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**Federal Railroad
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Passenger Train Emergency Systems: Development of Prototype railEXODUS Software for U.S. Passenger Rail Car Egress

Office of Research
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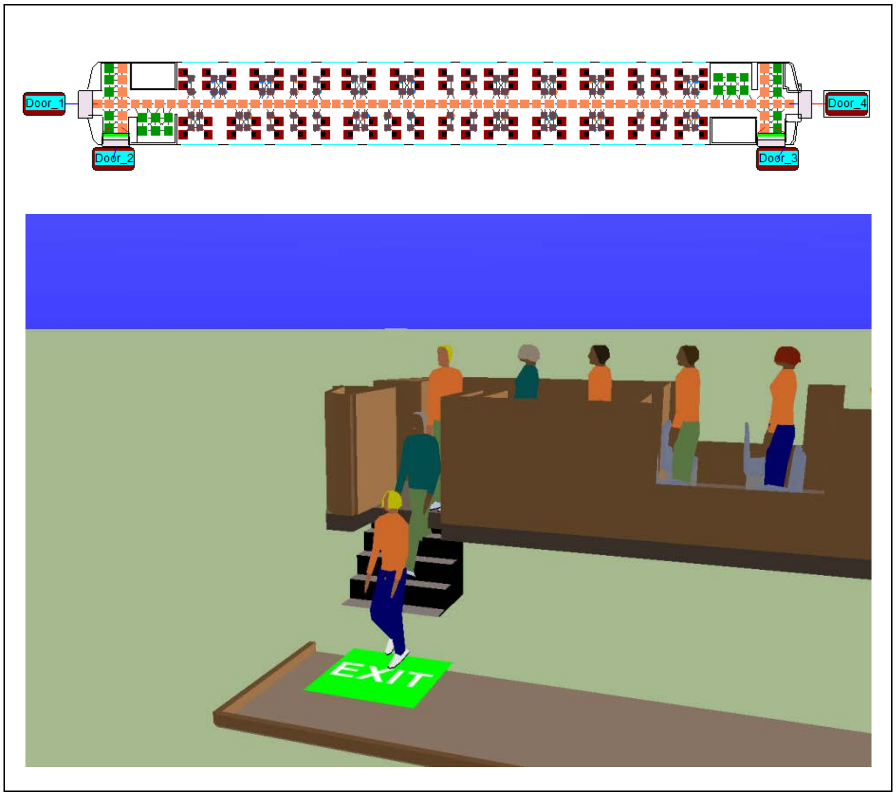
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

The Federal Railroad Administration (FRA), U.S. Department of Transportation (U.S. DOT), is sponsoring a research program, which includes investigation of the applicability of time-based egress performance requirements to U.S. passenger rail cars. This report describes the development of a new prototype railEXODUS computer software (Prototype Software) that can be used to evaluate the applicability of time-based egress requirements to U.S. passenger rail cars. The new Prototype Software is based on modifications to existing railEXODUS prototype software, which were implemented to adapt the EXODUS model for use in accurately predicting U.S. passenger rail car egress times.

All movement and behavior data for individuals (agents) within the new Prototype Software are derived from analysis of U.S. passenger rail car egress experimental trials conducted in 2005 and 2006. The experimental trials included egress of individuals from commuter rail cars using end- and side-door exits to: (1) a high platform under normal and emergency lighting conditions and (2) low platform and right-of-way locations under normal lighting. (All of the egress trials were conducted under best-case, non-competitive conditions.) This research found that the use of such software is essential for performing thorough analyses of passenger train emergency evacuation scenarios.

14. SUBJECT TERMS

passenger trains, railroads, passenger rail, commuter rail, Federal Railroad Administration, transportation, emergency preparedness, emergency evacuation, emergency egress, emergency exits, egress computer models, egress experiments, egress simulation, emergency evacuation simulation

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1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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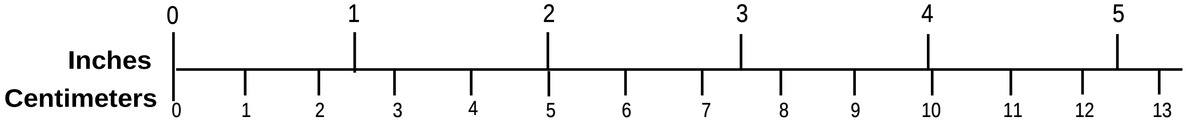

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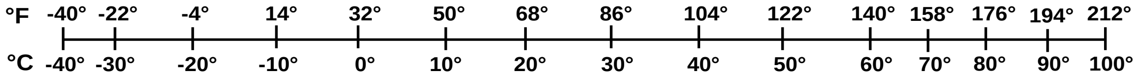

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Leonard Allen, Chief, and Suzanne Horton, both of the Systems Engineering and Safety Division; John Pollard, Surface Transportation Human Factors Division; Michael Coltman, Chief, and Matthew Lyons, both of the Structures and Dynamics Division; all Volpe Center staff; provided review of the final report. The original technical report was reorganized and revised for FRA publication.

Cassandra Oxley, MacroSys, Inc. provided editorial review of the final report.

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Executive Summary

The Federal Railroad Administration (FRA) Office of Research and Development, U.S. Department of Transportation (U.S. DOT) is investigating ways to further improve passenger train safety. Specific issues relating to the safe, timely, and effective emergency egress being reviewed and evaluated are the number, location, and operation of emergency exits; emergency lighting; and egress conditions. In addition, FRA is interested in determining the feasibility and suitability of applying performance-based emergency evacuation time requirements that specify evacuation times, such as those of the Federal Aviation Administration (FAA) (e.g., 90 seconds from an aircraft that is configured with a specific number of egress points and carrying a defined maximum number of passengers), to passenger rail cars.

Currently, the only way to determine the validity of passenger rail car occupant egress time predictions is to conduct actual (simulated) emergency evacuations, exercises, or egress experiments from the car. However, such activities have significant cost, as well as risks of injury to participants. Accordingly, the use of computer models that simulate egress behavior could conceivably reduce the number of actual tests that need to be performed to determine occupant egress times for various passenger rail car designs and passenger loads. Furthermore, using a simulation model rather than a hydraulic flow calculation to determine passenger rail car egress time estimates, may permit more rail car egress designs to be evaluated with greater accuracy. Furthermore, a simulation model can provide realistic estimates of the range of egress times as a function of a variety of scenario variables.

Egress models that can accurately and reliably simulate emergency egress from U.S. passenger rail cars within various operating environments, including to low platform and right-of-way (R-O-W) locations, have not previously been available.

Accordingly, a wide range of potential applications exist for a validated passenger rail car egress model:

- **Design Applications.** Passenger rail car design engineers might use the software in early stage design to evaluate the level of evacuation safety built into passenger rail car designs. For example, the location, type, and number of exits could be evaluated.
- **Regulating Applications.** Regulatory agencies, in consultation with industry groups, could use the software to define performance-based evacuation requirements for different types of railroad operating environments and passenger load ladings.
- **Certification Applications.** Industry groups could use the software to determine whether new passenger rail car designs comply with prospective performance-based egress requirements.
- **Passenger Train Crew Training and Emergency Management Aid.** Passenger train operating agencies could use the software (with its virtual reality graphical capabilities) as an aid in evacuation safety training of train crews. The software could also be used to assist operating agencies in the development of operating procedures in the event of emergency situations. Finally, the software could assist emergency response organizations to plan their response.
- **Accident Investigation.** Accident investigators could use the software to assist in the analysis of accidents and other emergency situations.

- **Normal Operations.** Passenger rail car designer engineers, train operating agencies, and station managers could use the software to simulate normal operations, including the train-station interface and the efficiency of passenger boarding and alighting.

Under FRA sponsorship, the John A. Volpe National Transportation Systems Center (Volpe Center), U.S. DOT, conducted experimental egress trials in 2005 and 2006 to obtain human factors data relating to the amount of time necessary for individuals to exit from a U.S. passenger rail car. Those egress trials included egress of individuals from commuter rail cars using end- and side-door exits to: (1) a high platform, both under normal and emergency lighting and (2) low platform and R-O-W locations under normal lighting.

The collected exit-time data were intended for use in establishing passenger rail car egress time estimates/norms and evaluating various aspects of car design that may promote or impede prompt occupant egress. The experiment data were also intended for use as input to the development of a passenger rail car emergency egress simulation computer model that can predict emergency evacuation time for a variety of passenger rail car designs.

The Volpe Center contracted with the Fire Safety Engineering Group (FSEG) to develop a new prototype railEXODUS software (Prototype Software) which can be used to evaluate the applicability of time-based egress requirements to U.S. passenger rail cars. The new Prototype Software incorporates the capability to simulate egress from U.S. passenger rail cars for the following types of egress scenarios:

- One or two fully functioning side-doors to exit onto high platform locations in normal or emergency lighting conditions;
- One or two side-doors to exit in normal lighting conditions to:
  - Low platform locations and,
  - R-O-W;
- Inter-car end-door exit into the adjacent car in normal or emergency lighting conditions; and
- Movement of passengers in rail car aisle subjected to adverse angle of roll and the behavior or movement of passenger belongings under such forces.

The railEXODUS model design and software development utilized data derived from the 2005 and 2006 Volpe Center passenger rail car egress experiments, and when appropriate, other publicly available data. All data regarding movement/behavior of individuals in upright passenger rail cars within the new Prototype Software are derived from analysis of the Volpe Center trials. These data have also been used to verify and validate the new Prototype Software, where appropriate.

Appropriate human factors data relating to an individual's movement through adversely oriented passenger rail cars are not currently available. Because of the similarity between the experimental conditions in which the maritime data were generated and the target passenger rail car conditions, data and appropriate behaviors related to maritime egress data have been incorporated into the new Prototype Software to represent the passenger rail car subjected to a roll angle.

The results from this study verify that the new Prototype Software is functioning as intended and produces simulated occupant egress behavior consistent with that observed in the Volpe Center egress experiment trials involving an upright commuter rail car. Furthermore, the study validates that detailed numerical predictions of quantifiable egress parameters produced by the Prototype

Software V2.2, such as total egress times, egress time histories, aisle population density, etc., are a reasonably accurate representation of those measured in the Volpe Center egress trials.

It is emphasized that the Volpe Center data used in the new Prototype Software were based on passenger rail egress experiments conducted under “best-case” conditions. Application of such software to the innumberable real world scenarios, highly varied equipment pool, and operating conditions of commuter and intercity rail would require significant additional effort.

1. Introduction

One goal of Federal Railroad Administration (FRA), U.S. Department of Transportation (U.S. DOT) is to ensure that passenger rail equipment is designed, built, and operated with a high level of safety. FRA regulations in Title 49, Code of Federal Regulations (49 CFR), *Part 238, Passenger Equipment Safety Standards* and *Part 239, Passenger Train Emergency Preparedness,* address the safety of intercity passenger and commuter train occupants in various emergency scenarios such as collisions, derailments, and/or fire [1] [2].

FRA's Office of Research and Development is investigating how to further improve passenger train safety. Specific issues for safe, timely, and effective emergency egress being reviewed and evaluated include: the number, location, and operation of emergency exits; emergency lighting; and egress conditions. In addition, FRA is interested in determining the feasibility and suitability of applying performance-based emergency evacuation time requirements, such as those specified by FAA (e.g., 90 seconds from an aircraft), to passenger rail cars [3].

1.1 Background

At the time this research was initiated, egress models did not exist to accurately and reliably simulate emergency egress from U.S. passenger rail cars to the various operating environments, including low platform and right-of way (R-O-W) locations.

The main application of computer-based egress and evacuation modeling technology is in the building industry, where computer-based models are used to assist with the design of large, complex buildings for the safety of the occupants. These models are used primarily to demonstrate that the proposed building can be evacuated safely and are thus considered essential tools in international performance-based design analysis. In the maritime industry, computer egress models are also commonly used by naval architects/marine engineers to assess passenger ship designs and to demonstrate that the designs comply with international evacuation guidelines established by the International Maritime Organization (IMO) [5].

Under FRA sponsorship, the John A. Volpe National Transportation Systems Center (Volpe Center), U.S. DOT conducted experimental egress trials in 2005 and 2006 to obtain human factors data relating to the amount of time necessary for individuals to exit from a U.S. passenger rail car [4]. The collected exit-time data were intended for use in establishing passenger rail car egress time estimates/norms and evaluating various aspects of rail car design that may promote or impede prompt occupant egress.

Prior to the initiation of the FRA-sponsored contract, the Fire Safety Engineering Group (FSEG), University of Greenwich (United Kingdom), had developed prototype passenger rail car railEXODUS egress software (see Chapter 2). The Volpe Center contracted with FSEG to modify that prototype software and develop a new prototype railEXODUS (Prototype Software) software which can be used to evaluate the applicability of time-based egress requirements to U.S. passenger rail cars. The Volpe Center experiment data were used as input to the development of the new emergency egress simulation computer model to predict emergency evacuation time for a variety of U.S. passenger rail car designs.

1.2 Passenger Rail Car Egress Model Applications

Currently, the only way to determine the validity of passenger rail car occupant egress time predictions is to conduct actual (simulated) emergency evacuations, exercises, or egress experiments from the car. However, such activities have significant cost, as well as risks of injury to participants. Accordingly, the use of computer models that simulate egress behavior could reduce the number of actual tests that need to be performed to determine occupant egress times for various passenger rail car designs. Furthermore, using a simulation model rather than a hydraulic flow calculation to determine passenger rail car egress time estimates may permit more rail car egress designs to be evaluated with greater accuracy. Furthermore, a simulation model can provide realistic estimates of the range of egress times as a function of a variety of scenario variables.

Accordingly, a wide range of potential applications exists for a validated passenger rail car egress model:

- **Design Applications**. Passenger rail car design engineers could use the software in early stage design to optimize the level of evacuation safety built into new passenger rail car designs. For example, the location, type, and number of exits could be evaluated.
- **Regulating Applications**. Regulatory agencies, in consultation with industry groups, could use the software to define performance-based evacuation requirements for different types of railroad operating environments.
- **Certification Applications**. Industry groups could use the software to determine whether new passenger rail car designs comply with performance-based egress requirements.
- **Passenger Train Crew Training and Emergency Management Aid**. Passenger train operating agencies could use the software (with its virtual reality graphical capabilities) as an aid in evacuation safety training of train crews. The software could also be used to assist operating agencies in the development of operating procedures in the event of emergency situations. Finally, the software could also assist emergency response organizations to plan their response.
- **Accident Investigation**. Accident investigators could use the software to assist in the analysis of accidents and other emergency situations.
- **Normal Operations**. Passenger rail car design engineers, train operating agencies, and station managers could use the software to simulate normal operations, including the train-station interface and the efficiency of passenger loading and disembarking.

1.3 Purpose

This document describes the development of the new Prototype Software V2.2, based on modifications to the prototype railEXODUS software V1.0 that were implemented to adapt the EXODUS computer model for use in predicting U.S. passenger rail car egress times.

1.4 Objectives

The objectives of this contract were to:

- Complete transportation vehicle egress-related literature review;
- Identify necessary capabilities to enhance the prototype railEXODUS software V1.0;
- Assist in the analysis of results from the single-level passenger rail car egress experiments, as conducted by the Volpe Center in 2005 and 2006 [4];
- Incorporate, as feasible, the Volpe Center experiment data and other data, as available, within the EXODUS software;
- Further enhance the capabilities of the FSEG prototype railEXODUS software V1.0 to develop a new prototype railEXODUS software (Prototype Software), based on the Volpe Center experiment data;
- Perform verification and validation testing of the new Prototype Software, using the Volpe Center experiment data;
- Perform verification of the new Prototype Software, using maritime egress experiment data; and
- Provide demonstration examples of egress simulation times, based on U.S. passenger rolling stock in selected emergency evacuation scenarios.

1.5 Scope

The aim of this contract was to develop a new Prototype Software V2.2 by extending the capability of the prototype railEXODUS software V1.0 to incorporate the capability to simulate egress from U.S. passenger rail cars for the following types of egress scenarios:

- One or two side-doors to exit onto high platforms in normal or emergency lighting conditions;
- One or two side-doors to exit in normal lighting conditions to:
  - Low platform locations and
  - R-O-W;
- Inter-car end-door exit into the adjacent car in normal or emergency lighting conditions; and
- Movement of passengers in car aisle subjected to adverse angle of roll.

The model design and software development utilized data derived from the 2005 and 2006 Volpe Center passenger rail car egress experiments [4], and, when appropriate, other publicly available data. These data have also been used to verify and validate the new Prototype Software, where appropriate. The new Prototype Software is currently in "alpha" version, as it has only undergone in-house testing by FSEG and has been subjected only to limited external third-party (Volpe Center) "beta" testing.

1.6 Approach

The model design and software development were implemented in three phases:

- **Phase 1:** Extend capabilities of the existing prototype railEXODUS software V1.0 to include the simulation of egress to high platforms using passenger rail car side-door exits and inter-car egress using rail car end-door exits in both normal and emergency lighting conditions (Prototype Software V2.0).
- **Phase 2:** Extend the capabilities of the Prototype Software V2.0 to include the simulation of egress to low platforms and the R-O-W using passenger rail car side-door exits (Prototype Software V2.1).
- **Phase 3:** Extend the capabilities of the Prototype Software V2.1 software to include the capability to model the movement of individuals within passenger rail cars subjected to adverse angles of roll (Prototype Software V2.2).

Each development phase included a verification and/or validation phase to ensure that the new software performed as intended and was capable of reproducing the available experimental data.

Chapter 3 describes the three-phase development approach in more detail.

1.7 Report Organization

The remainder of this report is organized as follows:

- Chapter 2: EXODUS software description.
- Chapter 3: New Prototype Software V2.2 development approach.
- Chapter 4: Volpe Center 2005 and 2006 passenger rail car egress experiment data.
- Chapter 5: Prototype Software V2.0 development.
- Chapter 6: Prototype Software V2.0 verification and validation.
- Chapter 7: Prototype Software V2.1 development.
- Chapter 8: Prototype Software V2.1 verification and validation.
- Chapter 9: Prototype Software V2.2 development.
- Chapter 10: Prototype Software V2.2 verification.
- Chapter 11: Summary.
- Chapter 12: References.
- Appendices.

1.8 Terminology

General terminology used throughout this document is highlighted below. Specific terminology used primarily within a chapter is introduced within that chapter.

Model: Theoretical framework including data used to describe a phenomenon.

Software: Implementation of the model including data in computer code which enables the model to be run on a computer to produce predictions of the outcome of the phenomenon for a prescribed model scenario.

Scenario: A combination of factors which directly affect the egress performance of the passenger rail car population. This includes factors such as: exit configuration (i.e., location, type, and number of available exits), lighting conditions, rail car angle of inclination (i.e., roll and pitch), presence of fire, etc.

Model Scenario: A scenario specifically designed for examination using the Prototype Software V2.2.

Agent: Representation of an individual person within the computer software.

Software Verification: Process in which it is demonstrated that the software produces results which are consistent with the model design and, where available, qualitative observations of real-world data.

Software Validation: Process in which it is demonstrated that the software produces predictions which are in agreement with quantitative experimental measurements.

Observation: Qualitative information derived from analysis of the egress trial video recordings.

Measurement: Quantitative information derived from analysis of the egress trial video recordings.

Competitive Egress: Situations in which the egressing population senses a high degree of urgency which tends to make the egress more competitive. In such situations, quicker moving individuals may attempt to overtake slower moving individuals, exit queues may bunch up, some occupants may adopt atypical paths such as climb over furniture to circumvent slower moving occupants, and individuals are less likely to exhibit deference behaviors.

Non-Competitive Egress: Situations in which the egressing population does not sense a high degree of urgency. This lower degree of urgency may occur during an announced drill or trial, during normal deboarding, or even in a real emergency situation, if there is no sense of personal risk or immediate threat. In non-competitive egress situations, the population may exhibit a long response time, movement rates may be slow, there may be a high level of deference behavior, and people are more likely to be prepared to wait in lines (queues).

Terrain: Relates to the nature of a specified region of space and the potential impact that it might have on movement of individuals traversing that region.

2. EXODUS Model

Attempts to model egress from structures fall into two main categories of models: those which consider only human movement, the so-called “ball-bearing” models, and those which attempt to link movement with behavior. The first category of egress model concentrates solely on the carrying capacity of the structure and its various components. The “ball-bearing” model (also referred to as environmental determinism [6] has individuals treated as unthinking objects which automatically respond to external stimuli while exiting. Furthermore, the direction and speed of egress is determined only by physical considerations (e.g., population densities, exit capacity, etc.). The second category of egress model considers not only the physical characteristics of the structure but treats the individual as an active individual (i.e., agent), taking into consideration individual behavior, exit preference, etc., as well as individual movement and response to stimuli, such as fire hazards, etc.

This chapter provides an overview of the EXODUS individual movement egress model, as developed by the University of Greenwich. Chapter 3 provides more information about EXODUS in the context of the development of the new railEXODUS Prototype Software.

2.1 EXODUS Model

The EXODUS model consists of a suite of software tools designed to simulate evacuation and circulation dynamics exhibited by large numbers of persons within complex enclosures (e.g., high-rise buildings and underground transportation stations) and transportation vehicles (including aircraft and passenger ships). The EXODUS suite of software (buildingEXODUS, maritimeEXODUS, and airEXODUS) has been under continuous research and development since 1989 for the building, ship, and aircraft operating environments, respectively.

The basis of the existing EXODUS software has been described in many publications and therefore will only be summarized in this chapter. A selected number of EXODUS-related references are listed in Section 2.3 of this chapter. The FSEG Web site, http://fseg.gre.ac.uk/fire/pub.asp, provides a complete list of EXODUS-related publications.

The buildingEXODUS software has been used to simulate evacuation from a variety of buildings, road and rail tunnels, and subway station environments. The software also includes the effect of fire on the populations. However, EXODUS is not a passenger rail car-specific egress model.

The EXODUS software is based on a fine network of nodes and uses a rule-based system to describe person (agent) behavior. The EXODUS software takes into consideration three types of interactions: (1) people-people, (2) people-structure, and (3) people-fire. The software is able to track the route of each agent (i.e., individual) as they move around the enclosure geometry. In evacuation applications involving fire, the software can also predict when agents will be affected by fire hazards, such as heat, smoke, and toxic gases.

The EXODUS software is written in the programming language C++ using Object-Oriented techniques, which utilize rule-based technology to control the simulation. Therefore, the behavior and movement of each agent is determined by a set of heuristics or rules. For additional flexibility, these rules are categorized into five interacting sub-models (see Figure 1).

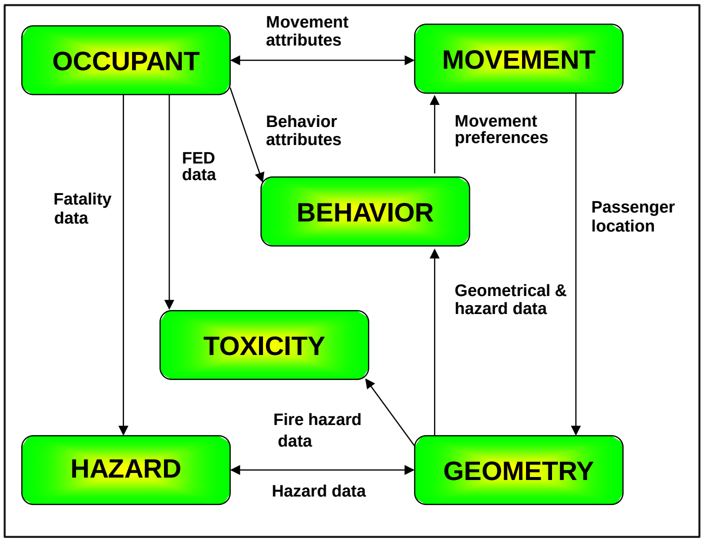

Figure 1. EXODUS Sub-Model Interaction

- Occupant,
- Movement,
- Behavior,
- Hazard, and
- Toxicity.

These sub-models operate in a region of space defined by the geometry of the enclosure. Each of these components is briefly described below.

2.1.1 Sub-Models

The **GEOMETRY** of the enclosure can be defined in several ways. It can be: (1) read from a *Geometry* library, (2) constructed interactively using the tools provided, or (3) read from a computer-aided design (CAD) drawing using the Drawing Exchange Format (DXF). Internally to the software, the entire space of the geometry is covered by a mesh of nodes. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single agent.

The **MOVEMENT** sub-model controls the physical movement of individual agents from their current position to the most appropriate neighboring location (i.e., adjacent node), or supervises the waiting period if one does not exist. The movement may involve behavior, such as overtaking, sidestepping, or other evasive actions.

The **BEHAVIOR** sub-model determines an agent's response to the prevailing situation on the basis of the agent's personal attributes and passes its decision on to the movement sub-model. The behavior sub-model functions on two levels: local and global.

The local behavior determines an agent's response to the local situation, while the global behavior represents the overall strategy employed by the agent. Global behavior may include behavior, such as exiting via the nearest available exit or exiting via the most familiar exit. Another capability of the software is the ability to assign agents with a list of tasks to perform. This capability can be used when simulating either emergency conditions or normal operations; for example, agents could be assigned a task to complete prior to leaving the geometry, such as shutting down equipment; agents could be assigned tasks to enter the geometry of the enclosure to represent emergency responders or crew.

The **OCCUPANT** sub-model describes an agent as a collection of defined attributes and variables including: name, gender, age, maximum running speed, maximum walking speed, response time, agility, mobility, etc. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other sub-models.

The **HAZARD** sub-model controls the atmospheric and physical environment, distributes pre-determined fire hazards, such as heat, smoke, and toxic products throughout the atmosphere, and controls the opening and closing of exits. While the thermal and toxic environment is determined by the Hazard sub-model, the software does not predict these hazards but rather distributes them through time and space. The software will accept hazard data, either from experimental measurements or numerical data from other models, including a direct software link to the CFAST (Consolidated Model of Fire and Smoke Transport) fire zone model [7] [8] and the SMARTFIRE fire field model [9] [10] [11] [12] [13].

The **TOXICITY** sub-model determines the effects on an agent of exposure to toxic products distributed by the Hazard sub-model. These effects are communicated to the behavior sub-model, which, in turn, feeds through to the movement of the agent. The toxicity sub-model functions on a Fractional Effective Dose (FED) concept and currently considers the narcotic fire gases CO, CO_2, HCN, Low O_2, as well as convective and radiative heat. Each agent is represented by the agent's own FED sub-model and the software calculates the effect on the agent of exposure to these products when exiting the structure. In addition, fire hazards may also impact an agent's mobility attribute, which in turn will have an impact on their travel speed.

2.1.2 EXODUS Output

EXODUS produces a range of graphical and textual output. Interactive two-dimensional animated graphics are generated as the software is running that allows the User to observe the evacuation as it takes place. Figure 2 provides a top level view representing the interactive graphics component within buildingEXODUS. The building possesses three floors and 600 agents. Graphs depict the number of agents using each exit.

The graphics can be displayed in individual mode or population density mode. In the latter, rather than graphically show agents, a color contour fill is used to represent the number of agents per square meter. This mode of view provides an immediate indication of points of congestion.

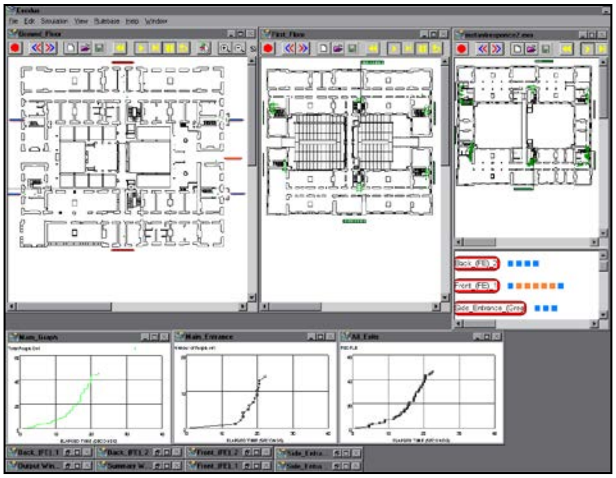

Figure 2. buildingEXODUS – Three-Story Building Layout Analysis

In addition, a post-processor virtual-reality graphics environment known as vrEXODUS enables an animated three-dimensional representation of the evacuation to be generated (see Figure 3, Figure 4, and Figure 5).

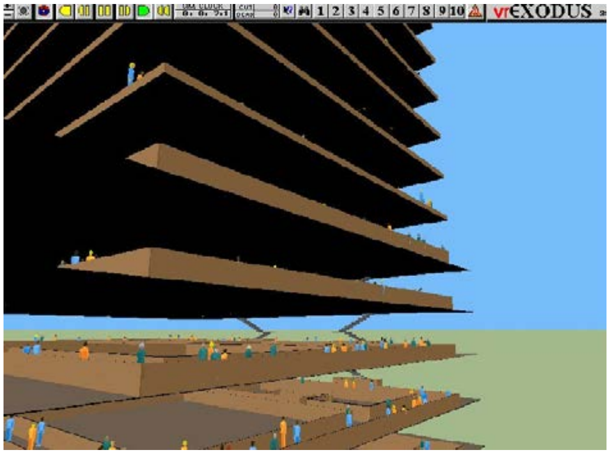

Figure 3. Post-Processed Virtual Reality Representation of buildingEXODUS Simulation

The maritimeEXODUS software has a number of unique capabilities, such as the ability to include the impact of heel (roll) and trim (pitch) of the ship on passenger and crew performance (see Figure 4). The maritimeEXODUS software also has the capability to represent the performance of both ship crew and passengers in the operation of watertight doors, vertical ladders, hatches, and 60 degree stairs. The software can also simulate the abandonment of the ship.

The airEXODUS version of the software (see Figure 5) has a range of special capabilities specific to aircraft, including: movement rates appropriate for aircraft environments, exit flow rates specific to aircraft exits, an ability to represent slides, and an ability to represent the action of the crew.

Figure 4. vrEXODUS Output for Large Passenger Ship Generated Using maritimeEXODUS

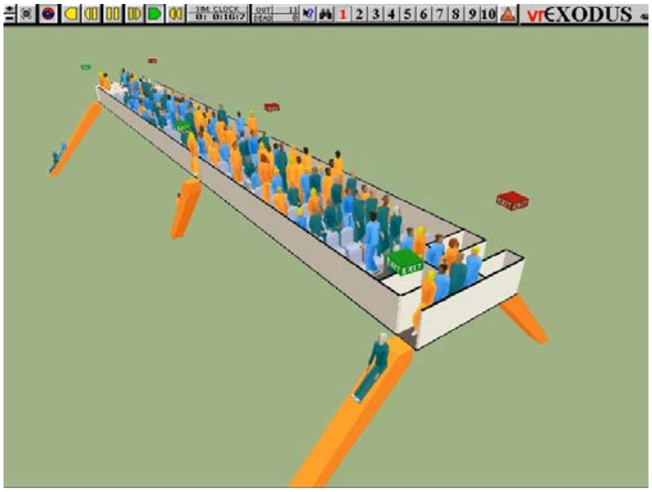

Figure 5. vrEXODUS Output for Aircraft Simulation Using airEXODUS

2.1.3 EXODUS Operation Modes

The EXODUS software has four modes of operation to assist the User in simulating an evacuation scenario. Each mode must be utilized in sequence in order to represent the evacuation/egress scenario to be simulated. Before viewing simulations in *Simulation* mode, it is first necessary to specify a geometry (*Geometry* mode), define a population (*Population* mode), and specify a scenario (*Scenario* mode). Only after these steps have been completed is it possible to run a simulation.

2.2 Previous EXODUS Passenger Rail Car Egress Software Development

The previously existing prototype railEXODUS software V1.0 was developed in the early 2000s, based on the demonstrated and validated success of the buildingEXODUS software, and incorporates many capabilities, such as the ability to consider egress from passenger rail cars to high platform stations (see Figure 6), multi-level rail car design, and the impact of fire on passengers.

