Design Improvements for School Bus Emergency Evacuation Systems

by

Leslie Alan Gunter

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
May 5, 2019

Keywords: School Bus Evacuation, Emergency Door, Escape Hatch, RFID

Approved by

Gerard A. Davis, Chair, Professor of Industrial and Systems Engineering
Richard F. Sesek, Associate Professor of Industrial and Systems Engineering
Mark C. Schall, Jr. Assistant Professor of Industrial and Systems Engineering
Sean Gallagher, Associate Professor of Industrial and Systems Engineering
Yousif Abulhassan, Assistant Professor, Occupational Safety & Health,
Murray State University

Acknowledgments

This dissertation would not be possible without the help of many people.

- I would like to express my deepest thanks, and appreciation, to my committee chair, Dr. Jerry Davis, for giving me the chance to take this endeavor on. There were occasions when I wanted to quit, but he was a constant encouragement.
- I would like to thank Dr. Richard Sesek for his help in setting up and tearing down the test fixtures and for his advice and encouragement during the process.
- I would like to thank Dr. Richard Garnett for his help in setting up and tearing down the test fixtures, for his advice and encouragement during the process, and for his true friendship through it all, and for his constant reminder that I am older than him.
- I would also like to thank the remaining committee members, Dr. Mark Schall and Dr. Sean Gallagher, and Dr. Yousif Abulhassan for their assistance with the completion of the testing, the dissertation, and their technical expertise.
- I would like to thank the Deep South Center of Occupational Health and Safety for the pilot grant that made this study possible.
- I would also like to thank the Auburn University IRB office for their help with getting all the paperwork in place to complete the study.
- Most of all I must thank my wife, Deborah Gunter, for her constant love, prodding, and encouragement. If it was not for her, I would not be here.

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Chapter 1

Introduction

1.1 Background

School bus accidents are often accompanied by high anxiety and traumatic headlines because these vehicles transport young pre-school and kindergarten children. Young children are extremely vulnerable during emergency egress scenarios due to their size, strength, limited cognition, and lack of experience. One recent example occurred in Chattanooga, Tennessee, on November 20, 2016 when a school bus carrying thirty-five kindergarten through fifth-grade students left the road, rolled over and struck a tree, killing six and injuring more than twenty-three additional children (Figure 1.1). First responders extricated the children through the various emergency exit systems of the bus, such as the rear exit door and roof hatches. On December 2, 2014, in East Knoxville, Tennessee, a collision caused a school bus to overturn killing two children, one adult, and injuring twelve others. More recently, on January 30, 2018, a school bus in Warner Robins, Georgia, carrying thirty students ranging in age from five to eleven years old, rolled onto its side while traveling downhill, killing a six-year-old child and injuring five others.

The risk of fatalities, or serious injury, is more likely if a bus rolls over. It is very difficult to ascertain the annual frequency of school bus rollovers due to the lack of data including detailed accident specifics, but we believe is most likely between 10 and 99 rollovers per year. Though this number is small in comparison to the total number of school bus accidents each year in the

United States, the potential severity of occupants not being able to escape in a timely manner, or at all (unassisted), makes this scenario a ‘credible’ one worthy of further investigation.

Figure 1.1 School bus accident in Chattanooga, Tennessee

School buses are statistically the safest means of transportation for students to and from school and extracurricular activities. Yet there are approximately 26,000 accidents involving school buses each year [24]. Between 2005 and 2014, 106 people either riding in, or driving a vehicle designated as a school bus, were killed in the United States [24]. These numbers are remarkable considering that each school day in 2015, nearly 484,000 school buses transported over half of the United States K–12 student population (26.9 million children) to and from school and school-related activities [26].

A commonly used school bus is the type “D”, which has a capacity of up to 90 passengers depending on seating configuration [29]. School buses were first used in the United States in the early 1900’s as motorized vehicles when roadways began to emerge and develop. In 1939, a conference at Teachers College, Columbia University, drafted a set of forty-four specifications to standardize and improve safety for school buses including interior and exterior dimensions, as well as forward-facing seating. Modern school bus design requirements are mandated by the Federal Motor Vehicle Safety Standards (FMVSS) [7].

In the event of an accident involving a school bus, three factors contribute to the safety and wellbeing of the children aboard the bus in the aftermath: 1) The design of the emergency evacuation system, 2) The evacuation time required to clear the passengers, and 3) The response time for first responders. There are currently no federal standards for emergency response times for first responders [27]. A review of school bus crash files revealed that 47% of crashes had EMS response times of less than 10 minutes, 24% had response times of 10 to 14 minutes, and 29% had response times of greater than 15 minutes [28]. These statistics suggest that there is a significant probability that the school bus passengers may have to evacuate prior to the arrival of first responders during rollovers, fires, or other life-threatening events. Literature suggests that once a bus catches fire, it has the ability to completely burn out in three to five minutes [29]. The number, size, and location of emergency exits in school buses are specified in the FMVSS, but there are no federal specifications on evacuation times, which are a function of the number, location, and accessibility of exits [7]. However, Federal Aviation Administration (FAA) regulations require that any aircraft in the United States with a seating capacity larger than 44 passengers must demonstrate a full-scale evacuation of passengers and crew within 90 seconds under simulated emergency conditions, using only half the available exits [10]. In addition, the FAA establishes passenger/crewmember evacuation flow rates by performing certification tests and research.

Of paramount importance is the design of the school bus emergency evacuation system in place at the time of the emergency incident. These systems must provide rapid access and easy operation from inside and outside the vehicle no matter what orientation the school bus is in when it comes to rest. Again, the FMVSS mandate emergency system design by the number, size, location, and maximum force required to open various exits. However, **the FMVSS requirements do not account for the differences in strength and stature between adults and children**. Previous research has revealed that young children may not have the strength and/or cognitive abilities to open a roof hatch, or rear emergency door constructed to the current design requirements specified in the FMVSS [4,5,6].

1.2 Research Objectives

Having established a mismatch between the design mandates specified in the FMVSS and the actual abilities of children, the primary occupants of school buses, the objective of this research is to propose and evaluate potential solutions. Given the specific situation where the school bus is rolled over, two aspects of the emergency exit system are presented herein for redesign and evaluation: The rear emergency door, and the roof hatch. For the specific scenario where the school bus is rolled over onto the left side (facing forward), the rear emergency exit door is oriented with the door hinge along the top. Given that occupants will be able to unlatch the rear emergency door, occupants attempting egress will have to exit with an approximately 100-pound door hanging directly in the path of escape. A proposed design change to the rear emergency door hold-open device incorporates a ratcheting mechanism that keeps the door partially opened as occupants exit, causing the door to remain open at the aperture created by the size of the last person to exit. An experiment was conducted with fabricated test fixtures that replicated the school bus rear emergency door in this specific rolled over orientation for both the current design and the proposed design change. Participants in the experiment were videotaped and observed as they attempted to exit under both door hardware configurations.

A similar experiment was conducted to test the current and proposed design for the school bus roof hatch. Again, two test fixtures fabricated to replicate the school bus rolled over on its side so the roof hatch is oriented in a vertical plane. One test fixture is fitted with the current school bus roof hatch design and the other with the proposed design change. Participants in the experiment were videotaped and observed as they attempted to exit under both configurations.

Public school systems in the United States are mandated by State legislatures to conduct periodic school bus evacuation training for the benefit of their students. The approach to conducting this training varies widely between school systems and there exists only a scant trace of anecdotal records detailing specifics relating to this requirement. Radio-frequency identification (RFID) is becoming more prevalent in many applications relating to the safe transport of children on school buses [30]. A third experiment was conducted to establish actual evacuation times for large groups of participants using an actual school bus in an upright orientation and evaluate the use of RFID as a potential technology for use in tracking student egress versus the use of video.

The direct comparison of current and proposed designs of school bus emergency exit systems can be effective in eliminating the mismatches established between the design mandates specified in the FMVSS and the actual abilities of children. Furthermore, the use of RFID, or similar, technology could be a means of establishing a reliable nationwide repository of school bus evacuation data that would be helpful in establishing evacuation standards for school buses.

1.3 Research and Dissertation Organization

This dissertation has chapters organized in accordance with the Auburn University dissertation guide [Auburn University, 2015]. The dissertation consists of six chapters. Chapter One provides a traditional introduction. Chapter Two is a comprehensive literature review on the current standards and regulations for school bus emergency evacuation system design, as well as topics related to strength, anthropometry, and cognitive aspects of children and their ability to respond in an emergency scenario. Each of the remaining chapters is a unique manuscript which describes the purpose, methods, results and discussion of a specific experiment. The experiment described in Chapter Three measured the ability of first, fourth, seventh, and tenth grade students to exit two different designs of the rear emergency door of a school bus in a rolled-over orientation such that the rear door hinge is located at the top of the door. Chapter Four describes the experiment conducted to measure the ability of first, fourth, seventh, and tenth grade children to exit two different designs of the roof hatch of a school bus in a rolled-over orientation such that the roof hatch is in a vertical plane. Chapter Five contains a description of the experiment to measure evacuation times using larger groups of participants and RFID technology as a means of tracking the evacuation flow. The limitations of the experiments, further study recommendations, and overall conclusions are discussed in Chapter Six. The appendices contain details related to the recruitment and participation of human subjects, approved internal review board consent forms, and other supporting information.

1.4 Closing Statement

Though school buses are statistically the safest means of student transportation, school bus accidents and fatalities occur on a frequent basis in the United States. Because school districts across the United States operate many rural routes with very young passengers, the ability of children to evacuate through the emergency exits in a post-accident scenario may be the difference between life and death. Evaluating the current school bus rear emergency door and roof hatch components versus an improved proposed design could provide specific evidence of how to improve school bus emergency evacuation systems.

Chapter 2

Literature Search

2.1 Problem Statement

School bus emergency evacuation systems (EESs) should provide a path of escape that is accessible and usable for the complete spectrum of potential users. The current design of school bus EESs regulated by FMVSS 217 may not suitably address the strength and stature capabilities of all potential users. Previous research has revealed that young children (i.e. grades K through 2) may not have the strength capabilities to exert the maximum required force allowed in the FMVSS to unlatch an emergency exit, and flow rates are reduced by seat location and intrusion into the rear door exit opening [4]. Previous work has also shown that many young children are not able to open, or self-extricate, from a standard roof hatch of a school bus in a rolled-over orientation due to the location in the roof, latch operation complexity, and the strength requirements associated with pulling oneself up and through the current opening [6].

Therefore, it is paramount that improvements to the current EES design be pursued. Studying the differences in egress times and ease of exit use between current and improved EESs could help increase the probability of successful evacuation from a school bus rollover accident and identify any potential additional improvements that might be made.

2.2 General Evacuation System Design in Transportation

Human factors issues in the design of emergency evacuation systems are discussed here in the context of ambulatory, non-disabled passengers. All emergency exits in buildings, as well as passenger aircraft, ships, and trains, are primarily designed for ambulatory persons. In an emergency, able-bodied passengers are expected to release and open the emergency exits and assist other passengers who may require help [8]. In general terms, the geometry of transportation vehicles designed to move people can be described as tubular structures, or shells, designed to transport closely seated rows of passengers between two or more locations. Buses, trains, airplanes, and to some degree, ships can all be described as having this type of structure. The Federal Aviation Administration (FAA), Federal Railroad Administration (FRA), the United States Coast Guard (USCG), and the Economic Commission for Europe (ECE) all have specific requirements for vehicle emergency egress.

2.2.1 FAA

Commercial aircraft manufacturers and airline operators are required to comply with FAA stipulations per 14 CFR, Part 25 [10]. For example, § 25.803 establishes the requirement to demonstrate that all passengers can evacuate from an aircraft in 90 seconds or less using only half of the available exits. Testing must be performed with “a representative passenger load of persons in normal health.” This requires a minimum percentage of females, males, and various age levels. The regulation requires each aircraft meet extensive specific test criteria and performance requirements for the minimum number, type, location of emergency exits, and other emergency evacuation components established in § 25.807. The number, type, and size of the exits required are based on the number of seats on the aircraft. For example, for a passenger seating configuration of 41 to 110 seats, there must be at least two exits of a specific size in each side of the fuselage. The exit opening sizes are categorized such that the larger exit sizes provide egress for higher seating capacities. Type A through C exits are all floor level openings, with the largest being the type A. Type I through IV exits are floor level, and/or over wing openings that have step up and step down requirements. Furthermore, § 25.809 requires that each emergency exit must allow for an “unobstructed” opening, and that “each emergency exit must have a means to retain the exit in the open position, once the exit is opened in an emergency.”

2.2.2 FRA

Similarly, the FRA requires compliance with regulations defined in 49 CFR, Parts 238 and 239 [11] for both manufacturers and operators. Passenger rail cars must meet performance requirements that are related to the minimum number, type and location of emergency exits, rescue access locations, and other types of emergency egress components. Requirements for doors and windows that are intended to be emergency exits, and those intended to be rescue access windows and doors are established in § 238.113 and 114. This regulation requires “each emergency window exit in a passenger car…shall have a minimum unobstructed opening with dimensions of 26 inches horizontally and 24 inches vertically.” Emergency roof access per § 238.123 can be provided by either a hatch, or a conspicuously marked “structural weak point in the roof for access by properly equipped emergency response personnel.”

2.2.3 USCG

The USCG also has specific requirements for all passenger vessels, such as the provision of at least two means of escape from all areas accessible to passengers [12]. USCG requirements also specify vertical travel distance to exits, the sizing of stairways, and other provisions related to emergency egress. The Navigation and Vessel Inspection Circular (NVIC) 8-93 describes equivalent alternatives for meeting USCG requirements for means of escape, main vertical zones, and safe refuge areas on high passenger density dinner excursion and gambling vessels [13]. The USCG also recognizes the requirements of the International Maritime Organization /

Safety of Life at Sea (IMO/SOLAS) for United States (US) vessels that operate in international waters [14].

2.2.4 ECE

In addition to these U.S. standards and regulations, the Economic Commission for Europe (ECE) established standards for motorcoach emergency egress in ECE No. 36 [9]. These standards include requirements for additional side-door exits, larger emergency roof exit hatches than those required in the U.S., and the use of floor exit hatches.

The intent of these regulations are similar to that of FMVSS 217: "to minimize the likelihood of occupants being ejected…and provide a means of readily accessible emergency egress" for passengers under a multitude of emergency situations. However, effective emergency egress should not only be accessible, but also provide for an efficient flow of passengers to escape a vehicle in an emergency scenario. This characteristic is achieved by designing emergency egress systems to be unobstructed, and large enough to promote efficient passenger flows during an evacuation situation.

2.3 FMVSS 217, NHTSA, and FMCSA Requirements for Buses and School Buses

There are two U.S. government agencies that promulgate regulations related to motor vehicle safety including motorcoaches and school buses. They are the Federal Motor Carrier Safety Administration (FMCSA) and the National Highway Transportation Safety Administration (NHTSA). The FMCSA enforces regulations which establish standard care for trucks, truck companies, and drivers, termed the Federal Motor Carrier Safety Regulations (FMCSR).

2.3.1 FMCSA

The FMCSA regulations apply to vehicles engaged in interstate commerce that weigh 10,000 pounds, or more. This includes regulations for vehicles transporting passengers for compensation, and not for compensation. It also regulates the transportation of hazardous materials. Furthermore, these regulations address training and test standards for commercial driver's licenses, vehicle inspections, maintenance, and vehicle operations. FMCSR regulation 49 CFR 393.62 [15] specifies the emergency egress requirements for all buses manufactured after 1973 and operated in interstate commerce, including school buses, must comply with FMVSS 217 [7].

2.3.2 NHTSA

NHTSA promulgates the regulations for bus and school bus design and manufacture in 49 CFR, Part 571, known as the Federal Motor Vehicle Safety Standards (FMVSS). NHTSA defines "buses" as "a motor vehicle with motive power, except a trailer, designed for carrying more than 10 persons." It further defines "school buses" as a bus that is "sold or introduced in interstate commerce for purposes that include carrying students to and from school or related events but does not include a bus designed and sold for operation as a common carrier in urban transportation [1]." FMVSS 217 requirements for EESs are intended "to minimize the likelihood of occupants being thrown from the bus and to provide a means of readily accessible emergency egress" in diverse emergency scenarios, such as rollovers, fires, water immersion, or when immediate emergency evacuation is essential to prevent loss of life. These regulations cover the design, construction, performance, and safety related components of new motor vehicles.

FMVSS 217 requirements were issued by NHTSA in 1972 and became effective in 1973. These requirements for bus window retention and emergency exits [16] were for buses other than school buses. However, if school buses were equipped with emergency exits, those exits were require to comply with FMVSS 217 requirements [8]. Additional requirements for school bus emergency exits, including requirements for at least one side emergency exit door, or one rear emergency exit door with a push-out window, first became effective in 1977 [8].

Specifically, as it relates to this research, FMVSS 217 provisions specify the dimensional and physical requirements for emergency exits for school buses, including their size, location, opening, release operation, and related forces required to operate.

2.3.2.1 FMVSS 217

The FMVSS regulates the design of emergency evacuation systems for both motorcoaches and school buses, and the requirements for school buses are different. These requirements are organized by the following topics: window retention, the provision of exits, emergency exit release, emergency exit openings, emergency exit identification, and test conditions. Presented here are the requirements of FMVSS 217 for school bus emergency exits, exit opening size, and test conditions. The requirements of FMVSS 217 vary according to the type of bus and the gross vehicle weight rating (GVWR). The regulations apply to school buses with a GVWR in excess of 10,000 pounds. The industry defines four basic types of school buses. Types A and B are small compared to the larger types C and D, with the latter having a GVWR in excess of 10,000 pounds. Type C school buses are the most common, representing 70 percent of school bus sales in 2014 (23,715 of 34,021 buses) according to figures reported by *School Bus Fleet* [17].

A. Provision of Emergency Exits for School Buses (S5.2.3)

Unobstructed openings of a minimum size must be provided for use as emergency exits during an emergency evacuation. The exit openings are subject to minimum type and size provisions which focus on side and rear door exits with provision for additional emergency exits based on seating capacity (Table 2.1). School buses are permitted to meet the minimum number of emergency exit doors by using one of two options: 1) one rear emergency door that opens outward, hinged on the right side; or 2) one left side emergency door, hinged on the forward side, with one push out rear window of a specific minimum size.

Table 2.1 School bus emergency exits requirements [7]

Seating Capacity	Emergency Exits Required
1-57	None
58-74	1 right side exit door, or 2 exit windows
75-82	1 right side exit door or 2 exit windows, and 1 roof exit
83 and above	1 right side exit door or 2 exit windows, and 1 roof exit, and any combination of door (CC=16), window (CC=8), roof exit (CC=8) such that the total Capacity Credit (CC) specified plus 82 is greater than the capacity of the school bus

Regardless of which option is used, school buses are required to have additional emergency exits such as doors, emergency exit windows, or roof hatches, based on the capacity of the bus. Emergency exit windows that are used to meet the requirement for additional exits for higher bus capacities must be of an even number and evenly divided between the left and right side. Roof hatches may also be installed to meet the requirements for higher capacity buses. Hatches must be hinged at the forward edge, operable from both inside and outside of the bus, and located at the midpoint, for one hatch, or equidistant from each other, of more than one is installed [8]. Seating capacity is calculated by dividing the width of the school bus bench in millimeters by 380, rounding to the nearest whole number, then multiplying by the number of benches on the bus [18]. The basis number "380" is derived from providing enough space to accommodate a 5th percentile adult female [18]. The space required for a person to sit is generally measured by hip and shoulder breadth in a sitting position [19]. Because these NHTSA standards are based on adults, it is possible to exceed the capacity rating of buses when passengers are kindergarten through second grade students [4].

B. Emergency Exit Opening Size for School Buses (S5.4.2)

In accordance with the regulation, the unobstructed opening for a rear emergency exit door must permit the passage of a rectangular parallelepiped 1,145 mm (45 in.) high, 610 mm (24 in.) wide, and 305 mm (12 in.) deep. The 1,145 mm dimension must remain vertical, and the 610 mm dimension must remain in contact with the floor and parallel to the opening at all times. The bottom edge of the rear-most surface of the parallelepiped must be tangent to the plane of the door opening. Roof hatches are required to provide an opening of at least 41 cm (16 in.) high by 41 cm (16 in.) wide.

