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Memorandum

**National Highway
Traffic Safety
Administration**

Subject: Motorcoach Safety Research

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Safety Standards Engineer

Reply to
Attn of:

To: Docket No. NHTSA-2007-28793

Thru: Lori Summers *Lori Summers*
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Chief Counsel

Dorothy R. Nakama June 15, 2010
for

Attached is a report titled, "Human Factors Issues in Motorcoach Emergency Egress – Year 2 Final Report," prepared by the John A. Volpe National Transportation Systems Center. This report presents the results of the second year of a two-year NHTSA-funded research effort to address human factors issues related to the emergency evacuation of motorcoaches and other human factors elements of Federal Motor Vehicle Safety Standard (FMVSS) No. 217, "Bus emergency exits and window retention and release," that apply to buses other than school buses.

This interim report describes the results of the second year of a two-year NHTSA-funded study. Two human factors experiments were conducted using a bus mock-up that included: 1) a series of egress trials to measure egress rate under different lighting conditions, using a stairway and two wheelchair-access door configurations; and 2) a series of tests to measure the human strength required to release and open motorcoach emergency exits. In addition, further information is provided related to the increased conspicuity of motorcoach emergency exits, including the use of high performance photoluminescent marking material, crashworthy emergency lighting; or dual-mode systems, which combine both technologies.

Attachment

Human Factors Issues in Motorcoach Emergency Egress

YEAR 2 FINAL REPORT

PREPARED FOR

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Vehicle Safety Research Office
National Highway Traffic Safety Administration
U.S. Department of Transportation
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words) FMVSS 217, Bus Emergency Exits and Window Retention and Release specifies a series of dimensional and physical requirements for emergency exits. The intent of NHTSA is “to minimize the likelihood of occupants being ejected from the bus and to provide a means of readily accessible emergency egress” for those occupants under crash and other emergency scenarios. These scenarios can include catastrophic bus accident situations, such as a vehicle fire, rollover, or water immersion where immediate emergency evacuation is necessary under life-threatening and difficult conditions. In 2007, NHTSA issued a research plan to address priority actions specifically related to motorcoach emergency egress. This interim report describes the results of the second year of a two-year NHTSA-funded study. Two human factors experiments were conducted using a bus mock-up that included: 1) a series of egress trials to measure egress rate under different lighting conditions, using a stairway and two wheelchair-access door configurations; and 2) a series of tests to measure the human strength required to release and open motorcoach emergency exits. In addition, further information is provided related to the increased conspicuity of motorcoach emergency exits, including the use of high performance photoluminescent marking material, crashworthy emergency lighting; or dual-mode systems, which combine both technologies.					
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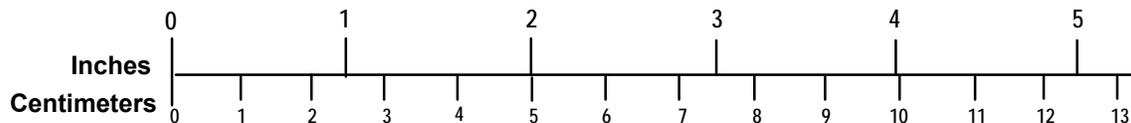
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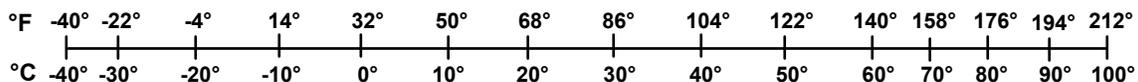
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PREFACE

The mission of the National Highway Traffic Safety Administration (NHTSA) is to reduce motor vehicle crashes and injuries. NHTSA safety regulations for bus and school bus design are contained in Title 49, Code of Federal Regulations (49 CFR), Part 571, Federal Motor Vehicle Safety Standards (FMVSS)

FMVSS 217, *Bus Emergency Exits and Window Retention and Release*, specifies a series of dimensional and physical requirements for emergency exits, including their size, location, opening forces, and marking, in addition to a series of release and retention tests for all windows, other than windshields. The intent of NHTSA is “to minimize the likelihood of occupants being ejected from the bus and to provide a means of readily accessible emergency egress” for those occupants under crash and other emergency scenarios. These scenarios can include catastrophic bus accident situations, such as a vehicle fire, rollover, or water immersion, where immediate emergency egress is necessary under life threatening and difficult conditions.

In 2007, NHTSA prepared a comprehensive research plan to address motorcoach safety issues that identified several improvements for motorcoach design as priority items for consideration in future rulemaking. One consideration identified in this plan is to address items on the National Transportation Safety Board (NTSB) “Most Wanted List” of safety improvements, such as “easy opening windows and roof hatches that stay open during evacuations” (H-99-9).

NHTSA asked the John A. Volpe National Transportation Systems Center (Volpe Center) to provide human factors research, evaluation, and technical support to identify potential motorcoach design changes related to passenger emergency egress.

This second interim report describes the results of the second year of the NHTSA-funded Volpe Center two-year study related to design changes that could increase passenger egress rates and reduce the risk of injury during emergency egress. While this effort is directed at intercity and charter / tour over-the-road motorcoaches, many findings may be relevant to emergency egress requirements for any bus or school bus.

The four topic areas addressed in this second interim report are: 1) egress rates via alternative second side doors with and without stairs; 2) human strength / ability to apply the forces needed to release and open emergency exits; 3) emergency exit identification; and 4) emergency exit lighting.

After NHTSA review, the content of the first year interim report and this second-year final report will be integrated into a technical summary report.

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1. INTRODUCTION

The mission of the National Highway Traffic Safety Administration (NHTSA) is to reduce motor vehicle crashes and injuries. NHTSA safety regulations for buses and school buses are contained in the Federal Motor Vehicle Safety Standards (FMVSS) included in Title 49, Code of Federal Regulations (49 CFR), *Part 571*.¹

Subsection 571.217, (FMVSS 217), *Bus Emergency Exits and Window Retention and Release*² specifies a series of release and retention tests for all windows, other than windshields, as well as a series of dimensional and physical requirements for bus emergency exits, including their size, location, opening forces, and identification. The intent of the NHTSA regulation is “to minimize the likelihood of occupants being ejected from the bus and to provide a means of readily accessible emergency egress” for those occupants under a variety of crash and other emergency scenarios. These scenarios can include catastrophic bus accident situations, such as a vehicle fire, rollover, or water immersion, where immediate emergency egress is necessary, under life-threatening and hazardous conditions.

1.1 BACKGROUND

In 2007, NHTSA prepared a comprehensive research plan to address motorcoach* safety issues, identifying several improvements for motorcoach design as priority items for consideration in future rulemaking.³ One consideration identified in this plan is to address items on the National Transportation Safety Board (NTSB) “Most Wanted List” of safety improvements, such as “easy opening windows and roof hatches that stay open during evacuations” (H-99-9).⁴

NHTSA asked the Volpe National Transportation Systems Center (Volpe Center) to provide human factors research, evaluation, and technical support in developing recommendations for updating to identify potential motorcoach design changes that may improve passenger egress from large buses during emergencies.

This final report describes results of the second year of the two-year study. Accordingly, the focus is on certain potential motorcoach design changes that may increase passenger egress rate and reduce risk of injury during emergency egress that were identified during the first year. Four topic areas are addressed: 1) egress rates via alternative second-side door exits with and without stairs; 2) human strength measurement of the ability to apply forces needed to release and open emergency exits; 3) emergency exit identification; and 4) emergency exit lighting.

* The NHTSA research program plan refers to motorcoaches as “intercity-transport buses.”

1.2 YEAR 1 SUMMARY

The Volpe Center completed a variety of activities and developed a preliminary list of potential motorcoach designs for NHTSA consideration to increase the passenger egress rate and risk of injury during emergencies; the Year 1 interim report contains the details.⁵ The following subsections provide a summary.

1.2.1 Activities

To gain knowledge of various factors affecting motorcoach passenger egress rates, the following tasks were completed:

- A literature search to review prior research for emergency egress from buses; other related U.S. transportation regulatory agency and industry standard organization emergency egress requirements; as well as international bus-emergency egress requirements;
- Naturalistic observations of passengers exiting from motorcoaches located at large bus terminals under normal conditions;
- Development of instrumentation to measure opening forces, primarily for emergency exit windows and emergency roof exit hatches;
- Field data collection to:
 - Catalog current-design motorcoaches in terms of front door, emergency exit window, and emergency roof exit hatch design and marking
 - Understand amount of force required to operate emergency exit windows and emergency roof hatches,
 - Understand how to operate and use emergency exit windows and emergency roof exit hatches on two different models, and
- Experiments to determine egress flow rate estimates for different types of exits, using:
 - Full bus (n=54) of subjects for front door egress, and
 - Smaller sample (n=5) of subjects for emergency exit window and wheelchair-access-door egress; and
- Measurement of luminance or illuminance of exemplars of the latest commercially available emergency exit signage, markings, and lighting.

1.2.2 Overview of Findings

1.2.2.1 Literature Review

The principal findings from the review were that:

- Very little research relevant to motor coach egress has been conducted since federally funded work was completed at the University of Oklahoma Research Institute in the 1970s.^{6,7,8}
- None of the known existing research literature addresses egress through emergency window exits currently installed in motorcoaches, which have sill heights and window weights much greater than those of buses tested in the 1970s.
- FMVSS 217 emergency exit requirements are different for school buses in various aspects than for other types of buses. Each school bus is required to have at least one emergency exit door and emergency exit identification requirements are more extensive. These requirements could be adapted for application to motorcoaches.
- Other U.S. transportation regulatory agencies and industry standard organizations specify requirements for emergency exits, including emergency exit identification and emergency lighting, which could be adapted for application to motorcoaches.
- The Economic Commission for Europe (ECE) has established requirements for motorcoach emergency egress, which could be adapted for application to U.S. motorcoaches. These standards include requirements for a second side-service or emergency door; larger emergency roof exit hatches than those required in the U.S.; floor exit hatches; and emergency exit identification and instructions for their operation on the bus exterior, as well as interior.

1.2.2.2 Egress Rates

Naturalistic observations of normal front-door egress at bus terminals showed that it requires three to four minutes for all passengers to egress from a fully loaded motorcoach (i.e., the egress rate is less than 20 persons per minute (ppm)). However, from time-to-time, clusters of passengers with minimal hand luggage were observed exiting at rates above 30 ppm.

A series of experimental egress trials was conducted at the Volpe Center in Cambridge, Massachusetts, using a motorcoach with federal employees serving as volunteer subjects. These trial results generated egress time estimates using the front-door, emergency-exit windows, and wheelchair-access door, all under ideal daytime conditions, and starting with the door or window already locked in the open position. Emergency roof exit hatch estimates were derived from observations by Volpe Center staff in February 2008 of only three individuals at the MGA Research, Inc., test facility, located in Burlington, WI, using two different overturned motorcoaches. Egress times for typical motorcoach passengers are likely to be longer, except for doors with stairs. The egress experiment trial results provided the basis for the motorcoach egress time estimates shown in Table 1-1.

All of the estimates are based on the assumption that all passengers know how to use the exits and that windows have “hold open” devices and are also based on the behavior of volunteers who judged themselves to be capable of performing the required actions without risk of injury.

Table 1-1. Volpe Center Year 1 Motorcoach Egress Time Estimates – 56 Passengers

EGRESS PATH	NUMBER OF EXITS USED	OPENING TIME (min)	FLOW RATE (ppm/exit)	EGRESS (min)	TOTAL [#] (min)
Front door	1	.05	36	1.56	1.61
Windows	6	.2	9	1	1.20
Wheelchair-access door	1	.2	25	2.24	2.44
Roof hatch	2	.1	12	2.33	2.43

[#] Equals the sum of opening time plus egress time and assumes all emergency exits are used.

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 take a minute or more to pass through the exit hatch unless they are assisted by other passengers.

These results indicate that evacuation of a motorcoach passenger could be achieved using any of these exits in less than three minutes. However, numerous obstacles may exist during an actual motorcoach emergency:

- In a frontal motorcoach crash, the front door may be blocked, or the driver may be incapacitated. Without a driver to operate the door control, passengers may incur substantial delay in figuring out how to open the door.
- Passengers who try to use the emergency window exits may find it difficult to raise and maintain the windows at sufficient height to allow safe egress.
- The wheelchair-access door cannot be opened from inside of any of the motorcoaches currently in use.
- Emergency roof exit hatches are useful only when a bus is overturned on its side.

1.2.2.3 Emergency Exit Operation

Release and opening forces for U.S. motorcoach emergency exit windows are within current FMVSS 217 regulatory limits; however, these forces are close to the limit for the larger exit windows. The opening force for top-hinged emergency-exit windows (currently used on all U.S. motorcoaches) increases with the size of the opening (i.e., as a greater portion of the window's mass must be supported by the passenger rather than by the hinge). Many adults require a larger opening size to egress without injury than the current NHTSA regulation and test procedures specify. The forces required to release and open roof emergency roof exit hatches varied over a

wide range, but were never found to exceed one half of the current regulatory limit value, 268 N (60 lbf), when measured with the bus upright. With the bus overturned on its side, the roof hatch swings freely on its hinges, and the opening force is largely determined by the force of wind acting on the hatch (i.e., the force can be negligible.)

1.2.2.4 *Emergency Exit Identification and Lighting*

Field measurements of illumination and letter sizes conducted by Volpe Center staff for emergency exit markings showed that those in current use were visible, whenever there is at least a low level of illumination present (i.e., in daylight or when the fluorescent boarding lights or adjacent reading lights are in use). However, the typical level of illumination provided at night (0.1 to 0.8 lux (0.01 to 0.08 fc)) by the “night-lights” does not allow the exit signage to be conspicuous or easily legible, even at very short viewing distances.

1.2.3 Summary

Issues relating to barriers to rapid motorcoach emergency egress have been documented in various NTSB reports and NHTSA-funded research study reports, as described in the Year 1 interim report. The results of the current Volpe Center study are consistent with the findings contained in those reports.

Other U.S. transportation regulatory agency requirements for vehicle emergency exits, including exit identification, and emergency lighting, could be adapted for application to motorcoaches. These requirements (extensively described in the Year 1 interim report) include: an emergency exit door in addition to the front service door, larger emergency roof exit hatches, photoluminescent marking of emergency exits on the interior, retroreflective marking of emergency exits on the exterior, and independently-powered emergency lighting.

Certain provisions of existing FMVSS 217 requirements for school bus emergency exits and standards established by the Economic Commission for Europe for motorcoaches operated in other countries may also be adapted and applied to motorcoaches.

1.3 YEAR 2 RESEARCH SCOPE

Volpe Center conducted human-factors experiments to determine:

- Rates of egress through:
 - Wheelchair-access doors with two different configurations and clearances, and
 - Stairways similar to those used as the second service door on many buses in other countries;

- Effects of illuminance levels on egress rates; and
- Human strength of adult subjects (evenly balanced by age and gender) to apply pulling and pushing forces needed to open doors and top-hinged emergency exit windows.

In addition, specification and performance criteria were developed for:

- Electrically illuminated emergency exit signs;
- Photoluminescent emergency exit signs;
- Emergency exit lighting; and
- Dual-mode sign systems, combining both technologies.

1.4 REPORT ORGANIZATION

Chapter 2 provides an overview of the human factors experiments conducted by the Volpe Center during Year 2 of this study. Chapter 3 presents and discusses the results of the human factors experiments involving egress from the bus mock-up. Chapter 4 presents and discusses the human strength test results for releasing and opening the simulated emergency exit window and door of the mock-up. Chapters 5 and 6 present information relating to emergency exit identification and emergency exit lighting. Finally, Chapter 7 summarizes Year 2 findings and conclusions.

2. HUMAN FACTORS EXPERIMENTS

The experiments described in this chapter address the following questions:

1. How best to provide an additional means of motorcoach emergency egress at the floor level – one that would be accessible and easier to use to more passengers than the emergency window exits. The alternative side exit configurations tested for egress rates were:
 - A second stairway and door, located in the rear half of the motorcoach, similar to those used in other countries.
 - A modified wheelchair-access door that can be opened by passengers from inside the bus for emergency egress. Because there are two substantially different configurations in wide use for wheelchair-access doors (mid-side and near the rear adjacent to the lavatory), investigation of this alternative required that both configurations be tested.
2. How much force can typical adults exert in all of the emergency-exit-releasing and opening actions, where 268 N (60 lbf) forces are permissible in FMVSS 217?
3. How do the performance requirements for emergency-exit identification signs affect egress rates for wheelchair-access doors and for the second door with a stairway of the type used on many motorcoaches outside the U.S.?

2.1 SIDE STAIRWAY AND WHEELCHAIR-ACCESS DOOR EGRESS RATES

As noted in the first interim report for this study, several significant changes in motorcoach design have occurred in the decades since the University of Oklahoma research studies⁶⁷⁸ were completed, making it necessary to update passenger egress rate estimation using current bus designs. These motorcoach design changes include:

- An increase in floor height of 30 to 61 cm (12 to 24 in);
- “Kneeling” capability (which lowers the height of the bottom step from 43 cm to 30 cm (17 in to 12 in) for the front service door;
- An increase in window sill height above the ground of about 60 cm (2 ft);
- A large increase in window size and weight;
- Elimination of rear side doors for emergency egress; and
- Introduction of wheelchair-access doors (which cannot be opened from the inside in current intercity motorcoaches).

Motorcoach egress rates for anything other than the normal, front-door exit path are highly variable and affected by numerous factors, particularly:

- Fitness of egressing persons;
- Knowledge of procedures for opening, securing, and traversing exits;
- Assistance from driver and/or other passengers;
- Lighting conditions;
- Physical orientation of the vehicle; and
- Ground conditions at the end of the egress path.

2.1.1 Overview

During the first year of this study, Volpe Center staff conducted a series of pilot experiments to measure egress rates using a real motorcoach. The results of those experiments indicated that passenger flow through the wheelchair-access door (or another side door) as an emergency exit could be as high as 25 persons per minute (ppm). This finding led Volpe Center staff to develop a follow-up experiment to measure occupant egress rates using a side stairway similar to those used on many motorcoaches operated in other countries and two wheelchair-access-door configurations.

The first issue in the experiment design to measure motorcoach egress rates was whether to conduct them in a real motorcoach or in a mock-up of a portion of a bus. The first option would have provided greater face validity. However, it was not feasible for the following reasons:

- It would not have been practicable to test the second stairway configuration, because no such motorcoaches were available for rental in the U.S; and
- There was no facility available to conduct the experiments indoors and in reasonable proximity to the Volpe Center, making it difficult to control illumination down to very low light levels.

Accordingly, Volpe Center staff constructed a mock-up section of a motorcoach to simulate the three side egress paths: a rear side stairway and two wheelchair-access-door configurations.

2.1.2 Objectives

The first experimental objective was a comparison of egress rates for two different wheelchair-access-door configurations, as well as with a side stairway like those used on many motorcoaches in other countries as the second service door.

A second objective of the egress-rate experiment was to measure the effect of different illuminance levels of emergency lighting or illuminated emergency exit signage. Thus, this experiment was also designed to measure egress rates for the three exit paths under various lighting conditions, ranging from normal room lighting to complete darkness, except for PL markings (which used during only one stairway trial).

