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Increasing evacuation flow through school bus emergency roof hatches

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ABSTRACT

Emergency escape roof hatches are used to evacuate school buses in rolled-over orientations. In the United States, the minimum opening size of a roof hatch is defined by Federal Motor Vehicle Safety Standard (FMVSS) no. 217. With the prevalence of rising obesity rates among children, the minimum roof hatch opening size may not be large enough to accommodate larger passengers. Post-accident conditions such as injuries, disorientation, and exit obstructions may also prevent unobstructed passage for egress within acceptable time limits. The purpose of this study was to redesign and fabricate a roof hatch with a larger opening and evaluate its egress characteristics for a range of typical school bus passengers. The larger roof hatch opening allows greater evacuation flow rates, and is almost functionally equivalent to the evacuation flow rate of the front door on an upright school bus.

1. Introduction

While the annual frequency of school bus rollover accidents is difficult to ascertain, there is no doubt that the severity of such accidents is significant. After a rollover (vehicle on its side), the front door and window exits become unusable, and the emergency roof hatches emerge as a viable exit. The most common performance measure for the effectiveness of an emergency exit is flow rate, which is measured by the number of passengers per minute (PPM) evacuating through an exit. It has been estimated that a fire could engulf the interior of a school bus in 3–5 min (Matolcsy, 2010). Therefore, in the event of a rollover, ensuring the availability of effective emergency exits is essential to improve survivability rates.

Roof hatches are a primary means of egress when a school bus is in a rolled-over orientation (Matolcsy, 2010). Federal Motor Vehicle Safety Standard (FMVSS) No. 217 requires roof hatch openings on school buses to be larger than 41 × 41 cm (16 × 16 in) (NHTSA, 2011). The standard roof hatch used by most current school bus manufacturers in the United States provides a 57 × 57 cm (22.5 × 22.5 in) opening, which exceeds the minimum requirement. The Economic Commission of Europe requires roof hatches on motorcoaches to have an opening of at least 4000 cm^2, and be able to fit a rectangle shape that is 50 cm high and 70 cm wide (Economic Commission for Europe (ECE), 2008). However, with the increase in obesity rates among children, the minimum opening size of roof hatch mandated by FMVSS No. 217 is most likely not representative of the actual size of some school bus occupants (Lobstein and Jackson-Leach, 2007).

The ability to successfully evacuate a school bus relies heavily on the post-accident circumstances. Under optimal post-accident circumstances, passengers will experience only minor injuries, and outside assistance is immediately available to support the evacuation process. However, under the most extreme 'credible' circumstances, passengers may experience major injuries and no external assistance would be immediately available to assist with the evacuation process. In the most extreme conditions, it is also likely that evacuation time is limited due to life-threatening hazards such as fires. The probability of successful escape depends on the design and capabilities of the emergency exit system as well as the training and ability of the occupants to successfully use the emergency exit system in a timely manner.

The effectiveness of different roof hatch openings was first measured at the Oklahoma Research Institute (OKRI) where flow rates from a roof hatch mockup representing a rolled-over bus with an opening of 61 × 102 cm (6222 cm^2) was compared to a mockup with a roof hatch opening of 61 × 61 cm (3721 cm^2) (Sliepcevich et al., 1972). The mockups were constructed so that the opening of the roof hatch was on the same level as the ground. This allowed 60 child participants from all

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12 grade levels to crawl through the opening **without having to pull themselves up** as they would on a roof hatch currently used on all school buses (Sliepcevich et al., 1972). The observed flow rates through both hatches were approximately 30 PPM. While this study shed some light on the issue of emergency escape via roof hatches, the lack of realism limits its generalizability to roof hatches located on the centerline of the roof of a school bus. To estimate flow rates through a roof hatch located in the centerline of a roof, a follow-up study was conducted to measure the flow rate through a 49 × 54.6 cm motorcoach roof hatch opening. However, in this study, adult participants were used to measure the evacuation flow rates (Purswell et al., 1978). The observed flow rate with the roof hatch opening being at an elevated level from the ground with adult participants was much less, between 4.6 and 10.7 PPM (Purswell et al., 1978).

