downward. The head impacted with the frontal seatback for the HIII-5F dummy. As the upper torso continued to rotate downward, the head was forced to rotate rearward relative to the seatback and the neck was suffered large shear force and flexion moments. Much energy was absorbed by the deformation of the dummy neck, head, and shoulder at this stage besides those portions absorbed by lap belt and the seatback. When the shoulder contacted with the frontal seatback for quite a while, the neck flexion and deformation approximately reached the maximum and began to recover from former posture. The heads did not or slightly impact with the frontal seatback for the HIII-6C and P-3C dummies restrained by the lap belt due to their small sizes, thus the injuries would not occur to them.

For the dummy with no seatbelt restraint (Fig. 4b), they first moved forward until lower extremities contacted with the frontal seatback, then the upper torso began to rotate downward as the dummy continued to move forward. The heads, necks, and upper torsos of HIII-5F, HIII-6C and P-3C dummies impacted to the tilted seatback which made the heads rotate rearward until these dummies started to rebounded, and consequently causing injuries to