U.S. Department of Transportation

Federal Railroad Administration

Passenger Train Emergency Systems: Review of Egress Variables and Egress Simulation Models

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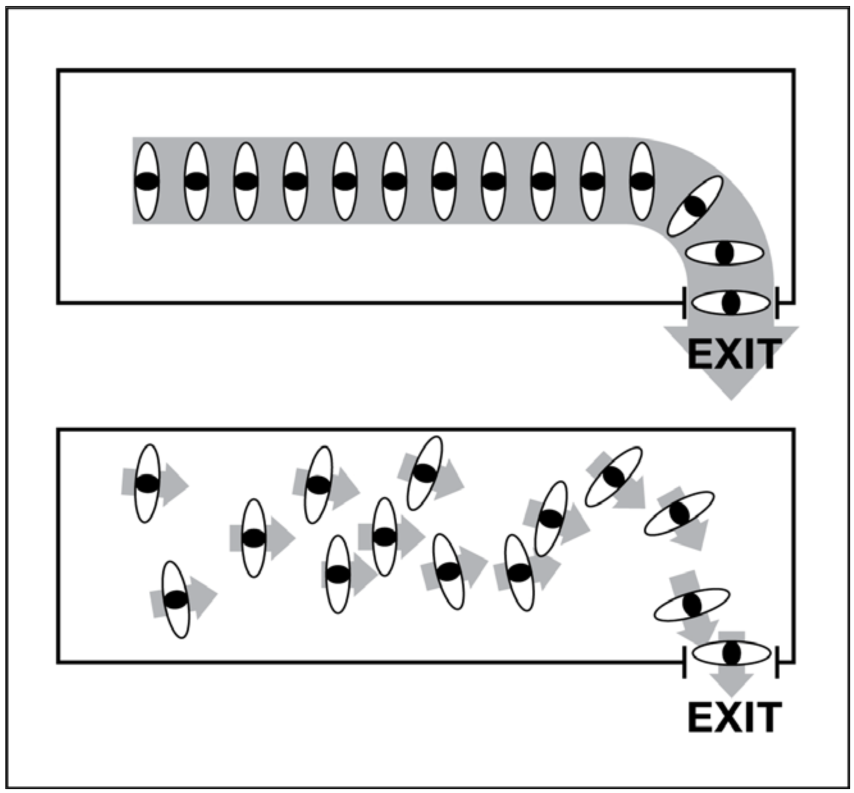
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

Federal Railroad Administration (FRA) regulations are intended to ensure the safe, timely, and effective evacuation of intercity and commuter rail passengers when necessary during passenger train emergencies. Although it is recognized that during the majority of emergency scenarios, it is much safer for passengers to remain on the train, it may be necessary for passengers and crew to evacuate a passenger train quickly, due to certain life-threatening conditions (e.g., fire).

FRA is sponsoring a research program to investigate a variety of emergency evacuation concepts, strategies, and techniques for applicability to passenger trains operating in the United States.

One aspect of the FRA research program is directed at evaluating the potential applicability to passenger trains of performance-based criteria specifying minimum necessary evacuation times. No methodology currently exists for evaluating the passenger rail car emergency egress system as a whole, or the effects on egress times of failures within this system.

This report presents the results of a review of passenger rail car egress variables and evaluation of the potential application of computer models that simulate egress for developing passenger train evacuation times.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds	=	0.9 tonne (t) (lb)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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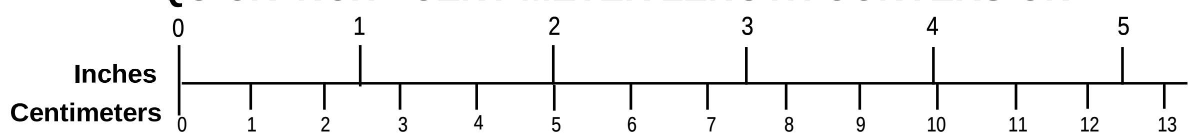

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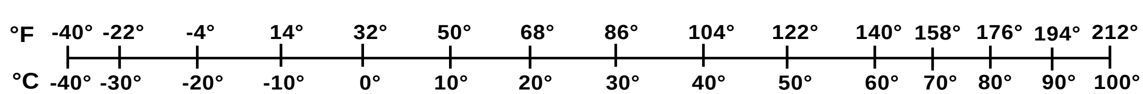

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Claire Orth, former Chief, Equipment and Operating Practices Division, FRA; and N. Thomas Tsai, former Manager, FRA Occupant Protection Program, provided initial specific research program direction.

The contents of this report are based on a review of egress variables and models which simulate egress from structures originally completed by staff of Hughes Associates, under contract to the Volpe Center in 2003. However, the previously prepared report by Hughes Associates has been substantially reorganized, revised, and updated by Volpe Center staff. Accordingly, although Hughes Associates staff reviewed the final draft of this report and provided technical review comments, as well as new or updated information for certain egress models, the findings in this published report are the responsibility of Volpe Center staff.

In addition, Garnett (Mac) MacLean, Civil Office of Aviation Medicine, Federal Aviation Administration, U.S. DOT, provided technical peer review and comments for the final draft report.

Finally, Robert Gaumer, formerly of Chenega Advanced Solutions and Engineering, LLC (CASE) provided extensive editorial review and reorganization of the initial Hughes draft report; Barbara Siccone, formerly of CASE, provided extensive formatting and typing support for the draft final report; Cassandra Oxley, MacroSys, LLC, and Chinenye Okparanta, Hawley-Thomas Enterprises, Inc., provided editorial review of this final report. Ms. Okparanta prepared the report for FRA Web publication.

CONTENTS

CONTENTS

ILLUSTRATIONS

TABLES

EXECUTIVE SUMMARY

U.S. intercity passenger and commuter rail train system operators have maintained a very good safety record, and the number of passenger trains involved in accidents or other emergency situations is low. The majority of passenger train emergencies are usually resolved quickly and evacuation from the train is not necessary since passengers are generally safer if they remain on the train. Nevertheless, emergency situations continue to occur and, at times, they result in occupant casualties. In certain cases, the delay, difficulty, or inability of passengers and crew to evacuate the train can contribute to the number and severity of casualties.

The majority of Federal Railroad Administration (FRA), U.S. Department of Transportation (U.S. DOT) regulations for passenger train emergency systems are specified in Title 49, Code of Federal Regulations (49 CFR), *Part 238*, *Passenger Equipment Safety Standards* and *Part 239, Passenger Train Emergency Preparedness.* The intent of the FRA regulations is to ensure the safety of intercity and commuter rail passengers and crew, as well as the safe, timely, and effective evacuation of passenger trains when necessary during emergencies.

FRA's Office of Research and Development is sponsoring an ongoing research program that is investigating how to enhance the safety of passengers and crew during passenger train emergencies. One aspect of the FRA research program is directed at evaluating the potential applicability to passenger trains of performance-based criteria which specify evacuation times.

Emergency egress from a passenger train is a complex process that depends on a number of dynamic factors and conditions. Many variables that affect the time necessary for passengers to exit from a passenger train in an unusual or emergency situation must be considered.

No methodology currently exists for evaluating the passenger rail car emergency egress system as a whole, or the effects on egress times of failures within this system.

Several methods have been used to establish transportation vehicle occupant egress time: 1) hydraulic hand-calculation and analysis, based on the number of occupants and simple exit routes; 2) simulated emergency evacuations or egress experiments, during which occupants exit from the actual vehicle; or 3) analysis using an egress computer model. Building occupant egress data are readily applicable for use with these available analytical tools for estimating emergency egress times. However, none of the building egress models have been validated using actual passenger rail car occupant data. In addition, individual agility and physical obstacles have a significant impact on the amount of time necessary for persons to exit from a passenger rail car, depending on its location.

Various existing egress models were evaluated for their capability to predict the time necessary to evacuate U.S. passenger rail cars under various emergency conditions. Passenger car egress variables were also reviewed to determine their usefulness as data inputs to an egress computer model. Passenger rail car designs were reviewed, representative evacuation scenarios were developed, and necessary data inputs were identified for modeling purposes.

With adaptation, certain egress simulation computer models could be expected to provide reasonable predictions of necessary egress times for different passenger rail car types with the rail car upright and passengers exiting either from one upright car to the adjacent car, onto high or low station platforms, or to the right-of-way (ROW).

Data from actual passenger rail car egress experiments provide a key means, when combined with known physical characteristics of each type of individual, physical characteristics of the rail car, and the operating environment at the time the data were recorded, to validate egress time predictions for upright cars generated by these egress simulation computer models. However, because of the inherent risk of injury to participants, passenger rail car egress experiments that provide egress-related time data involving higher-risk emergency scenarios (egress from cars overturned or extremely tilted on their sides, egress from exit windows, egress of severely mobility-impaired occupants, etc.) to validate the egress models may not be feasible.

1. INTRODUCTION

U.S. intercity passenger and commuter rail train system operators have maintained a very good safety record, and the number of passenger trains involved in accidents or other emergency situations is low. The majority of passenger train emergencies are usually resolved quickly and evacuation from the train is not necessary since passengers are generally safer if they remain on the train. Nevertheless, emergency situations continue to occur and, at times, they result in occupant casualties. In certain cases, the delay, difficulty, or inability of passengers and crew to evacuate the train can contribute to the number and severity of casualties.

The majority of Federal Railroad Administration (FRA), U.S. Department of Transportation (U.S. DOT) passenger rail equipment regulations related to emergency systems are specified in Title 49, Code of Federal Regulations (49 CFR), *Part 238, Passenger Equipment Safety Standards* [1] and *Part 239*, *Passenger Train Emergency Preparedness* [2]. The intent of these requirements is to ensure the safety of intercity and commuter rail passengers. FRA first issued extensive emergency preparedness and emergency system equipment regulations in 1998 and 1999 [3] [4]. FRA issued subsequent revisions to these regulations, most recently in 2008 [5]. In early 2012, FRA also indicated the intent to further revise the regulations to further enhance passenger and train crew safety during emergency situation in a new notice of proposed rulemaking [6].

The FRA Office of Research and Development has sponsored an ongoing research program that is investigating a variety of emergency evacuation concepts, strategies, and techniques for applicability to U.S. passenger trains and to assist in further enhancing emergency systems requirements specified in *Part* 238 [1] and *Part 239* [2]. As part of the FRA research program, the John A. Volpe National Transportation Systems Center (Volpe Center), Research and Innovative Technology Administration (RITA), U.S. DOT is assisting FRA in evaluating the potential feasibility of specifying performance-based criteria for passenger rail car egress times.

No methodology currently exists for evaluating the passenger rail car emergency egress system as a whole, or the effects on evacuation times of failures within systems.

1.1 PURPOSE AND SCOPE

The purpose of the study described in this report is to assist FRA in evaluating the applicability of performance-based minimum evacuation time standards for passenger rail cars to supplement existing prescriptive regulations for emergency exits and related emergency systems. The study scope focused on the potential application of computer models to predict U.S. passenger rail car egress times. With adaptation, egress computer models could potentially provide reasonable estimates of the minimum egress times necessary for different rail car types with the rail car upright with passengers exiting from one car to the next adjacent car, out onto a station high or low platform location, or to the right-of-way (ROW). Although more difficult, it may also be feasible to provide passenger egress time estimates for when the rail car is not in an upright position.

1.2 OBJECTIVES

Various existing egress models were evaluated for their capability to predict the time necessary to evacuate U.S. passenger rail cars under various emergency conditions. Passenger car egress variables were also reviewed to determine their usefulness as data inputs to an egress computer model. Passenger rail car designs were reviewed, representative evacuation scenarios were developed, and necessary data inputs were identified for modeling purposes.

1.3 BACKGROUND

1.3.1 U.S. DOT Prescriptive Vehicle Egress Design Requirements

FRA [1] [2], the Federal Aviation Administration (FAA) [7], and the U.S. Coast Guard (USCG) [8], respectively, require that passenger rail cars, commercial passenger aircraft, and passenger ships comply with extensive prescriptive emergency egress-related design requirements for the number, type, location, identification, and operation of emergency exits; and the type, location, operation, and duration of emergency lighting. The National Highway Traffic Safety Administration (NHTSA) also requires that large buses and school buses comply with specific emergency exit requirements depending on the type and size of the bus, but does not currently require emergency lighting [9]. The general principle, whatever the type of public transportation vehicle, is that provision of clearly identified emergency exits that are easily operable will allow occupants during an emergency to effectively and efficiently evacuate, when necessary, to a point of safety.

1.3.2 Performance-Based Vehicle Design Requirements

A "performance-based" systems approach to emergency egress recognizes that addressing one aspect of the "system" in isolation does not always yield the best outcome for the desired objective of occupant safety. For example, the time necessary for passenger train crew decision-making and providing instructions to passengers may have a greater influence on passenger evacuation from a passenger car in an emergency than the number, type, location, and operation of emergency exits. Accordingly, since it is usually safer for passengers, due to other hazards such as passing trains, to remain on board the train during the majority of emergencies, focusing only on passenger rail car exits could result in a lower level of passenger safety.

As previously noted, FRA,[*] FAA, and USCG regulations specify prescriptive design requirements related to emergency exits and related emergency systems for passenger rail cars, commercial aircraft, and passenger ships. In addition, FRA, FAA, and USCG regulations contain minimum requirements for the proper training of crews in procedures to evacuate passengers during emergency situations.

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[*] As of the date of the original report (April 2013), FRA requires emergency lighting only for new equipment ordered on or after September 8, 2000, or placed in service for the first time on or after September 9, 2002.

However, aircraft and ships are currently the only U.S. public transportation vehicles specifically required to demonstrate emergency evacuation time capability. FAA requires that transport aircraft carrying more than 44 passengers be shown to be capable of being evacuated in 90 seconds or less [10]. USCG requires that, when transporting passengers in international waters, U.S.-registered ships comply with International Maritime Organization (IMO) guidelines [11] specifying completion of an evacuation analysis which demonstrates that a ship can be evacuated within 60 minutes. The IMO guidelines have been established in recognition of the hazards (e.g., fire, hull damage, etc.) likely to be encountered in maritime operations, as well as the availability and effectiveness of emergency exits, associated safety equipment, and life support systems.

U.S. DOT agencies do not currently specify emergency evacuation time requirements for buses or passenger trains.

Extensive egress time studies have been conducted for a range of public structures, from high-rise office buildings to stadiums and mass transit stations. In addition, FAA sponsored and conducted several emergency evacuation studies, which are further discussed in Chapter 2.

1.4 TECHNICAL APPROACH

Volpe Center developed the following work plan to investigate the feasibility of using egress computer models to evaluate how quickly passengers and crew are able to evacuate passenger rail cars in various emergencies:

Task 1: Review and evaluate literature on existing public transportation vehicle requirements, research studies, and existing publicly available egress models for applicability to passenger rail car egress. In addition, emergency egress time considerations will be identified. Egress models will be evaluated for their potential applicability to passenger rail cars. A series of likely emergency egress scenarios will be identified, along with necessary critical data inputs.

Task 2: Design and conduct a series of egress experiment “trials” using: different types of passenger rail cars; a variety of participants, in multiple scenarios; and, if feasible, low-ambient (i.e., emergency) light conditions. These trials will provide actual data for analysis of the selected scenarios identified in Task 1.

Task 3: Develop an egress computer model including: related modeling tools for different types of passenger rail car geometries and emergency scenarios. Significant occupant behaviors and times based on the results of Tasks 1 and 2 will be used as inputs to the model. Model test, evaluation, documentation, and validation will be completed.

Task 4: Using the completed egress computer model, develop a library containing U.S. passenger rail car geometries, as well as time estimates for occupant egress from individual rail cars and complete trainsets (and consists), using a variety of exits and exit routes.

This report presents the results of Task 1. The results of Task 2 are summarized in a research brief published by FRA [12], and more extensively described in another Volpe Center-prepared report, published by FRA in 2012, which describes single-level commuter rail car egress experiments conducted in 2005 and 2006 [13]. The results of the egress computer model development (Task 3) are expected to be published by FRA in 2013. Task 4 is still in progress.

1.5 REPORT ORGANIZATION

Chapter 2 summarizes the results of an international literature review of egress time prediction research.

Chapter 3 summarizes the results of a review of selected National Transportation Safety Board (NTSB) investigations of accidents involving passenger rail car emergency egress and discusses egress time variables.

Chapter 4 summarizes current methods for predicting passenger rail car egress times.

Chapter 5 presents the results of a review of the types and capabilities of existing egress computer models and discusses their applicability to typical passenger train emergency egress scenarios.