2.1.3 Subjects

Twenty-six able-bodied subjects were recruited from the Volpe Center population of federal employees; this included two extra individuals, in case of no-shows on the day of the experiment. Participation was limited to Volpe Center federal employees-for the following reasons:

- Security restrictions;
- Health Service nurse was authorized to provide care only for federal employees;
- Subjects received their normal salaries while participating, so no additional compensation was necessary; and
- The Workmen's Compensation Act applied in the unlikely event of a serious injury.

Individuals with physical disabilities were excluded from all experiments for the following reasons:

- Risk of injury from falls would have been much greater; and
- Large variance in the egress time would be introduced and mask the effects of design changes.

All of the subjects were briefed by one of the Volpe Center staff investigators using the Institutional Review Board (IRB) protocol prior to the conduct of the egress experiments. All subjects reviewed and signed an informed consent form. The subjects were physically fit and indicated that they were confident of their ability to perform the respective egress procedures, after watching video illustrations and receiving briefings from Volpe Center staff. Only individuals who judged themselves to have sufficient upper-body strength to support their body weights were included as subjects. On the day of the egress trials, the selected 24 subjects were free to make a final judgment about whether they had sufficient strength after viewing a demonstration by the Volpe Center Lead Experimenter of the egress methods using the mock-up stairway and two wheelchair-access door openings.

The distribution by age group and gender of subjects in the egress rate experiment is shown in Table 2-1.

Table 2-1. Subject Age and Gender Distribution

GENDER	UNDER 35	35 TO 55 YEARS	OVER 55 TO 65 YEARS
Female	4	4	2
Male	5	4	5

Subjects were recruited so that there would have been equal numbers in each cell. However, there were two “no-shows” in the older group of female subjects, requiring the use of replacement subjects – one young male and one older male.

2.1.4 Apparatus

The egress experiments were conducted in a mock-up of a portion of a motorcoach constructed in a Volpe Center laboratory building, with 3.7-m (12-ft) ceilings to provide sufficient clearance for the subjects to walk upright, as illustrated in Figure 2-1. The mock-up included two sets of bus seats, the end entry stairway and side egress stairways, and two simulated wheelchair-access door egress openings.

Overall dimensions of the platform floor were 3 m (10 ft) long by 1.5 m (5 ft wide). The mock-up steel frame was constructed of *Superstrut*[®] components. The boarding stair projected an additional 1.8 m (6 ft) from the right end of the platform. The landing mat that subjects jumped onto from the wheelchair-access side door openings measured 1.2 m (4 ft) by 2.4 m (8 ft) by 10 cm (4 in) thick and was constructed from polyurethane foam covered with vinyl.



Figure 2-1. Motorcoach Mock-up – Exterior

All of the critical dimensions that influence egress rates were replicated from motorcoaches typical of the U.S. fleet. The platform height was 1.52 m (60 in), which is almost as high as the highest floor heights found on U.S. buses. The stairway shown on the right in Figure 2-1, which was used by the subjects to ascend to the platform, had eight 19-cm (7.5-in) risers, providing a slope of 37° – typical of the majority of stairs in modern buildings, which are sloped from 30 to 38° . The left stairway, which simulated the configuration used with a second door on buses operated in other countries, had five 30-cm (12-in) risers and a 50° pitch. This stair run was inherently limited to the width of a pair of seats (i.e., 102 cm [40 in]). The stair treads were 61 cm (24 in) wide. The clearance between hand rails was 57 cm (22.5 in), as measured on a *MAN model D20* bus, shown in Figure 2-2, beside a close-up of the mock-up stairs.



Figure 2-2. Similar Dimensions of Second-Door Stairs in a Bus and Mock-up Stairs

The seats installed in the mock-up were of a type in wide use on U.S. intercity buses.

The spacing for a door located adjacent to a motorcoach lavatory was reproduced from an *MCI J-4500* bus, while the spacing between seats reflected that of a *Prevost X345*. The aisle width was 51 cm (20 in), which is typical of U.S. motorcoaches. The side openings in the mock-up were modeled from the wheelchair-access doors of the *Prevost X345* and *MCI J-4500* motorcoaches. Both door openings were 107 cm (42 in) wide. Figure 2-3 shows the real bus “Mid-Door” and its mock-up with the opening counterpart.

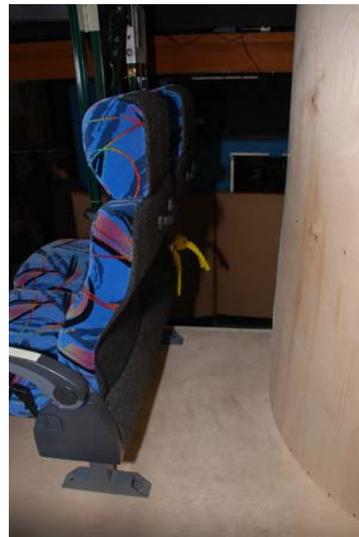
The rear side door opening, modeled on the wheelchair-access door of the *MCI J-4500*, was designated the “Lavatory-Door” because of its location adjacent to the lavatory on the real bus.

a. *Prevost X345*

b. Mock-up

Figure 2-3. Similarities of *Prevost X345* Wheelchair-Access Door and Mock-up – Interior

This door was fitted with a side-hinged door that was locked in the full-open position for the egress trials. A curved plywood partition was erected adjacent to the rear opening to duplicate the narrower exit path caused by the lavatory. Figure 2-4 shows the real bus lavatory door and its mock-up opening counterpart.

a. *MCI J-4500*

b. Mock-up

Figure 2-4. Similarities of *MCI J-4500* Wheelchair-Access Door and Mock-up – Interior

“High performance photoluminescent” (HPPL)** path markings were mounted on the all stairway steps and handrails, along the mock-up floor aisle, the top jamb and threshold of the

** “High-performance photoluminescent” material exhibits significantly enhanced surface brightness for a much longer time period compared with zinc sulfide photoluminescent material.

open “Mid-Door” and “Lavatory-Door” of the mock-up, as shown in Figure 2-5, and Figure 2-6 as well as obstacles, such as the edge of the landing mat and the open “Mid-Door.”

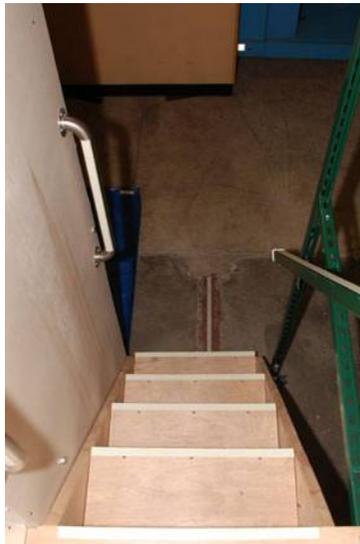


a. Normal Lighting



b. Darkness

Figure 2-5. Mock-up HPPL Exit Signs and Path Marking – Looking Along Main Aisle



a. Normal Lighting



b. Darkness

Figure 2-6. Mock-up HPPL Path Marking – Side Stairway

Electrically powered, backlit HPPL material “EXIT” signs with 5-cm (2-in) high letters were located above the “Mid-Door” and “Lavatory-Door,” as well as above the side stairway (see Figure 2-7). Luminaires (“luminaire” is the term used in the lighting industry to describe the combination of a light fixture with its lamp(s), power supply, controller, and housing) were turned on for each egress trial for the respective exit path and illumination level.

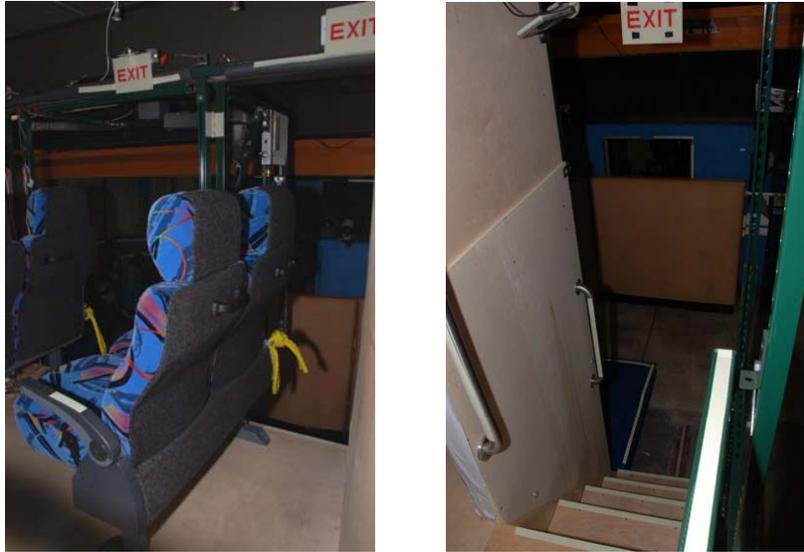


Figure 2-7. Mock-up HPPL “EXIT” Side Door and Stairway Signs

Ten video cameras were installed inside and outside of the mock-up at various locations to provide detailed views of each portion of the egress and to record subject actions and times for each trial. Eight ceiling-mounted cameras were connected to the *GeoVision*® digital video recording system, while two tripod-mounted cameras were connected to independent recorders for backup in case the main recording system malfunctioned. The *GeoVision* system provided a common time-stamp (hh:mm:ss.sss format) on every video frame of each channel to facilitate precise determination of the time that each action occurred.

The egress trials were conducted under four different light level conditions:

- Normal room lighting from the overhead fluorescent luminaires – 100 to 200 lux (9 to 18 fc);
- Reduced lighting from white light emitting diodes (LED) emergency luminaires – 4 to 8 lux (0.4 to 0.8 fc);
- Dim lighting from red LED emergency luminaires – 0.2 to 0.6 lux (0.02 to 0.06 fc);
- Pitch darkness, except for the HPPL signs and egress path markings.

Switching of the different light conditions occurred between trials. Except during the normal lighting condition, the area surrounding the mock-up was dark. However, HPPL strips were used to mark the exit path and all obstacles along the route path from the mock-up back to the adjacent room where subjects assembled after each trial.

Figure 2-8 illustrates the three exit aisle way paths as seen under normal lighting from the perspective of a person standing in the aisle inside the mock-up. Figure 2-9 shows the perspective of the subjects looking down from the mock-up “Lavatory-Door” and “Mid-Door,” prior to the sitting and controlled drop egress trials.



Figure 2-8. Side-by-Side View of the Three Egress Paths

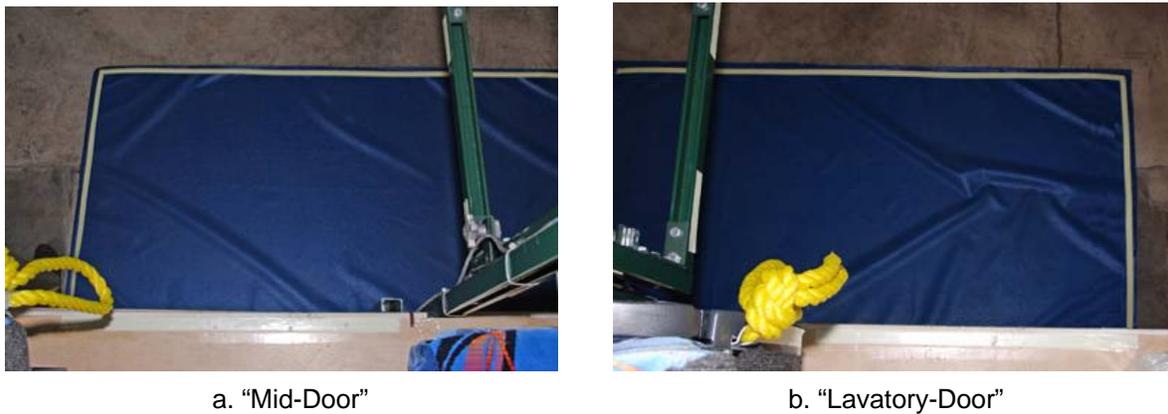


Figure 2-9. Subject View: Exit Openings for Sitting Jump and Controlled Drop—Simulated Wheelchair-Access Door

The location of the various mock-up components, cameras, and the three exit paths is shown schematically in Figure 2-10.

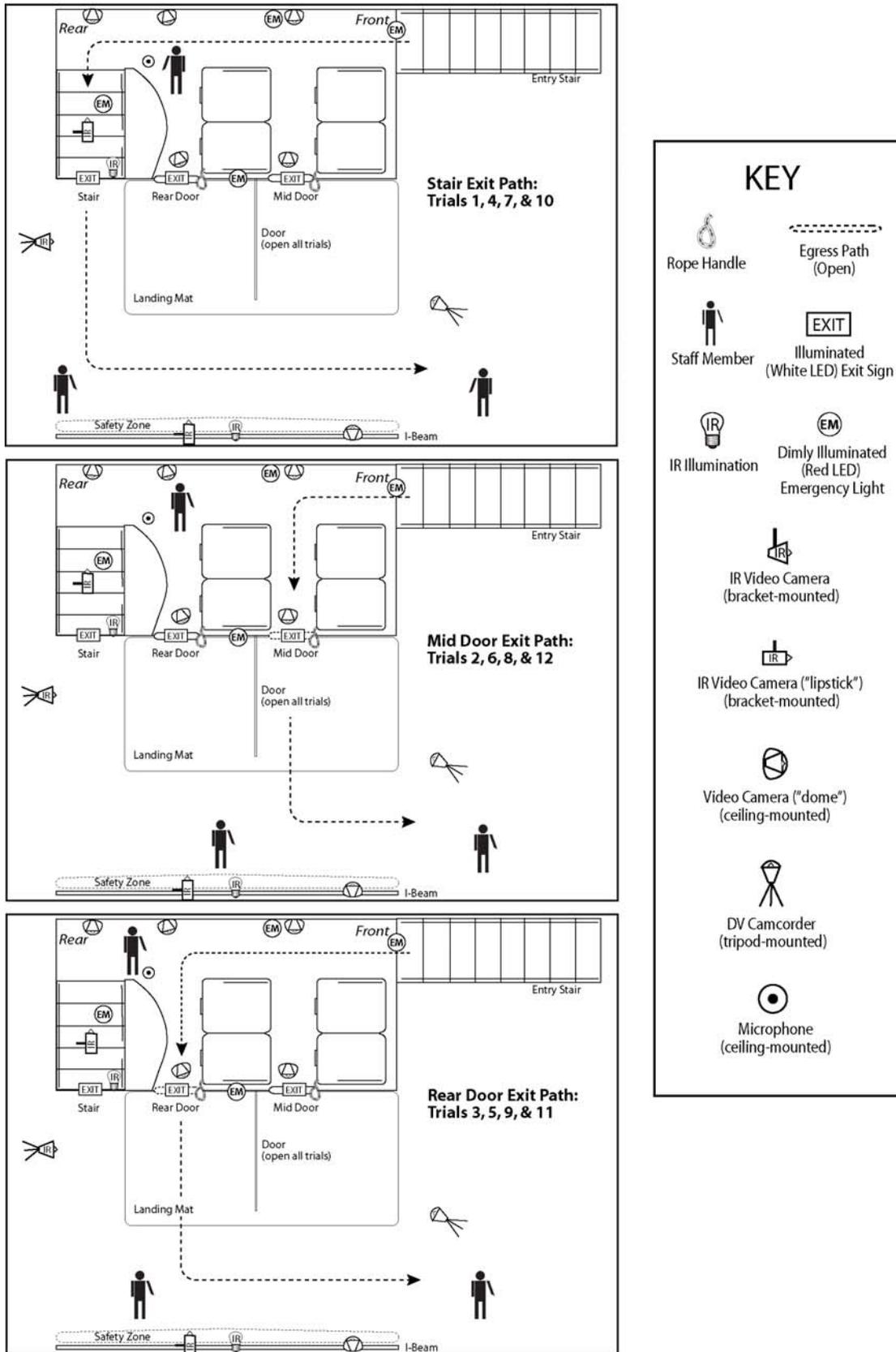


Figure 2-10. Bus Mock-up Schematic Diagram

2.1.5 Experimental Protocol

As noted previously, subjects were briefed individually according to the informed consent form required by the IRB.

Volpe Center subjects assembled at the appointed time and were outfitted with numbered vests and PL arm bands. During the registration procedure, subject vest numbers were recorded along with their gender and age group.

Subjects then observed the Experimenter who demonstrated each of the methods they were to use to egress from the bus mock-up during the various trials, including: 1) descending the stairs while holding the handrails and grab bars, and 2) performing the “sitting jump” and “controlled drop” from both wheelchair-access doors.

The sitting jump consisted of sitting on the door threshold with the subject’s legs hanging down, and then pushing off with both hands on the sill, so as to retard the rate of fall as much as possible. The controlled drop method was similar except that the rope handhold allowed subjects to retard their rate of fall more than in the sitting jump, and also gave them an additional means of maintaining balance on contact with the landing mat. The three egress paths and methods are illustrated in Figure 2-11 and Figure 2-12.



a. Stairway



b. Sitting jump – “Mid-Door” and “Lavatory-Door”



Figure 2-11. Subject Egress Using Side Stairway and Simulated Wheelchair-Access Doors

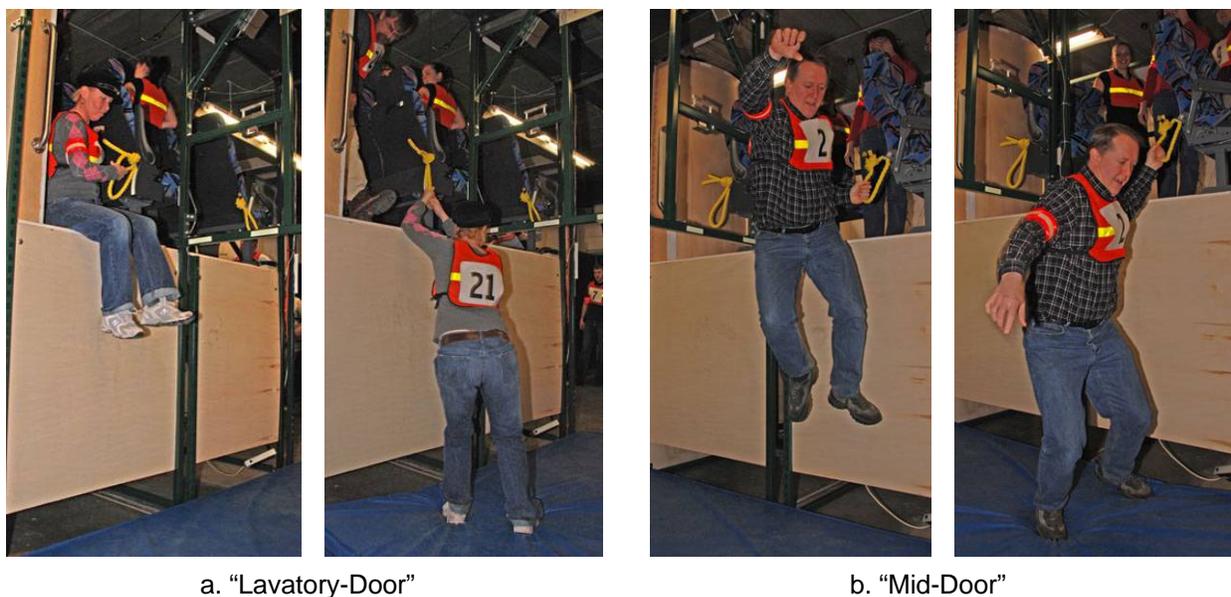


Figure 2-12. Subject Egress Using Simulated Wheelchair-Access-Doors – Controlled Drop

After the egress method demonstrations by the Experimenter, the subjects were led through the mock-up up and down the stairway of the mock-up, once with normal room lighting to familiarize them with such stairs prior to the reduced lighting condition of the experiment. This was done to reduce the risk of subjects falling due to the high risers of the side stairway.