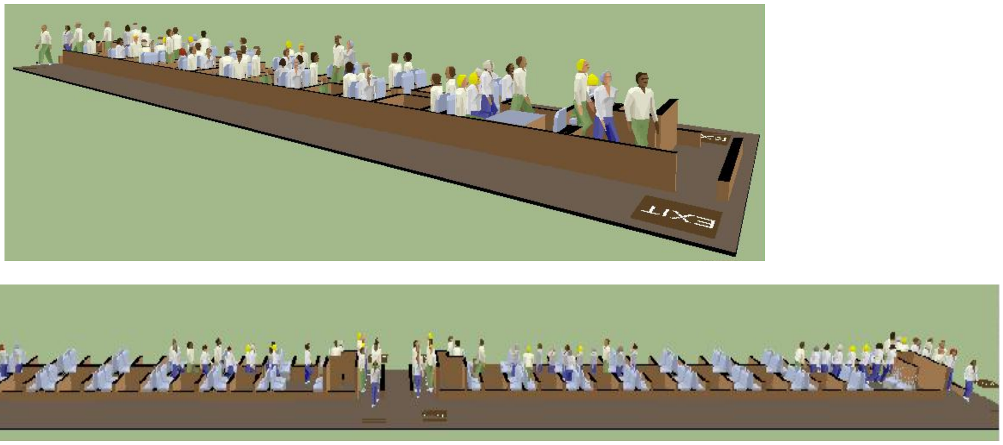

Figure 6. Simulation Using Prototype railEXODUS Software V1.0 Showing Agent Disembarkation to High Platform from Single Car and Two Car Configurations

Accordingly, that existing prototype railEXODUS software V1.0 had the ability to: define rail car internal stairways (and thus model multilevel passenger rail cars), interface with the CFAST zone and SMARTFIRE CFD (Computational Fluid Dynamics) fire simulation models (and thus model the impact of fire on individuals in passenger rail cars), accept rail car drawings in CAD DXF file format, and generate three-dimensional virtual reality animations using vrEXODUS. However, the prototype railEXODUS software V1.0 did not possess actual data that characterizes and quantifies human performance in passenger rail car-specific operating environments. These environments can include egress from rail cars to low platform and R-O-W locations, as well as egress from cars that are inclined at an adverse angle (overturned).

The original prototype railEXODUS software V1.0 provided the initial development platform for the new Prototype Software V2.2. To avoid confusion with subsequent software developments described in the later chapters of this report, the original prototype railEXODUS software, as described in this report, will be always be identified as prototype railEXODUS software V1.0.

2.3 EXODUS References

This section contains a selected listing of EXODUS reports, documents, etc., by author and year. The University of Greenwich FSEG Web site, http://fseg.gre.ac.uk/fire/pub.asp, provides a complete list of EXODUS-related publications.

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3. railEXODUS Prototype Software Development

Data that characterize and quantify actual human performance in passenger rail car-specific operating environments were not available to validate or verify the prototype railEXODUS software V1.0. Therefore, the simulation of emergency egress from U.S. passenger rail cars to the various operating environments, including egress from rail cars to low platform and R-O-W locations and egress from cars that are inclined at an adverse angle (overturned), could not be accurate and reliable.

This chapter describes the preliminary tasks completed to determine what data and specific capabilities would be necessary to incorporate into the prototype railEXODUS software V1.0 to develop a new Prototype Software which realistically simulates emergency egress from U.S. passenger rail cars.

3.1 Literature Review

In order to provide a knowledge base for the remainder of the contract tasks, FSEG conducted a literature review [14], which is summarized in Appendix A. The items in the review included: passenger train accident data, transportation vehicle egress experiments, and egress models. The literature review also identified passenger rail, marine, and aviation egress accident and experiment data bases. This information was used to assist in the development of the desirable modeling capabilities for the new Prototype Software. In addition, experiment data and other data were identified that could be used for the inclined rail car egress scenario.

To accurately represent passenger rail car evacuation, the new Prototype Software must have the capabilities to address how passengers behave and the resulting human dynamics relating to the following issues:

- Since emergency egress situations seldom occur when the train is at a platform, it is important to consider alternate egress routes.
  - Internal egress, in which passengers move from a place of danger to a place of relative safety within the train or from car to adjacent car, often occur.
  - External egress routes to the R-O-W, using the side doors or windows.
- Structural deformation damage resulting from the incident can eliminate normal means of egress, such as side-door exits, car-to-car egress routes, and interconnecting stairways in multi-level cars.
- Passengers may be thrown about in an accident and injured. These injuries may make self-evacuation impossible.
- Passenger rail cars may overturn in accident situations making evacuation difficult in accidents; it may be difficult or impossible for passengers to travel between overturned rail cars even when the cars have not decoupled.
- Passenger rail cars may be inclined at an adverse angle in accident situations. The angle of orientation at which the cars come to rest and their decoupling may make evacuation routes difficult.

- The external physical environment in which the accident takes place can have an impact on the ability to evacuate a passenger rail car.
- In some circumstances, fire may spread rapidly through the passenger rail car, exposing survivors to fire hazards such as smoke, heat, and toxic gases, making rapid egress essential.
- Low visibility due to smoke, dust, and obscured windows may hamper rapid egress of survivors even in daylight conditions.
- In accidents that occur at night, emergency lighting may assist passengers to assess their circumstances and find suitable exit routes, which may positively affect the evacuation efficiency.
- Passenger rail car windows may be used as an egress route by passengers, and ladders may be necessary to reach passengers trapped in multi-level cars or when the car is overturned at an angle.
- In some accidents, a significant number of passengers may be forced to exit through windows;
  - Of those exiting through windows, a significant number may exit from the high side of the overturned car;
  - Access to and egress through windows may be made more difficult due to the orientation and position of the car. If the car has overturned, the only way to exit the car may be through the windows that are now in the ceiling area;
  - Use of emergency windows can be very difficult when located on an upper level of a multi-level car; and
  - Multilayer windows make it difficult for passengers and even emergency crew to evacuate passengers via windows (as the windows are more difficult to break);
- Low levels of visibility due to smoke, dust, and failure of emergency lighting may hamper movement.
- Fire may spread rapidly through the car, exposing survivors to fire hazards;
- Egress from an upright or partially or fully overturned car (s) environment:
  - Internal egress from car to adjacent car using an end door,
  - External egress using:
    - Side doors to a high or low platform, or the R-O-W, or
    - Car windows.

Since data were limited or non-existent, the following specific scenarios were selected for incorporation into the new Prototype Software for passenger car egress time prediction:

- One or two side-door exits onto a high platform in normal or emergency lighting conditions;
- One or two side-door exits in normal lighting conditions:
  - Low platform or
  - R-O-W;

- Inter-car end-door exit into the adjacent car in normal or emergency lighting conditions; and
- Passengers subjected to adverse angle of roll.

3.2 Basic Required Modeling Capabilities

From a modeling perspective, passenger rail car emergency egress environments and scenarios share many similarities with egress situations in the building, marine, and aviation environments. Accordingly, a simulation tool capable of modeling passenger train egress situations would share many of the basic capabilities of building, maritime, and aviation egress models:

- Representing space and time;
- Representing the target population and their movement capabilities;
- Ability to modify the movement rates of agents in crowds;
- Representing main behavioral responses such as overtaking capabilities, exit selection, agent response times, etc.; and
- Incorporating fire data into the evacuation simulation and determining the impact of fire products (e.g., toxic gases and heat) on the exposed population.

While these capabilities are common to passenger rail car and other egress modeling environments, the passenger train system operating environment is different. For example, the movement rate of agents within the passenger rail car aisle differs from the movement rate of agents walking along building corridors, and flow rates through passenger rail car doors differ from flow rates in the building environment.

3.3 New Data Requirements

While the prototype railEXODUS software V1.0 already incorporated all of the basic capabilities identified in Section 3.2, the data associated with calibrating these capabilities are different from those used in building or other applications. Moreover, passenger rail car egress data have not been available in a form that could be used for accurate modeling of the various rail car egress environments. In addition, several additional capabilities required by the new Prototype Software are not required or available in other egress models. For example, additional capabilities not currently represented within the prototype railEXODUS software V1.0 include egress from a passenger rail car to a low platform or the R-O-W, or egress from a rail car at an adverse inclination (overturned on its side).

The new Prototype Software requires data that characterize the performance of individuals in the actual U.S. passenger rail car environment. For example, data are required relating to passenger flow rates and travel speeds along rail car aisles, as well as passenger egress behaviors, by a representative population. Data are very limited or unavailable for individual egress from the passenger rail car through an inter-car end-door exit to an adjacent car and through side-door exits to high platform locations; and to low platform and R-O-W locations, where the vertical drop may vary from no distance (high platform) to two (.6 meters) or more feet down to the R-O-W.

Accordingly, the majority of the required human factors data used in the development of the new Prototype Software was derived from the 2005 and 2006 Volpe Center-conducted egress experiments [4], unless otherwise indicated. The required data include:

- **Aisle travel speeds.** Unhindered typical travel speeds of males and females of various ages moving along the passenger rail car interior aisle.
- **Exit flow rates**. Passenger rail car exit flow rates associated with passenger rail car exits from car to high platform, car to adjacent car, car to low platform, and car to the R-O-W.
- **Stairway travel speeds—multi-level cars.** Unhindered typical travel speeds of males and females of various ages traveling down and up internal stairways in multi-level passenger rail cars. However, since the data are not available from the literature or the Volpe Center-conducted experiments, the stairway travel speeds are based on standard stairway travel speeds, as used in the buildingEXODUS egress model.
- **Response times.** Response time distributions for individuals involved in various rail egress scenarios. Response time is the time taken by individuals to decide whether and which way to exit after becoming aware of emergency. Realistic response time data relevant to passenger rail car emergency scenarios are not currently available from the literature or the Volpe Center-conducted egress experiments. This parameter is highly scenario-specific and would ideally be extracted from analysis of past passenger train accidents. Accordingly, this parameter is treated as a free parameter that can be set at the discretion of the User.

In addition, the required data for passenger rail car design-specific features, such as aisle and exit widths, were derived from Volpe Center-provided rail car drawings [15]. Data for passenger movement rates along rail car aisles and passenger exiting behaviors, etc., have also been generated as a result of FSEG video analysis of the 2005 and 2006 Volpe Center egress experiment trials.

3.4 Additional Modeling Capabilities

FSEG review of past passenger train accidents and analysis of the data from the 2005 and 2006 Volpe Center-conducted egress experiment trials imply that passenger rail car environments and egress scenarios pose special challenges not usually found in building, ship, and aircraft egress scenarios. (See Section 3.1, Appendix A and References 5 and 16.)

Potential passenger rail car emergency egress scenarios include: internal egress from one passenger car to another and external egress from the car to high- and low platform locations, to the R-O-W, as well as egress from overturned cars; all under potential low levels of visibility and failure of emergency lighting.

As noted in Section 3.1, numerous issues in emergency egress situations influence the way in which persons will behave and the resulting human dynamics. For example, the egress flow rate will vary if passengers exit:

- Traversing passenger rail car side-door exits, where the vertical drop may vary from no distance (high platform) to several feet (meters) down to the R-O-W;

- Through inter-car end-door exits to an adjacent car; and
- During low levels of visibility due to smoke, dust, and failure of emergency lighting, all of which may hamper individual and group movement.

In addition, passenger car design-specific features, such as aisle and exit widths, movement rates along passenger rail car aisles, and passenger exiting behaviors, etc., affect passenger travel speed.

Accordingly, to accurately simulate passenger rail car egress for a variety of emergency scenarios, it is desirable that the new Prototype Software be capable of addressing how passengers behave and the resulting human dynamics, to represent the unique passenger train operating environment in order to accurately predict passenger rail car egress time.

These challenges required additional modeling capabilities for incorporation within the prototype railEXODUS software V1.0 to permit the new Prototype Software V2.2 to provide a reasonably accurate representation of occupant egress behavior under different passenger rail car exiting conditions.

3.4.1 Passenger Rail Car Exits and Associated Exiting Behavior of Individuals

Passenger rail cars vary in the type of normal and emergency exits provided. Individuals may typically egress from a rail car using an inter-car end-door exit to an adjacent car, or one or two side-door exits from a car to a high platform, low platform, or the R-O-W. Due to the geometry of the passenger rail car design and unique railroad operating exiting environment, occupant travel speeds, egress flow rates, and exit times of occupants, particularly those with mobility issues, will be different and may vary substantially.

3.4.2 Adverse Orientation of Passenger Rail Car and Associated Behavior and Movement of Individuals inside Car

In a passenger train accident, the passenger rail car may be at an adverse incline. However, not all rail cars associated with a train may be subjected to adverse orientation in the passenger train operating environment. Indeed, each car may have a unique orientation. The passenger rail car may undergo a range of different orientation changes including: a simple roll around its long axis, the elevation of one of its ends (pitch), or a combination of roll and pitch. It is desirable for the new Prototype Software to have the capability to represent some or all of these orientations. While this type of capability is available in some maritime egress models, the passenger train environment is different from the marine environment. In the marine environment, the entire passenger ship is affected by the orientation. However, in the passenger train environment, not all the cars associated with a train may be subjected to adverse orientation.

3.4.3 Different Levels of Lighting and Associated Behavior of Individuals

Most of the parameters and capabilities discussed above will be influenced by the level of light available. Therefore, it is desirable for the new Prototype Software to have the ability to represent egress situations in normal and emergency lighting conditions.

3.5 Prototype Software V2.2 Development

The new Prototype Software V2.2 possesses all the capabilities of the prototype railEXODUS software V1.0, including the capabilities to simulate multi-level passenger rail cars; and also incorporates the impact of a developing fire on the evacuating population.

A multi-phase development process was used to extend the capabilities of the prototype railEXODUS software V1.0 to develop the new Prototype Software V2.2 by adding additional modeling capabilities to the existing software functionality. These functionalities include the capability to model passenger egress from a passenger rail car to

- One or two side-doors to exit onto high platform locations in normal or emergency lighting conditions;
- One or two side-doors to exit in normal lighting conditions to:
  - Low platform locations and,
  - R-O-W;
- Inter-car end-door exit into the adjacent car in normal or emergency lighting conditions; and
- Movement of passengers in rail car aisle subjected to adverse angle of roll.

Each development phase, as described in Sections 3.5.1 and 3.5.2, included verification and validation tasks to ensure that the new Prototype Software V2.2 performs as intended and is capable of reproducing the available experimental data. Since maritime data were used for the rail car at adverse angle conditions, only verification of the new Prototype Software V2.2 was completed.

3.5.1 Phase 1: Upright Car – Exit to High Platform or Adjacent Car

The capabilities of the prototype railEXODUS software V1.0 were extended to include the simulation of egress to high platforms using passenger rail car side-door exits and inter-car egress using car end-door exits, in both normal and emergency lighting conditions.

While limited exit flow rate data for passenger rail car exit doors on trains operated in other countries are publicly available, these data may not be appropriate for U.S. rail cars because of different rail car and platform design. Accordingly, appropriate data for U.S. passenger rail cars were extracted from the 2005 Volpe Center egress experiments [4] and analyzed. The incorporation of that passenger rail car data, including appropriate behaviors associated with an individual’s use of internal end doors to exit to an adjacent car and external side doors to exit onto a high platform resulted in the Prototype Software V2.0.

3.5.2 Phase 2: Upright Car – Exit to Low Platform or R-O-W

The capabilities of the Prototype Software V2.0 were extended to include the simulation of egress from the passenger rail car to low platform locations and to the R-O-W, using car side-door exits in normal lighting conditions.

As previously noted, the limited publicly available flow data for passenger rail car exit doors may not be appropriate for U.S. passenger rail cars because of different rail car and platform design. The appropriate data for U.S. cars were extracted from the 2006 Volpe Center egress experiments [4] and analyzed. The incorporation of that data, including behavior associated with individuals exiting from rail car side doors onto a low platform or to the R-O-W, resulted in the Prototype Software V2.1.

3.5.3 Phase 3: Car at Adverse Angle (Inclined) – Behavior and Movement inside Car

The capabilities of the new Prototype Software V2.1 were extended to include the ability to model the behavior and movement of individuals within passenger rail cars subjected to adverse angles of roll, resulting in the new Prototype Software V2.2.

Appropriate human factors data relating to movement of individuals in passenger rail cars subjected to adverse angles of roll were not available. To represent adverse angles of roll, data from the maritimeEXODUS software [17] and appropriate behaviors were incorporated because of the availability of the data set and the similarity between the experimental conditions in which the marine data were generated and the target passenger rail car egress conditions.

The incorporation of the maritime data, including behavior associated with individual movement inside a passenger rail car located at an adverse angle, resulted in the Prototype Software V2.2. However, Users of this capability should note that the data are **not** passenger rail car-specific when using this feature.

3.6 Summary

The capabilities of the Prototype Software V2.2 software address all of the egress scenarios identified in Reference 16, which are summarized in Table 1.

Table 1. Prototype Software V2.2 Passenger Rail Car Egress Scenarios

EGRESS CONFIGURATION	NORMAL LIGHTING	EMERGENCY LIGHTING	NON-COMPETITIVE	COMPETITIVE	MULTI-LEVEL	FIRE CONDITIONS	CAR WITHIN TUNNEL	INCLINED CARS
Car – Car	√√√	√√	√√√	√	√√	√√√	√√	√
Car Door Exit – High Platform	√√√	√√	√√√	√	√√	√√√	√√	√
Car Door Exit – Low Platform	√√√	√√	√√√	√	√√	√√√√	√√	√
Car Door Exit – R-O-W	√√√	√√	√√√	√	√√	√√√	√√	√

Table Key:

√ : Capability exists within software, appropriate data required
√√ : Capability exists within software, additional data desirable
√√√: Capability exists within software, sufficient data available

Where “sufficient data available” is highlighted, a sufficient amount of predictive capability of the Prototype Software V2.2 exists for passenger rail car egress times. When “more data desirable” is highlighted, it indicates that although some data are currently available that can be used to undertake rail car egress simulations, additional data would be required in order to have a reasonable amount of confidence in the predictive capability of the simulations produced by the Prototype Software V2.2.

Finally, when “appropriate data required” is highlighted (i.e., competitive and inclined passenger rail car egress situations), although the modeling capability exists within the Prototype Software V2.2, no passenger rail car-specific egress data are currently available. Accordingly, while the Prototype Software V2.2 can be used to simulate the indicated egress scenario, there is low confidence in the reliability and accuracy of the simulation results.

4. Volpe Center Egress Trial Data Used in Prototype railEXODUS Software

4.1 Background

The new Prototype Software V2.2 required data to characterize individual performance in the passenger rail car environment. FSEG extracted data from a detailed analysis of the 2005 and 2006 Volpe Center-conducted egress experiment trials as part of the development of the new Prototype Software V2.2.

In 2005, Volpe Center staff conducted a series of 12 egress experiment trials, with the cooperation of the Massachusetts Bay Transportation Authority (MBTA), to obtain human factors data related to egress from a single-level passenger rail car. Participants were recruited from the population of passengers who traveled regularly to the North Station commuter rail station in Boston, MA. A single group of 84 individuals participated in all the egress trials, with the exception of Trial 1, in which there were only 81 participants. Males represented 46 percent of the population while females represented 54 percent. The ages of the participants were specified in three age bands, with 32 percent of the participants being under 30, 37 percent being between 30 and 50, and 31 percent being over 50. Only one participant self-reported as having a mobility impairment (walked with a cane).

The sequence of main egress experiment trials involving the number and type of door exits which the participants used and type of lighting conditions is listed in Table 2.

Table 2. Volpe Center Passenger Rail Car Experiment Egress Trial Sequence

EGRESS TRIAL #	DESTINATION	LIGHTING
1	Platform – 1 side-door exit	Emergency
2	Adjacent car – Inter-car end-door exit	Normal
3	Platform – 2 side-door exits	Emergency
4	Platform – 2 side-door exits	Normal
5	Platform – 1 side-door exit	Normal
6	Adjacent car – Inter-car end-door exit	Emergency
7	Platform – 1 side-door exit	Emergency
8	Adjacent car– Inter-end door exit	Normal
9	Platform – 2 side-door exits	Emergency
10	Platform – 2 side-door exits	Normal
11	Platform – 1 side-door exit	Normal
12	Adjacent car – inter-car end-door exit	Emergency

(In addition to the main egress experiment trials, two other individuals with mobility impairments participated in separate, very limited, egress trials under normal lighting.)

In 2006, Volpe Center staff conducted a second series of egress experiment trials at the MBTA Boston Maintenance Facility in Somerville, MA, to obtain human factors data related to egress from a single-level commuter passenger rail car to the R-O-W (April) and to a simulated low platform location (May). These experiments consisted of two types of egress trials. The first type of egress trial involved each participant individually exiting the car, allowing measurements of individual exiting performance to be made. The second type of egress trial, which was repeated five times, involved the entire group of participants exiting the car; all trials were conducted under normal lighting conditions. Appendix B contains a summary of the conduct of the Volpe Center egress experiment trials while the complete report description is contained in Reference 4.

The primary data derived from this series of experimental egress trials consisted of qualitative and quantitative data, including occupant exiting behavior and occupant exit times when a passenger side-door exit was used for egress. These quantitative measurements and qualitative observations were categorized according to the egress system component being observed, enabling the component to be better characterized within the new Prototype Software V2.2.

The Volpe Center experiment egress trial data were used in the following stages of the model development:

- **Design –** Qualitative data informed the types of components and behaviors which were included in the model, along with the manner in which they should be implemented.
- **Calibration –** Quantitative data informed the set of behaviors available to individual agents and then the performance levels associated with these actions. Similarly, the data were used to inform performance levels of dedicated egress components (new objects within the railEXODUS software).
- **Validation and verification –** Qualitative and quantitative data were used for comparison purposes with numerical predictions to ensure that the eventual performance of the new Prototype Software was acceptable.

The remainder of this chapter summarizes the Volpe Center-conducted egress trials in terms of data collection, discusses FSEG analysis techniques, and identifies the data generated for use in the new Prototype Software.

4.2 Egress Trial Terminology

During the FSEG analysis discussion of the Volpe Center 2005 egress trial video data, certain terms are used as listed in Section 4.2.1.

4.2.1 2005 Egress Trials

Passenger rail car geometry features (as applicable to the type of egress trial) include:

- **Wall side:** Block of dual seats on the wall side of the passenger rail car;

- **Platform side:** Block of dual seats on the station platform side of the passenger rail car;
- **Aisle seat:** Particular seat in a dual seat combination closest to the aisle;
- **Window seat:** Particular seat in a dual seat combination closest to the window;
- **Side-door exit:** One of the two doors located in the side of the rail car that leads onto the platform;
- **Left side-door exit:** Left side-door exit when viewed from the platform;
- **Right side-door exit:** Right side-door exit when viewed from the platform;
- **Inter-car end-door exit:** Connecting door leading to an adjacent rail car;
- **All one-door exit egress trials:** All egress trials involving one exit, including side-door and inter-car end-door exit egress trials; and
- **One side-door exit egress trials:** Only those egress trials involving one side-door exit, excluding inter-car end-door exit egress trials.

The Volpe Center egress trial passenger rail car-specific terms are illustrated in Figure 7. The seat row numbering is measured from the left side-door exit and means that the closest seat row to the left side-door exit is seat Row 1 (see Figure 7).

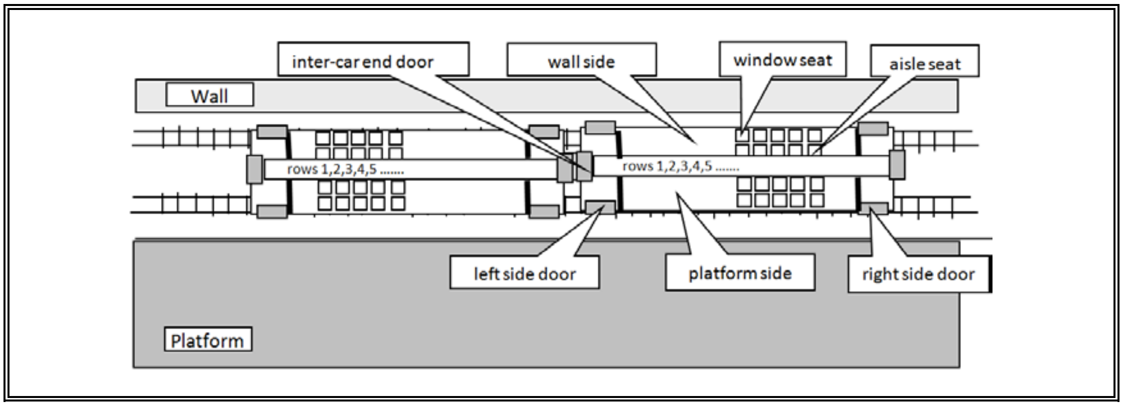


Figure 7. 2005 Commuter Rail Car (#1531) Terminology and Location of Egress-Related Features

4.2.2 2006 Egress Trials

Due to the nature of the 2006 Volpe Center egress experiments, additional definitions are presented in Section 4.5.

4.3 2005 Egress Trials

4.3.1 Data Analysis Methodology

The detailed analysis performed by FSEG followed a two-step process. First, the appropriate raw data were identified and extracted from the Volpe Center-generated video recordings.

Second, the extracted data were analyzed, producing either a set of qualitative findings or a quantitative data set.

The data analysis of the egress trials was intended to provide qualitative insight into human behavior issues to then be embedded within the new Prototype Software: quantitative data to calibrate the software, data for software validation/verification purposes, and, finally, data that could be used in the operation of the software.

The information derived from this analysis includes the following:

- Qualitative Human Factors Observations
  - Behavior issues derived from questionnaire analysis,
  - Qualitative behavior issues,
  - Deference behaviors;
- Quantitative Human Factors Measurements
  - Exit flow rates and exit flow times,
  - Aisle flow rates,
  - Individual aisle travel speeds;
- Row clearance times; and
- Times from seat to movement down the aisle.

4.3.2 Qualitative Data Analysis Methodology

Three sets of qualitative data analysis were completed, one based on the analysis of the questionnaires and two analyses based on video data:

- Behavior issues derived from questionnaire analysis (2005 and April 2006);
- Qualitative behavior issues; and
- Deference behaviors.

The questionnaire analysis provided input into the structure and nature of the subsequent analysis. The qualitative observations from each egress trial that were determined to be the most informative for egress model development are described. These observations are categorized according to their source (i.e., the questionnaire, video analysis focusing on general behaviors, and video analysis focusing specifically on deference behavior).

4.3.2.1 *Questionnaire Analysis Methodology*

Each participant was required to provide demographic data prior to starting the egress trials. After each of the egress trials was finished, each participant completed a written six-part, one-page questionnaire by checking responses and matching their experiences during the respective egress trial. Analysis of the participant replies shown are based on two types of percentages, one in which the divisor is based on the total number of responses (not shown in brackets, e.g., X%), and one based on the total number of participants (the preferred type, shown in brackets, e.g., [Y%]).

4.3.2.2 *Video Based Qualitative Behavior Observations*

Qualitative participant behaviors were noted from observation of the video recordings and egress trial notes. Through an iterative process of review and marking, a set of significant recurring behaviors were identified, as were potentially significant unique behaviors. Of particular interest were participant deference behaviors.

Deference is a situation in which an individual yields to one or several individuals attempting to enter or cross his or her flow stream. Deference behavior may occur if the aisle flow defers to the seat flow or if the seat flow defers to the aisle flow. In the context of the Volpe Center-conducted egress trials, deference behavior refers to one of two specific behaviors. In the first case, a participant located in the aisle is in position to proceed along the aisle but elects to allow one or several persons from the seat rows into the aisle ahead of them. This type of behavior is "aisle deference." In the second case, a participant in one of the seat rows who is in a position to access the aisle elects to allow one or more participants already in the aisle to proceed ahead of them. This type of behavior is labeled "seat deference." Figure 8 shows a sequence of stills taken from the start of egress Trial 8 (Camera 6) demonstrating an example of seat deference.

(a) Initiating deference to those in aisle

(b) Action of deference

(c) Still in the seat row

Figure 8. Example of Seat Deference by Participant 82

4.3.3 Qualitative Results

4.3.3.1 *Questionnaire*

Results were collected from the first set of trials (Trials 1–6) and the second set of trials (Trials 7–12). The main findings of the questionnaire analysis for these egress trials are summarized as follows:

- Seated participants either waited for a gap to form in the aisle before joining, or aisle participants deferred to seated persons. This behavior appeared to be independent of age, gender, and lighting levels. Given the low level of urgency perceived by the participants, this behavior is likely to be less frequent in a real emergency.
- A significant number of participants, (i.e., ([62%]) were unable to move at the speed they wanted to in the rail car aisle because of congestion. Incidents of pushing and attempted overtaking were negligible, with a high degree of deference towards seated participants. These results appeared to be independent of age, gender, and lighting levels. It is likely that the ability of participants to move at the desired speed would be less common during an emergency given the more urgent movement of participants producing less orderly conditions.
- A great majority of participants experienced no difficulties in exiting the passenger rail car. The high platform and inter-car transfer posed no significant obstacles to movement. These results appear to be independent of age, gender, and lighting levels. It is expected that greater difficulties may be experienced under nighttime conditions given the further reduced visibility inside and outside the car.
- The evacuation process was very orderly. Under emergency evacuation conditions, the process may be different, given the more urgent response and movement of the population leading to their simultaneous arrival in the aisle and resulting in greater levels of congestion.
- The majority of participants reported that they used their nearest exits, even under emergency lighting conditions. This result appears to be independent of age and gender. For the “under 30” pool of participants, the length of exit queue was also a factor in exit selection, while for the “over 50” pool, following instructions was a factor.
- Low-lighting scenarios produced faster results. This may be due to the darker conditions encouraging more motivated movement without being so dark as to inhibit movement.
- While the majority of participants were not greatly affected by reduced lighting levels, a significant minority [21%], reported reduced travel speeds in low-light conditions. Also, low-lighting levels appeared to reduce the impact of both age and gender upon performance.

4.3.3.2 *Qualitative Behavioral Analysis*

Across all 12 egress trials, participants displayed a consistent set of behaviors. A matrix of behaviors observed throughout the 12 egress trials and from all camera views was developed.

Table 3 presents a non-exhaustive set of examples of the types of observations made during this analysis.

The qualitative behavioral analysis of the video data generated the following observations:

- Participants responded immediately upon the egress trial signal.
- Participants moved down the aisle and exited the car in single file.

Table 3. Examples of Observed Egress Trial Behaviors from FSEG Video Analysis

Single file movement
Participant mobility impairment
Deference behavior observed
Congestion in the aisle
Other congestion (on platform)
Flow slower than other egress trials
Participants noted carrying questionnaires
Participants noted completing questionnaires
Baggage relinquishment halted flow
Participants sat waiting
A single participant bypassed an exit
Participant seen carrying an object

- The behavior of participants did not appear to change under the reduced lighting conditions; this may have been due to the egress trials being performed with bright station and car side and -end door lighting, allowing the lighting conditions to be less severe than might have been expected. Therefore, the data generated from the 12 egress trials may not be representative of situations involving darkness or low visibility.
- Item retrieval times varied from 1.6 to 10 seconds with a mean of 4.7 seconds. In all but one case, the act of retrieving the baggage did not impede the flow down the aisle because the baggage retrieval was undertaken in the early part of the egress trial while the adjacent participants were delayed in congestion.
- Quantitative data generated from the 12 passenger rail car egress trials may not be representative of real emergency situations. However, given the absence of actual data, it provides a foundation from which to extrapolate emergency conditions and passenger response.

A high frequency of deference behavior was noted throughout the egress trials, with about 29 percent of participants deferring to others across all the egress trials. On a trial by trial basis, the number varied from 15 to 37 percent of the total number of participants. This reflects a lower level of urgency than would be expected in an emergency situation. It is noted that the nature of the data set derived from this experiment is reflected in the new Prototype Software V2.2.

The key findings from the behavioral analysis are summarized as follows:

- The most common number of participants deferred by another participant was one, but several participants deferred to two, three, and four participants. The highest number of participants deferred to in a single event was six.

- Both aisle and seat deference behavior was quite common, with aisle deference occurring approximately 2.5 times more frequently than seat deference.
- The relative frequency of aisle and seat deference behavior was not affected by the type of lighting condition.
- From the limited number of available deference events in which the gender of the interacting parties was clear, males were twice as likely to defer to others as females.
- Females were deferred to by males more than by other females.
- Males were as likely to defer to other males as to females, and females are likely to defer to other females in the same proportion as to male participants.
- While the gender data imply that there may have been a gender effect, the data are insufficient to demonstrate a reliable gender deference parameter.

Given ethical concerns (the possibility of injuring participants if the trials were conducted on a more competitive basis), it would have been a challenge to reproduce conditions of a high degree of urgency without compromising safety. However, the data do provide a useful benchmark for representing non-urgent egress behavior. The core data can also be used as a basis to represent emergency conditions. However, additional capabilities will be implemented within the model to account for more highly motivated behaviors expected to be found in some emergency situations.