Chapter 6 describes various rail car emergency scenarios for potential egress modeling studies and identifies potential data inputs for egress computer models.

Chapter 7 contains a summary of the report.

The Appendix contains a bibliography of selected U.S. transportation modal agency and selected international regulatory organization regulations, research, and guidelines related to public transportation vehicle emergency egress.

2. EMERGENCY EGRESS TIME

2.1 LITERATURE REVIEW

A follow-up literature review was performed to supplement preliminary searches previously conducted by Volpe Center staff (and Hughes Associates in 2003) in order to identify research conducted for human behavior and crowd characteristics potentially relevant to passenger rail car egress variables and emergency evacuation.

The literature review identified only a few studies that specifically focus on passenger train evacuation. However, documents relevant to specific aspects of passenger rail car emergency egress were identified, including variables that affect egress time. These are discussed in the remainder of this chapter. The Appendix contains a bibliography of selected U.S. transportation modal agency and selected international transportation vehicle regulations, research, and guidelines related to public transportation emergency evacuation. (An extensive list of other documents describing a variety of egress computer models is contained in Chapter 5.)

2.2 PASSENGER RAIL CAR EMERGENCY EGRESS TIME PREDICTION

The typical means to establish transportation vehicle occupant egress times has been to conduct simulated emergency evacuations or egress experiments, during which occupants exit from the actual vehicle. However, such “demonstrations” have significant cost, as well as safety and health issues. The safety issues include slipping, tripping, or falling by the participants. A major challenge to conducting a valid test of egress behavior and safety features is how to create a realistic test without putting individuals at significant risk of injury. Consequently, the use of analytical methods, such as computer models that have been developed to simulate egress behavior, could reduce the number of actual egress tests that need to be performed to determine egress times for various passenger rail car designs. These models can make use of actual occupant egress rates (data inputs) obtained from prior egress studies and vehicle evacuation certification trials. In addition, using an egress computer model may permit many more passenger rail car emergency egress system designs to be evaluated in a far shorter time period and at less cost than lengthy and complicated hand-recorded data and subsequent calculations.

The development of an analytical methodology to predict the minimum necessary egress time for passengers and crew from a passenger rail car to a point of safety could provide a tool to evaluate the performance of specific egress design features within the design of the overall “emergency egress system” for a representative set of emergency egress scenarios.

2.3 EMERGENCY EGRESS TIME PERFORMANCE CRITERIA

An emergency egress performance criterion for passenger rail cars could be that the minimum time necessary for passengers to exit from the rail car (i.e., *necessary* egress time) must be shorter than the *available* emergency egress time. (Available egress time is defined as the time provided by the materials and design of the car before the interior of the car becomes untenable due to fire, smoke, or other hazardous conditions.)

Therefore, an appropriate safety criterion for a passenger rail car could be that the minimum *available* egress time must be longer than its actual *necessary* emergency egress time. This safety criterion is important, especially in the FRA progression from prescriptive safety design standards for passenger train safety toward performance-based standards. Thus, it is critical to determine both the minimum *necessary* egress time period required by occupants to exit from passenger rail cars of any design, as well as the minimum *available* time to evacuate the rail car safely when necessary.

2.4 EGRESS TIME STUDIES

Although theoretical evacuation time studies for passenger trains have been developed by consultants for the Amtrak *Acela Express* high-speed intercity passenger rail trainset cars [14] and MARC commuter rail passenger cars [15] (see Chapter 4), very few passenger rail car egress time estimates are based on actual evacuation times since these data are often not publicly available. As a result, the majority of theoretical passenger rail car egress time studies that have been previously conducted rely primarily on building occupant egress flow rate estimates. Accordingly, a limited number of scientifically designed experiments using a human factors "systems" approach, are available to provide actual egress time data for evacuation from passenger rail cars. Thus, it is not currently possible to have the same level of confidence in emergency egress data and time predictions for passenger train emergency evacuation as those calculated for buildings, aircraft, or ships. Moreover, the differences between the passenger train operating environment related to emergency egress and the emergency egress environment of buildings, aircraft, passenger ships, and buses, as well as occupant characteristics and behaviors, may all contribute to significant differences in exit path routes taken and other egress behaviors of occupants, and thus alter the actual necessary egress times.

As part of the FRA-sponsored occupant safety research program, a series of fire hazard analyses using a modified version of a fire growth zone compartment computer model was conducted. This fire growth model was configured to generate a series of fire performance design curves, based on heat release rate (HRR), to determine untenable (e.g., life-threatening) conditions and egress times for three intercity passenger rail car types [16]. Although proof of concept for the computer fire modeling application to passenger rail cars was demonstrated, calculations of the minimum *necessary* egress times were based on a theoretical average (based on building and aircraft data) for all passengers using the rail car end doors as the preferred evacuation route to go from one car to the next, under nonpanic "fire drill" conditions. (For example, the egress time for 72 passengers to exit a single-level coach was calculated as 88 seconds.) Egress times for other egress scenarios, such as using side doors to exit from the rail car to a high-platform station, or down steps to the right-of-way (ROW) track bed using stairway steps, were not calculated.

Reliable actual egress flow rate data for occupants using the passenger rail car end doors, as well as side doors to other egress locations (e.g., high- and low-platform locations and the ROW) could increase confidence in the accuracy of the predicted minimum necessary egress times versus actual occupant egress times.

2.4.1 Passenger Rail Car Egress Studies

2.4.1.1 *Volpe Center Egress Experiments*

Volpe Center staff conducted a series of passenger rail car egress experiments using a single-level commuter rail car. The experiments were conducted in 2005 and 2006 and detailed results are described in Reference [13]. In the 2005 experiment, which was conducted at a high-platform station, 84 participants exited under either emergency or normal lighting conditions from the rail car to either an adjacent car or to the station platform, using either one or two side doors. To the authors' knowledge, the 2005 commuter rail car experiment was the first time that U.S. passenger rail car egress time trials were conducted with regular commuter rail passengers as "test" participants.

Two follow-up experiments were conducted by Volpe Center staff in 2006. The experiments consisted of a series of more limited egress trials for 15 and 17 Volpe Center individuals, respectively, who exited from one commuter rail car side door using the stairway step, either to the ROW (track level) using a step box, or to a paved surface simulating a low-platform station.

The Volpe Center egress experiment data were collected to assist in establishing estimates and norms for passenger rail car egress times and to evaluate various aspects of car design that may impede prompt emergency evacuation.

Participant egress flow times in terms of persons per second (pps) (persons per minute (ppm)) varied significantly by the number of door exits used and the exit route taken from the commuter rail cars. The results are summarized in Table 1.

Table 1. Volpe Center 2005 and 2006 Egress Experiment Results

EGRESS PATH ROUTE	AVERAGE ELAPSED TIME TO FIRST PERSON OUT (s)	AVERAGE FLOW RATE PER DOOR# (pps / ppm)
High platform / adjacent car	5	0.88 / 52##
Side-door stairway to low platform	6	0.70 / 41
Side-door stairway to ROW	9	0.34 / 20

\# Representative of best-case conditions which do not reflect actual emergency conditions
\## Values are rounded

It is emphasized that the 2005 Volpe Center commuter rail experiment egress trials were conducted under most favorable conditions to establish a baseline for egress computer model calibration verification and for comparisons with the 2006 egress trials, which were conducted under conditions that would more closely approximate an emergency scenario requiring evacuation to a location other than a high-platform station.

2.4.1.2 *British Passenger Train Studies*

The Railway Safety and Standards Board (RSSB), United Kingdom (UK), was established to carry out research and develop rail industry-wide standards for the national railroad network, following the privatization of passenger train operations in the UK. In particular, RSSB sponsored a number of studies to respond to a 1999 passenger train accident that resulted in numerous casualties, including 29 deaths [17]. These studies included the performance of passenger rail vehicle evacuation time exercises and the development of a "Stay or Go" evacuation risk model to estimate the probability of fatalities and injuries to passengers if they evacuated a passenger train or remained on the train under various emergency scenarios. The 2002 report documenting the results of the risk model study indicated that in the majority of cases, it was safer for passengers to remain on the train rather than be evacuated immediately [18].

Evacuation experiments conducted for Virgin Railways in 2001 and 2003 became the basis for inclusion of requirements in a RSSB Railway Group Standard [19], which specifies that the total evacuation time to a high platform must not exceed 90 seconds, with a minimum egress flow rate of 40 ppm (0.67 pps). For evacuation to the track level from an end door, the minimum required egress flow rate is 30 ppm (0.5 pps). For example, the required evacuation times for a fully-loaded car with 100 seated passengers would be 149 and 200 seconds (2.5 to 3 minutes), to the high-platform and ROW (track level) locations, respectively.

In addition, the RSSB commissioned two projects that analyzed passenger train escape and evacuation data and included recommendations for the specific types of human factors data to be collected during accident investigations [20] [21]. An extensive appendix contains examples of the detailed human factors data considered necessary to obtain during accident investigations.

In 2000, the First Great Western Rail company conducted an experiment using four passenger rail cars that simulated an evacuation due to a fire on board a stopped high-speed train [22]. More than 100 persons took part in the simulation, including children and individuals with mobility impairments. The exercise was designed to test the effectiveness of existing safety measures, such as information notices, lighting, and other emergency procedures, as well as measures being considered for the future. Smoke was used and normal lighting was turned off. However, detailed information for evacuation time or egress flow rates is not publicly available.

In 1999, the University of Greenwich conducted two full-scale experiments involving noncompetitive (e.g., orderly) evacuation of 32 persons from the open end doors of an overturned "standard" passenger rail car having a seated capacity of 62 persons, with and without theatrical smoke [23]. The participants were positioned lying down in the car to simulate their having fallen out of their seats. (The occupants had been told beforehand during both experiments that one end door would be unavailable but not which one.) During the first trial, the average occupant flow rate was 8.7 ppm (0.15 pps), with a total time estimate of 3 minutes and 34 seconds for 62 persons to evacuate the car, using both ends of the car; and a time estimate of 7 minutes and 8 seconds, with only one car end used. During the second experiment, which introduced nontoxic smoke into the car, the average occupant flow rate was 5 ppm (0.08 pps) from one end of the car, with a time estimate of 13 minutes and 19 seconds to evacuate the full load of 62 passengers. Smoke was found to slow the egress flow rate because of visual obscuration. However, egress time was shortened by increasing the number of train crew overseeing the evacuation, as well as the removal of interior dividers in the rail car. Study recommendations included: provision of internal doors that slide open from both directions; an escape hatch in the car roof; airline style luggage compartments to contain luggage; and "pop-out" windows to make access by rescue personnel easier and permit possible escape by passengers.

A 1997 conference paper discussed criteria for the design and evaluation of passenger train emergency evacuation exercises from a human factors perspective [24]. A major point of the paper stated that the accuracy of predictions for crowd control is dependent on proper crowd management. The paper also stated the importance of testing public response and behavior, as well as the interactive effects of emergency systems, procedures, and staff training, rather than just incorporating predicted crowd behavior into the emergency plan.

A 1994 conference paper addresses the importance of using a technical model to estimate evacuation times for passenger rail vehicles during an accident occurring in a tunnel [25]. The study concludes that the model should provide a means to quantify evacuation time from a passenger rail car by understanding the movement of passengers during a crisis situation and that the model should be validated against known accident scenarios. No particular model is recommended for passenger rail car evacuation, but the importance of a mathematical model is stated.

In 1991, evacuation experiment trials were conducted by the Cranfield Institute (now University of Cranfield), UK, for a single British Mark III passenger rail coach with 76 seats, to evaluate the egress times with different passenger loads during noncompetitive and competitive evacuations for an intercity car [26] [27] [28]. Noncompetitive evacuation is defined as orderly movement (i.e., without high motivation and with no pushing) to an exit by occupants. In contrast, competitive evacuations are not orderly and can be induced by the immediate threat to oneself or family members in an actual emergency or, in the case of experiments, by financial reward. The participants were mostly students, who were paid ₤10 (about $18 in 1991) for attendance with an additional ₤5 (about $9 in 1991) if they were among the first half of the subject pool to exit during the competitive trials.

Passengers were allowed to evacuate through all doors on one side of the vehicle onto a station platform. In the fully-loaded trials (76 seated participants), egress to a high platform through the side doors was completed in 53 seconds in the noncompetitive trials and 39 seconds in the competitive trials. These times imply egress flow rates of 43 and 58 ppm (0.72 and 0.97 pps) per door, respectively. Competitive evacuation times were faster than noncompetitive evacuations at 100 percent of seating capacity. However, when a trial was attempted with 103 persons (135 percent of capacity), injuries occurred and the trial was stopped at the point at which only 89 individuals had exited. This increase in injury potential with high-passenger densities in competitive conditions is consistent with aircraft evacuation study results. The study report also discusses certain aspects of passenger rail car geometry and the operating environment that may affect evacuation, including interior features, such as barriers, drop-down tables, and armrests, and provides related recommendations on how to improve evacuation.

2.4.1.3 *Austrian Passenger Train Study*

The Austrian National Railways (ÖBB), in conjunction with Vienna University of Technology, conducted two evacuation trials for a new commuter rail car type using three cars, which are described in a 2007 report [29].[**] The center car had two sets of side doors, while the end cars had one set of side doors. Both trials involved the same 192 persons and the use of nontoxic smoke located in different areas of the train, which was assumed to be moving. One trial simulated a train on the normal ROW while the second simulated a train in a tunnel. The closed car doors were opened after 2 minutes to permit people to exit onto the ground or platform for which there was a drop of about 26 in (65 cm). In the first trial, the smoke was generated in a toilet in one of the end cars; after 2 minutes all the side doors on the platform side of the train were opened and the participants exited. For the second trial, the smoke was generated in the other end car and use of the set of side doors in that car was blocked, making it necessary for individuals to move to the next adjacent car to exit. In addition, the doors were not opened for 15 minutes, simulating the delay in reaching an evacuation location safer than the tunnel. Most of the observations recorded are qualitative and refer to passenger behavior and included references to acoustic messages, signage systems (particularly in smoke), operating instructions, and the height of the drop from the car to the ground.

The exit flow rates in both egress trials were approximately 1 pps. Using the exact flow rate value (1.03 pps) and the average exit time of 60 seconds when using more than one door, the ppm was calculated as approximately 62 for both high-platform and adjacent car egress and egress to the ROW. However, the number of persons who were in each car was not provided in the cited reference. (An additional report (in German) which further describes the two egress trials provides more information for car exit times [30].) Since the only verbal instructions were via an audio link, and there was no train crew, another important observation was the role of "leaders" among the passengers who took charge and directed the evacuation.

2.4.1.4 *Spanish Passenger Train Study*

The Spanish Railroad Administration (RENFE) conducted a series of high-speed trainset evacuation drills in 2009, which were later analyzed by the University of Cantabria to develop egress flow rates [31]. The 218 participants in the 2009 drills were railroad employees and some of their family members. All participants in the 11-car trainset (which included 1st and 2nd class cars and a lounge car) were required to use car end doors to move through the train and then use only a single car side door exit from one car to a 5-foot, 10-inch (1.7-meter)-wide platform walkway along the tunnel wall. (There was a height difference of (9.8 in) 25 cm between the "exit" rail car floor and the walkway platform, and a gap of 15.7 in (40 cm) from the door threshold to the edge of the platform. Participants had no luggage, but were allowed to gather personal belongings and carry them out during the drills. Participants were often observed to behave deferentially to each other; in particular, men often stopped to allow ladies first. The 2009 passenger flow rate result was approximately 0.57 pps (35 ppm).

[**] Information was derived from Austrian report information provided by University of Greenwich.

To take a more comprehensive view of emergency evacuation, and reflect actual real-world passenger evacuation, the data collection and analysis framework of the Spanish research team included the following elements:

- Pre-evacuation Stage
  - Time from ignition to detection,
  - Time from detection to sounding of alarm,
  - Time for passengers to recognize alarm,
  - Time to decide how and which way to move,
  - Movement within the train before it stops;
- Evacuation Stage
  - Opening doors, deploying emergency ladders, and
  - Actual movement of passengers off the train.

Results from the 2011 Spanish paper imply that (1) default values in current building egress models may not be adequate for passenger trains, because of the need to stop the train before evacuation begins, differences in passage widths, and stair riser heights, etc., and (2) different coaches can produce different response times depending on the timing of information about the emergency. In addition, when passenger rail cars are not fully occupied, response time is a key parameter in determining the total evacuation time. Otherwise, the total evacuation time depends on the flow capacity of the exits.