Subjects were instructed that during each trial, they should exit as rapidly as possible without risking injury. They were then queried as to whether they felt confident of their abilities to perform each of the egress methods without risk of injury; none expressed reservations and the egress trials began immediately thereafter, according to the sequence of conditions listed in Table 2-2.

Subjects began each egress trial in a darkened room adjacent to the mock-up room. For the first trial, they lined up in an order of their own choosing. The subjects were told that as soon as a verbal cue was given, they were to follow the research assistant into the mock-up and immediately begin exiting by whichever route had a lighted “EXIT” sign above it. For each egress trial, the research assistant stepped out of the selected route and effectively blocked subjects from going past it. Between egress trials, subjects walked back into the darkened adjacent room, where they reassembled and were instructed to line up for the next trial in a different order than in the previous trials.

In all, 12 egress trials were conducted using three different exit paths and three methods, under four different light level conditions (normal, reduced, dim, and pitch darkness), as shown in Table 2-2.

Table 2-2. Sequence of Conditions for Egress Rate Trials

TRIAL NO.	EGRESS PATH	METHOD	ILLUMINANCE	
			Lux (fc) *	Level
1	Stair	Walk	~0.001 (.0001)	Pitch dark [#]
2	Mid-Door	Free Choice	105 (10)	Normal
3	Lavatory-Door	Free Choice	227 (21)	Normal
4	Stair	Walk	217 (20)	Normal
5	Lavatory-Door	Controlled Drop	8.5 (.8)	Reduced
6	Mid-Door	Controlled Drop	8.2 (.8)	Reduced
7	Stair	Walk	0.25 (.02)	Dim
8	Mid-Door	Sitting Jump	8.2 (.8)	Reduced
9	Lavatory-Door	Sitting Jump	8.5 (.8)	Reduced
10	Stair	Walk	4 (.4)	Reduced
11	Lavatory-Door	Free Choice	0.6 (.06)	Dim
12	Mid-Door	Free Choice	0.66 (.06)	Dim

* These values were the highest measured on the floor or bottom stair tread directly below the luminaire. Much lower values would have been recorded with the photometer sensor displaced from the "bright spot."

Except for HPPL path marking

All twelve egress trials were completed within 45 minutes.

At the conclusion of the egress trials, subjects were given a debriefing questionnaire to complete and return by e-mail. Questions included:

1. Which egress path did you prefer (stairway, side door between seats, or side door adjacent to the lavatory wall)?
2. In a real emergency, would you use the nearest exit as soon as possible or wait for access to the preferred path?
3. When you descended from the side doors, did you prefer the sitting-jump method or the controlled drop? Please explain factors that might influence your preference.
4. Did your behavior change appreciably between the high-level and the lower level emergency-lighting conditions? What did you do differently?
5. In a real emergency, if the landing area beneath the door had been littered with crash debris, would you have been willing to jump under the lower-level lighting condition?

Subjects were encouraged to volunteer additional comments.

2.1.6 Data Reduction

The exact time of each event in each trial could be precisely determined from review of the *GeoVision* files. To determine group egress rates, only the start time and end time were needed. The egress rate (ppm) for an experiment with 24 subjects is calculated as:

$$\text{Egress Rate (ppm)} = 60 * 24 / (\text{End time} - \text{Start time}) \quad (1)$$

“Start time” was defined as the moment at which the first subject reached the beginning of the egress path – either the top of the side stairway or a point along the aisle adjacent to the wheelchair-access door being used for a particular trial. “End time” was the moment that the last subject’s feet hit the floor or landing mat. (Note: Start and end times are expressed in seconds.)

To determine gender effects on egress rates, the time of landing for each subject during each egress trial was recorded in a spreadsheet along with vest number. The records from each trial were then sorted with a lookup function for gender derived from the registration records. The egress time for each subject was calculated as the difference between that subject’s landing time and that of the previous subject. For each trial, these individual times were summed and averaged to determine the gender group average.

Results for each of the 12 combinations of egress path and lighting conditions for the experiment trials are reported in Chapter 3.

2.2 MEASUREMENTS OF HUMAN STRENGTH TO RELEASE AND OPEN EXITS

2.2.1 Overview

Volpe Center staff measured the forces required to open emergency window exits and roof exit hatches in the first year of this study. Although all of the samples measured were within the current FMVSS 217 limit of 268 N (60 lbf), one measured 260 N and one measured above 200 Newtons (N), as described in the Year 1 interim report. Furthermore, a recent University of Nottingham study of human strength in pulling on an underhand grip, somewhat similar to the release bar on an exit window, indicated that fewer than 10% of the subjects tested could exert a force of as much as 268 N.⁹

Although the strength of humans in applying pulling and pushing forces has been extensively studied among certain segments of the population (e.g., military personnel, astronauts, college students, and persons with disabilities), there has been relatively little study of the strength of

typical adults in performing the types of actions necessary to release and open motorcoach emergency exits. Moreover, the maximum force that an individual can exert is dependent on the specific posture and grip in which the force is applied. No extant research was found regarding the human strength required in applying force in particular postures and grips to release and open motorcoach emergency exits.

FMVSS 217 requires a limit of 268 N (60 lbf) for releasing and operating emergency exits in “high force” areas (generally those located between 61 and 132 cm [24 to 52 in] above the floor). A lower limit of 89 N (20 lbf) applies in hard-to-reach areas below or above those height dimensions. These limits apply to the emergency exit windows and emergency roof exit hatches used for motorcoach emergency egress. However, during measurements of the forces required to release and open exits during the first year of this study, Volpe Center staff found no exits designed to have release or opening forces applied outside of the high-force areas. Furthermore, all of the roof hatches could be released and opened with force applications that were far below the limit; in fact such forces would be negligible in the situation in which roof exits would be used, i.e., with the bus overturned on its side. Thus, it was not necessary to measure human strength to open emergency roof exit hatches.

2.2.2 Objectives

The second objective of this study was to gather human strength data from subjects applying the various forces necessary to release and open motorcoach emergency exits. The measure of human strength used is “maximum voluntary contraction,” i.e., the maximum force an individual is willing to exert without risking pain or injury for a particular posture and grip. The eight specific force applications for (simulated) emergency exits included: release (pulling) forces for closed windows and doors; and opening (pushing) forces for open and closed windows and doors. Depending on the test, the subjects used one or two hands.

2.2.3 Subjects

The same subjects who participated in the egress trials also participated in the exit strength tests, except that two of the male subjects who had replaced the female “no-shows” at the egress trials, were excluded. Two additional female subjects were recruited from the Volpe Center federal employee population in order to make the subject population for the exit human strength experiment evenly balanced by gender and across the three age groups.

2.2.4 Apparatus

Because the maximum force an individual can exert is strongly affected by posture and grip, a critical aspect of the experimental design was to duplicate as much as possible the exact postures and grips that would be used in applying release and opening forces to motorcoach emergency exits. Therefore, the same mock-up used for the egress trials was also used as a framework for the exit strength-test apparatus.

2.2.4.1 Emergency Exit Windows

Two fundamentally different types of release mechanisms are in widespread use in the current motorcoach fleet. *MCI* and *Prevost* buses use a bar release that extends across the full width of each emergency exit window, shown in Figure 2-13a. Three samples of this type of mechanism tested during the Year 1 field survey required more than 190 N (43 lbf) to release. The side-mounted, pivoting release lever used on *Van Hool* coaches (Figure 2-13b) generally requires much less force. Because of the pivot action, the required force varies inversely with the distance from the pivot at which the force is applied. Samples measured with force applied near the end of the lever required less than 60 N (14 lbf) to release. Forces of such magnitude are within the ability of the majority of adults who may ride motorcoaches. Only the horizontal release-bar configuration was used for the human strength tests.



a. *Prevost* Release Bar



b. *Van Hool* Release handle

Figure 2-13. Emergency Window Exit Releases

The forward door opening of the mock-up, simulating the *Prevost* design for a wheelchair-access door located midway along the side of the bus, was fitted with a top-hinged “exit” window that was swung up and out of the way for the egress trials. Seat pitch in the real *Prevost* at the wheelchair-access door and in the mock-up was 96 cm (38 in). For the human-strength tests, a

sill was installed in this opening to which the sash could be locked as needed (see Figure 2-14). A pair of *Omega Engineering Model LCAE-100KG* load cells were mounted on the bottom rail of the sash. Two load cells were used to prevent the application of off-axis forces, which would not be measured accurately. Each of these load cells can measure forces of up to 980 N (220 lbf) in either direction. Attached to the load cells by four studs was a 43-cm (17-in) length of extruded aluminum angle stock with cross-sectional dimensions similar to the release bars used on most motorcoach emergency window exits. The studs passed through the sash frame and were not visible in the close-up views from inside and outside shown in Figure 2-14.



Figure 2-14. Close-ups of Apparatus for Measuring Forces Applied to the Window Sash

A pair of *Omega Engineering Model DMD-465* signal conditioners were used to excite the load cells and to amplify and low-pass filter their signals. The signal conditioners were mounted to the bottom rail of the sash as shown in Figure 2-14. The amplified signals were digitized by a 16-bit *Dataq DI-720* data acquisition system mounted under the floor of the mock-up and recorded on a notebook computer using *WinDaq®* software. See Subsection 2.2.6 for further description of this data file.

The window sash was locked to the sill with a pair of 0.5 x 3-in bolts for the closed-window tests. For the open-window tests, the sash was locked open by 51 cm (20 in) with a pair of struts made of 5-cm (2-in) aluminum angle stock.

The tests were designed to measure the release and opening forces used by the subjects to release the simulated horizontal release handle “bar” and push open the top-hinged “exit window.”

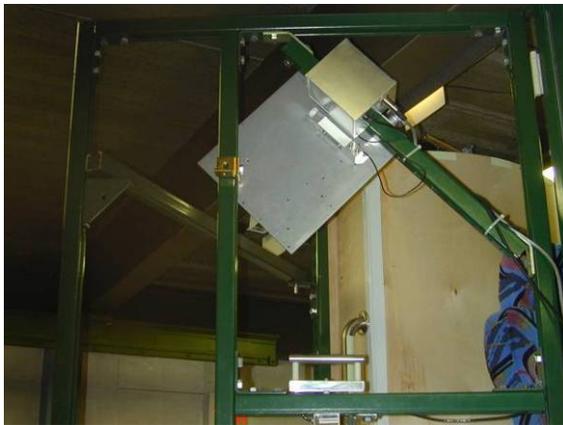
2.2.4.2 Wheelchair-Access-Door Exits

The apparatus to measure strength in applying force to a door release consisted of a pull-handle attached to an *Omega Engineering Model LCCA-200* “S”-beam load cell, as shown in Figure 2-15.



Figure 2-15. Close-up View of Apparatus for Measuring Door-Release Forces

The diameter of the rod to which the subject applies force was 1.9 cm (0.75 in). Measurements of forces applied to push the door outward had to be made at two different locations. When the door was closed, the most effective place to apply opening force was near the rear edge of the door. However, when the door was open by a sufficient amount to provide a 61-cm (24in) clearance in the center of the exit path, it was impossible to reach the edge of the door since it was 107 cm (42 in) wide. Thus, the opening force measurement had to be made at a point that could be reached by an individual standing inside the mock-up and holding onto a seat for leverage. This point was roughly at the center of the door. Accordingly, the force measurement apparatus for these tests was constructed from a sheet of 0.32-cm (1/8-in) aluminum, fitted with a thumbscrew bracket, so that it could be quickly mounted and removed in either the center or the edge of the door, as shown in Figure 2-16.



a. Center placement



b. Edge placement

Figure 2-16. External Views of Apparatus for Measuring Door Pushing Forces

2.2.5 Experimental Protocol

Subjects were scheduled for the strength tests individually at times of mutual convenience for the subject and the Experimenter. They were told that the tests would take about 5 minutes.

The eight force application measurements completed for each subject included:

- Release (pulling) forces
 - o Windows (one-handed and two-handed) and
 - o Doors (one-handed only); and
- Opening (pushing) forces
 - o Windows
 - Closed (one-handed and two-handed)
 - Open by 51 cm (20 in) (two-handed only) and
 - o Doors
 - Closed (one-handed)
 - Open by 61 cm (24 in) (one-handed).

The force applications are illustrated in Figure 2-17 and Figure 2-18.



One-handed window release pull



Two-handed window release pull



Door release pull

Figure 2-17. Applications of Release (Pulling) Forces



One-handed and two-handed pushing on closed window



Pushing window opened by 20 inches



Pushing on door in the closed and open positions

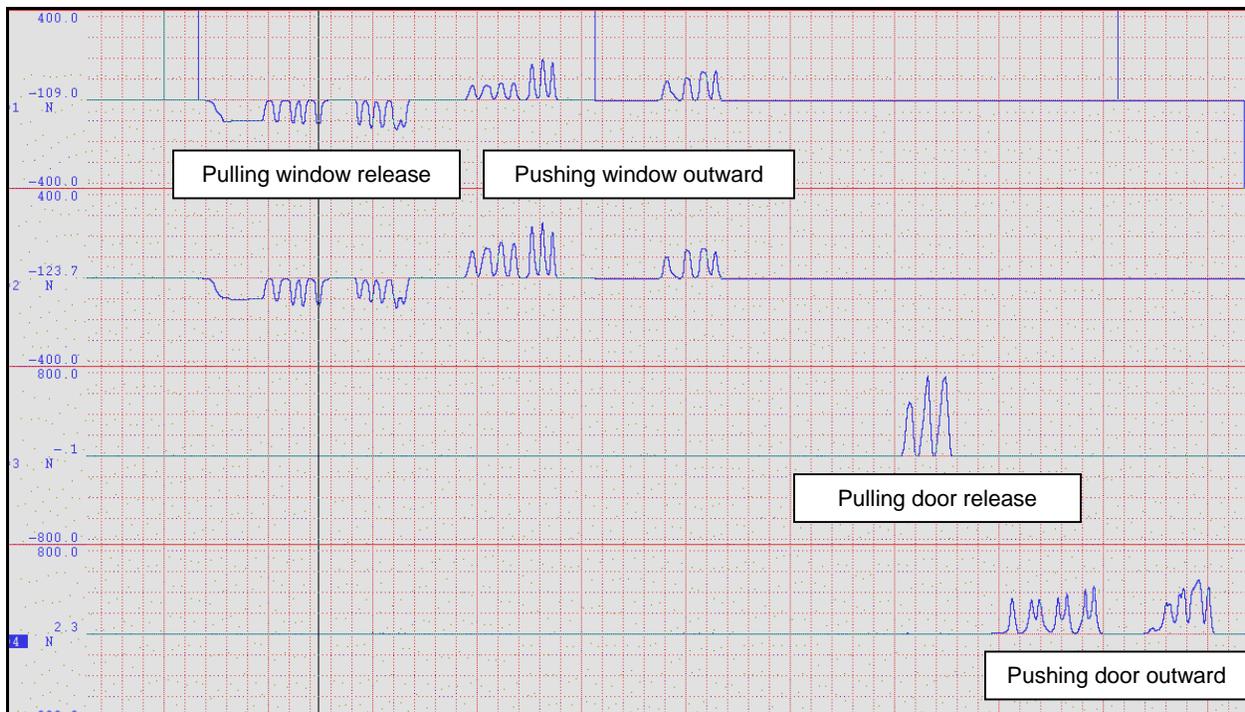
Figure 2-18. Applications of Opening (Pushing) Forces

2.2.6 Data Reduction

For each subject, the *WinDaq*® software generated a graphic record of the forces applied to the sensors like the one shown in Figure 2-19, which is displayed with the time axis compressed so that the entire record fits on one page. For the extraction of data, the time axis was expanded

greatly so that the peak force could be readily discerned. When the *WinDaq* cursor is placed on this peak, the corresponding value is displayed at the left of the trace, as shown in Figure 2-19.

The traces on Channels 1 and 2 (upper two traces in Figure 2-19) represent forces applied to the pair of load cells on the window sash. The negative excursions are pull forces – the first group with one hand, and the second group with two hands. The positive excursions represent pushing forces, the first group being with one hand on a closed window, the second with two hands on the closed window, and the third being a two-handed push with the window open by 51 cm (20 in). The values from Channels 1 and 2 must be summed to determine the total forces applied to the window sash. The trace on Channel 3 (third from top in Figure 2-19) represents pulling forces on the door-release handle. The first group of excursions on Channel 4 (bottom trace in Figure 2-19) represents pushing on the closed door with the sensor near its edge, and the second group represents forces applied to the sensor mounted near the lateral center of the door with the door open by 61 cm (24 in), as measured at the center.



Notes: Vertical axis represents applied force in Newtons (N).

Horizontal axis represents time (1.5 seconds per division).

Vertical spikes on Channel 1 are artifacts marking resumption after a pause in data recording, and not spikes resulting from participant actions.

Figure 2-19. Graphic Display of Strength Forces Exerted by One Subject

The highest values extracted from each group of exertions were entered into an Excel® spreadsheet. Summary statistics – including mean, median, standard deviation, minimum, and maximum values – were calculated for each of the eight types of force applications, and are reported in Chapter 4.

3. SIDE STAIRWAY AND WHEELCHAIR-ACCESS DOOR EGRESS

FMVSS 217 states that the door area equipped with a wheelchair-access lift on school buses may be counted toward the additional required emergency door exits, if the lift folds or stows in such a manner that the area is available for persons not needing the lift. In addition, FMVSS 217 includes requirements to prevent blockage of school bus emergency exit doors by wheelchairs.

As currently designed, wheelchair-access doors are intended solely for loading and unloading wheelchairs, and cannot be opened from the inside of the motorcoach, school bus, or transit bus. The door release mechanism is located in the compartment below the door where the lift is stowed. This compartment is locked and is normally opened only by the bus driver. This arrangement prevents accidental opening by passengers inside the bus.

Previous research conducted by the University of Oklahoma Research Institute (OKRI) in 1972⁷ demonstrated that adults could egress from a motorcoach at the rate of 22 persons per minute (ppm) through a rear side emergency door of an upright bus in a lighted condition, by means of a standing jump from a height of 91 cm (36 in).

A similar flow rate of 25 ppm for a sitting jump from an unobstructed motorcoach wheelchair-access door with a sill height of 1.33 m (53 in) was found in the 2008 Volpe Center-conducted pilot experiments to measure egress rates. Those experiments demonstrated that high egress rates could be achieved by individuals through a floor-level door, even at the much higher floor heights of current motorcoaches.