4.3.4 Quantitative Data Analysis Methodology

The quantitative human factors measurements, based on video data analysis of each of the 12 Volpe Center egress trials, focused on five issues:

- Exit flow rates and exit times,
- Aisle flow rates,
- Individual aisle travel speeds,
- Row clearance times, and
- Times from seat to movement down the aisle.

Appendix C contains the data analysis results discussed in the following sections in table format.

4.3.4.1 *Exit Flow Rates and Exit Times*

Two types of passenger rail car exits were characterized:

- Inter-car end-door exit to an adjacent car and
- Side-door exit leading to a high platform.

In addition, two types of lighting conditions were considered: normal and emergency lighting. The exit flow rate parameter for various types of exits under different lighting conditions was specified as part of the input data in the development of the Prototype Software 2.2. The Volpe

Center egress trials provide the basis for the specification of this data and the exit times provide data with which the Prototype Software V2.0 can be validated.

The *exit flow rate* is the number of participants that travel through the exit over a given period of time. This analysis considers the average exit flow rate over the duration of the flow period, measured in all three types of egress trials (i.e., one-door exit egress trials, two door-exit egress, trials, and inter-car end-door-exit egress trials), and represents the average flow of participants passing through the exit during the entire duration of the particular egress trial.

The two time periods used to calculate the average exit flow rate were the time required for the first participant to reach the exit threshold and the time required for the last participant to travel over the threshold of a door. This rate was calculated for the side-door and inter-car end-door exits used during the egress trials. The times are taken from the time stamped onto the original video recordings. The exit threshold was defined so that it could be identified easily from the video recording throughout each egress trial.

For egress trials involving one or two side-door exit(s), the threshold was defined by an easily identifiable line on the car floor (see red arrow in Figure 9).

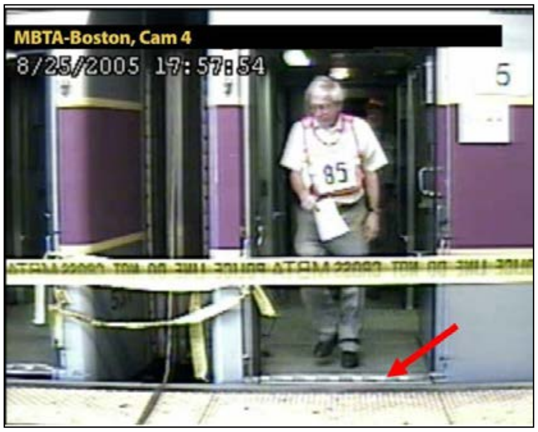


Figure 9. First Participant Reaches Side-Door Exit Threshold

The average exit flow rate was then calculated as the number of participants (persons) who passed through the door, divided by the time of the last person through the exit minus the time of the first participant to the exit, to produce the average flow rate measured in persons per second (pps). The persons per minute (ppm) is obtained by multiplying the pps by 60 (see Equation 1):

$$\textbf{Average exit flow rate (ppm)} = \textbf{(\# persons through exit / (time of last person – time of first person)) x 60} \qquad \textbf{(1)}$$

To measure this time for each participant, the original Volpe Center-provided egress trial video files were loaded into *Adobe Premiere Pro 2.0*^{R}. For each participant, only the first and second (repeat) egress trials conducted in normal lighting conditions were considered. The egress trials conducted in emergency lighting conditions were not included since these lighting conditions did not significantly influence the outcome.

The time at which the last participant passed the car mid-point in the one-door exit egress trials (i.e., one side-door exit and inter-car end-door exit egress trials) was determined. These data were extracted from the videos of each of the one-door exit to platform in normal lighting (i.e., Trials 5 and 11) and emergency lighting conditions (i.e., Trials 1 and 7). Similar measurements were made for the inter-car end-door exit egress trials under normal lighting (Trials 2 and 8) and emergency lighting conditions (Trials 6 and 12). In the case of the two side-door exit egress trials, a similar analysis was performed using the quarter way points.

4.3.4.2 *Aisle Flow Rates*

Two types of flow rate measurement are made:

- Average aisle flow rate for the entire car over the duration of the egress trial and
- Spot flow rates at various locations along the aisle and at various times throughout the egress trial.

In the development of the new Prototype Software V2.0, these parameters are intended for calibration and validation and verification purposes.

The *aisle flow rate* is essentially the number of participants that travel past a fixed point in the aisle over a given period of time. Two types of flow rate are considered in this analysis: an average flow rate and spot flow rates.

The *average aisle flow rate* has been measured in all three types of egress trials (i.e., one side-door exit egress trials, two side-door exit egress trials, and inter-car end-door exit egress trials). The measurement represents the average flow of persons passing a fixed marker across the aisle during the entire duration of the egress trial. The marker at which the participant count is taken is a line passing parallel to and adjacent to the seat backs of the row of seats prior to the door vestibule. There are two measuring locations for egress trials with two side-door exits: one at each end of the car aisle (Lines 1 and 23 in Figure 10). Every person passing the marker during the duration of the egress trial is counted through observation of the egress trial video recording in slow motion. The time interval over which the participant count is made is determined by subtracting the time of the first participant to the marker from the time of the last participant who passed the marker.

The average flow rate (measured in pps) is then calculated by dividing the number of participants who passed the marker by the time of the last participant who passed the marker, minus the time of the first participant to pass the marker. The ppm can be obtained by multiplying the pps by 60 (see Equation 2):

$$\textbf{Average aisle flow rate (ppm)} = \textbf{(\# persons past marker / (time of last person} - \textbf{time of first person))} \times \textbf{60} \qquad \textbf{(2)}$$

The *spot flow rate* is a measure of the number of participants passing fixed markers across the aisle over 5-second time intervals. Several different markers are used to generate the flow rate at different locations along the aisle. In the one-door exit egress trials (both one side-door exit and inter-car end-door exit), three markers are used, corresponding to the mid-points between seat Rows 5–6, 12–13, and 17–18 (see top markers in Figure 10). For example, as a participant

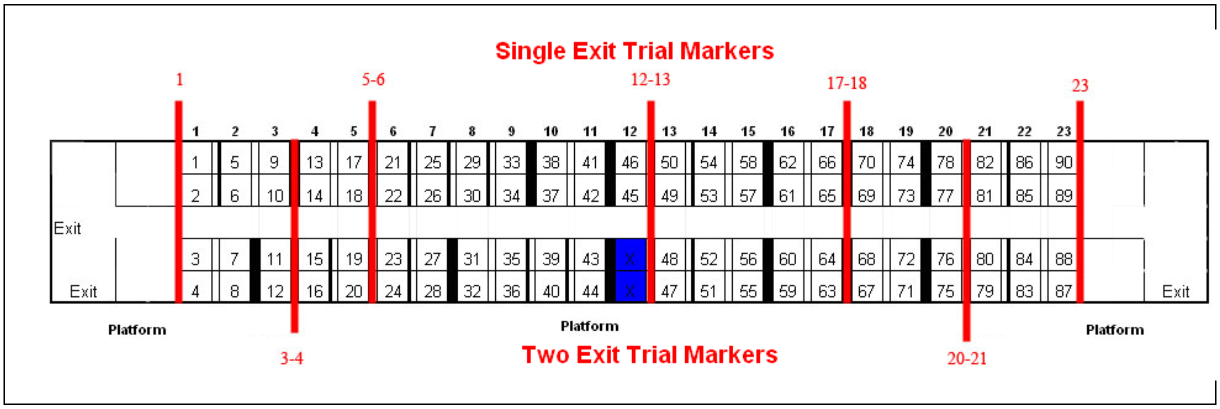


Figure 10. Marker Locations Used to Establish Spot Aisle Flows for Exit to High Platform Side-Door Exit Egress Trials

passes between Rows 5 and 6, he or she travels over the Row 5 marker. Since only participants passing between the seats were considered, persons seated in the marker rows were ignored. In the two side-door exit egress trials, only two markers were used between Rows 3–4 and 20–21 (see bottom markers in Figure 10). Selecting these seat rows enabled a comparison to be made of the flow rates at either end of the car and equidistant from the exit; it also maximized the number of participants that would be counted.

The number of participants passing the marker was counted in 5-second intervals with the time being determined from the time stamp on the Volpe Center egress trial video recordings (see Equation 3):

$$\textbf{Spot flow rate (ppm)} = \textbf{(\# of persons past marker in 5 sec. interval / 5) x 60} \tag{3}$$

4.3.4.3 *Individual Aisle Travel Speeds*

Two sets of travel speed were characterized:

- Free-flow travel speeds and
- Restricted travel speeds.

In the development of the Prototype Software 2.0, the free-flow participant travel speed is a parameter which must be specified as part of the input data. The Volpe Center egress trials provided the basis for the specification of this data and a means for checking average travel speeds produced by the model.

The travel speed of an individual will vary depending on the density of the crowd in which the person is immersed. Two travel speed measurements were made along with the density for stationary groups:

- **Free-Flow Travel Speed:** Travel speed of a participant unencumbered by the presence of other persons. In total, 34 measurements were made of free-flow travel speeds using all 12 egress trials.

- **Restricted Travel Speed:** Travel speed of a participant who has restricted freedom of motion due to the presence of other persons around them. In total, 11 measurements of restricted travel speed and associated group densities were made.
- **Average Density of a Stationary Group**: Number of observed stationary participants located in close proximity to each other in relation to the area they occupy.

Due to the nature of the egress trials, only the first few participants exiting from the passenger rail car in each egress trial experienced free-flow travel conditions. All 12 egress trials were analyzed to generate 34 estimations of free-flow travel speed. This relatively small number of measurements is due to the limiting conditions necessary to guarantee free movement occurring for only a small selection of the overall population (i.e., only those participants seated nearest the exit). The free-flow travel speed data were obtained for all egress trials.

Three different areas where participants were considered to be in free flow were identified during the FSEG video review of the Volpe Center egress trials. These areas were all located in the passenger rail car end sections (see Figure 11).

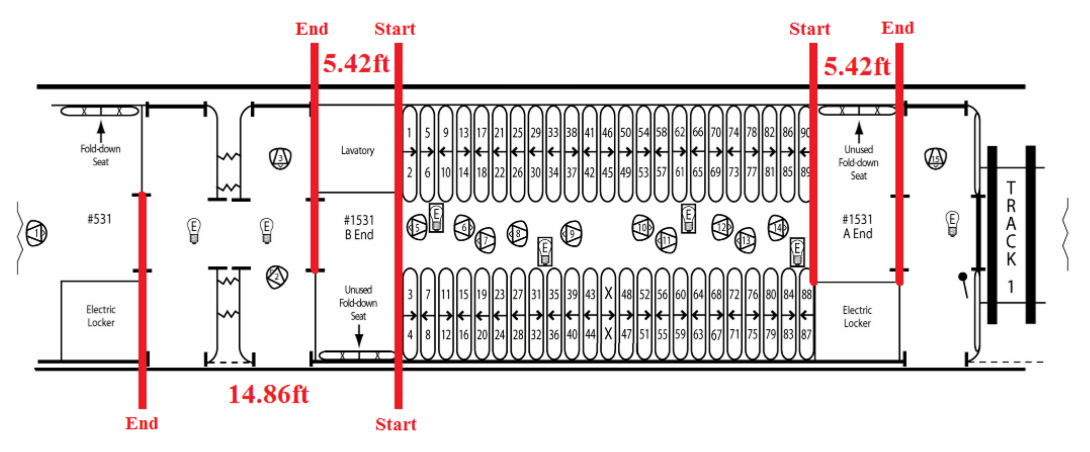


Figure 11. Start and End Points Used to Measure Free-Flow Travel Speed

The travel time was determined by the time the leading edge of the person crossed the start line and the time the leading edge of the person crossed the finish line.

In each egress trial, the first several participants were observed as they traveled the defined distances. If the participants were determined to have traveled the distance at their Free Travel Speed, the time that they passed the start and end points was recorded from the time stamp on the video. The difference between these two times is the time required by the participant to travel the distance and the travel speed can be calculated using Equation 4:

$$\textbf{Travel Speed (ft/s)} = \textbf{Distance (ft) / Time Taken (s)} \qquad \textbf{(4)}$$

The restricted travel speed experienced by participants was extracted from the video recording by measuring the average travel speed within a given population density group. However, the density of the group must remain uniform or almost uniform over the measurement period. It was difficult and time consuming to identify appropriate groups since group density could often vary due to participants entering the aisle from seats, group bunching produced by a decrease in the travel speed of group members, or group spreading produced by an increase in the travel speed of group members. Ideally, all group members should be traveling at a constant speed over the measurement period.

Only the egress trials using one exit (side and end doors) had sufficient travel distance and egress trial duration to meet the above conditions. Furthermore, it proved difficult in the emergency lighting egress trials to accurately judge the position of participants. Therefore, only egress trials involving normal lighting conditions were used to determine restricted travel speed.

A minimum group size of five participants was selected to ensure that the participants in the center of the group had sufficient participants around them to impact their travel speed. Once a suitable group was identified, the number of participants in the group was counted and a density estimate was made by estimating the aisle length over which the group extended. The density estimate (persons/ft^2 (persons/m^2)) was then calculated, using Equation 5:

Density = (number of persons in group) / (group length x aisle width) (5)

After the identification of suitable participant groups and the specification of fixed marker locations, the average travel speed of the group was determined. A target participant in the center of the group was identified (see black dots in Figure 12) and the travel speed (V) of that person was determined using Equation 4. The distance travelled by the target participant during the measurement period is shown by d2 in Figure 12. The travel speed measurement is subject to similar inaccuracies as the density estimate and also the errors associated with time stamp accuracy. As a check on the consistency of the group travel speed, the travel speed of the last member of the group was also calculated using the same time period as identified for the target participant.

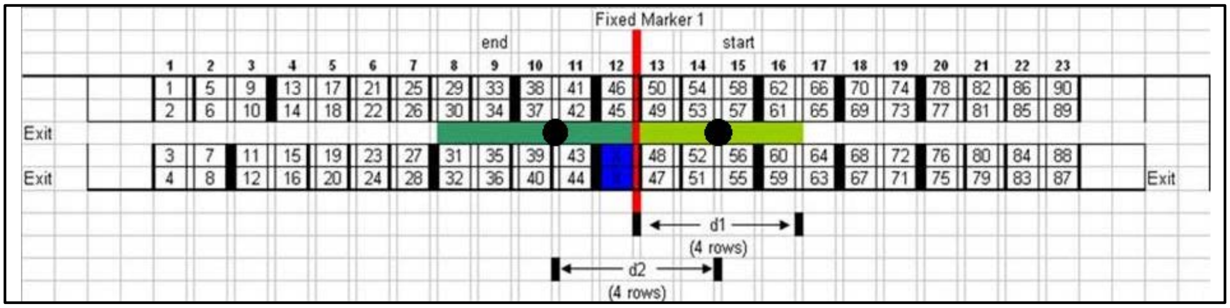


Figure 12. Distances Measured to Calculate Group Density and Travel Speed

The travel distance was taken as the distance traveled by the last person during the measurement period (d1 in Figure 12). If the two travel speeds were approximately equal, this confirmed that the group density remained approximately constant over the measurement period. These travel speeds could then be associated with the population density determined for the group. Those groups that did not conform to these strict checks were discarded.

A total of 11 restricted travel speeds and associated group density measurements were made.

A final measurement was made to record the density of a stationary group within the car aisle. This measurement provided a maximum value for the density in the aisle and bounds the conditions under which participants are able to move (i.e., with first unrestricted flow, then restricted flow, and then no movement).

The group population was measured by dividing the rail car into several sections, each of which was covered by one or more of the available video cameras. In this way, the number of persons in each section could be counted separately to ensure that no person was counted twice. The density was then calculated using Equation 5.

In addition to the 12 egress trials, four independent free-flow trials were conducted with two participants who displayed possible movement disabilities. These trials took place in normal lighting conditions, with one trial conducted inside the rail car (the participant was asked to walk the entire length of the car as fast as possible without running) and one outside on the platform, alongside the car (measured over a similar travel distance). One person was a female, 8 months pregnant and between 31 and 50 years of age. The other was a male between 31 and 50 years of age who had a severe limp and used a walking stick.

4.3.4.4 *Row Clearance Times*

The determination of the time required to clear each seat row in the rail car was intended to identify any discernible trends in row clearance times that could be used for the Prototype Software verification. This analysis involves a measure of the time at which each car seat row was clear of participants. Two time measures per seat row were collected: (1) the time for the Wall Side seats and (2) time for the Platform Side seats to clear. The time to clear the seat row was measured in seconds, from the time of the whistle signifying the start of the egress trial, to the time at which the last participant seated in the dual block of row seats accessed the aisle. The greater of the two seat row clearance times (Wall Side or Platform Side) is considered the time at which that entire seat row was clear of participants.

4.3.4.5 *Times from Seat to Movement Along the Aisle*

The determination of the time required by participants to gain access to the rail car aisle and the time required for “free movement” in the aisle to commence was intended for software verification purposes.

The “aisle seat” is the seat adjacent to the aisle and the “window seat” is the seat adjacent to the window. Two time measures were collected from a review of the Volpe Center egress trial video:

- **T1:** Time from (aisle or window) seat to aisle, as measured from the start of the egress trial (i.e., sound of the start whistle), to the point when the participant’s shoulder crossed over the plane of the seat arm rest.
- **T2:** Time to start of free movement (the participant walking unimpeded) in the aisle, as measured from T1 (when the participant’s shoulder crossed over the plane of the seat arm rest).

Using these definitions, the total wait time, T3, is defined in Equation 6 as:

$$\mathbf{T3} = \mathbf{T1} + \mathbf{T2} \qquad \mathbf{(6)}$$

The analysis used a sample of 10 participants in five locations for each of the 12 egress trials. The five seat row locations selected for analysis were:

- Two seat rows from the front (i.e., Row 2, 'the front' being the active inter-car end-door exit);
- Two seat rows from the end of the rail car (Row 22);
- Row 6 – mid-forward;
- Row 12 – central; and
- Row 17 – mid-rear.

4.3.5 Quantitative Results

4.3.5.1 *Exit Flow Rate and Exit Time Analysis*

Exit flow rates to characterize passenger rail car side-door exits leading to a high platform under normal and emergency lighting were calculated data from Trials 1, 3, 4, 5, 7, 9, 10, and 11 (see Table 4).

The exit flow rates for inter-car end-door exit egress under normal and emergency lighting conditions (Trials 2, 6, 8, and 12) were also made (see Table 4).

Table 4. Mean and Range of Exit Flow Rates for High Platform Side-Exit Door(s) and Inter-Car End-Door Exit Egress Trials

TRIAL #	EGRESS ROUTE	LIGHTING	EXIT FLOW RATE (ppm))
4, 5, 10, 11	Side-Door Exit (s) to High Platform	Normal	51.6 [49.2–53.5]
1, 3, 7, 9,		Emergency	52.0 [48.3–54.8]
2 and 8	Inter-Car End-Door Exit	Normal	52.2 [51.5–53.1]
6 and 12		Emergency	53.4 [52.5–54.2]

These mean results compare to 52.8 ppm (normal lighting) and 51.6 ppm (emergency lighting), as contained in the Volpe Center egress experiment report [4].

A consistent finding for the exit flow rates, time for the first participant to reach the exit, and exit time taken to clear the rail car was that there was little variation between egress trials. The lighting level, the door type, and the repeated egress trial (e.g., Trial 9 is a repeat of Trial 3) had a negligible impact on the results produced. However, congestion on the platform at the car right (end) side door of the two side-door exits used in Trial 3 created a blockage which reduced the exit flow rate and exiting times for this trial. (The platform blockage was not intended to be part of the planned experimental egress trial procedures.)

The graphs in Figure 13 and Figure 14 have been grouped to show the Exit to High Platform using one side-door exit (Trials 5 and 11) and the Exit to Adjacent Car using the inter-car end-door exit (Trials 2 and 8) trials so that a direct comparison can be made between the first and second egress trials and the similarities of egress trials using one side-door exit and one inter-car end door exit under normal lighting. The exit flow rate (shown by the gradient of the line) is fairly constant in both egress trials, and there is little variation between the first and second egress trials. For the one side-door exit egress trials, the exit flow rate was fairly constant in both egress trials.

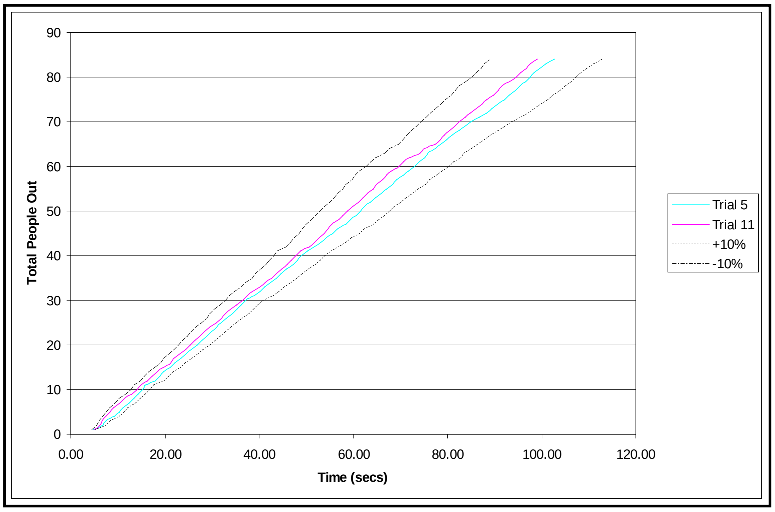


Figure 13. Participant Exit Times: One Side-Door Exit to High Platform Egress Trials

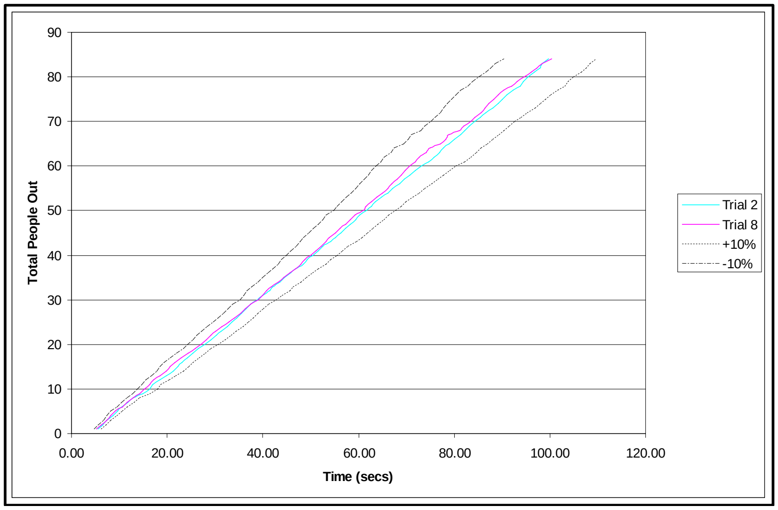


Figure 14. Participant Exit Times: Exit to Adjacent Car – Inter-Car End-Door Egress Trials

Figure 15 shows the participant exit time results for the two side-door exit egress trials (Trials 4 and 10). For the two side-door exit egress trials, the exit flow rate was fairly constant in both of the trials.

The curves shown in Figure 13, Figure 14, and Figure 15 provide a window of variation, representing the possible spread in experimental trial results for the one and two side-door Exit to High Platform and the Exit to Adjacent Car inter-car end-door exit egress trials. In addition, each graph shows +/- 10 percent variation curves. These curves are determined by taking +10 percent of the maximum trial result at any time and -10 percent of the minimum trial result at any time.

These curves thus provide an indication of the extent of this variation from the FSEG measured Volpe Center egress trial results. When comparing the Prototype Software V2.0 predictions for each of these cases, if the numerical predictions fall within the window produced by the variation curves, then the predictions are within +/-10 percent of the measured experimental trial results.

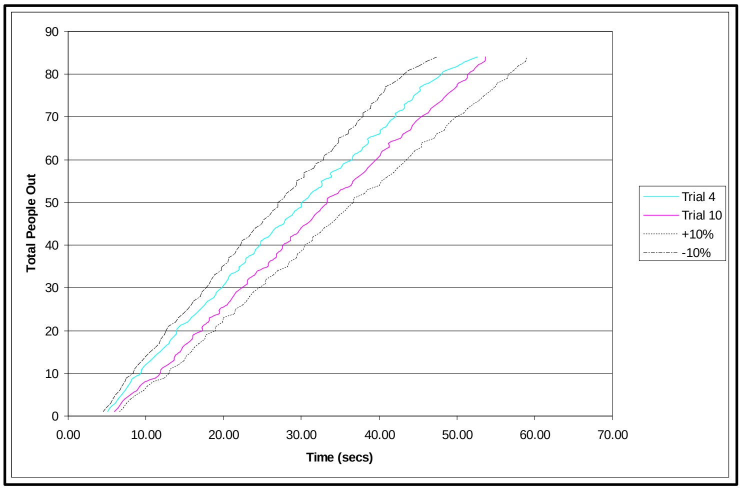


Figure 15. Participant Exit Times: Two Side-Door Exit Egress Trials

The exit time curves shown in Figure 13 to Figure 15 provide validation and verification data to demonstrate that the Prototype Software V2.0 is capable of reproducing the Volpe Center egress trials. The data in these figures were used to compare against the simulation results and established that the software is producing results consistent with the experimental data obtained from the egress trials (see Chapter 5).

Time measurements for the last person to cross the mid-point of the car were made from the video recording for the one side-door exit to platform egress trials under normal lighting conditions (Trials 5 and 11) and emergency lighting conditions (Trials 1 and 7). Table 5 shows the time measurements for the last person to cross the mid-point of the passenger rail car in the one side- door exit to high platform egress trials under normal lighting conditions (Trials 5 and 11) and emergency lighting conditions (Trials 1 and 7).

Table 6 shows the time measurements from the egress trial video recording for the last person to cross the quarter point of the rail car in the two side-door exit to high platform egress trials under normal lighting conditions (Trials 4 and 10) and emergency lighting conditions (Trials 3 and 9).

Table 5. Mean and Range of Mid-Point Times for One Side-Door Exit to High Platform Egress Trials

TRIAL #	EGRESS ROUTE	LIGHTING	LAST PERSON TO REACH MID-POINT (s)
5 and 11	Side-Door Exit to High Platform	Normal	51.6 [49.2–53.5]
1 and 7		Emergency	86.4 [85.1–87.9]
2 and 8	Inter-Car End-Door Exit	Normal	84.6 [81.7–87.5]
6 and 12		Emergency	86.7 [85.1–88.2]

Table 6. Mean and Range of Quarter-Point Times for Two Side-Door Exit to High Platform Egress Trials

LIGHTING	LAST PERSON TO REACH QUARTER POINT	
	Left Exit (s)	Right Exit (s)
Normal	42.4 [39.4–45.3]	
Emergency	41.1 [38.5–43.6]	46.0 [44.5–47.4]

The data can be used as part of the validation and verification process. This data can be used to compared against the simulation predictions and establish whether the Prototype Software is producing the results consistent with the Volpe Center experimental results.

4.3.5.2 *Aisle Flow Rates Analysis*

At the start of each egress trial, all the participants appeared to react almost immediately to the start signal. As a result, the aisle became crowded almost immediately. This crowding delayed people moving along the aisle and towards the exit. This delay in start time varied depending on the distance of the participant from the car side-door location.

For persons located just to the rear of the center of the passenger rail car (i.e., Marker Rows 12–13; see Figure 10), the delay is 35–40 s, while for persons located towards the rear of the passenger rail car (i.e., Marker Rows 17–18; see Figure 10), the delay increased to 55–60 s.

The average aisle flow rate across all egress trials ranged from 50.2 to 56 ppm with a mean value of 53.5 ppm.

The mean aisle flow rate for the normal lighting condition was 52.8 ppm.

The mean aisle flow rate for the emergency lighting condition was 53.8 ppm.

The spot aisle flow rates across all the egress trials ranged from 40 to 60 ppm, with occasional peaks of 70 ppm being achieved for brief periods.

The lack of a significant difference between the aisle flow rates for the different lighting conditions, if a real effect, may have been due to the crowded conditions in the aisle (i.e., the crowded aisles produced congested conditions that dominated any reduction in travel speeds due to the lighting levels).

4.3.5.3 *Individual Aisle Travel Speeds Analysis*

The free-flow individual aisle travel speed data collected from these egress trials related to information from 16 males and 18 female participants. The free-flow data were collected under conditions of normal (16 data points) and emergency lighting (18 data points).

The travel speed data collected in the egress trials are intended to help in the implementation and calibration of the new Prototype Software V2.0. Accordingly, the values shown in Table 7 can be used in the Prototype Software to characterize the free-flow travel speeds of participants under emergency and normal lighting conditions.

Table 7. Free-Flow Travel Speeds Measured during Volpe Center Egress Trials

GENDER	NORMAL LIGHTING			EMERGENCY LIGHTING		
	Average Speed	Min Speed	Max Speed	Average Speed	Min Speed	Max Speed
Male	5.00 ft/s (1.52 m/s)	4.00 ft/s (1.22 m/s)	6.51 ft/s (1.98 m/s)	4.65 ft/s (1.42 m/s)	4.17 ft/s (1.27 m/s)	6.02 ft/s (1.98 m/s)
Female	4.29 ft/s (1.31 m/s)	3.32 ft/s (1.01 m/s)	5.81 ft/s (1.77 m/s)	4.17 ft/s (1.27 m/s)	3.01 ft/s (0.92 m/s)	5.08 ft/s (1.55 m/s)

Both male and female participants appeared to have slightly higher average free-flow travel speeds during normal lighting conditions compared to their average free-flow travel speed during emergency lighting conditions. However, the difference was not as pronounced as may have been expected because the free-flow travel speed measurements were made in the vicinity of the exits where the external light enters the car. Therefore, these measurements should not be taken as an indication of travel speed in very low visibility conditions, such as during smoke obscuration or darkness.

A total of 11 restricted travel speeds and associated group density measurements were made. The restricted travel speed values can be used to verify the average travel speeds produced by the Prototype Software V2.0. However, when using these values, it is noted that there was a low level of urgency during these egress trials, and the emergency lighting data should not be taken as being representative of individuals' likely exit performance in conditions of darkness or low visibility.

The travel speed data has been plotted against the crowd density data (see Figure 16). The relationship between travel speed and crowd density can be expressed as shown in Equations 7a and 7b:

$$\mathbf{V\ (ft/s) = \quad 5.6 - 17.9 \times D\ (persons/ft^2)} \qquad \mathbf{(7\ a)}$$

$$\mathbf{V\ (m/s) =- \quad 1.7 - 0.51 \times D\ (persons/m^2)} \qquad \mathbf{(7\ b)}$$

Where D is the crowd density, which varies from 0.12 persons/ft^2 (1.3 persons/m^2) to 0.24 persons/ft^2 (2.6 persons/m^2).

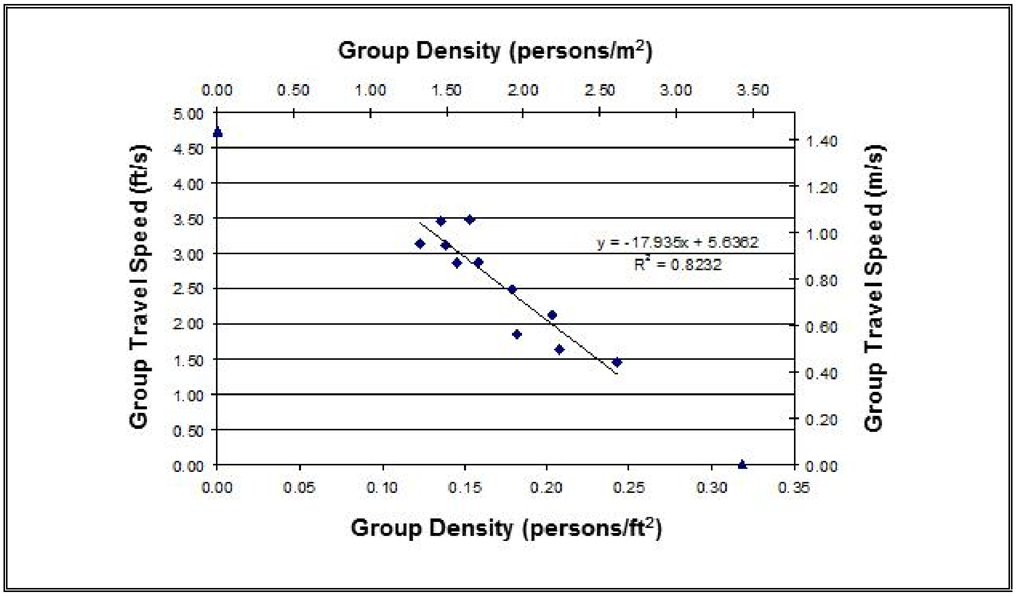


Figure 16. Density and Travel Speeds Derived from Egress Trial Data

This relationship is very similar to the relationship used in the building environment for travel of persons along corridors or aisles [19].