C. Rear Emergency Door Hold-Open Device Requirement for School Buses [S5.4.2.1 (a)(3)(i)]

Rear emergency doors must also be equipped with a positive door hold-open device. The hold-open device is referred to in the FMVSS 217 as a “positive door opening device.” However, the device does not actually open the door, it holds the door in an open position after the release mechanism on the door has been operated and the door has been opened to its maximum position. This document will refer to the device as a hold-open device (HOD) instead of a positive door opening device. According to the requirements, with the bus in the upright position (per the requirements of S6.1 stating that the vehicle is on a flat, horizontal surface), and the rear emergency door open, the device must:

(A) Bear the weight of the door;

(B) Keep the door from closing past the point at which the door is perpendicular to the side of the bus body, regardless of the body’s orientation; and

(C) Provide a means for release, or override.

2.3.2.2 FMVSS 220

It should also be noted that FMVSS 220 also requires school bus roof crush tests to provide rollover protection, which specify that all emergency exits remain operable during and after the tests [20]. A force is applied to the school bus roof structure by means of a specific force plate. The force must be equivalent to 1 ½ times the vehicle unloaded mass. The performance criteria for the force test states that the roof defection shall not exceed 130 mm (5 in.). Also, all emergency exits must be able to operate during the full force application and after removal of the force. Roof hatches are exempt from the requirement of being capable of opening during the test, however, it must be operable after the force is removed. Furthermore, the test requirements specify that the exits are to be open during the application of the force, then the exits must be capable of opening, after the release of the force on the roof of the bus.

2.3.3 Historical Background

Buses that operated in interstate commerce were first subject to Interstate Commerce Commission (ICC) Bureau of Motor Carrier (BMCS) safety regulations in 1937 when a bus was defined as “any motor vehicle designed and used for carrying passengers.” The ICC released regulations for bus emergency exits in 1952 which required the total exit area in square inches to be equal to the number of seats multiplied by 67. Motor vehicle regulations were transferred from the ICC to the Department of Transportation in 1967, eventually resulting in the formation of FMCSA and NHTSA. Then in 1972 NHTSA released FMVSS 217, with an effective date of May 1, 1973.

The minimum unobstructed bus emergency exit opening size was increased due to findings of a National Highway Safety Bureau (NHSB), which is now NHTSA, sponsored study conducted at the University of Oklahoma Research Institute (OKRI). The rule provided alternatives for emergency exits that included a combination of windows, doors, and roof hatches. Several revisions to the FMVSS 217 and 220 have been issued since 1973.

The Federal Register Proposed Rules (2014) released documentation expressing concern over the operability of emergency exits after a rollover accident and the impact of inoperable exits on emergency evacuations, and whether a rollover scenario will still meet the requirements of the upright orientation [21].

2.3.3.1 University of Oklahoma Research Institute Studies

The University of Oklahoma Research Institute (OKRI) conducted two research studies related to motor vehicle post-crash “escapeworthiness” under contract with NHTSA (then NHSB) which were published in 1970 [1] and 1972 [2]. A third study specifically on motorcoach emergency evacuation was completed in 1978 [3]. This work is the only known U.S. bus evacuation experimental data prior to experiments conducted by the Volpe Center [22].

The OKRI research related to school buses used sixty subjects representing all twelve grades, consisting of approximately half girls and half boys. The primary independent variable was body breadth as it relates to the various exit sizes. Subjects were measured to ascertain shoulder width, elbow-to-elbow width, and hip width (sitting). Other demographics, such as age, were also considered in order to provide a reasonable cross section of participants. Trials were conducted using an upright school bus, as well as an overturned school bus mock-up. Using the upright configuration, the escape routes tested included the front door, exit windows, and rear emergency exit door. The rolled over mock-up was used for testing a rear emergency door and emergency roof hatches. In some of the trials the subjects wore goggles to simulate darkness.

The major findings from the 1970 study revealed that escape from buses was significantly affected by post-crash bus position, exit size, the height of the exit above the ground, the weight of the emergency exit windows / doors in some bus orientations, and the effect of darkness.

Also, the physical size and age of the subjects significantly affected escape time from buses, and the use of rear emergency doors and roof hatches significantly reduced egress times [1]. A major finding from the 1972 OKRI report recommended that an acceptable time for passengers to escape from a bus using only half the exits should not exceed 90 seconds [2]. The OKRI major findings from the 1978 study [3] on motorcoach emergency "escapeworthiness" included:

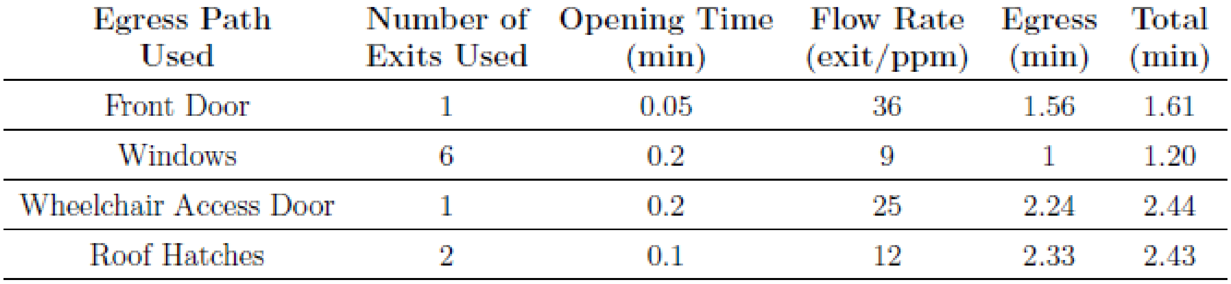
- A recommendation that a standard for maximum evacuation time should be considered.
- A toehold on the inside and outside of the bus to improve the use of roof hatches during egress.
- Clear instruction on the use of emergency exits should be provided to all passengers.
- An emergency illumination system should be considered for buses.
- A performance specification should be considered for bus windows that swing out to prevent them from breaking off under the load imposed as passengers attempt to hold on to them during egress.

2.4 The Volpe Center

A study to establish the egress times of a fully loaded 56 passenger motorcoach was conducted by the Volpe Center, a federal agency under the Department of Transportation [22]. Emergency evacuation trials for each type of exit were performed separately. The participants in the study were the staff of the Volpe Center, which had some knowledge of the bus evacuation system [22]. Hold-open devices were used to keep emergency windows open after they were unlatched [22]. The results for the egress study are displayed in Table 2.2. Some of the main conclusions were that evacuation times will likely be significantly higher for children on a school bus, and other factors that may result in higher evacuation times include no hold-open device, an incapacitated driver that cannot assist passengers, injured passengers, passengers with limited experience using emergency exits, passengers lacking the strength and agility to use or extricate themselves from exits, and exits not staying open [22].

The rear emergency exit door of a school bus has a typical weight of 90 to 100 pounds and the hold-open device does not secure the door in the open position until the door is opened such that it is approximately 90 degrees from the rear of the school bus. If the school bus is rolled over on the left side facing forward, or driver’s side, the rear emergency door hinge would be located at the top of the door. Opening the door to the 90 degree position from the inside of the bus would be almost impossible for an adult. Opening the door only partially would result in the door falling back down in the path of escape, hindering unobstructed egress.

Table 2.2 Volpe Center 56 passenger motorcoach egress times [22].

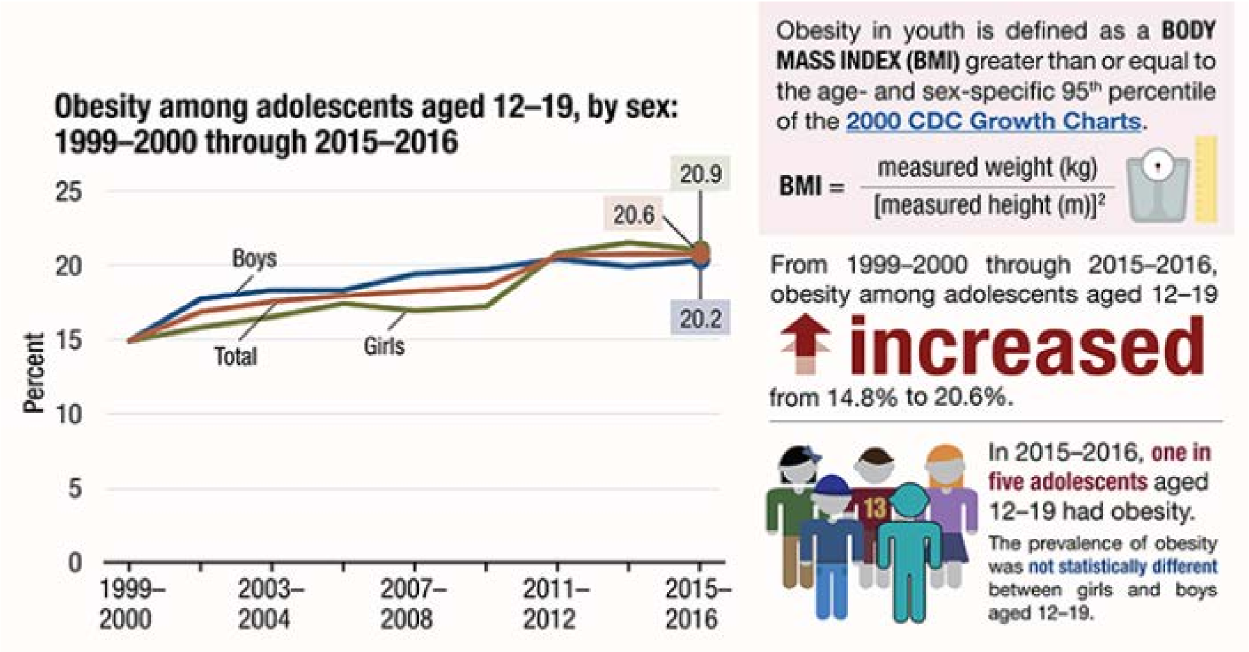


Egress Path Used	Number of Exits Used	Opening Time (min)	Flow Rate (exit/ppm)	Egress (min)	Total (min)
Front Door	1	0.05	36	1.56	1.61
Windows	6	0.2	9	1	1.20
Wheelchair Access Door	1	0.2	25	2.24	2.44
Roof Hatches	2	0.1	12	2.33	2.43

Based on the data in Table 2.2, the egress flow rate for the roof hatches was only about a third that of the front door. The obvious conclusion is “that size matters” as it relates to emergency exits. The same conclusion was drawn from the school bus studies conducted by OKRI in 1970 [1] as it evaluated the relatively smaller exit size of roof hatches and emergency exit windows compared to the much larger front door and emergency exit door.

2.5 The Stature of Children

The size and access used in emergency exit system design should consider the size and shape of the users of the system. The opening sizes of emergency exits should be based on morphology, such as shoulder (bi-deltoid) breadth, and width of the pelvis (bi-iliac breadth). According to the FMVSS 217, roof hatches designated as emergency exits must be no less than 40.6 cm by 40.6 cm (16 in. by 16 in.). However, with the increasing prevalence of obesity in the U.S., the minimum roof hatch size may not be sufficient for emergency egress of all passengers on a school bus (Figure 2.1) [23, 37].



Obesity among adolescents aged 12–19, by sex: 1999–2000 through 2015–2016

Obesity in youth is defined as a **BODY MASS INDEX (BMI)** greater than or equal to the age- and sex-specific 95th percentile of the 2000 CDC Growth Charts.

$$\text{BMI} = \frac{\text{measured weight (kg)}}{[\text{measured height (m)}]^2}$$

From 1999–2000 through 2015–2016, obesity among adolescents aged 12–19 ↑ **increased** from 14.8% to 20.6%.

In 2015–2016, **one in five adolescents** aged 12–19 had obesity.

The prevalence of obesity was **not statistically different** between girls and boys aged 12–19.

Figure 2.1 Increasing trend in BMI in the U.S. [37].

An anthropometric consideration is that of school bus passenger height. Height measurements are shown in Table 2.3. Figure 2.2 illustrates the access of a school bus roof hatch of a bus that is rolled over onto the side an average height adult male versus an average kindergartener. The child would have to reach over his/her head to operate the mechanism to open the roof hatch, then lift themselves through the opening of the hatch. After the child's center of mass gets through the hatch opening, they could fall as much as 40 inches to the ground due to the drop off on the outside of the bus. Previous research revealed that a significant

Table 2.3 Height of children in the U.S., 2002 (inches) [23].

MEAN MALE HEIGHT (INCHES) U.S.				MEAN FEMALE HEIGHT (INCHES) U.S.		
AGE	SAMPLE SIZE	MEAN		AGE	SAMPLE SIZE	MEAN
5	157	44.5		5	190	44.3
7	187	49.7		7	200	49.0
10	188	55.7		10	164	56.4
12	301	60.9		12	318	61.4
15	287	68.4		15	271	63.8
17	317	69.0		17	258	64.2
19	275	69.6		19	231	64.2

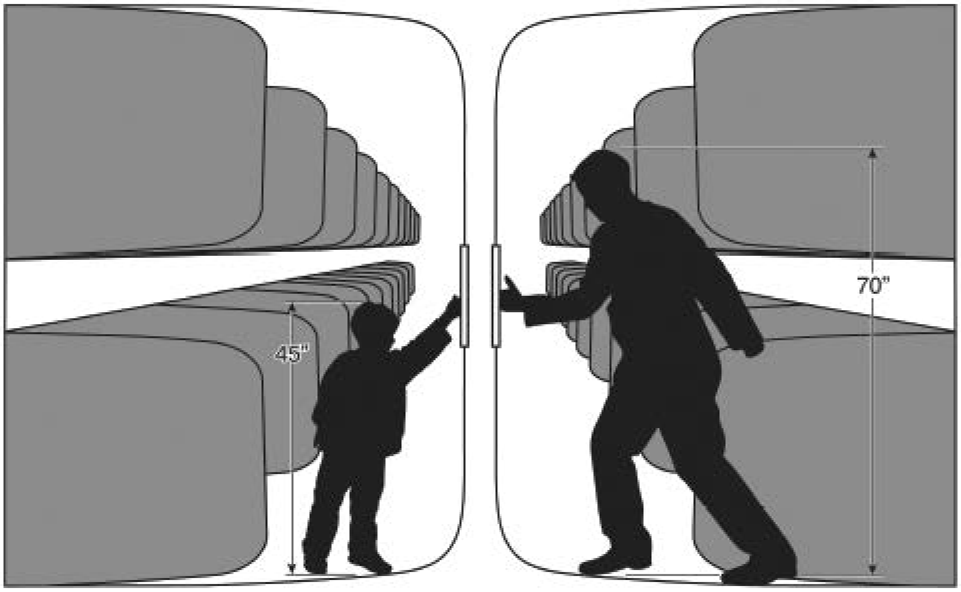


Figure 2.2 Comparison of access to rolled-over school bus roof hatch.

number of young school children tested (K through 2nd grade) were not able to either open the roof hatch, or self-extricate through the hatch [6].

Similarly, the difference between the stature of an average kindergarten student and an average adult male is illustrated in Figure 2.3 in relation to opening a rear emergency door on a school bus that has rolled over onto the left, or driver's, side such that the hinge of the door is at the top. The illustration assists in the visualization of the posture required to lift the 90 to 100 pound door to a horizontal position perpendicular to the body of the bus where the current hold-open device will prevent the door from obstructing the emergency exit opening.

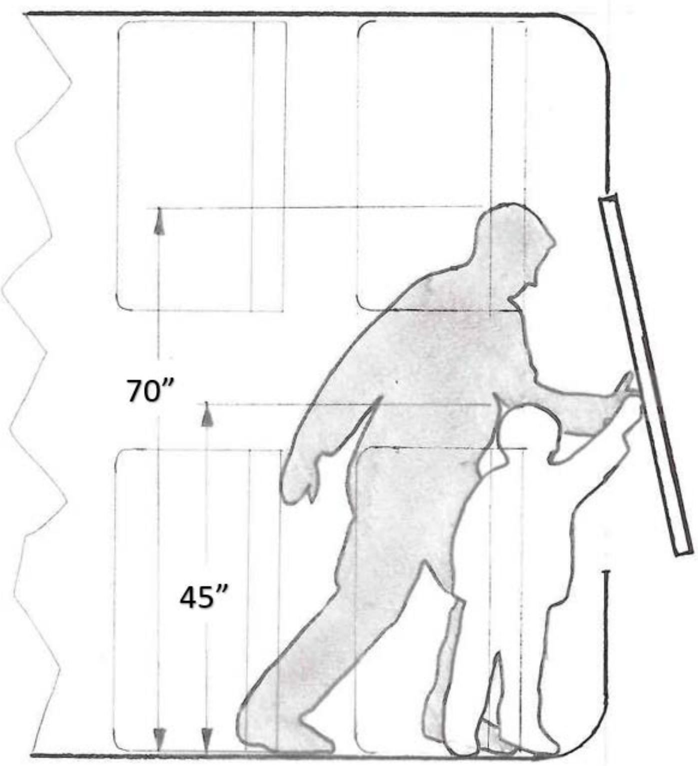


Figure 2.3 Presentation of the school bus rear emergency door.

2.6 Limitations of Existing Research

Research related to emergency evacuation of school buses is very limited. With the exception of the studies performed by Purswell and Dorris [1,2,3], published in the 1970’s, and Abulhassan *et al* [4,5,6] published from 2016-2018, very little is known about the ability of children to successfully evacuate a school bus post-accident. This is especially true if the bus is in any orientation other than its normal upright orientation. Prior research specifically related to roof hatch egress and rear emergency door egress in the unique situation when the school bus is rolled over onto the left, or driver’s, side has revealed that the current design of these components of the school bus evacuation system has flaws that could significantly impede evacuation in the case of a school bus accident involving a roll over.

2.7 Use of RFID for Tracking School Bus Evacuation Training

Public school systems in the United States are mandated by State legislatures to conduct periodic school bus evacuation training for the benefit of their students. The approach to conducting this training varies widely between school systems and there exists only a trace of anecdotal records detailing specifics relating to this requirement, other than that it was completed with scant details. The use of RFID associated with school buses has increased significantly over the past decade. Researchers in Qatar published a paper [30] in 2013 detailing a number of possibilities for RFID to enhance the safety of bus riders. The authors mention monitoring students as they enter and exit the bus, discuss examples of students attempting to get off at the wrong stop, and students who have been left on the bus after the route is completed [31]. The authors also mention that passive RFID tags are preferred over active tags as they last longer, cost much less, are safe for use around children as they are only powered when near a reader

[30]. A 2015 paper [32] discusses the use of Short Message Service (SMS) enabled by RFID to notify parents and school officials of other than expected incidents.

2.8 Specific Aims

The aim of this research is to: (1) Evaluate a rear emergency door intervention designed to improved passenger flow rate during evacuation. Two school bus mock up test fixtures were fabricated representing a bus rolled over on the left side: one equipped with a current rear emergency door hold-open device design, and the other equipped with an improved device design. The experiment compared the performance of each device by observing and analyzing the ease of egress for participants by measuring time to exit the door in each fixture; (2) Evaluate a emergency roof hatch intervention designed to improved passenger flow rate during evacuation. Two school bus mock up test fixtures were fabricated representing a bus rolled over onto its side: One equipped with a current roof hatch design, and the other equipped with an improved roof hatch design. The experiment compared the performance of each device by observing and analyzing the ease of egress for participants by measuring time to exit the hatch in each fixture; and (3) Evaluate the accuracy of RFID versus video as a way of tracking and recording the egress of student during required school bus evacuation drills conducted in each state.

Chapter 3

Increasing the Evacuation Flow Rate through a School Bus Rear Emergency Door

3.1 Abstract

The United States Federal Motor Vehicle Safety Standards (FMVSS) define requirements for school bus exit system components. One component of the evacuation system requires that the rear emergency door of a school bus must be fitted with a device that is capable of holding the door in an open position at the point at which the door is perpendicular to the rear of the bus body, regardless of the bus orientation. In the specific situation when a school bus is rolled over onto the driver's side (left side facing forward), the rear emergency door hinge will be located at the top of the door, and due to the weight of the door, pushing the door up and locking it in the open position would require substantial effort for an adult. For smaller adults and most children, this may not even be possible. Thus the door hanging in the opening would obstruct the egress of each passenger as they attempt evacuation. Such conditions suggest that current rear emergency door exits could not allow unobstructed passage in such a rolled over bus orientation, unless evacuees and/or external assistance was provided to hold the door open, or partially open. The unassisted situation would significantly lessen passenger flow rates during an evacuation. The purpose of this study was to redesign, fabricate (prototype), and test a rear emergency door hold-open device to allow the door to be held partially open, alleviating the need for the door to be fully opened to provide unobstructed passage. The results revealed that the improved device facilitated significantly faster flow rates than the rear emergency door hold-open device currently in use.