Another study investigating emergency evacuations was conducted by the Volpe Center. Estimated flow rates of adults via roof hatches of an overturned motorcoach was approximately 12 PPM; however, some individuals with limited physical capabilities required more than 1 min to evacuate through the roof hatch opening unless assisted by other adults (Pollard and Markos, 2009). Based on the findings of this study, it was noted that the minimum opening size required by FMVSS No. 217 may not allow larger individuals to evacuate through a roof hatch opening and that a larger roof hatch opening of 4000 cm^2 may significantly increase evacuation flow rates (Pollard and Markos, 2009). During the motorcoach evacuation trials, three unique methods of roof hatch evacuation were identified: (1) the somersault – when an individual approaches the exit opening head first; (2) the whole body lift – when an individual holds onto the top edge of the opening with both feet swinging in front of the body and out the exit; (3) the cautious approach – when an individual cautiously approaches the opening one limb at a time (Pollard and Markos, 2009). The observed flow rates for the somersault, whole body lift, and cautious approach were 15 PPM, 12 PPM, and 1.5 PPM, respectively.

More recently, flow rates of children through a typical school bus roof hatch opening (57 × 57 cm) were measured using a test fixture that was constructed from a roof section of a 2013 Blue Bird Vision School Bus (Abulhassan et al., 2018b). The observed flow rates for children in kindergarten through second grade ranged from 11 to 15 PPM. In this study, safety mats were stacked on the outside of the hatch opening, allowing participants to crawl out of the hatch without falling, or in the case of many, the ability to reach out and support themselves while exiting from the hatch (Abulhassan et al., 2018b). It was speculated that the **flow rates would have been dramatically reduced** from those observed if the safety mats had not used (Abulhassan et al., 2018b).

2. School bus roof emergency escape hatch

FMVSS No. 217 requires that school buses provide a specific number of emergency exits based on seating capacity (NHTSA, 2011). Type “C” and “D” school buses can have large seating capacities, which requires the use of two roof hatches. To meet, or exceed, the requirements of the standard, all current school bus manufacturers that manufacture Type “C” and “D” buses provide one roof hatch toward the front of the school bus, and another roof hatch toward the rear of the school bus, both located on the roof centerline.

The Federal Aviation Administration (FAA) establishes specific requirements for the number and size of emergency exits based on aircraft seating capacity (Federal Aviation Administration (FAA), 2008). FAA regulations require that aircraft with a seating capacity in excess of 44 passengers must be able to demonstrate the capability to evacuate all passengers and crew to ground level within 90 s with half of the exits blocked (Federal Aviation Administration (FAA), 2008). To evacuate a tightly populated space with that level of efficiency, it is important to have exits large enough to provide unobstructed flow. In the scenario where a school bus is rolled onto either side, the normal entrance door to the bus, as well as any emergency exit windows become difficult, if not impossible, to use for emergency egress. This situation leaves only the roof hatch(es) and the rear emergency door for egress. Aircraft with a seating capacity of 41–110 seats must have least two exits, one of which must be 24″ wide by 48” high, or larger as shown in Fig. 1 (Federal Aviation Administration (FAA), 2008). The proposed roof hatch design modification evaluated in this study increases the opening size of a school bus roof hatch from the current size of 57 × 57 cm (22.5 × 22.5 in), to an opening that is 57 cm wide by 117 cm high (22.5 × 46 in), close in size to that mandated by the FAA.

When mounted symmetrically at the center of the roof, the resulting decrease in the height of the opening reduces the step-up distance inside the bus and step-down distance outside the bus for the roof hatch by over 30%. The current hatch has a step-up distance of approximately 81 cm (32 in) and a step down distance of approximately 91 cm (36 in). Previous research has shown that the current configuration makes it difficult for all occupants because the opening is not large enough to allow passengers to keep their feet under them during evacuation, and some passengers need to climb up to simply reach the roof hatch opening (Purswell et al., 1970; Sliepcevich et al., 1972; Purswell et al., 1978; Abulhassan et al., 2018b).