In addition to the video data for the 12 egress trials, four independent free-flow trials were undertaken with two participants (one male and one female) who displayed possible movement disabilities. This data will be used to represent individuals with movement impairments within the Prototype Software V2.0.

The male's free-flow walking speed was 2.9 ft/s (0.88 m/s), significantly lower than both the average measured speed for all males in normal lighting of 5 ft/s (1.5 m/s) and the minimum for all males of 4 ft/s (1.2 m/s). This equates to a *Mobility* factor (a feature used in the EXODUS software) of 0.58 where the *Mobility* factor is a multiplier used to reduce travel speed**.**

The female's speed was 4.8 ft./s (1.5 m/s), slightly greater than the average female speed under normal lighting of 4.3 ft/s (1.3 m/s), but less than the maximum measured speed of 5.8 ft/s (1.8 m/s). These data imply that being 8 months pregnant did not manifest itself as a severe mobility impairment for the female participant. However, the data were not collected in a crowded environment. Under crowded conditions, the pregnant female may travel considerably slower as she attempts to protect herself from other persons.

4.3.5.4 *Row Clearance Times Analysis*

Table 8 show the passenger rail car row clearance time data used as part of the validation and verification process for verifying that similar behaviors are noted in the Prototype Software V2.0 simulation (see Table 8).

Table 8. Mean and Range of Row Clearance Times

EGRESS TRIAL	ROW CLEARANCE TIME (s)
All one-door exit egress trials	36.4 [5.8–74.3]
Two-door exit egress trials	20.2 [5.7–38.6]

For all egress trials involving one available side- or end-door exit:

- The row clearance time generally increased with the distance from the active exit.
- The average maximum seat row clearance time was 74.3 s and generally occurred one or two rows ahead of the last row.
- The average minimum row clearance time was 5.8 s and generally occurred in Row 1.

In egress trials with two available side-door exits:

- Maximum row clearance times peaked towards the center of the car.
- The average maximum seat row clearance time was 38.6 s.
- The average minimum row clearance time was 5.7 s and generally occurred in the rows closest to each of the available exits.

There was little difference between row clearance times under normal and emergency lighting conditions and between first and repeat egress trials.

4.3.5.5 *Seat to Aisle Movement Analysis*

Time taken to access the passenger rail car aisle and move down the aisle are important parameters for the verification of the Prototype Software 2.0. Analysis of the T1 (time from (aisle or window) seat to aisle), T2 (time to start of free movement (the participant walking unimpeded) in aisle), and T3 (total wait time) across all the egress trials implies that the times derived from the second series of egress trials were on average shorter than those for the first attempt egress trials (see Appendix C). This implies that there may have been a learning effect on the behaviors exhibited.

The primary purpose of this analysis was to determine the time required to enter the car aisle and to start free movement in a crowded or fully occupied situation.

The analyses of T1 and T2 imply that there are differences between times to access and freely move in the aisle based upon participant location in the passenger rail car. The summarized results are:

- The overall average T1 for an aisle-seated participant under:
  - Normal lighting conditions was 4.1 s.
  - Emergency lighting conditions was 3.3 s.
- The overall average T1 for a window-seated participant under:
  - Normal lighting conditions was 32.9 s.
  - Emergency lighting conditions was 25.2 s.
- For all one-door exit egress trials (side and inter-car), T3 increases with the distance from the exit, with the maximum value always occurring in the last seat row.
- For two side-door exit egress trials, T3 increased with distance from the exit, with the maximum value always occurring in the middle of the passenger rail car (i.e., the point furthest from the exit use).
- The average maximum values of T3 for:
  - One side-door exit under:
    - Normal lighting conditions was 72.8 s.
    - Emergency lighting conditions was 73.2 s.
  - Two side-door exits under:
    - Normal lighting conditions was 36.8 s.
    - Emergency lighting conditions was 38.3 s.

4.4 2006 R-O-W and Low Platform Egress Trials

The two 2006 Volpe Center egress experiments consisted of two types of egress trials in which Federal employees participated. The first type of egress trial involved each participant individually exiting the car, allowing measurements of individual exiting performance to be made. The second type of egress trial involved the entire group of participants exiting the car, which allowed both individual and group measurements of exiting performance to be made.

Each egress trial was repeated five times and all were conducted under normal lighting conditions. The primary data derived from this series of experimental egress trials consisted of qualitative and quantitative data and addressed egress behavior, side-door exit travel speeds, and exiting times.

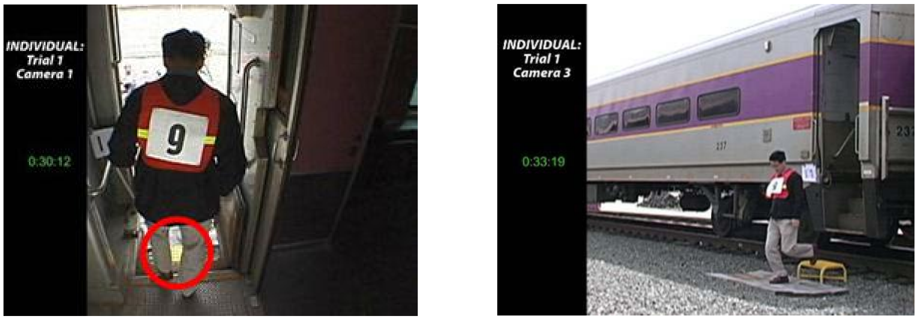
Appendix C contains further information for participant demographics for the two series of egress trials.

4.4.1 Terminology

4.4.1.1 *R-O-W*

The following exit definitions were used for the exit start and end points for the passenger rail car Exit to R-O-W egress trials, which are depicted in Figure 17.

- **Exit Start:** The moment the participant has reached the side-door exit and begins to step down with his or her leading foot (the foot that is placed on the first step below) crossing the vertical plane made by the yellow line at the top of the steps (see Figure 17a).
- **Exit End:** The moment the participant's trailing foot breaks contact with the yellow step box (see Figure 17b).



(a) (b)

Figure 17. Exit to R-O-W: Participant Start and End Points

Participant 9 can be seen to start exiting when his lead foot has passed over the yellow line, as shown in the red circle of Figure 17a, breaking the vertical plane extended up from this line. This point marks the start of the exiting process. The end of the exiting process for Participant 9 is shown in Figure 17b, which shows the participant's trailing foot breaking contact with the yellow step box.

4.4.1.2 *Low Platform*

The following exit definitions were used as the start and end points for the passenger rail car Exit to Low Platform egress trials, which are shown in Figure 18:

- **Exit Start:** When the participant has reached the side-door exit and begins to step down with his or her leading foot—the foot that is placed on the first step below—crossing the vertical plane made by the yellow line at the top of the steps (see Figure 18a).
- **Exit End:** When the participant's trailing foot breaks contact with the lowest step (see Figure 18b). If a person jumps, then the end point is when he or she crosses the horizontal plane made by the lowest step (see Figure 18c).

Figure 18 allows comparison between the different exiting techniques to the low platform. Participant 12 starts exiting when her lead foot has passed over the yellow line, shown in the red circle of Figure 18a, thus breaking the vertical plane extended up from this line. This point marks the start of the exiting process. The end of the exiting process for Participant 12 is shown in Figure 18b, which shows the participant's trailing foot breaking contact with the last step.

(a) (b) (c)

Figure 18. Exit to Low Platform: Participant Start and End Points

4.4.2 Exit System Capacity

In the 2006 Volpe Center egress trials, the nature of the passenger rail car side-door exit was such that more than one person could occupy the exit system (in this case the combination of internal side door and stairway leading down to the low platform or R-O-W) at a time. A person is considered to be in the exit system if he or she has passed the start point of the exit system but has not crossed the end point. The number of participants in the exit system was noted at the point when any participant started or finished the exiting process. This information was used to calculate the time intervals between the events of persons entering and leaving the system. The analysis was completed using a spreadsheet to calculate the percentage of the total exit time when the system was occupied by zero, one, two, or three persons. Figure 19a shows an example of two participants “within” the exiting system at the same time for the Exit to R-O-W egress trials; Figure 19b presents a similar view for the Exit to Low Platform egress trials.

(a) To R-O-W (b) To Low Platform

Figure 19. Two Participants in the Passenger Rail Car Side-Door Exit System

4.4.3 Data Analysis

A detailed analysis of the Volpe Center egress trial data were completed to assist in the development of the new Prototype Software V2.1.

In observing each participant’s exiting behavior from the passenger rail car to the R-O-W or low platform, it was clear that the exiting process was very different from that for participants exiting to a high platform. While the latter can be represented by an experimentally derived flow rate, the former involves a complex process in which participants must exit through a side-door exit, descend a short flight of stairs, and then step off the final distance from the stairway step onto the

R-O-W or low platform. For the Exit to the R-O-W trials, the distance of this final step-off can be large; in this case, it was 25 in (9.8 cm).

The exiting process typically involves three parts:

- Some initial hesitation as the participant decides how to approach the descent;
- Actual descent down the stairway, which for some participants may be quite a slow process; and
- Final step-off the bottom of the stairway, which can also involve hesitation and can be quite slow.

However, this entire process can be longer for older participants, those with disabilities, or participants who are obese. The use of simple flow rate data to represent exit performance tends to average these personal hesitations and limitations in exiting performance, producing a crude representation of the actual passenger rail car exit flow performance. Accordingly, it is considered inappropriate to represent the exiting capabilities of these types of exit within the Prototype Software V2.1 by a simple flow rate. Rather, an exit time probability distribution, similar to that used in airEXODUS for aircraft exits, was considered more appropriate to represent the exit performance, in circumstances involving the Exit to Low Platform or Exit to R-O-W egress trials. Therefore, the video analysis involved extracting exiting times for each participant and producing a probability distribution of exit times to be associated with the Exit to Low Platform or Exit to R-O-W egress trials.

While the data collected in the 2006 Volpe Center egress trials is different from that collected in the 2005 egress trials, the analysis followed a similar two-step process as described for the 2005 data. In the first step, the egress trial videos were reviewed to derive an overall understanding of the processes involved in the exiting behavior. The second step of the video analysis involved studying the video in greater detail to extract the exiting data using a set of definitions that outlined key actions or events (see Section 4.4.1).

4.4.4 Data Analysis Methodology

The behavior exhibited by each participant as he or she exited the passenger rail car was noted and involved categorizing the manner and style in which they exited. These observations ensured the integrity of the data being collected by enabling any atypical exiting time data to be potentially explained by the nature of the behavior exhibited by the participant. This process will not be described further as it does not directly result in data used in the Prototype Software V2.1.

To measure the time taken for each participant to exit the passenger rail car, the original video files from the Volpe Center 2006 egress trials were loaded into *Adobe Premiere Pro 2.0*^{R}. All three camera views were correctly synchronized on the (same experimental) timeline, which allowed the exit start point to be marked using one camera view, and then switched to the second camera view to mark the exit end point. The same methodology was applied to individual and group egress trials.

4.4.5 Quantitative Results

Appendix C contains the data analysis results in table format that are discussed in the following sections.

4.4.5.1 *Exit to R-O-W*

The exit times in seconds for each person to step down from the passenger rail car and onto the R-O-W for the individual Exit to R-O-W egress trials and the minimum, maximum, and mean times for each egress trial were determined. Three data points were discarded because of the participants incorrectly exiting the passenger rail car (according to the procedural definitions in Section 4.4.1). The minimum, maximum, and mean exit times for all participants across all the individual egress trials were 1.7 s, 13.7 s, and 5 s, respectively. A total of 72 data points were collected, with a standard deviation of 2.7 s.

The minimum, maximum, and mean exit times for all participants across all the group egress trials were 1.9 s, 10.3 s, and 5 s, respectively. A total of 75 data points were collected, with a standard deviation of 2.2 s.

The minimum, maximum, and mean flow rates for all participants across all group egress trials were 17.4 ppm, 20.4 ppm, and 19.2 ppm, respectively.

The exit time curves for each of the Exit to R-O-W egress trials are plotted in Figure 20. A natural variation exists in exit performance for repeated egress trials.

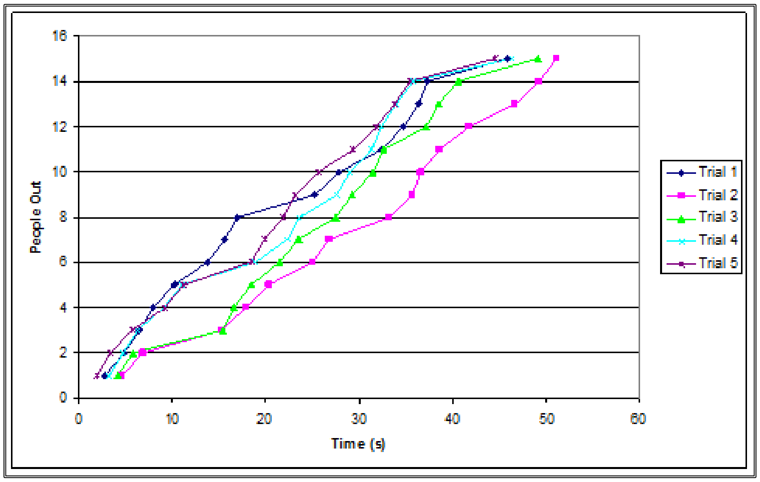


Figure 20. Exit to R-O-W: Group Egress Trial Exit Time Curves

By taking the minimum and maximum time for the exiting of each person, an experimental window of results can be produced (see Figure 21). Computer model predictions of this egress trial which fall within the window are considered to be acceptable since they demonstrate that they are capable of reproducing the performance measured in the egress trial. This distribution is useful in validating the predictions of the Prototype Software V2.1 for the Exit to R-O-W egress scenarios.

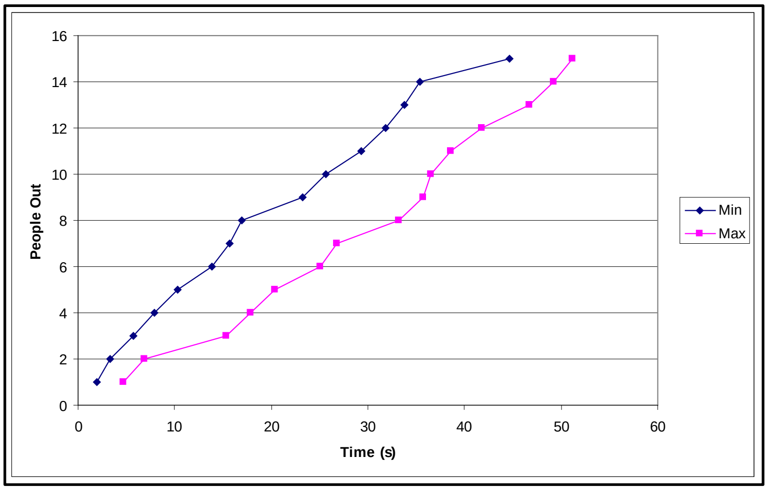


Figure 21. Exit to R-O-W: Performance Window Produced by Minimum and Maximum Exit Times for Group Egress Trials

Learning and fatigue did not appear to be significant factors in any of the Exit to R-O-W egress trials. Accordingly, the data for the repeated egress trials were combined, producing a single distribution for the individual egress trials (72 data points) and a single distribution for the group egress trials (75 data points).

The probability distributions for the exiting data collected from the individual Exit to R-O-W egress trials and the group egress trials were very similar. In addition, the mean time for a participant to exit across all of the individual egress trials (5 s) and the mean time across all of the group egress trials (5 s) were very similar. A minor difference between the two distributions concerned the tail at longer exiting times. The time required by the slower participants to exit was faster in the group egress trials compared with the individual egress trials. This difference could be due to the added physical incentive to exit faster in the group egress trials as a result of the inclusion of the faster participants.

Because of the similarity in the curves for the group and individual egress trials, the data from both Exit to R-O-W egress trials were combined to produce a single frequency distribution made up of 147 data points.

However, one over-50-year old female participant and one mobility-impaired male participant had significantly slower exit times than the mean for both individual and group egress trials.

Since FSEG believed that including these data five times would unfairly bias the data set with uncharacteristically long exit times, the repeat egress trial data for these two participants was removed. Therefore, the data set was reduced from 147 to 131. With these repeat egress data points removed, the number of data points was reduced to 64. The minimum and maximum exit times for the Exit to R-O-W egress trials were 1.7 s and 13.7 s, respectively, with the mean reduced to 4.4 s and the standard deviation reduced to 1.9.

Similarly, the data derived from the Exit to R-O-W group egress trials also had the slow repeated data removed, resulting in a total of 67 data points. The minimum time remained unaltered at 1.9 s, with the maximum time reduced to 9.3 s, the mean reduced to 4.4 s, and the standard deviation reduced to 1.6 s. When all 131 data points from the individual and group egress trials were combined, the minimum exit time was 1.7 s, the maximum 13.7 s, and the mean exit time 4.4 s, with a standard deviation of 1.8 s.

Figure 22 shows that the Exit to R-O-W distribution is approximately of log normal form. It is reasonable to infer that given enough data points from unique participants, irregularities in the curve would smooth out into a log normal shape. For the Prototype Software, it would be desirable to smooth the distribution into its ideal form.

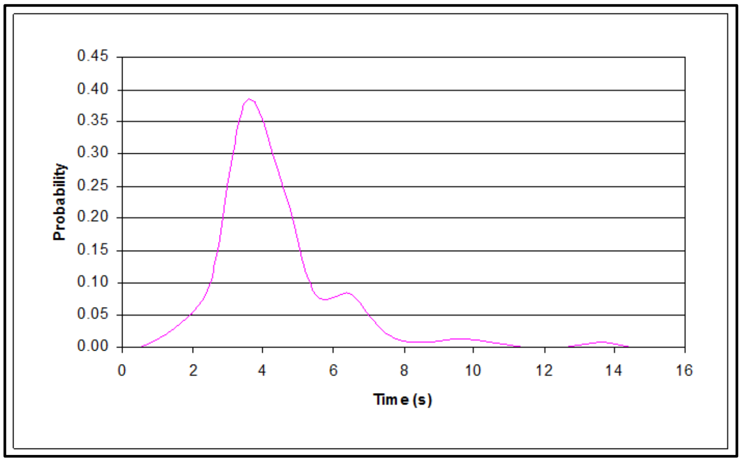


Figure 22. Exit to R-O-W: Combined Individual and Group Egress Trial Exit Time Data – Normalized

Figure 23 also shows two log-normal curves for the Exit to R-O-W distributions. The red dotted line is determined using the mean and standard deviation of the raw exit times (t) (i.e., the actual data points (where mean Ln(t) = 1.413 and standard deviation Ln(t) = 0.357). The blue solid line uses a log-normal distribution estimated to produce a curve which best fits the data used in the Prototype Software (using a mean Ln(t) = 1.194 and a standard deviation Ln(t) = 0.329).

The equation, y = f (t), used to define the log-normal distribution (Equation 8):

$$y = f(t) = \frac{1}{\sigma t\sqrt{2\pi}} \exp\left[-\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right] \qquad \textbf{(8)}$$

Where: *y* is probability, *t* is time (s), μ is the mean of Ln (t) and σ is the standard deviation of Ln (t). (“Ln” refers to the natural logarithm of the variable following Ln).

For ease of input into the Prototype Software V2.1, model time ranges with equal probability were combined into a large time interval (see Appendix C).

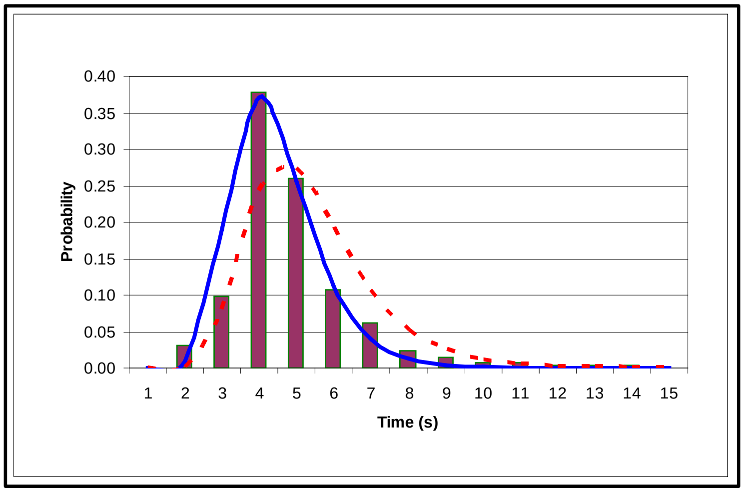


Figure 23. Exit to R-O-W: Smoothed Exit Time Probability Distribution

4.4.5.2 *Exit to Low Platform*

The exit times in seconds for each person to step down from the passenger rail car side-door exit and onto the low platform for the individual Exit to Low Platform egress trials was determined, as well as the minimum, maximum, and mean times for each egress trial. Three data points were discarded due to the participants incorrectly exiting the passenger rail car (according to the procedural definitions in Section 4.4.1). The minimum, maximum, and mean exit times for all participants across all the individual egress trials were 0.88 s, 7.3 s and 2.1 s, respectively. A total of 82 data points were collected (from the 85 participants with three points discarded), with a standard deviation of 1.3 s.

Data collected from the Exit to Low Platform group egress trials resulted in minimum, maximum, and mean exit times for all participants across all egress trials of 0.9 s, 5.7 s, and 2 s, respectively. A total of 85 data points were collected, with a standard deviation of 0.99s.

The minimum, maximum, and mean exit flow rates for all the participants across all group egress trials for the Exit to Low Platform trials were 37 ppm, 41 ppm, and 39 ppm, respectively.

The average exit flow rate for the Exit to Low Platform trials is 39 ppm, which is 103 percent faster than the Exit to R-O-W average flow rate of 19.2 ppm. This exit flow rate compares with the average exit flow rate of 52.6 ppm derived for the Exit to High Platform in normal lighting egress trials (see Subsection 4.3.5.1).

The exit curves shown in Figure 24 demonstrate the natural variation in exit performance for repeated egress trials.

As with the Exit to R-O-W egress trial data, by taking the minimum and maximum exit time for each participant, a window of experimental results can be produced (see Figure 25).

These exit time curves are used for validating the Prototype Software V2.1 for the Exit to Low Platform egress scenarios.

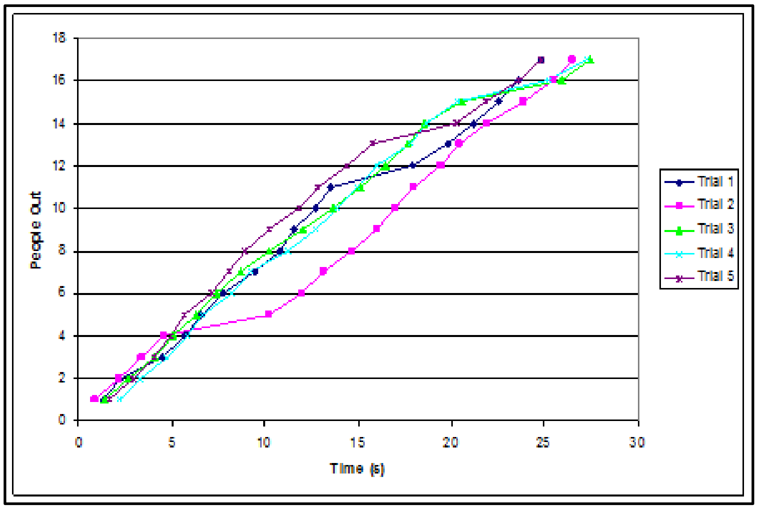


Figure 24. Exit to Low Platform: Group Egress Trial Exit Time Curves

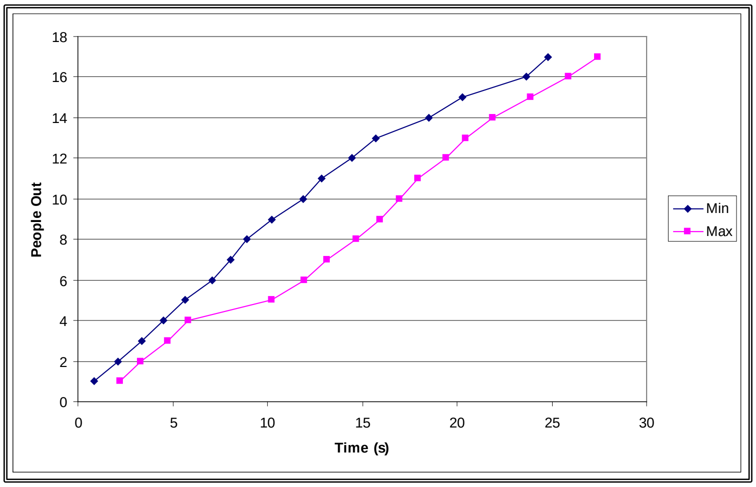


Figure 25. Exit to Low Platform: Performance Window Produced by Minimum and Maximum Exit Times for Group Egress Trials

These exit time curves are used for validating the Prototype Software V2.1 for the Exit to Low Platform egress scenarios.

As with the Exit to R-O-W egress trial data, the Exit to Low Platform egress trial data imply that learning and fatigue did not appear to be significant factors in either the individual or group egress trials. Therefore, the data for the repeated egress trials were combined, producing a single distribution for the individual egress trials (82 data points) and a single distribution for the group egress trials (85 data points).

Similar to the Exit to R-O-W trial data, the Exit to Low Platform probability distributions for the exiting data collected from the individual and the group egress trials are very similar. In addition, the mean exit time for a participant to exit across all of the individual egress trials (2 s) and the mean exit time across all of the group egress trials (2 s) are identical. In addition, as with the Exit to R-O-W egress trials, a minor difference between the two distributions concerned the tail at longer exiting times. The likely reason is as stated for the Exit to R-O-W trials in that the time required by the slower participants to exit was faster in the group egress trials compared with the individual egress trials because of the added physical incentive to exit faster in the group egress trials caused by the interaction of the faster participants with the slower participants. Due to the similarity in the exit time curves for the group and individual egress trials, the data from both types of egress trials were combined to produce a single frequency distribution made up of 167 data points.

However, as in the Exit to R-O-W egress trials, one participant's exit times were significantly slower than the mean for both individual and group egress trials. FSEG believed that including these data five times would unfairly bias the data set with uncharacteristically long exiting times and so the repeat egress trial data for this participant was removed. Accordingly, the data set was reduced from 167 to 159. When all 159 data points from the individual and group egress trials are combined, the minimum exit time was 0.9 s, the maximum was 6.8 s, the mean was 1.8 s, with a standard deviation of 0.7 s.

As with the Exit to R-O-W egress trials, the combined group and individual exit time probability distribution for the Exit to Low Platform trials was of the log-normal form (see Figure 26). Again, it is reasonable to infer that given enough data points from unique participants, the irregularities in the curve would smooth out into the log-normal shape.

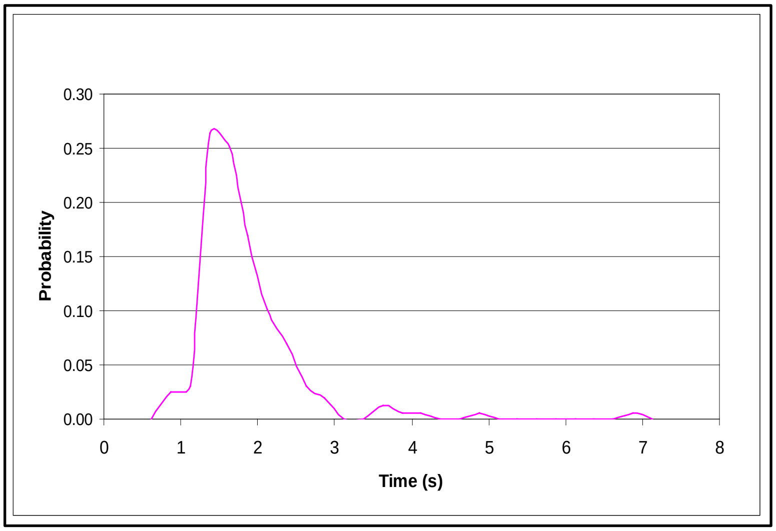


Figure 26. Exit to Low Platform: Combined Individual and Group Egress Trial Exit Time Data – Normalized

For use in the Prototype Software V2.1, it is desirable to smooth the exit time distribution into its ideal form (as shown in Figure 27).

Figure 27 shows two log-normal curves. The red dotted line is determined using the mean and standard deviation of the raw times (t) (i.e., the actual data points (where mean Ln (t) = 0.388 standard deviation Ln (t) = 0.150)). The blue solid line uses a log normal distribution (see Equation 8) estimated to produce an exit time curve which best fits the data to be used in the new Prototype Software V2.1 (using a mean Ln(t) = 0.372 and a standard deviation Ln (t) = 0.231).

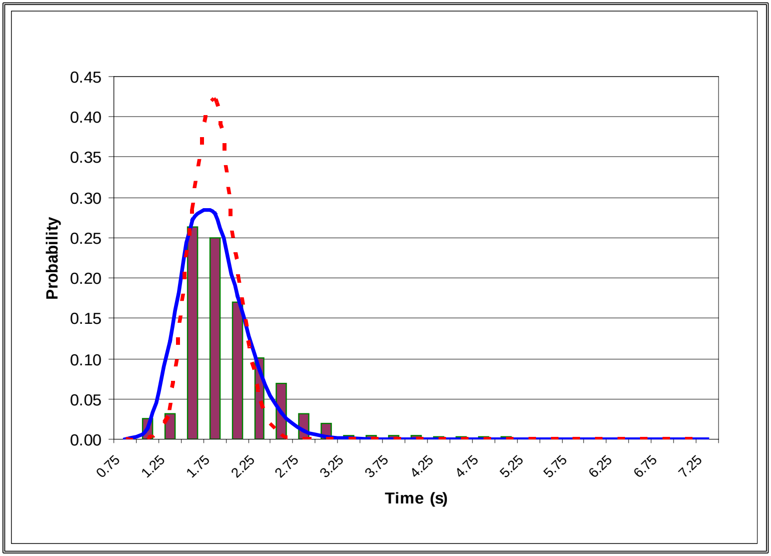


Figure 27. Exit to Low Platform: Smoothed Exit Time Probability Distribution

4.4.5.3 *Comparison of Exit from Passenger Rail Car to R-O-W and Low Platform Probability Distributions*

To compare the relative exit performance of the participants during the Exit to R-O-W and Exit to Low Platform egress trials, the best fit probability distributions for both situations are shown in Figure 28.

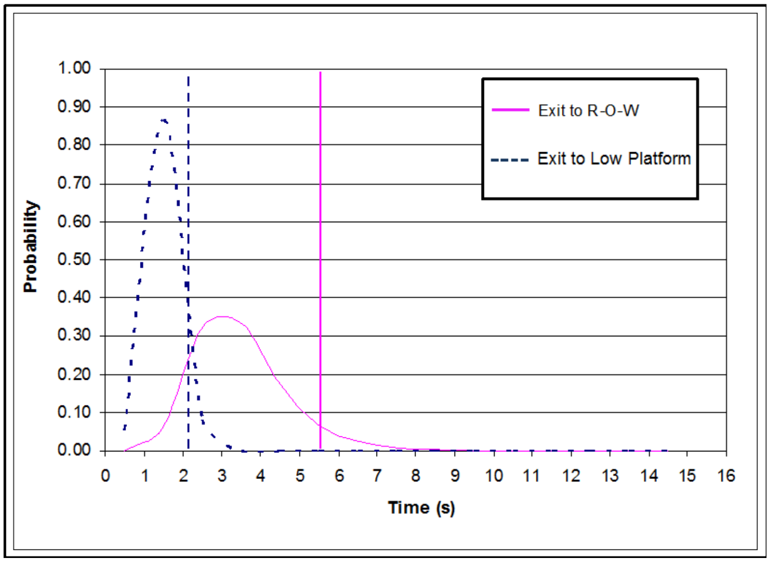


Figure 28. Comparison of Exit Time Probability Curves (Best Fit Distribution): Exit to R-O-W and Exit to Low Platform Egress Trials

As Table 28 shows, the time required to Exit to Low Platform is considerably shorter than the time required to Exit to R-O-W. The maximum time, as measured in the Volpe Center Exit to Low Platform egress trials, was 6.8 s, while the maximum time measured in the Exit to R-O-W egress trials was 13.7 s. Therefore, the slowest time for the Exit to R-O-W trials was twice as long as the slowest time for the Exit to Low Platform trials. Accordingly, the time for the Exit to R-O-W egress trials shows a much wider variability in possible exit times. The modal time (i.e., the time with the highest frequency) for Exit to Low Platform trials was 1 to 2 s while the modal time for the Exit to R-O-W egress trials was 3 to 4 s, a difference of approximately 133 percent. Therefore, the majority of participants required 133 percent longer for egress during the Exit to R-O-W compared with the amount of exit time required in the Exit to Low Platform trials. Figure 28 also shows the 95th percentile times for each distribution. The 95th percentile exit time for the Exit to R-O-W trials is 5.7 s (solid vertical line), while the 95th percentile exit time required tor the Exit to Low Platform trials is 2.1 s (dashed vertical line).