3.2 Introduction

Very little research has been conducted pertaining to school bus emergency evacuations. Except for the studies performed by Purswell and Dorris [1,2,3], published in the 1970's, and Abulhassan *et al* [4,5,6] published 2016-2018, literature related to the ability of children to successfully evacuate a school bus post-accident is sparse. This is especially true if the bus is in a rolled-over orientation. Due to a lack of detailed data, the annual frequency of school bus rollovers is difficult to ascertain. However, we believe it is most likely between 10 and 99 rollovers each year. This number is not insignificant in comparison to the approximately 26,000 school bus accidents each year in the United States because of the potential severity of occupants (children) not being able to escape in a timely manner, or at all (unassisted). The specific rollover scenario under investigation in this study involves the rear emergency door with the school bus resting on the driver's side, or left side.

3.3 Rear Emergency Door Hold-Open Device

FMVSS 217 mandates that school buses be equipped with a rear emergency exit door that opens outward and is hinged on the right side facing forward [7]. In addition, the regulation requires that each school bus emergency door shall be equipped with a "positive opening device" that:

- Bears the weight of the door;
- Keeps the door from closing past the point at which the door is perpendicular to the side of the bus body, regardless of the orientation of the bus body; and
- Provides a means for release, or override [7].

In the unique orientation of the bus resting on the driver's side (or left side facing forward), the school bus rear emergency door hinge will be aligned with the top edge of the door, and the door will open out and up, away from the inside of the bus (Figure 3.1).

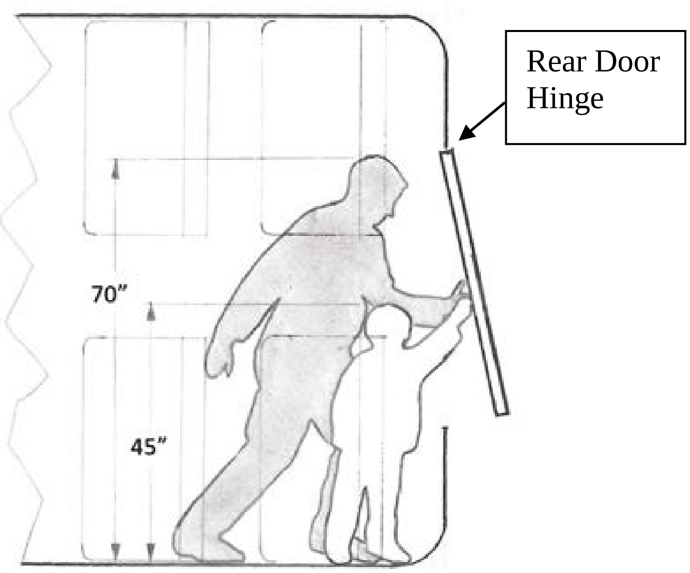


Figure 3.1. Adult and child attempting to open a school bus rear emergency door.

Because the typical school bus rear emergency door is fabricated from mild steel, and is fitted with two large windows glazed with safety glass, the weight of the door is approximately 90 to 100 pounds. Attempting to escape through the rear emergency door of a bus rolled over in this orientation would require opening the door and pushing it up and away from the bus. The forces required to open the door can be estimated as shown in Figure 3.2.

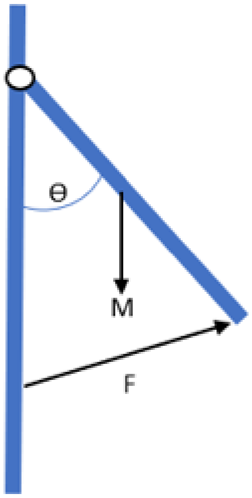


Figure 3.2. Free-body diagram of forces to push open rear door.

Assuming the mass of the emergency exit door is distributed symmetrically, the force required to support it at a given angle (Θ) may be estimated by assuming that the center of gravity is located between the hinge and edge of the door with the latching device [8]. If the force is applied perpendicular to the lower edge of the door as illustrated by the free-body diagram in Figure 3.2, the force required to push it open can be estimated using Equation (3.1):

$$F = M \times A/2(\sin \Theta) \quad - \quad \text{Equation (3.1)}$$

Where:

F = Force required (Newtons)

M = Mass of door

A = Acceleration of gravity (9.8 m/sec^2)

Θ = Angle of door opening

A passenger standing inside the bus would not be able to maintain a perpendicular force application as the angle of the opening gets larger. Assuming the force applied by the passenger would be applied in a line from the latch edge of the door opening to the latch edge of the door, the force, P, could be estimated using Equation (3.2):

$$P = F/\cos(\Theta/2) \quad - \quad \text{Equation (3.2)}$$

Figure 3.3 reveals the estimated force to push a 100-pound door open to a position perpendicular to the bus body. This estimate assumes that the passenger would maintain a pushing position at the far edge of the door as it opens. This would require reaching out 114 centimeters (45”) and applying 314 Newtons (70 pounds-force). Such a feat would be extremely difficult for any adult and impossible considering the strength and stature of a small child [4]. The required force is

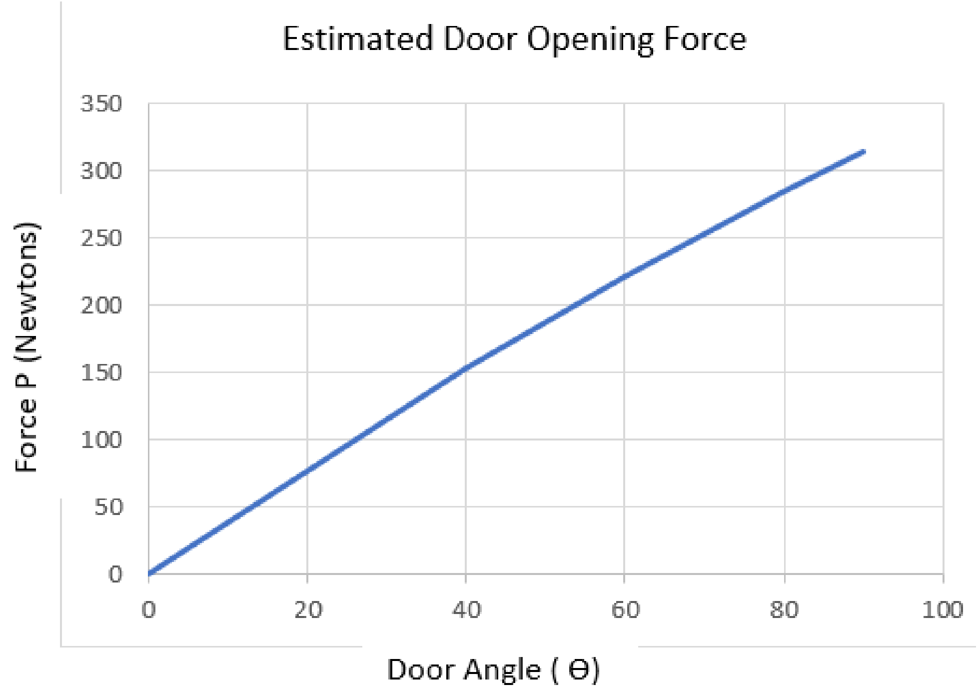


Figure 3.3. Estimated force to open rear emergency door to any angle (Θ).

higher as the passenger applies the pushing force closer to the center of the door. However, this is what would be required for the rear emergency door to get to the position in which the hold-open device, currently in use today, would hold the door out of the way for evacuation.

We propose the idea of replacing the current hold-open device with a device that employs a ratcheting mechanism to allow the door to remain in an open position at multiple positions from fully closed to fully open, or perpendicular, to the bus body. This design would allow the first passenger to exit the door by unlatching it, and pushing it open to some position that provides enough opening for their body to egress. Then the remaining evacuees may follow through the opening. If a larger evacuee exits subsequent to the first evacuee, the door could further open and be held at a larger aperture, to allow for easier egress for the remaining passengers using this exit. Such an improved design should incorporate all the FMVSS requirements for the hold-open device currently in the standard.

The device currently in use consists of two mild steel roll formed channels that telescope together such that the device can extend and contract as the rear emergency door opens and closes. These devices are available in multiple lengths and with various mounting brackets for attaching to the doors and door frames on the various styles and brands of buses (Figure 3.4). The device mounts on the door frame at one end and to the top of the rear emergency door at the other end (Figure 3.5). It is designed so that when it is fully extended, and the door is fully opened and perpendicular to the bus body, a metal rotating component riveted to one of the slides rotates into position to prevent the slides from contracting, thus holding the door open.

Pushing the door in the opening direction again to its extreme open position causes the rotating component to reset, allowing the door to close once again.

Figure 3.4. Emergency door hold-open device currently in use.

Figure 3.5. Typical rear emergency door hold-open device location.

The goal in redesigning the rear emergency door hold-open device is to develop a device that will simply replace the current one, so that it can bolt, or fasten in place identically replacing the current device. The reason for this is simplicity, cost effectiveness, and to make it more likely to be used. In order to achieve this, the current device was modified to provide the operation desired.

To ascertain the loads placed on the hold-open device, a free-body diagram of the forces associated with holding the door perpendicular to the body of the bus is shown in Figure 3.6. The assumption is made that all the forces are in equilibrium and the door is static. Further, the door weighs approximately 45 Kg (100 lbs), is 81.3 cm (32 inches) wide, and the center of mass is assumed to be located halfway across the door at 16 inches from the hinge. The load on the hold-open device can be determined by summing all the moments about point A, which is the hinge of the door.

$$\Sigma M_A = 0; \qquad (7)\,R\,(\sin\Theta) - M\,(16) = 0 \qquad \text{Equation (3.3)}$$

$$R = 1067\text{ N } (239.8\text{ lbf})$$

If a 113 Kg (250 lbs) weight is added to the door edge opposite to the hinge such as someone hanging on the edge of the door, the load on the hold-open device would increase to 6,405 N (1,440 lbf).

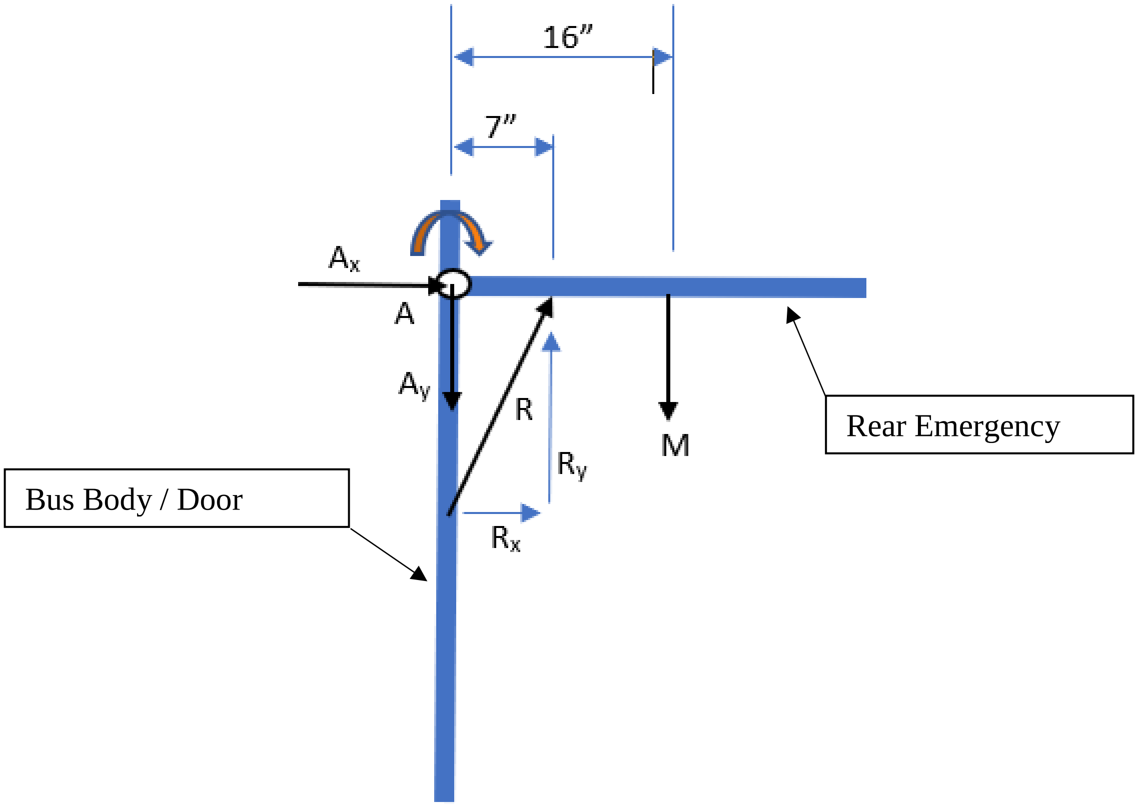


Figure 3.6. Free-body diagram of door supported by hold-open device.

Because the hold-open device is loaded along the longitudinal axis, it is subject to buckling. In order to evaluate that mode of failure Euler's equation for the critical buckling load is used [35], Equation (3.4):

$$F = \frac{\pi^2 EI}{(KL)^2} \quad \text{- Equation (3.4)}$$

Where: F = Critical buckling load

E = Modulus of elasticity

I = Moment of inertia of the cross section of the support

L = Column unsupported length

K = Column effective length factor

The modulus of elasticity for mild steel is 200 GPa ($29(10^6)$ psi), the moment of inertia for the roll formed section of the hold-open device was determined to be 1.143 mm^4 (0.045 in^4), the length of the support is 58.4 cm (23 inches), and the column effective length factor is 1.0 because the ends of the hold-open device are pinned, and free to rotate. The theoretical maximum load prior to buckling is determined to be 11,045 N (2,483 lbf). This value is approximately 10 times the load induced onto the hold-open device by the door.

The locking cog inside the hold-open device that rotates to prevent the door from closing once it is fully opened is secured to one of the roll formed rails using a rivet that is 6 mm (.25 inch) in diameter at the narrowest point where it protrudes through the rail. It would be loaded in shear by the weight of the door. Shear stress is calculated using Equation (3.4) [9]:

$$\tau = F/A \quad - \quad \text{Equation (3.4)}$$

Where: τ = Shear stress

F = Load

A = Cross section area

Solving this for the maximum load for the 6 mm (.25 inch) diameter mild steel rivet, using a maximum shear stress for mild steel of 240,000 kPa (34,800 psi), yields a theoretical failure load of approximately 7562 N (1,700 lbf). This value is 7 times the load induced by the door onto the hold-open device.

The locking cog could theoretically fail by shear tear out of the hole the rivet goes through. In this situation, instead of the rivet shearing off, the rivet is pulled through the cog. The same formula for shear applies, and solving for the theoretical failure load yields a value of 9675 N (2,175 lbf). This value is 9 times the load induced by the door onto the hold-open device when the door is fully open.

These calculations for the strength of the current hold-open device establish a basis for maintaining the materials and thicknesses of the components of the device as we modify it to ratchet and hold the door at different positions as it opens. The modifications involved removing and replacing the rotating component mentioned earlier with a different rotating component called a pawl. The pawl is spring loaded using an off-the-shelf purchased component called a spring plunger. The spring plunger is adjustable so that the tension on the pawl can be set. A third component called a castle bar is welded into place in the inner telescoping rail. The pawl and the castle bar interact to provide the ratcheting feature of the device. The spring plunger interacts with the pawl to locate it in one of two positions. One position sets the pawl so that it interacts with the castle bar to make the device ratchet while it is extending. The other position sets the pawl in the second position so that the device no longer ratchets, allowing it to freely contract. A protrusion feature on one of the rails interacts with the pawl to reset it to the second position at the point where the door is fully opened. Figure 7 is a photograph of the prototype developed for the project displaying the various components.

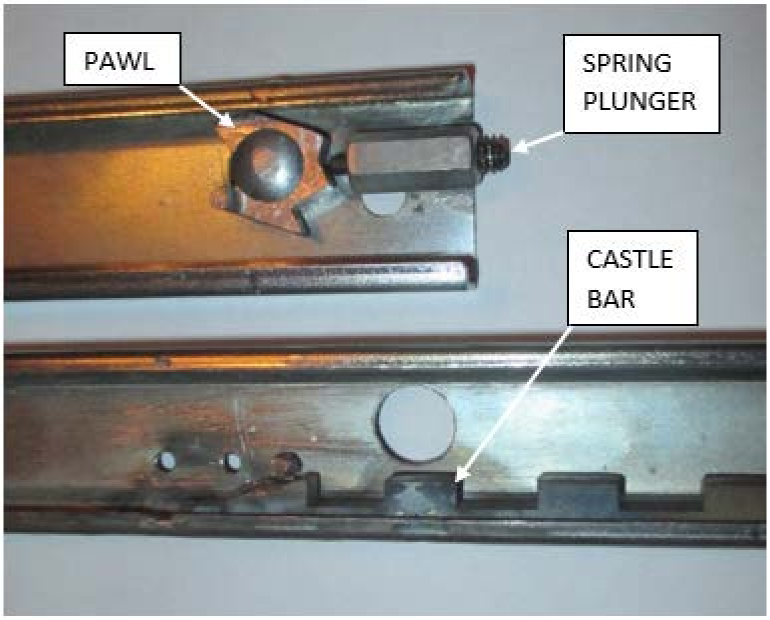


Figure 3.7. Components of modified door hold-open device.

All the components added to the prototype were machined from mild steel. The pawl and rivet were fabricated to be the same thickness and size of mild steel as the current device in order to support the loads presented by the door. It is believed that the pawl and castle bar components could be fabricated as stampings to reduce manufacturing costs. It may also be possible to incorporate the features of the castle bar into the roll formed inner channel.

3.4 Methods: Evaluation of the Hold-Open Device Design Changes

3.4.1. Methods: Component Testing of Hold-Open Devices

Three samples of both current and new design hold-open devices were tested to determine the ultimate axial strength when loaded in compression. The machine used to test the samples was an MTS 810 Material Test System, capable of tensile and compression testing. The test setup is shown in Figure 3.8.

Figure 3.8. Compression testing of door hold-open device.

Testing was conducted in accordance with ASTM E9-09 (2018) [36]. The maximum deflection for each of the samples was 10mm (0.394 inch). The devices were loaded axially using a pin connection through the mounting holes designed into the device for mounting onto the actual rear emergency door of a school bus. This was done so that the loads applied by the test machine would exactly replicate loads applied by a school bus door.

In addition to the compression testing, an attempt was made to conduct an endurance test of the new device. One device was mounted to the test fixture shown in Figure 3.10 and the door was opened repeatedly until the device failed to operate. The normal operation of the rear emergency door is with the bus in an upright orientation, such that the weight of the door is completely supported by the hinges. This test was conducted with the rear door in a rolled-over orientation, which is more severe because the weight of the door is supported by the hold-open device during operation. There are a total of 180 school days in a typical school year in Alabama. The assistant to the Auburn City School system school bus coordinator, Amanda Chandler, stated that the rear emergency door is checked by the driver twice daily prior to beginning the morning and afternoon bus routes each day. It was determined that an endurance test of 400 operations would indicate satisfactory operation of the device.

3.4.2 Methods: Comparison of Current versus New Rear Door Hold-Open Devices

For their study, Abulhassan *et al* [4] designed and constructed an evacuation testing fixture from actual wrecked school buses. A device was fabricated from the rear emergency door and immediate rows of seats (Figure 3.9). The first study [4] tested the rear emergency exit door by simulating a school bus in an overturned condition (Figure 3.9).

Figure 3.9. Rear emergency exit door with safety mats in place.