The time to stop a high-speed train travelling at full speed was estimated by the authors to be 3 minutes and can be much longer in some situations.

2.4.1.5 *Summary*

Data from the Volpe Center-conducted egress experiments for U.S. passenger rail cars, as well as similar rail car emergency evacuation experiments conducted in the United Kingdom, Austria, Spain, are reasonably consistent with regard to egress to a high platform or an adjacent car – the egress flow rate is slightly less than 1 pps (60 ppm), as shown in Table 2.

However, if passengers must traverse an elevation difference substantially greater than normal stairway step heights, as is typically the case in passenger train evacuations to the ROW, egress flow rates become much more variable. To avoid the risk of injury to persons of low agility, some experiments have excluded exiting to the ROW entirely, or tested this path using only young, physically fit participants. As a result, reported egress flow rates for egress from a rail car to the ROW range from below 6 to 60 ppm (0.1 pps to about 1 pps). However, the experiment participant populations are often unrepresentative of the general traveling public.

In an actual time-critical passenger rail evacuation to the ROW, it is likely that to expedite egress it will be necessary for train crew members and physically fit passengers to assist persons with mobility impairments who have difficulty getting down from the car door the low platform or ROW due to the varying distance between door threshold and the track level. However, due to the risk of injury, very limited experimental egress data are available for persons with mobility impairments.

Table 2. Comparison of Rail Car Egress Flow Rates – Recent Experiments

EGRESS PATH ROUTE	U.S. (Volpe / MBTA) (pps / ppm)#	UNITED KINGDOM (pps / ppm)#	AUSTRIA (pps / ppm)#	SPAIN (pps / ppm)#
Side door to high platform or end door to adjacent car##	0.9 / 52	0.7–0.9 / 43–55	~1 / 62	-
Side door to tunnel side platform walkway###	-	-	-	0.6 / 34
Side-door stairway to low platform####	0.7 / 41	-	-	-
Side-door stairway to ROW##### and platform #######	0.3 / 20	-	~1 / 62-	-

\# All numbers have been rounded.

\## Noncompetitive / competitive.

\### 9.8-in (25-cm) height from door threshold to platform and 15.7-in (40-cm) gap from door threshold to platform.

\#### 15-in (38-cm)-height difference from bottom of last step of side-door stairway to pavement.

\##### 25-in (63.5-cm)-height difference from door threshold to platform.

\###### 26-in (65-cm)-height difference from bottom of last step to track level.

2.4.2 Aircraft Evacuation Studies

2.4.2.1 *FAA/CAMI*

The Appendix of this report contains a complete listing of FAA/Civil Aerospace Medical Institute (CAMI) aircraft-related evacuation studies.

CAMI has conducted an extensive research program to determine the effects of type, size, location, and operation of emergency exits, as well as emergency lighting and “floor proximity” escape path marking on the time required by passengers and crew to evacuate from aircraft. CAMI also funded several studies related to the development of a computer model for aircraft emergency evacuation time prediction [32] [33] [34] [35].

For example, in well-controlled tests conducted by CAMI during the 1990s, 174 adults between 18 and 40 years of age repeatedly exited an aircraft fuselage mockup [36]. The door openings were 30-inch (76-centimeter) wide in all tests, but door heights ranged from 4 to 6 ft (1.2 to 1.8 m). Just outside the door was either a slide or a platform at the same height as the door sill. For the condition most similar for egress from a passenger rail car (to a low-platform or ROW location), the average egress flow rate was about 2 pps (114 ppm), using a 6-foot (1.8-meter)-high door to the platform). This relatively high rate is consistent with the relatively younger age of the FAA test participant population.

Egress flow rates through aircraft over-wing window exits (“Type III”) have been a particular topic of interest to FAA. In a 2001 meta-analysis of the factors relating to “Type III” exits [37], the findings applicable to passenger rail car egress included the following:

- Human factors effects predominate in controlling evacuation performance and obscure the effects of other evacuation factors. Controlling human factors (and other confounding effects) is necessary to clarify the effects of other factors, such as passageway configuration.
- Passageways between 13- and 25-inch (33- and 64-centimeter) wide provide essentially equivalent egress flow rates, whereas those with narrower widths (especially for older passengers) are less effective. Widths above 25 in (64 m) show slightly lower flow rates in competitive trials because two subjects may attempt to pass through at the same time.
- Blockages of the Type-III exit by participants during competitive evacuation trials are related more to the attitudes and motivation levels of individuals than to passageway configuration, as blockages or extremely delayed evacuations have occurred for almost all studied passageway widths.
- Information materials, such as safety briefing cards related to emergency evacuation activities, have been poorly rendered; consequently, passengers either cannot understand the intent of the materials or do not feel obliged to read and follow the instructions.
- Directions from a flight attendant can organize passenger behavior during both actual and experimental evacuations without producing idiosyncratic effects or interactions that necessarily render the results of evacuation studies inapplicable to rulemaking.

The implication of the FAA/CAMI studies is that only individual-movement egress computer models are capable of incorporating all of the factors that affect egress time because these models are able to establish consequences of human response based on the specific scenario conditions. Of particular significance is the fact that the linear relationship between the width of passageways and the passenger flows through them, characteristic of hydraulic building egress models, breaks down for the narrow aisles of aircraft and passenger rail cars because faster individuals are not able to pass slower-moving individuals.

Several of the FAA/CAMI studies also discuss the importance of the design of evacuation experiments, noting that the variable factors evaluated during a series of evacuations may be affected by other factors. For example, in one report evaluating the effect of seat row and bulkhead passageway width on occupant access to the exit, the study authors observed that placement of the exit hatch after it was removed had a variable impact on the results [38]. The inconsistent placement of the hatch resulted in discrepancies in the data that could have been avoided by having the participants place the exit hatch in the same location during each test.

2.4.2.2 *CAA/FAA*

The Civil Aviation Authority (CAA), UK has sponsored two aircraft evacuation time studies, the latter of which was conducted in coordination with the FAA [39] [40] [41].

The aircraft evacuation experiments conducted by the University of Cranfield, UK, evaluated the effects on evacuation times of: 1) passenger motivation, 2) the width of the bulkhead opening leading to a door exit, and 3) the width of the passageway leading to over-wing exits. The competitive behavior of passengers was established by the prospect of a financial reward.

In the evacuations using the door exit, the influence of the opening between the two bulkheads leading to the exit was dependent on whether the evacuation was orderly or competitive. In orderly evacuations, changing the width of the opening did not have an impact until one of the bulkhead walls was completely removed.

Competitive evacuation times decreased with an increase in opening width; however, these evacuations had an initial surge of people toward the exits, which caused congestion in the vicinity of the exit. The fastest evacuation time recorded was again achieved with one of the side bulkhead walls removed; however, this configuration also resulted in other difficulties. With one bulkhead wall removed, the surge to the rear door exit by people was so sudden that the cabin staff member had difficulty opening the door; she was, in a number of trials, pushed out of the aircraft by the occupant surge.

In the evacuations through the over-wing exit, effects on evacuation time were evaluated for: 1) variable longitudinal spacing between seats adjacent to the exit row and 2) removal of the outboard seat. Evacuations were slowest when the seats adjacent to the exit were separated by a 3-inch (7.5-centimeter)-wide passageway between the rows, while seat row passageways to the exit that were 6–25 in (15–64 cm) in width resulted in approximately the same evacuation times. Competitive occupant evacuations with the 3-inch (7.5-centimeter)-wide passageway between seat rows caused blockage due to congestion at the exit opening, severe enough that the evacuation had to be stopped in three of the trials. Noncompetitive orderly evacuations using a 34-inch (85-centimeter)-wide passageway to the exit resulted in about an approximately 5 second faster time. However, this wider passageway to the exit resulted in the formation of two lines of occupants who then competed for use of the exit. A similar result was obtained when the increased room adjacent to the exit resulted in passenger lines in front of and in back of the exit row seats. Again, occupants competed for the exit.

Tests conducted on an aircraft with two deck levels to evaluate the difference in evacuation times between the lower and upper decks showed that occupant hesitation times at the upper-deck escape slides were higher, indicating that passengers will delay egress more at exits located higher above the ground [42].

The European Transport Safety Council (ETSC) conducted a study that reviewed various aircraft crashes and investigated the idea that all airplane crashes lead immediately to death [43]. The study paper stated that providing training to crew and cabin staff and maximizing the opportunity for an orderly evacuation can increase the chance that passengers survive a transportation accident.

2.4.3 Bus Evacuation Studies

During the 1970s, NHTSA (then National Highway Safety Bureau) commissioned the University of Oklahoma to study evacuation from school buses and intercity buses. The published reports provide important insights into the ability of people to safely exit a bus after an accident, especially if the accident renders the main entrance and exit door(s) unusable [44] [45] [46]. The significant findings potentially applicable to passenger train egress time are summarized below:

- Exits are usually not used in optimal fashion. Passengers do not minimize the total egress time; they will take the path that seems best to them at the time.

- Passengers are reluctant to use exits that require a multistep process to initiate, e.g., emergency exit windows with a latch system that needs two hands and two operational steps to open.
- Children are very reluctant to jump from window exits and are more likely to queue at a door exit than to use an available window exit.
- For vehicles overturned onto their sides, end doors and roof hatches are the best exits. The drop to ground from a roof hatch is 2 to 4 ft (.6 to 1.2 m), compared with over 7 ft (2.1 m) for windows. Roof hatches on all buses were recommended.
- Pre-trip instructions on use of exits and other emergency considerations were recommended.
- Operation of emergency exits should not require more than 35 lbs of force.
- Emergency exit design needs to consider how to reduce chance of injury and accommodate use by the obese, aged, disabled, and injured.
- Emergency lighting is needed in all vehicles.
- Effects of low visibility are magnified in overturned vehicles.

A more recently completed Volpe Center study in 2009 included the measurement of egress flow rates by occupants who exited from a typical intercity bus and from a mock-up bus [47]. In the first case, participants exited from an actual intercity bus using the front door and alternative exits, such as emergency exit windows and roof exit hatches, under daylight conditions. In the second case, participants exited from a bus mockup using a simulated second side-door stairway, as well as from two wheelchair-access doors of different widths, under various lighting conditions. The study report indicated that "normal" egress times for able-bodied adults during an evacuation from a fully loaded motorcoach, using any of the tested egress paths and exits, could be less than three minutes. However, the finding with application to passenger rail car emergency egress is that occupant egress flow rates are likely to be considerably longer if:

- Passengers do not understand how to open or use the emergency exits.
- Passengers cannot find or see how to use the emergency exits because of darkness or smoke.
- Passengers are injured or lack the agility and strength to use emergency exits, other than doors.
- Exits will not stay open (or are unusable due to blockage or damage).

2.4.4 Other Related Studies

Occupant selection of an exit has been shown to depend on a number of variable factors. Two studies determined that people tend to exit from an emergency situation through the door they entered [48] [49]. Those 1996 and 1988 studies found that staff encouragement to use other emergency exits would prompt more people to use alternative exits. These findings indicate that train crew personnel may have a significant impact on passenger rail car evacuation by notifying passengers of their potential exit routes and how to manually open the exits. Another study concluded that staff instructions help reduce pre-movement (e.g., decision-making) times [50], estimated by the 2003 Society of Fire Protection Engineers (SFPE) human behavior engineering guide (SFPE *Guide*) to be as much as 75 percent of total evacuation times [51]. Thus, the reduction of pre-movement times could result in a marked improvement in total evacuation time. Three other studies indicate that instructions during evacuation can aid people in finding exits and moving away from unsafe conditions [52] [53] [54].

2.5 EFFECTS OF SMOKE AND EMERGENCY LIGHTING AND EXIT MARKING SYSTEMS

Numerous studies describe the effects of smoke and emergency lighting on the movement of people toward exits. This section summarizes the results of selected studies, which are relevant to passenger rail car emergency lighting and emergency exit marking.

The University of Greenwich study report cited earlier [23] stated that passenger movement was reduced in evacuation tests conducted inside passenger rail cars with smoke, compared with tests without smoke. Another study concluded that smoke does not affect passenger movement until the optical density[**] of smoke is less than 1.5 [55]. Two other studies cited in the previous section indicate that even when visibility is significantly reduced by smoke, people will continue to move and attempt to find exits, but evacuation times will increase [52] [53]. This finding has been recognized by the 2003 SFPE *Guide* [51]. In addition to reduced visibility resulting from smoke, smoke will also affect the movement of persons as noted in a 1997 paper [56]. Two additional studies found that occupant movement was affected more by visibility through smoke and familiarity with the building layout than by heat [57] [58].

Several other studies evaluating emergency lighting, as well as the visibility and legibility of emergency exit signs and exit path marking, were presented in papers presented at a 2001 conference. One paper concluded that while the effectiveness of emergency lighting and "wayguidance" (i.e., emergency exit signs and exit path marking) systems depended on the illuminance at floor level, visual cues provided by the lighting system were more important in leading occupants to exits [59]. Another conference paper reported that additional overhead lighting did not make it easier to see exit signs, but that signs were most easily seen under emergency lighting or without overhead lighting [60].

In addition, the earlier 1997-cited study determined that exit signs with flashing lights were more effective than continuously lit signs [56]. A 2001 study conference paper concluded that a blue-colored flashing light is most effective, but that the blue flashing light should only be activated during an emergency to bring attention to all alternative emergency exits [61]. However, green was demonstrated to be a better color for lighted signs according to another study paper presented at a 2005 conference [62].

A National Research Council of Canada (NRC) field study of photoluminescent (PL) wayguidance systems, as installed in the stairways of an office building, concluded that the PL systems appeared to be as effective as emergency lighting in providing guidance to the building

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[**] Optical density is the measurement of the attenuation of the test chamber light beam by the quantity of smoke produced and collected in the chamber. The lower the optical density, the higher the visibility of the test object.

occupants who exited down the stairways [63]. A follow-on field study by the NRC evaluated different installations of PL material in building stairways and confirmed that use of this material to mark the exit path was positively commented upon during an evacuation drill, but that the density of the occupants had a greater impact on the evacuation times than the type of PL material used [64]. Another study found that exit finding was improved when PL and tactile markings were used to guide occupants toward exits [65]. The importance of clear visual cues provided by the wayguidance system was also demonstrated in another study in which less clear cues resulted in people not following the specified escape path [66]. That same study also found that audible and tactile wayguidance systems were as effective as visual systems.

2.6 SUMMARY

The studies discussed in this chapter relate to various factors that affect the calculation of emergency evacuation time predictions for theoretical and regulatory purposes. However, major differences exist between the passenger train operating environment and the operating environment of aircraft, buses, and ships. These differences include the type of vehicle seating configurations, the number and type of door and other exits that can be used in an emergency, and the distance the occupant must traverse from the exit to the ground or other safe area. Therefore, it is important to carefully consider the impact of those differences, as well as common egress factors, when selecting variable factors for calculating passenger rail car egress times.

3. PASSENGER RAIL CAR EGRESS TIME VARIABLE FACTORS

The majority of "unusual" or other nonaccident emergency situations can be addressed by the passenger train crew without evacuating passengers because in most cases, it is safer to remain on the train. Some conditions, such as locomotive power failure or derailed locomotives or passenger cars as a result of an accident, may require the transfer of passengers from one train to another or evacuation of the train to another location off the train. If the evacuation of passengers is handled properly by the train crew, the safety of passengers is maintained, and there is a relatively low risk of injury to passengers and train crew.

However, occupant egress time from a passenger train can be a complex process affected by numerous dynamic factors and conditions. Accordingly, these variables and conditions that affect the time necessary for passengers to exit must be considered when developing passenger rail car egress time predictions.

FRA regulations in 49 CFR, *Part 225*, subsection 225.9 require that railroads immediately report a train accident resulting in the evacuation of a passenger train [67]. However, this notification and the FRA reporting form required to be completed by the railroad do not include requirements for specific information, such as number of passengers evacuated from the train, identification of which doors or other emergency exits were used, length of time required for the evacuation or transfer of passengers, or specific actions of the train crew. Since the emphasis of the railroad unusual condition or FRA investigation reports is on the cause of the collision or derailment rather than passenger egress (or emergency evacuation), detailed information concerning passenger egress is usually very limited.

With certain exceptions, the NTSB accident investigation reports and accident brief reports for passenger train accidents normally do not contain any detailed information concerning passenger train evacuation, beyond simply stating that an evacuation took place. The NTSB objective is to identify the probable cause of the accident and issue recommendations for railroads; FRA; state or regional agencies; or industry groups, such as the Association of American Railroads (AAR) and the American Public Transportation Association (APTA). Therefore, in most cases, detailed information concerning passenger egress is usually very limited.