Figure 29 shows the envelope of exit times for the Exit to R-O-W and Exit to Low Platform egress trials. As noted for the exit time probability distributions, the Exit to R-O-W trials produce considerably longer exit times with wider variability.

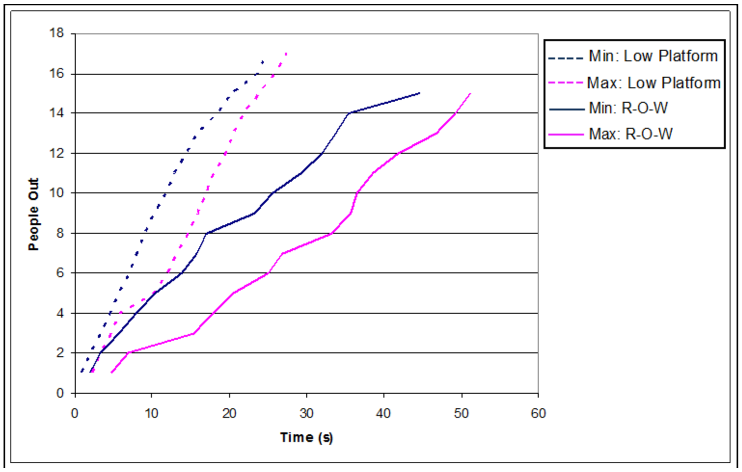


Figure 29. Comparison of Exit Time Curve Envelopes: Exit to Low Platform and Exit to R-O-W Egress Trials

4.4.5.4 *Number of Persons in the Passenger Rail Car Exit System*

From observation of the Volpe Center egress trial video recordings, FSEG measured the number of persons within the passenger rail car exiting system at any one time during the group egress trials. For the Exit to R-O-W egress trials, the maximum number of participants observed to be within the exit system at any one time was three. However, the exit system was rarely occupied by three participants, which occurred an average of only 2 percent of the total egress time. For the majority of time, the number of persons in the system was either one (44%) or two (53%). For Exit to R-O-W egress scenarios, the Prototype Software has been configured to allow a maximum of two agents to occupy the exit system at any one time. This is conservative and approximates the overall egress experimental trial results more closely.

For the Exit to Low Platform egress trials, the maximum number of persons observed to be within the exit system at any one time was two. During those egress trials, the exiting system was occupied by the maximum number of participants 33 percent of the time. The Exit to Low Platform egress trials were less likely to have two persons in the exit system at the same time, as observed in the Exit to R-O-W egress trials. Thus, for the Exit to Low Platform scenarios, the

Prototype Software V2.1 has been configured to allow a maximum of two agents to occupy the exit system at any one time.

4.5 Limitations

The Volpe Center passenger rail car egress trials were safely and successfully conducted and produced a great amount of valuable data. However, it is important to note the limitations of the egress trials and the resulting data, which primarily relate to the use of the data to represent emergency conditions. Several comments are of general relevance and are described while more specific comments can be found in the relevant sections of this report.

4.5.1 2005 Egress Trials

Limitations included:

- No overtaking, urgency, or two-abreast movement at either the passenger rail car aisle or the exit were noted in any egress trial, although participants had been told to hurry as though late for an appointment. During competitive behavior, two-abreast movement through the aisle may have been possible. However, there would certainly have been sufficient space for two-abreast movement in the approach to the car side-door exits and within the vestibule.
- A great amount of deference behavior was noted across all egress trials, with participants in the rail car aisle yielding to seated persons. This behavior led to an orderly emptying of the car from front, (i.e., nearest the exit) to back (i.e., furthest from the exit). This level of deference behavior is more likely to be observed in non-emergency egress situations than in emergency evacuations.
- During the egress trials, participant response was usually instantaneous, followed by standing and waiting to start walking towards the exit, or sitting back down again in some cases during their passage to the exit, as they knew their progress was blocked. This type of behavior is not normally observed in emergency situations.
- As participants took part in the 12 egress trials (six of which were repeats), learning effects in many of the observed behaviors were apparent in the repeated egress trials. However, a review of the data relating to these behaviors (within the car itself) showed negligible effects on measured exiting rates.
- In several cases, the participant’s egress performance under emergency lighting conditions is superior to his or her performance in normal lighting conditions. Furthermore, the behavior of the participants did not appear to change under the reduced emergency lighting conditions for those egress trials.

  For example, participants did not need to guide themselves through the darkness. The implication is that the conditions during the emergency lighting egress trials may not have been representative of those that could be expected during emergency egress from a passenger rail car under low light or darkness conditions.

- During the egress trials, some participants were seen to be completing their questionnaires rather than attempting to exit. This behavior usually occurred just after the participants stood up and prior to their moving down the aisle or (occasionally) during movement along the rail car aisle or even while exiting. Although the impact of this behavior on the flow of movement is unclear, it would not have occurred during a real event. In addition, it also indicates that some participants had a lower sense of urgency.

For these reasons, the data derived from the Volpe Center passenger rail car egress trials may not be representative of individuals' performance under actual emergency conditions. For practical reasons, the experimental conditions could not represent a real passenger train emergency incident and thus the data have limitations in representing such conditions. While potential discrepancies between the experimental conditions and emergency conditions guiding the future use of the experimental data have been identified, the egress trials represent a valuable source of data and thus provide an important basis for egress model development.

4.5.2 2006 Egress Trials

Limitations included:

- Only a relatively small sample of data was collected in the passenger rail car egress trials due to the small number of participants. Therefore, the range of performance expected of the traveling population may not be represented in the experimental data set.
- In the April 2006 rail car egress trials, a small additional step box was used to ensure participant safety. It is difficult to determine the exact impact of this step on the results without having another data set for which the step box was not used.

In both series of egress trials, a lower level of urgency was present than might be expected in an emergency situation.

4.6 Recommendations for Additional Data Collection

While the Volpe Center passenger rail car egress trials provide a basis for the development of the new Prototype Software, the software development would benefit from additional data. The additional data would be used to provide:

- Insight into important human behaviors expected in emergency situations that are not currently represented.
- Quantification of important human behaviors expected in emergency situations that are not currently represented.
- Further quantification of human factors parameters used.
- Further validation data sets to test performance.

It is noted that the data derived from the suggested additional egress trials would not only prove useful for the further development of the new Prototype Software, but would also be useful in providing a reproducible factual base on which to formulate safety regulation. This data would increase understanding of the human behavior factors involved in emergency egress; establish human performance criteria; and prioritize alternate means that could improve egress performance.

The following egress trials have been prioritized into two groups. The first group is considered high priority while the second group is considered a lower priority. Within each group, the list is ordered from the highest priority to the lowest priority.

The high priority group consists of the following:

1. Repeat the 2005 emergency lighting egress trials in conditions of near darkness, to simulate a night evacuation, where the only illumination is provided by the emergency lighting system. This trial repetition would provide a more reliable data set for emergency lighting conditions.
2. Repeat the 2006 experiments with larger numbers of participants. The greater the number of data points, the more likely the data sets produced will account for variations in the population, the greater the repeatability of the data, and the greater the statistical power of the results.
3. Using a representative population mix, determine participant performance while moving along the car aisle and exiting performance when the car is inclined at different angles (using the FRA-sponsored Rollover Rig Facility [20]; this would provide a data set to better understand human factors issues associated with inclined cars and would also provide a data set for exit at adverse angles).
4. Repeat the 2005 egress experiment (normal and emergency lighting conditions) under more competitive behavior conditions. This would provide a data set expected to be more representative of emergency conditions.

The lower priority group consists of the following:

1. Repeat the 2006 experiments with different external stairway configurations and different size vertical drops to explore the dependence of the exit time probability distribution on those parameters.
2. Repeat the 2005 experiments in the presence of (theatrical) smoke of different concentrations (i.e., reduced visibilities). This would provide a data set for human performance in fire conditions.
3. Repeat (2) using the FRA sponsored rollover rig facility [20] to determine evacuation performance in the presence of (theatrical) smoke of different concentrations and different angles of roll.
4. Repeat the first series of egress trials (normal and emergency lighting) to explore repeatability of the data set.
5. Repeat the first series of egress trials (normal and emergency lighting) using different seating configurations. This would explore issues of impact of car configuration on evacuation performance.
6. Data similar to the first series of egress trials could be extracted from in-service passenger cars during peak conditions by installing cameras in in-service cars.

This would provide a potentially very large data set for exiting under non-competitive conditions.

For all of the above suggested egress trials, the greater the number of observations (i.e., the number of participants involved) the more likely the data sets produced will account for variations in the population, behaviors exhibited, and the conditions that emerge. It would also increase the statistical power of the data sets.

4.7 Summary

The 2005 and 2006 Volpe Center passenger rail car egress experiment trials provided a considerable quantity of data for:

- Exit flow rates for egress from a commuter rail car using one or two side doors for the Exit to High Platform egress scenario and the Inter-Car End Door egress scenario to move to an adjacent car;
- Exit time frequency distributions for Exit to Low-Platform and Exit to R-O-W egress scenarios; and
- Participant travel speeds within the rail car.

This Volpe Center egress trial data has been used in the development of the new Prototype Software V2.1. In addition, data are available for use in the validation and/or verification of the new Prototype Software 2.1.

5. Prototype railEXODUS Software V2.0 Development

The development of the Prototype Software V2.0 followed the three-phase process outlined in Section 3.5. This process built on the prototype railEXODUS software V1.0 (see Chapter 2) and used data generated from the 2005 Volpe Center passenger rail car egress trials (see Chapter 4). The first development phase extended the V1.0 software by incorporating data and appropriate behaviors (see Section 4.3) associated with participant use of inter-car end-door exits and side-door exits onto high platforms, in non-competitive conditions, with normal and emergency lighting conditions. Since egress under emergency conditions may be expected to be more urgent (i.e., competitive), a capability to represent competitive egress behavior has been included, albeit without a corresponding comprehensive data set.

The modifications to the EXODUS model are complex as changes to one of the sub-models could have an impact on the other sub-models. For example, changes to the *Behavior* sub-model to incorporate exiting behavior through the passenger rail car side-door exit onto the high platform would also involve modifying the *Geometry* sub-model to represent a new exit type, as well as changes to the *Occupant* sub-model to incorporate additional movement rates. To make the modifications easier to follow, the changes to the model are described in terms of how the User would encounter these changes in using the software (i.e., by describing the changes to the four core modes of software operations: *Geometry* mode, *Population* mode, *Scenario* mode, and *Simulation* mode.

5.1 Terminology

Several terms are frequently used to describe model features throughout the remainder of this report:

Node: Region of space which can be occupied by a single agent within EXODUS. There are a variety of node types representing, for example, free space, seats, aisles, etc.

Potential Map: A means by which agents can navigate to an exit. Each node has a potential value which increases the further the node is located from an exit.

Arc: An arc is used to connect a node to its neighboring node. The arc also represents the physical distance between the connecting nodes. Agents move from node to node along the arcs.

Transit Node: Within EXODUS, transit nodes are used as a means of representing self-contained links between different regions within a structure, where complex behavior may be exhibited. Existing transit nodes can be used to represent components such as flights of stairs, ladders, and escalators. Each individual component can be modeled entirely by a single transit node, with agents moving internally within each transit node. In addition, transit nodes also enable either the maximum flow rate of agents through them to be restricted, or alternatively enable agents to encounter delays.

5.2 *Geometry* Mode Development

Several new objects have been developed within the EXODUS software to enable the representation of movement between adjacent cars and to high platform locations. The modifications implemented in *Geometry* mode within the Prototype Software V2.0 are:

- ***Inter-Car Conx* transit node.** This is a new feature intended to represent the physical connection between passenger rail cars (i.e., passage through an inter-car end-door exit to an adjacent car). Associated with this new node type are maximum flow rates for normal and emergency lighting conditions, under non-competitive egress situations. A capability to include flow rates under competitive egress situations has also been introduced.
- ***High Plat. Exit* transit node.** This is a new feature intended to represent the passenger rail car side-door exit connecting to a high platform. Associated with this new node type are maximum flow rates for normal and emergency lighting conditions, under non-competitive egress situations. A capability to include flow rates under competitive egress situations has also been introduced.
- ***Car Aisle* node.** This is a new node type intended to represent the terrain associated with the main car and vestibule aisles leading to the side-door exits. Associated with this node type are a range of associated movement behavior rules for non-competitive and competitive egress situations.

5.2.1 Inter-Car Connection

Within the Prototype software V2.0, the inter-car connection is achieved using a new transit node type called *Inter-Car Conx*. The *Inter-Car Conx* transit node is intended to represent the physical space of the connection between two adjacent passenger rail cars (see Figure 30), assuming that the inter-car end-door exit is available and open. The parameters defining the physical performance of the *Inter-Car Conx* transit node are: *Lanes*, *Capacity*, *Flow Direction*, *Length*, and *Width*.

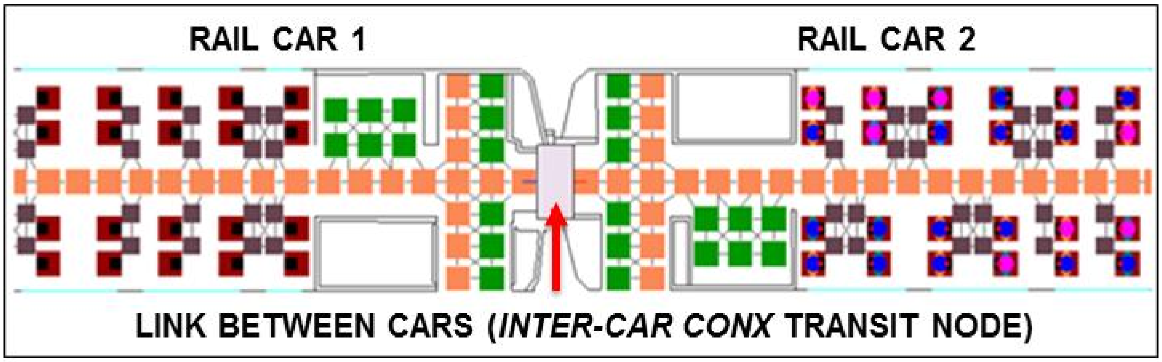


Figure 30. Representing the Passenger Rail Car Inter-Car Connection within railEXODUS V2.0

It is possible to specify and modify several physical and performance characteristics of the *Inter-Car Conx* transit node which are defined according to the following set of parameters:

LANES: The number of *Lanes* within transit nodes corresponds to number of agents capable of moving through the transit node side by side. As the default, the number of lanes is set to 1.

CAPACITY: The *Capacity* of the transit node defines the total number of agents who can simultaneously occupy the inter-car region.

FLOW DIRECTION: Within transit nodes, the *Flow Dir.* parameter controls the direction agents are permitted to travel through the transit node during a simulation. The movement through the transit node can either be set to *Up/Forward*, thereby permitting agents to only travel through it in a forward direction. Conversely, the flow direction can be set to *Down/Backward*, thereby restricting the movement of agents through the transit node in the opposite direction. Alternatively, the flow direction can be set to *Bidirectional*, thus imposing no restriction on the direction of travel, thus enabling agents to travel through the transit node in either direction.

LENGTH: The *Length* parameter is set to the approximate length of the inter-car end connection. Changing the length of the *Inter-Car Conx* will effectively change the time required by agents to traverse the inter-car connection. Within the Prototype Software V2.0, the time required to traverse the inter-car connection is derived from the flow rate associated with this transit node, which was derived from the Volpe Center egress trials (see Section 4.3) where the inter-car connection measured 1.6 ft (0.5 m).

WIDTH: Another parameter that can be specified on the *Inter-Car Conx* transit node is the *Width.* This defaults to 3.3 ft (1.0 m). The *Width* parameter has no direct impact on the simulation. Its only function is to control the visual appearance (i.e., the width) of the inter-car connection within the virtual reality tool, vrEXODUS. Therefore, increasing or reducing the width will **not** affect the number of agents capable of entering or occupying the transit node or the number of agents who flow through it.

The functionality of the *Status* and *Potential* parameters and the *Times* parameters can only be edited in *Scenario Mode* and are thus disabled within *Geometry Mode*. These parameters relate to the availability of the transit node and its effect on the potential map. Having defined the physical characteristics of the *Inter-Car Conx* component, it is necessary to connect it via arcs in the same manner as conventional EXODUS nodes. The transit nodes are connected (via arcs) to the conventional nodes from which agents are able to directly access the transit node.

The Volpe Center egress trials produced a range of flow rates for participants traveling between the rail cars under conditions of normal and emergency lighting when subject to non-competitive egress behavior (see Section 4.3), as shown in Table 9.

Table 9. Minimum and Maximum Exit Flow Rates for *Inter-Car Conx* Transit Node under Non-Competitive Conditions

LIGHTING	MINIMUM EXIT FLOW RATE ppm (pps)	MAXIMUM EXIT FLOW RATE ppm (pps)
Normal	51.5 (0.86)	53.0 (0.88)
Emergency	52.5 (0.88)	54.2 (0.90)

These flow rates (corresponding to non-competitive behavior) were incorporated into the *Inter-Car Conx* transit node as the default values for each corresponding lighting condition. Within the software, the competitive nature of the scenario (i.e., competitive or non-competitive) is defined by a new behavioral switch, as is the lighting level experienced (*Normal* and *Emergency* lighting). As a result, four separate sets of flow rates can be defined for the *Inter-Car Conx* transit node:

- Non-competitive behavior in:
  - *Normal* lighting
  - *Emergency* lighting, and
- Competitive behavior in
  - *Normal* lighting
  - *Emergency* lighting.

Since the 2005 Volpe Center passenger rail car egress trials were conducted under non-competitive egress behavior, no data are currently available relating to flow rates through the inter-car end-door exit region during competitive egress conditions. To not have zero values for the competitive flow rates, the measured flow rates during the non-competitive egress trials (see Table 9) were assumed as the default values for the competitive flow rates. It is noted that the default maximum and minimum flow rate values can be altered to whatever value is required.

5.2.2 *Exit to High Platform* Connection

When individuals exit a passenger rail car through the side-door exits, they can do so onto a high platform, a low platform, or directly onto the R-O-W. A capability was developed to represent exiting to a high platform. Within the Prototype Software V2.0, the side-door exit represents a connection between the rail car interior and the exterior, similar to a building exterior door, within buildingEXODUS. However, unlike a building exterior door, the rail car has several possible exiting configurations (high platform, low platform, and R-O-W locations) resulting in very different exiting behavior and, thus, exit flow rates. To represent the different possible exiting configurations, the side-door exit is represented within the Prototype V2.0 by a specially defined *Transit Node*.

Within the Prototype Software V2.0, when a group of agents travels through the rail car side-door exit onto a high platform:

- Agents physically travel a distance equivalent to that of stepping out onto the platform;
- There is a maximum number of agents that the exit can accommodate at any one time, which is set to a predefined maximum; and
- The average flow rate of agents passing through the exit is such that it does not exceed a predefined maximum.

These performance characteristics for the side-door exit are based on data derived from the 2005 Volpe Center egress trials (see Section 4.3).

Within the Prototype Software V2.0, the side-door exit onto a high platform is represented using a new transit node type called *High Plat. Exit.* The *High Plat. Exit* transit node is intended to represent the small physical space between the outer edge of the passenger rail car and the high platform and is used to both connect the car to the high platform and model the transition behavior. The *High Plat. Exit* transit node has parameters representing its corresponding *Width*, the number of *Lanes* (i.e., the number of agents capable of moving through the transit node side by side), *Flow Direction,* and the maximum flow rate that can be achieved through the exit. The nature of each parameter is briefly described below.

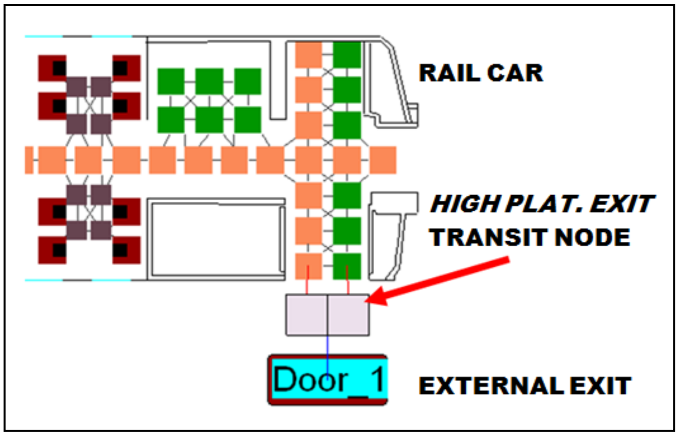
LANES: As with the *Inter-Car Conx* outlined previously, the number of *Lanes* represents the number of agents capable of moving through the transit node side by side, while the *Capacity* represents the total number of agents who can simultaneously occupy the exit system. The number of lanes (and therefore the capacity) was set to 2, although it was noted that during the 2005 Volpe Center egress trials the participants passed through the side-door exit onto the high platform in single file, with no more than one person occupying the exit at any one time (see Section 4.3). However, the width of the exit (i.e., approximately 3.3 ft (1 m)) would be sufficient to accommodate two agents abreast in competitive evacuation scenarios, so the default number of lanes (and therefore capacity) of the *High Plat. Exit* transit node was set to 2. However, it is noted that in non-competitive egress model scenarios, agents are required to exit using only the non-emergency routes defined by *Car Aisle* nodes (see Section 5.2.3). In these cases, agents will only be able to enter the *High Plat. Exit* transit node via one of the available lanes. As a result, the number of lanes used (and thus total capacity) in these cases is limited to 1, thereby replicating the behavior observed within the 2005 Volpe Center egress trials.

FLOW DIRECTION: This parameter is defined in the same way as for the *Inter-Car Conx.*

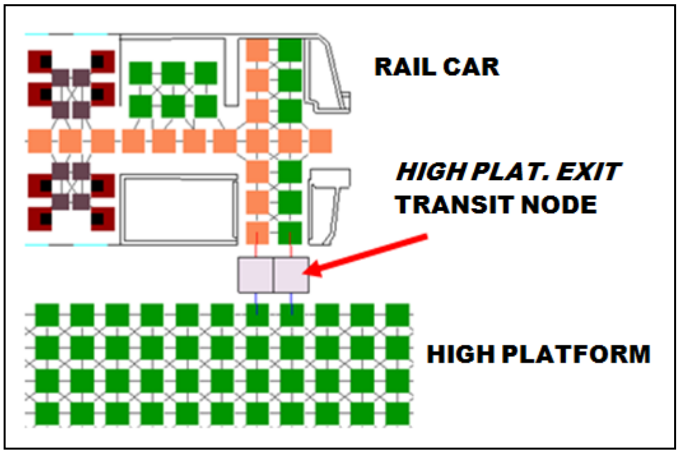
WIDTH: Another parameter that can be specified on the *High Plat. Exit* transit node is the *Width.* As with the *Inter-Car Conx* transit node outlined previously, the *Width* parameter has no direct impact on the simulation. Its only function is to control the visual appearance (i.e., the width) of the exit connection within the virtual reality tool, vrEXODUS. It is noted that the distance between the outer edge of the car and the platform is considered in the arc lengths connecting the *High Plat. Exit* to the platform. It is also noted that the *Use Flow Rate* option is automatically selected and not available for alteration. As with the *Inter-Car Conx* transit node, the User must define the flow rate of agents through the exit to the high platform in persons per seconds as opposed to defining their entry and travel delays in seconds.

Having defined the physical characteristics of the *High Plat. Exit* transit node, the User is then required to connect it via arcs in the same manner as conventional EXODUS nodes (see Figure 31). As with the *Inter-Car Conx* transit node, the *High Plat. Exit* transit nodes are connected (via arcs) to the conventional nodes from which agents are able to directly access the transit node.

The2005 Volpe Center egress trials produced a range of flow rates for participants passing from the passenger rail car to the high platform under normal and emergency lighting conditions, when subject to non-competitive egress behavior, as shown in Table 10.



(a) *High Plat. Exit* Connected Directly to an External Exit



(b*) High Plat. Exit* Connected to Conventional Nodes

Figure 31. Creating a *High Plat. Exit* Transit Node within Prototype Software V2.0

Table 10. Minimum and Maximum Flow Rates for *High Plat. Exit* Transit Nodes – Normal and Emergency Lighting Conditions

LIGHTING	MINIMUM EXIT FLOW RATE ppm (pps)	MAXIMUM EXIT FLOW RATE ppm (pps)
Normal	49.2 (0.82)	53.5 (0.89)
Emergency	48.3 (0.81)	54.8 (0.91)

These flow rates (corresponding to non-competitive behavior) were incorporated into the *High Plat. Exit* transit node as the default values for each corresponding lighting condition. Within the model, the competitive nature of the scenario (i.e., competitive or non-competitive) is defined by a new behavioral switch, as is the lighting level experienced (*Normal* and *Emergency* lighting).

As a result, four separate sets of flow rates can be defined for the *Inter-Car Conx* transit node:

- Non-competitive behavior:
  - *Normal* lighting
  - *Emergency* lighting, and
- Competitive behavior:
  - *Normal* lighting
  - *Emergency* lighting.

Since the 2005 Volpe Center egress trials were conducted under non-competitive egress behavior, no data are currently available relating to flow rates through the inter-car region during competitive evacuation conditions. So as not to have zero values for the competitive flow rates, the measured flow rates during the non-competitive egress trials (see Table 10) were taken as the default values for the competitive flow rates. It is noted that the default maximum and minimum flow rate values can be altered to whatever value the User requires.

5.2.3 *Car Aisles*

As noted previously, the behavior of the participants during the 2005 Volpe Center egress trials was non-competitive. Passenger behavior during emergency situations may be expected to be more competitive, especially as conditions deteriorate, such as in a developing fire. During the egress trials, participants instead proceeded towards their nearest exit point in an orderly single-file manner, maintaining personal space while walking. Even at the exit point, the observed behavior was orderly and in single file, although both the vestibule areas (i.e., the regions at the end of each rail car leading to the side-door exits; see Figure 32), and the exit could accommodate two participants side by side.

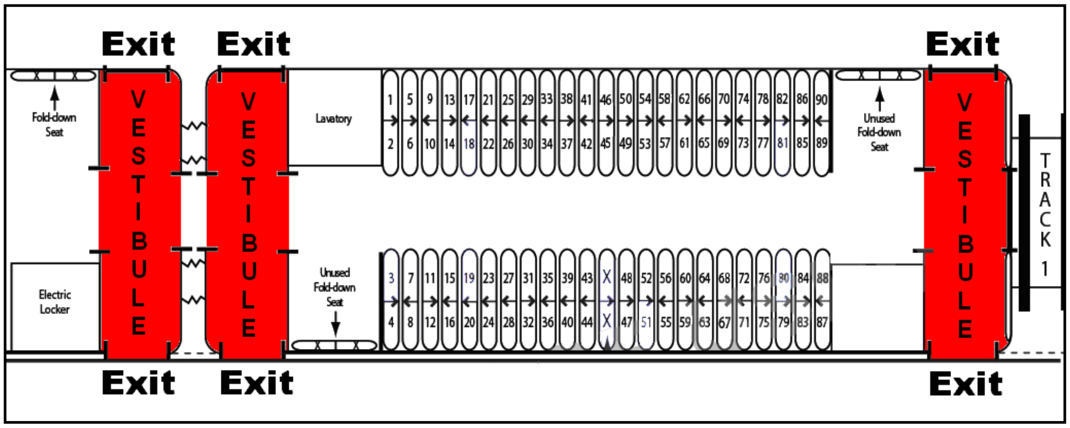


Figure 32. Vestibule Areas within a Typical Passenger Rail Car

Within the existing prototype railEXODUS software V1.0, the movement behavior is more competitive, with agents bunching up and attempting to overtake whenever possible, making the best use of the space available. Therefore, it was necessary to modify that software to reflect the ordered non-competitive occupant behavior observed during the 2005 Volpe Center egress trials. This modification involved introducing a new terrain type or node type (i.e., *Car Aisle* node), which could influence the behavior of agents, and a new behavioral switch to indicate the competitive nature of the scenario to be modeled.

Individuals involved in non-competitive and competitive rail egress situations are expected to display different behaviors. In the non-competitive 2005 Volpe Center egress trials, FSEG noted that participants exited in a very orderly style, in single file, with no bunching and no overtaking. The *Car Aisle* node enables the different behaviors to be implemented; however, the software must be set up to either execute a non-competitive or competitive evacuation model scenario (see Figure 33).

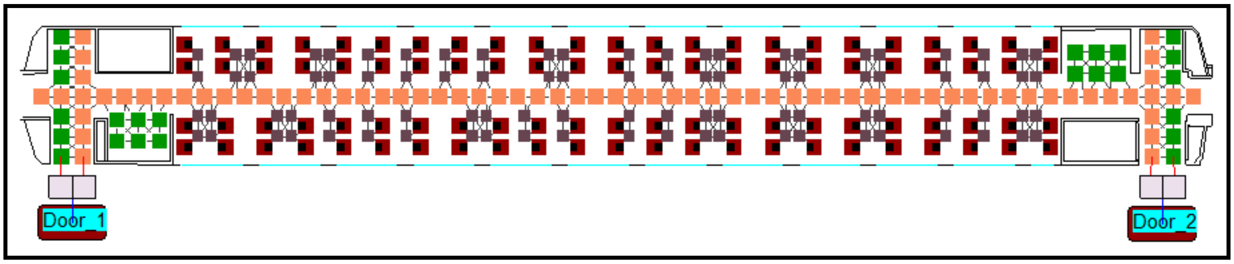
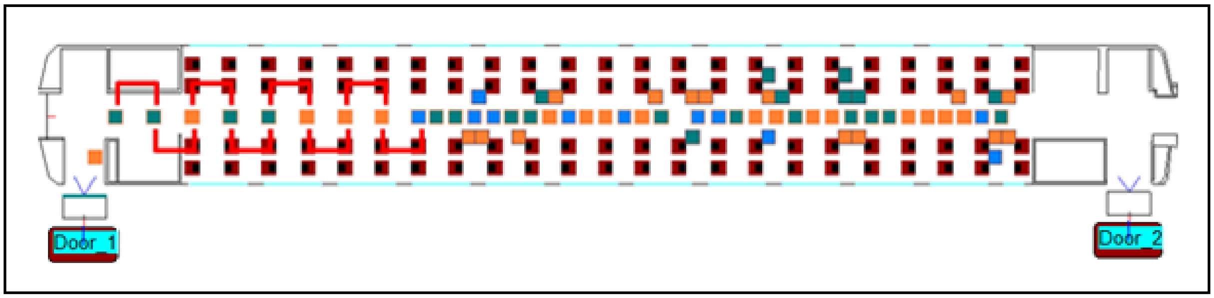
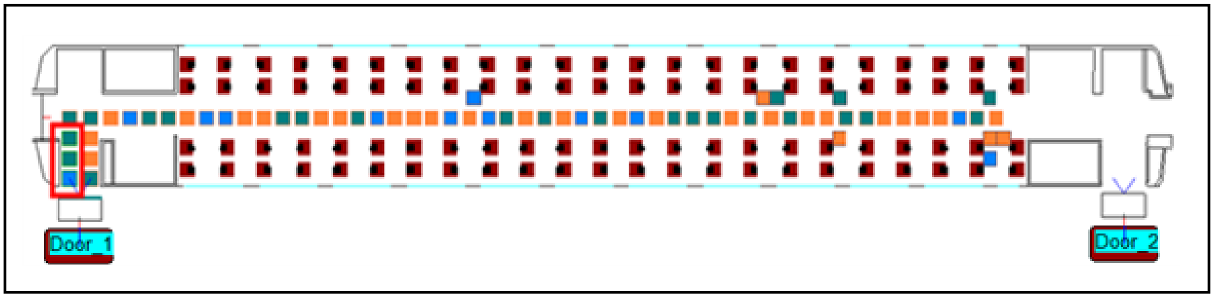


Figure 33. Passenger Rail Car with Non-Emergency Routes Defined via *Car Aisle* Nodes (Shown in Orange)

If the *Competitive Evacuation* behavior is not enabled, agents will exit in an orderly manner, maintaining a space between themselves and the person in front while free walking (see Figure 34a).