The egress rates observed in both the OKRI and Volpe Center experiments are higher than those typical of non-emergency front-door deboarding. (See Chapter 4 of the Year 1 interim report.)

Accordingly, egress rates for a second side door, either with or without steps, became a focus of the second year of this study. However, neither the OKRI experiments nor the Volpe Center pilot experiment reflected conditions for typical current motorcoach operations, in which the wheelchair-access doors are normally partially obstructed by adjacent seats.

Before determining that motorcoach wheelchair-access doors could be reconfigured by manufacturers for able-bodied-passenger emergency egress, the following questions must be answered:

- How rapidly can non-injured adult passengers egress from a wheelchair-access door?
- How does the door placement (between seats or between the last row of seats and lavatory) affect passenger egress rates?

- How does the egress rate through a wheelchair-access door compare with a true emergency door with a stairway, such as those found on school buses or motorcoaches operated in other countries?
- Are handholds and/or footholds needed?
- What existing FMVSS 217 school bus requirements for wheelchair access doors could be applied to motorcoaches?

Previous pedestrian behavior has demonstrated that walking speeds decline in low-light conditions, as well as with increasing stair pitch.¹⁰ Because that prior research has been conducted in relation to the establishment of building regulations, the use of stairways as steeply pitched as those required to fit in the space available for a second door on a motorcoach has not been evaluated. The steepest stairs studied in previous known research were pitched at 39°.¹¹ The pitch of straight stairs fitted between the aisle of a motorcoach and a second side door is calculated by the following formula:

$$\text{Stair Pitch} = \text{Arctangent} ((\text{Floor height} - \text{Bottom step height}) / \text{Distance from aisle to side of bus}) \quad (2)$$

Floor heights on single-level motorcoaches range from about 127 to 157 cm (50 to 62 in) (as reported in the manufacturers' specification sheets), while the bottom step at the front door is typically about 30.5 cm (12 in) above the ground when the bus is kneeling. The distance from the aisle to the bus side is about 96 to 101 cm (38 to 40 in). Thus, if a second stair were installed in a typical single-level U.S. motorcoach, it would have a pitch of 44 to 53°. The stairs in the mock-up are pitched at 50°. The combined effects of steep stair pitch, very low illumination, and bright PL material path marking on egress rates were not found in the known literature.

The following sections describes the results of 24 subjects to: 1) use the wheel chair-access door and stairway egress trials in terms of group egress rates and individual egress rates, and 2) release and open simulated emergency exits. (See Chapter 2 for specific subject demographics.)

It is also noted that no wheelchairs that could block the egress of the 24 subjects were included in the aisle. In addition, the egress rate trials did not take into account how much time it would take to evacuate a person who uses a wheelchair. It should be recognized that a more representative sample of the general population, containing frail, mobility-impaired, and/or very heavy or large individuals, could take more time to open and release an emergency exit or egress from a motorcoach during an emergency.

3.1 SIDE STAIRWAY AND WHEELCHAIR ACCESS DOOR EGRESS RATES – GROUP

Table 3-1 shows the results of all 12 group egress trials in the order in which they were conducted. Elapsed time was measured from the time that the first subject began moving from the mock-up aisle towards the specified exit path until both feet of the last of the 24 subjects were on the floor or landing mat.

Table 3-1. Subject Egress Rates for 12 Trials

TRIAL NO.	EGRESS PATH	METHOD	ILLUMINANCE		ELAPSED TIME (h:mm:ss)	FLOW RATE (ppm)
			Lux (fc) [#]	Condition		
1	Stair	Walk	~0.001 (.0001)	Pitch dark*	0:01:05	22
2	Mid-Door	Free Choice	105 (10)	Normal	0:01:46	14
3	Lavatory-Door	Free Choice	227 (21)	Normal	0:02:31	10
4	Stair	Walk	217 (20)	Normal	0:00:48	30
5	Lavatory-Door	Controlled Drop	8.5 (.8)	Reduced	0:02:44	9
6	Mid-Door	Controlled Drop	8.2 (.8)	Reduced	0:01:59	12
7	Stair	Walk	0.25 (.02)	Dim	0:00:55	26
8	Mid-Door	Sitting Jump	8.2 (.8)	Reduced	0:01:48	13
9	Lavatory-Door	Sitting Jump	8.5 (.8)	Reduced	0:02:19	10
10	Stair	Walk	4 (.4)	Reduced	0:00:50	29
11	Lavatory-Door	Free Choice	0.6 (.06)	Dim	0:02:21	10
12	Mid-Door	Free Choice	0.66 (.06)	Dim	0:01:54	13

As measured at the brightest point directly below the luminaire.

* Except for HPPL markings

The egress rate data from the four trials involving use of the stairway show a trend toward more rapid egress with higher illuminance (see Table 3-1 and Figure 3-1). The egress rate as a function of the illuminance for able-bodied adults using a stairway and wheelchair-access door with the same geometry as the mock-up can be estimated from the following equation:

$$y = 0.6621 \ln(x) + 27.037 \quad (3)$$

where y = egress rate in ppm

x = illuminance in lux

Note: $\ln(x)$ is the natural logarithm of x , which is a computationally efficient function for fitting regression curves

This equation was fitted to the data points in the top line in Figure 3-1, which range from 22 ppm under HPPL marking only to 30 ppm in the normal light condition. Review of the video recording showed the difficulties that many subjects had in fitting through the narrow space of the simulated wheelchair-access doors, creating between 2 to 4 sec per person delay, depending on the path. Subjects in the Volpe Center 2008 pilot motorcoach egress experiment were able to egress through an unobstructed wheelchair-access door at the rate of 25 ppm, or one every 2.4 sec. Interpersonal intervals through the partially obstructed doorways of this 2009 egress experiment increased to almost 5 sec for the wider “Mid-Door” path and 6 sec for the narrower “Lavatory-Door” exit path. These results should be interpreted with caution, owing to the small sample size and the fact that the experiment subjects were self-selected to be confident of their abilities to drop down from the wheelchair-access doors, which requires greater physical fitness than descending the stairway. As noted previously, the egress of the 24 subjects was not blocked by a wheelchair and the egress trials did not consider how much time it would take to evacuate a person who uses a wheelchair.

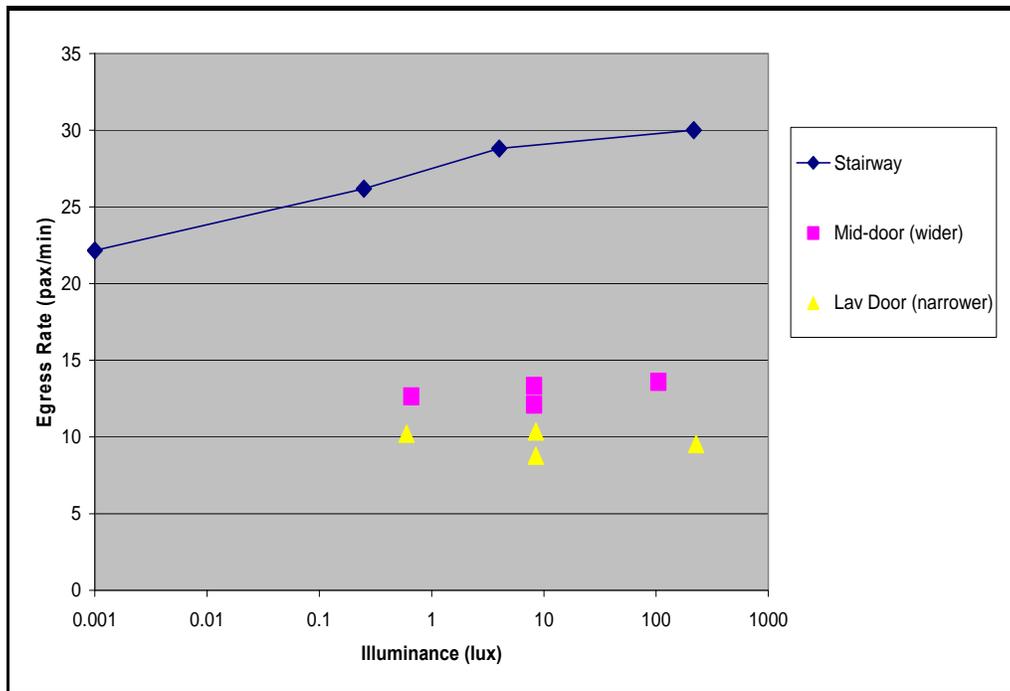


Figure 3-1. Comparison of Egress Rates across All Trials by Egress Path and Lighting Level

There was no apparent effect from changing illuminance levels for egress from the two wheelchair-access doors by the subjects, although the absolute “pitch dark” condition (using only HPPL path marking) was not tested due to concern for risk of injury.

3.2 SIDE STAIRWAY AND WHEELCHAIR ACCESS DOOR EGRESS RATES – INDIVIDUAL DIFFERENCES

The individual egress time data (i.e., interpersonal interval, defined as the time difference between one subject's landing on the floor or mat and that of the previous subject) were extracted from the video imagery and compiled in a spreadsheet containing 276 cells. (The first subject's impact with the mat or floor provided the reference point for timing the second, so each trial generated 23 individual egress times, rather than 24; $23 \times 12 = 276$.) These data were then disaggregated by gender, as shown in Table 3-2, Table 3-3, and Table 3-4.

Table 3-2. Interpersonal Intervals during Side Stairway Egress Trials

TRIAL NO.	LIGHTING	INTERPERSONAL INTERVAL (Sec)	
		Female	Male
1	Photoluminescent only	3.0	2.3
4	Normal room light	2.0	1.8
7	Dim (~ 0.5 lux)	2.0	2.5
10	Good emergency (~5 lux)	1.9	2.0
AVERAGE		2.2	2.2

Table 3-3. Interpersonal Intervals during Side "Mid-Door" Egress Trials

TRIAL NO.	LIGHTING	INTERPERSONAL INTERVAL (Sec)	
		Female	Male
2	Normal room light	5.0	3.9
6	Good emergency (~5 lux)	5.4	4.7
8	Good emergency (~5 lux)	5.2	4.1
12	Dim (~ 0.5 lux)	5.0	4.2
AVERAGE		5.2	4.2

Table 3-4. Interpersonal Intervals during Side “Lavatory-Door” Egress Trials

TRIAL NO.	LIGHTING	INTERPERSONAL INTERVAL (Sec)	
		Female	Male
3	Normal room light	6.4	6.0
5	Good emergency (~5 lux)	6.8	6.0
9	Good emergency (~5 lux)	5.7	5.8
11	Dim (~ 0.5 lux)	5.6	6.1
AVERAGE		6.1	6.0

Observation of subject behavior during the egress trials and in the video recordings suggested that the differences in interpersonal intervals did not have much to do with age or gender. Statistical tests were conducted on the data from Trial 2 (“Mid-Door,” “Normal Light”); Trial 2 values had the largest difference between mean interpersonal intervals – 5 sec for females versus 4 sec for males. A ‘t-test’ of the data from this trial, which had 15 degrees of freedom, returned a value of 1.31, which is not significant at the 0.05 confidence level.

Given the lack of statistical significance of gender in the egress trial with the largest difference in group means, no further such tests were conducted. Observation of the video recordings showed that the slightly longer average egress times associated with the females resulted primarily from the behavior of two “outliers.”

3.3 DEBRIEFING QUESTIONNAIRE ANALYSIS

Tabulation of subject responses to the debriefing questionnaire (described in Section 2.1.4) showed the following results:

- Twenty-one of the 24 subjects stated that they preferred the stairs to the wheelchair-access door openings because they found the stairs faster, safer, and easier to use.
- Two subjects chose the “Mid-Door,” one had no preference, and no one preferred the “Lavatory-Door.”
- Despite their preference for the stairs, all subjects indicated that in a real emergency they would exit by whatever means was nearest and/or fastest, rather than wait to use the preferred means.
- Sixteen of the 24 subjects preferred the sitting jump to the controlled drop. However, four subjects qualified this by stating that had the landing area contained hazards, such as rocks or crash debris, they would have preferred the controlled drop.

- In the four trials in which subjects were given a free choice as to which method to use, they chose to use the sitting jump 57% of the time and the controlled drop 43% of the time.
- One subject, who was also the shortest person in the group, used the controlled drop, even during the trials in which she was directed to do the sitting jump.
- Eighteen of the 24 subjects stated that they noticed no significant change in their behaviors across the varying levels of illumination. The others noted that they were slower and more cautious under dimmer light conditions.
- Several of those who said they did not change their behavior during the various trials also said they would have been more cautious and slower in a real emergency, because they would have no foreknowledge that the egress landing area was soft and free of hazards.

When asked to imagine a real emergency and a landing area littered with crash debris, 20 of the 24 subjects stated they would be willing to jump onto the debris, while the others indicated they would seek some form of assistance to avoid impact with the hazards.

3.4 DISCUSSION

3.4.1 Egress Paths

The results of the Year 1 motorcoach pilot egress rate experiments, indicated that egress rates for the front stairway averaged about 36 ppm for able-bodied adults in normal lighting. The egress trials conducted in the bus mock-up measure egress rates for stairs with 30 cm (12 in) risers, representing the steepest stair pitch that might be used. The four trials were carried out under illumination levels ranging from immeasurable (pitch dark except for HPPL signs and path markings) to normal room lighting. Egress rates ranged from 22 to 30 ppm. As would be expected, subjects preferred using the side stairway to jumping from the wheelchair-access doors.

The results of the Year 1 motorcoach pilot egress rate experiments indicated that passenger flow through the wheelchair-access door (or another side door), if used as a motorcoach emergency exit, could be as high as 25 passengers per minute (ppm).

The average egress rate for the four trials involving egress through the wider exit path of the “Mid-Door” configuration was 13 ppm, as compared to 10 ppm for the narrower path adjacent to the “Lavatory-Door.” The implication is that in a time-critical evacuation scenario, 30% more passengers could exit before conditions became untenable due to smoke, fire, submersion, etc. Had the seat bottom adjacent to the “Mid-Door” been placed in the raised position, it is likely that the egress rates by this path would have been higher than those observed.

Below a height of 70 cm (28 in) above the floor, the “Mid-Door” configuration allowed a clearance of 46 cm (18 in) with the rear seat bottom down and 66 cm (26 in) with the seat bottom up. Above 70 cm (28 in), the clearance was 54 cm (21 in) with the forward seat back upright and 37 cm (15 in) with the forward seat back at maximum recline. In the experimental egress trials reported herein, the forward seat back was upright, and the rear seat bottom was down.

The “Lavatory-Door” configuration has its narrowest clearance at about 110-115 cm (43-45 in) above the floor, i.e., at the height of the headrest. This clearance was only 30 cm (12 in) with the adjacent seat back upright (the position tested in these experiments). If the seat back had been fully reclined, the clearance would have decreased to 16 cm (6 in). Below a height of 70 cm (28 in) from the floor, this design has a minimum clearance of 40 cm (16 in) set by the seat frame and not affected by the degree of recline. To provide the same clearance as the “Mid-Door” configuration, the seat adjacent to the “Lavatory-Door” would need to be moved forward by 23 cm (9 in).

Individuals with waist sizes up to approximately 102 cm (40 in) can “slip” through a 30 cm (12 in) opening without noticeable delay. About 75% of the U.S. adult population, excluding pregnant women, has waist sizes of less than 102 cm (40 in).¹² To accommodate the remaining quarter of the population, a wider exit-row aisle way (as required by the ECE) could increase the egress rate for motorcoach passengers using the emergency door exit: 1) 30 cm (12 in) up to a height of 70 cm (28 in) above the floor and 2) 55 cm (22 in) above that height.^{13 14}

In the two egress trials in which all subjects were directed to perform the sitting jump, the average egress rate was 12 ppm, as compared to 10 ppm in the two controlled-drop trials – a difference of 13.5%, as shown in Table 3-1 and Figure 3-1. The controlled drop takes longer than the sitting jump because it involves the extra step of the subject finding and securing a firm grip on the handhold. However, if the landing area outside of a bus during an emergency is hazardous, it is likely that passengers exiting from a motorcoach in an emergency would show greater hesitation in jumping than they did under the benign conditions of this egress experiment.

During the egress trials, the aisle ways to the wheelchair-access door exit paths were not blocked by a wheelchair and how much time it would take to evacuate a person who uses a wheelchair was not considered.

3.4.2 Lighting Conditions

Comparison of egress rates under the benign laboratory bus mock-up conditions, as shown in Figure 3-2, indicates that increasing illuminance on the stairway increases the egress rate, but the effect is modest. The change from the normal light condition to 8 lux (0.8 fc) for the reduced

(emergency) lighting reduced the egress rate only slightly (from 30 ppm to 29 ppm). For the dim lighting condition (0.3 lux or 0.033), the egress rate decreased to 26 ppm. Under conditions of darkness with only HPPL path markings for guidance, an occupant egress rate of 22 ppm can be achieved, which is slightly faster than the normal deboarding rate of 16 to 20 ppm via the front service door with normal lighting (as described in Chapter 4 of the Year 1 interim report). This implies that 55 persons can exit from a motorcoach using a side stairway in 2.5 minutes.

The egress trial results showed that under emergency lighting conditions, able-bodied adult subjects jumped from wheelchair-access doors at a rate ranging from 9 to 14 ppm, despite a 1.5 m (5 ft) drop to the floor, similar to their egress rates under normal lighting. Although no egress trials were conducted in total darkness (with the exception of HPPL signs and markings) due to potential injury to subjects, it is reasonable to expect egress rates would greatly reduced in total darkness.

Varying the levels of illumination from about 0.6 lux (.06 fc) to 100 lux (9 fc) had no effect on wheelchair access door egress rates. However, it is recognized that 49% of motorcoach fatalities are associated with trauma occurring during a rollover event.³ In that situation, the exit path typically becomes more complex and may contain more hazardous obstacles than that of a normal upright bus, necessitating more illumination for occupants to see them.

3.5 SUMMARY

The Year 1 motorcoach pilot egress rate experiments results indicated that passenger flow through the wheelchair-access door (or another side door), if used as a motorcoach emergency exit could be as high as 25 passengers per minute (ppm). However, neither the OKRI experiments nor the Volpe Center Year 1 pilot experiment reflected conditions for typical current motorcoach operations, in which the wheelchair-access doors are normally partially obstructed by adjacent seats.

Accordingly, egress rates for a second side door, either with or without a stairway, was the focus of the second year of this study. The results of the Volpe Center mock-up egress rate experiments with a group of 24 able-bodied federal employees, evenly balanced across age groups and roughly balanced by gender, indicated the following:

- A second door opening with a stairway provided a much faster egress path for subjects than either of the wheelchair-access door opening configuration options:
 - o Under benign conditions and with normal lighting, the egress rate was about 30 ppm for the steps with 30 cm (12 in) risers, almost as high as the corresponding front-door egress rate of 36 ppm observed in the Year 1 pilot experiment of this study.