The proposed roof hatch design maintains the width of the current hatch(es) used on school buses to allow the redesigned roof hatch to fit in between the main structural supports in the existing roof structure. FMVSS No. 220 requires that school buses must be capable of withstanding roof-loading forces that may be encountered if the bus were to roll over (NHTSA, 2008). To meet the requirements of FMVSS No. 220, roof deflection of a school bus must not exceed 12.7 cm (5 in) when a force equal to 1 ½ times the vehicle unloaded mass is applied to the roof structure using a force plate (NHTSA, 2008). The roof structure of the school bus is constructed of radial components (hoops) as continuous steel members and the axial members on the side of the school bus are

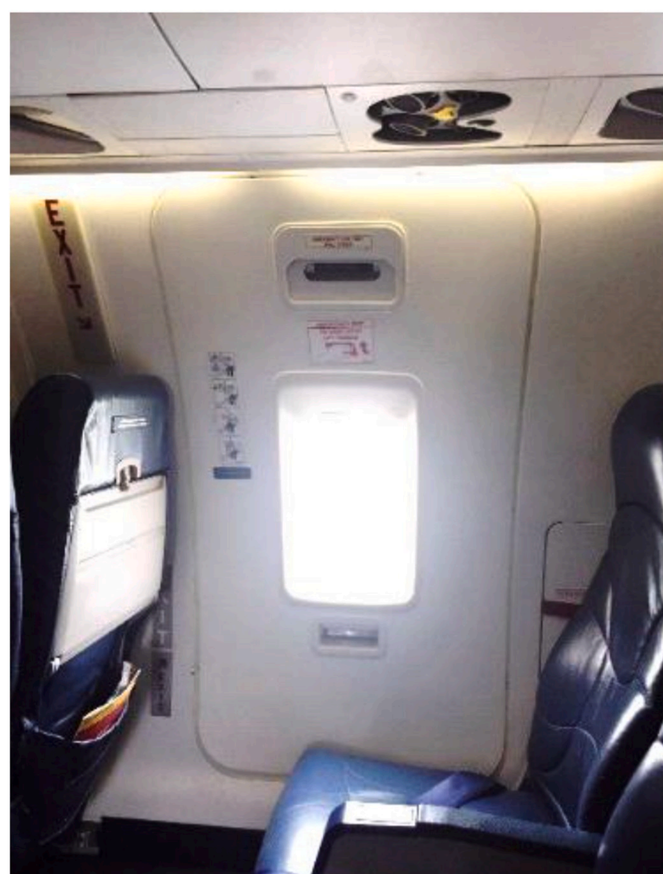

Fig. 1. Over-wing exit door.

welded to tie the hoops at preset distances as shown in Fig. 2. For the larger roof hatch design proposed herein, the axial ties can be slightly relocated to accommodate a larger hatch opening, and the section of roof around the hatch stiffened as appropriate.

Another design criterion taken into consideration is the complexity of the current design of the emergency escape roof hatch. Most hatches currently installed on school buses are designed for, and primarily used for, ventilation purposes, which is not necessarily the case with motor coaches and transit buses. This seemingly benign design feature complicates the operating mechanism in that the hatch must be able to open to an intermediate ventilation position, and also fully open for evacuation. The complexity of the hatch tested contributed to many younger children not being able to understand how to operate the roof hatch for evacuation purposes (Abulhassan et al., 2018b). To address this concern, our modified proposed roof hatch was designed to be used solely for evacuation purposes, and eliminates the ability to use the roof hatch as a ventilation device.

In summary, a significant mismatch has been previously identified between the design and operational requirements of current school bus emergency exit systems, including the emergency escape roof hatch and considerations for the strength and size of young school bus passengers (Abulhassan et al., 2016, 2018a; 2018b). It is doubtful that all young occupants could successfully evacuate from a rolled-over school bus without adult intervention. As such, the purpose of this study was to: (1) Redesign certain aspects of a typical emergency escape roof hatch that abates previously identified weaknesses; and (2) Evaluate and compare the alternative design to the current model to quantify potential gains attributable to the design improvements.