The test device had the hinge located on the top of the door, but for safety reasons, the door was tied open, offering unimpeded access via the emergency exit. In other words, the door would tend to swing shut (by gravity) after each evacuee left the device. However this effect was mitigated, as the door was tied open. Even with such a limitation, the flow rate reported via the rear emergency door by young children ranged between 11-16 persons per minute (ppm) with the rear seat somewhat obstructing flow and 20-41 ppm without the seat in place [4]. The authors speculated that had the rear door be left unconstrained, that the flow rates would have been dramatically reduced from those observed. For the present study, an essentially identical testing/training device was designed and fabricated to include changes (improvements) based on the results achieved by Abulhassan *et al* [4] (Figure 3.10). The research team partnered with two (2) Pike County, Alabama Schools, Goshen Elementary School (first and fourth grades), and

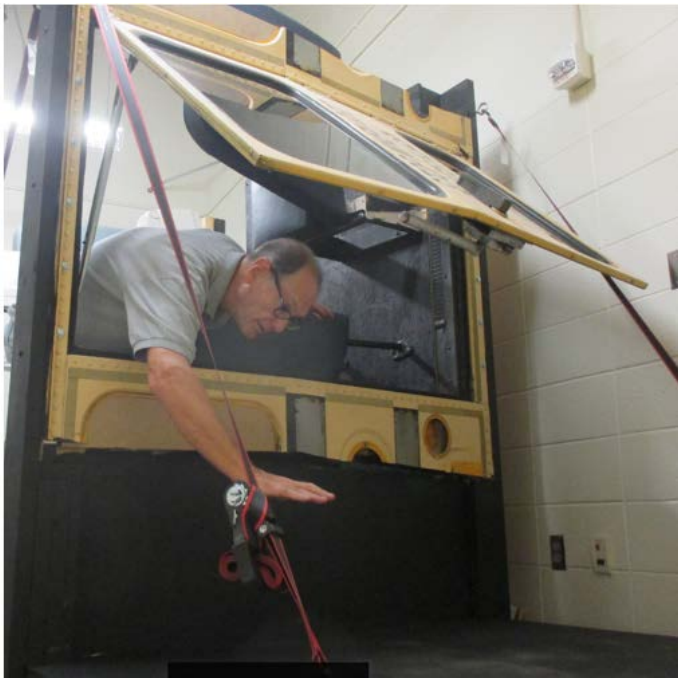


Figure 3.10. Rear emergency exit door partially open.

Goshen High School (seventh and tenth grades), to recruit subjects for the experiment. Parents/Guardians of all subjects provided written informed consent, and verbal assent was obtained from each subject as well. The study consisted of group evacuation trials consisting of participants from each of four grade levels: first, fourth, seventh, and tenth grades. One additional trial was conducted that included grade levels seven and ten combined.

A total of 139 elementary and high school students consisting of 69 males and 70 females participated. Demographic information collected from the students included height, weight, age, grade, and gender. This was used to calculate BMI, which is listed in Table 3.1. Subjects were outfitted with personal protective equipment such as bicycle helmets prior to participation. All subject testing occurred during physical education classes at each school. Subjects were assigned a unique number, which was fixed to the helmet, and each group evacuation was videotaped for subsequent analysis.

Table 3.1. Demographic information of participants.

GRADE	**NO. OF SUBJECTS**	**MALE**	**FEMALE**	**AVERAGE BMI**	**STANDARD DEVIATION BMI**	**MIN. BMI**	**MAX. BMI**
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				

Two stations were set-up corresponding to each device (current and improved) used in the trials. Each station was staffed with one (or two) Graduate Research Assistant(s), and the entire data collection process was supervised to ensure safety and compliance with the study protocol.

Figure 3.11. Door fixture setup at Goshen Elementary gym.

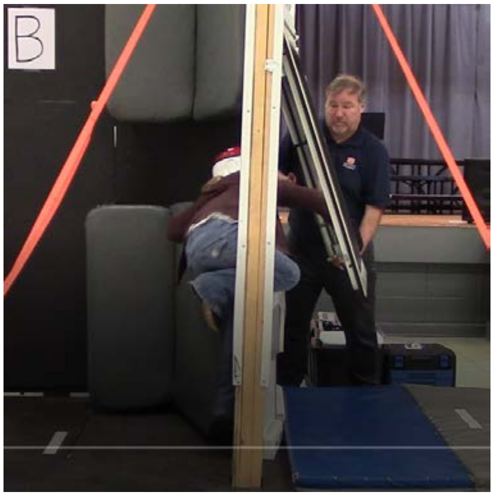


Figure 3.12. Old (current) door design.

Figure 3.13. New door design.

Group trials consisted of organizing all subjects in single file behind one device, informing them what they were going to do, obtaining verbal assent, and then giving the start signal. No assistance was provided unless it was required for safety purposes. Each trial was videotaped. Students were deemed to not want to participate if they were asked three times whether they wanted to participate, and no response was given; verbally assented but failed to start within thirty seconds of the start signal (two attempts at this; or the child verbally stated they did not want to participate). The group trial ended when the last subject exited the device. After completing the evacuation at each station, groups were moved to the next randomly assigned station. This testing was conducted in combination with the hatch testing described in Chapter 4. The remaining group evacuation trials proceeded in a similar manner on the other device. The order of each group is given in Table 3.2. At the conclusion of each testing session, subjects were thanked and returned to their normal schedule. All personal protective equipment was cleaned and sanitized between trials.

Table 3.2. Order of execution of door test fixtures.

GROUP (GRADE)	NEW DOOR (FIXTURE A)	OLD DOOR (FIXTURE B)
1A	2	1
1B	2	1
4A	2	1
4B	1	2
7	2	1
10	2	1
7 & 10	2	1

3.5 Results

3.5.1. Results: Component Testing

The theoretical analyses in section 3.3 revealed that the weakest link in either device (new or current design) was the rivet that secures and locates the locking pawl that interacts with the sliding rails to lock and hold the door open. The rivet did not shear as discussed in the theoretical analysis, but the rivet material yielded and began to pull out of the slide to which it was attached.

The slide, or rail, also eventually yielded under the compression load. On the current design, the pawl itself also yielded and bent out of shape. Figure 3.14 illustrates the damaged induced by the compression testing. As the samples were loaded the applied force increased at a constant rate until the mild steel materials began to yield. When the material began to yield, the load versus deflection curves flatten out. Figure 3.15 displays the force versus deflection curves for all the samples tested (note that the negative numbers on the axes indicate the loads were applied in compression versus tension). Samples 1 through 3 are the new design, and samples 4 through 6 are the current design door hold-open device. The maximum loads achieved by the three new design hold-open devices, represented by curves 1, 2, and 3 on Figure 3.15, were 3834, 4310,

NEW DEVICE:
COMPRESSION TEST BENT THE SLIDE BAR AND LOOSENED THE RIVET

CURRENT DEVICE:
COMPRESSION TEST BENT STAR POINT ON THE PAWL AND LOOSENED THE RIVET

Figure 3.14. Compression test failure modes.

and 4777 N (862, 969, and 1074 lbf) before the device yielded, or bent, 10 mm (0.394 inch). The corresponding maximum loads achieved by the three current design hold-open devices, represented by curves 4, 5, and 6 on Figure 3.15, were 2215, 2277, 1779 N (498, 512, and 400 lbf) before the device yielded, or bent, 10mm (0.394 inch). The higher loads achieved by the new design can be attributed to the larger diameter rivet and thicker material used for the pawl.

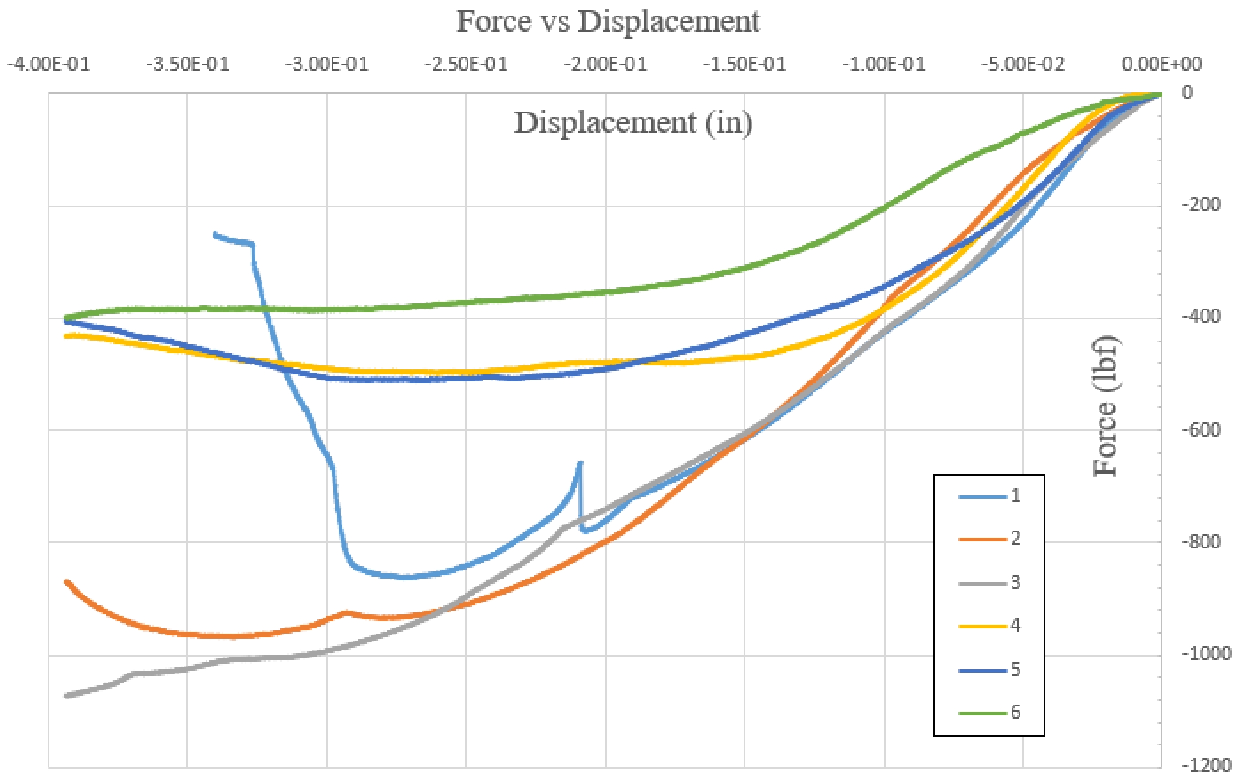


Figure 3.15. Force versus displacement on current and new design hold-open devices.

3.5.2. Results: Rear Emergency Door Evacuation Trials

The new door hold-open device operated such that the door remained in an open position after the initial person in each trial pushed the door open to approximately 30 degrees from vertical. The multiple hold-open locations provided by the new door design resulted in a substantial increase in evacuation flow rate, measured in passengers per minute (PPM). The flow rate data is given in Table 3.3, and graphically in Figure 3.16. The data in Table 3.3 for first and fourth grade are based on the average of the two groups from each grade. The data reveals that the fourth, seventh and tenth grade students displayed progressively faster flow rates over the first grade students through the current design door that did not remain open. This may be indicative of the advantage of students with taller stature and upper body strength.

Table 3.3. Evacuation flow rates in passengers per minute (PPM).

GRADE	OLD DOOR (FIXTURE B)	NEW DOOR (FIXTURE A)	% INCREASE
1	5.0	8.9	78.0
4	8.1	16.5	103.7
7	12.5	27.7	121.6
10	18.5	26.9	45.4
7 & 10	15.5	26.3	70.8

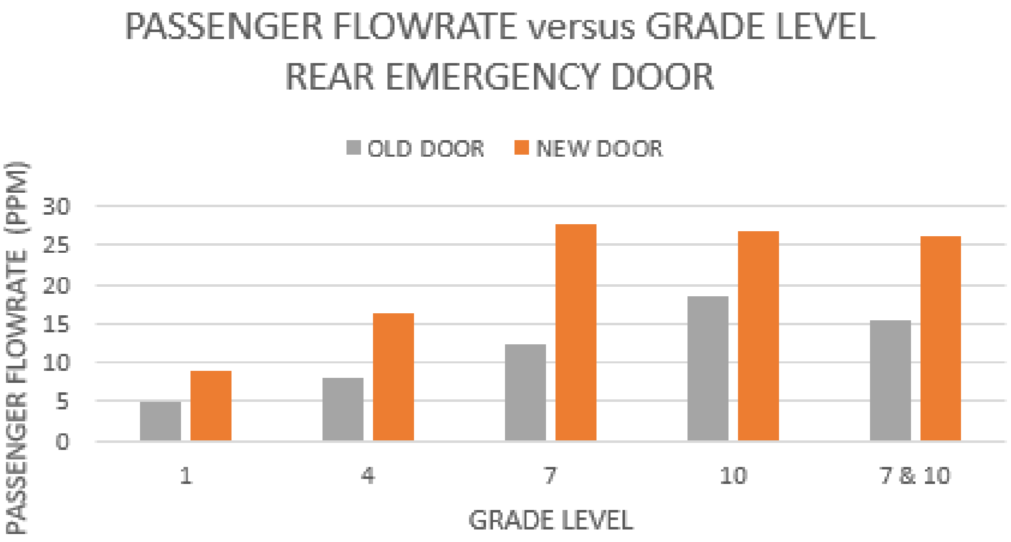


Figure 3.16. Flow rate versus grade level.

The new door design prevents the evacuees from fighting the weight of the door as they exit the bus, whereas the current design mandates that passengers must push on the door the entire time they are exiting. It should be noted that in the combined seventh and tenth grade trial, the participants proceeded through each test fixture a second time.

Individual egress times were extracted from the video of each group trial, from the moment when the subject arms moved toward the opening until both feet were on the floor. A Minitab regression analysis was conducted using the individual and demographic data previously mentioned (Table 3.4). Time was established as the response variable. Age, BMI, and subject were designated as continuous predictors, and door (1 for the new design, and 0 for the old design) was a categorical predictor. The results of the analysis revealed three significant predictors for the time response were age, BMI, subject, and the door itself (old versus new). There were no valid interactions noted in the analysis.

Table 3.4. Evacuation response time regression analysis (all grades).

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	1.05641	0.264103	58.42	< 0.001
SUBJECT	1	0.03094	0.030943	6.85	0.009
AGE	1	0.58580	0.585796	129.59	< 0.001
BMI	1	0.06238	0.062379	13.80	< 0.001
DOOR	1	0.40379	0.403791	89.33	< 0.001
Error	273	1.23409	0.004520		
Total	277	2.29050			

The resulting regression equation reveals that as age increases, or if the new door hold-open design is utilized, the response time decreases. Conversely, as BMI increases, the response time increases. The equation coefficient for the SUBJECT term is very small and, for the purposes of this research, considered insignificant. The following equation could be used to provide an estimate of evacuation time in minutes based on age, BMI and door hold open device (HOD) used.

$$\text{Time} = 0.2712 - 0.01780\ \text{AGE} + 0.002800\ \text{BMI} - 0.07622\ (\text{HOD: } 1=\text{NEW};\ 0=\text{OLD}) \qquad \text{Equation (3.5)}$$

The first evacuee through the door with the new design HOD was always slower than all the subsequent evacuees in each group. This is because the first person has to push the door open, which slows them down. Once the HOD engages in a given hold-open position, the subsequent evacuees egress time is much lower (faster) since they do not have to push on the door. The difference between the first evacuees egress time and the average of all the subsequent evacuees in each trial group ranged from 2 times to as much as 4.5 times longer.

3.6 Discussion

The compression load at which the HOD began to yield was approximately twice as high for the new design compared to the current design. The improvement is due to the use of a larger diameter rivet and thicker material for the pawl. The rivet was predicted to be the weakest link in the chain, however, the significant deflection of the slide rail was unexpected. The calculated load from the weight of the door was 1067 N (240 lbf). The average maximum load for the current design was 2091 N (470 lbf) providing a factor of safety (FS) equal to 2, and for the new design was 4306 N (968 lbf) providing a FS equal to 4.

Although two students opted to not attempt egress through the doors (one first grader, and one tenth grader), the vast majority were able to self-extricate through the test fixtures. The video of the participants attempting to evacuate through the door with the current HOD clearly illustrates how the approximately 100 pound door hanging in the opening impedes the flow of evacuees. This is because each evacuee must "fight" the door as they exit, and the person behind them must wait for their predecessor to clear the opening before proceeding. The flow rates provided by the improved HOD design allows the evacuees after the first person to egress with significantly less impediment. The evacuees cannot just step through the opening as they have to stoop, or drop to their knees, after they clear to lower edge of the door opening. The average flow rate for all the trials (1st through 10th grade) through the current door HOD design was 12 PPM, which is comparable to the 12 PPM rates measured by the Volpe Center [22] for the roof hatch, and to the 18 PPM rates measured by Abulhassan et al [5] for egress through the rear emergency door of an upright bus with K through 3rd graders without adult assistance. The average flow rate across all the trials conducted on the current door HOD design at Goshen Elementary was 11.9 PPM. The amount of improvement with the new HOD design results in a flow rate that is 78% faster.

Figure 3.16 displays how the flow rate for current HOD design increases for each grade level, which is indicative of the increasing relative size and strength characteristics for the participants. The older and stronger students had much less difficulty managing the weight of the door. Also, the difference between the first evacuee, and subsequent evacuees for the new HOD design was significantly less for the 7th and 10th grades compared with the 1st and 4th grades.

3.7 Conclusions

Evacuation trials were conducted that simulated the evacuation of a rolled over school bus to compare the current rear emergency door HOD to a new HOD design that complies more closely the federal requirement of an unobstructed emergency exit. When seconds count in a critical emergency evacuation, the new HOD could make the difference. This research suggests that the new HOD design is a possible lifesaver by the fact that it significantly increased passenger flow rates, enabled the exit to be unobstructed, and reduced the risk of injury from the door closing.

3.8 Limitations

The following limitations are acknowledged:

1) The use of components from one type (manufacturer) of school bus.
2) Limited sample sizes. Subjects were recruited from four (4) of the thirteen (13) grades that ride school buses.
3) Safety mats were used on the outside of the current (existing) rear emergency door apparatus.
4) Test fixtures are mockups fabricated from bus components and do not fully represent a bus in a rolled over configuration.
5) No attempt was made to simulate the intensity of an actual rollover emergency evacuation.

3.9 Acknowledgement

The research was partially supported by the Deep South Center for Occupational Health and Safety, a National Institute for Occupational Safety and Health (NIOSH) Education and Research Center (Grant 2 T42 OH008436-13). The contents are solely the viewpoint of the authors and do not necessarily represent the official views of the Deep South Center or NIOSH.

We would like to extend our sincere gratitude to Dr. Mark Bazzell, Superintendent Pike County Schools, Dr. Wanda Corley, Principal Goshen Elementary School, Mr. Kendrick Britford, Principal Goshen High School, Eric Wells, Pike County Schools Maintenance Supervisor, and all the wonderful school children that graciously participated in this study. Finally, Pat Hicks, proprietor of Dublin Machine, was invaluable in fabricating prototypes for testing.

Chapter 4

Redesign and Testing of a School Bus Emergency Escape Hatch

4.1 Abstract

The design criteria for the various components of United States school bus emergency evacuation systems are defined in the Federal Motor Vehicle Safety Standards. These regulations specify that emergency exits provide openings that are large enough to permit unobstructed passage. One component of the regulations specifies that the minimum opening for an emergency escape roof exit, or roof hatch, shall be no less than 41 cm by 41 cm (16 in by 16 in). In the specific situation when a school bus is rolled over onto its side, the rear emergency door and the roof hatch are the primary remaining options for evacuation. The mandated minimum roof hatch opening may not be large enough to accommodate larger passengers, especially in view of increasing obesity in the population. Such conditions suggest that current emergency roof hatches might not allow unobstructed passage in such a rolled over orientation, in sufficient time to survive potential fires (and other hazards). The purpose of this study was to redesign and fabricate (prototype) a larger roof hatch opening to provide greater unobstructed passage, and to test the improved design on a broader size range of typical school bus passengers. The results of the evaluation revealed that the larger hatch opening is almost functionally equivalent to the front door of an upright bus.

4.2 Introduction

With the exception of the studies performed by Purswell and Dorris [1,2,3], published in the 1970's, and Abulhassan *et al* [4-6] published 2016-2018, very little is known about the ability of children to successfully evacuate a school bus post-accident. This is especially true if the bus is in other than its normal upright orientation. It is very difficult to ascertain the annual frequency of school bus rollovers due to the lack of data including detailed accident specifics, but we believe is most likely between 10 and 99 rollovers per year. This number is small in comparison to the approximately 26,000 school bus accidents each year in the United States, but the potential severity of occupants not being able to escape in a timely manner, or at all (unassisted) makes this a ‘credible’ scenario worthy of further investigation. The ability to successfully escape lies somewhere between the optimal post-accident circumstances (bus gently rolls over on its side, rear emergency door falls open (hinge located on bottom of door) due to gravity, a few minor injuries, higher grade levels of students onboard, an adult available to assist, no other hazard present) and the most extreme circumstances (multiple rollovers, rear exit door oriented with hinge up, multiple major injuries, very young children, no adult available to assist, and other hazards present). The probability of successful escape depends primarily on the design and capabilities of the emergency exit system, and the training and ability of the students to successfully use the emergency exit system in a timely manner.