- o Egress rates declined very slightly under emergency-lighting conditions to about 29 ppm. Even with no lighting at all and only HPPL signs and markings to guide subject egress, flow rates of 22 ppm were observed.
- Egress from the wheelchair-access door openings, even when partly obstructed by seats, was achieved by the subjects faster than through the emergency window exits observed in the Year 1 pilot experiment:
 - o Egress rates of 12 to 14 ppm were achieved for the wheelchair-access-door configuration located between two rows of seats with a 97 cm (38 in) pitch and a clearance at waist height of 54 cm (21 in).
 - o The wheelchair-access door configuration adjacent to a simulated lavatory wall with only a 30 cm (12 in) clearance at waist height between the lavatory and the adjacent seat, reduced egress rates to 9 to 10 ppm.
- Egress rates declined in low-light conditions, but the effect was not very large in the experiment, where the exit paths were free of hazards:
 - o Subjects exited via the side stairway at the rate of 22 ppm (slightly higher than normal front door deboarding rates of 16 to 20 ppm in revenue service) with only HPPL markings, in an otherwise pitch-dark environment.
 - o Subjects were able to perform sitting jumps or controlled drops from the wheelchair-access-door openings on the 1.5 m (5 ft) high platform of the mock-up at rates of 9 or 10 ppm in very dim lighting (~ 0.6lux).
 - o Although subjects were not tested in complete darkness, the majority said that they would have been reluctant to jump from the wheelchair-access door openings under such conditions.

It should be recognized that a more representative sample of the general population, containing frail, mobility-impaired, and/or very heavy or large individuals, could take more time to open and release an emergency exit or egress from a motorcoach during an emergency.

In a complex emergency, such as a rollover crash, the exit path typically becomes more complex and may contain more hazardous obstacles than that of a normal upright bus, necessitating more illumination for occupants to see them, than provided during the egress trials.

4. HUMAN STRENGTH TO OPERATE EMERGENCY EXITS

FMVSS 217 requires that bus emergency exit operating force limits (release and opening) be no higher than the following:

- Motorcoaches
 - o 268 N (60 lbf) in high-force regions
 - o 89 N (20 lbf) in low-force regions; and
- School buses
 - o 178 N (40 lbf) in high-force regions
 - o 89 N (20 lbf) in low-force regions.

The maximum force that a person can exert varies greatly depending on the specific posture, orientation of hands, grip, etc., in which it is applied. The existing research literature is inconclusive with regard to the force levels that can be applied to the emergency exit window-opening tasks by the general public. Because no published data were found regarding the human strength needed for the specific force applications to release and open motorcoach emergency exits, Volpe Center staff conducted original research on this topic. The experiment design is described in Chapter 2; the results are reported in the remainder of this chapter.

4.1 RELEASING AND OPENING EMERGENCY EXIT WINDOWS AND DOORS

Table 4-1 summarizes the results of the eight different tests of human strength for 24 study subjects to release and open emergency exits. To provide demographic balance, volunteer subjects were selected so as to have equal numbers of males and females, and equal numbers in three age-groups (under-35, 35 to 55 and over 55-65). For each test, data are presented describing the mean peak force developed in Newtons (N), its standard deviation, the maximum and minimum values measured, and the limits of the 95% confidence interval.

For a motorcoach emergency exit, all of these force applications occur in the FMVSS 217-defined “high force” areas, which means that the releasing and opening mechanisms may require forces of as much as 268 N (60 lbf) to operate. Table 4-1 shows that the maximum voluntary muscle contractions of a majority of subjects were less than 268 N in three of the tests. Some subjects failed to reach 268 N on several tests and there was at least one subject who failed on every test. Figure 4-1 shows the percentages of the subjects who were able to apply a force of at least 268 N in each of the tests.

Table 4-1. Summary Descriptive Statistics of Subject Strength Measurements in Newtons (N) for Releasing and Opening Simulated Emergency Exits[#]

STATISTIC	PULL WINDOW RELEASE		PUSH CLOSED WINDOW		PUSH WINDOW OPEN BY 51 cm (20 in)	PULL DOOR RELEASE	PUSH CLOSED DOOR	PUSH DOOR OPEN BY 61 cm (24 in)
	One hand	Two hands	One hand	Two hands	Two hands	One hand		
Mean	263	339	242	376	208	514	325	327
Median	266	336	233	370	212	523	360	335
Standard Deviation	70	90	118	149	79	170	103	115
Minimum	126	190	68	186	83	249	124	150
Maximum	401	495	550	637	352	840	505	529
95% Confidence Interval (+/-)	28	36	47	60	32	68	41	46

[#] Defined as maximum voluntary contraction

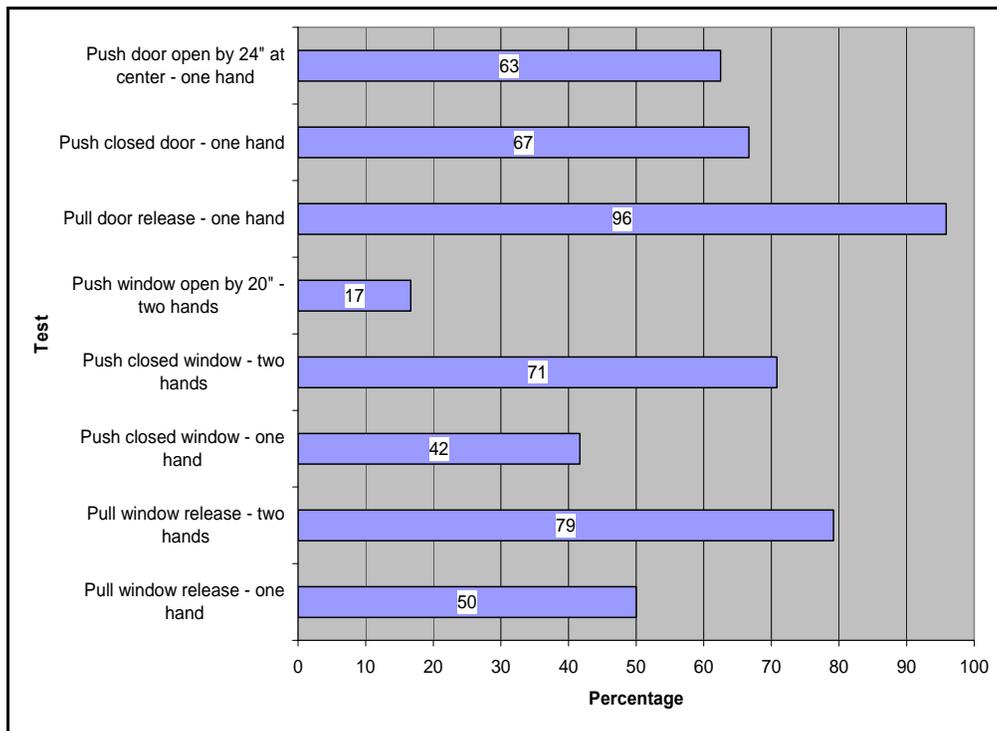


Figure 4-1. Percentages of 24 Subjects Able to Apply a Force of 268 N (60 lbf) or More

4.2 DISCUSSION

The human strength test results indicate that in all but two of the conditions, less than 75% of the subjects were able to exert forces that exceed the maximum allowable operating forces for certain aspects of operating motorcoach emergency exits. This was most pronounced when pushing the exit window outward, as only 4 of the subjects (17%) were able to produce the necessary force. For buildings, the NFPA 101 *Life Safety Code* limits for opening forces on emergency doors are 222 N (50 lbf) for existing buildings, and 133 N (30 lbf) for new construction.¹⁵ The NFPA 101 door-exit-latch-release forces are limited to 67 N (15 lbf).

However, for passenger trains and planes, the need for ease of emergency egress from vehicles must be balanced against the need for structural integrity and the need to protect passengers from unintended openings caused by operating and crash forces.

To comply with structural strength requirements, aircraft over-wing emergency exits can weigh as much as 29 kg (65 lbs). The NTSB documented cases where use of those heavy over-wing exits caused difficulties in emergency evacuations, such as passenger delay in opening those exits and stowing the hatch.¹⁶ The NTSB also noted that Boeing has a new over-wing exit for its 737 series airplanes based on human factors principles. The exit is hinged and opens outward as passengers would intuitively expect (shown below in Figure 4-2). It is spring loaded so that passengers are not required to exert any force to lift it. This design also eliminates the problem of where to stow the exit hatch because it moves up and out of the egress route. In short, the design eliminates any guesswork about how the exit operates or what to do with the exit hatch once it is opened.



Figure 4-2. New Design Type III Exit for Boeing 737-600, 700, 800, and 900 Aircraft

Egress through emergency exit windows on motorcoaches could be facilitated through the use of hold-open mechanisms to help lift and support the window.

FRA regulations require that each emergency window exit be designed to permit “rapid and easy” removal from the inside of the passenger rail car during an emergency, without requiring the need to use a tool or other implement. However, no definition is provided for “rapid and easy.”¹⁷ In addition, passenger railroads do not screen passengers, or restrict their seating location, with respect to their abilities to open emergency window exits.

If the maximum forces needed to operate motorcoach emergency exits were 222 N (50 lbf), the proportions of subject individuals who could apply such forces would be increased to the values shown in Figure 4-3.

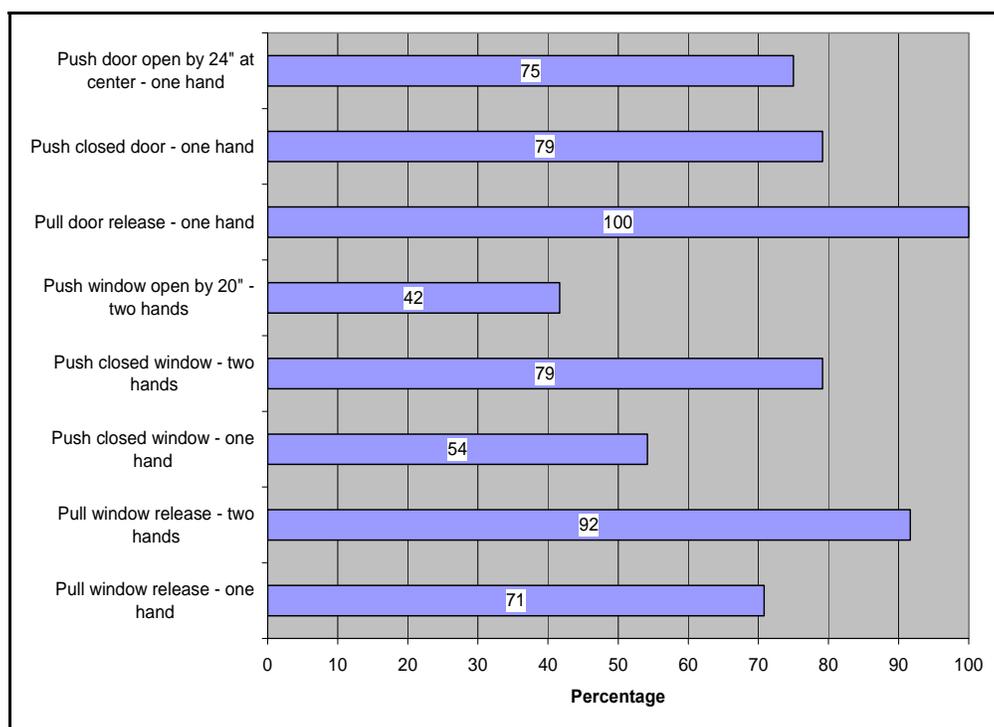


Figure 4-3. Percentages of 24 Subjects Able to Apply a Force of 222 N (50 lbf) or More

For school buses, FMVSS 217 limits the maximum forces in the high force areas for releasing and opening emergency exits to 178 N (40 lbf). If these limits were applied to motorcoaches, the percentages of the experimental subjects who would be able to meet or exceed those limits would increase further to the values shown in Figure 4-4.

A comparison of Figure 4-1, Figure 4-3, and Figure 4-4 shows how reducing the maximum allowable opening force limits from 268 N to 222 N or 178 N would have increased the proportions of the subject population able to operate the exits.

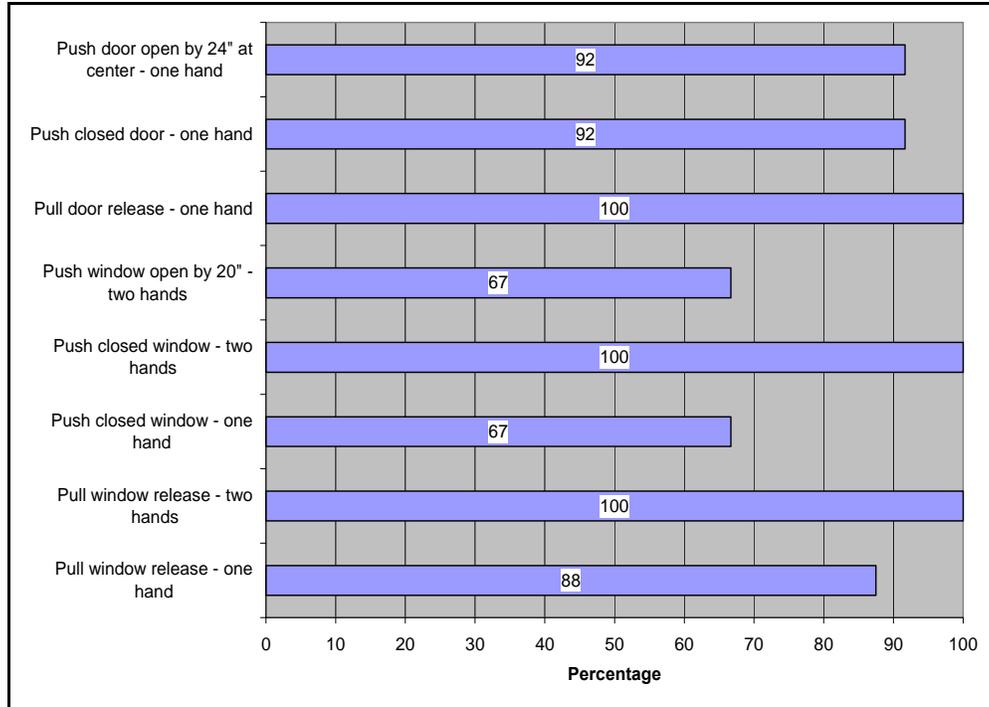


Figure 4-4. Percentages of 24 Subjects Able to Apply a Force of 178 N (40 lbf) or More

4.3 SUMMARY

The results of the simulated exit strength tests showed that for the 24 able-bodied subjects:

- Significant fractions of the subjects were not able to apply forces of 268 N (60 lbf) in the majority of the postures and grips used to release and open motorcoach emergency exits.
- Pushing emergency exit windows open by the required minimum distance – 51 cm (20 in) – barely sufficient to allow for a controlled drop to the ground, was the most challenging test. Only four of the subjects (17%) were able to apply 268 N in this test without risking injury to themselves.
- Reducing maximum allowable forces for the high region to the same limit as for school buses – 178 N (40 lbf) – could have allowed 16 of the subjects (66 %) to operate all exits without risk of muscular strain.

There is a trend toward designing emergency exits for lower opening forces in both buildings and aircraft. That trend stems in part from recognition that most humans cannot exert large pushing forces when their arms are fully extended laterally.

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5. EMERGENCY EXIT IDENTIFICATION

While FMVSS 217 requires a minimum letter height for of 5 cm (2 in), and high color contrast with the background emergency exit signs, requirements for motorcoach emergency exit sign letter size and color contrast are not specified. FMVSS 217 requires that motorcoach emergency exit signs and instructions for the exit release be legible to occupants having corrected visual acuity of 20/40 (Snellen ratio) under normal nighttime illumination in the seat next to the exit, adjacent seating location, and other adjacent locations when standing in the aisle.

As noted in the Year 1 interim report for this study, there is no known research that specifically addresses emergency exit identification for motorcoaches or other buses, but numerous studies and analyses have been conducted in other contexts. The following factors have been identified that affect sign legibility:

- Visual acuity of the observer (20/20, 20/40, etc., on the Snellen scale);
- Letter height and stroke width;
- Luminance of letters or symbols and their backgrounds (contrast);
- Distance from observer to sign;
- Angle between the observer's line-of-sight (LOS) and the plane of the sign;
- Obscuration by smoke or dust; and
- Dark adaptation.

Once these variables are specified quantitatively, there are established formulas to calculate required letter sizes. Extensive research has established the levels of illumination required to perform various tasks, such as reading characters of a specified size from a specified distance.¹⁸ A 1983 National Institute of Standards and Technology (formerly National Bureau of Standards) technical report¹⁹ contains formulas for calculating the requirements for legibility in terms of the visual acuity of the observer, letter height, stroke width, contrast, luminance, and viewing angle (see also Section 8.5 of the Year 1 interim report). Color may also influence sign readability.

This chapter addresses performance requirements for emergency exit signage and instructions.

5.1 OVERVIEW

The field survey of motorcoach emergency signage conducted in the first year of this study and described in Chapter 8 of the Year 1 interim report showed substantial variation in readability depending on such factors as letter size, color, and contrast. The right emergency exit window in

Figure 5-1 and both emergency exit windows in Figure 5-2 show motorcoach emergency exit signs and instructions with larger letter size and bright color with high contrast background compared to the left photo in Figure 5-1.



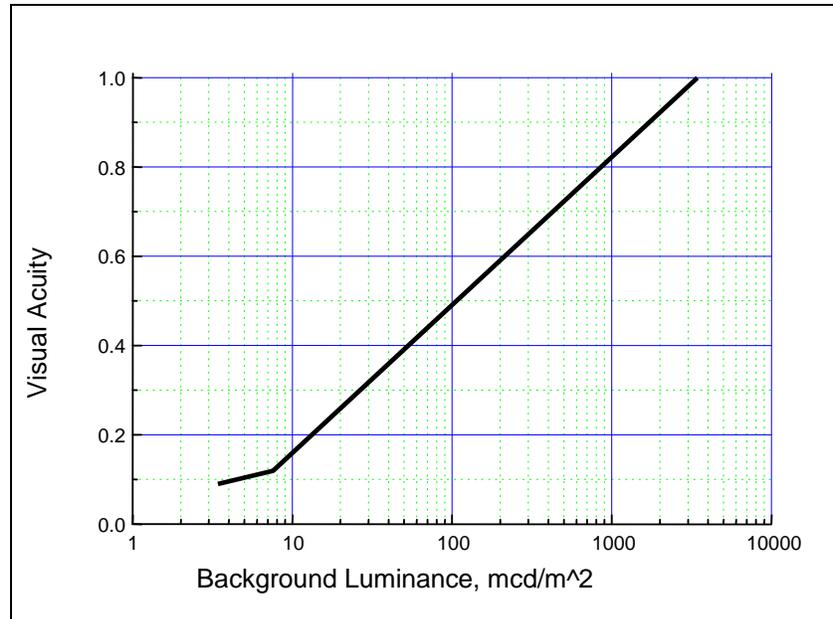
Figure 5-1. Motorcoach Emergency Exit Window Marking and Instructions (1)



Figure 5-2. Motorcoach Emergency Exit Window Marking and Instructions (2)

The same field survey indicated that those signs and instructions in current use are readable whenever there is at least a low level of illumination present (i.e., in daylight or when the fluorescent boarding lights or adjacent reading lights are in use). The reading lights provide illumination of about 5 lux (0.5 fc) for emergency exit signage mounted adjacent to the window sill, while the overhead fluorescent lights provide much higher levels of illumination.