3. Methods

3.1. Test fixtures

Evacuation through existing school bus roof hatches was measured using a test fixture constructed from the roof section of a 2013 Blue Bird Vision school bus (Fig. 3). An essentially identical test fixture was designed and fabricated with the newly designed larger roof hatch which nearly adheres to the FAA passenger design opening requirements to the maximum extent practical without affecting the structural integrity of the roof structure (Fig. 3) (Federal Aviation Administration (FAA), 2008). The newly designed roof hatch increases the opening area of the roof hatch from 3249 cm^2 to 6669 cm^2. In addition to the 205% increase in opening area, the step-up distance to the exit opening was reduced to allow for faster egress.

Fig. 2. School bus roof structure (courtesy of Blue Bird Corporation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Participants

A total of 139 participants were recruited to participate from Goshen Elementary School (first and fourth grades), and Goshen High School (seventh and tenth grades) in Pike County, Alabama. Demographic information of the participants is provided in Table 1. This study was approved by the Institutional Review Board (IRB) at Auburn University, AL. Parents and guardians of all participants provided signed informed consent, and verbal assent was obtained from each child prior to the start of the study.

3.3. Evacuation data collection procedure

A total of 14 evacuation trials through the current and reconfigured roof hatch opening were conducted with seven groups of participants. The first six groups contained participants of the same grade level, and the last group was a mixture of students in the seventh and tenth grade. Each group proceeded through each test fixture once due to logistical constraints, except for the group containing students in both the seventh and tenth grade who were able to proceed through each test fixture twice. The order in which the participants went through both test fixtures was randomly selected based on the order in which they entered the testing area. Additionally, the order of participants in the mixed group of seventh and tenth graders were randomly alternated based on their grade level. Participants were outfitted with bicycle helmets to protect them during their participation. Participants were assigned a unique number, which was fixed to their helmet, and each group evacuation was videotaped for subsequent analysis. Two researchers were stationed by each test fixture to supervise the evacuation process and ensure safety and compliance with the study protocol.

Group trials consisted of organizing all participants into a single file line behind one device, informing them what they were going to do, obtaining verbal assent, and giving the start signal. No assistance was provided unless it was required for safety purposes. Each trial was videotaped. The group trial ended when the last participant exited the device. Each group participated in an evacuation through each test fixture once. After completing the evacuation at each station, groups were moved to the other station. The subsequent group evacuation trials proceeded in a similar manner on the other device.

3.4. Statistical analyses

Video analysis of the evacuation trials was used to extract individual egress time data. An analysis of variance was performed with individual egress time as the dependent variable, and the independent variables were individual, age, body mass index (BMI), and roof hatch type. An alpha value of 0.05 was used to determine the level of significance of the independent variables.

4. Results

The larger opening provided by the redesigned roof hatch resulted in a substantial increase in evacuation flow rates (Table 2). The data for first and fourth grade are based on the average of the two groups from each grade. The data suggests that the fourth grade and seventh grade students displayed greater flow rates than the first grade students. This may be indicative of the advantage of students with greater stature and upper body strength. The new hatch design allowed the evacuees to keep their feet underneath their bodies as they evacuated the bus, whereas the current design mandates that passengers must climb out of the relatively small opening. Results of the analysis of variance are illustrated in Table 3. The analysis suggests that age, BMI, and roof hatch opening had a statistically significant effect on egress times through roof hatches ($p < 0.05$).

Fig. 3. Current roof hatch test fixture (left) and redesigned roof hatch test fixture (right).

Table 1
Participant demographics.

Grade Level	Total Participants	Male Participants	Female Participants	BMI (SD)	BMI Range
1	40	20	20	18.3 (5.8)	11.2–38.0
4	53	33	20	19.4 (5.0)	11.7–35.1
7	24	8	16	20.1 (3.4)	13.7–27.4
10	22	8	14	25.4 (6.9)	16.6–40.4
Total	139	69	70		

Table 2
Evacuation flow rates (PPM).