Purswell and Dorris [1,2,3] performed the first investigations in the literature pertaining to school bus evacuation at the Oklahoma Research Institute (OKRI) in the 1970’s. Two aspects of these studies are of interest. First in 1972, they mocked up roof hatches [2] representing an overturned bus in two sizes, 61 cm by 102 cm (24” by 40”) equaling 6,222 cm^2 and 61 cm by 61 cm (24” by 24”) equaling 3,721 cm^2. Sixty subjects (from all 12 grades) crawled out of two of the 3,721 cm^2 (577 sq.in.)openings at floor level, and also from the single elevated 6,222 cm^2 (964 sq.in.) hatch opening (floor covered with matting), to develop evacuation flow rates. The mock ups were constructed so children had direct access (same level) to the hatch openings **without** having to pull themselves up and through a real world hatch opening. Children were able to crawl through both sized hatches at a rate of approximately 30 persons per minute (PPM) [2]. Though the study shed light on the issue of emergency escape via a roof hatch, the lack of realism limits its generalizability for hatches located on the roof centerline. Second (1978), the same researchers [3] rolled over a motor coach and had adults evacuate through an actual roof hatch, while testing the impact of lighting level. Flow rates through the 49 cm by 54.6 cm (21.5" by 19.25") hatch varied between 4.6-10.7 ppm.

The Volpe Institute conducted a series of motor coach evacuation experiments and published the results in a 2009 report [8]. Though primarily dealing with motor coaches, they do discuss similarities and differences between motor coaches, school buses, and transit buses. Their reported flow rate through the roof hatch was twelve (12) persons per minute (PPM), though they state "The majority of able-bodied adults can egress through the emergency roof exit hatch of an overturned bus at the rate of approximately 12 ppm. Individuals of more limited physical ability can each take a minute or more to pass through the exit hatch, unless they are assisted by other passengers, or the bus driver." They [8] further state "Many adults require a larger opening size than the minimum specified in FMVSS 217 to egress safely…". Their recommendation for improved motor coach hatch design is "Larger aperture dimension of 4,000 cm^2 (620 sq.in.)." This larger size agrees with the standards established by the Economic Commission of Europe [9]. Current guidelines [7] require roof hatch openings in school buses to be at least 1,681 cm^2 (256 sq.in.).

Further, the Volpe Report [8] identified three (3) methods that subjects used to evacuate the motor coach hatch (somewhat applicable to a school bus hatch):

The **Somersault –** “the occupant’s head and torso emerged from the hatch first. The occupant then bends down as far as possible, extending arms so that they nearly reach the ground and resting body weight on the lower edge of the hatch. With a slight thrust from the leg muscles, body center of gravity is shifted outward, while arm, back and hip muscles are used to pull the rest of the body through the opening in a somersault.” A flow rate of 15 ppm (4 seconds per person) was reported from hatches 4,524 cm^2 (701 sq.in.) and 3,136 cm^2 (486 sq.in.) for these limited trials [8].

The **Whole Body Lift –** “This method is similar to that used by ship personnel to traverse bulkhead doors rapidly. It involves the occupant lifting both feet through the opening simultaneously by grasping some part of the bus structure above the hatch with both hands and raising the torso to a height such that the legs clear the lower edge of the roof hatch. This method requires sufficient upper-body strength to raise one’s entire body weight, sufficient finger strength to grasp whatever handhold can be found, the ability to see or feel that handhold, and the presence of such a handhold.” A flow rate of 12 ppm (5 seconds per person) was reported from hatches 4,524 cm^2 (701 sq.in.) and 3,136 cm^2 (486 sq.in.) for these limited trials [8].

The **Cautious Approach –** “An occupant unwilling to accept the risks or lacking the strength to use the foregoing methods would probably elect to use a cautious approach, extending only one limb at a time and keeping the body well supported, in order to egress through the emergency roof exit hatch.” A flow rate of 1.5 ppm (40 seconds per person) was reported from the 4,524 cm^2 (701 sq.in.) and well over one (1) minute for the 3,136 cm^2 (486 sq.in.) hatch. The Volpe Report [8] further states “In a time-critical evacuation scenario, it would be advisable for passengers to assist each other out of the emergency roof hatch, which should provide a **much more rapid flow** [emphasis added] than the cautious approach.” These researchers [8] suggest that factors such as hatch size, number of hatches, orientation of the bus, and the strength and agility of evacuees, strongly influence the egress rate.

The definitive school bus evacuation studies to date, that used actual bus components as mockups and school children as subjects, were performed by Abulhassan *et al* [4-6]. One of these studies [6] tested the ability of young children to evacuate via a school bus emergency escape roof hatch. The test device was made from a section of school bus roof that included a roof hatch and adjacent window (Figure 4.1). As with the Purswell and Dorris study [1], Abulhassan *et al* [6] included the use of a safety mat on the outside of the hatch opening, allowing subjects to have diminished impact from a fall from the hatch, or in the case of many, the ability to reach out and brace themselves while transiting the hatch. Even with such a limitation, the flow rate reported [6] via the roof emergency escape hatch, 57cm x 57cm (22.5” by 22.5”), by young children ranged between 11-15 ppm. The authors speculated that had the safety mat been removed, the **flow rates would have been dramatically reduced** from those observed.

4.3 School Bus Roof Emergency Escape Hatch

FMVSS 217 requires that school buses provide a specific number of emergency exits based on the seating capacity [7]. Type “C” and “D” school buses can have large seating capacities, which requires the use of two roof hatches. In order to meet, or exceed, the requirements of the standard, all current school bus manufacturers that sell these types of buses provide them with two roof hatches. FMVSS 217 specifies a minimum opening size of 41 cm by 41 cm (16 in by 16 in). The standard hatch used by all current school bus manufacturers provides a 57 cm by 57 cm (22.5 in by 22.5 in) opening, which exceeds the minimum requirement.

Figure 4.1. Roof hatch test fixture developed by Abulhassan *et al*. [6].

The Federal Aviation Administration (FAA) establishes specific requirements for the number and size of emergency exits [10], which is based on aircraft seating capacity. The 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 seconds with half of the exits blocked. In order to evacuate any 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. The FAA standard [10] requires that for a passenger seating configuration of 41 to 110 seats, there must be at least two exits, **one of which must be 24" wide by 48" high, or larger**, Figure 4.2. We propose to redesign the school bus hatch by increasing the size from the current size of 57cm by 57cm (22.5 in by 22.5 in), to 57cm wide by 117cm high (22.5 in wide by 46 in high).

Figure 4.2. Over-wing exit door.

When mounted symmetrically at the center of the roof, the decrease in the height of the opening significantly **reduces the step-up distance inside the bu**s, 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 because the opening is not large enough to allow the passenger to keep their feet under them during evacuation [1,2,3,6]. The 1978 OKRI study noted that because of the need to climb up to and out of the roof hatch, some type of ladder, or toehold, should be provided to assist egress [3].

Another concept behind this proposed design improvement was to maintain the width the same as the current hatch in order to allow the hatch to fit in between the main structural supports in the roof structure. FMVSS 220 [20] requires that school buses must be capable of withstanding roof-loading forces that may be encountered if the bus were to roll over. In accordance with the standard, a force equal to 1 ½ times the vehicle unloaded mass is applied to the bus roof structure using a force plate. The test standards require that the roof deflection must not exceed 12.7 cm (5 in). The roof structure in Figure 4.3 illustrates the radial components (hoops) as continuous steel members and the axial members welded to tie the hoops at specific

Figure 4.3. School bus roof structure (courtesy of Blue Bird Corporation).

distances. For the larger roof hatch 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.

A final factor for 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 used primarily 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 ventilate position, and also fully open for evacuation as well. Abulhassan *et al* [6] stated that the complexity of the hatch they tested, contributed too many smaller children not being able to understand how to open the hatch for evacuation purposes. We propose to remove this potential hurdle for younger passengers by suggesting that the improved hatch design solely be used for evacuation purposes and ventilation considerations be addressed elsewhere in the bus structure.

In summary, a significant mismatch has been previously identified [4, 6] between the design and operational requirements of current school bus emergency exit systems, including the emergency escape roof hatch, as specified in FMVSS 217, and considerations for the strength and size of young bus occupants. 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) Acknowledge identified limitations of the emergency escape roof hatch by redesigning certain aspects to abate identified weaknesses; and (2) Test the improved design side-by-side with the current model to quantify potential gains attributable to the design improvements.

4.4 Methods: Evaluation of the Design Changes

For their study Abulhassan *et al* [6] designed and constructed two evacuation testing/training devices from actual wrecked school buses. A device was fabricated from a section containing a window, and roof curvature, including a roof escape hatch (Figure 4.1). For the present study, an essentially identical testing/training device was designed and fabricated to include changes (improvements) based on the results obtained by Abulhassan *et al* [6] (Figure 4.4), while adhering to the FAA passenger design mandates to the maximum extent practical.

Figure 4.4. Redesigned roof hatch providing a larger opening.

To perform the tests, we partnered with two (2) Pike County, Alabama Schools; Goshen Elementary School (first and fourth grades), and Goshen High School (seventh and tenth grades), to recruit subjects for the experiment. Parents or Guardians of all subjects provided written informed consent, and verbal assent was obtained from each subject as well. The study consisted of group evacuation trials consisting of participants from each of four grade levels: first, fourth, seventh, and tenth grades. One additional trial was conducted that included grade levels seven and ten combined.

A total of 139 elementary and high school students consisting of 69 males and 70 females participated. Demographic information collected from the students included height, weight, age, grade, and gender. This was used to calculate BMI, which is listed in Table 4.1. Subjects were outfitted with personal protective equipment such as bicycle helmets prior to participation. All subject testing occurred during physical education classes at each school. Subjects were assigned a unique number, which was fixed to the helmet, and each group evacuation was videotaped for subsequent analysis.

Table 4.1. Demographic information of participants.

GRADE	**NO. OF SUBJECTS**	**MALE**	**FEMALE**	**AVERAGE BMI**	**STANDARD DEVIATION BMI**	**MIN. BMI**	**MAX. BMI**
1	40	20	20	18.3	5.8	11.2	38.0
4	53	33	20	19.4	5.2	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				

Two stations were set-up, current and improved, for the trials, as shown in Figures 4.5 through 4.7. Each station was staffed with one (or two) Graduate Research Assistant(s), and the entire data collection process was supervised to ensure safety and compliance with the study protocol.

Figure 4.5. Hatch fixture setup at Goshen Elementary gym.

Figure 4.6. Current hatch design.

Figure 4.7. Improved hatch design.

Group trials consisted of organizing all subjects in single file behind one device, informing them what they were going to do, obtaining verbal assent, and then giving the start signal. No assistance was provided unless it was required for safety purposes. Each trial was videotaped. Students were deemed to not want to participate if they were asked three times whether they wanted to participate, and no response was given; verbally assented but failed to start within thirty seconds of the start signal (two attempts at this; or the child verbally stated they did not want to participate). The group trial ended when the last subject exited the device. After completing the evacuation at each station, groups were moved to the next randomly assigned station. This testing was conducted in combination with the door testing described in Chapter 3. The remaining group evacuation trials proceeded in a similar manner on the other device. The order of each group is given in Table 4.2. At the conclusion of each testing session, subjects were thanked and returned to their normal schedule. All personal protective equipment was cleaned and sanitized between trials.

Table 4.2. Order of execution of hatch test fixtures.

GROUP (GRADE)	NEW HATCH (FIXTURE C)	OLD HATCH (FIXTURE D)
1A	2	1
1B	2	1
4A	2	1
4B	1	2
7	2	1
10	1	2
7 & 10	2	1

4.5 Results

The larger opening provided by the new hatch design resulted in a substantial increase in evacuation flow rate, measured in passengers per minute (PPM). The flow rate data is given in Table 4.3, and graphically in Figure 4.8. The data for first and fourth grade are based on the average of the two groups from each grade.

Table 4.3. Evacuation flow rates (PPM).

GRADE	OLD HATCH (FIXTURE D)	NEW HATCH (FIXTURE C)	% 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

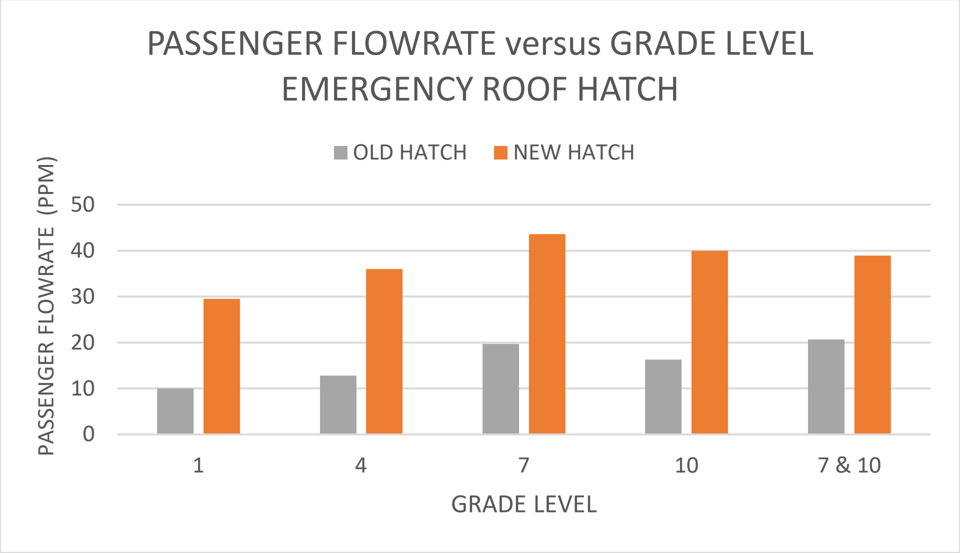


Figure 4.8. Evacuation flow rate versus grade level.

The data reveal 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 taller stature and upper body strength. The new hatch design allows the evacuees to keep their feet underneath their bodies as they exit the bus, whereas the current design mandates that passengers must climb out of the relatively small opening. It should be noted that in the combined seventh and tenth grade trial, the participants proceeded through each test fixture for a second time.

Individual egress times were extracted from the video of each group trial, from the moment when the subject arms moved toward the opening until both feet were on the floor. A Minitab regression analysis was conducted using this individual data and demographic data previously mentioned (Table 4.4). Time was established as the response variable. Age, BMI, and subject were designated as continuous predictors, and hatch (1 for the new design, and 0 for the old design) was a categorical predictor. The results of the analysis revealed three significant predictors for the time response were age, BMI, and the hatch itself (old versus new). There were no valid interactions noted in the analysis.

Figure 4.4. Evacuation response time regression analysis (all grades).

Analysis of Variance

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
HATCH	1	0.164818	0.164818	133.66	< 0.001
Error	273	0.336637	0.001233		
Total	277	0.555507			

The resulting regression equation reveals that as age increases, or if the new hatch design is utilized, the response time decreases. Conversely, as BMI increases, the response time increases. The following equation could be used to provide an estimate of evacuation time in minutes based on age, BMI and hatch opening size.

Time = 0.12010 – 0.004776 AGE + 0.000820 BMI – 0.04870 (HATCH: 1=NEW; 0=OLD)

Equation (4.1)

The BMI factor in egress time was studied further by separating the data into the individual classes and performing regression analysis on each class. The analysis revealed that BMI was not statistically significant with the first grade students, but became statistically significant with the fourth grade students. Further, the relative significance of BMI increases with the higher grade levels as seen in Tables 4.5 through 4.8.

Table 4.5. Evacuation response time regression analysis (first grade).

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.080474	0.026825	14.67	< 0.001
SUBJECT-1	1	0.000522	0.000522	0.29	0.595
BMI-1	1	0.000923	0.000923	0.50	0.480
HATCH-1	1	0.079065	0.079065	43.23	< 0.001
Error	76	0.139001	0.001829		
Total	79	0.219474			

Table 4.6. Evacuation response time regression analysis (fourth grade).

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.082069	0.027356	18.70	< 0.001
SUBJECT-4	1	0.002096	0.002096	1.43	0.234
BMI-4	1	0.006591	0.006591	4.50	0.036
HATCH-4	1	0.073909	0.073909	50.52	< 0.001
Error	102	0.149234	0.001463		
Total	105	0.231303			

Table 4.7. Evacuation response time regression analysis (seventh grade).

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.010405	0.003468	21.12	< 0.001
SUBJECT-7	1	0.000015	0.000015	0.09	0.767
BMI-7	1	0.000890	0.000890	5.42	0.025
HATCH-7	1	0.009158	0.009158	55.76	< 0.001
Error	44	0.007226	0.000164		
Total	47	0.017632			

Table 4.8. Evacuation response time regression analysis (tenth grade).

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	0.016282	0.005427	18.85	< 0.001
SUBJECT-10	1	0.000553	0.000553	1.92	0.174
BMI-10	1	0.001784	0.001784	6.20	0.017
HATCH-10	1	0.014256	0.014256	49.51	< 0.001
Error	40	0.011518	0.000288		
Total	43	0.027801			

Overall, the three significant factors are AGE, BMI, and which HATCH design was used. As AGE increases, evacuation time decreases. The data from Table 4.1 indicates that the average BMI increases from first to tenth grade, and the regression data indicates that increasing BMI decreases evacuation time. The use of the larger hatch opening results in a significant reduction in evacuation time, regardless of grade level.

4.6 Discussion

Although three students opted to not attempt egress through the old hatch design (two first graders, and one tenth grader), the vast majority were able to self-extricate through the test fixture. The video of the participants clearly illustrates how the 56 cm by 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 orifice, and the person behind them must wait for their predecessor to clear the opening before proceeding. The flow rates provided by the improved, 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 Volpe Center [22], and by Abulhassan et al [6]. The average flow rate across all the trials conducted on the old hatch design at Goshen Elementary was 15.9 PPM. The amount of improvement with the larger hatch design results in a flow rate that is comparable to that of the main door in the bus. The flow rate measured by the Volpe Center [22] through the front door was 36 PPM. The average flow rate across all the trials conducted on the new, larger, hatch design at Goshen Elementary was 37.6 PPM. **The larger hatch opening is functionally equivalent to the front door of an upright bus.**

The significance of BMI also provides evidence of the need to increase the hatch size due to the fact that BMI is increasing Nationwide. The BMI data is interesting because it indicates an effect of slowing down exit time even though older, bigger, stronger, children are able to egress faster. This BMI consideration provides another reason to use physically larger openings for emergency egress.

4.7 Conclusions

Trials to simulate the evacuation of a rolled over school bus were conducted to compare the current emergency roof hatch design to a larger design that was based on an emergency exit door in the side of an aircraft. Group egress flow rates through the larger emergency roof hatch, were equivalent to that of the front door of an upright bus. This research suggests that larger emergency roof hatch openings significantly improves overall school bus emergency evacuation system safety.

4.8 Limitations

The following limitations were identified:

1. The use of components from one model and manufacturer of school buses.
2. Limited sample sizes. Subjects were recruited from four (4) of the thirteen (13) grades that usually ride school buses.

3. Safety mats were used on the outside of the current (existing) emergency escape hatch apparatus, which reduce the step-down distance on the outside of the hatch.
4. Test fixtures are mockups fabricated from bus components and do not fully represent a bus in a rolled over configuration.
5. No attempt was made to fabricate and test an operating mechanism for the improved hatch design.
6. No attempt was made to simulate the intensity of an actual emergency evacuation.

4.9 Acknowledgement

The research was partially supported by the Deep South Center for Occupational Health and Safety, a National Institute for Occupational Safety and Health (NIOSH) Education and Research Center (Grant 2 T42 OH008436-13). The contents are solely the viewpoint of the authors and do not necessarily represent the official views of the Deep South Center or NIOSH.

We would like to extend our sincere gratitude to Dr. Mark Bazzell, Superintendent Pike County Schools, Dr. Wanda Corley, Principal Goshen Elementary School, Mr. Kendrick Britford, Principal Goshen High School, Eric Wells, Pike County Schools Maintenance Superintendent, and all the wonderful school children that graciously participated in this study.