Visual acuity degrades with the luminance of the object being observed, but the human eye adapts so well that even a 10,000-fold reduction in available light causes only a 90% reduction in acuity (see Figure 5-3). This means that there is no sharp demarcation between conditions in which there is sufficient light for emergency exit sign legibility and those in which there is not.



Note: Visual acuity of 1 = 20/20 on Snellen scale; 0.1 = 20/200 Snellen.

Figure 5-3. Human Visual Acuity as a Function of the Luminance of the Observed Object

However, when the bus is operating at night, and “running” lights are the only source of illumination, as is typical when passengers are sleeping, non-illuminated emergency exit signage is barely visible and is not conspicuous or readable, even at very short viewing distances. Conspicuity and readability of motorcoach emergency exit signs cannot be easily achieved simply through increases in letter size. For example, letter size would need to be increased by a factor of 10 for night light conditions (i.e., 10-cm (4-in) letter heights) to provide legibility at the same distance that 1-cm (3/8-in) letters (commonly used for motorcoach emergency exit signs including instructions) do under daylight conditions (see Figure 5-1 and Figure 5-2).

Electrical illumination and PL material technology alternatives to improve motorcoach emergency exit signs and their advantages and disadvantages are described and discussed in the remainder of this chapter. In addition, certain emergency-exit-identification requirements of U.S. transportation regulatory agencies and industry-standard organizations, extensively described in the Year 1 interim report of this study, are noted.

5.2 ALTERNATIVES TO IMPROVE EMERGENCY EXIT IDENTIFICATION

The fundamental ways to increase the conspicuity and legibility of typical motorcoach emergency exit signs and instructions (see Figure 5-4a), as currently required by FMVSS 217 for school buses, are to:

- Install the signs in a location more visible to passengers, i.e., at the top or side of the emergency exit; and
- Increase letter height to 5 cm (2 in) (and increase stroke width), and use bright colors with high contrast (see Figure 5-4b).

There are two currently available, applicable technologies that can be used to make motorcoach emergency exit signs more visible and readable under dim and dark conditions, as well as under normal daylight conditions:

- Electrical illumination (external or internal electric lighting); and
- PL (photoluminescent) materials.

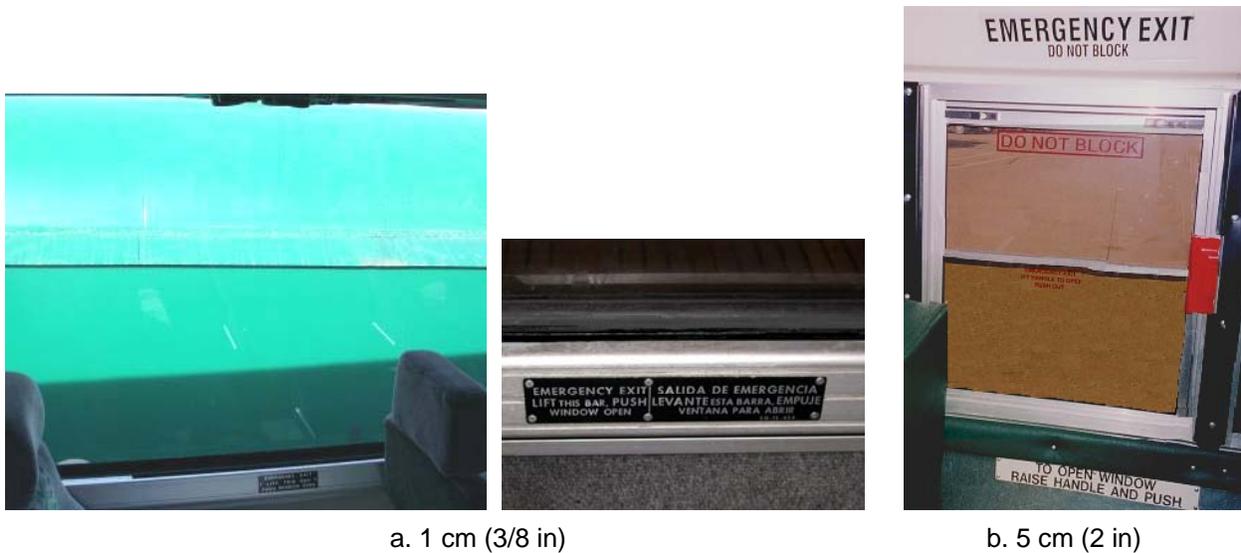


Figure 5-4. Motorcoach and School Bus Emergency Exit Signs – Letter Height

Recently, vendors have begun to supply “dual-mode” emergency exit signage systems that combine electrical illumination using independent power supply with HPPL material backings. This type of sign is not solely dependent on emergency electrical power and thus is more likely to be visible after a motorcoach crash.

Tritium (a radio-isotope of hydrogen) is still used to provide back lighting in some emergency exit signage, but Volpe Center staff does not consider such signage to be a good option for motorcoaches due to high initial costs and high disposal costs. In addition, while such emergency signage was once widely used for commercial aircraft emergency exit signage and is still permitted by the FAA, it is no longer being installed in aircraft because the improved performance and cost characteristics of the competing technologies have rendered it obsolete.

Alternative electrical illumination and HPPL material technologies for potential application to motorcoach emergency exit signs are described below.

5.2.1 Electrically Illuminated Signs

At primary emergency exits (e.g., doors on passenger aircraft and trains, as well as buildings), electrically illuminated signage and markings, using independent energy storage, are required by FAA regulation²⁰ and the NFPA *101 Life Safety Code*,¹⁵ respectively. NFPA 101 and FRA¹⁷ also permit the use of PL signage as an alternative to electrically illuminated emergency exit signs, as discussed in Subsection 5.3.2). Such signs are often designed to provide light for individuals to identify the exit location, to see how to navigate the egress path, and to operate exit release and opening mechanisms.

Duration performance requirements for electrically powered emergency exit signage including a requirement for independent power supply have generally been specified for minimum periods of 60 to 90 minutes for passenger trains and buildings. These values were established by the responsible regulatory organization based on the estimated time to complete egress.

Because FMVSS 217 does not require lighted emergency exit signs on motorcoaches, Volpe Center staff are not aware of any such products currently on the market specifically designed for buses.

FAA, the APTA rail car emergency signage standard,²¹ and NFPA 101 require that electrically illuminated emergency exit signs meet criteria for a minimum letter height and stroke width ratio, as well as background area and color contrast. Emergency exit signs intended for use in buildings must have letter heights of 15 cm (6 in), while those intended for passenger aircraft must have letter heights of 3.8 cm (1½ in). For passenger trains, the APTA emergency sign standard specifies that door exit signs have 3.8 cm (1½ in)-high letters and emergency exit windows have 2.5 cm (1 in)-high letters.²¹ (Both the APTA standard and FAA regulation include specifications for letter stroke width, color contrast, and background area, which are further discussed in Subsection 5.3.2).

The disadvantages of electrically illuminated emergency exit signs, with self-contained energy storage have been:

- Estimated material cost per independent unit (~\$300-400) - could be reduced based on bulk pricing for bus manufacturers;
- Requirement to provide electric power to each unit with unknown cost;
- Fragility of lamps and batteries used in many older devices;

- Battery maintenance cost; and
- Physical volume of batteries and lamps.

Recent advances in energy-storage technology and lighting have greatly reduced the fragility, maintenance cost, and physical volume of these devices. Solid-state lamps (LEDs, organic LED (OLED)s, etc.) are typically rated for 50,000 hours, which is equivalent to the entire service life of a bus at a normal duty cycle.

Supercapacitors for energy storage are rated by their manufacturers as having service lives of 15 or 20 years and millions of charge-discharge cycles. Storage batteries are rated for 200 to 1,000 charge-discharge cycles. Manufacturers' specifications state that service lives are six to six or seven years in "emergency-only" service, (i.e., smart controllers are used that prevent unnecessary discharge when the bus is out of service).

The physical volume of newer technology devices is generally smaller than that of older ones. (See Section 5.3.1 and Chapter 6 for additional discussion relating to emergency exit lighting.)

During the Volpe Center mock-up egress rate experiments, high performance photoluminescent (HPPL) "EXIT" signs (see Figure 5-5) with 5-cm (2-in) high letters and a total area of 310 cm² (48 in²) were mounted on three luminaires that were located above the three respective door openings of the mock-up used for the egress rate experiments designated as "Mid-Door," "Lavatory-Door," and "Side Stairway," according to the interior location of the exit where they were used. (See Subsection 5.3.2 for further specific discussion of HPPL signage performance characteristics and Chapter 6 for additional discussion relating to these specific exit signs.)

Illuminance tests conducted on these "EXIT" signs showed that even the emergency luminaire with the least light output rated at 10 lumens (providing an illuminance of at least 8 lux (.7 foot-candles (fc)) on the floor directly below the exit opening) illuminated the signs at values of 0.5 to 500 lux (0.05 to 50 fc), depending on the specific placement of the sign with respect to the lamp. For some measurements, the sign was attached about 30 cm (1 ft) below the luminaire, as though mounted on the window exit glass. The "EXIT" signs were observed by Volpe Center staff to be readily visible from a distance of 6 m (20 ft), even for the lowest illuminance condition.



Figure 5-5. Illuminated / HPPL Wheelchair-Access Door and Side Stairway “EXIT” Signs

5.2.2 Photoluminescent (PL) Material Signage

Certain types of HPPL material for emergency exit signage have become an acceptable alternative to electrical illumination as the technology has improved to allow for useful luminance and glow times of several hours, as specified in the various previously cited passenger aircraft, passenger rail car, and building requirements. Their unit costs range from \$6 to \$20 for the sizes that would be used on motorcoaches. (Exit sign costs could be reduced based on bulk pricing for bus manufacturers.)

HPPL materials are produced in a wide range of performance ratings. A complete performance specification for such materials includes:

- Required minimum luminance values at various points in time during discharge; and
- Definition of charging conditions (illuminance, spectral characteristics, duration, and ambient temperature).

Duration performance requirements for HPPL signage have generally been specified for periods of 60-90 minutes for passenger trains and buildings. These values were established by the responsible regulatory organization based on the estimated time to complete egress.

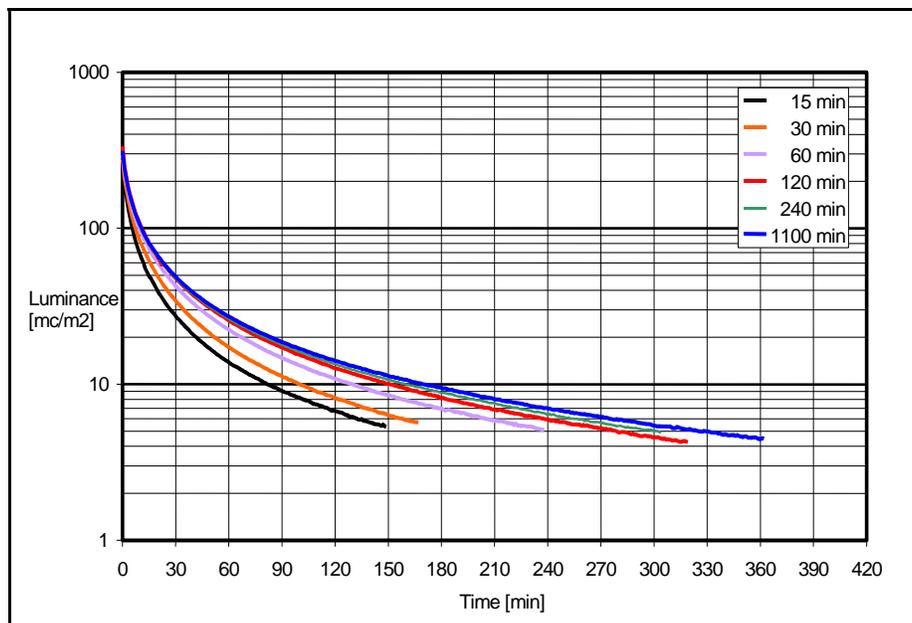
For example, the American Public Transportation Association (APTA) standard for passenger rail car emergency exit signage²¹ requires that HPPL signage produce a luminance of at least 7.5 mcd/m^2 for at least 90 minutes. These criteria must be met for new rail cars after being charged at normal room temperature for 1 hour at an illuminance of 1 (fc) about 11 lux), by a

fluorescent lamp with a color temperature of 4,000 to 4,500 Kelvins (K). The APTA standard designates such signage as “High Performance Photoluminescent-1” (for 1 fc charging), abbreviated as “HPPL-1.” This standard also requires a minimum letter height of 3.8 cm (1.5 in) for doors used as emergency exits and 2.5 cm (1 in) for emergency window exits.

Emergency exit window signage compliant with the above APTA standard criteria is readable at a distance of 3 m (10 ft) for a person with visual acuity of 0.5 (or 20/40 on the Snellen scale), for at least 90 minutes following loss of normal lighting.

Figure 5-6 shows the effect of different charging durations on one sample of “HPPL-1” material under typical charging conditions of 54 lux (about 5 fc).

Volpe Center staff recently conducted long-duration measurements of various samples of emergency exit signage that conform to the APTA emergency signage standard luminance criteria for new passenger rail equipment. These samples were charged at an illuminance of only about 11 lux (1 fc), which approximately corresponds to the illuminance present at motorcoach window sills when the adjacent reading light is the only source of illumination. “HPPL-1” sample charging durations are specified in Figure 5-7.



Note: The horizontal axis is time in the dark.

Figure 5-6. “HPPL-1” Sample Luminance Decay and Charging Time – 54 lux (about 5 fc)

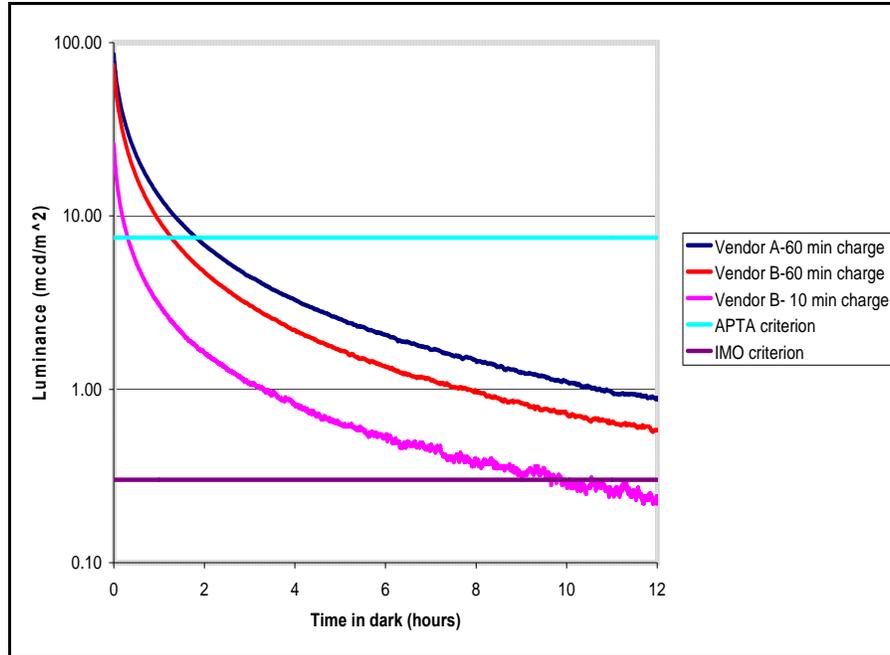


Figure 5-7. “HPPL-1” Sample Luminous Decay and Charging Light – about 11 lux (1 fc)

5.3 DISCUSSION

5.3.1 Electrically Illuminated Signage

Electrically illuminated “EMERGENCY “EXIT” signs, with independent storage batteries for backup in the event of loss of normal electrical power, have been required for passenger aircraft (see Figure 5-8) and public buildings for decades. Electrical illumination addresses the issues of emergency exit sign legibility in extremely dark conditions. As long as the electrical lighting devices remain functional during an emergency, they are superior to other approaches in terms of speed of passenger egress, because of both the specific exit location illumination and general illumination provided. However, many such emergency sign devices currently in service



Figure 5-8. Aircraft Electrically-Illuminated Emergency Exit Sign

on passenger trains contain glass lamps and wet batteries that have limited ability to withstand motorcoach crash forces. Moreover, the batteries in these older types of devices require periodic replacement. The latest generation of illuminated signage devices, which embody solid-state lamps and super-capacitors for energy storage, address these shortcomings. The only current disadvantages of the new technology are the initial cost, the space necessary for energy storage devices, and the need to supply electrical power at each location where these devices are to be installed.

For internally illuminated emergency exit signs, the APTA passenger rail car emergency exit signage standard²¹ requires that the luminance value of signs / markings using incandescent, fluorescent, or EL point sources be at least 1000 mcd/m² on the sign surface and that each LED must have a minimum peak intensity of 35 mcd for LEDs that spell out “EXIT.” The same surface luminance value could apply to dual-mode signage, as it was easily met by all three of the tested mock-up “EXIT” sign devices.

For externally illuminated signs, an emergency luminaire with a minimum output of at least 10 lumens (see Chapter 6 for additional discussion), located within 0.5 m (1.6 ft) of the motorcoach emergency exit sign, would provide sufficient illumination for the sign to be visible at a distance of 6 m (20 ft), provided that some of the light was directed toward the sign surface. For example, if one of the existing lights over the wheelchair-access door (see Figure 5-9) were modified to function as an emergency light, it would provide sufficient illumination to make an emergency exit sign mounted on that door (or other service door) or on nearby emergency window exit glazing readily visible to persons standing in the aisle and persons seated adjacent to or across the aisle from the seat. Moreover, for an overhead emergency luminaire that



Figure 5-9. Overhead Lighting Fixture Located above Wheelchair Access Door

produces an illuminance of 10 lux (1 fc), as measured 63 cm (25 in) above the floor directly below the luminaire with the light sensor in horizontal orientation, the emergency signage on the adjacent wall or window should be visible from 6 m (20 ft) and 1 cm (3/8 in) letter size instructions should be readable by persons with normal vision standing in the aisle. An observation test under darkness conditions using electrically illuminated and /or HPPL emergency exit signage as installed in motorcoaches could confirm that exit signs and instructions are visible and legible.

If emergency exit signage is placed on windows or walls that can be covered with curtains or shades, an additional means of indicating the exit location must be provided near or adjacent to the exit indicate the location when the curtain or drape is closed.

Although red lights have been used in many emergency exit lighting applications, they should not be used in motorcoaches for the following reasons:

- Human vision is relatively insensitive to red light, i.e., humans cannot see as well under red light as they can with white light at the same power level.
- Red lighting on signs with red letters results in poor contrast between the lettering and the background, making the signs difficult to read; and
- Red light will not charge HPPL signage.

An issue for electrically lighted emergency exit signs that is unique to motorcoaches is that for other modes of transportation and in building applications, illuminated emergency exit signs are required to be lighted continuously. These emergency exit signs are normally out of direct view of the locomotive engineer or aircraft pilot and thus do not interfere with night vision or create distracting reflections on the windshield. For motorcoaches, emergency exit lighting could be designed to be illuminated continuously during operations low at low light output (surface luminance less than 100 mcd/m²), and the light output increased in an emergency when triggered by an automatic device, such as a crash sensor; and by manual over-ride in non-crash situations.