Accordingly, specific passenger evacuation information for egress variable factors is incomplete for the majority of NTSB passenger train accidents described in this chapter. However, it is important to note that the specific evacuation "issues," whether documented or not for certain accidents, may have a major impact on whether an "unusual occurrence" develops into an emergency that results in injuries or casualties to passengers. Thus, the discussion of variable factors in this chapter is intended to provide examples of those egress factors that may or may not be controllable, particularly in terms of input into a passenger rail car egress simulation model, and regardless of their applicability to specific passenger train emergencies.

3.1 RAIL CAR GEOMETRY AND CONFIGURATION

Passenger rail car design factors which have an obvious impact on occupant egress times during emergency scenarios include the following: type and size of car, number of seating levels, width of aisles and stairways (if multilevel), number of doors and exit windows, exit locations, exit dimensions, and construction materials. Other important factors are emergency exit identification, emergency lighting, exit accessibility, design of emergency exit-release mechanisms, and placement and content of instructions for release mechanisms. Special consideration is necessary to address the exit design differences for various configurations of multilevel cars, as well as sleeping cars and food service cars, in order to improve passenger ability for egress from survivable accident scenarios.

FRA regulations contained in *Part 238* and *Part 239* [1] [2] include requirements to address these design factors (e.g., type, number, location, size, as well as exit marking and operating instructions for emergency exits and emergency lighting) since the inaccessibility of doors and other exits in passenger rail cars has been cited in several NTSB accident investigation reports as being the cause of significant evacuation delays. Such delays depended on the severity of the emergency, if passenger car and interior stairways and side and end doors were crushed or damaged, thereby preventing train crew or passengers from opening them.

The NTSB accident investigation report of the 2003 collision of a multilevel commuter train and a freight train in Placentia, CA, found that access from the upper level to the exterior of the rail car was not possible due to substantial crush damage to a stairwell and “misaligned” end doors [68]. Passengers on the upper car level removed the emergency exit windows and climbed ladders down to the ground.

After the 1996 collision of an Amtrak train and a commuter train in Silver Spring, MD, multiple commuter rail car exits were inoperable or inaccessible. Moreover, the NTSB accident investigation report stated that emergency evacuation from the cars was impeded because the cars lacked readily accessible and identifiable quick-release mechanisms for the exterior side doors [69]. Therefore, egress through the emergency windows was considerably slower than what might have been possible if passengers had been able to exit using the car doors. One passenger reported that it took him 3 minutes to remove an emergency window exit and an additional 7 minutes to get himself and one injured person out of the commuter rail car. Another survivor reported not being able to open either of the rear side doors of the car. He escaped through an opening created during the collision, which resulted in a total evacuation time of 5 minutes. Several passengers died because of fuel fire intrusion into the car and their inability to exit the commuter car, which had been heavily damaged during the collision.

In the December 1990 collision of an Amtrak train and a commuter train in Boston, MA, some passenger rail car end vestibules were crushed, rendering the doors unusable; the window exits were the only viable options for egress. Evacuation was further slowed by heavy smoke inside the car and the lack of emergency lighting. The NTSB accident investigation report concluded that some passengers may have chosen not to wait for the side door to be opened manually but instead may have attempted to exit through an end door into an adjacent car [70].

According to the NTSB accident investigation report for the 1989 Amtrak train collision with a semi-trailer truck accident in Stockton, CA [71], passengers decided to leave the train via the emergency exit windows, at least in part because of the absence of visible interior markings and operating instructions at the vestibule end and side doors.

In addition to the 1996 Silver Spring commuter train and Amtrak accident cited above [69], NTSB concluded that lack of emergency lighting significantly slowed evacuation during several

Amtrak passenger train accidents, including Kingman, AZ, in 1997 [72] and Selma, NC, in 1994 [73], as well as the 1998 commuter train accident in Portage, IN [74]. NTSB first made its recommendation concerning passenger rail car emergency lighting in its accident investigation report for the 1966 Everett, MA, commuter rail accident [75].

These accidents provided the basis for the FRA regulation that new passenger car equipment be equipped with emergency lighting [1]. In early 2012, FRA requested comments in a proposed rulemaking for revising Part 238 [76] to require, by incorporation by reference, compliance by railroads with the APTA emergency lighting standard, which requires self-contained emergency lighting on new and existing passenger rail cars (see Reference [6]).

3.2 OPERATING ENVIRONMENT

Passenger trains carry occupants between stations along a unique operating environment, including track, tunnels, bridges, and waterways, which may complicate and delay the evacuation of passengers, if necessary. Exterior conditions, such as location of the train, if it is stopped between stations, or weather conditions, can increase the time required to exit from the rail cars and hinder passengers from being able to reach a point of safety in a timely manner. Considerable differences in egress conditions, egress flow rates, and egress time estimates for passenger train evacuations are affected by the following exit routes (all of which may be remote from emergency responders):

- From an upright car to:
  - Another adjacent car,
  - Station platform
    - High-level and
    - Low-level;
  - Pavement or ground away from a station platform;
  - ROW next to adjacent tracks with passing trains;
  - Hillside with sloped terrain;
- From a derailed rail car (upright or on its side) to above locations, which are located:
  - In a ditch;
  - Inside a tunnel
  - On a bridge over water;
- From rail car located in or under water; and
- From the car under the above listed conditions, to the above locations, during severe weather or conditions of darkness.

A 2009 paper describes the results of a study for the Swedish rail agency that focused on controlled nonemergency evacuations [77]. The paper stated that most passenger train evacuations are low-hazard situations which are effectively managed by the train crew. However, the paper noted that factors, including length of time on the train, environmental conditions (e.g., high temperatures), and number of train crew, could result in spontaneous evacuation, which if not controlled could lead to risk of injury due to the outside train environment.

In May 2006, a power outage disrupted all rail traffic on Amtrak's Northeast Corridor between Washington, D.C. and New York City during the morning rush hour, stranding approximately 112 trains with tens of thousands of passengers on board. Many passengers remained on trains for several hours, including trains in tunnels located in Baltimore, New York City, as well as locations in New Jersey. Immediate passenger evacuation in these locations was not desirable.

Evacuation from a passenger rail car on a bridge is naturally slower due to the caution required to prevent occupants from falling into the water. In the 1993 Amtrak train collision with a bridge that occurred near Mobile, AL [78], the evacuation of the two passenger rail cars that remained on the bridge was slowed because emergency responders had difficulty gaining access to the rail cars.

3.3 RAIL CAR ORIENTATION

Passenger rail car orientation can present additional egress challenges for passengers. The majority of rail cars remain in the upright position during most accidents. However, in other accidents, cars tilt or roll onto their sides. When a rail car is resting on its side, side- and end-exit doors and exit windows are located overhead or on the ground.

The 2002 derailment of the Amtrak *AutoTrain* near Crescent City, FL, resulted in eight passenger cars being overturned onto their sides and into a ditch. The NTSB report noted that the assistant conductor in the overturned dining car assisted passengers in climbing upward out of the "top" of the car through what had been a side door [79]. Since 7 other passenger cars were overturned and 5 other derailed cars were leaning in various angles along the ROW, the report stated the likelihood that many other passengers either climbed out of or were evacuated from side doors and emergency exit windows located "on top" of the overturned car, with the assistance of train crew or emergency responders, the exits being as much as 10 ft (3 m) above the track level.

The NTSB investigation report of the 1998 Amtrak train derailment in Arlington, TX, noted that some passengers in rail cars that were not upright could not exit from the doors or emergency exit windows and had to evacuate the cars by ladders that responders put through open emergency windows [80].

3.4 OCCUPANT CHARACTERISTICS

The process of estimating the time and ability of passengers to safely egress from a train must also consider occupant demographics. Intercity passenger trains are likely to carry a broad spectrum of people, including families with children and elderly individuals, as well as mobility-impaired persons who use wheelchairs. In contrast, commuter trains are usually occupied by working age, able-bodied passengers who tend to be regular riders and are thus more familiar with the rail car configuration, including location of doors and emergency exits.

Accordingly, different occupant characteristics and train crew interaction with passengers, in relation to rail car orientation, lighting conditions, and the operating environment, can cause significant variations in egress times.

As noted in the previously cited Amtrak 2002 Crescent City, FL [79], and 1998 Arlington, TX [80], accidents, significant delays in evacuation can result for less physically able passengers or those injured in the accident.

Individuals who have low agility or other mobility issues may find it difficult to exit by using the passenger rail car side-door stairways to a low-platform location or to the ROW (even with a step box), without additional assistance from the train crew or other passengers, thus increasing the total time to exit from a fully-loaded car. In addition, if passenger rail side-door stairways are not available (such as on the *Acela Express* trainset cars) or cannot be used, egress times would be much longer.

3.5 TRAIN CREW, PASSENGER, AND EMERGENCY RESPONDER ACTIONS

Before evacuation of a passenger train can begin, train crew and passengers must first be aware of the emergency. Passengers and train crew must then define what is happening and recognize the appropriate action to take, which may or may not include evacuation from the train. From that point, if egress is necessary, the following iterative process can occur depending on the situation: 1) taking action, 2) having success or failure, 3) re-evaluating based on success or failure, and finally, 4) taking more action. Accordingly, the decision-making process and actions could be crucial to the overall objective of safe passenger egress from the train, if necessary. A few minutes' delay due to indecision or an incorrect decision can make the difference between passenger safety or potential injury or death.

The FRA requirement in subsection 239.101 of *Part 239* requires that passenger train operating crews be properly trained according to the railroad emergency plan [2]. Additional nonregulatory but extensive information relating to passenger train crew training in emergency procedures is contained in a 1993 FRA research report that discusses recommended guidelines for passenger train crew training as part of the operating railroad emergency plan [81]. (FAA and USCG also recognize the importance of well-trained, assertive crewmembers and therefore require flight and ship crews to undergo intensive initial and ongoing training in responding to emergency scenarios [82] [83].)

In addition, subsections 238.113, 238.114, and 238.123 of the FRA *Part 238* regulations [1] require that passenger rail car emergency exits be clearly marked and instructions for their use be provided. These requirements are intended to enable passenger train occupants to locate, reach, and operate emergency exits, if it becomes necessary to immediately evacuate the train in an emergency. In support of the FRA rulemaking process, Volpe Center has conducted an extensive research investigation program to identify new, longer-lasting, and more cost-effective technologies for marking emergency egress locations [84]. These technologies include "high-performance" photoluminescent materials, as well as components for emergency lighting, including LED lamps and independent power sources.

Several passenger train accidents highlight the importance of emergency evacuation training and education for passenger train crew, emergency response personnel, and passengers.

For example, train crew actions, such as not using the public address system to direct passenger evacuation, contributed to the slow or unnecessary egress to the ROW under hazardous conditions, according to the NTSB investigations of the 1991 Amtrak Lugoff, SC, and the 1996 Secaucus, NJ, commuter rail accidents [85] [86].

Emergency responder actions have had major impacts on timely occupant evacuation, especially from passenger rail cars that are on their sides. In accidents that occurred in Arlington, TX (1998) [80], Russell, IA (1997) [87], Kingman, AZ [72], and Intercession City, FL (1993) [88], emergency responders accessed door and emergency window exit openings and used ladders to help trapped passengers escape from the cars. Emergency responders at the Russell, IA, and Intercession City, FL, accidents removed injured passengers through emergency exit windows using backboards and lifts.

3.6 FIRE AND SMOKE AND OTHER HAZARDOUS CONDITIONS

Evacuations can be further complicated by fire and smoke, such as in the previously-cited 1996 Silver Spring Amtrak and commuter train collision and fire [69], and the 1983 Amtrak Gibson, CA, train fire [89]. Fire outside the car (e.g., resulting from a collision) in any passenger rail car operating environment can also complicate evacuation. In fact, egress from the train in even the least challenging rail-operating environments, (e.g., at a high-platform station) may be hindered by smoke accumulation.

Fire and smoke conditions within passenger rail cars also have multiple effects on emergency evacuation. Injury and death can result from exposure to flames, heat, and/or from inhalation of toxic products. Toxic products, such as carbon monoxide, can affect cognitive processes and slow movement, even before lethal levels are reached. Reduction in visibility also slows movement and can contribute to the occurrence of injury during egress, as well as lead to incorrect decision-making due to lack of information.

FRA regulations in *Part 238*, subsection 238.103 [1] address passenger rail car fire safety by requiring that new equipment designs and construction materials provide sufficient fire resistance to reasonably ensure adequate time is available to detect a fire and safely evacuate passengers and crew members if a fire cannot be prevented.

3.7 POTENTIAL VARIABLES FOR EGRESS AND TIME ESTIMATES

A variety of potential variables that can affect the time necessary for occupants to exit from a passenger train in an emergency may be categorized as follows for input to an egress model:

- Passenger Characteristics
  - Age and gender,
  - Weight (body mass),
  - Agility and strength,
  - Mobility impairments (including injuries and disabilities),
  - Number of persons in rail car,
  - Seat location, and
  - Frequency of rail travel and familiarity with rail car;

- Rail Car Geometry and Configuration
  - Car type,
  - Number of levels (single or multilevel),
  - Number and arrangement of seats,
  - Aisle and stairway arrangement, and
  - Door and emergency window location, size, and operation;
- Operating Environment
  - Location of emergency
    - Station:
      + High-platform: best case
      + Low-platform, and
    - ROW (ballast, tunnel, bridge): worst case,
  - Time of day and lighting conditions,
  - Weather conditions,
  - Platform or ROW conditions,
  - Car condition (damage) and orientation of car(s), and
  - Hazardous condition
    - Fire,
    - Smoke, and
    - Water immersion;
- Train Crew (and emergency responder) Training
  - Plan and procedures and
  - Equipment;
- Passenger Awareness;
- Passenger Assistance in Exiting,
  - Direction and assistance from train crew,
  - Assistance from other passengers; and
- Assistance from emergency response personnel.

3.8 SUMMARY

Various egress factors, whether documented or not for certain types of passenger train emergency scenarios, may have a major impact on the length of time necessary for occupant egress from passenger rail cars, as well as whether an "unusual occurrence" develops into an emergency that requires evacuation. Moreover, many of these variable factors may or may not be controllable. However, to the extent feasible, these egress factors must be considered in order to develop realistic egress time predictions that reflect the unique railroad-operating environment.

4. METHODS FOR PREDICTING PASSENGER RAIL CAR EGRESS TIME

Four primary methods can be used to estimate emergency egress time: prescriptive structural specifications and equipment design standards; hand and spreadsheet calculations; estimates based on past egress experiment trials; and egress computer models.

4.1 PRESCRIPTIVE SPECIFICATIONS AND STANDARDS

Specifications and standards, such as those contained in the FRA and other transportation agency regulations, prescribe requirements (e.g., number of exits and their dimensions) for various elements of the passenger rail car egress system. Implicit in these prescriptive requirements is the assumption that compliance will provide the necessary evacuation time under maximum occupant loading conditions and during anticipated accident scenarios. The specifications imply that such consideration has been given to the minimum requirements. However, scientific justification for the prescriptive requirements is often limited or left unstated.

4.2 EGRESS TIME ESTIMATES USING MODELS

To develop the total necessary time for occupant egress from a structure, the egress flow rate (number of persons per unit of time flowing through an exit) and walking speed (distance traveled per unit of time) must be calculated.

4.2.1 Hydraulic Models – Theory and Methods

When required to predict egress and emergency evacuation times, passenger rail car designers and builders, as well as passenger train system operators, have historically opted to use hand-calculation methods based on the hydraulic theory because the methods are simple, readily available, cost little to apply, and provide a reasonable result, unless the scenario is complex. Hydraulic models for egress calculations treat exiting individuals as “fluid” moving through a network of pipes. In the hydraulic model, people movement is controlled by occupant density and the width of openings of doorways, stairs, and corridors. The entire population is assumed to move (walk) with the same speed, and the overall flow rate is determined by the most restrictive point ahead of the flow. When occupant density in a flow element (e.g., a corridor) is low, the speed will equal the maximum person walking speed observed by researchers. As occupant density increases above a critical value, the walking speed begins to decrease due to congestion. The critical value does not apply to occupants walking along a narrow passenger rail car.

Typical assumptions associated with this methodology include the following:

- All persons will start to evacuate at the same instant.
- Occupant flow will not involve any interruptions caused by decisions of the individuals involved.
- All or most of the persons involved are free of disabilities that would significantly impede their ability to keep up with the movement of a group.