Chapter 5

Using RFID to Quantify School Bus Evacuation Training Times

5.1 Abstract

Public school systems in the United States are mandated by State legislatures to conduct periodic school bus evacuation training for the benefit of their students. The approach to conducting this training varies widely between school systems and there exists only a trace of anecdotal records detailing specifics relating to this requirement, other than that it was completed. Radio-frequency identification (RFID) is becoming more prevalent in many applications relating to the safe transport of children on school buses. The purpose of this study was to explore the use of RFID to measure evacuation times compared to video and/or stopwatch measurements, for thirty-four passengers on a Type "D" school bus. The results obtained over three evacuation scenarios (front door only; rear door only; and both doors simultaneously) revealed no statistically significant difference between those times recorded by RFID and those observed by video analysis for all trials. Based on these findings, RFID has the potential to provide a fast, cheap, non-invasive way to record school bus passenger evacuation times, eliminating the need for lengthy video analysis. Elimination of stopwatch and/or videotape analysis may lead to numerous schools uploading evacuation training times into a central repository, building a reliable source of information for benchmarking and potential design changes for school bus emergency exit systems.

5.2 Introduction

There is strong evidence that transporting students on school buses is the safest means to move children to and from schools. Approximately six billion (6,000,000,000) miles are driven annually to transport approximately twenty-six million (26,000,000) students on a daily basis [26]. Public school systems in the United States are mandated by State legislatures to conduct periodic school bus evacuation training for the benefit of their students [38]. The approach to conducting this training varies widely between school systems and there exists only a trace of anecdotal records detailing specifics relating to this requirement, other than that it was completed. The use of RFID associated with school buses has increased significantly over the past decade. Researchers in Qatar published a paper [30] in 2013 detailing a number of possibilities for RFID to enhance the safety of bus riders. The authors mention monitoring students as they enter and exit the bus, discuss examples of students attempting to get off at the wrong stop, and students who have been left on the bus after the route is completed [31]. The authors also mention that passive RFID tags are preferred over active tags as they last longer, cost much less, are safe for use around children as they are only powered when near a reader [30]. A 2015 paper [32] discusses the use of Short Message Service (SMS) enabled by RFID to notify parents and school officials of other than expected incidents.

5.3 School Bus Evacuation Standards

In 2019, Davis [33] drafted a Perspective Paper titled “Should the United States Mandate School Bus Evacuation Times?” This paper contains a detailed comparison between aircraft and school buses, and questions why standard evacuation times are required in aviation, but not in the transportation of school children. The author [33] states “the school bus industry, Federal

Motor Carrier Safety Administration (FMCSA), and the National Highway Transportation Safety Administration (NHTSA) do not have uniform prescriptive requirements for evacuation times" in stark contrast to the Federal Aviation Administration (FAA), nor "a methodology for collecting, analyzing, and disseminating routinely performed evacuation data and information."

Sparse research exists on school bus evacuation times. Abulhassan *et al.* published a methodology to establish baseline times in 2016 [5]. The authors conducted numerous evacuations via the front door (only), rear door (only), and both doors (simultaneously) for kindergarten and elementary school (1st, 2nd & 3rd grade) aged children. The Abulhassan *et al.* study [5] used wireless security cameras to record student evacuation movements and entailed an extensive amount of time analyzing the video to ascertain individual and group evacuation times. Davis [33] suggests that the FAA evacuation time of 90 seconds or less should be the goal, or 'time to reach', in all school bus evacuations. Such a notion was first broached in 1978 when Purswell and Dorris reported that "A standard for maximum evacuation time should be considered" [34]. The use of RFID to quantify individual evacuation times could eliminate the burden of analyzing video recordings, to help school systems collect and report standard evacuation times and practices. Literature suggests that once a bus catches fire, it has the ability to be completely engulfed within three (3) to five (5) minutes [29]. Therefore time is a critical factor for evacuation training. It is possible that the use of RFID will empower schools with this technology on their buses to collect and report bus evacuation times, and more easily determine if they are meeting their goals during evacuation training drills.

The purpose of this study was to evaluate the use of RFID to measure evacuation training times and compare them to video and/or stopwatch measurements, for thirty-four passengers on a Type “D” school bus in three evacuation scenarios (front door only; rear door only; and both doors simultaneously).

5.4 Methods

5.4.1 Objective and Hypothesis

The objectives of this experiment were to compare two methods used to measure and track school bus evacuation exercises by performing the following tests:

1. Measure the evacuation time of adult subjects through the front door only, the rear door only, and both the front and rear doors simultaneously.
2. Compare the evacuation time measurements of each passenger as recorded by RFID with measurements recorded by screening the video of each passenger.
3. Determine the flowrate (passengers per minute) for adults evacuating through the front door only, the rear door only, and both the front and rear doors simultaneously.

The hypothesis for item 2 above are as follows:

Hypothesis: There are significant differences in the evacuation times for those measured with RFID compared with the same subjects measured with video analysis.

$$H_0: \mu_{\text{RFID}} = \mu_{\text{Video}}$$

$$H_1: \mu_{\text{RFID}} \neq \mu_{\text{Video}}$$

A nearby school system provided a Type (D) school bus (Figure 5.1) for the experiment. Passive RFID tags [Smartrac Dogbone RFID Wet Inlay (MONZA R6-P)] were adhered to name badges on lanyards (Figure 5.2) and worn around participants’ necks, who randomly sat in one of the thirteen (13) rows on the bus. Once assigned, the participants' returned to the same seating position for each of the three (3) trials. Participants' consisted of Auburn University students enrolled in an undergraduate occupational safety and ergonomics course. A pre-event brief covered the purpose of the study, why evacuation is important for school aged children, and

Figure 5.1. Type "D" school bus and test setup.

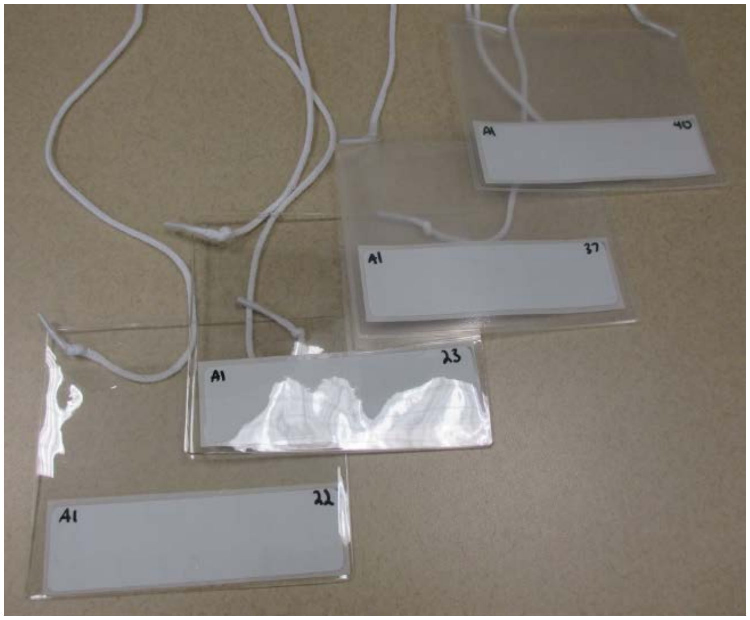


Figure 5.2. RFID tags attached to lanyards.

instructions on how to exit the bus and where to stand after exiting. Auburn University subjects provided informed consent approved by the institutional review board prior to participating in the trials. The three trials consisted of evacuating via the front door only, the rear door only (using a ‘sit and scoot’ posture versus jumping) and from both the front and rear doors simultaneously. Video cameras were positioned at each door to record passengers’ as their last foot touched the ground, and later analyzed for individual evacuation times. RFID readers (Zebra FX7500-42325A50-WR) and antennas (Alien ALR 8697) were placed in close proximity just outside of each door (Figure 5.1) and the power adjusted to recognize the RFID tag as close as possible to the subject actually (physically) being off the bus. A Paired t-Test was used to perform a hypothesis test to analyze the data at a α = 0.05 level of significance.

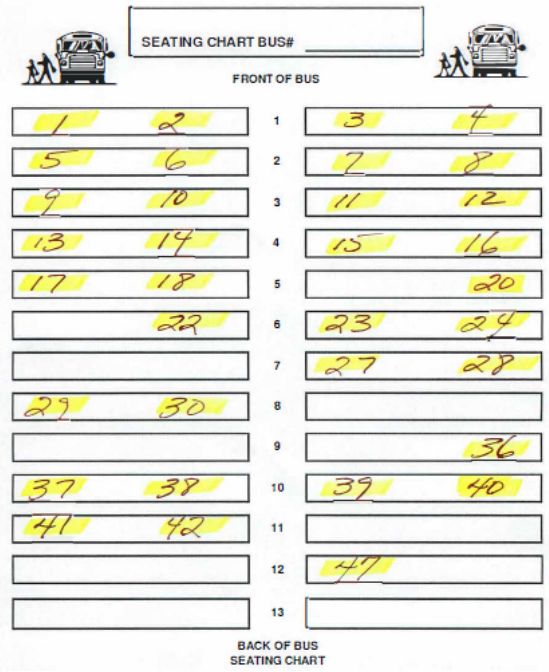


Figure 5.3. Passenger seating arrangement.

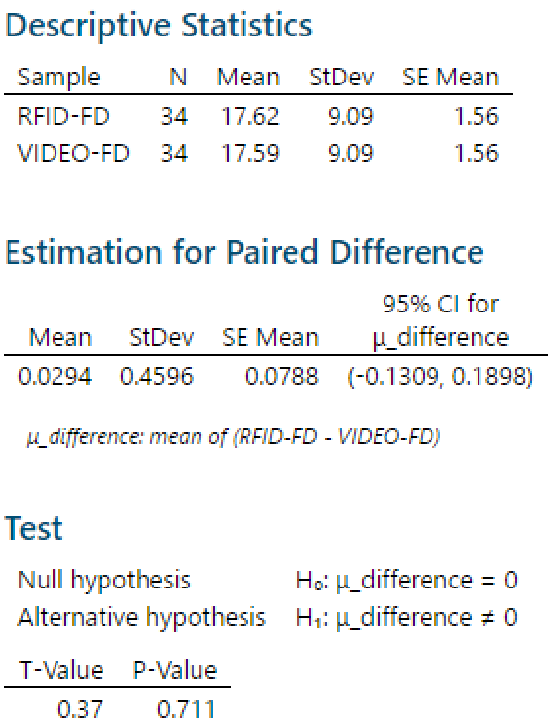
5.5 Results

Thirty-four adult participants, seated as shown (Figure 5.3), evacuated from the bus when given a start signal. The times (seconds) associated with RFID and those from video analysis is presented in the following format (RFID:VIDEO).

Front-Door Only –The first passenger exited the bus at (2:3) seconds and the last passenger at (32:33) seconds. The mean passenger departure interval (the successive time between passengers (2-34) leaving the bus) was 0.91 seconds, ranging between 0-2 seconds. RFID counted the passenger before the video analysis three (3) times, counted the passenger the same as the video analysis twenty-seven (27) times, and counted the passenger after the video analysis four (4) times. All seven (7) disagreements in time between RFID and the video analysis were within one (1) second. A Paired t-Test failed to reject the null hypothesis of no difference between the RFID times and the video analysis times for passengers evacuating via only the front door (see Minitab results in Figure 5.4). The mean flow rate for the front exit door was **61.9 passengers/minute**.

Rear-Door Only - The first passenger exited the bus at (2:3) seconds and the last passenger at (55:55) seconds. The mean passenger departure interval (the successive time between passengers (2-34) leaving the bus) was 1.6 seconds, ranging between 0-2 seconds. RFID counted the passenger before the video analysis fourteen (14) times, counted the passenger the same as the video analysis twelve (12) times, and counted the passenger after the video analysis eight (8) times. All twenty-two (22) disagreements in time between RFID and the video analysis were

Paired t-Test and CI: RFID-FD, VIDEO-FD



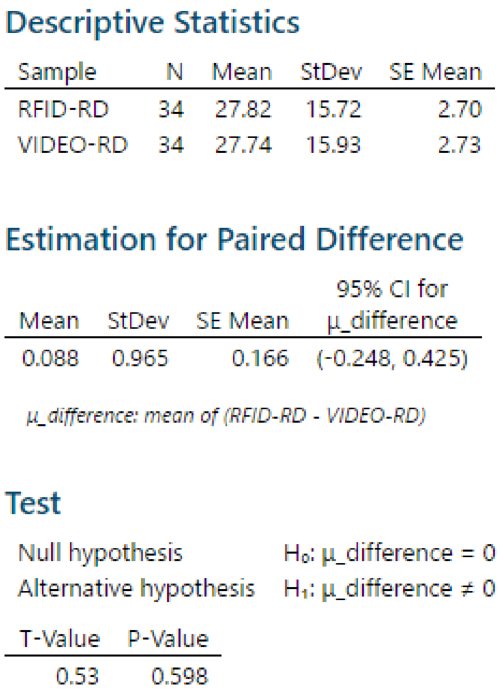
```
Descriptive Statistics

Sample      N    Mean   StDev   SE Mean
RFID-FD    34   17.62    9.09      1.56
VIDEO-FD   34   17.59    9.09      1.56

Estimation for Paired Difference

                                   95% CI for
  Mean     StDev   SE Mean        μ_difference
0.0294    0.4596    0.0788    (-0.1309, 0.1898)

  μ_difference: mean of (RFID-FD - VIDEO-FD)

Test

Null hypothesis          H₀: μ_difference = 0
Alternative hypothesis   H₁: μ_difference ≠ 0

T-Value   P-Value
   0.37     0.711
```

Figure 5.4. Minitab Paired t-Test of front door only evacuation.

within two (2) seconds. A Paired t-Test failed to reject the null hypothesis of no difference between the RFID times and the video analysis times for passengers evacuating via only the rear emergency door (see Minitab results in Figure 5.5). The mean flow rate for the rear exit door was **37.1 passengers/minute**.

Both Doors - The first passenger exited the front door of the bus at (3:2) seconds and the last passenger at (22:22) seconds. The mean passenger departure interval (the successive time between passengers (2-34) leaving the bus from the front door) was 0.61 seconds, ranging between 0-2 seconds. RFID counted the passenger before the video analysis four (4) times, counted the passenger the same as the video analysis twenty-four (24) times, and counted the passenger after the video analysis six (6) times. All ten (10) disagreements in time between RFID

Paired t-Test and CI: RFID-RD, VIDEO-RD



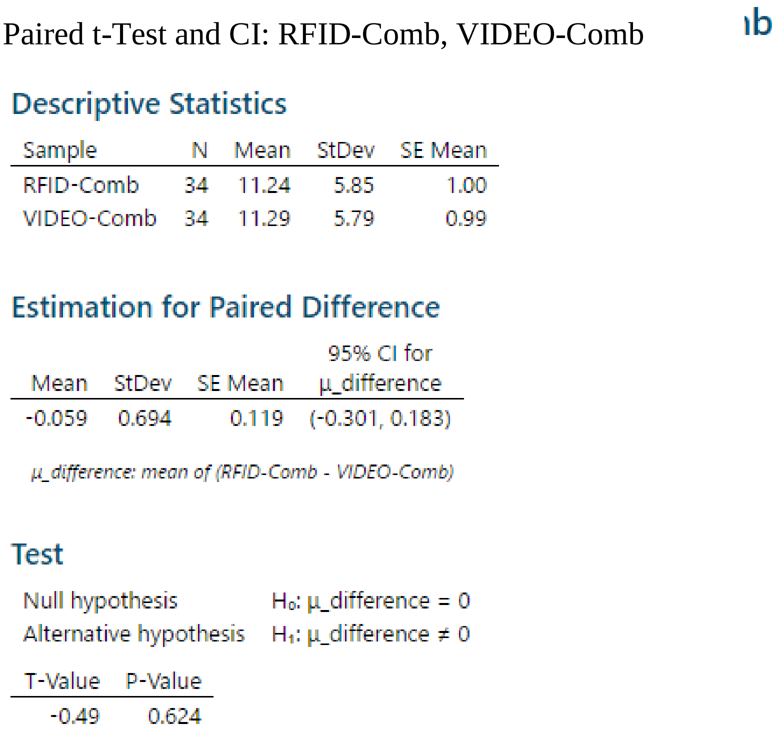
```
Descriptive Statistics

Sample      N   Mean   StDev  SE Mean
RFID-RD    34  27.82   15.72     2.70
VIDEO-RD   34  27.74   15.93     2.73

Estimation for Paired Difference

                                  95% CI for
Mean    StDev   SE Mean         µ_difference
0.088   0.965     0.166   (-0.248, 0.425)

µ_difference: mean of (RFID-RD - VIDEO-RD)

Test

Null hypothesis          H₀: µ_difference = 0
Alternative hypothesis   H₁: µ_difference ≠ 0

T-Value   P-Value
   0.53     0.598
```

Figure 5.5. Minitab Paired t-Test of rear door only evacuation.

and the video analysis were within two (2) seconds. A Paired t-Test failed to reject the null hypothesis of no difference between the RFID times and the video analysis times for passengers evacuating via the front door and the rear emergency door simultaneously (see Minitab results in Figure 5.6). The mean flow rate for both exit doors was **92.7 passengers/minute**.

5.6 Discussion

The RFID times matched the video analysis times for 61% of the observations. As RFID recognized the tag (subject) in 21% of the observations before the video analysis time, it is possible that the receiver was located too close to the exit of the bus, and/or the receiver was not adequately shielded. As the receiver is omnidirectional, it is possible to read the tag before the subject exits (or fully exits) the bus. Posture while exiting the bus can also affect the data. When evacuees are exiting through the front door, they are only slightly leaning forward in order to see the stairs. However, when they are exiting through the rear door using the ’sit-and-scoot’ method, they lunge forward in the doorway to sit down, then push off before both feet hit the ground. These natural gyrations associated with egress may have an effect on RFID sensing



Paired t-Test and CI: RFID-Comb, VIDEO-Comb

```
Descriptive Statistics

Sample       N   Mean   StDev   SE Mean
RFID-Comb   34  11.24    5.85      1.00
VIDEO-Comb  34  11.29    5.79      0.99


Estimation for Paired Difference

                              95% CI for
  Mean   StDev   SE Mean   μ_difference
-0.059   0.694     0.119  (-0.301, 0.183)

μ_difference: mean of (RFID-Comb - VIDEO-Comb)


Test

Null hypothesis          H₀: μ_difference = 0
Alternative hypothesis   H₁: μ_difference ≠ 0

T-Value   P-Value
  -0.49     0.624
```

Figure 5.6. Minitab Paired t-Test of combined door evacuations.

accuracy. The present study was conducted using four tags per evacuee, one hanging on a lanyard in the front, one hanging on a lanyard in the back, and one on each shoulder of each participant. However, the data from only the tag that hung in front was used for this study. Shaaban, Bekkali, Ben Hamida, Kadri [30] reported that the use of two tags per person "led to accurate detection of all people who participated".

During preliminary trials it was noted that passengers should not be allowed to hold any item during the evacuation due to the potential of the RFID tag being blocked from the receiver. Even a single sheet of paper can potentially hide the tag(s) from the receiver(s). Items like back packs and loose clothing should be avoided as well. Also, the receivers should not be attached to the bus doors because subjects tend to evacuate in a rhythmic (bouncing) pattern which could affect the stability of the receivers.

Statistically, there was no difference between the RFID times and the video analysis times for the front door, rear emergency door, and combined door trials. The video analysis facilitated the measurement of the point that both feet of the subject were on the ground outside the bus to the nearest second. The RFID sensors provided data in fractions of a second, however it was rounded to the nearest second for comparison purposes. It should be noted that because the RFID sensors are omnidirectional the setup of the school bus to accurately read precise departure of the bus is tedious. However, it may be possible to develop a system designed specifically for attaching to school buses to measure evacuation. Such a system would incorporate the appropriate means to fasten it to the bus and be designed to obtain accurate measurements.

In this study, we measured and analyzed the individual bus departure times. For evacuation training purposes, the only time of practical interest is the time that it takes for the last passenger to exit the bus. For all trials, the RFID times and video analysis times were identical for the last passenger.

5.6.1 Lessons Learned

1. Do not allow passengers to hold any item during evacuation training trials as even a single sheet of paper can potentially hide the tag(s) from the receiver(s).
2. Receivers should not be attached directly to the bus doors as subjects tend to evacuate rhythmically causing the steps to rise and fall.
3. It may be beneficial to attach two (2), or more, RFID tags [31], versus the use of a single tag, to the upper arms or shoulders to increase the probability of detecting a tag. Combinations of passenger size and exit velocity may contribute to tags being missed. No tags were missed, or not read during the present study.