5.3.2 Photoluminescent (PL) Signage and Instructions

High-performance PL signage provides a means to guide passengers to the motorcoach front door and emergency exits at a much lower cost than their electrically illuminated counterparts.

The critical human-factors issue in the application of emergency exit marking and instructions comprised of PL material is how well they can be seen and read. Accordingly, a major issue is whether the performance criteria for motorcoach emergency-exit signage should be based on legibility or visibility.

5.3.2.1 *Legibility*

The relationship between visual acuity for persons with normal vision and object luminance is shown in Figure 5-3. At typical levels of room lighting, visual acuity has a value of 1.0 (corresponding to 20/20 on the Snellen scale). Visual acuity varies more among different observers at very low luminance levels than it does in normal lighting. Out of a group of 10 subjects tested in an unpublished 1999 Volpe Center experiment, all with 20/20 vision in normal lighting, differences of 3 to 1 in visual acuity were noted at luminance levels below 10 mcd/m². This means that estimates of maximum reading distances are inherently imprecise. Accordingly, all reading distance estimates discussed herein are approximate.

The formulas for calculating sign letter-height requirements contained in the NBS Technical Note 1180¹⁹ were not validated for applications with luminance below 1 cd/m². However, the calculated values are consistent with observations of legibility distances conducted by Volpe Center staff, even at very low levels of sign luminance. Volpe Center staff calculations using these formulas imply that maximum reading distance for an emergency exit sign with a luminance of 0.9 mcd/m² would be about 10% of the distance at which a given observer could read the sign in normal (daylight) conditions. For example, if an individual could read a sign with 5-cm (2-in) high-letters from a distance of 35 m (115 ft) in normal light, then that person should be able to read the sign with a luminance level of 0.9 mcd/m² at a maximum distance of 3 m (10 ft). However, the effective legibility distance may be reduced to less than half of that predicted by the NBS formula for many older persons.

“EMERGENCY DOOR” or “EMERGENCY EXIT” signs should be legible to nearly all persons with normal, dark-adapted vision at a distance of 1.2 m (4 ft), if 5-cm (2-in) letter height is used on “HPPL-1” material, and if the APTA signage emergency standard²¹ criteria are met. These criteria include: width-to-height ratio between 3:5 and 1:1; a stroke-to-width ratio between 1:4 and 1:6; spacing between letters of a minimum of 1/16 the height of the upper case letters; and a luminance-contrast ratio of not less than 0.5. Furthermore, such signage will be visible at distances of at least 6 m (20 ft), if the background area (excluding the letters) is at least 135 cm² (21 square in) as required by FAA²⁰, and the APTA standard, thus assisting passengers to locate an exit inside the motorcoach. However, instructional signage, such as the currently commonly used 1-cm (3/8-in) lettering on motorcoach emergency window exit-release mechanisms (see Figure 5-1, Figure 5-2, and Figure 5-4a), which is readable in ordinary room light at a distance of 3 m (10 ft), by a person with 20/20 vision, will be readable only when the distance is reduced to less than 0.5 m (19 in).

5.3.2.2 *Visibility and Conspicuity*

For emergency egress during conditions of darkness, the visibility and conspicuity^{***} of emergency exit signage identifying exit location is more important than their legibility. Previous research conducted by Lufthansa for aircraft indicated that 68% of subjects identified the emergency exit by the light alone, while only 28% relied on reading the word “Exit.”²² The tests were conducted 145 minutes (about 2.5 hours) into the discharge phase of the PL path marking material, at which point the sign luminance values were approximately 6 mcd/m².

Results from a 1998 FAA research report²³ indicated that all of the 19 subjects in an egress experiment could see a certain type of PL path marking strip, even when the luminance had decayed to 2.4 mcd/m² after 2 ½ hours.

As noted in the Year 1 interim report of this study, Advisory Circulars (AC) issued by FAA provide guidance to aircraft manufacturers and operators in evaluating systems to ensure that they comply with the floor proximity emergency exit path criteria. The first AC provides guidance to demonstrate that the system: 1) enables passengers to visually identify the escape path along the cabin aisle after leaving their seats, and 2) that the marking will enable passengers to readily identify each exit from the exit path by referring only to marking and visual features when all illumination located 122 cm (4 ft above the floor) is obscured by smoke, and it is dark.²⁴ The other AC (issued in 1997) provides guidance to demonstrate that PL path marking will provide the functional equivalent of electrically powered floor path marking.²⁵ The wording of the latter AC text indicates that strontium aluminate (“High Performance Photoluminescent”) material must be used; however, this material is permitted only for the path marking component, not emergency exit signs, which must be electrically illuminated.

For passenger aircraft and railroad transportation, a legibility-based signage standard has been achievable with the currently available technology, because some level of illumination is normally present until the onset of any emergency, and evacuation can usually be accomplished within the specified duration limits which range from 90 seconds for passenger aircraft to 90 minutes for passenger trains and buildings, for the emergency lighting systems.

In contrast, passenger ship evacuations typically may require several hours, during which time electrical power from the main generators and backup sources may have been lost. Thus, the International Marine Organization (IMO) exit path standard²⁶ is based on visibility (0.3 mcd/m²)

*** “Conspicuity” is defined as: visual characteristic that is highly recognizable and attracts attention by using size, brightness, and high contrast.

after 24 hours in the dark, rather than sign legibility. PL material that meets this IMO requirement at 24 hours is approximately equivalent in performance to material that meets the APTA “HPPL-1” luminance criterion of 7.5 mcd/m^2 at 90 minutes.

As noted in the Year 1 interim report, emergency egress from a single level motorcoach can normally be accomplished in less than 3 minutes, via the front door. However, because there may be no illumination to charge the emergency exit signage for several hours before an emergency occurs, the PL material performance constraints are similar to those applicable in the maritime industry.

The authors of this Year 2 final report have observed samples of “HPPL-1” material signage using 5 cm (2 in) letter height, glowing with luminance values below 0.5 mcd/m^2 and found it to be visible at distances of at least 6 m (20 ft), but the signage is not legible at a distance more than 1.2 m (4 ft).

5.3.2.3 Charging Light

In existing motorcoaches, nearly all of the light during nighttime conditions that could charge PL emergency exit signage currently comes from overhead reading lights. Due to the downward angle of current reading lights, **** they will provide very little charging light. Moreover, since the reading lights are controlled by passengers, as soon as these lights are turned off so that passengers can sleep, the luminance of PL signs will start to decrease. Therefore, if a motorcoach emergency occurs shortly before dawn, the luminance of these “HPPL-1” materials may be about 0.9 mcd/m^2 , substantially below the criterion values specified for passenger trains (7.5 mcd/m^2 after 90 minutes) or aircraft (510 mcd/m^2 initial brightness). The luminance of “HPPL-1” materials is unlikely to ever fall below 0.9 mcd/m^2 because of the residual charge remaining from daylight exposure during the previous day. The luminance decay through the night hours may be partially offset if the overhead fluorescent lights are turned on for station or rest stops. No data for motorcoaches under revenue operating conditions were obtained for the distribution of charging light levels for potential use of any PL material.

Figure 5-6 and Figure 5-7 show that after a few hours in the dark, even “HPPL-1” material will have a very low luminance. For example, after 5 hours in the dark, the luminance may decline to about 2 mcd/m^2 , (see Figure 5-6). After 12 hours in the dark (worst-case) and charging at about 11 lux (1 fc) for 1 hour (see Figure 5-7), an emergency exit sign comprised of “HPPL-1”

**** To a first approximation, the effective charging illuminance on a given surface falls off with the cosine of the angle of incidence. (The angle of incidence is the angle between the incident light beam and a line perpendicular to the surface in question.)

material (with letter height of at least 5 cm (2 in)) will have a luminance of about 0.9 mcd/m², bright enough to be visible to a person with normal, dark-adapted vision at a distance of at least 6 m (20 feet). However, as noted previously, that same signage is not legible at a distance more than 1.2 m (4 ft).

5.3.3 Dual-Mode Systems

For emergency exit signage and instructions to remain legible in worst-case conditions, from longer distances away and to improve passenger situational awareness if the bus is not upright, a dual-mode system, combining both electrical illumination (e.g., external emergency lighting or internal LEDs) and “HPPL-1” material, could be used for emergency exit identification. This system could provide a soft glow at all times that would not interfere with sleeping, but would ensure that the HPPL signage luminance would be bright enough to allow passengers to read the emergency exit sign and instructions under dim and dark conditions, if the emergency exit lighting system is not operational in a severe crash.

5.4 SUMMARY

Emergency exit signage and instructions currently used in motorcoaches are readable by persons standing in the aisle during the day or when the overhead lights are on or when an adjacent reading light is on. However, when all of these lights are off, often the case in the midnight-to-dawn hours, the sign readability would be marginal or nil, unless the emergency exit signage is electrically illuminated with an independent power source and/or is comprised of “HPPL-1” material. Accordingly, the use of one or both of these alternatives may make motorcoach emergency exit signs more conspicuous and legible and thus could assist passengers in locating and operating the exits under dark and dim light conditions, as well as under normal conditions.

An observation test under darkness conditions using electrically illuminated and /or HPPL emergency exit signage, as installed in motorcoaches, could confirm that exit signs and instructions are visible and legible.

5.4.1 Electrically Illuminated Signage

Electrically illuminated emergency exit signs with independent crash-survivable internal energy storage devices are superior to other approaches in terms of providing sign conspicuity and legibility. Such a sign system is typically designed to internally illuminate the exit sign and should be economical to install in new equipment.

Internal illumination with the following minimum performance characteristics-could increase the visibility and readability of motorcoach emergency exit signage:

- Background luminance value for incandescent, fluorescent, or EL point sources of at least 1 cd/m^2 measured on the sign surface; and
- Peak intensity for each LED of at least 35 mcd for LEDs, which spell out “EMERGENCY DOOR” and “EMERGENCY EXIT.”

The APTA passenger rail car standard and many building codes require that compliance with luminance performance criteria must be certified by an independent, certified testing laboratory.

Externally illuminated emergency exit signage with 5-cm (2-in) high letters is visible at a distance of 6 m (20 ft), if it is illuminated by an emergency light placed within 0.5 m (1.6 ft) of the sign, which has a minimum output of at least 10 lumens. This luminaire should emit white light and be placed so as to direct the most of the light toward the signage and the floor directly below the exit, e.g., as in the typical placement of lights over a wheelchair-access door.

For both internally and externally illuminated emergency exit signage, the following minimum performance characteristics are important to ensure that the signage system is available (operational) during emergency conditions:

- Duration of at least 30 minutes on a charge;
- Solid-state independent, self-contained energy-storage device that is not vulnerable to battery failure due to loss of or shutdown of engine-generated power;
- Continuous illumination during revenue operation at low light output (surface luminance less than 100 mcd/m^2), with increased light output during an emergency:
 - o When triggered by an automatic device, such as a crash sensor, and
 - o By a manual override for non-crash situations; and
- Ability to withstand crash forces (e.g., 20-g, 3-axis shock rating).

Chapter 6 contains additional information relating to emergency exit lighting.

5.4.2 Photoluminescent (PL) Signage

During the bus mock-up egress rate experiments, subjects exited via the side stairway at the rate of 22 ppm (higher than normal debarking rates of 16-20 ppm in motorcoach revenue service), with only HPPL-markings in an otherwise pitch-dark environment.

Accordingly, emergency exit signs and instructions meeting APTA-designated “HPPL-1” material criteria or similar specifications may assist motorcoach passengers to locate and operate emergency exits.

Emergency exit signage using HPPL material can meet minimum requirements for conspicuity and legibility at a small fraction of the cost for electrically illuminated components. The technology for HPPL emergency exit signs (and path markings) has continued to improve rapidly, leading to higher luminance output for a given charge from ambient light, lower costs, and a broader range of color options.

HPPL material with the following minimum performance characteristics could increase the visibility and readability of motorcoach emergency exit signage, particularly under dim and dark conditions

- 5-cm (2-in) size letters;
- Luminance of at least 7.5 mcd/m^2 after 90 minutes in the dark following a minimum ambient light charging at about 11 lux (1 fc) for 1 hour; and
- Placement in a location that receives the minimum charging light for at least one hour.

In addition, emergency exit-signs using “HPPL-1” material should glow with sufficient luminance for 12 hours under nighttime conditions (worst-case), to enable motorcoach passengers with dark-adapted eyes to:

- Identify the emergency exit location from at least 6 m (20 ft) away, although the signs would not necessarily be legible;
- Read the words “EXIT DOOR” or “EMERGENCY EXIT” from a distance of 1.2 m (4 ft), provided that signs comply with the following performance criteria:
 - Letter heights of 5 cm (2 in), consistent with current requirements for school buses,
 - Criteria for a width-to-height ratio between 3:5 and 1:1; a stroke-to-width ratio between 1:4 and 1:6; spacing between letters of a minimum of 1/16 the height of the upper case letters, and a luminance contrast ratio of not less than 0.5, and
 - Background area (excluding the letters) of 135 cm^2 (21 square in); and
- Read exit operating instructions with 1-cm (3/8-in) letters, currently commonly used on motorcoach emergency exits, from a distance typically less than 0.5 m (19 in), if they met the latter two above provisions.

5.4.3 Dual Mode Systems

For maximum conspicuity, legibility, and survivability in severe crashes, dual-mode signage combining internal electrical illumination with HPPL material backgrounds represents the current state-of-the-art in emergency exit signage.

A dual-mode emergency exit identification system that combine both electrical illumination using an independent power supply and HPPL material technologies could ensure that the signage luminance would be bright enough to provide for motorcoach passenger situational awareness and for passengers to locate emergency exits and read operating instructions under dim and dark conditions, if the emergency exit lighting system is not operational.

6. EMERGENCY EXIT LIGHTING

6.1 OVERVIEW

There is diverse opinion as to how much emergency lighting is needed when normal lighting is not available. The minimum required values for emergency illumination levels vary by factors of 30 to 1 for buildings and transportation vehicles depending on the regulatory and standards setting organizations involved and the operating environment. The following organizations specify a minimum illumination value of 1 fc (about 11 lux) at the emergency exit location for a 90-minute time period:

- FRA for new passenger rail cars, as measured at the door floor, as well as an average of 1 fc (about 11 lux) along the center of the aisle;¹⁷
- Underwriters Laboratory in UL 924, Supplement SH3;²⁷ and
- National Fire Protection Association (NFPA), *Life Safety Code Handbook*¹⁵ (same as FRA).

This high level of illuminance has been easily achieved for many years in buildings because there was no constraint on space for the required storage batteries. However, that high illumination level became feasible for passenger rail equipment only recently, as technologies for lighting and energy storage improved.

For commercial aircraft, FAA (14 CFR, subsection 25.812) requires a mean illuminance of only 0.05 fc (0.5 lux) in the aisle, at the armrest level for a duration of 10 minutes²⁰. However, FAA requirements reflect the limits of the technology that existed at the time the regulation was originally developed (1966).

Regulatory requirements for emergency lighting are very low or even nonexistent for private motor vehicles and residences. The illuminance level of commercial-grade emergency lighting (i.e., that required by UL 924²⁷ or by NFPA 101¹⁵) allows for obstacles and hazards in the exit path to be seen, thereby assisting persons to egress more rapidly and with less risk of injury.

The Volpe Center bus mock-up experiments showed that a lower level of emergency lighting has only a limited effect on egress rates (see Figure 3-1), as long as the exit path is free of obstacles and hazards. However, moving about in a pitch-dark environment presents a different situation, which may cause egress rates to decline to a small fraction of normal values as passengers try to feel around for obstacles and hazards. Due to the potential risk to study subjects, Volpe Center staff did not conduct egress rate trials in complete darkness conditions, except for one trial in which all handholds, stair treads, door opening thresholds, and obstacles, etc., were clearly

marked with “high performance” PL (HPPL) materials. The egress rates reported in Chapter 3 of this report should be considered as “best case” for the illumination levels provided during the various egress trials. The experiments resulted showed that stairway egress rates increased from 22 ppm for HPPL material “EXIT” signs and egress path markings alone to 29 ppm for the reduced 4 lux (.4 fc) emergency lighting condition.

As noted in Chapters 2 and 5, PL signs with 5-cm (2-in) “EXIT” letters were mounted on three luminaires that were located above the three door openings of the mock-up used for the egress rate experiments and designated as “Mid-Door,” “Lavatory-Door,” and “Side Stairway,” according to the interior location of the exit where they were used (see Figure 5-5).

Figure 6-1 shows the lighting devices used in the bus mock-up egress rate experiments without their sign covers and with the HPPL signage overlay. The lighting device characteristics are listed in Table 6-1. All exit sign devices used white LEDs. (In addition, emergency lighting was also provided during certain egress trials by red LED luminaires located above the top of both mock-up stairways, above the rear seat assembly (next to the Lavatory Door) and above the mock-up aisle walkway opposite the Mid-Door (see Figure 2-1.)



Without photoluminescent overlays



With photoluminescent overlays

Figure 6-1. Illuminated / HPPL Wheelchair-Access Door and Side Stairway “EXIT” Signs

**Table 6-1. Characteristics of Lighted “EXIT” Signs
Used in Volpe Center Egress Experiment**

CHARACTERISTIC	MID-DOOR	LAVATORY-DOOR	SIDE STAIRWAY
LAMPS	Multi-emitter LED with prismatic diffuser aimed straight down	6-LED linear array angled 45° from vertical	16-LED array aimed straight down
POWER CONSUMPTION	0.3 W	3.8 W	2 W
ENERGY STORAGE TECHNOLOGY	Supercapacitor	N/A [#]	Nickel-metal-hydride battery
ENERGY STORAGE CAPACITY	1.2 W-hr	N/A [#]	7.7 W-hr
LUMINANCE OF SIGN BACKGROUND	1-3 cd/m ²	8-90 cd/m ²	1-3 cd/m ²
ILLUMINANCE-MEASURED 1.5 M DIRECTLY BELOW DEVICE	8.2 lux	8.5 lux	8 lux

This sign did not have self-contained energy storage

Other characteristics of the commercially available luminaires installed in the mock-up for the egress experiments, which could be applicable to motorcoach emergency lighting, include:

- Duration of 60-90 minutes on a charge;
- Solid-state independent power source;
- Ability to survive crash forces (e.g., with 20 g, 3 axis shock rating);
- Volume less than 1 liter (61 in³);
- Power consumption of 0.3 to 4 W;
- Estimated initial cost: ~ \$300-400 per unit; and
- Long service life with 5 year+ maintenance cycle.

6.2 DISCUSSION

Current performance criteria for building and transportation vehicle (e.g., aircraft and passenger rail cars) emergency lighting have been established primarily on the basis of what could be readily achieved at an acceptable cost at the time the criteria were developed.

For commercial buildings, where space requirements for batteries are not an issue, emergency lighting systems are required to produce a mean illuminance of 1 fc (about 11 lux), as measured on the floor.