Grade Level	Current Roof Hatch	Redesigned Roof Hatch	Percent Increase
1	10.0	29.5	195.0
4	12.8	36.0	181.3
7	19.7	43.6	121.3
10	16.3	40.0	145.4
7 & 10	20.7	38.9	87.9

Table 3
Evacuation response time regression analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.218870	0.054717	44.37	<0.001
Subject	1	0.000171	0.000171	0.14	0.710
Age	1	0.042165	0.042165	34.19	<0.001
BMI	1	0.005352	0.005352	4.34	0.038
Roof Hatch	1	0.164818	0.164818	133.66	<0.001
Error	273	0.336637	0.001233		
Total	277	0.555507			

5. Discussion

Although three students opted to not attempt egress through the current hatch design (two first graders, and one tenth grader), the vast majority were able to self-extricate through the test fixtures. Video recordings of the evacuation trials clearly illustrate how the 56 × 56 cm (22 in by 22 in) opening, with a step up height of approximately 81 cm (32 in), impedes the flow of evacuees through the current hatch design. This is because each evacuee must climb through the hatch opening, and the individual behind them must wait for their predecessor to clear the opening before proceeding. The flow rates provided by the redesigned larger escape hatch design allows the evacuees to egress without impediment. The flow rates through the current hatch design of the first and fourth grades were comparable to the 12 PPM rates measured by the Pollard and Markos (2009) and Abulhassan et al. (2018b). The average flow rate across all the trials conducted with the current roof hatch design at Goshen Elementary was 15.9 PPM. The improvement with the larger hatch design is clearly evident, as it is comparable to the flow rate of the main door (36 PPM) in the front of a bus (Pollard and Markos, 2009). The average flow rate across all the trials conducted on the new, larger, hatch design at Goshen Elementary was 37.6 PPM. Therefore, the results of this study suggest that the larger hatch opening is functionally equivalent to the front door of an upright bus, which is a notable improvement in egress. More importantly, we believe the redesigned roof hatch can be incorporated in current school buses without modification to the structural supports of the roof. The redesigned roof hatch would fit between the main structural supports to maintain the structural integrity of the roof and meet the roof deflection standards specified by FMVSS No. 220 (NHTSA, 2008). Additionally, the proposed roof hatch redesign will increase the opening area of the roof hatch from 3249 cm^2 to 6669 cm^2. The 205% increase in opening area would exceed the 4000 cm^2 roof hatch opening requirement on motorcoaches set by the Economic Commission for Europe standards (Economic Commission for Europe (ECE), 2008).

The significance of BMI also provides evidence of the need to increase the hatch size due to the increase in the rate of obesity. The BMI factor in this study is interesting because it indicates an effect of slowing down exit times even though older, bigger, stronger, children are able to egress faster. Taking into consideration the changing morphology of children is a significant factor to justify using larger openings for emergency egress on school buses.

There were several limitations to this study. The participants in the study were selected from four grade levels, and may not represent all grade levels of students riding school buses. To ensure participant safety during egress, safety mats were placed on the outside of the roof hatch openings. This may have artificially increased the flow rate through the current roof hatch design, as participants may have felt more comfortable landing on a softer surface. Factors such as injuries and environmental stressors (e.g., fire) were not studied, and it is hypothesized that they would significantly impede (lengthen) the evacuation process. The redesigned roof hatch opening requires an operating mechanism and that would need to be evaluated in future studies to determine its usability by young children and school bus passengers.

6. Conclusions

In conclusion, evacuation trials through test fixtures simulating a rolled-over school bus were conducted to evaluate flow rate of current roof hatches used on a typical school bus, and compare that to a redesigned roof hatch opening. The redesigned roof hatch was intended to be similar to an opening of an over wing exit on an aircraft. Group egress flow rates through the larger emergency roof hatch, were approximately equivalent to that of the front door of an upright bus. This research suggests that the larger emergency roof hatch opening significantly improves overall school bus emergency evacuation system safety.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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