Accordingly, the "modeled time" calculated using the hydraulic method will likely differ from the actual egress time. Because of the basic assumptions, this method is most useful to make estimates of the optimal egress time for a structure (i.e., determining the fastest possible egress time). The optimal evacuation time will be achieved if the distribution of occupants using the available exits is such that the egress efficiency is at its highest, and no delays are encountered during the egress process. These hand calculations are not intended to account for the influence on evacuation caused by decision-making. Past accidents have demonstrated that decision-making can be crucial to the outcome of an emergency. Instead it is common practice to apply a safety factor to the modeled egress time with the intention of bounding the answer. However, there is a significant level of uncertainty in trying to choose an appropriate safety factor, especially when factors, such as car orientation, come into play that do not affect building evacuation. In building egress prediction, a factor of 2 is the most common safety factor, although no strong scientific reasoning exists for this value.

Hydraulic prediction of egress flow rates is a function of parameters, such as passenger density, effective aisle width, pitch of stairs, etc. The coefficients in these egress calculations are based on observations of occupant egress from buildings, and are usually described as the number of ppm per unit of passageway width. These methods work well enough that their use has been accepted by the National Fire Protection Association (NFPA) and other organizations concerned with building life and fire safety codes. The Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering* (SFPE *Handbook*) specifies calculation methods for egress from buildings [90]. Formulas are based on observations of both uncontrolled and controlled evacuations, as well as several empirical studies by Predtechenskii and Milinskii [91] and Fruin [92].

However, the application of these hydraulic calculation methods directly to passenger rail car egress is problematic for the following reasons: 1) different methods estimate quite different flow rates for specified exit openings and 2) the widths of aisles and pitches of passenger rail car stairways are outside the ranges observed in buildings. For building egress, the flow rate through a given opening is estimated as directly proportional to its effective width. (Effective width is actual width minus the "boundary effect," an "adjustment" factor of 4 to 18 in (10 to 46 cm).) However, this linear relationship between width and flow rate does not necessarily hold for widths less than 43 in (109 cm or 1.1 m) [92].

In buildings, room and corridor widths are large enough that evacuating individuals who wish to overtake slower persons can easily do so, but passing other persons becomes progressively more difficult as widths diminish below 43 in (109 cm). Flow rates per unit of width in passenger rail car aisles are certainly lower than for buildings, but there has been little agreement on exactly how much lower.

As a result, different analysts have come to substantially different conclusions about passenger rail car egress times for similar egress scenarios. For example, in the 1998 *Acela Express* high-speed train evacuation time assessment prepared for Amtrak [93], the methodology for transit stations, as described in the NFPA 130 *Standard for Fixed Guideway Transit Systems* (1997 edition) [94], was used. The 1998 analysis was based on an egress flow rate of 0.83 pps (50 ppm) through an end door, as specified in the 1997 NFPA 130 standard for one "exit lane." This flow rate is consistent with the actual egress flow rates observed during the 2005 Volpe Center passenger rail car egress experiment [13]. However, this value was then multiplied by 1.5, resulting in an adjusted flow rate of 1.25 pps (75 ppm). The rationale was that the 35 in door width is 1.5 times the minimum width of an exit lane (22.5 in). However, this rationale is problematic since before the passengers reach the end door exit, they would likely be walking in single file down the narrower rail car aisle at the lower 0.83 pps (50 ppm) flow rate.

The egress flow estimation formula for station exits in the 2000 edition of the NFPA 130 *Standard* was changed to 2.27 ppm per inch of doorway width, which would result in an egress flow rate of 1.32 pps (79 ppm) for the *Acela Express* trainset car end door [95]. The 2010 NFPA 130 standard revised the station exit door flow coefficient downward to 2.08 ppm per inch, which would change the egress flow rate to 1.2 pps (73 ppm) for the same trainset end door exit [96].

Notwithstanding the more conservative station exit egress flow rate in the later NFPA 130 standard, use of the NFPA 130 station egress calculation method in the context of developing passenger rail car egress time estimates is not realistic due to the much wider NFPA 130 required minimum corridor width of 68 in (173 cm) versus the 22.5 in (57 cm) rail car aisle, which train passengers must walk along before reaching the car end door.

An analysis prepared for the Maryland Area Rail Commuter (MARC) system passenger rail cars [97] included an estimate of egress flow rates based on the SFPE *Handbook* calculation method [90]. Egress flow rates were estimated using a formula that includes density and boundary layer factors, as well as average walking speed. However, "density" was defined as the total number of passengers divided by the floor area of the rail car, but should have been defined instead as the usable floor area (the reciprocal of the number of square feet of floor area for each person in the moving stream of exiting passengers). Accordingly, instead of only the usable floor area, the MARC analysis calculations used the entire floor area of the car, including all of the area occupied by seats. Estimates were prepared for various MARC rail car configurations, which included using an end door to an adjacent car. The calculated egress flow rate was 0.36 pps (21.5 ppm).

The observed flow rates in the Volpe Center 2005 experiment [13] for exiting to an adjacent car were 0.88 pps (52 ppm). This value implies that the egress flow-rate estimates developed for the *Acela Express* trainset cars are too high, while the estimates for the MARC cars are too low. The discrepancies between the *Acela* and MARC flow-rate calculations and the actual flow-rate based on the 2005 Volpe Center experiment observations are the result of the use of formulas developed from observations of pedestrian flows in large building spaces using much wider corridors and door exits.

In the only other known example of an egress rate calculation for a U.S. rail car, a 1980 analysis estimated that for a Bay Area Rapid Transit (BART) rail car located in a tunnel, the passenger egress flow rate through the tunnel, not the door, would be the limiting factor; thus, all aspects of car geometry were ignored [98].

In summary, hydraulic calculations provide a quick method for generating estimates of egress times and methods that can be referenced to publications of recognized fire-safety organizations. However, egress time calculations for passenger rail car egress based only on occupant egress behavior from buildings do not consider that building corridors are much wider than passenger rail car aisles and building stairway step heights are much lower than the height of stairway steps used from a side-door stairway to the ROW or low-platform location. Depending on which method is chosen, what assumptions are made about the boundary-layer effect, and how the effective floor area is measured, occupant-flow rate estimates can vary by a factor of three or more. Therefore, the reliability of passenger rail car egress time prediction based on hydraulic hand-calculation methods using only floor-area and passage-width data is low. Hydraulic calculations based on actual observations of passenger egress have a greater likelihood of reliability, but still represent only the "best case" conditions under which such experiments are conducted without risk of injury to participants. The primary shortcoming of hydraulic models is that they treat all rail car passengers as having equal ability to navigate the egress path. This assumption does not consider individual differences in agility and movement, especially in difficult emergency situations. Accordingly, the shortcomings in the hydraulic modeling approach justify the development and use of computer models that specifically simulate emergency egress from passenger rail cars.

4.2.2 Egress Computer Models

Computer models that simulate egress range in levels of sophistication from those that include the hydraulic calculations mentioned above to those that simulate individual person movement and decision-making. One of the attractive features of using computer models to simulate passenger rail car egress time is that it is very easy to explore the influence of one or more individual variable factors on the egress system. Models require that the User create and input a representation of the structure, in this case, the passenger rail car, and in some cases, the exiting areas outside the passenger train. Such models can be divided into two main categories, based on the underlying principle defining people movement: hydraulic models and individual person movement models. Individual-movement models have only recently been developed and are still in the early stages of application to the passenger rail car egress environment.

4.2.2.1 *Computer-Generated Hydraulic Models*

Hydraulic computer models (sometimes called network models) use the same principles as hand hydraulic calculations and typically use a global method to represent the population to be evacuated. Using such a global entry method, the population will usually have uniform characteristics, such as body size and movement speed (see Figure 1). Typically, hydraulic models do not represent individuals at all, but instead assume that movement can be represented by flows of people described by population size, as well as speed, flow, and density relationships.

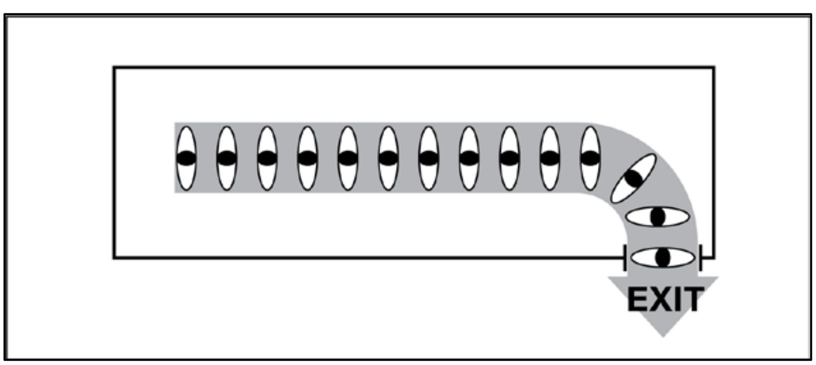

Figure 1. Hydraulic Model – Simple Example

Some models allow the User to specify percentages of the population that have subsets of certain characteristics. Each group type (e.g., able-bodied, working-age women) is then assigned its own set of characteristics that control the egress of that subgroup.

The SFPE *Handbook* [90] states that the hydraulic model is limited in the factors it can represent. For example:

- Behaviors that detract from movement are not explicitly considered.
- Numbers of people in a structural component are considered rather than their identity and their individual attributes.
- Movement between egress components is considered (e.g., from room to room), rather than within them.
- Results are deterministic and will therefore remain the same unless changes are made to the scenario or the assumptions employed.

As noted for hydraulic hand-calculation methods (see Section 4.2.1), building corridors are much wider than passenger rail car aisles, and normal interior step heights down a stairway are much lower than those in passenger rail car exterior side-door stairways (if provided) that an occupant would use to exit to a low platform or to the ROW. Accordingly, occupant egress flow rates based on building egress times do not reflect the reality of the passenger rail car egress environment.

4.2.2.2 *Computer-Generated Individual-Movement Models*

Individual-movement models attempt to model the egress behavior of occupants as they assess the situation and make decisions based on their personal characteristics and any other imposed limiting factors. Decision-making is typically controlled by the interaction between individual occupant characteristics, conditions and events experienced during the particular scenario, and the algorithmic rules built into the model. The sophistication and scope of the representation of this interaction vary between models.

Many of these models give the User the flexibility to define characteristics for each individual person or groups of people, in relation to the structure. For example, variable factors, such as maximum walking speed, age, gender, motivation, and knowledge of the passenger rail car structure, can influence the egress behavior of each specific individual, and thus the group. These variable factors can be interpreted in terms of the effect of individual agility on egress time. Time predictions can be generated for specific passenger rail car egress scenarios, such as egress using only one car door to ROW or low-platform locations under emergency lighting conditions. The reliability of the model egress time predictions is dependent on the availability of observational data collected from actual people movement. Model capabilities may also make it easier to include some of the unique aspects of passenger rail car egress scenarios.

Individual-movement models calculate travel speed differently from hydraulic models. Instead of having a global speed controlled by density, each person has his or her own individual maximum walking speed. If there are no hindrances (e.g., injuries), individuals will move with this speed until they encounter an obstacle, such as a person moving more slowly. At this point, the speed of the faster person behind is "capped" by the person in front, unless the space is wide enough for two-abreast movement. The exact method used to achieve this effect differs between models since they employ headway calculations, approximate speed/density relationships, and incur delays when vying for specific locations, etc. Depending on the decision-making rules employed in the model, persons may "decide" to overtake other persons, choose another route if available, or continue in the queue. Some models add a degree of randomness to these decisions. Individual-movement models are more suited than hydraulic models to incorporating decision-making because the decisions are more naturally translated into their individual movement (see Figure 2.

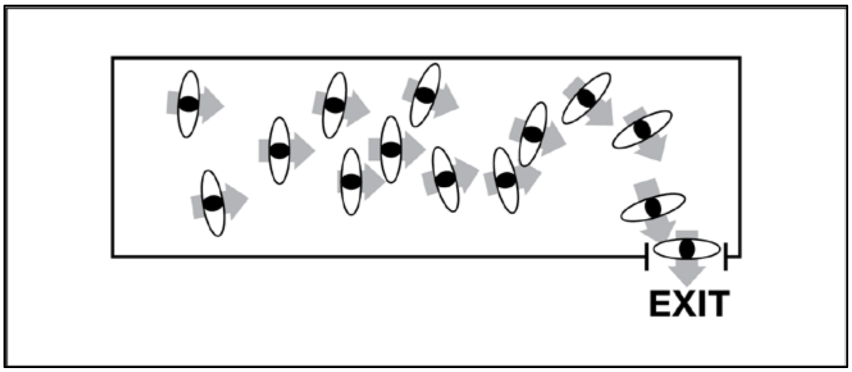

Figure 2. Individual-Movement Model – Simple Example

The inclusion of decision-making in the calculation of egress time is important because it gives the computer model the ability to simulate a wider range of emergency scenarios. This model capability takes into account the fact that passenger rail car occupants are faced with different choices, depending on the emergency egress scenario variables. The same population will react differently if the passenger train is stalled on a bridge over water, as opposed to if the train is stalled inside a tunnel. The influence of the presence of trained railroad personnel can be incorporated more readily into the egress time calculations if the User can define individuals in the group who have particular attributes that lead them to make different decisions and take different actions from other passengers. By representing occupant behaviors individually, rather than imposing them across the entire group, individual-movement models allow new conditions to develop, providing new insights into different accident scenarios and potential mitigation efforts.

Some computer models simulate the effect of fire conditions on the occupants as they evacuate the structure. For example, hazardous smoke conditions in one location may overcome some occupants, while individuals located in another area would still be able to move to the exit. In other models, calculated egress times can be compared with calculations of independent hazard development to see if occupants are able to escape, in the minimum time necessary, the hazardous (e.g., untenable) conditions. If individuals must traverse an area directly affected by fire, smoke, or other toxic products, delays caused by the interaction with the hazardous conditions must be reflected in the egress times.

4.3 PASSENGER RAIL CAR EGRESS TIME SIMULATION

FAA described the following objectives for computer models which simulate aircraft passenger evacuation that could be adapted for application to passenger rail car egress [35]:

“(1) The model must be capable of analyzing various cabin configurations without requiring changes to its source code.

(2) The model must run in real time or near real time.

(3) The model must be able to conduct simulations of both certification tests and accident evacuations.

(4) The model must consider relationships among passengers. For instance, the influence on evacuation behavior of a mother traveling with an infant versus a passenger traveling alone must be incorporated.

(5) The model must consider the impact a flight attendant’s behavior has on passengers. This feature will allow passenger management to be explored, such as determining the optimal number of flight attendants per passenger load.

(6) The model must offer dynamic behavior, as opposed to behavior that is fixed at the time of model execution. That is, the model must allow the behavioral characteristics to change over time.

(7) The model must take into account the dynamic, toxic environment of fire and consider the physiological, as well as psychological effects of fire and smoke on human behavior.

(8) The model must support simulation output analysis, design of experiments, and sensitivity analysis.

(9) The model must provide animation of the evacuations to support model validation and presentation.”

In contrast to aircraft evacuation modeling, methods of estimating egress times by U.S. passenger railroad system operators and rail car builders have not employed evacuation simulation modeling.

Moreover, none of the egress simulation computer models described in Chapter 5 of this report appear to have the ability to directly simulate all of the various operating environments for passenger rail car egress since it would be difficult and costly for any model to take into account all the variable factors (see Section 3.7) that could influence passenger rail car emergency egress time.

The results of passenger rail car egress experiments can provide the necessary data for developing a reliable passenger rail car-specific egress model for egress time prediction if the numerous factors that affect egress flow rate are carefully considered and specifically controlled in a repeatable and consistent way.

It may also be possible to determine appropriate delay factors for each category of emergency scenario, including those that require opening a rail car door and exiting to a low-platform station or to the ROW, which could be applied to the exit availability or added to the total egress time.

For example, commercial passenger airplane evacuation studies have allowed for the characterization of delays associated with occupant use of emergency slides (see References [36] and [99]). A similar characterization for passenger rail car egress could be delays associated with sitting jumps by passengers from rail cars that do not have side-stairway steps installed (e.g., *Acela Express* trains which normally only stop at high-platform stations).

Moreover, individual agility and physical obstacles have a significant impact on the amount of time necessary for persons to exit from a passenger rail car. Experiments to evaluate rail car-exit geometry for simulating egress to low-platform or ROW locations, should employ “within-subject” designs (i.e., the same participants must be used for all conditions) so that differences in individual abilities do not affect the results of the experiment).