(a) *Non-Competitive* Scenario



(b) *Competitive* Scenario

Figure 34. Behaviors Displayed by Agents after 24 Seconds in One Side-Door Exit to High Platform Model Scenario

5.2.4 *Inter-Seat* (Aisle) *Space*

FSEG analysis of the 2005 Volpe Center egress trials implies that the region between seats could become congested with participants as they attempt to enter an already densely occupied main aisle. Participants were noted to remain standing in the region between seats for some time, as they attempted to gain entry into the densely occupied main aisle. The average time for aisle-seated participants to enter the aisle was 4.1 s and 3.3 s for normal and emergency lighting conditions, respectively. Conversely, the average for window-seated participants under normal lighting conditions was 32.9 s, while the time decreased to 27.9 s under emergency lighting conditions (see Section 4.3). In the worst case, a participant initially located in the window seat of Row 22 of the exit to adjacent car in normal lighting egress trial (i.e., Trial 1) required 75.9 s to access the aisle. To represent this behavior, the development of a new node type with associated behavior was required.

In order to replicate the population densities between the seats and participant behaviors around the seats observed in the Volpe Center egress trials, it was necessary to add nodes in front of each seat row. These nodes were intended to represent the positions (and therefore the small space occupied) by agents after they had gotten up from their seats and commenced or attempted to commence their exit.

In order to model this physical space (and the corresponding behaviors observed within it), a new node type was developed, called the *Inter-Seat Space* node (see Figure 35).

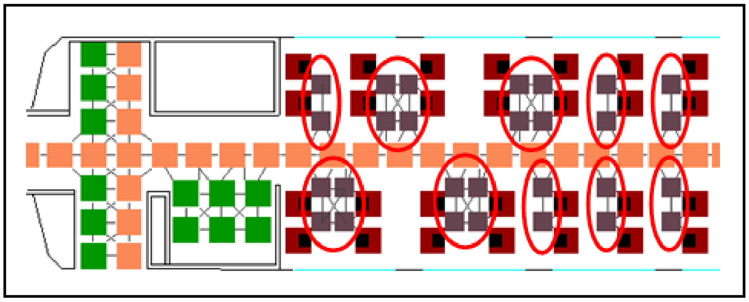


Figure 35. *Inter-Seat Space* Nodes Representing the Positions Occupied by Agents after Getting Up from Their Seats

The *Inter-Seat Space* nodes were typically offset towards the aisle, relative to their corresponding seat row, in order to mimic the tendency of participants to move directly towards the aisle upon getting up from their seat. In all cases, the *Inter-Seat Space* nodes were offset by approximately half the width of their corresponding seat. Since the width of each block of two seats according to the provided car drawing plans [17] was 3.3 ft (1 m), each individual seat was 1.7 ft (0.5 m) in width. Consequently, each *Inter-Seat Space* node (representing the space in front of each seat) was offset by approximately half this width, 0.9 ft (0.3 m), towards the aisle. As the space represented by the *Inter-Seat Space* nodes (and the arcs connecting these to the *Seat* and *Car Aisle* nodes) is intended to represent a smaller amount of space than the default node size, the nodes are represented graphically as a smaller size than the normal node size.

When agents pass over an *Inter-Seat Space* node, their travel speed is reduced to their designated *Walk* speed (i.e., as opposed to the *Fast Walk* speed used on conventional *Free Space* nodes). This reduction in travel speed is intended to address the limited space available on these nodes.

5.3 *Population* Mode Development

The modifications made to the railEXODUS V1.0 software to represent the required changes to agent performance in *Population* mode are:

- **Modifying travel speeds for the default population.** The population panel is modified to accept the default *Fast Walk* speeds associated with normal and emergency lighting conditions.
- **Modifying travel speeds of an individual agent.** A means of interrogating and modifying the travel speed characteristics of a single agent is shown.
- **Modifying travel speeds for a selected group of agents**. A means of modifying the travel speed characteristics for a group of agents is shown.

5.3.1 Changing Travel Speeds

The agent travel speeds used within the Prototype railEXODUS Software V 2.0 were derived from the 2005 Volpe Center egress trials (see Section 4.3). The data were derived from the free walk analysis of 16 persons (10 males and 6 females) in normal lighting conditions and 18 persons (6 males and 12 females) under emergency lighting conditions (see Table 11).

Table 11. Minimum and Maximum *Free Walk* Travel Speeds Derived from the 2005 Volpe Center Egress Trials

CATEGORY	DATA POINTS	MIN SPEED	MAX SPEED
Male – Normal Lighting	10	4 ft/s (1.2 m/s)	6.5 ft/s (2 m/s)
Female – Normal Lighting	6	3.3 ft/s (1 m/s)	5.8 ft/s (1.8 m/s)
Male – Emergency Lighting	6	4.17 ft/s (1.3 m/s)	6 ft/s (1.8 m/s)
Female – Emergency Lighting	12	3 ft/s (0.92 m/s)	5.1 ft/s (1.5 m/s)

The data extracted from these egress trials allowed the derived agent travel speeds to be related to both gender and lighting conditions. It is noted that the data are similar to the data used in the building environment where males tend to be faster than females [21] [22]. However, the maximum speeds are quite high compared to that observed in the building environment which typically has a maximum value of around 5.25 ft/s (1.6 m/s) for males and 4.59 ft/s (1.4 m/s) for females. The differences may be due to the relatively short travel distances involved in the passenger rail car egress trials. In addition, the free walking speeds were typically measured for those participants who were in the front of the evacuating groups and thus unobstructed by other participants, therefore producing higher travel speeds. These participants may have experienced a sense of urgency by leading the crowd and thus moved faster than normal. As these unobstructed walking rates are quite high, it was not felt appropriate to introduce a set of competitive walking rates and so the one set of walking rates applies to both competitive and non-competitive situations.

The mean and standard deviation of the normal distribution defining the *Fast Walk* travel speeds for each gender and lighting condition are shown in Table 12.

Table 12. Mean and Standard Deviation for Normal Distribution Defining *Fast Walk* Travel Speeds for Gender and Lighting Conditions

CATEGORY	MIN SPEED	MAX SPEED	MEAN	STD DEV
Male – Normal Lighting	4 ft/s (1.2 m/s)	6.5 ft/s (2m/s)	5.2 ft/s (1.6 m/s)	0.43 ft/s (0.13 m/s)
Female – Normal Lighting	3.3 ft/s (1 m/s)	5.8 ft/s (1.8 m/s)	4.6 ft/s (1.4 m/s)	0.43 ft/s (0.13 m/s)
Male – Emergency Lighting	4.2 ft/s (1.3 m/s)	6 ft/s (1.8 m/s)	5.1 ft/s (1.6 m/s)	0.33 ft/s (0.10 m/s)
Female – Emergency Lighting	3 ft/s (0.92 m/s)	5 ft/s (1.5 m/s)	4.07 ft/s (1.2 m/s)	0.36 ft/s (0.11 m/s)

5.3.2 Changing Individual and Group Travel Speeds

Within the prototype railEXODUS software V1.0, it was possible to modify agent attributes at the individual and group level. This capability was expanded within the Prototype Software V2.0 to accommodate the dependence of the travel speed attributes on lighting condition. Within the Prototype Software V2.0, the *Movement Rates* option is replaced by two options: *Normal Lighting Movement Rates* and *Emergency Lighting Movement Rates*.

5.4 *Scenario* Mode Development

The Prototype Software V2.0 has the ability to represent egress under both normal lighting and emergency lighting conditions. To specify these conditions, the zone capability used within the prototype railEXODUS software V1.0 was modified by extending an existing *Zone* feature to accommodate the specification of lighting conditions on a car-by-car basis. The new feature is called a *Car Zone*.

Within the prototype railEXODUS software V1.0 software, it was possible to define a range of Zones or physical regions of space over which a particular model attribute could be specified. In addition, within the V1.0 software, a range of different zone types was available (e.g., *Hazard*, *Response*, *Obstacle*, *Compartment*, etc.) Each zone type allows the specification of particular attributes associated with it. For example, the *Hazard Zone* allows the specification of atmospheric hazards associated with fire, such as temperatures, toxic gas concentrations, radiative flux, etc.

The new *Car Zone* is used to specify the lighting condition within the identified region of space. The physical extent of the *Car Zone* is defined in the same manner as the other zone types (i.e., by selecting the nodes within the region to which it corresponds). After a *Car Zone* (or collection of *Car Zones*) has been defined, the lighting condition (normal or emergency lighting) associated with each zone can be specified. By default, all zones are assumed to have normal lighting conditions. Any areas not included within *Car Zones*, and thus left undefined, will also be assumed to be in normal lighting conditions.

After the lighting condition within the *Car Zone* is specified, agents within the *Car Zone* will assume the appropriate travel speed for the lighting condition defined within the zone. In addition, each *High Plat. Exit* and *Inter-Car Conx* transit node within a *Car Zone* will assume the flow rate parameters appropriate for the lighting condition.

The new capability has flexibility to be further extended to include a third lighting condition defined as darkness without any emergency lighting (for which egress data are not currently available). The *Car Zone* will also be utilized in the further development of the Prototype Software V2.1 and V 2.2 (see Sections 7.2 and 9.1).

5.5 ***Simulation*** Mode Developments

The Prototype Software V2.0 has a range of new or modified *Simulation* mode capabilities compared with the prototype railEXODUS software V1.0. These capabilities are summarized as follows:

- **Defining conflict times for non-competitive egress situations.** The conflict resolution model within the Prototype Software V2.0 better represents interactions between agents as they attempt to enter the rail car aisle in non-competitive and competitive egress situations.
- **Defining behavior for competitive and non-competitive egress situations.** The *Behavior* sub-model within the Prototype Software V2.0 allows the specification of competitive and non-competitive agent behaviors.
- **Modifying the output files to reflect new capabilities.** The ASCII data represented in the *.sim output files include the new rail car geometry, as well as personal and behavioral capabilities of the Prototype Software V2.0.

5.5.1 Conflict Times

Analysis of the 2005 Volpe Center egress trial video (see Section 4.3) implied that when participants entered the aisle from the seat rows, the transition was relatively smooth. Significant disruption to the aisle flow was not generated and gaps did not form between the participants entering the aisle and participants ahead of them. In contrast, within the railEXODUS software V1.0, large gaps in the aisle flow would form as the agent entered the aisle. This is a result of the conflict resolution process within the EXODUS model, which is designed to accommodate more competitive egress situations in more open (e.g., building hallway) geometries. To address this issue, the conflict time data assigned to agents in competition for space was adjusted to represent the situation in the rail car egress trials (i.e., confined physical space and non-competitive behavior).

Within the EXODUS suite of software, agents competing to occupy the same region of space (node) at the same time are said to be in conflict and as part of the conflict resolution process the winners and losers incur time penalties. When two or more agents are simultaneously seeking to occupy a single node, the *Drive* attributes of the agents are used to resolve the conflict and determine which agent is permitted to move to the node and which is required to wait. In these cases, if one of the agents vying for the node has a *Drive* significantly higher than the others (i.e., > 10%), this agent is automatically assumed to eventually occupy the node. However, if the *Drives* of the competing agents are sufficiently close (i.e., < 10%) then the winner is randomly selected. In both cases, time penalties are assigned in order to represent the time lost by the agents due to interaction. The size of the time penalty typically varies depending upon the manner in which the conflict is resolved. Conflicts resolved as a result of clear differences in the *Drives* incur small time penalties randomly generated between a predefined penalty range (i.e., Range 1), while conflicts resolved in situations where the *Drives* are closely matched incur greater time penalties randomly generated between a second penalty range (i.e., Range 2).

Analysis of agent behavior within the limited environment of the passenger rail car when modeled with the railEXODUS V1.0 conflict times implied that modifications to the conflict time distributions were needed to reflect the non-competitive interactions taking place when agents moved from the seat spaces to the aisle spaces. This modification was due primarily to the high level of aisle deference behavior, where participants in the aisle would defer to participants in the seat rows, allowing them to enter the aisle. This aisle deference behavior was observed to occur 2.5 times more frequently than seat deference behavior, where participants in the seat rows would defer to those in the aisle.

The conflict time distributions were tuned through comparison with video from the Volpe Center egress trials and involved varying the range of the conflict time parameter and noting the impact on the simulated passenger flows in the aisle. This process was continued iteratively until the simulated passenger behavior closely matched that observed in the egress trials and resulted in the modified conflict time distribution:

- Range 1 conflict times were changed from 0.5s – 0.7s to 0.1s – 0.2s, and
- Range 2 conflict times were changed from 0.8s –1.5s to 0.3s – 0.5s.

The method of assigning conflict times was also modified. The method of assigning conflict time penalties to agents was extended to include the nature of the simulation represented and the location at which the conflict occurs, as well as the *Drives* of the agents involved:

- In non-competitive egress, when conflicts occur as agents attempt to occupy a *Car Aisle* node, the modified set of conflict times is used. In conflicts involving all other node types, the original set of conflict times is used.
- In competitive egress, all conflicts that occur make use of the original conflict time distributions. This is based on the assumption that competition for aisle nodes will become more competitive during these types of emergency egress.

5.5.2 Competitive and Non-Competitive Behavior

To reflect the expected difference between ordered non-competitive behavior (observed during the 2005 Volpe Center egress trials) and competitive behavior (which may occur in real emergency situations), it was necessary to incorporate a capability to switch between the expected behaviors and agent performance attributes. When *Competitive Evacuation* is selected, the following performance and behavior options are selected:

- All exit flow parameters switch to the *Competitive* data set.
- Agent aisle behavior switches to the *Competitive* rule set.
- Conflict resolution is performed using only the standard set of conflict times.

If *Competitive Evacuation* is **NOT** selected, the egress scenario being modeled is considered to be a non-competitive egress scenario and the following performance and behavior options are selected:

- All exit flow parameters switch to the *Non-Competitive* data set.
- Agent aisle behavior switches to the *Non-Competitive* rule set.
- Conflict resolution is performed using both the standard and modified sets of conflict times.

In addition, depending on the nature of the simulation being undertaken, the User also has the option of activating the EXTREME Behavior option. This option should only be considered in *Competitive* evacuation situations in which there are multiple exits available within the car. In this case, agents who are towards the end of a slowly moving exit line may decide to attempt to utilize the alternate exit if they believe they are not making timely progress towards the original target exit.

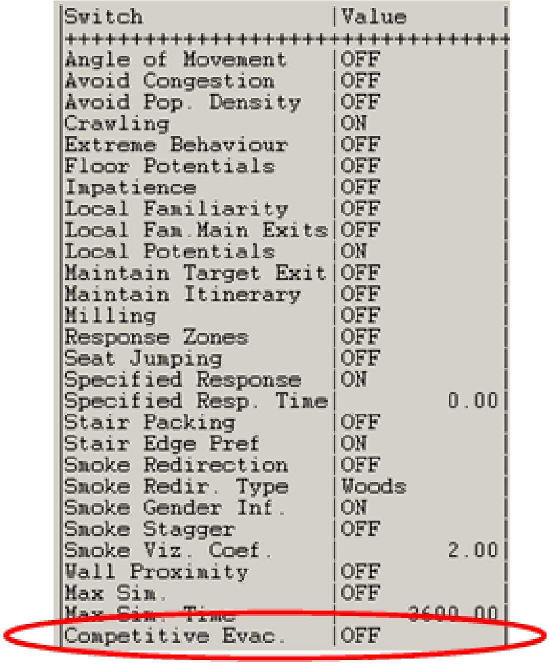
5.5.3 Data Output

The prototype railEXODUS software V1.0 had a range of data output capabilities. Essentially, the entire set of agent personal attributes and specific transit nodes, such as exits, can be output to the simulation output file (*.sim) as ASCII data. This output capability was modified to address the new attributes and geometric components introduced into the Prototype Software V2.0.

Each output file (*.sim) typically consists of six main sections:

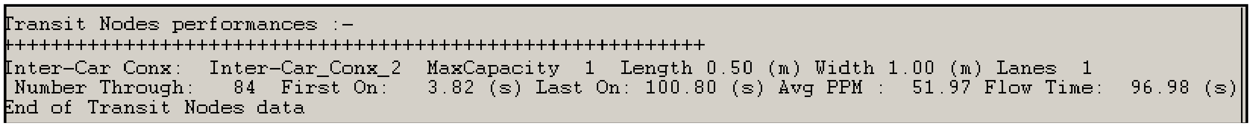
- Header information,
- Input parameter summaries,
- Individual agent results,
- Exit performance summary,
- Internal exit/transit node summary, and
- Graph data.

As a result of the various modifications made to the simulation output file, modifications were also required within the accompanying data analysis tool, “askEXODUS.” These changes were required in order to enable the various movement rates within each of the two lighting conditions to be averaged across the entire population. Examples of new output related to the options selected and the performance of several of the new node types are shown in Figure 36 and Figure 37.



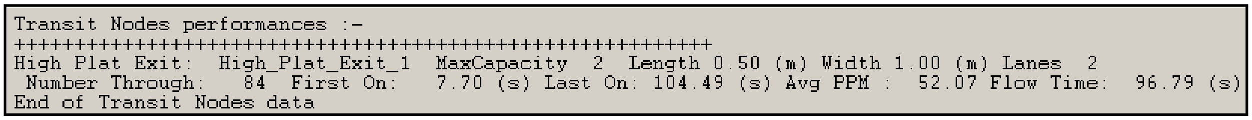
```
|Switch              |Value       |
+++++++++++++++++++++++++++++++++++
|Angle of Movement   |OFF         |
|Avoid Congestion    |OFF         |
|Avoid Pop. Density  |OFF         |
|Crawling            |ON          |
|Extreme Behaviour   |OFF         |
|Floor Potentials    |OFF         |
|Impatience          |OFF         |
|Local Familiarity   |OFF         |
|Local Fam.Main Exits|OFF         |
|Local Potentials    |ON          |
|Maintain Target Exit|OFF         |
|Maintain Itinerary  |OFF         |
|Milling             |OFF         |
|Response Zones      |OFF         |
|Seat Jumping        |OFF         |
|Specified Response  |ON          |
|Specified Resp. Time|        0.00|
|Stair Packing       |OFF         |
|Stair Edge Pref     |ON          |
|Smoke Redirection   |OFF         |
|Smoke Redir. Type   |Woods       |
|Smoke Gender Inf.   |ON          |
|Smoke Stagger       |OFF         |
|Smoke Viz. Coef.    |        2.00|
|Wall Proximity      |OFF         |
|Max Sim.            |OFF         |
|Max Sim. Time       |     3600.00|
|Competitive Evac.   |OFF         |
```

Figure 36. **Behavior Options Section in the *Simulation Output* File**



```
Transit Nodes performances :-
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Inter-Car Conx:  Inter-Car_Conx_2  MaxCapacity  1  Length 0.50 (m) Width 1.00 (m) Lanes  1
 Number Through:   84  First On:   3.82 (s) Last On: 100.80 (s) Avg PPM :  51.97 Flow Time:  96.98 (s)
End of Transit Nodes data
```

(a) *Inter-Car Conx* Performance Data



```
Transit Nodes performances :-
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
High Plat Exit:  High_Plat_Exit_1  MaxCapacity  2  Length 0.50 (m) Width 1.00 (m) Lanes  2
 Number Through:   84  First On:   7.70 (s) Last On: 104.49 (s) Avg PPM :  52.07 Flow Time:  96.79 (s)
End of Transit Nodes data
```

(b) *High Plat. Exit* Performance Data

Figure 37. *Transit Node* Performance in the *Simulation Output* File

5.6 Summary

The first phase in the development of the new software resulted in the Prototype Software V2.0. The software development included embedding egress data generated from the 2005 Volpe Center egress trials.

The Prototype Software V2.0 now has a capability to simulate non-competitive egress in the following egress scenarios:

- Exit to Adjacent car, using inter-car end-door exits,
    - *Normal lighting*, single-level cars
    - *Emergency lighting*, single-level cars, and
- Exit to High Platform, using one or two car side-door exits
    - *Normal lighting*, single-level car
    - *Emergency lighting*, single-level car.

However, to run the Prototype Software V2.0 under emergency lighting conditions with a high level of confidence, more data associated with exit flow rates are required.

In addition, the Prototype Software V2.0 has the capability to repeat the above model scenarios in a competitive emergency evacuation situation. However, to run these model scenarios with a high level of confidence will require the collection of an appropriate data set (e.g., to characterize exit flow rates under competitive situations).

The Prototype Software V2.0 also has the capability to mode the following scenarios:

- Egress from an upright multi-level passenger rail car (using building stairway data) during normal and emergency lighting conditions by:
    - Exit to Adjacent Car using inter-car end-doors
    - Exit to High Platform using one or two side-door exits; and
- Egress from an upright single-level or multi-level passenger rail car involving a fire within the car by:
    - Exit to Adjacent Car, using inter-car end-doors
    - Exit to High Platform, using one or two side-door exits.

  (Note: Fire data can be generated either using the CFAST zone or SMARTFIRE CFD fire models.)

6. Verification and Validation of Prototype railEXODUS Software V2.0

This chapter describes the verification and validation analysis of the Prototype Software V2.0 utilizing data derived from the 2005 Volpe Center egress experiment trials [4] and summarizes the simulation results. In order to verify and validate the Prototype Software V2.0, a total of six model scenarios, which corresponded to the six different non-competitive 2005 egress trials, were simulated:

- Scenario 1a: One Side-Door Exit to High Platform – normal lighting conditions (Trials 5 and 11);
- Scenario 2a: Two Side-Door Exits to High Platform – normal lighting conditions (Trials 4 and 10);
- Scenario 3a: Inter-car End-Door (connection) Exit to Adjacent Car – normal lighting conditions (Trials 2 and 8);
- Scenario 1b: One Side-Door Exit to High Platform – emergency lighting conditions (Trials 1 and 7);
- Scenario 2b: Two Side-Door Exits to High Platform – emergency lighting conditions (Trials 3 and 9); and
- Scenario 3b: Inter-car End-Door (connection) Exit to adjacent car – emergency lighting conditions (Trials 6 and 12).

In addition, to demonstrate the difference in predicted evacuation performance between competitive and non-competitive modes, two additional model scenarios under competitive behavior were simulated:

- Scenario 4a: One Side-Door Exit to High Platform—normal lighting conditions; and
- Scenario 4b: Inter-car End-Door (connection) Exit to Adjacent Car—normal lighting conditions.

As part of the validation and verification process, the numerical predictions for the following parameters are compared with the corresponding time from the Volpe Center egress trials:

- Time for the first person to exit the car;
- Time for the last person to exit the car (the total egress time);
- The exiting time history for each experimental egress trial (i.e., the exit time graph for the egress trial);
- Average exit flow rate achieved;
- Time to commence free walking for selected rows;
- Time for the last person to cross the car mid/quarter-point;
- Aisle densities; and
- Qualitative observations of general behavior.

6.1 *Geometry* Mode

The *Geometry* of the passenger rail cars including seating arrangements within the Prototype Software V2.0 was constructed from car drawings supplied by the Volpe Center [15]. The *Geometry* used to model each of the required scenarios is comprised of two connected passenger rail cars. Within each model scenario, only one rail car was initially populated, with the adjacent left car being unoccupied (see Figure 38).

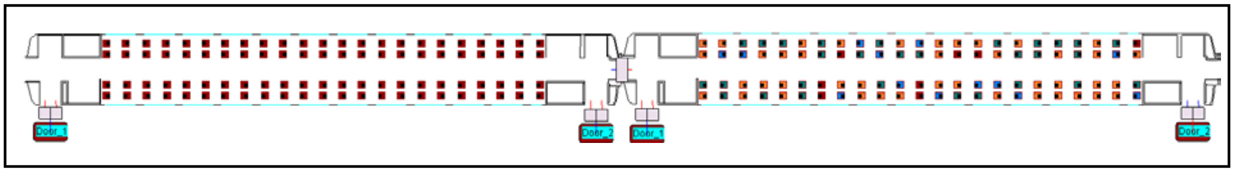


Figure 38. *Geometry* Layout Used in all Egress Simulations (Left Car is Unpopulated)

6.2 *Population* Mode

Within each of the model scenarios, the passenger rail car was populated with agents generated using the default Prototype Software V2.0 population panels. Each of the simulated scenarios involved 84 agents positioned according to the appropriate seating plan, as provided in the Volpe Center egress experiment report [4].

6.3 Software Set-up

For all of the simulation results shown, the Prototype Software V2.0 default settings are used unless otherwise stated. The model scenarios were all run using the non-competitive mode. In total, 10 simulations of each lighting condition were run, with the position of agents being swapped between runs. The swapping of agents in this manner ensured that the starting locations of the population remained fixed (i.e., the same seats were occupied within each of the simulations), while the agent at each location was liable to change. Each agent was also assumed to respond instantly to the call to exit (i.e., agents did not experience delays prior to commencing their exit).

For the Exit to Adjacent car using the inter-car end-door egress model scenarios, agents were required to move to the adjacent car from where they could exit to the high platform via another available side-door exit at the far end of the adjacent car. However, the agent's time was limited to being measured only until the point that he or she entered the adjacent car.

6.4 Simulation Results

This section summarizes the main results of the verification and validation analysis. Model predictions are compared with corresponding 2005 Volpe Center egress trial results (see Section 4.3). For each of the six egress scenarios, the software was set up to model the selected scenario and the software was run. Each simulated scenario was run a minimum of 10 times, randomizing the starting location of the population between each run. The results are provided for each significant parameter predicted by the software.

6.4.1 Time Prediction for First and Last Person to Exit Car – Normal Lighting

Table 13 shows the results for the time for the first and last person to exit the passenger rail car in normal lighting conditions, for the one side-door for Exit to High Platform scenario, measured in the egress experiment (Trials 5 and 11), and in the numerical predictions (Scenario 1a).

Table 13. First and Last Person Exit Times: One Side-Door Exit to High Platform – Normal Lighting

EGRESS TRIAL #	TIME OF FIRST PERSON OUT (s)	TIME OF LAST PERSON OUT (s)
5	4.73	102.7
11	5.00	99.0
Mean Experimental	4.87	100.9
Mean and Range Prototype Software V2.0	4.40 [3.98-4.68]	101.4 [100.8-102.0]

Table 14 shows the two side-door Exit to High Platform results, measured by FSEG for the Volpe Center egress experiment (Trials 4 and 10) and in the numerical predictions (Scenario 2a).

Table 14. First and Last Person Exit Times: Two Side-Door Exits to High Platform – Normal Lighting

EGRESS TRIAL #	FIRST PERSON OUT OF EXIT 1 (s)	LAST PERSON OUT OF EXIT 1 (s)	FIRST PERSON OUT OF EXIT 2 (s)	LAST PERSON OUT OF EXIT 2 (s)
4	5.1	48	5.4	52.7
10	6.5	54	6	53.5
Mean Experimental	5.8	51	5.7	53.1
Mean and Range Prototype Software V2.0	4.7 [4.1-5.5]	52 [51-52.2]	4.6 [4.1-5.2]	53.8 [53.3-54.2]

Table 13 and Table 14 show that the average predicted time for the first agent to exit the rail car was between 10 percent faster and 20 percent faster than the average measured in the various egress trials. The average predicted time for the last agent to exit the car was 1 to 2 percent slower than the average measured for the egress trials.

Table 15 shows the results for the times for the first and last person to exit the passenger rail car, in normal lighting conditions, using the inter-car end-door Exit to Adjacent Car scenario, measured in the experiment (Trials 2 and 8), and in the numerical predictions (Scenario 3a). Table 15 shows that the average predicted time for the first agent to exit the car was between 14 percent faster than the average measured in the egress trials. The average predicted time for the last agent to exit the car was 2 percent slower than the average measured in the egress trials.

Table 15. First and Last Exit Person Times: Exit to Adjacent Car – Normal Lighting

EGRESS TRIAL #	TIME OF FIRST PERSON OUT (s)	TIME OF LAST PERSON OUT (s)
2	5.6	99.8
8	5.3	100.4
Mean Experimental	5.5	100.1
Mean and Range Prototype Software V2.0	4.7 [4.36-5.1]	101.7 [101.1-102]

6.4.2 Exit Time Prediction for First and Last Person to Exit Car – Emergency Lighting

Table 16 shows the results for the times for the first and last person to exit the passenger rail car, in emergency lighting conditions, for the one side-door Exit to High Platform scenario, measured by FSEG for the experiment (Trials 1 and 7) and in the numerical predictions (Scenario 1b).

Table 16. First and Last Exit Person Times: One Side-Door Exit to High Platform – Emergency Lighting

EGRESS TRIAL #	TIME OF FIRST PERSON OUT (s)	TIME OF LAST PERSON OUT (s)
1	5.1	99.8
7	5.4	95.2
Mean Experimental	5.3	97.5
Mean and Range Prototype Software V2.0	4.6 [4.2-5.3]	101.6 [101.1-102.2]

Table 17 shows the results for the two side-door Exit to High Platform scenario in emergency conditions measured in the experiment (Trials 3 and 9) and in the numerical predictions (Scenario 2b).

Table 17. First and Last Person Exit Times: Two Side-Door Exits to High Platform – Emergency Lighting

EGRESS TRIAL #	FIRST PERSON OUT OF EXIT 1 (s)	LAST PERSON OUT OF EXIT 1 (s)	FIRST PERSON OUT OF EXIT 2 (s)	LAST PERSON OUT OF EXIT 2 (s)
3	4.6	46.8	6.6	62.6
9	5.1	53.8	5.8	52.2
Mean Experimental	4.8	50.3	6.1	57.4
Mean and Range Prototype Software V2.0	4.6 [4.4-4.8]	54.4 [53.4-56.5]	5 [4.56-5.7]	51.4 [50-53.2]

Table 16 and Table 17 show the average predicted time for the first agent to exit the car was between 5 percent and 18 percent faster than the average measured by FSEG for the various Volpe Center egress trials. The average predicted time for the last agent to exit the car was 8 percent slower to 11 percent faster than the average measured in the various 2005 egress trials.

Table 18 shows results for the time for the first and last person to exit the passenger rail car, in emergency lighting conditions, for the Inter-Car End-Door Exit scenarios, as measured by FSEG for the experiment (Trials 6 and 12), and for the numerical predictions (Scenario 3b).

Table 18. First and Last Person Exit Times: Exit to Adjacent Car – Emergency Lighting

EGRESS TRIAL #	TIME OF FIRST PERSON OUT (s)	TIME OF LAST PERSON OUT (s)
6	5.4	99.9
12	4.5	93.7
Mean Experimental	5	96.8
Mean and Range railEXODUS v2.0	5 [4.2–5.8]	102.3 [101.4–103.0]

Table 18 shows the average predicted time for the first agent for the Exit to the Adjacent Car was 3 percent slower than the average that measured for the egress trials. The average predicted time for the last agent to exit the car was 6 percent slower than the average measured in the egress trials.

These results demonstrate that the Prototype Software V2.0 is capable of predicting the time required for occupants of a fully-loaded passenger rail car for the Exit to a High Platform or Exit to Adjacent Car scenario, in normal or emergency lighting conditions, under non-competitive egress conditions, to within 11 percent of the exit times measured for the Volpe Center egress trials. The time for the first agent to exit is affected by the response time distribution used in the simulations. In the simulations, an instant response time was used, while in the egress trials participants had a small but non-zero response time. As a result, the predicted time for the first agent to exit is expected to be faster than the measured value.