5.7 Limitations

1. Small sample size (N=34). Assuming older/larger passengers are capable of seating two abreast, such a bus could hold up to 56 passengers.
2. Did not use school aged children for this demonstration study.
3. No attempt was made to simulate the intensity of an actual emergency evacuation.

5.8 Conclusions

To the best of our knowledge, this is the first study that has attempted to compare RFID with Video analysis to determine school bus passenger evacuation times. The RFID technology demonstrates that it is capable of recording the times from evacuating passengers and presenting that information to decision makers in a minimal amount of time. Use of this technology could provide more information to transportation coordinators and also eliminate some of the subjectivity associated with timing such trials manually. Future research should seek to find better placement of RFID receivers (perhaps a bit further from the doors), improved shielding techniques, and potential locations of passive RFID tags on subjects, to more accurately record individual evacuation times.

5.9 Acknowledgement

The research supporting this viewpoint was partially supported by the Deep South Center for Occupational Health and Safety, a National Institute for Occupational Safety and Health (NIOSH) Education and Research Center (Grant 2 T42 OH008436-13). The contents are solely the viewpoint of the authors and do not necessarily represent the official views of the Deep South Center or NIOSH.

We also wish to thank Don Ingram, Transportation Coordinator at Auburn City Schools, Auburn, Alabama, for providing school buses for our study. We thank Shivaprasad Nageswaran for his assistance and expertise in RFID technology.

Chapter 6

Conclusions

6.1 Introduction

Successful evacuation through an emergency evacuation system is highly dependent on the design of the system with respect to those who will use it. School buses are the safest mode of transportation for students. However, over 26,000 school bus accidents occur every year. Therefore, it is important to study the effectiveness of emergency evacuation designs in order to improve survivability post-accident. Federal Motor Vehicle Safety Standard (FMVSS) No. 217 regulates the design of school bus emergency exits by specifying the location, opening size, and forces required to operate the emergency exits. However, FMVSS No. 217 does not consider the size and stature of small children or situations where a bus accident results in a rolled-over orientation.

In general terms, the geometry of transportation vehicles moving large groups of people, such as airplanes, or buses, can be described as tubular structures, or shells, designed to transport closely seated rows of passengers between two, or more, locations. Aircraft emergency evacuation systems are subjected to stricter standards than those imposed by the FMVSS No. 217. Aircraft emergency exits are evaluated, and tested, for passenger flow rates in simulated emergency tests and the actual data is used to establish the number and size of the exits used. Very little research has been conducted to determine school bus emergency exit flow rates, especially in rolled-over configurations. School bus routes that have very small children are common in the United States, and usually the school bus driver is the only adult on the bus. If an accident or illness renders the driver unable to assist in an emergency, the children may be on their own until outside assistance arrives.

6.2 Summary of Findings

Three experiments were conducted for this dissertation. The first experiment was conducted to evaluate and compare the passenger flow rate through a school bus rear emergency door equipped with an improved hold-open device design beneficial in the unique situation when the bus is rolled over onto the left, or driver's side. The second experiment was conducted to evaluate and compare the passenger flow rates through two designs of a school bus emergency roof hatch for the situation when the bus is rolled over on either side. The aforementioned first and second experiments were conducted with a total of 139 students from the first, fourth, seventh and tenth grades. The third experiment was conducted to evaluate and compare two technologies for monitoring and tracking passengers during emergency evacuation drills through the front door, rear emergency door, or both doors simultaneously. The third experiment was conducted using 34 college students.

The findings of the first experiment are summarized as follows:

1. All of the students that attempted to exit either door fixture were capable of self-extricating. Two of the 139 participants chose not to attempt the fixtures.
2. The flow rate through the rear emergency door fixture with the improved door hold-open device was substantially higher than the fixture equipped with the current hold-open device for all grade levels.
3. Age, BMI, and the door fixture (current versus improved) were statistically significant predictors of the individual egress time for students overall.

The findings of the second experiment are summarized as follows:

1. All of the students that attempted to exit either roof hatch fixture were capable of self-extricating. Four of the 139 participants chose not to attempt the current design fixture.
2. The flow rate through the emergency roof hatch fixture with the larger opening was substantially higher than the fixture equipped with the current roof hatch opening size for all grade levels.
3. Age, BMI, and the hatch fixture (current versus improved) were statistically significant predictors of the individual egress time for students overall.

The findings of the third experiment are summarized as follows:

1. RFID technology is a valid approach for tracking, recording, and managing State mandated school bus evacuation training exercises and resulting data.
2. RFID recorded individual exit time accuracy was not statistically different from data recorded using video analysis.

For both of the first two experiments, older students have a distinct height and strength advantage for speed of egress up to the seventh grade where it appears to level out. One of the primary concepts stated in the FMVSS No. 217 is that emergency exits should provide an unobstructed opening for passenger egress. These experiments revealed the relative effect of a rear emergency door that weighs approximately 100 pounds hanging in the opening, or a roof hatch that requires lifting the body, or climbing through in order to evacuate to safety. They exhibited that a simple design change in the emergency evacuation system can have a profound effect on the overall passenger flow rate. The third experiment presents a novel approach to tracking, and managing evacuation training exercises that may lead to numerous schools uploading evacuation training data into a central repository and building a reliable source of information for benchmarking school bus emergency evacuation systems.

6.3 Limitations of the Research

Limitations of the research included:

1. Gym mats were used on the outside of the current roof hatch design fixture as a safety measure to prevent the risk of injury. This may have affected the posture of students as they self-extricated because the mats reduced the step-down distance outside the hatch by approximately twelve inches. Had the mats been removed, the flow rate may have been reduced.
2. The use of components from one model and manufacturer of school buses.
3. Limited sample sizes. Subjects were recruited from four (4) of the thirteen (13) grades that usually ride school buses.
4. Test fixtures are mockups fabricated from bus components and do not fully represent a bus in a rolled over configuration.
5. No attempt was made to fabricate and test a roof hatch with an operating door and mechanism for either hatch design.
6. No attempt was made to simulate the intensity of an actual rollover accident.

6.4 Recommendations for Future Research Studies

Future research into school evacuation studies could:

- Compare evacuation flow rates using a significantly lighter rear emergency door versus the 100 pound door currently in use today.

- Evaluate various designs for the school bus emergency roof hatch door and latching mechanisms with the goal to simplify the operation during egress.
- Evaluate the effects of environmental factors such as darkness, smoke, or evacuation training on flow rate.
- Measure the evacuation flow rates through emergency evacuation windows in the side of the bus.
- Develop simulation models for predicting evacuation times for various accident scenarios.
- Evaluate the effect of the use of seat belts in school buses on the egress of students in a rolled-over accident scenario, including passenger capability to release themselves from seatbelts post-crash, while suspended in mid-air.

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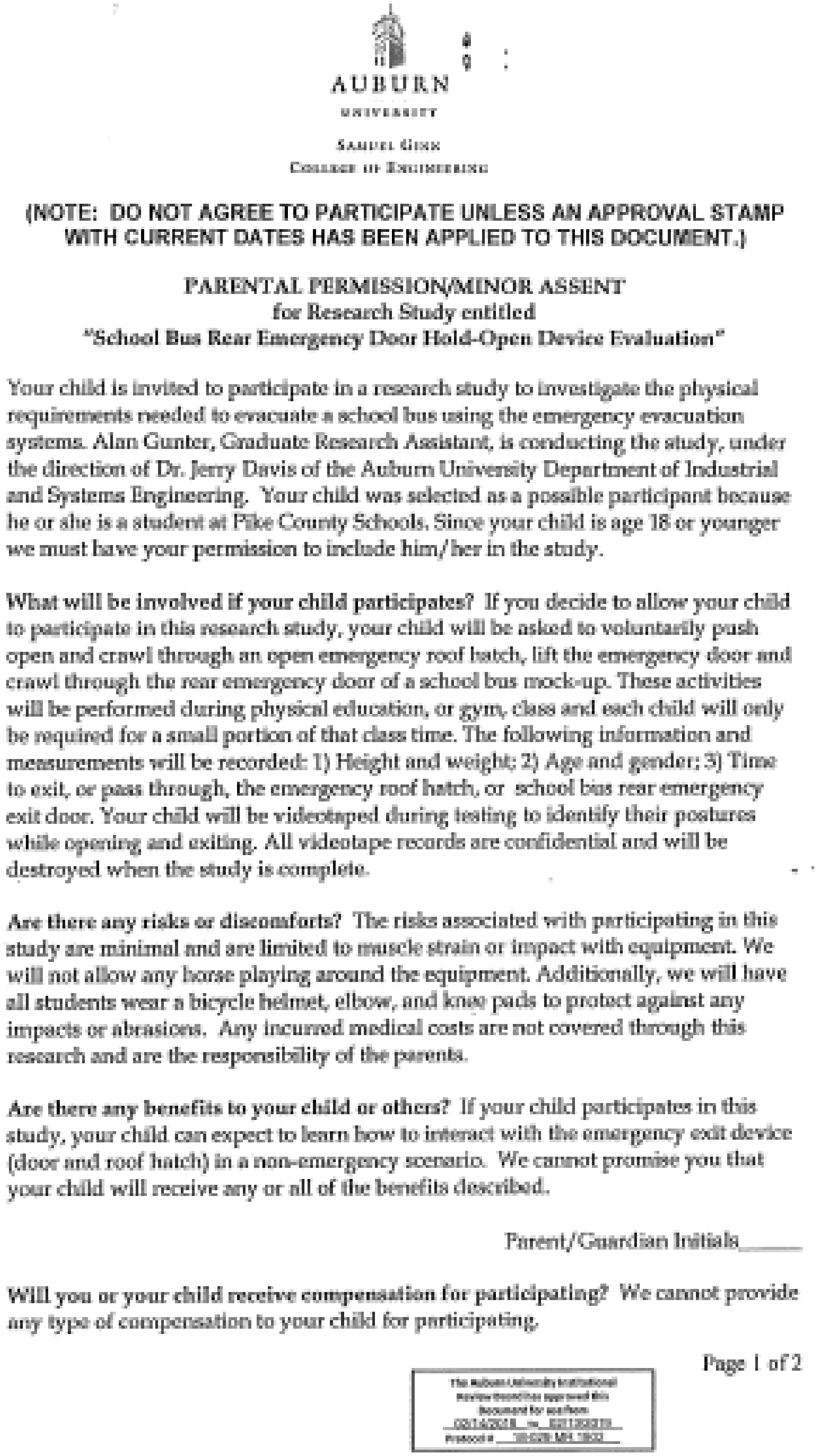
APPENDIX A



AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

(NOTE: DO NOT AGREE TO PARTICIPATE UNLESS AN APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

PARENTAL PERMISSION/MINOR ASSENT
for Research Study entitled
"School Bus Rear Emergency Door Hold-Open Device Evaluation"

Your child is invited to participate in a research study to investigate the physical requirements needed to evacuate a school bus using the emergency evacuation systems. Alan Gunter, Graduate Research Assistant, is conducting the study, under the direction of Dr. Jerry Davis of the Auburn University Department of Industrial and Systems Engineering. Your child was selected as a possible participant because he or she is a student at Pike County Schools. Since your child is age 18 or younger we must have your permission to include him/her in the study.

What will be involved if your child participates? If you decide to allow your child to participate in this research study, your child will be asked to voluntarily push open and crawl through an open emergency roof hatch, lift the emergency door and crawl through the rear emergency door of a school bus mock-up. These activities will be performed during physical education, or gym, class and each child will only be required for a small portion of that class time. The following information and measurements will be recorded: 1) Height and weight; 2) Age and gender; 3) Time to exit, or pass through, the emergency roof hatch, or school bus rear emergency exit door. Your child will be videotaped during testing to identify their postures while opening and exiting. All videotape records are confidential and will be destroyed when the study is complete.

Are there any risks or discomforts? The risks associated with participating in this study are minimal and are limited to muscle strain or impact with equipment. We will not allow any horse playing around the equipment. Additionally, we will have all students wear a bicycle helmet, elbow, and knee pads to protect against any impacts or abrasions. Any incurred medical costs are not covered through this research and are the responsibility of the parents.

Are there any benefits to your child or others? If your child participates in this study, your child can expect to learn how to interact with the emergency exit device (door and roof hatch) in a non-emergency scenario. We cannot promise you that your child will receive any or all of the benefits described.

Parent/Guardian Initials______

Will you or your child receive compensation for participating? We cannot provide any type of compensation to your child for participating.

Page 1 of 2

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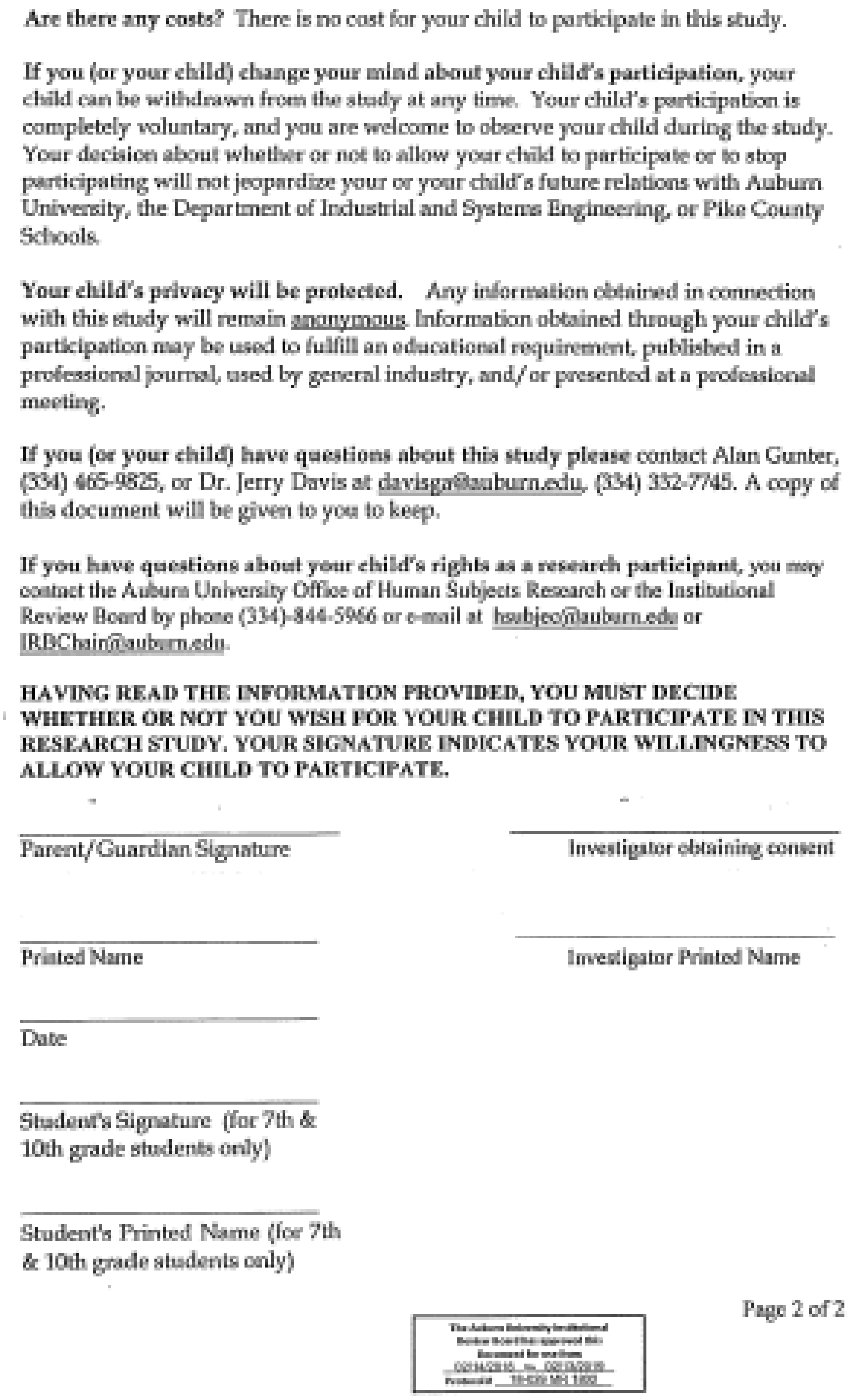
Protocol # [illegible]



Are there any costs? There is no cost for your child to participate in this study.

If you (or your child) change your mind about your child's participation, your child can be withdrawn from the study at any time. Your child's participation is completely voluntary, and you are welcome to observe your child during the study. Your decision about whether or not to allow your child to participate or to stop participating will not jeopardize your or your child's future relations with Auburn University, the Department of Industrial and Systems Engineering, or Pike County Schools.

Your child's privacy will be protected. Any information obtained in connection with this study will remain anonymous. Information obtained through your child's participation may be used to fulfill an educational requirement, published in a professional journal, used by general industry, and/or presented at a professional meeting.

If you (or your child) have questions about this study please contact Alan Gunter, (334) 465-9825, or Dr. Jerry Davis at davisga@auburn.edu, (334) 332-7745. A copy of this document will be given to you to keep.

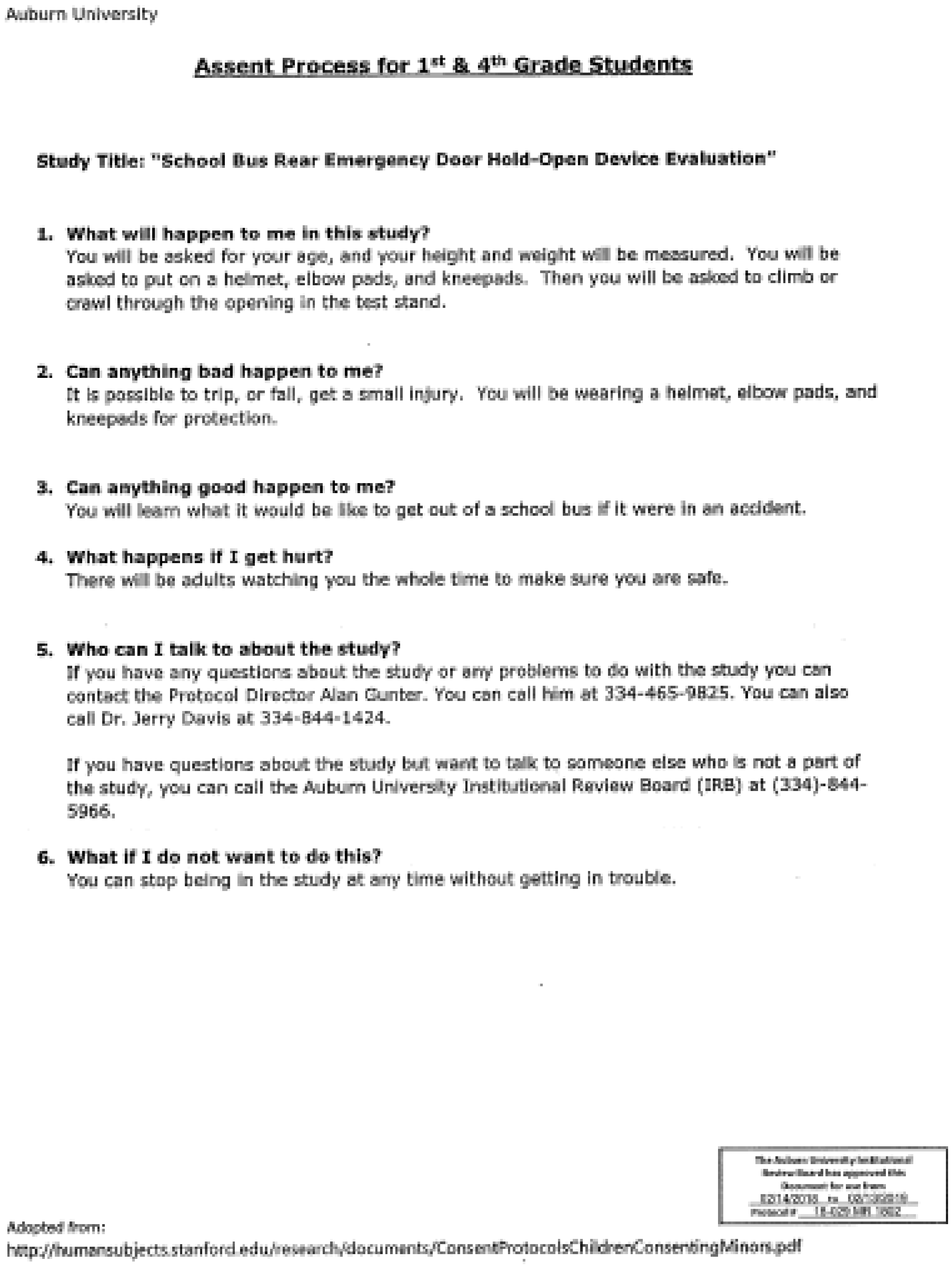
If you have questions about your child's rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH FOR YOUR CHILD TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO ALLOW YOUR CHILD TO PARTICIPATE.