For passenger aircraft, much lower values, e.g. 0.05 fc in the aisle, were chosen because the lighting and battery technologies available at the time the FAA emergency-lighting regulation was originally developed (1966) were more limited. Furthermore, aircraft emergency evacuation-certification trials are required to complete passenger evacuation in 90 seconds, with half the exits disabled and only the emergency lights used for illumination. However, there is greater risk of injury from tripping or colliding with unseen obstacles at these low levels of illumination due to the many variables involved. Lighting and energy storage technologies have both advanced substantially since emergency lighting systems in buildings, as well as passenger aircraft, trains, and ships were first constructed and installed.

The total visible energy output of any light source is measured in lumens and is included in the manufacturer's performance specifications for ordinary light bulbs, fluorescent tubes, and LED lamps. The "lumen" rating is a measure of the total light output, while "illuminance" is a measure of how much light falls in a specific small surface area (1 sq ft or 1 sq m). A luminaire with a highly directional output (e.g., a flashlight) can produce a high illuminance value in a small area even with a very low lumen output. Lumen rating tests are normally done by specialized laboratories because total light output (i.e., lumens) must be measured in all directions in three-dimensional space. The relation between light output (lumens) and energy consumed (Watts (W)) is called "efficacy." An ordinary incandescent light bulb produces about 16 lumens per W. Compact fluorescent bulbs or tubes yield roughly 50 lumens per W. The efficacies of LEDs and other solid-state lamps vary over a wide range. Currently available LED luminaires typically have efficacies of 20 to 50 lumens per W, but more recently developed products exceed 100 lumens per W.

The amount of illumination (fc) (lux)) that a given light source of a specified number of lumens will produce at a target location is affected by the distance from the source to the location, beam-dispersion characteristics, and the reflective properties of all of the surfaces surrounding the source and target. If there is a high angle of incidence between the light beam and the surface on which it is measured (e.g., a light placed directly above a sign on a window), small differences in the angular orientation of the sensor will produce inconsistent measurements. To address this issue, the APTA rail standards specify emergency lighting requirements in terms of illuminance criteria, as measured at specific locations, i.e., the floor or on the armrests, where it is possible to get consistent data. If an overhead emergency luminaire produces an illuminance of 10 lux (1 fc) at the floor, the emergency signage on the adjacent wall or window will be visible from 6m

(20 ft) and 1-cm (3/8 in) letter size instructions will be readable by persons with normal vision standing in the aisle

The egress rates in the bus mock-up experiments described in Chapter 3 were nearly identical during both the emergency lighting trials and the normal room light trials. The total light output produced by the LED luminaires (see Figure 6-1) ranged from about 10 to more than 80 lumens. Despite a 10-fold difference in power consumption and noticeable differences in the area around the sign that was well backlit, the “EXIT” sign lighting devices provided similar illuminance levels on the floor at the threshold of the mock-up wheelchair-access door openings and the side stairway. Emergency lighting luminaires with a rated light output of 10 lumens per lamp are now commercially available with supercapacitor power supplies, which could be installed in motorcoaches. This level of light output can be readily achieved with only 0.3 W of electric power for currently available solid-state systems.

Electrically illuminated lighting systems using solid-state luminaires offer the advantages of using small size self contained power sources, with lower energy consumption, longer service life, and ability to withstand crash forces.

An observation test under darkness conditions using emergency lighting as installed in motorcoaches could confirm that exit locations, signs, and instructions are visible and legible.

6.3 SUMMARY

The purpose of emergency lighting is to provide situational awareness and allow individuals to locate, operate and use emergency exits under conditions of darkness. Accordingly, motorcoach emergency lighting could both increase the passenger egress rate and reduce the risk of injury in an otherwise pitch-dark emergency environment.

The installation of electrically illuminated emergency exit signs with light outputs of at least 10 lumens each – one over the motorcoach front service door and one in the rear half of the bus located at the wheelchair-access door or other door that could be used for passenger emergency egress – could provide adequate light (e.g., 5-8 lux (about 0.5-0.7 fc)) for able-bodied adults to locate, reach, and operate those exits during an emergency and leave a motorcoach at egress rates comparable to those estimated in Figure 3-1.

Overturning has been identified as the most severe event in 49% of motorcoach fatalities.³ When the bus is on its side, use of the front door or window exits is more difficult. During darkness conditions, crashworthy emergency lighting luminaires located next to or at emergency windows exits and emergency roof exit hatches could illuminate the exit path and assist motorcoach

passengers to locate and operate those emergency exits, particularly when a bus is overturned and the front door is unavailable.

Emergency lighting devices with the following minimum performance characteristics could increase the conspicuity and legibility of motorcoach emergency exits and signage:

- Solid-state systems with light output of at least 10 lumens for each luminaire at or adjacent to each emergency exit location, and
- Illuminance at each emergency exit location of at least 1 fc (about 11 lux), measured 63 cm (25 in) above the floor directly below the luminaire, with the light sensor in a horizontal orientation;

The following performance characteristics are important to ensure that the emergency lighting system is available (operational) during emergency conditions:

- Duration of at least 30 minutes on a charge;
- Solid-state independent power source that is not vulnerable to battery failure due to loss of or shutdown of engine-generated power;
- Continuous illumination during revenue operation at low light output (surface luminance less than 100 mcd/m^2), with increased light output during an emergency:
 - o When triggered by an automatic device, such as a crash sensor, and
 - o By a manual override for non-crash situations; and
- Ability to survive crash forces (e.g., with 20 g, 3 axis shock rating).

An observation test under darkness conditions using electrically illuminated and /or HPPL emergency exit signage, as installed in motorcoaches, could confirm that emergency exit signs and exit operating instructions are visible and legible.

7. SUMMARY OF YEAR 2 FINDINGS AND CONCLUSIONS

This final report describes results of the second year of the Volpe Center study. The focus is on certain potential motorcoach design changes that may increase passenger egress rate and reduce risk of injury during emergency egress that were identified during the first year. Four topic areas are addressed: 1) egress rates via alternative second-side door exits with and without stairs; 2) human strength measurement of the ability to apply forces needed to release and open emergency exits; 3) emergency exit identification; and 4) emergency exit lighting.

Volpe Center staff conducted two series of human factors experiments under benign laboratory conditions, using a bus mock-up constructed and located on the Volpe Center campus. A series of experimental egress trials evaluated egress rates for 24 Volpe Center federal employees, representing almost equal groups of males and females in three age groups, who used three different egress paths under various lighting conditions. The alternative egress paths consisted of a second side door with a stairway like those used on many motorcoaches operated in other countries, and wheelchair-access doors in two configurations in common use in the U.S. How these egress rates vary with lighting conditions was also analyzed.

Another-series of experimental tests measured the forces that typical able-bodied adults (using 24 Volpe Center federal employees) are able to apply to the tasks of releasing and opening motorcoach emergency exits.

In addition, other U.S. transportation regulatory agency and industry standard performance criteria for emergency exit signs and instructions were further evaluated in terms of their potential applicability to assist motorcoach passengers in locating, reaching, and operating emergency exits, and in relation to well-known characteristics of human vision and recently developed technologies.

7.1 EGRESS RATES

The results of the Year 1 motorcoach pilot egress rate experiments indicated that passenger flow through the wheelchair-access door (or another side door), if used as a motorcoach emergency exit, could be as high as 25 passengers per minute (ppm). However, neither the OKRI experiments nor the Volpe Center pilot experiment reflected conditions for typical current motorcoach operations, in which the wheelchair-access doors are normally partially obstructed by adjacent seats or wheelchairs. In addition, the egress trials did not consider how much time it would take to evacuate a person who uses a wheelchair.

The Year 2 bus mock-up egress rate experiments of three alternative egress paths, using the side door with stairway and wheelchair-access doors in two configurations, conducted under benign laboratory conditions, during various lighting levels, with no obstacles, resulted in the following principal findings:

- A second side door opening with a stairway provided a much faster egress path for subjects than either of the side wheelchair-access door configuration options tested:
 - Under normal lighting, the egress rate was about 30 ppm for the steps with 30 cm (12 in) risers, almost as high as the corresponding front-door egress rate of 36 ppm observed during the Year 1 pilot experiment.
 - Egress rates declined very little under emergency-lighting conditions to about 29 ppm. Even with no lighting at all and only HPPL signs and markings to guide egress, flow rates of 22 ppm were observed.
- Egress from the wheelchair-access door openings, even when partly obstructed by seats, was achieved by the subjects faster than through the emergency window exits observed during the Year 1 pilot experiment:
 - Egress rates of 12 to 14 ppm were achieved for the wheelchair-access-door configuration located between two-rows of seats with a 97 cm (38 in) pitch and a clearance at waist height of 54 cm (21 in).
 - The wheelchair-access door configuration adjacent to a simulated lavatory wall, with only a 30 cm (12 in) clearance at waist height between the lavatory and the adjacent seat, reduced egress rates to 9 to 10 ppm.
- Egress rates declined in low-light conditions, but the effect was not very large in the experiment, where the exit paths were free of hazards:
 - Subjects exited via the side stairway at the rate of 22 ppm (higher than normal front door debarking rates of 16-20 ppm in motorcoach revenue service) with only HPPL markings in an otherwise pitch-dark environment.
 - Subjects were able to perform sitting jumps or controlled drops from the wheelchair-access-door openings on the 1.5 m (5 ft) high platform of the mock-up at rates of 9 or 10 persons per minute in very dim lighting (~ 0.6 lux).
 - Although subjects were not tested in complete darkness, the majority said that they would have been reluctant to jump from the wheelchair-access door openings under such conditions.

It should be recognized that a more representative sample of the general population, containing frail, mobility-impaired, and/or very heavy or large individuals, could take more time to open and release an emergency exit or egress from a motorcoach during an emergency.

In a complex emergency, such as a rollover crash, the exit path typically becomes more complex and may contain more hazardous obstacles than that of a normal upright bus, necessitating more illumination for occupants to see them, than provided during the egress trials.

7.2 HUMAN STRENGTH FOR OPERATING EMERGENCY EXITS

FMVSS 217 requires that the forces needed to release and open motorcoach emergency exits not exceed 268 N (60 lbf) in the high region. However, field measurements during Year 1 of this study showed that forces near the limit value had to be applied in some cases to open emergency window exits wide enough to permit unobstructed egress. Accordingly, during Year 2, able-bodied subjects were tested, using the bus mock-up, to determine the maximum forces they could apply in eight different locations and grip combinations that simulated releasing and opening motorcoach emergency exits. All but two of the experiment participants were the same persons who participated in the egress rate trials.

The principal Year 2 emergency exit strength test findings were:

- Significant fractions of the able-bodied subjects were not able to apply forces of 268 N (60 lbf) in the majority of the postures and grips used to release and open motorcoach emergency exits.
- Pushing emergency exit windows open by the required minimum distance – 51 cm (20 in) –barely sufficient to allow for a controlled drop to the ground, was the most challenging test. Only 4 of the 24 of subjects (17%) were able to apply 268 N in this test without risking injury to themselves.
- Reducing maximum allowable forces for the high region to the same limit as for school buses – 178 N (40 lbf) – would have allowed two-thirds of the subjects to operate all exits without risk of muscular strain.

7.3 EMERGENCY EXIT IDENTIFICATION

The fundamental ways to increase the conspicuity and legibility of motorcoach emergency exit signs and instructions, as currently required by FMVSS 217 for school buses, are to:

- Install the signs in a location more visible to passengers (i.e., at the top or side of the emergency exit; and
- Increase letter height to 5 cm (2 in), and use bright colors with high contrast.

In addition, motorcoach emergency exit signs can be made more visible and readable and thus assist passengers in locating and operating motorcoach exits under dark and dim light conditions, as well as normal light conditions by:

- Electrical illumination (external or internal emergency lighting); and / or
- Photoluminescent (PL) materials.

Volpe Center staff reviewed and evaluated other U.S. transportation regulatory agency and industry standard organizations, as well as recent technology developments for emergency exit signage using electrical illumination and /or HPPL material for potential applicability to motorcoach emergency egress.

7.3.1 Electrically Illuminated Signage

Internal illumination with the following minimum performance characteristics could increase the conspicuity and legibility of motorcoach emergency exit signage:

- Background luminance value using incandescent, fluorescent, or EL point sources of at least 1 cd / m^2 ; and
- Peak intensity for each LED of at least 35 mcd for LEDs that spell out “EMERGENCY DOOR” or “EMERGENCY EXIT.”

Externally emergency exit illuminated signage with 5-cm (2-in) high letters is visible at a distance of 6 m (20 ft), if it is illuminated by an emergency light placed within 0.5 m (1.6 ft) of the sign, which has a minimum output of at least 10 lumens. To ensure visibility of the sign and instructions, this luminaire should emit white light and be placed so as to direct most of the light toward the signage and instructions and the floor, e.g., as in the typical placement of lights over currently installed wheelchair-access doors.

For both internally and externally illuminated emergency exit signage, the following minimum performance characteristics are important to ensure that the system is available (operational) during emergency conditions:

- Duration of at least 30 minutes on a charge;
- Solid-state, independent, self-contained energy-storage device that is not vulnerable to battery failure due to loss of or shutdown of engine-generated power.
- Continuous illumination during revenue operation at low light output (surface luminance less than 100 mcd/m^2), with increased light output during an emergency:
 - o When triggered by an automatic device, such as a crash sensor, and
 - o By a manual override for non-crash situations; and
- Ability to survive crash forces (e.g., with 20 g, 3 axis shock rating).

7.3.2 Photoluminescent (PL) Material Signage

During the bus mock-up egress rate experiments, subjects exited via the side stairway at the rate of 22 ppm (slightly higher than normal motorcoach debording rates in revenue service), with only HPPL-“EXIT” signs and path-markings, in an otherwise pitch-dark environment.

HPPL material with the following minimum performance characteristics could increase the visibility and readability of motorcoach emergency exit signage:

- Luminance of at least 7.5 mcd/m² after 90 minutes in the dark, following a minimum ambient light charging at about 11 lux (1 fc) for 1 hour; and
- Placement in a location that receives the minimum charging light for at least 1 hour.

Emergency exit-signs using this “HPPL-1” material should glow with sufficient luminance for 12 hours under nighttime conditions (worst-case) to enable motorcoach passengers with dark-adapted eyes to:

- Identify the emergency exit location from at least 6 m (20 ft) away, although the signs would not necessarily be legible;
- Read the words “EMERGENCY DOOR” or “EMERGENCY EXIT” from a distance of 1.2 m (4 ft), provided that signs comply with the following performance criteria:
 - o Letter heights of 5 cm (2 in), consistent with current requirements for school buses,
 - o Criteria for a width-to-height ratio between 3:5 and 1:1; a stroke-to-width ratio between 1:4 and 1:6; spacing between letters of a minimum of 1/16 the height of the upper case letters, and a luminance contrast ratio of not less than 0.5, and
 - o Background area (excluding the letters) of 135 cm² (21 square in), and
- Read exit operating instructions with 1-cm (3/8-in) letters, currently commonly used on motorcoach emergency exits, from a distance typically less than 0.5 m (19 in), if they met the latter two above provisions.

Compliance with an observation test under darkness conditions using electrically illuminated and /or HPPL emergency exit signage as installed in motorcoaches could confirm that emergency exit signs and exit operating instructions are visible and legible under dark and dim lighting conditions.

7.4 EMERGENCY EXIT LIGHTING

The Year 2 mock-up egress experiment described in Chapter 3 showed that under emergency lighting conditions, able-bodied adult subjects jumped from wheelchair-access doors at a rate ranging from 9 to 14 ppm, despite a 1.5 m (5 ft) drop to the floor, similar to their egress rates

under normal lighting. Although no egress trials were conducted in total darkness (with the exception of HPPL signs and markings) due to potential injury to subjects, it is reasonable to expect egress rates would be greatly reduced in total darkness.

Crash-survivable emergency luminaires for motorcoaches applications are now commercially available that provide illumination similar to the “reduced emergency lighting” condition tested during the Year 2 experiments.

Emergency lighting with the following minimum performance characteristics may increase the egress rate by passengers from an upright bus during conditions of darkness, via either a second side service door with a stairway or a wheelchair-access door opening, at similar egress rates as during daylight conditions:

- Solid-state systems with light output of at least 10 lumens per luminaire at or adjacent to each emergency exit location; and
- Luminance at the emergency exit location measured at armrest height directly below the emergency luminaire of at least 1 fc (about 11 lux), and

The following minimum performance characteristics are important to ensure that the emergency lighting system is available (operational) during emergency conditions:

- Duration of at least 30 minutes on a charge;
- Solid -state independent, self-contained energy-storage device that is not vulnerable to battery failure due to loss of or shutdown of engine-generated power.
- Continuous illumination during revenue operation at low-light output (surface luminance less than 100 mcd/m²); with increased light output controlled by the bus driver, and triggered when necessary by an automatic device, such as a crash sensor; and
- Ability to withstand crash forces (e.g., 20-g, 3-axis shock rating).

Compliance with an observation test under darkness conditions using electrically illuminated emergency exit lighting, as installed in motorcoaches could confirm that emergency exit signs and exit operating instructions are visible and legible under emergency lighting.

7.5 DUAL-MODE EMERGENCY EXIT IDENTIFICATION AND LIGHTING SYSTEMS

Dual-mode emergency-exit signage systems, which integrate electric illumination using an independent power source for emergency exit lighting and a HPPL material background, could provide the highest conspicuity, legibility, and probability of functionality in a severe motorcoach crash under darkness conditions.

provide the highest conspicuity, legibility, and probability of functionality in a severe motorcoach crash under darkness conditions.

7.6 CONCLUSIONS

To increase the rate of emergency egress from motorcoaches and reduce the likelihood of injury to passengers during such egress, certain existing FMVSS 217 school bus requirements, as well as certain provisions of FAA, FRA, and USCG regulations respectively, for passenger aircraft, passenger trains, and passenger ships, could be adapted for application to U.S. motorcoaches.

The experiments and analyses conducted during this two-year study indicated the technical feasibility of adapting certain U.S. transportation agency vehicle regulations and Economic Commission for Europe (ECE) emergency egress performance requirements for application to motorcoach emergency egress. The following potential motorcoach design changes may increase passenger egress rate and reduce the risk of injuries during emergencies:

- An emergency exit door or a second service door that can be used as emergency exit, as the primary means of emergency egress, as required for school buses and most motorcoaches operated in other countries; and as required for U.S. passenger aircraft and passenger trains, as well as buildings;
- Lower limits for maximum permissible release and opening forces, similar to the high region 178 N (40 lbf) limits for school buses;
- Larger size exit signs and larger size instructions, using high performance photoluminescent material (HPPL), to assist passengers to locate and operate the emergency exits;
- Crash-survivable emergency exit lighting, to assist passengers to locate and operate the emergency exits by providing illumination of emergency exit location, as required by FAA for all passenger aircraft and FRA for new passenger rail cars; and
- Dual-mode emergency-exit signage, which integrates electric illumination using an independent power source and HPPL material background, could provide the highest conspicuity, legibility, and probability of functionality in a severe motorcoach crash under darkness conditions.

The Volpe Center is preparing a final technical summary report that integrates the information relating to the preliminary list of motorcoach design considerations described in the Year 1 interim report and the results of the experiments and analysis described in this Year 2 final report.

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