However, because of the inherent risk of injury to participants, passenger rail car egress experiments that provide new egress-related time data involving higher-risk emergency scenarios (e.g., egress from cars overturned or extremely tilted on their sides, egress from exit windows, egress of severely mobility-impaired occupants, etc.) to validate computer models that simulate egress may not be feasible or may be very expensive to conduct due to safety considerations.

Chapter 5 provides a survey review of egress computer models and their applicability to specific types of passenger rail car emergency scenarios.

4.4 SUMMARY

Egress time calculations for simple structures with low-level risk probability (e.g., occupant exiting from passenger rail cars at high-platform stations) can be routinely carried out through reference to structural specifications and design standards, or by using “back-of-the-envelope” hand-calculation methods. However, for complex egress situations, such as exiting from a passenger rail car to a low-platform station or ROW location, advanced modeling approaches may provide a more accurate prediction of egress time.

For egress time predictions to reflect the actual railroad operating environment, regardless of whether the model uses calculations based on a hydraulic or individual-movement model, passenger rail car egress experiment results can provide the necessary data for developing a reliable passenger rail car-specific egress model if the numerous factors that can affect egress flow rate are carefully considered and specifically controlled in a repeatable and consistent way. However, it is noted that individual agility and physical obstacles have a significant impact on the amount of time necessary for persons to exit from a passenger rail car.

5. APPLICABILITY OF EGRESS COMPUTER MODELS TO PASSENGER RAIL CAR EMERGENCY SCENARIOS

Numerous computer models for egress time prediction have been developed. The majority were developed for use in predicting or evaluating egress from a range of public building structures, including high-rise office buildings, stadiums, and mass transit stations. Along with other performance metrics, such as the distances traveled or the congestion experienced, the models also typically give the User an estimate of the potential time it would take for all occupants to reach the exterior of the structure (e.g., the point of safety).

5.1 EXISTING EGRESS COMPUTER MODELS

References [100] [101] [102] contain more detailed information about the egress computer models reviewed in this chapter. In addition, Section 5.5 contains a reference list for the models that are summarized in Table 3. The column descriptions used have the following meanings:

Model Name – The version number is included only if it is actually part of the name, e.g., "EVACNET4," rather than "EVACNET+."

Author(s) – The author(s) of the model, as noted in the available documentation.

Organization – The employer or sponsor of the author(s). In some instances it may be the organization that currently maintains the software.

Date – The year of release, as determined from the references reviewed. A blank entry indicates that the references used in this report gave no information about when the models were developed.

Typical Use – Structures that are typically analyzed using this model.

Model Description, Type – The basic principle behind the egress calculations: hydraulic or individual movement. "Probability driven variations" means that the model is capable of conducting several simulations to evaluate the impact of probabilistic variables within the model.

Model Description, Type and Data Source – The basis for the model assumptions, defaults, and calculations. "Random Selection" means that the model uses the Monte Carlo (stochastic) technique to choose values for parameters that vary with a known probability distribution.

Required Inputs and Options – Data inputs needed and the options available to the User. "Standard" inputs are: layout and dimensions of the structure; number of people; and quantity, dimensions, locations and capacity of exits.

Output and Results – Information given by the model upon completion of the calculations.

Table 3. Overview of Current Egress Computer Models – Sheet 1

MODEL NAME	ORGANIZATION & AUTHOR(S)	DATE DEVELOPED	TYPICAL USE(S)	MODEL DESCRIPTION		INPUTS & OPTIONS	OUTPUT & RESULTS
				Type	Data Source(s)		
ALLSAFE	Interconsult, Group. Norway A. Heskestad G. Jensen	1998	Buildings, passenger vehicles	Hydraulic	Research by IGP and SINTEF	Standard; occupant characteristics like sleep/wake, route familiarity and social role	Minimum total evacuation time for all occupants
ASERI	Integrierte Sicherheits-Technik, (Integrity-Security-Technology) Frankfurt, Germany V. Schneider	1995	Buildings, mass transport vehicles	Individual movement with probability driven variations	Statistical analysis of options; Purser's model for tenability; effects of visibility studies by Jin; observations of evacuations	Standard; fire conditions versus time; characteristics of individuals, including body size, incapacities, social interdependence; building knowledge	Evacuation times of individual occupants, incorporating effects of heat, smoke, toxic products and visibility; bottlenecks in the egress system
BGRAF	NJ Institute of Technology F. Ozel+	1985	Buildings	Individual movement	Random selection	Standard	Evacuation or incapacitation time for individuals
CRISP	Fire Research Station, United Kingdom WGB Phillips J. Fraser Mitchell	1992	Buildings	Individual movement with probability driven variations	Tenability from Purser	Standard Options: Difficulty of use of each vent; behavioral characteristics of occupants	Evacuation or incapacitation time for individuals
EESCAPE	Cobau Ltd., Austria E. Kendik R. Friedman	1983	Multistory buildings	Hydraulic	Predtechenskii and Milinskii	Standard	Total evacuation time
EGRESS	AEA Technologies, United Kingdom N. Ketchell	1991	Buildings, rail stations, ships, buses	Hybrid – hydraulic with some basic individual movement	Predtechenskii and Milinskii; full-scale evacuations	Standard	Total evacuation time

Table 3. Overview of Current Egress Computer Models – Sheet 2

MODEL NAME	ORGANIZATION & AUTHOR(S)	DATE DEVELOPED	TYPICAL USE(S)	MODEL DESCRIPTION		INPUTS & OPTIONS	OUTPUT & RESULTS
				Type	Data Source(s)		
EVA	Rutgers University H.C. Gea	2004	Aircraft	Individual movement		Structure layout, physical attributes of passengers, occupancy level, group behavior	Distributions of total aircraft evacuation time, distributions of exit usage time, no. of passengers using each exit, visualization (animation) of evacuation process
EVACNET4	University of Florida Kisko & Francis	1984	Buildings	Hydraulic	Fruin; Pauls	Standard (network description of building); initial number of people at each node	Minimum total evacuation time; floor clearing times; identifies bottlenecks
EVACS	Fujita & Building Research Institute, Japan Takahashi & Tanaka	1988	Buildings	Hydraulic	Study by K. Togawa; and work of Predtechenskii and Milinskii	Standard; number of people in each space; walking speed	Total evacuation time, congestion points in building
EVACSIM	Victoria University of Technology, Australia L. Poon	1994	High-rise buildings	Hydraulic	Nelson & MacLennan	Standard; behavioral characteristics, maximum travel speed, body size Optional: fire conditions	Evacuation sequence for each occupant
EXIT89	NFPA R. Fahy	1991	High-rise buildings	Hydraulic	Predtechenskii and Milinskii; Hillier & Lieberman; Levin	Standard; fire conditions. Options: explicit inclusion of children, disabled, etc.; User-specified delays, walking speeds, and route familiarity	Total evacuation time for each exit element, floor, and/or the entire building. Also can track the movement of each occupant throughout evacuation

Table 3. Overview of Current Egress Computer Models – Sheet 3

MODEL NAME	ORGANIZATION & AUTHOR(S)	DATE DEVELOPED	TYPICAL USE(S)	MODEL DESCRIPTION		INPUTS & OPTIONS	OUTPUT & RESULTS
				Type	Data Source(s)		
EXITT	NBS (NIST) B. Levin	1987	Small residential buildings	Individual movement	Controlled experiments; case studies; expert judgment	Standard; age, sex, location, and condition of occupants; smoke conditions; smoke detector action	Evacuation sequence for each occupant
air EXODUS	University of Greenwich, UK Galea, Galparsoro & Owen	1993	Aircraft, mass transport vehicles	Individual movement	Evacuation studies, especially, aircraft (e.g., Muir)	Standard; fire conditions; detailed demographics; physical attributes	Evacuation time of each individual and their physiological condition
building EXODUS	University of Greenwich, UK Galea, Lawrence & Gwynne	1993	Buildings, especially public assembly occupancies	Individual movement	Studies of building evacuations; human behavior research, e.g., Bryan, Wood, Jin, Fruin, Purser, etc.	Standard; fire conditions; detailed demographics; physical attributes; procedure employed	Evacuation time of each individual and their physiological condition, component performance
maritime EXODUS	University of Greenwich, UK Galea, Lawrence & Gwynne	2007	Passenger ships	Individual movement	Studies of building evacuations; human behavior research e.g., Bryan, IMO, Wood, Jin, Fruin, Purser, etc.	Standard; fire conditions; detailed demographics; physical attributes	Evacuation time of each individual and their physiological condition, component performance
FDS_Evac	VTT (Finland) & NIST Korhonen & Hostikka	2005	Buildings	Individual movement	Existing Helbing model; research conducted by Langston, Thompson, & Proulx	Standard; fire conditions (via FDS); detailed demographics; physical attributes	Evacuation time of each individual and their physiological condition

Table 3. Overview of Current Egress Computer Models – Sheet 4

MODEL NAME	ORGANIZATION & AUTHOR(S)	DATE DEVELOPED	TYPICAL USE(S)	MODEL DESCRIPTION		INPUTS & OPTIONS	OUTPUT & RESULTS
				Type	Data Source(s)		
GRIDFLOW	Building Research Establishment, UK Purser	2002	Buildings	Individual movement	Nelson & MacLennan, Purser, Jin, Thompson	Standard; fire conditions; detailed demographics; physical attributes	Evacuation time flow conditions, component performance
LEGION	University of Warwick, UK G.K. Still Legion Limited	1997	Buildings	Individual movement	Maia Institute	Standard; fire conditions; detailed demographics; physical attributes	Evacuation time of each individual and their physiological condition, component performance
MAGNETIC SIMULATION	Kyoto University, Kyoto[1] & Fukui University, Fukui[2], Japan Okazaki[1] & Matsushita[2]	1979	Buildings; analysis of queue spaces, e.g., turnstiles at rail stations	Individual movement	Physical laws governing magnetic fields	Standard; actual starting point of individuals, walking speed, delay to start walking. If large no. of occupants, data are entered for groups of people, not individuals Option: specify destination of occupants	Visual depiction of evacuation process; evacuation time; points of congestion and amount of time spent in queue
MYRIAD I & II (Evolution of VEGAS)	Crowd Dynamics, Ltd, UK G.K. Still	1992 (VEGAS)	Large crowds in public spaces	Individual movement	Not enough information	Geometry imported from CAD program; objectives of individuals	Movement patterns of occupants; congestion points; egress time
NOMAD	Daamen & Hoogendoorn Delft University of Technology	2009	Buildings, large public spaces	Individual movement	Observations or assumptions about walking speeds, stair-climbing speeds, etc.	Description of the walking infrastructure Parameters describing behavior of the different pedestrian types Activity patterns Demand for each activity pattern Location of detectors Run-time parameters	

Table 3. Overview of Current Egress Computer Models – Sheet 5

MODEL NAME	ORGANIZATION & AUTHOR(S)	DATE DEVELOPED	TYPICAL USE(S)	MODEL DESCRIPTION		INPUTS & OPTIONS	OUTPUT & RESULTS
				Type	Data Source(s)		
PATHFINDER	RJA Group J. Cappucio (Now, Thunderhead Engineering)	2003 (relaunched 2011)	Buildings	Individual movement	Nelson & MacLennan, Reynolds, Amor	Structure layout, occupant characteristics, occupant behaviors, individual or hydraulic movement	Evacuation time, flow rates, component/floor performance of each individual and their physiological condition
PEDROUTE	Halcrow Fox, UK G. Weston	1984	Public transport stations	Hydraulic	Surveys at underground train stations	Structure layout, occupancy levels versus time during peak and near peak use times of day; User can enter flow rates of stairs, platforms, etc. or use defaults	Passenger flow patterns; average delay; areas of congestion; levels of use of building elements, such as escalators or stairs
SIMULEX	University of Edinburgh, UK Thompson & Marchant	1994	Large, complex buildings, including transit stations	Hydraulic	Predtechenskii & Milinskii; Fruin	Standard, occupant density in each area of the structure	Minimum evacuation time of structure
STEPS	Mott McDonald Group, UK Hoffman & Henson	1997	Public assembly occupancies, including train stations	Individual movement	Not enough information	Standard; familiarity with the environment, patience and walking speed.	3-D visualization of the evacuation; evacuation times; flow rates through exits; bottlenecks
WAYOUT	Fire Modeling & Computing, Australia V. Shestopal	2000	Multiroom & multistory buildings	Hydraulic	Predtechenskii & Milinskii	Standard; start times for occupants in different sections of the structure	Maximum evacuation time for a group

5.2 FEATURES AND CAPABILITIES OF EXISTING EGRESS COMPUTER MODELS

The egress computer models evaluated in this study are either hydraulic models that use established calculation methods similar to those found in the SFPE *Handbook* [90], or individual-movement models that simulate the egress of individual persons. The features and capabilities of each model are summarized in Table 4, based on the descriptive documentation available, which varies widely. The column titles in Table 4 have the following meanings:

Egress Path Characteristics – The model's ability to account for exits being blocked before or during evacuation, different levels of difficulty for each exit type, and the impact of different levels of lighting.

Controlled Egress – Whether the model can simulate the control of egress being directed by a crew member or other person.

Occupant Characteristics – Whether the model can simulate individual characteristics in the population and options for varying its demographic breakdown. "Global" means that the User can enter the number of people (or a density of people) in an area. "Individual," means that the User can enter details about each occupant individually. Many of the individual models also have the option to use a global entry method.

Decision-making – Whether the model can simulate the decision-making of occupants during evacuation and to what extent this is done.

Fire Conditions – Whether the model can simulate the impact of fire, smoke, toxic products, and their interaction with occupants.

5.3 APPLICATION OF COMPUTER MODELS TO RAIL CAR EGRESS SCENARIOS

As discussed in Chapter 4, egress time from a passenger rail car depends on variable factors that are unique to this type of transportation vehicle, because of its design and railroad operating environment. The impact of many relevant variable factors has not been experimentally quantified. As a result, some egress models do not include many of the relevant factors in a potential passenger train emergency scenario, limiting the utility of these models to passenger rail car egress simulations. Therefore, a thorough evaluation of the model must assess its capabilities for at least the following categories:

- Egress to an adjacent car or to a station platform;
- Egress to ROW (track level); and
- Egress from a car on its side.