6.4.3 Exit Time History Prediction – Normal Lighting

To enable a thorough understanding of the underlying processes that evolve during a model scenario, each of the three normal lighting egress scenarios (Scenarios 1a, 2a, and 3a) was examined in greater detail. This process involved selecting a single simulation from each scenario and studying it in detail in order to better appreciate the evacuation dynamics and the variation evident within each simulation run. The single simulation was selected that most closely approximated the mean overall exit time for each scenario in order to best represent the overall series of results produced.

For the selected simulation (for each scenario), an exit time curve is produced which shows the time for each agent to exit the passenger rail car. This curve is then compared with the experimental curves produced by the two repeat egress trials for each specific exit scenario. These two curves, derived from the Volpe Center egress trials, provide an indication of the spread in exiting times that may be expected in the experimental results. In addition, dotted lines representing ±10 percent variation in the experimentally derived maximum and minimum time required for any given number of individuals to exit are also plotted. These dotted curves provide an indication of the magnitude of deviation that the predicted exit curve is from the measured values.

Figure 39 shows the experimental time curves (Trials 5 and 11), the ±10 percent variation exit time curves, and the model exit time predictions (Scenario 1a) for the one-side door Exit to High Platform scenario in normal lighting conditions. The predicted exit history curves fall within the window generated by the experimental results and thus are well within the ±10 percent variation curves.

Figure 40 shows the experimental exit time curves (Trials 2 and 8), the ±10 percent variation curves, and the model predictions (Scenario 3a) for the end-door Exit to Adjacent Car scenario in normal lighting condition scenario. The predicted exit time history curves fall within the window generated by the experimental results and are thus well within the ±10 percent variation curves.

Figure 41 shows the experimental time curves (Trials 4 and 10), the ±10 percent variation curves and the model predictions (Scenario 2a) for the two-side door Exit to High Platform scenario in normal lighting conditions. The predicted exit time history curves fall within the window generated by the experimental results and thus are well within the ±10 percent variation curves.

These results validate that the Prototype Software V2.0 is capable of not only estimating the total egress time, but is also capable of representing the time for each agent to exit the rail car.

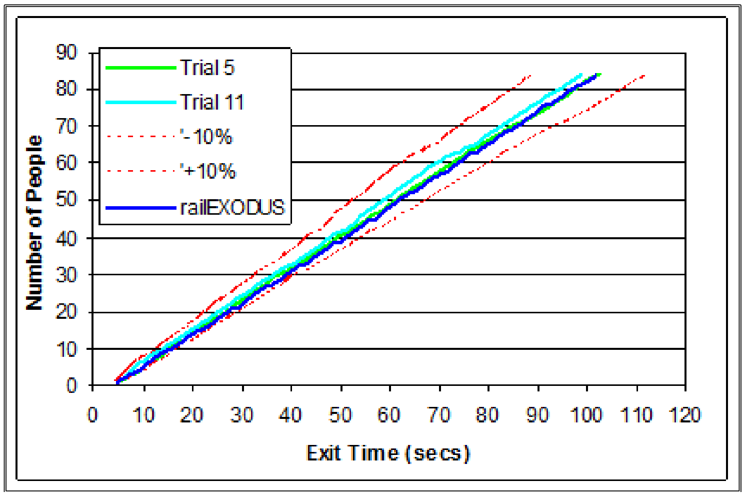


Figure 39. Exit Time Curves: One-Door Exit to High Platform – Normal Lighting

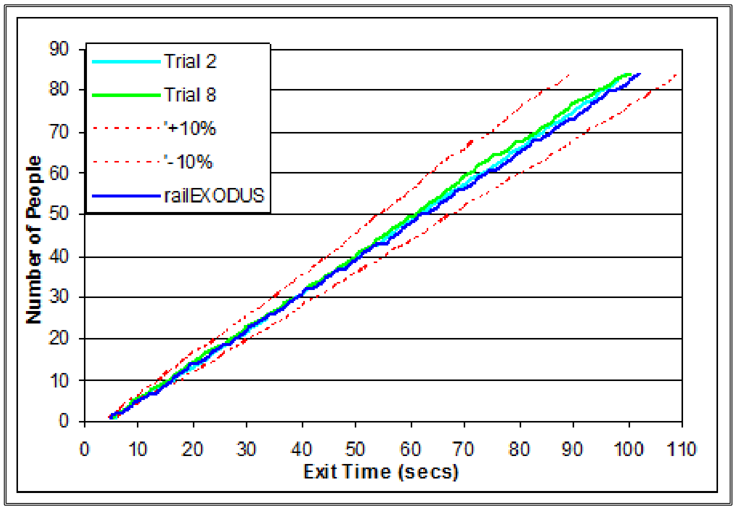


Figure 40. Exit Time Curves: Exit to Adjacent Car – Normal Lighting

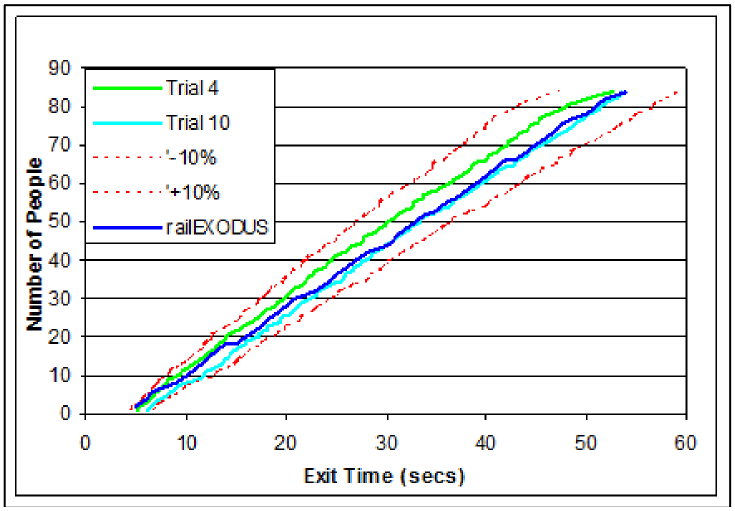


Figure 41. Exit Time Curves: Two-Door Exits to High Platform – Normal Lighting

Accordingly, these results show that the Prototype Software V2.0 is capable of representing the dynamics of non-competitive passenger rail car egress.

6.4.4 Average Exit Flow Rate Prediction

An analysis was conducted to identify and compare the following predicted average exit flow rates for the model scenarios and with the Volpe Center egress trials as measured by FSEG:

- ***Normal Lighting***
    - **Side-Door Exit to High Platform:** Predictions from Scenario 1a and 2a were compared with measured flow rates from Trials 4, 5, 10, and 11. The average predicted exit flow rate was within the range of average flow rates measured in the egress trials.
    - **Inter-Car End-Door Exit to Adjacent Car:** Predictions from Scenario 3a were compared with measured flow rates from Trials 2 and 8. The average predicted exit flow rate was within the range of average flow rates measured in the egress trials.
- ***Emergency Lighting***
    - **Side-Door Exit to High Platform:** Predictions from Scenario 1b and 2b were compared with measured flow rates from Trials 1, 3, 7, and 9. The average predicted exit flow rate was within the range of average flow rates measured in the egress trials.
    - **Inter-Car End-Door Exit to Adjacent Car:** Predictions from Scenario 3b were compared with measured flow rates from Trials 6 and 12. The average predicted exit flow rate was 1 percent less than the lower end of the maximum average flow rates measured in the egress trials. While just outside the range of measured values, the discrepancy is small and is within +/- 10 percent of the measured values.

These results verify that the Prototype Software V2.0 accurately represents the average exit flow rate at high platform side-door exits and inter-car end-door exit connections in normal and emergency lighting conditions.

6.4.5 Average Time Predictions to Commence Free Walking

An analysis was conducted of the time taken by individuals in specific seat rows to commence free walking (i.e., to be able to walk freely without being hindered by individuals directly in front of them). Five separate rows were analyzed: Rows 2, 6, 12, 17, and 22. The analysis considered whether the agent was seated next to the aisle, or seated by the window. In each case, the results from the Prototype Software V2.0 were determined (where available) for agents initially seated on both the platform side of the aisle and the wall side of the aisle. These results were then compared with the times obtained from analysis of the corresponding 2005 Volpe Center egress trial videos (see Section 4.3). The predicted results are:

- ***Normal Lighting***
    - **Side-Door Exit to High Platform:** Predicted exit times for Scenario 1a and 2a were compared with measured exit times from Trials 4, 5, 10, and 11. The average predicted time to commence free walking in the aisle, excluding those

agents/participants in the exit rows, was within 21 percent of the measured values in the egress trials.

  - **Inter-Car End-Door Exit to Adjacent Car:** Predicted exit times for Scenario 3a were compared with measured times from Trials 2 and 8. The average time predicted to commence free walking in the aisle, excluding those agents/participants in the exit rows, was within 14 percent of the measured values in the egress trials.

- ***Emergency Lighting***

  - **Side-Door Exit to High Platform:** Predicted exit times for Scenario 1b and 2b were compared with measured times from Trials 1, 3, 7, and 9. The average predicted time to commence free walking in the aisle, excluding those agents/participants in the exit rows, was within 19 percent of the measured values in the egress trials.
  - **Inter-Car End-Door Exit to Adjacent Car**: Predicted exit times for Scenario 3b were compared with measured times from Trials 6 and 12. The average predicted time to commence free walking in the aisle, excluding those agents/participants in the exit rows, was within 7 percent of the measured values in the egress trials.

These results demonstrate that the Prototype Software V2.0 is capable of reasonably predicting the time to commence free walking in non-competitive passenger rail car egress scenarios. Furthermore, the trends in the Volpe Center experimental results in which the longest times to commence free walking are located furthest away from a working exit are also reproduced by the simulations. These results further validate that the detailed dynamics represented within the simulations accurately represent those found within the experimental results.

6.4.6 Average Time Prediction for Last Agent to Cross Mid-Point En Route to Exit

An analysis was performed of the time required for the last agent to travel past the mid-point in the rail car *en route* to an exit. For egress cases involving a single exit (one side-door to Exit to High Platform or inter-car end-door to Exit to Adjacent Car), this location was in the middle of the car. For cases involving two exits (two side-doors to Exit to High Platform, the mid-point was located a quarter of the way along the car from each exit. The predicted results were selected from the simulation which produced a total time closest to the mean of the predicted values:

- ***Normal Lighting***

  - **Side-Door Exit to High Platform**: Predicted times from Scenario 1a and 2a were compared with measured times from Trials 4, 5, 10, and 11. The average predicted time for the last agent to cross the mid-point *en route* to exit was 2 to 4 percent faster than the average measured in the various egress trials.
  - **Inter-Car End-Door Exit to Adjacent Car:** Predicted times from Scenario 3a were compared with measured times from Trials 2 and 8. The average predicted time for the last agent to cross the mid-point *en route* to exit was 4 percent slower than the average measured in the egress trials.

- ***Emergency Lighting***
  - **Side-Door Exit to High Platform:** Predicted exit times from Scenario 1b and 2b were compared with measured times from Trials 1, 3, 7, and 9. The average predicted time for the last agent to cross the mid-point *en route* to exit was 9 percent slower to
    11 percent faster than the average measured in the various egress trials.
  - **Inter-Car End-Door Exit to Adjacent Car:** Predicted exit times from Scenario 3b were compared with measured times from Trials 6 and 12. The average predicted time for the last agent to cross the mid-point *en route* to the exit was 2 percent faster than the average measured in the egress trials.

These results demonstrate that the Prototype Software V2.0 is capable of estimating the total egress time and also other key times (i.e., time to reach the mid-point and time to commence free walking). The results further validate that the overall dynamics for non-competitive egress is realistically represented within the software.

6.4.7 Qualitative Behaviors

An analysis was also completed to compare the observed behaviors of the agents within the representative Prototype Software V2.0 simulation with those observed in the Volpe Center egress trials. Figure 42 shows the population within the passenger rail car (as displayed within vrEXODUS) at various times throughout the egress process. Figure 42a shows the population approximately 3 s into the simulation. The entire length of the aisle is densely populated. Agents can also be observed standing within seat rows throughout the passenger rail car, both in the rows furthest from the one available exit door and also those rows closest to it. Since the egress has only just started at this time, none of the agents within the seating area have yet commenced free walking.

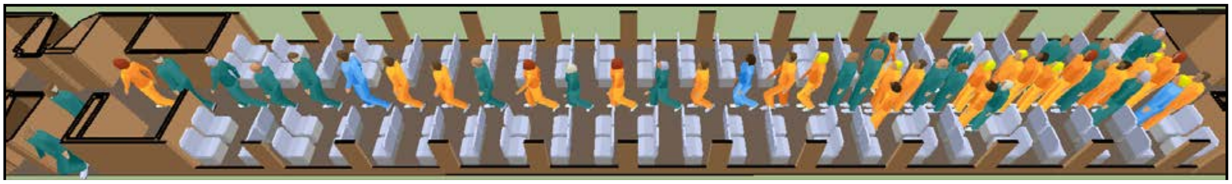
Figure 42b shows the population approximately 13 s into the simulation. Some agents closest to the side-door exit are starting to free walk. This area of free walking extends back down the aisle as far as Row 3, with the agents in this region typically spaced approximately 3.3 ft (1 m) apart and not densely packed together, as is evident within the remainder of the car. Figure 42b also shows the absence of agents standing within seat Rows 1–3. Although agents were standing within these seat rows earlier in the simulation (see Figure 42a), the spacing of the agents within the free walking region enabled these agents to gain entry into the aisle. However, agents can still be observed standing in seat rows further down the aisle where, in contrast, the continuing high densities have prevented them from entering the aisle.

Figure 42c shows the population approximately 47 s into the simulation, at which point it can be seen that the free walking region (comprising agents spaced 3.3 ft (1 m) apart) has extended past the mid-point of the car down to Row 16, with no agents observed standing in the seats up to this row. Agents can still be observed standing in seat rows further down the aisle, a direct consequence of the continuing high aisle densities within this region of the rail car.

Figure 42d shows the population at 57 s into the simulation. The free walking region can be seen to have extended almost to the rear of the rail car.


(a) 3 seconds


(b) 13 seconds


(c) 47 seconds

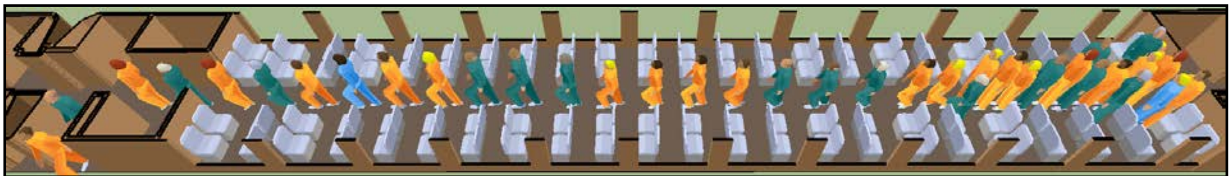

(d) 57 seconds

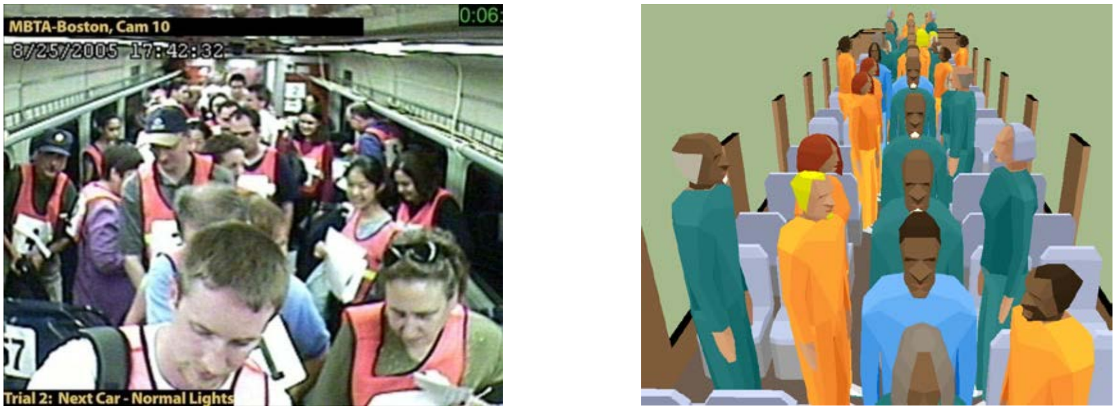
Figure 42. vrEXODUS Depiction of Agent Behaviors: One Side-Door Exit to High Platform – Normal Lighting

The agent behaviors observed in the simulation of the one side-door exit to the high platform in normal lighting scenario closely match the observed behaviors within the corresponding egress trial video (i.e., Trials 5 and 11). The spacing between free walking agents and the manner in which the free walking region eventually moves down the rail car with time were clearly observed in the video for all the egress trials. In addition, the behavior noted in the video, where participants standing between the seat rows gained entry to the aisle as the free walking region extended to their location, was also reproduced in the simulations.

These results demonstrate that the Prototype Software V2.0 can produce a realistic representation of the dynamics in non-competitive passenger rail car egress scenarios.

6.4.8 Average Aisle Densities

An attempt was made to compare predicted aisle densities with those measured in the egress trials. Figure 43 shows an initial direct comparison between predicted and measured congestion levels within the rail car for Trial 2 (Exit to Adjacent Car in normal lighting conditions). Trial 2 was selected for the analysis since it provided an ideal scenario to gauge crowd densities as they build from the center of the rail car towards the rear. This situation occurs after approximately



(a) Trial 2 (b) vrEXODUS

Figure 43. Congestion Evident towards Rear of Passenger Rail Car after 6 Seconds – Exit to Adjacent Car

6 s. Also evident is the large number of participants standing within the seat rows attempting to enter the aisle. In Figure 43b, vrEXODUS shows a similar situation occurs at approximately the same time. Although the exact positions of individual persons may vary, the overall predicted aisle density and queuing within seat rows closely match what was observed in the egress trials.

A more detailed analysis was completed in which the density within the rail car aisle was approximated using various video images from the same point in time. The measured densities varied from 0.28 persons/ft^2 (3 persons/m^2) to 0.40 persons/ft^2 (4.3 persons/m^2) while the predicted densities varied from 0.32 persons/ft^2 (3.4 persons/m^2) to 0.42 persons/ft^2 (4.5 persons/m^2). The minimum density was over-predicted by 14 percent while the maximum density was over-predicted by 8 percent. The average measured density throughout the aisle was 0.33 persons/ft^2 (3.5 persons/m^2) while the predicted average aisle density was 0.37 persons/ft^2 (4 persons/m^2). The average aisle density was over predicted by 12 percent.

It is noted that while measuring the number of persons within a given space is straightforward with the Prototype Software V2.0, estimating the number of persons from the Volpe Center egress trial video data is difficult and subject to error. Using video data to determine when a participant is partially within the rail car aisle is difficult because of camera angles and thus is subject to interpretation. As a result, the estimated numbers of participants derived from the Volpe Center egress trial video data, especially in high-density regions, are approximate.

Overall, these results suggest that the Prototype Software V2.0 is capable of producing a realistic representation of the crowd densities that develop during non-competitive egress.

6.4.9 Competitive and Non-Competitive Behaviors

Two additional model scenarios (Scenarios 4a and 4b) were run in the model using the Prototype Software V2.0 and investigated to highlight the differences resulting from the simulation of competitive and non-competitive exiting. These differences related both to the behavior of agents during their exiting and to the overall egress performance. In each case, the results from the competitive egress model scenarios were directly compared with the corresponding non-competitive results (Scenarios 1a and 3a).

It is noted that since no data are currently available to cap the maximum flow rates of passenger rail car exits in competitive situations, the maximum flow rates for the exits are set by default to the same values measured within the egress trials (i.e., non-competitive scenario). Therefore, the maximum flow rate through the *High Plat. Exit* transit node in normal lighting is set to vary between 49.2 and 53.5 ppm (0.82 and 0.89 pps) per lane while the maximum flow rate through the *Inter-Car Conx* transit node in normal lighting is set to vary between 51.5and 53 ppm (0.86 and 0.88 pps) per lane.

Therefore, the flow rate restriction per lane through the *High Plat. Exit* and the *Inter-Car Conx* transit nodes are the same within both the competitive and non-competitive model scenarios. This is unlikely to be the case in actual competitive egress situations, particularly for the *High Plat. Exit* (as the maximum flow rate in the competitive case is doubled due to two exit lanes being available). Therefore, the quantitative results for the competitive case should not be considered reliable. Of more relevance to this analysis are the qualitative differences that result from the different behaviors implemented in the competitive and non-competitive model scenarios.

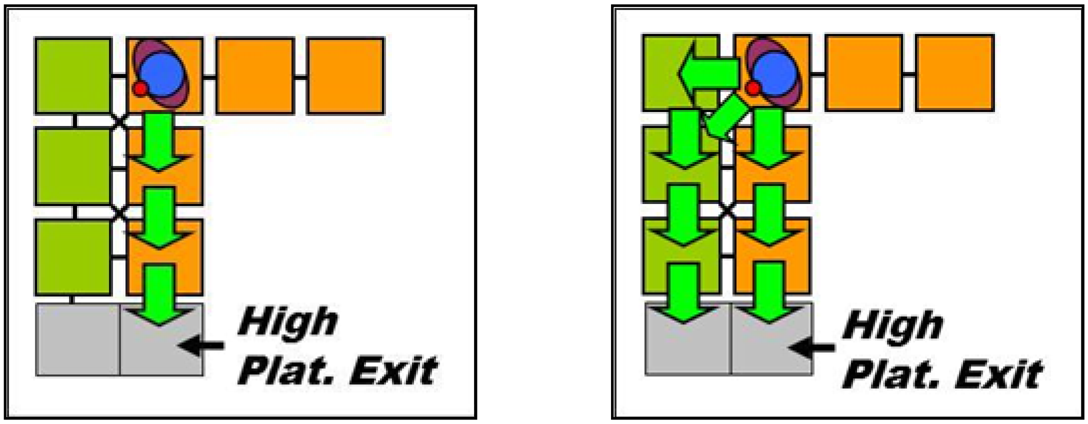
6.4.9.1 *Exit to High Platform Scenario: Competitive and Non-Competitive Behaviors*

For the One Side-Door Exit to High Platform model scenarios (Scenario 1a, non-competitive, and Scenario 4a, competitive), agents were required to move to the high platform via a single available side-door exit. The setup of the software for the competitive scenario was identical to that for the non-competitive scenario, with the exception that the competitive behaviors were activated.

Within the competitive model scenarios, agents were not restricted to non-competitive routes. Agents were therefore free to exit using any type of available node (i.e., *Free Space*). Since the agents were not forced to maintain a single file, they were free to attempt to overtake one another. In the vestibule area, the agents were free to form two lanes, as they approached the *High Plat. Exit* (see Figure 44).

In addition, agents were free to use the entire width of the *High Plat. Exit*, allowing two agents to travel through the exit onto the platform at the same time. However, it is noted that the flow rate restriction per lane for the *High Plat. Exit* transit node used in the competitive scenario was identical to that used in the non-competitive scenario because data are not available to specify the maximum flow under competitive conditions which may be less than the flow for non-competitive conditions.

In comparing the results for the competitive case (Scenario 4a) with the results of the non-competitive case (Scenario 1a), a difference in the time prediction for the last agent to exit the car was noted. In the non-competitive model scenario, the average total exit time was 101.4 s, while in the competitive model scenario the average exit time was 72.3 s, about 29 percent faster. It is also noted that a wide range existed in the total exit time for the competitive model scenario, varying between 67.6 and 82.3 s, corresponding to a range of 14.7 s, while for the non-competitive model scenario, the variation was only 1.2 s. Furthermore, it is noted that the average exit flow rate in the competitive model scenario was 74.7 ppm (1.2 pps), about 44 percent greater than the average flow rate in the non-competitive model scenario (52 ppm or 0.87 pps).



(a) Non-competitive (b) Competitive

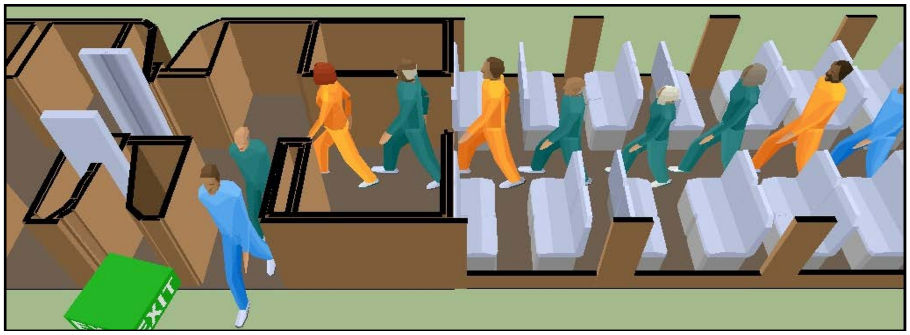
Figure 44. Potential Available Exit Routes by Agents within a Vestibule Exit

As the number of lanes to the passenger rail car exit was doubled and the effective maximum flow through the exit doubled (the number of lanes through the exit doubled, while maintaining the same maximum flow rate per lane), it may have been expected that the total egress time would be half and the average effective flow rate would double. The reason for this discrepancy is complex and is a result of the effective flow rate of the single aisle feeding into the vestibule area and the nature of the conflicts occurring throughout the rail car due to the competitive nature of the behavior.

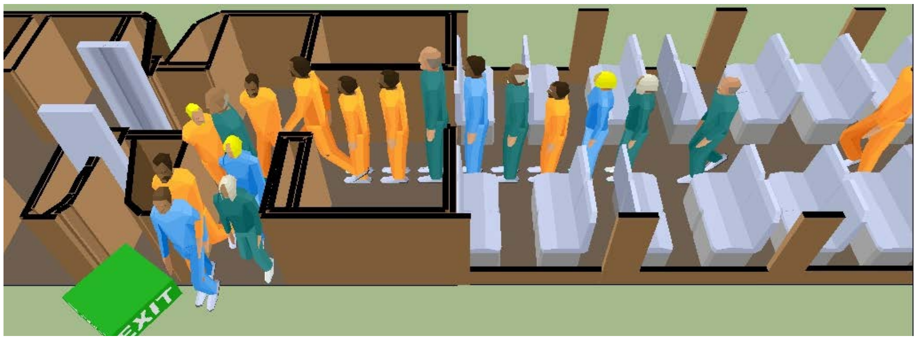
In the confined space of the passenger rail car, a greater number of space conflicts will occur in the competitive model scenario since agents competing for space may be expected to hinder progress. This is represented in the model with the conflict resolution algorithm, which awards a time penalty to agents who compete for space. A time penalty is added to the travel time of both the loser and the winner of the conflict. In the competitive model scenario, a greater number of conflicts occur throughout the car, not only as agents attempt to overtake each other (particularly in the vestibule area), but also as they attempt to enter the aisle from the seats. This will have a negative impact on the overall egress performance. The range of conflict times used in competitive cases is greater than that used in non-competitive model scenarios (see Section 5.5.1). Therefore, the time delays incurred in conflicts for the competitive case will be greater than those in the non-competitive case. The greater number of conflicts occurring throughout the rail car and the greater time delays incurred in each instance will tend to slow down the overall egress in the competitive case. However, of greater importance is that in the competitive model scenario, the single main aisle cannot supply sufficient agents to the two-lane exit door to keep the door "working" at full capacity. For both of these reasons, the door in the competitive model scenario does not achieve twice the flow rate of the door in the non-competitive case.

However, the improvement in performance provided by allowing the use of two lanes in the rail car vestibule area and through the exit greatly outweighs the negative performance aspects resulting from increased conflicts and flow limitations of the single aisle. This use of two lanes results in the competitive model scenario achieving better egress performance than the non-competitive model scenario. It should be noted that the flow rate restriction per lane through the exits in the competitive case is set to the same value as in the non-competitive case. It is unlikely that the flow rate value in the competitive case will be as high as the flow rate in the non-competitive case. Therefore, the high flow rate may contribute to the better performance observed in the competitive scenario than could be the case in reality.

Figure 45 shows scenes from the non-competitive (see Figure 45a, Scenario 1a) and competitive (see Figure 45b, Scenario 4a) high platform egress scenarios, 32 s into the simulation.



(a) Non-competitive (Scenario 1a)



(b) Competitive (Scenario 4a)

Figure 45. Exit to High Platform Scenarios: Congestion within Aisle and around the Side-Door Exit after 32 Seconds

Within the non-competitive model scenario (see Figure 45a), agents can exit in an orderly single file, with no overtaking within either the main aisle or vestibule of the rail car. This orderly single file can also be observed through the one side-door Exit to High Platform scenario. It can also be observed that agents always maintain a space between themselves and the agent in front when free walking. As a result of these behaviors, there is no significant congestion within the vestibule itself throughout the entire simulation, and the number of space conflicts is relatively small. The lack of congestion within the vestibule in the non-competitive model scenario is in stark contrast to the congestion observed within the competitive model scenario (see Figure 45b).

As a result of agents not being restricted to simply move on the rail car aisle nodes, significant congestion developed around the one side-door exit to the high platform. Also evident was the formation of two exit lanes. Agents were tending to bunch up within the aisle and vestibule. This behavior resulted from the agents not maintaining a space between themselves and the agents ahead of them as they attempted to overtake the other agents.

6.4.9.2 *Inter-Car End-Door Exit to Adjacent Car Scenarios: Competitive and Non-Competitive Behaviors*

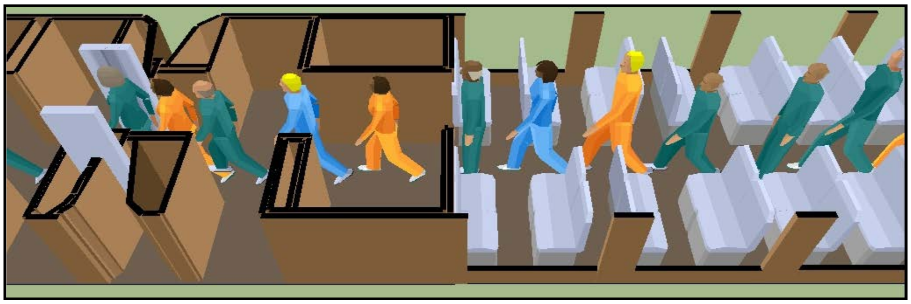
For the inter-car end-door Exit to Adjacent Car model scenarios (Scenario 3a, non-competitive, and Scenario 4b, competitive), agents were required to move to the adjacent car; they could exit to the platform from that car by using an available end-door at the far end of the passenger rail car. However, the end-point of the model scenario was the point they entered the adjacent car. The set-up of the software for the competitive scenario was identical to that for the non-competitive scenario, with the exception that the competitive behaviors were activated.

In comparing the results for the competitive case (Scenario 4b) with the results for the non-competitive case (Scenario 3a), a small difference in the time prediction for the last agent to exit the car was noted. In the non-competitive model scenario, the average total exit time was 101.7 s, while in the competitive model scenario, the average exit time was 106.7 s, 5 percent longer. Furthermore, it is noted that the average exit flow rate in the competitive egress model scenario was 49.8 ppm (0.83 pps), 4 percent less than the average flow rate in the non-competitive model scenario (52 ppm (0.87 pps)).

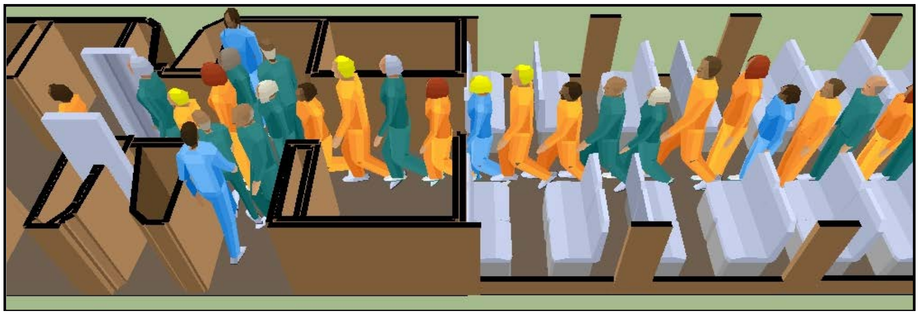
This difference in performance between the competitive and non-competitive model scenarios is due to the increased number of space conflicts which occur in the competitive model scenario. Unlike the case with the one side-door Exit to High Platform scenario, there are no compensating factors (e.g., two lanes in vestibule and two lane exit) to counteract this degradation in performance. Therefore, the overall result is that the exiting time performance decreases (i.e., occupants take a longer time to exit the car) in the competitive model scenario.