Parent/Guardian Signature	Investigator obtaining consent
Printed Name	Investigator Printed Name
Date	
Student's Signature (for 7th & 10th grade students only)	
Student's Printed Name (for 7th & 10th grade students only)	

Page 2 of 2

APPENDIX B



Auburn University

Assent Process for 1st & 4th Grade Students

Study Title: "School Bus Rear Emergency Door Hold-Open Device Evaluation"

1. **What will happen to me in this study?**
   You will be asked for your age, and your height and weight will be measured. You will be asked to put on a helmet, elbow pads, and kneepads. Then you will be asked to climb or crawl through the opening in the test stand.

2. **Can anything bad happen to me?**
   It is possible to trip, or fall, get a small injury. You will be wearing a helmet, elbow pads, and kneepads for protection.

3. **Can anything good happen to me?**
   You will learn what it would be like to get out of a school bus if it were in an accident.

4. **What happens if I get hurt?**
   There will be adults watching you the whole time to make sure you are safe.

5. **Who can I talk to about the study?**
   If you have any questions about the study or any problems to do with the study you can contact the Protocol Director Alan Gunter. You can call him at 334-465-9825. You can also call Dr. Jerry Davis at 334-844-1424.

   If you have questions about the study but want to talk to someone else who is not a part of the study, you can call the Auburn University Institutional Review Board (IRB) at (334)-844-5966.

6. **What if I do not want to do this?**
   You can stop being in the study at any time without getting in trouble.

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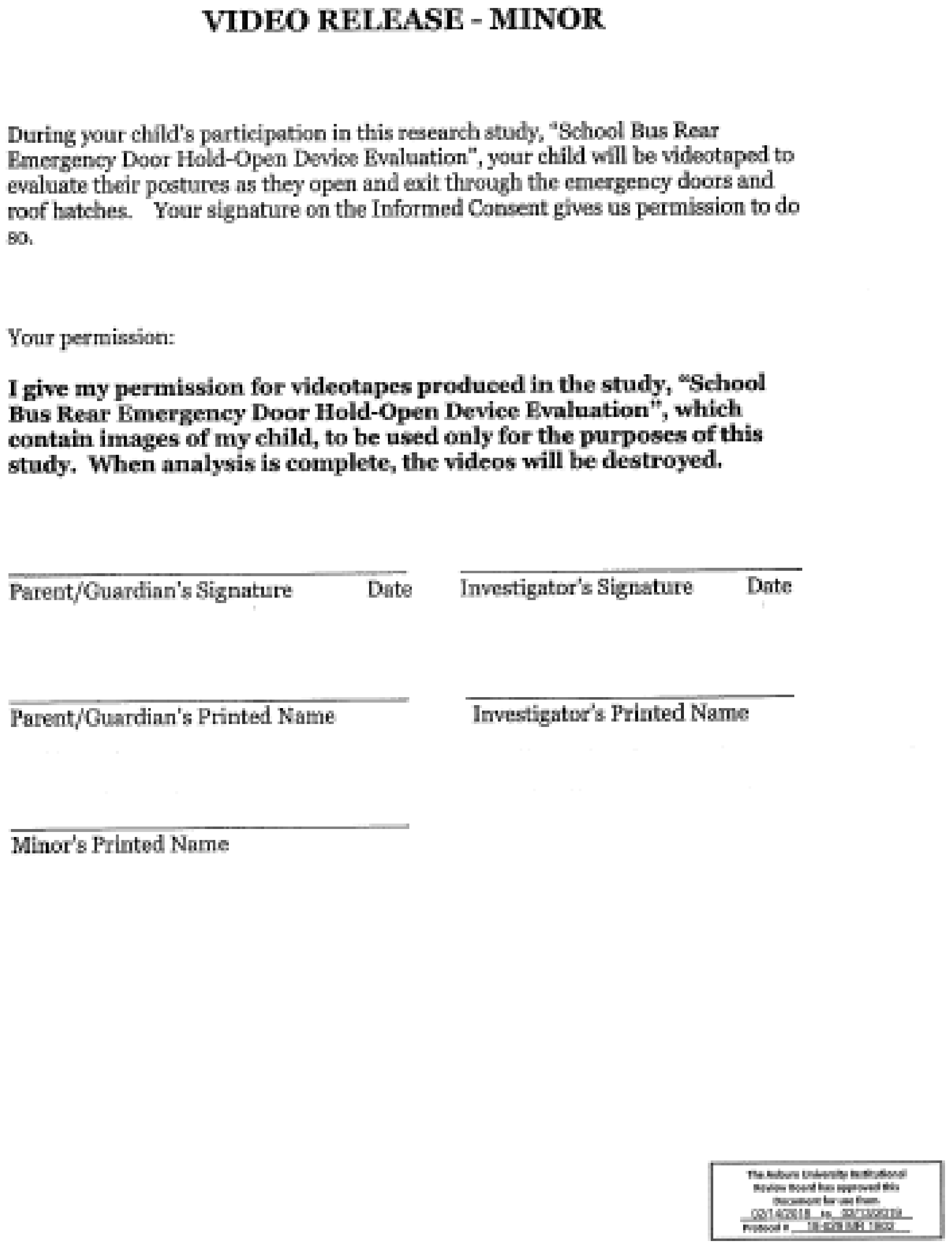
Protocol # 18-029 MR 1802

Adopted from:
http://humansubjects.stanford.edu/research/documents/ConsentProtocolsChildrenConsentingMinors.pdf

APPENDIX C



VIDEO RELEASE - MINOR

During your child's participation in this research study, "School Bus Rear Emergency Door Hold-Open Device Evaluation", your child will be videotaped to evaluate their postures as they open and exit through the emergency doors and roof hatches. Your signature on the Informed Consent gives us permission to do so.

Your permission:

I give my permission for videotapes produced in the study, "School Bus Rear Emergency Door Hold-Open Device Evaluation", which contain images of my child, to be used only for the purposes of this study. When analysis is complete, the videos will be destroyed.

Parent/Guardian's Signature Date	Investigator's Signature Date
Parent/Guardian's Printed Name	Investigator's Printed Name
Minor's Printed Name	

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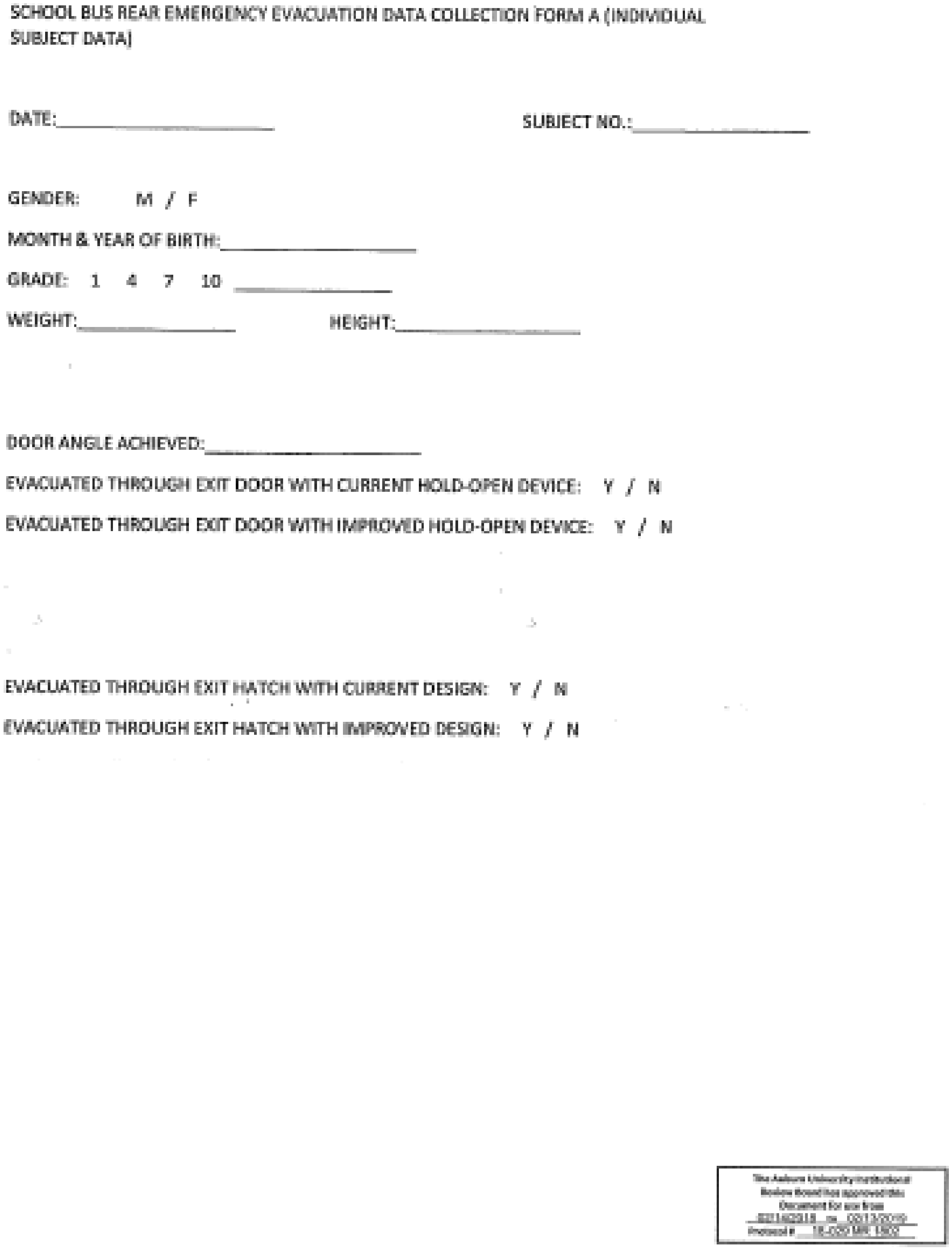
[illegible] to [illegible]
Protocol # [illegible]

APPENDIX D



SCHOOL BUS REAR EMERGENCY EVACUATION DATA COLLECTION FORM A (INDIVIDUAL SUBJECT DATA)

DATE:____________________ SUBJECT NO.:____________________

GENDER: M / F

MONTH & YEAR OF BIRTH:____________________

GRADE: 1 4 7 10 ________________

WEIGHT:________________ HEIGHT:____________________

DOOR ANGLE ACHIEVED:____________________

EVACUATED THROUGH EXIT DOOR WITH CURRENT HOLD-OPEN DEVICE: Y / N

EVACUATED THROUGH EXIT DOOR WITH IMPROVED HOLD-OPEN DEVICE: Y / N

EVACUATED THROUGH EXIT HATCH WITH CURRENT DESIGN: Y / N

EVACUATED THROUGH EXIT HATCH WITH IMPROVED DESIGN: Y / N

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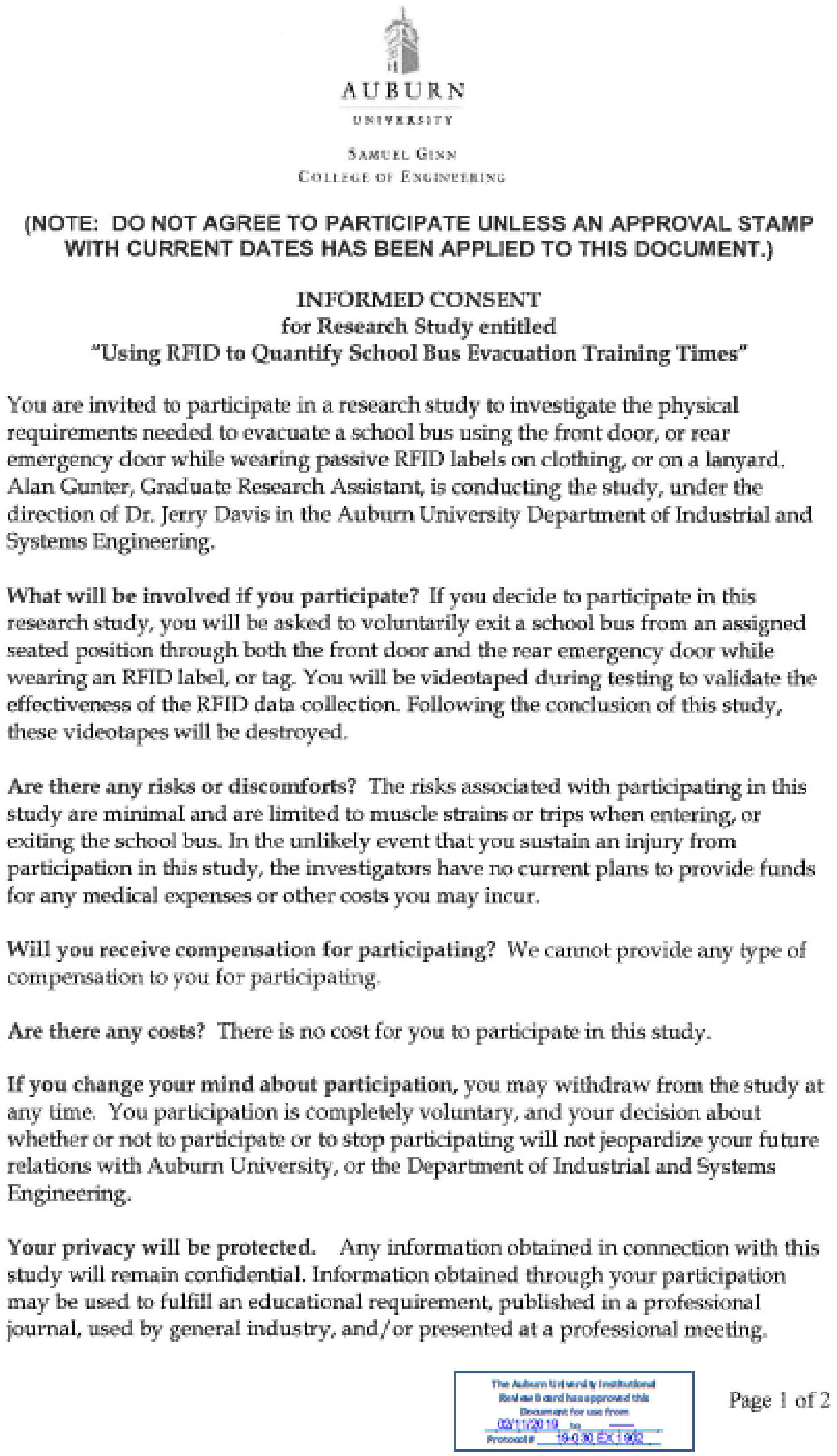
Protocol # 18-020 MR 1802

APPENDIX E



AUBURN
UNIVERSITY
SAMUEL GINN
COLLEGE OF ENGINEERING

(NOTE: DO NOT AGREE TO PARTICIPATE UNLESS AN APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT
for Research Study entitled
"Using RFID to Quantify School Bus Evacuation Training Times"

You are invited to participate in a research study to investigate the physical requirements needed to evacuate a school bus using the front door, or rear emergency door while wearing passive RFID labels on clothing, or on a lanyard. Alan Gunter, Graduate Research Assistant, is conducting the study, under the direction of Dr. Jerry Davis in the Auburn University Department of Industrial and Systems Engineering.

What will be involved if you participate? If you decide to participate in this research study, you will be asked to voluntarily exit a school bus from an assigned seated position through both the front door and the rear emergency door while wearing an RFID label, or tag. You will be videotaped during testing to validate the effectiveness of the RFID data collection. Following the conclusion of this study, these videotapes will be destroyed.

Are there any risks or discomforts? The risks associated with participating in this study are minimal and are limited to muscle strains or trips when entering, or exiting the school bus. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

Will you receive compensation for participating? We cannot provide any type of compensation to you for participating.

Are there any costs? There is no cost for you to participate in this study.

If you change your mind about participation, you may withdraw from the study at any time. You participation is completely voluntary, and your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, or the Department of Industrial and Systems Engineering.

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. Information obtained through your participation may be used to fulfill an educational requirement, published in a professional journal, used by general industry, and/or presented at a professional meeting.

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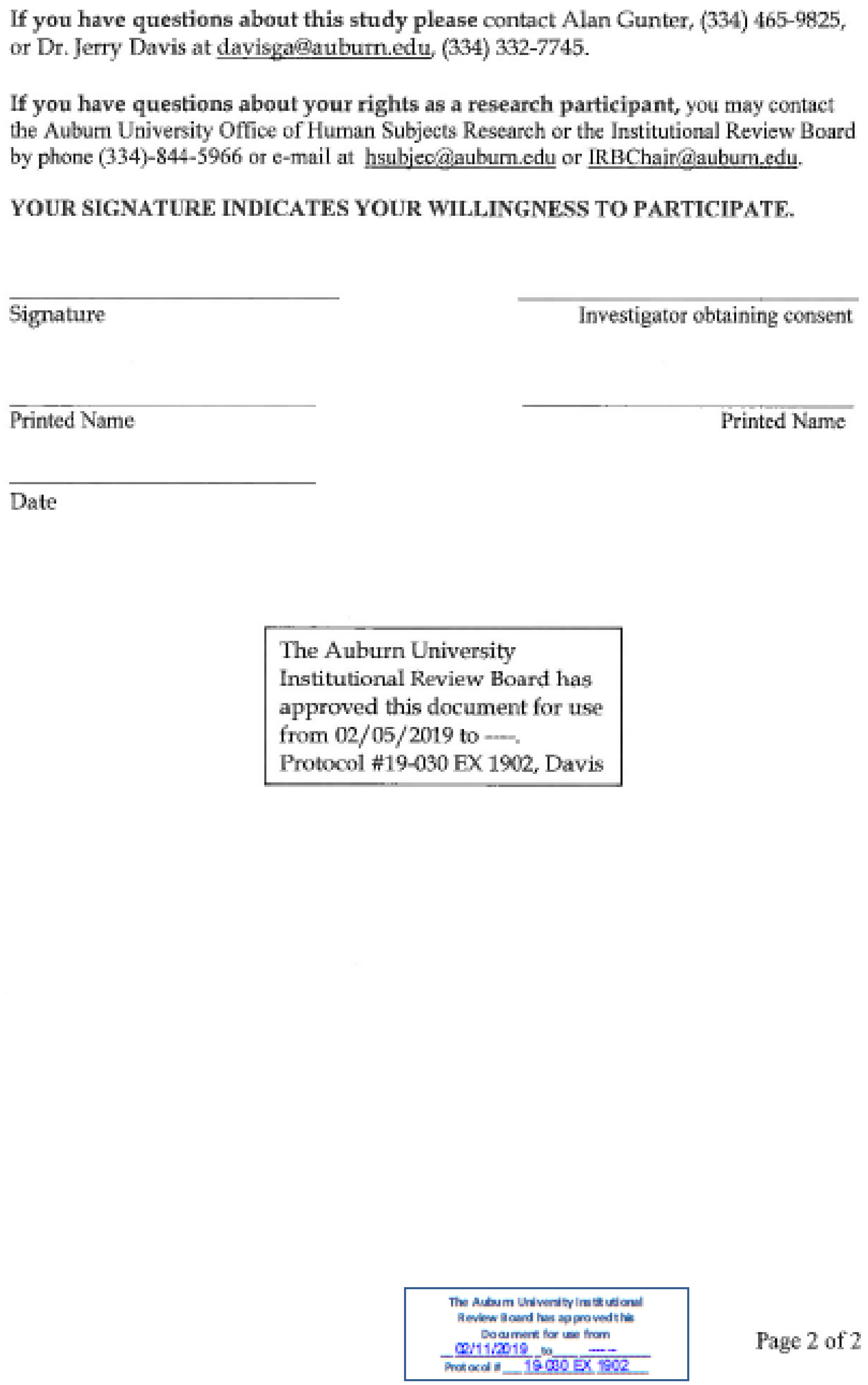
Protocol # 19-030 EX 1902



If you have questions about this study please contact Alan Gunter, (334) 465-9825, or Dr. Jerry Davis at davisga@auburn.edu, (334) 332-7745.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

______________________	______________________
Signature	Investigator obtaining consent
______________________	______________________
Printed Name	Printed Name
______________________	
Date	

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Protocol # 19-030 EX 1902

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