Table 4. Key Features of Egress Computer Models in Relation to Passenger Rail Car Egress Scenarios – Sheet 1

MODEL NAME	EGRESS CHARACTERISTICS	CONTROLLED EGRESS	OCCUPANT CHARACTERISTICS		DECISION-MAKING	FIRE CONDITIONS
			Entry Method	Demographics		
ALLSAFE	Not enough available information	No	Not enough information	Social roles, e.g., patients, visitors, customers	Not modeled	Not modeled
ASERI	Availability of any exit can change during the simulation if fire conditions become hazardous in that area	No	Can do both global and individual	User chooses random computer assignment or generic person	Heat, smoke, and toxic product values over time imported from a fire hazard model Passengers' behavioral responses dependent on individual thresholds	Heat, smoke, and toxic product values over time imported from a fire hazard model Passengers' behavioral responses dependent on individual thresholds
BGRAF	Not enough available information	Not enough available information	Not enough information	Not enough information	Route choice decisions based on environment and other occupants	Not enough information
CRISP	Difficulty of use can be adjusted by tenability calculations Availability is initially randomly set by the program, then is controlled by the difficulty of the exit Smoke obscuration is modeled	Not explicitly modeled, but could possibly be captured in the assigned degree of difficulty	User can define individuals or have random placement of individuals performed by the simulation	Breakdown by roles, such as leader, led, dependent These can be randomly assigned to individuals in the population	Decisions are based on rules associated with their role, interactions with the environment, e.g., smoke blockage and random selection based on statistics	Flame spread, heat, smoke, toxic products, obscuration effects
EESCAPE	Availability set for entire simulation	No	Global	One generic person	Not modeled	Not modeled
EGRESS	Availability set for entire simulation	No	Global	One generic person	Not modeled	Not modeled
EGRESSPRO	Availability set for entire simulation	No	Global	One generic person	Estimates time to detection	Estimates time to detection

Table 4. Key Features of Egress Computer Models in Relation to Passenger Rail Car Egress Scenarios – Sheet 2

MODEL NAME	EGRESS CHARACTERISTICS	CONTROLLED EGRESS	OCCUPANT CHARACTERISTICS		DECISION-MAKING	FIRE CONDITIONS
			Entry Method	Demographics		
EVA	Availability of an exit can change during the evacuation, based on fire or other conditions	Trained crew to redirect passengers	Global / Individual	All passenger physical attributes are summed as a passenger fitness level	Not modeled	Not modeled
EVACNET4	Availability set for entire simulation	No	Global	One generic person	Not modeled	Not modeled
EVACS	Availability set for entire simulation	No	Global	One generic person	Not modeled	Not modeled
EVACSIM	Availability set for entire simulation	Can include evacuation warden to direct egress of occupants	User can define characteristics for individuals or group types	By roles, e.g. passenger, personnel, etc.	Can import from a fire hazard model	Can import from a fire hazard model
EXITT	Exits can be blocked by smoke	No	Individual	Age; sex; location; physical condition, travel speed	Smoke layer density and position are imported from a fire hazard model	Smoke layer density and position are imported from a fire hazard model
air EXODUS	Availability of an exit can change during the evacuation based on fire conditions, awareness, or User selection	Trained personnel can greatly impact evacuation	Individual	Sex; age; weight; condition; mobility; agility; travel speed; breathing volume; incapacitation dose; response time; drive; patience	Choices based on rules and heuristics derived from statistical analysis of human behavior studies and "90 second" certification tests Individual adaptation possible	Heat, smoke, toxicity info entered from calculations done by a hazard development model
building EXODUS	Availability of an exit can change during the evacuation based on fire conditions, awareness, congestion or User selection	Trained personnel can greatly impact evacuation	Individual	Sex; age; weight; condition; mobility; agility; travel speed; breathing volume; incapacitation dose; response time; drive; patience	Choices based on rules and heuristics derived from statistical analysis of human behavior studies Individual adaptation possible	Heat, smoke, toxicity info entered from calculations done by a hazard development model

Table 4. Key Features of Egress Computer Models in Relation to Passenger Rail Car Egress Scenarios – Sheet 3

MODEL NAME	EGRESS CHARACTERISTICS	CONTROLLED EGRESS	OCCUPANT CHARACTERISTICS		DECISION-MAKING	FIRE CONDITIONS
			Entry Method	Demographics		
maritime EXODUS	Availability of an exit can change during the evacuation, based on fire conditions, awareness, congestion or User selection	Yes	Individual	Sex; age; weight; condition; mobility; agility; travel speed; breathing volume; incapacitation dose; response time; drive; patience	Choices based on rules and heuristics derived from statistical analysis of human behavior studies Individual adaptation possible	Heat, smoke, toxicity info entered from calculations done by a hazard development model
FDS_Evac	Availability of an exit can change during the evacuation	Yes	Individual	Sex; response time; speed; age	Choices based on function, modified by proximity and exit selection	Heat, smoke, toxicity info entered from calculations done by a hazard development model
GRIDFLOW	Availability set for entire simulation	Yes	Individual	Initial delay, speed, FED characteristics	Exit selection, local navigation	Heat, smoke, toxicity info entered from calculations done by a hazard development model
LEGION	Not enough information	Yes	Individual	Not enough information	Not enough information	Not enough information
MAGNETIC SIMULATION	Availability set for entire simulation	No	Individual and global	Maximum walking speed	Not modeled	Not modeled
MYRIAD	Availability set for entire simulation	No	Global and individual	Walking speed	Limited decision-making based on congestion experienced along egress route	Not modeled
NOMAD	Demand for a given exit can be time dependent	Not enough information	Individual	Walking speed, body size, trip purpose, etc.	Pedestrians interact with each other and obstacles based on observational studies	Not modeled

Table 4. Key Features of Egress Computer Models in Relation to Passenger Rail Car Egress Scenarios – Sheet 4

MODEL NAME	EGRESS CHARACTERISTICS	CONTROLLED EGRESS	OCCUPANT CHARACTERISTICS		DECISION-MAKING	FIRE CONDITIONS
			Entry Method	Demographics		
PATHFINDER	Availability set for entire simulation, although agent may select between them based on congestion	Yes	Global	Age; sex, impairment; speed; size; profile; initial delay; task	Decision-making based on steering, congestion experienced along egress route, procedure	Not modeled
PEDROUTE	No	No	Global	Not enough information	Not modeled	Not modeled
SIMULEX	Availability set for entire simulation	No	User can choose individual or global	Building familiarity (e.g., office staff versus visitor); body type; response time; exit bias	Reevaluation of egress path based on obstructions	Not modeled
STEPS	Availability can change during simulation	Not enough information	Individual	Familiarity with structure; walking speed; patience; body size; fitness levels	Occupants change egress routes based on familiarity, queuing, patience, and fitness levels	Not enough Information
WAYOUT	Availability set for entire simulation	No	Global	Not considered	Not modeled	Not modeled

5.3.1 Egress to Adjacent Car or Station Platform (Including Fire)

Typically, the simplest egress scenario is the situation, with no fire or smoke inside the passenger rail car, where passenger egress is from one rail car end door into the adjacent car. The next simplest type of egress scenario from a rail car is passenger egress from the side doors when a train is located at a high- or low-platform station. Passengers are usually able to exit via the side doors, which are the normal entrance points. For these scenarios, the majority of the calculation methods, including hand calculations, are appropriate. The parameters that have the greatest impact on the results produced for rail car egress are essentially the same as for building evacuations; e.g., aisle (corridor) width; door quantity, width, and location; occupant load; travel distance; and travel speed. Without obstacles in the egress path and possible interruptions to egress that are associated with many accident scenarios (e.g., finding a blocked exit and needing to decide on a new route), the effects of individual decision-making are small.

In contrast, if a fire occurs in the rail car to be evacuated, more factors must be considered to obtain an accurate depiction of the evacuation. Fire and smoke can potentially block access to the preferred exits and egress route. In addition, decreased visibility and the effects of toxic products can slow the decision-making and movement of occupants. Therefore, fire hazard development and its effect on the tenability of the space must also be modeled.

Although it is theoretically possible to use hand and spreadsheet calculations to track hazard development, people movement, and the effect of fire and smoke on passenger rail car occupants, computer models can perform these simultaneous calculations more efficiently. Among the models reviewed, CRISP calculates fire hazard development and ASERI, EVA, EVAC, EVACSIM, EXIT89, EXITT, FDS-Evac, GRIDFLOW, and the three EXODUS models all have the capability to import the time-based data from computer fire models and integrate their effect on the evacuation event. Documentation for some of the other models suggests that the User can complete the fire and egress modeling independently and then compare times to determine if tenability thresholds are reached before egress is complete, in which case, persons remaining on board the car are assumed to be dead. Although this latter practice has some value, it does not lend itself to incorporation of injuries and the influence on evacuation (travel speed and decisions to change route) of smoke and toxic products before the lethal threshold is reached.

Of the nine models that can incorporate fire conditions into egress calculations, seven (ASERI, CRISP, EVA, EXITT, and the three EXODUS models) use the individual-movement approach, while EVACSIM and EXIT89 are hydraulic models. Moreover, ASERI, EVA, EXITT, FDS-Evac, EVA, GRIDFLOW, and the three EXODUS models give the User the option to assign detailed physical attributes (such as smoke tolerance) to individuals or types of individuals. This feature allows potential modeling of individual differences in physiological response to fire, smoke, and toxic products. It is not clear from the available literature if CRISP has this capability.

5.3.2 Egress to ROW (Track) Level

Evacuation from a passenger train located away from the station platform introduces the influence of the operating environment and a greater degree of decision-making. If passengers exit via the end door and a stairway is not available; or exit via side doors and cannot use the side stairway steps at all; there is a drop from the door sill to track level of about 4 ft (1.2 m). Having to jump a distance of 4 ft from the rail car to nonlevel ground with a potentially steep slope can be intimidating for some people and virtually impossible for those that are physically impaired. Disorientation from being in a dark tunnel with knowledge that a high-voltage third rail may be nearby, or the fear induced by being suspended on a railroad bridge over water, are further complications.

None of the egress models reviewed in this chapter explicitly addresses the difference in egress path characteristics when occupants exit from a building-like structure compared with exiting from a passenger rail car. Instead, the last step from the building door to the exterior is usually considered a trivial matter. However, in some of the models, it is possible to account for the delays that can result during egress from particular exits. CRISP allows the User to assign different degrees of difficulty to the use of each exit. AirEXODUS attaches time delays to the use of emergency exit elements, such as slides, based on observations taken during certification testing of aircraft. ASERI, EVA, EXIT89, SIMULEX, and STEPS also have specific features that allow inclusion of this variable factor.

Three selected papers describe the use of building egress models to develop passenger rail car egress time estimates for different exit paths to a variety of locations.

A 2011 paper describes the use of the STEPS model to develop egress time predictions for egress from two high-speed trainsets, based on the actual data obtained from the 2009 Spanish Railroad RENFE high-speed trainset evacuation drills, as described in Chapter 2 [31]. The STEPS model was selected due to its capability to change the availability of exits that can be used by occupants during the simulation. Fourteen various scenarios were simulated, which included different fire locations on the train (and thus car exit locations) and evacuation to either a tunnel walkway platform or the ROW. A major focus of the analysis was the effect of train crew instructions on the egress time. Before completion of this report, the authors were unable to complete a quantitative analysis of the 2011 study (and other related Spanish studies cited in that paper). However, since the study used data from actual passenger trainset evacuation drills as input to the STEPS model, the study recognizes the important effect on egress time of train crew directions, passenger behavior, and the unique railroad operating environment, including train design and exit locations such as tunnels.

A 2007 paper describes the results of a study using the NOMAD model to develop egress time predictions from a variety of rail cars to a side walkway in a tunnel [103]. The study results include evacuation time estimates as a function of car type and capacity, number of doors, and load factors. The NOMAD study also described the option to include different transit times through a doorway depending on the different elevations in the door threshold and the walkway. For example, a 19.6-in (50-cm) difference in height from the door threshold to the walkway was assumed to take 2 seconds for the average person to traverse. With a door width of 4.3 ft (1.3 m), the study assumption was that 1.5 persons could exit simultaneously through the door, thus producing an egress flow rate of .75 pps (45 ppm).

A 2001 paper describes the results of SIMULEX runs for exiting from 4- and 8-car trains to walkways located adjacent to the trains in a 2-track tunnel; and from the end door of an 8-car train to the track level of a 1-track tunnel [104]. The model simulations were based on 150 persons (4-car train) or 200 persons (8-car train) exiting from each car, with a walking speed of 3.3 fps (200 fpm) (based on NFPA 130, 2000 edition [95]). The paper concluded that that there was very little benefit associated with increasing the cross passage width because queuing occurred on the 36-inch (.9-meter)-wide walkway. However, the paper did indicate that a meaningful reduction in total egress time for the 1,600-passenger 8-car train could be achieved if an end-door “gangplank” were provided to allow occupants to promptly exit the car down to the track level and then walk out to the portal. The egress flow rate was estimated to be 1.66 pps (95 ppm), if a 16-foot (4.8-meter)-long, 4-foot (1.2-centimeter)-wide ramp were available for passengers to descend to the ROW (track level) for the 1,600 passengers. Use of this gangplank could reduce train egress time from 29.5 minutes to less than 17 minutes. However, the logistical challenges of storing and deploying a 16-foot (4.8-meter)-long, 4-foot (1.2-meter)-wide gangplank on the train or in train tunnels were not addressed.

NOMAD was previously validated by laboratory walking speed experiments for normal walking conditions; however, neither the SIMULEX nor the NOMAD egress time predictions were based on observations of persons actually exiting from a passenger rail car. In addition, neither of the of the two cited studies considered the effect of occupant mobility impairments which could impact the amount of time necessary for persons to exit from a passenger rail car, depending on its location.

For any model to realistically simulate the railroad operating environment, observational data regarding what people do when actually exiting from a passenger rail car are necessary. Most of the body of knowledge about people movement from passenger trains to the outside environment is contained in NTSB and other investigation reports. However, this information is inadequate for modeling purposes because those reports do not typically contain the necessary detailed data for model input, such as the average time for people to climb down from an end or side door located 4 ft (1.2 m) above the ground or jump down from an emergency window located 7 ft (2.1 m) above the ground. In addition, for these “inconvenient” egress environments, mobility-impaired, as well as injured passengers (as a result of a collision or derailment), will be slow to or unable to exit the car without assistance.

The reciprocal of the occupant flow rate from the emergency exit comprises the egress time, in which case a hand-calculation or hydraulic model may provide adequate accuracy in predicting that time, if the population size is known. However, decision-making and other occupant characteristics are likely to have a significant impact on passenger rail car egress time. Accordingly, the use of individual-movement models is necessary to simulate complex passenger train emergency scenarios.

5.4 EGRESS FROM RAIL CARS THAT HAVE OVERTURNED ONTO THEIR SIDES

Perhaps the most difficult scenario to model is egress from a car overturned on its side. The University of Greenwich study cited earlier in this report [23] included two evacuation trials involving a passenger rail car on its side. According to that study, flow rates through the end doors (which become narrow doorways 5 ft (1.5 m) above the ground) could be as little as 10 percent of the values specified in building exit standards. In addition, flow rates decreased an additional 50 percent in the presence of nontoxic smoke. With the car turned on its side, passengers had to walk on an irregular surface (e.g., windows, seats) since the available side doors and emergency exit windows were now located 10 ft (3 m) off the ground. In an actual emergency, such as a collision or derailment, the passenger rail car is also likely to contain debris, such as luggage. None of the existing egress computer models consider any of these factors, particularly egress from passenger rail cars through an opening that could be located 10 ft (3 m) above the ROW (track).

5.5 MODEL REFERENCES

Two comprehensive modeling survey reports contain reviews of a variety of hydraulic and individual-movement computer egress models [100] [101] [102]. In addition, the following list contains references for the models reviewed in Table 3 and Table 4.

The following specific references for the different computer models are listed by type of model (in alphabetical order), Web site/email contact, model documentation, and author (in alphabetical order) of article or other document.

ALLSAFE

William Heskestad: awh@interconsult.com

Heskestad, A.W., et al., IGP AS Consulting Engineers. "Allsafe – An Engineering Tool for Evacuation Safety Design." *Proceedings of the Fire Safety by Design Conference, Oslo, Norway, July 10, 1995*. 1996. *Norway*.

Heskestad, A.W., et al. IGP AS Consulting Engineers. "Systematic Fire Safety Design and Documentation by the Allsafe Tool," *Proceedings of Interflam '96: Seventh International Fire Science and Engineering Conference, Cambridge, England, March 26–28, 1996. United Kingdom*.

ASERI

IST-HSK@t-online.de

ASERI – Users' Guide and Technical Reference (hard copy and complete online documentation).

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EGRESS

neil.ketchell@aeat.co.uk

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AEA Technology. *Modeling of Crowd Evacuation: Guidance on the Method*. Report no. AEA/CS/16405219/5/A. August 1995. *United Kingdom*.

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6. POTENTIAL COMPUTER MODEL INPUTS FOR PASSENGER RAIL CAR EGRESS TIME ESTIMATION

Classes of passenger rail car egress scenarios have been developed to identify the potential effects of different variable factors (data inputs) and their interaction on egress time for each scenario. However, actual passenger rail experiments are required to obtain the specific data of interest for a passenger rail car egress computer model.

6.1 EGRESS SCENARIOS

Analysis of all passenger rail egress scenarios based on combinations of all the variable factors within each category listed in Chapter 2 would result in an impractical number of data inputs. Therefore, classes of scenarios were developed using only the first three categories: rail car type, rail car orientation, and operating environment. The scenarios are listed in Table 5. Many are similar to historical accident conditions. Within each scenario class, there are several potential egress scenarios.

The passenger rail car type (single-level intercity, multilevel, sleeping, and single-level commuter) were the initial variable factors selected because of their differences in exit size, exit location, and interior layouts through which passengers travel to reach the exits.

Many single-level commuter and intercity passenger rail cars differ in the size and location of exits within the car. Some commuter rail car side-door exits are typically wider and are directly adjacent to the seating area. However, during an emergency evacuation, it is preferable or it may be necessary for passengers to exit the seating area along a narrow aisle, and then through the interior end door(s) into a separate vestibule area, where the side and end doors are located; thus limiting the exit flow rate. Interior doors leading to the vestibule and side-end doors in intercity rail cars are narrower compared to some commuter rail side doors, and a single vestibule in this type of rail car typically serves the two adjacent cars, potentially limiting the egress flow at this type of exit.

Evacuations from passenger rail cars overturned on their sides, as well as upright cars, were included as additional scenarios because of the dramatic differences in the exit locations, accessibility, and passenger movement capability. Several NTSB accident reports indicated that when rail cars are overturned on their sides, exits are more difficult to reach and occupants encountered obstacles, such as seats and luggage, as they made their way to exit (see Section 3.1 and Section 3.3).

Table 5 includes egress to five common operating environments: to the next adjacent car, outside to high-platform and low-platform stations, outside the car to ROW (track) level, outside the car while on a bridge, and outside the car while within a tunnel.

In passenger rail car-to-car and car-to-platform egress situations, upright orientations are most common, whereas rail cars in accidents along the ROW often roll onto their sides. This latter situation provides another egress variable that multiplies data inputs for both the upright and overturned rail car scenario conditions, as does egress into confined, dimly-lit tunnel conditions.

Table 5. Passenger Rail Car Emergency Egress Scenarios

EGRESS PATH/OPERATING ENVIRONMENT	SCENARIO CLASS NUMBER	PASSENGER RAIL CAR TYPE	PASSENGER RAIL CAR ORIENTATION
1. Car to Next Adjacent Car	1 a	*Single Level*	Upright
		Commuter car	
	1 b	Intercity coach	
	1 c	Intercity sleeping car	
	1 d	Food service car	
	1 e, f, g, h	*Multilevel*	
		See above	
2. Car to High-Platform Station	2 a, b, c, d	*Single Level*	
		See above	
	2 e, f, g, h	*Multilevel*	
		See above	
3. Car to ROW	3 a, b, c, d	*Single Level*	
		See above	
	3 e, f, g, h	*Multilevel*	
		See above	
4. Car within Tunnel	4 a, b, c, d	*Single Level*	
		See above	
	4 e, f, g, h	*Multilevel*	
		See above	
5. Car on Bridge	5 a, b, c, d	*Single Level*	
		See above	
	5 e, f, g, h	*Multilevel*	
		See above	
6. All (Various Combinations)	1, 2, 3, 4, 5, 6 a, b, c, d	*Single Level*	Overturned Onto its Side
		See above	
	1, 2, 3, 4, 5, 6 e, f, g, h,	*Multilevel*	
		See above	

The combination of rail car types, car orientations, and egress environments considered in these egress scenarios provides a "structural" basis for modeling passenger rail car egress.

For all passenger rail car types, exit availability, both initially and later in the evacuation, can be altered (opened or closed); study of the passenger choice of exit would provide data on egress flow rates through each individual exit type, delays associated with operating closed exits, and exit selection. Egress scenarios could also incorporate variable factors, such as car orientation, specific exit configuration, emergency exit signage, interior lighting levels, passenger density, occupant characteristics and decision-making, train crew and emergency responder decision-making and actions, and hazardous conditions including overturned cars and fires. This parametric series of egress scenarios could identify the effects of locating and accessing exits with different types of exit signage and different levels of interior car lighting, as well as their effect on egress time.

However, the scope of possible scenarios that can be tested in passenger rail car egress experiments is constrained by the potential for injury to the participants involved. Egress through doors to station platforms or an adjacent car at normal walking speeds poses minimal risk. In contrast, rapid egress to the ROW, by use of end or side doors (particularly if there are no side-stairway steps), or from rail cars that have overturned onto their sides, has a potentially higher risk of injury.

This potential risk is very evident in precautionary emergency evacuations from aircraft that resulted from cases in which crew members or passengers believed the probability of fire to be high, although no fire actually developed. Of 109 such incidents identified by FAA in the mid-1990s, 19 resulted in injuries to passengers; almost all (86 percent) of the 193 injured persons required medical assistance and most (67 percent) were treated at a hospital. The then-estimated cost to the airlines was approximately $10,000 per injured passenger for processing and compensation [105].

Even when extraordinary measures are taken to minimize the risk of injury in aircraft evacuation certification trials, significant numbers of participants have been injured. In the most recent large-scale trials [106], which also had the most elaborate safety measures, more than 2,500 participants stepped through "over-wing" (Type III exits) to a padded surface simulating a wing 27-in (6.6-m) below the exit sill. Fifty-eight participants (approximately 2 percent) sustained some type of injury, and eleven of those were serious, requiring a visit to an emergency room or a personal physician. The lesser injuries (e.g., cuts, abrasions, bruises, and sprains) were treated by nursing staff at the experiment site.

In recognition of the potential hazards, federal regulations require that any experiment with human participants be examined and approved by an Institutional Review Board (IRB) [107]. These regulations require that subjects be fully informed of the purpose of the research, what procedures will be followed in the experiment, what benefits will accrue to the subjects or to society, what records will be kept, and any foreseeable risks or discomforts they may experience. Risks must be minimized and must be reasonable in relation to the benefits of the research. There are also various requirements related to protection of the privacy of personal data.

Because of experience with aircraft evacuations and other egress tests, an IRB may not approve passenger rail car egress experiments that include higher-risk scenarios (cars extremely tilted on their sides, drops from windows, etc.). Moreover, it is preferable that experience with minimal-risk scenarios be gained before planning for higher risk egress conditions.

6.2 INPUT DATA FOR ESTIMATING EGRESS TIME

Potential input data for a computer model capable of simulating occupant egress from a passenger rail car were identified from the review and analysis discussed in the previous chapters of this report and from an APTA PRESS-conducted Emergency Systems survey [108]. The APTA PRESS survey focused on the dimensions and locations of passenger rail doors and emergency window exits—and related signage, as well as the location of emergency lighting.

Table 6 provides a list of potential input data. Specific data required by any egress model depends on the calculation method and the details of the egress scenario of interest. The majority of the models use only subsets from this list, as only the most comprehensive individual-movement models can incorporate all variable factors of potential interest. Some input data will have a more significant impact on egress time than other data. The relative importance of the variable factors must be established through passenger rail car egress experiments, the results from which could potentially reduce this list. Because very few egress experiments have been conducted using passenger rail cars, the input data required for a particular egress prediction method will also depend on the assumptions inherent in the model.

Comprehensive egress models require engineering drawings of the passenger rail cars, as well as measurements or photographs with scaling factors, for the specific railroad environment at which egress will occur.

6.2.1 Input Data for Hydraulic Models

Hydraulic models (see Subsection 4.2.2.1) require simplified input data for passenger rail car geometry and global occupant characteristics. Most of these models represent the occupant population in a generic sense. However, some of the models reviewed (e.g., EXIT89) are capable of defining multiple occupant subgroups, so that important characteristics of occupants can be considered. For example, definition of occupant subgroups, based on mobility characteristics or age, may produce results more representative of the occupant group as a whole. A list of variables for potential use in hydraulic models is included in Table 7. Some of these variables may appear somewhat repetitive; this is because the input data (variables) used depend on the specific model. For example, some models may use a fixed-flow rate through a door, while others calculate the flow rate from door dimension, occupant density, and physical size of occupants.

As noted previously, hydraulic models do not typically include occupant decision-making or account for general assistance from passenger train crew or emergency responders, although these models may include some specific effects of crew assistance and emergency responders, such as assistance at, or opening of, exits. For example, a door may be inaccessible until emergency responders open it, thus making it usable for only part of the evacuation. Such assistance would be incorporated in the models as an increase in the flow rate through the exit only in the latter stages of an evacuation, based on changing input by the User.

Table 6. Potential Input Data for Calculating Egress from Upright Passenger Rail Cars

CATEGORY	INPUT DATA
Rail Car Type and Geometry	Single or multilevel
	Car interior dimensions
	Seating layout
	Aisle/exit path width and height
	Stair location, width, height, step rise, and run
	Obstructions – size and location
Passenger Loading	Number of passengers
	Passenger locations within rail car just prior to egress
Operating Environment	Width and height of operating environment egress path
	Visibility and fire conditions external to rail car
Exit Type	Door locations and dimensions
	Emergency window locations and dimensions
	Other emergency exits – description, location, and dimension
Exit Accessibility	Open, closed and need to be manually opened, or blocked
	Time to manually open exit
	Location of manual opening directions relative to exit
Fire Conditions	Visibility
	Gas temperature
	Gas toxicity
Emergency Signage	Location and size of signs
	Light emitting or light reflecting
Lighting Levels	Illumination levels
	Duration of power to lights
Occupant Characteristics	Gender
	Age
	Mobility (able-bodied, disabled, injured), ability to reach exit
	Movement time through aisles, doors, windows
	Hesitation time at exits
Decision-making	Pre-movement time (detection, frequency of false alarm, notification)
	Willingness to assist, responsibility
	Social affiliation
	Commitment
	Familiarity
	Alertness and limitation
	Patience/competitiveness
Crew Actions	Training
	Verbal assistance – public address system
	Physical assistance
Emergency Responder Actions	Number of responders
	Training
	Amount and type of gear on emergency responder
	Physical assistance (aiding egress through exits, opening/unblocking exits, ladder to windows, cutting car body)

6.2.2 Input Data for Individual-Movement Computer Models

Individual-movement models, as discussed in Subsection 4.2.2.2, allow more flexibility in defining rail car geometry and occupant characteristics and require more data inputs than the hydraulic models. Individual-movement models could potentially make use of all the input variables listed in Table 7.

These models are capable of including significant detail regarding passenger rail car geometry and occupant characteristics, as well as obstacles that make some routes more difficult or impossible to traverse. Some models will define occupant characteristics in a stochastic manner (i.e., based on the probability distribution) based on limited input data or allow the User to define the characteristics of each individual passenger.

In addition, some of these models are capable of incorporating significant data, including a decision -making aspect that is not present in most hydraulic or network type models. The rules of the decision-making are embedded within the model and are a function of the decision-making characteristics of the occupant. Occupant characteristics may be represented stochastically within a broad category, based on limited differences in input data, or discretely defined by the User in terms of individual occupant characteristics. The algorithmic rules of such decision-making are embedded within the model and are a function of decision-making behaviors displayed by occupants in empirical egress studies or actual emergencies. Examples include decisions related to how the motivation and assertiveness of a passenger may affect how long a passenger is willing to wait in line for a specific exit before trying to seek another exit or attempting to push past other passengers also waiting to exit. As with occupant characteristics, decision-making characteristics may be defined in a stochastic manner or by the User.

Table 7. Potential Input Data for Hydraulic and Individual-Movement Models

CATEGORY	INPUT DATA
Passenger Rail Car Type and Geometry	Single or multilevel
	Car interior dimensions
	Seating layout
	Aisle/exit path width and height
	Stair location, width, height, step rise and run
	Obstructions – size and location
Rail Car Orientation	Upright or on side
Operating Environment	Drop from railcar exit to operating environment egress path
	Width and height of operating environment egress path
	Visibility and fire conditions external of rail car
Exit Type	Door locations and dimensions
	Emergency window locations and dimensions
	Other emergency exits – description, location and dimension
Exit Accessibility	Open, closed and need to be manually opened, or blocked
	Time to manually open exit
	Location of manual opening directions relative to exit
Fire Conditions	Some hydraulic models include provision for inputs from an external fire model
Lighting Levels	General and exit location illumination level
Passenger Loading	Number of passengers
	Passenger locations within rail car just prior to egress
Occupant Characteristics	Gender
	Age
	Mobility (able-bodied, disabled, injured)
	Movement time through aisles, doors, windows (including hesitation times)
Train Crew Actions	Physical assistance
Emergency Responder Actions	Physical assistance (aiding egress through exits, opening/unblocking exits, ladder to windows, cutting car body)

6.3 SUMMARY

Passenger rail car egress scenarios have been developed to identify the potential effects of different variable factors (data inputs) and their effect on egress time for each scenario. Analysis of all passenger rail emergency egress scenarios based on combinations of all potential variable egress factors would result in an impractical number of data inputs.

Specific data required by any egress model depends on the calculation method and the details of the passenger rail car egress scenario of interest. Some input data will have a more significant impact on egress time than other data. The relative importance of the variable factors must be established through passenger rail car egress experiments, the results from which could potentially reduce this list. However, the scope of possible scenarios that can be tested in passenger rail car egress experiments is constrained by the potential for injury to the participants involved.

Individual-movement egress models allow more flexibility in defining passenger rail car geometry and occupant characteristics but require more data inputs than hydraulic egress models.

7. SUMMARY

7.1 OVERVIEW

The safe and timely emergency evacuation of occupants from passenger trains has been addressed by FRA regulations for emergency preparedness and emergency systems for passenger rail equipment, as well as by APTA PRESS safety standards, which were developed to respond to lessons learned from major accidents and emergencies.

A systems approach is necessary to ensure the safety of train crew and passengers during passenger train emergency situations, and to enable the use of emergency systems on board the train to facilitate passenger and crew egress to a point of safety when evacuation is necessary. These requirements function to control the design of specific passenger rail car elements, such as emergency exits. This systems approach must take into account as many of the variable factors of passenger rail car design and operation as possible, including interactions among the factors that work to affect occupant egress capability.

Several limited passenger train egress experiments have been conducted in the United States, as well as in Europe. However, the majority of passenger rail car egress experiment trials have not involved regular passengers as volunteer participants and do not consider the unique operating railroad operating environment. Furthermore, the majority of data from these experiments either have not been made publicly available, or have not been documented in a consistent manner that permits comparison between the different types of rail cars and the different exit routes that were studied.

7.2 EMERGENCY EGRESS VARIABLES

Emergency egress from a passenger train is a complex process that depends on a number of dynamic factors and conditions. Many variables that affect the time necessary for passengers to exit from a passenger train in an unusual or emergency situation must be considered. Important variables to consider in evaluating passenger train egress time include the following:

- Passenger characteristics;
- Rail car geometry and configuration;
- Operating environment;
- Train crew (and emergency responder) training;
- Passenger awareness;
- Assistance to passengers in exiting; and
- Assistance from emergency responders.

7.3 EGRESS TIME PREDICTION AND USE OF EGRESS COMPUTER MODELS

An assessment of passenger rail car equipment, with a focus on emergency egress systems, as well as car equipment design and function, is required to understand the full context of the passenger train operational environment, in terms of egress time. This type of assessment has had a significant history in building design and in the aviation and maritime industries. The evacuation capability of aircraft and ship configurations and operational environments has been evaluated through numerous research studies that have provided a large body of empirical data for emergency egress. However, those emergency evacuation “demonstrations” and experiments have significant cost, as well as safety and health issues (for example, participant slipping, tripping, or falling that may result in injuries).

Several methods have been used to establish transportation vehicle occupant egress time: 1) complete a “back of the envelope” hydraulic hand-calculation and analysis, based on the number of occupants and simple exit routes; 2) conduct simulated emergency evacuations or egress experiments, during which occupants exit from the actual vehicle; or 3) complete an analysis using an egress computer model. The hand-calculation hydraulic model method and the hydraulic and individual-movement computer egress model analytical methods typically use passenger density, effective aisle width, pitch of stairs, etc., and have been accepted for use in building egress time estimates. However, the application of these calculation methods directly to passenger rail car egress is problematic for the following reasons: 1) different methods estimate quite different egress flow rates and egress times for specified exit openings and 2) the widths of aisles and pitches of passenger rail car stairways are outside the ranges observed in buildings.

Building occupant egress data are readily applicable for use with the analytical tools mentioned above (e.g., hand calculations and computer models are available for estimating emergency egress times). However, to Volpe Center’s knowledge, the applicability of the hand calculations or computer models which use these building-based data to simulate realistic occupant emergency evacuation within the passenger train operational environment has not yet been accurately demonstrated. None of the building models have been validated using actual passenger rail car occupant data.

In addition, individual agility and physical obstacles have a significant impact on the amount of time necessary for persons to exit from a passenger rail car, depending on its location. One of the challenges of conducting a valid test of egress behavior using members of the public is how to create a realistic test without putting individuals at significant risk of injury. Accordingly, the use of models that simulate egress behavior could reduce the number of actual egress tests that need to be performed to predict egress times for various passenger rail car designs.

However, because of the inherent risk of injury to participants, passenger rail car egress experiments that provide new egress-related time data involving higher-risk emergency scenarios (egress from cars overturned or extremely tilted on their sides, egress from exit windows, egress of severely mobility-impaired occupants, etc.) to validate computer models that simulate egress may not be feasible due to safety considerations or may be very expensive to conduct.

FRA funded the development of a new prototype passenger rail car egress computer model by the University of Greenwich, United Kingdom, under the direction of Volpe Center [109]. Calibration of this model required a great quantity of detailed data regarding the timing of all the movements of each individual occupant during egress from the rail car. Data from the Volpe Center 2005 and 2006 commuter rail car egress experiments provided a key means, when combined with the known physical characteristics of each type of individual, the physical characteristics of the rail car, and the operating environment at the time the data were recorded, to validate the passenger rail car egress time predictions generated by the new prototype model.

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