Figure 46 shows the conditions in the passenger rail car 54 s into the exiting time for both the non-competitive (see Figure 46a, Scenario 3a) and competitive scenarios (see Figure 46b, Scenario 4b).

Within the non-competitive scenario (see Figure 46a), agents exited the rail car in an orderly single file, with no attempted overtaking, and agents maintained a space between themselves and the agent ahead of them while free walking. As a result, significant congestion did not occur and the number of resulting space conflicts was relatively low. In the competitive model scenario (see Figure 46b) significant congestion developed around the entrance to the inter-car end-door exit region. Agents within the aisle and vestibule bunched up as they attempted to overtake and, as a result, the number of space conflicts was relatively high.



(a) Non-Competitive (Scenario 3a)



(b) Competitive (Scenario 4b)

Figure 46. Congestion within Aisle and around Entrance to Inter-Car Region in Exit to Adjacent Car Scenarios

6.5 Summary

The results from the validation and verification simulations show that the Prototype Software V2.0 is capable of realistically representing the dynamics of non-competitive passenger rail car egress involving use of side-door exit(s) to a high platform location and use of an inter-car end door to exit to an adjacent car, in normal and emergency lighting conditions. In addition, a capability to simulate competitive egress scenarios has been demonstrated.

The conduct of additional passenger rail car egress trials would allow exit flow rates to be obtained under competitive conditions. This data would make the Prototype Software V2.0 predictions under competitive conditions more reliable.

7. Prototype railEXODUS Software V2.1 Development

The first phase in the development of the new Prototype Software incorporated data and appropriate agent behaviors derived from the 2005 Volpe Center passenger car egress experiments, which involved occupants using end-door exits to move to an adjacent car and using side-door exits to move onto high platform locations, in both normal and emergency lighting conditions. This resulted in the Prototype Software V2.0 (see Chapter 5).

The second development phase involved extending the capabilities of the Prototype Software V2.0 by incorporating data and appropriate behaviors derived from the 2006 Volpe Center passenger car egress experiments (see Section 4.4) for occupants using side-door exits for egress to low platform and R-O-W locations. This chapter describes this further software development.

As with the Phase 1 development, the EXODUS software modifications are complex since changes to one of the sub-models has an impact on the other sub-models. To make the modifications easier to follow, the changes to the software are described in terms of how the User would encounter these changes in using the model (i.e., by describing the changes to three of the core modes of software operations: *Geometry* mode, *Scenario* mode, and *Simulation* mode). (Note: no changes were required to the *Population* mode.)

7.1 *Geometry* Mode Development

Several new objects have been developed within the Prototype Software V2.1 to enable the representation of movement of occupants exiting from a rail car to low platform and R-O-W locations. The software modifications implemented in *Geometry* mode are:

- ***Low Plat. Exit* transit node.** New feature intended to represent the passenger rail car side-door exit and stairway leading to a low platform. Associated with this new node type are travel speed distributions for normal lighting conditions under non-competitive egress scenarios.
- ***R-O-W Exit* transit node.** New feature intended to represent the passenger rail car side-door exit and stairway leading to the R-O-W. Associated with this new node type are travel speed distributions for normal lighting conditions under non-competitive egress situations.

7.1.1 Exit to Low Platform

Within the Prototype Software V2.1, the side-door Exit to Low Platform scenario is represented using a new *Transit Node* type called *Low Plat. Exit.* This new transit node ensures that the agent travels a distance equivalent to that of descending the stairway steps out onto the low platform. The maximum number of agents that the exit can accommodate at any one time is set to a predefined maximum and the travel speed (m/s) of each agent passing through the exit and descending the stairway is generated according to a probability distribution. These performance characteristics for the exit are set based on data derived from the Volpe Center egress trials (see Section 4.4).

The *Low Plat. Exit* transit node has parameters representing its corresponding *Width* (which does impact the performance), the number of *Lane*s, the *Capacity* of the connection, the *Flow Direction*, and *Height* and *Width*; and a probability distribution describing the range of travel speeds that can be achieved through the passenger rail car exit. The nature of each parameter is briefly described below.

LANES: This parameter is defined in the same way as for the *High Plat. Exit* defined in Section 5.2.2. However, the default setting is one lane.

FLOW DIRECTION: This parameter is defined in the same way as for the *High Plat. Exit* defined in Section 5.2.2.

WIDTH: This parameter is defined in the same way as for the *High Plat. Exit* defined in Section 5.2.2.

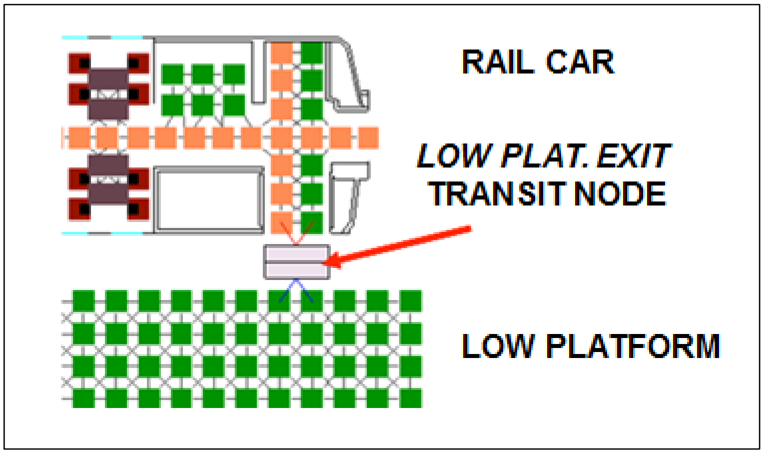
CAPACITY: The *Capacity* of the *Low Plat. Exit* transit node parameter defines the total number of agents who can simultaneously occupy the low platform exit. It is important to note that the *Capacity* does not relate to the capacity within a single lane, but instead within the transit node as a whole. Using this parameter it is possible to specify the number of agents simultaneously capable of occupying each lane. The *Capacity* defaults to two since it was observed during the 2006 Volpe Center egress trials (see Section 4.4) that there were frequently two participants on the exit stairway at the one time.

HEIGHT: This parameter defines the vertical distance through which the agent is required to descend. The default value for this parameter is 48 in (1.22 m), which is the total vertical distance measured in the 2006 Volpe Center egress trials (see Section 4.4). This distance comprises a 33 in (84 cm) descent down the passenger rail car side-door stairway and an additional 15 in (38 cm) from the bottom of the stairway to the low platform itself.

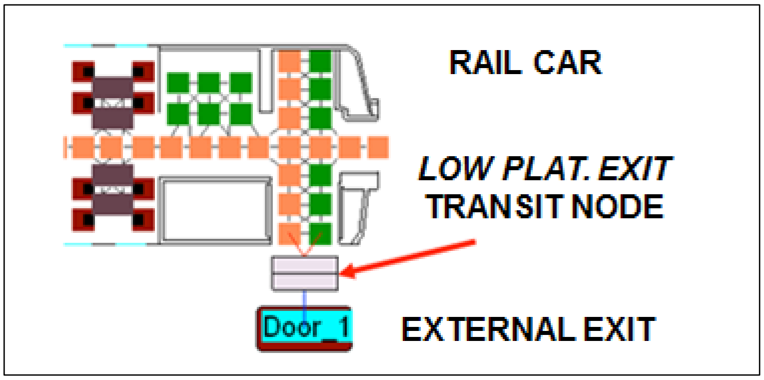
Having defined the physical characteristics of the *Low Plat. Exit* transit node, the User is required to connect it via arcs in the same manner as conventional EXODUS nodes. As with the *High Plat. Exit* transit node (see Section 5.2.2), the *Low Plat. Exit* transit nodes are connected (via *Arcs*) to the conventional nodes from which agents would be able to directly access the transit node (see Figure 47a).

In addition to connecting conventional node types to *Low Plat. Exit* transit nodes, the User also have the ability to connect external exit nodes (see Figure 47b). In these cases, agents moving through the *Low Plat. Exit* transit node to the external exit will be assumed to have exited the simulation, and therefore will no longer be modeled within the simulation. This type of connection is typically used when the User wishes to model the exit of agents to a low platform, but do not wish to explicitly model them onto the platform itself.

In order to determine an egress time for each agent, it was necessary to specify the traversal time for the agent to travel through the *Low Plat. Exit* to the low platform by using the 2006 Volpe Center egress trial data (see Section 4.4). A probability distribution of traversal times was generated from the Volpe Center data which represents the traversal times for the participants for the vertical drop to the low platform (including the top of the stairway and the distance from the bottom of the stairway to the low platform) that was used in the egress trials (4 ft (1.2 m)).



(a) *Low Plat. Exit* Connected to Conventional Nodes



(b) *Low Plat. Exit* Connected Directly to an External Exit

Figure 47. Creating a *Low Plat. Exit* Component within Prototype Software V2.1

In order to accommodate different height drops from the passenger rail car to the low platform, the traversal time distribution was converted to a distribution of vertical velocities (by dividing the travel distance by the travel time), producing the travel speed probability distribution shown in Figure 48. This travel speed distribution was incorporated into the *Low Plat. Exit* transit node as the default values for the non-competitive normal lighting condition. Since no data were available for the Exit to Low Platform during emergency lighting condition scenario, the travel speeds through the transit node in these conditions were by default set to 999 m/s, thereby indicating that they are undefined.

The time for an agent to traverse the *Low Plat. Exit* and reach the low platform is determined as the sum of two quantities:

- The time to traverse the *Low Plat. Exit* transit node is based both on the distance to be traveled (i.e., the *Height*) and the travel speed of the agent, as derived from the travel speed probability distribution.
- The time to travel the arcs to and from the *Transit Node*. These times are based on both the distance traveled (i.e., the length of the arc) and the corresponding personal travel speed of the agent (i.e., not the travel speed derived from the transit node travel speed distribution).

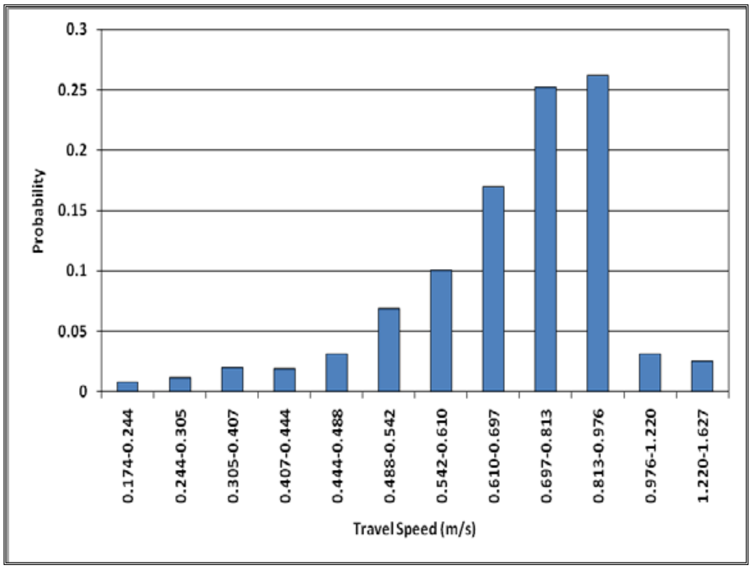


Figure 48. Probability Graph of the Default Travel Speed Distribution for *Low Plat. Exit* Transit Nodes

To accommodate potential differences between the conditions present in the Volpe Center egress trials and real emergency situations, the model was further extended to enable additional travel speed distributions to be defined for each lighting condition in competitive scenarios. Within the model, the competitive nature of the scenario being modeled (i.e., competitive or non-competitive) is defined by the *Competitive Evacuation* behavioral switch (see Section 5.5.2). As a result, four separate travel speed distributions can be defined for *Low Plat. Exit* transit nodes:

- Non-Competitive behavior
  - *Normal* lighting
  - *Emergency* lighting, and
- Competitive behavior
  - *Normal* lighting
  - *Emergency* lighting.

The measured travel speeds during the non-competitive egress trials were also assumed as the default values for the competitive travel speeds. Therefore, the default competitive and non-competitive travel speeds in normal lighting were both assumed to range between 0.57 ft/s (0.17 m/s) and 5.3 ft/s (1.6 m/s). Similarly, since no data relating to competitive and non-competitive travel speeds in emergency lighting were currently available, the travel speeds through the transit node in these conditions was once again by default set to 999 m/s, thus indicating that they are undefined. The User is not permitted to run emergency lighting simulations with the warning value of 999 m/s and is requested to manually define values for the transit node before continuing with the simulation. It is noted that when experimental emergency lighting and competitive values become available, they can be easily incorporated into the software.

7.1.2 Exit to R-O-W

Within the Prototype Software V2.1, the Exit to the R-O-W scenario using a side door is represented using a new *Transit Node* type called *R-O-W Exit.* This new transit node ensures that the agent travels a distance equivalent to that of descending the steps out onto the R-O-W. The maximum number of agents that the exit can accommodate at any one time is set to a predefined maximum and the travel speed (m/s) of each agent passing through the exit and descending the stairway is generated according to a probability distribution. Where appropriate, these performance characteristics for the exit are set based on data derived from the Volpe Center egress trials (see Section 4.4).

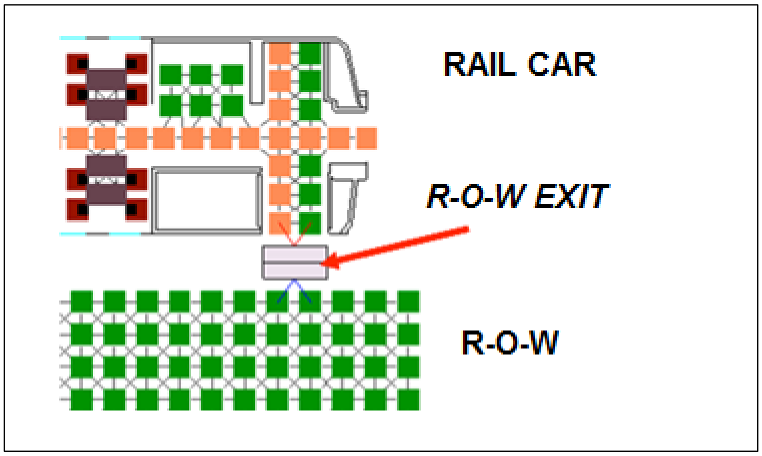
As with the *Low Plat. Exit*, the *R-O-W Exit* transit node has parameters representing its corresponding *Width* (which does impact the performance), the number of *Lanes*, the *Capacity* of the connection, the *Flow Direction*, and *Height* and *Width;* and a probability distribution describing the range of travel speeds that can be achieved through the exit. With the exception of the *Height* parameter, all these parameters are defined in the same way and have the same default values as the *Low Plat. Exit* transit node (see Section 7.1.1).

The only difference in the *Height* parameter between the *Low Plat. Exit* and the *R-O-W Exit* transit nodes is the default value assigned to this parameter. For the *R-O-W Exit*, the default value for this parameter is 58 in (1.5 m), which is the total vertical distance measured in the Volpe Center egress trials (see Section 4.4). This distance comprises a 33-inch (84-centimeter) descent down the passenger rail car stairway, and an additional 25 in (64 cm) from the bottom of the stairway to the R-O-W itself. It is noted that within the egress trials, participants were not required to descend the additional 25 in (64 cm) from the bottom of the stairway to the R-O-W in a single movement due to safety considerations. As a result, participants instead traversed this vertical drop by first descending 15.7 in (41 cm) to a step box that was provided, before then stepping off the box onto the ground, and thus descending the remaining 9.4 in (24 cm) (see Section 4.4).

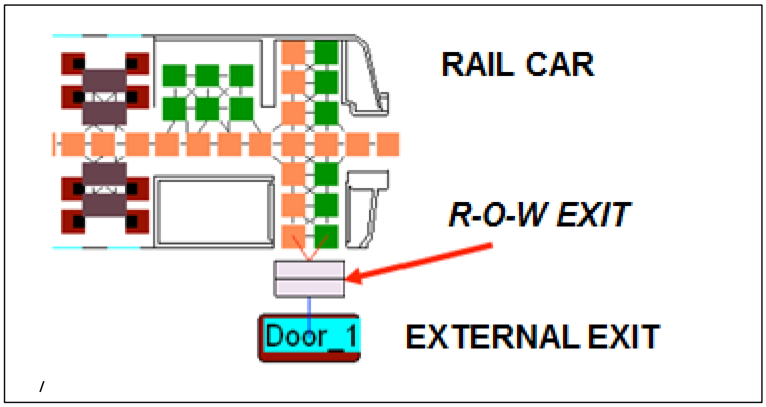
The *R-O-W Exit* transit node is connected to the nodes representing the R-O-W in the same way as the *Low Plat. Exit* was connected to the low platform (see Figure 49a). In addition to connecting conventional node types to *R-O-W Exit* transit nodes (see Figure 49a), the User also has the ability to connect external exit nodes (see Figure 49b). In these cases, agents moving through the transit node to the external exit will be assumed to have exited the simulation, and therefore will no longer be modeled within the simulation. This type of connection is typically used when the User wishes to model the exit of agents to the R-O-W, but do not wish to explicitly model them onto the R-O-W itself.

Finally, the exit traversal time for the agent to travel through the *R-O-W Exit* down to the R-O-W is determined in the same manner as for the *Low Plat. Exit*. The exit traversal time probability distribution for the *R-O-W Exit*, derived from the Volpe Center egress trial data, is converted to a travel speed probability distribution, as shown in Figure 50.

Travel speeds varied between 0.36 and 4.9 ft/s (0.11 and 1.5 m/s). The most common travel speeds are in the range 1.2 – 1.6 ft/s (0.37 – 0.50 m/s), while the least common travel speeds are in the range of 0.36 – 0.62 ft/s (0.11 – 0.19 m/s). After the height of the vertical drop is specified, the travel speed distribution can be used to determine the time required for an agent to



(a) *R-O-W Exit* Connected to Conventional Nodes



(b) *R-O-W Exit* Connected Directly to an External Exit

Figure 49. Creating a *R-O-W Exit* Component within Prototype Software V2.1

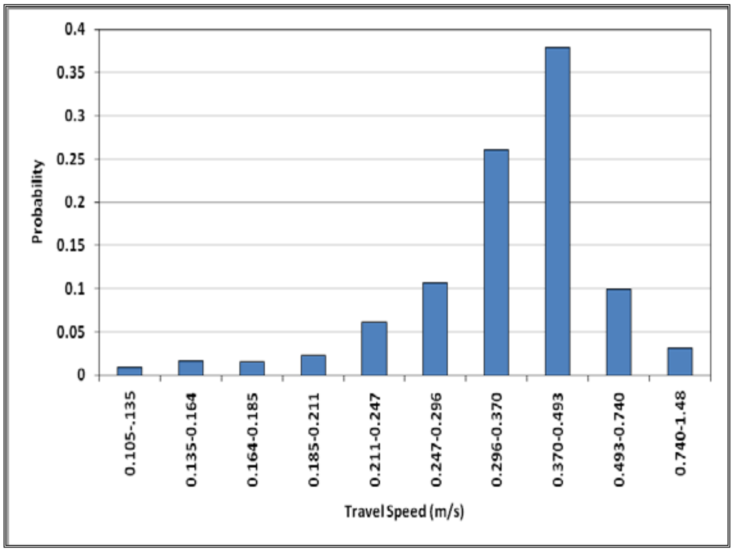


Figure 50. Probability Graph of the Default Travel Speed Distribution for *R-O-W Exit* Transit Nodes

traverse the *R-O-W Exit* transit node. This travel speed distribution was incorporated into the *R-O-W Exit* transit node as the default values for the non-competitive normal lighting condition.

Travel speeds have been incorporated in the Prototype Software V2.1 to characterize the performance of the *R-O-W Exit* transit node under competitive and non-competitive conditions and for emergency lighting conditions. As a result, four separate travel speed distributions can be defined for *R-O-W Exit* transit nodes:

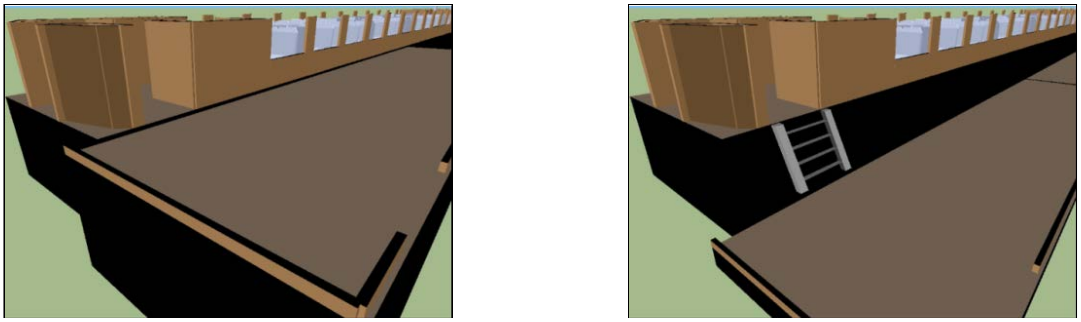
- Non-competitive behavior
  - *Normal* lighting
  - *Emergency* lighting, and
- Competitive behavior
  - *Normal* lighting
  - *Emergency* lighting.

As with the *Low Plat. Exit*, the measured travel speeds during the non-competitive egress trials were also assumed as the default values for the competitive travel speeds. Therefore, for the *R-O-W Exit* component, the default non-competitive and competitive travel speeds in the normal lighting condition were both assumed to range between 0.36 and 4.9 ft/s (0.11 and 1.5 m/s). Similarly, since data relating to non-competitive and competitive travel speeds in emergency lighting were unavailable, the User will be requested to manually define appropriate values for the transit node before being allowed to continue with the simulation. When more appropriate emergency lighting and competitive values become available, these can easily be incorporated within the software.

7.2 *Scenario* Mode Development

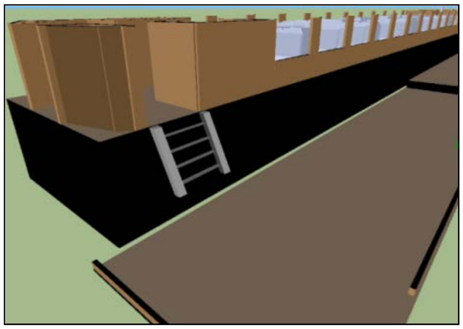
To visually demonstrate Prototype Software V2.1 capabilities to represent the Exit to Low Platform or Exit to R-O-W location using the three dimensional virtual reality postprocessor vrEXODUS, it is necessary to specify the height of the passenger rail car above the ground. This has been achieved through the *Car Zone* option.

Car Zones were implemented within the Prototype Software V2.0 software to enable the specification of normal and emergency lighting conditions (see Section 5.4). Typically, these zones correspond to individual passenger rail cars, thus enabling the specification of the lighting environment and egress performance within each passenger rail car. *Car Zones* are defined in the same manner as before by defining the nodes within each required region and then assigning both the lighting conditions corresponding to that region (i.e., normal or emergency), as well as its height. The ability to define regions at different heights enables the accurate representation of each of the three main exit scenarios within the virtual reality tool, vrEXODUS. Therefore, agent egress from a passenger rail car using Exit to High Platform (see Figure 51a), Exit to Low Platform station (see Figure 51b), or Exit to R-O-W scenarios (see Figure 51c) can be displayed within vrEXODUS.



(a) High Platform

(b) Low Platform



(c) R-O-W

Figure 51. Passenger Rail Car Exit Locations as Displayed within vrEXODUS

7.3 *Simulation* Mode Development

The data output capability of the Prototype Software V2.1 was expanded to accommodate data generated by the two new transit node exit types: *R-O-W Exit* and *Low Plat. Exit*. As a result of the various modifications made to the simulation output file, modifications were also required within the accompanying data analysis tool, “askEXODUS.”

In addition, the two new transit nodes were designed to function in both competitive and non-competitive situations, enabling the setting of competitive or non-competitive egress behaviors and associated agent performance attributes. When *Competitive Evacuation* is selected, the Prototype Software V2.2 adopts the competitive behavior options, as described in Section 5.5.2, which also applies to the *R-O-W Exit* and the *Low Plat. Exit* transit nodes.

7.4 Summary

The second development phase resulted in the Prototype Software V2.1. The software development included embedding egress data generated from the 2006 Volpe Center egress trials (see Section 4.4).

In addition to the capabilities of the Prototype Software V2.0, the Prototype Software V2.1 has the capability to simulate non-competitive exiting behavior by agents from an upright single-level passenger rail car during normal lighting conditions using one or two side doors for the following egress scenarios:

- Exit to Low Platform and
- Exit to R-O-W.

The Prototype Software V2.1 also has the capability to repeat the above model scenarios in competitive emergency egress situations and in emergency lighting conditions.

However, to run the Prototype Software V2.1 for these latter model scenarios with a high level of confidence will require the collection of an appropriate data set (e.g., particularly the traversal times/travel speed distributions associated with the various exit types in competitive egress situation and under emergency lighting conditions).

In addition, the Prototype railEXODUS Software V2.1 has the capability to simulate non-competitive and competitive exiting behavior by agents for the following egress scenarios:

- Egress from an upright multi-level passenger rail car (using building stairway data) during normal lighting conditions, using one or two side-door exits by:
    - Exit to Low Platform,
    - Exit to R-O-W;
- Egress from an upright single level or multi-level passenger rail car, involving a fire within the car, using one or two side-door exits by:
    - Exit to Low Platform
    - Exit to R-O-W.

  (Note: Fire data can be generated either using the CFAST zone or SMARTFIRE CFD fire models.)

8. Verification and Validation of Prototype railEXODUS Software V2.1

This chapter describes the verification and validation analysis of the Prototype Software V2.1, utilizing data derived from the 2006 Volpe Center egress trials [4], and summarizes the results from these scenario simulations. In order to verify and validate the Prototype Software V2.1, three sets of model scenarios were simulated:

- The first model scenarios were intended to verify that the Prototype Software V2.1 was capable of reproducing the specified transit node transit time distributions. A model scenario was developed, which utilized 84 seated agents and a single stairway side-door exit. The model scenario was run 250 times for both the *Low Plat. Exit* and the *R-O-W Exit* transit nodes and the predicted transit time distributions were then compared with the corresponding transit time distributions derived from FSEG analysis of the Volpe Center egress trials (Section 8.3.1).
- The second model scenarios were intended to validate the Prototype Software V2.1 using the group egress trial data. The software was configured so that 17 agents would exit as a group via the *Low Plat. Exit* transit node and 15 agents would exit as a group via the *R-O-W Exit* transit node. The resulting exit curves produced by the simulations could then be compared with the envelope of exit times derived from FSEG analysis of the Volpe Center egress trials for each exit configuration (Section 8.3.2).
- The third model scenarios were intended to verify that the Prototype railEXODUS Software V2.1 was capable of producing reasonably accurate exit predictions for the Exit to Low Platform and Exit to R-O-W model scenarios. As a basis for comparison, the results from these two model scenarios were compared with the Exit to High Platform model scenario.

A total of six model scenarios were modeled involving the full-rail car evacuation (i.e., comprising 84 agents) from a single-level car. Each of the three exit scenarios was modeled: Exit to High Platform, Exit to Low Platform, and Exit to R-O-W, for both one and two side-door exit availability (Section 8.3.3).

Each of these model scenarios was modeled only in normal lighting and non-competitive conditions, since egress data were only available for these conditions (see Section 4.4 and Section 4.5). The numerical predictions for the following parameters are compared for each scenario:

- Times for the first and last agent to exit the passenger rail car (the total egress time),
- Average exit flow rate achieved, and
- The exiting time history for each experimental egress trial (i.e., the exit time graph for the egress trial).

8.1 *Geometry* and *Population* Modes

The *Geometry* of the rail passenger rail car within the Prototype Software V2.1 was identical to that used in the validation of the Prototype Software V2.0 (see Chapter 6) but consisted of only a single rail car. There were a total of 92 seats: 56 arranged in facing blocks of four and the remaining 36 arranged in blocks of two. This *Geometry* was used for all the model scenarios. Within each model scenario, the car was populated in the *Population* mode with the appropriate number of agents generated, using the default Prototype Software V2.0 population panels.

8.2 Software Set-up

For all of the simulation results, the Prototype Software V2.1 default settings are used unless otherwise stated. The model scenarios were all run in normal lighting using the non-competitive mode. A total of 250 simulations of each model scenario were run, with the position of agents being changed after every 10 runs, unless otherwise specified. The change of agent position ensured that the starting locations of the population remained fixed (i.e., the same seats were occupied in each of the simulations), while the agent at each location was likely to change. Each agent was also assumed to respond instantly to the call to egress the car (i.e., agents did not experience delays prior to commencing their exit). Each agent was also assumed to respond instantly to the call to exit the car (i.e., agents did not experience delays prior to commencing their exiting behavior).

8.3 Simulation Results

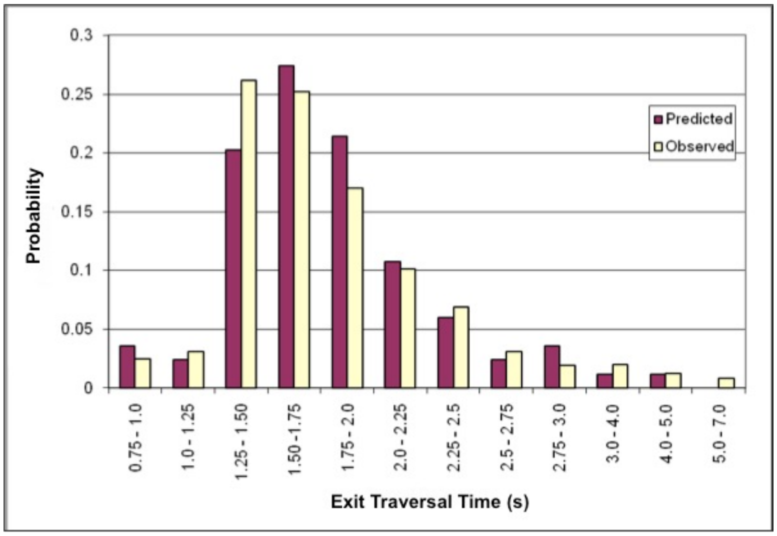
This section summarizes the main results of the verification and validation analysis. Model predictions are compared with the corresponding 2006 Volpe Center egress trial results (see Section 4.4).

8.3.1 Verification of Exit Traversal Time Distributions

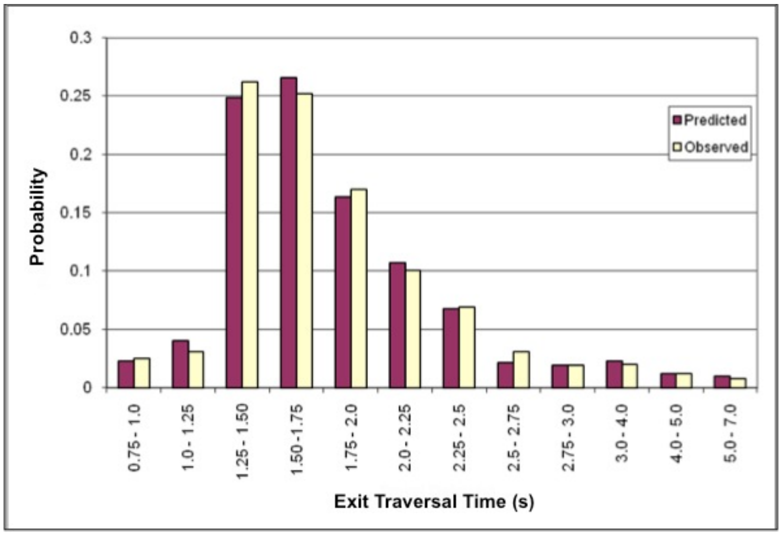
As part of the verification and validation process, the distribution of numerical predictions for the time that agents took to traverse the various transit nodes (i.e., *Low Plat. Exit* and *R-O-W Exit*) were directly compared with those measured within the Volpe Center experimental egress trials (see Section 4.4). In each case, the predicted exit traversal times of the agents moving through the transit nodes were taken from the corresponding one exit scenarios.

8.3.1.1 *Exit to Low Platform*

The verification process demonstrated that the predicted exit traversal time distribution matched the measured exit traversal time distribution for the Exit to Low Platform scenario. In the simulation, a population of 84 agents exited the passenger rail car through one side-door exit to the low platform. The simulation was repeated a total of 250 times. The predicted exit traversal times were placed in the same time bands as those used in the Volpe Center egress trials (see Section 4.4) and each exit traversal time was plotted as probability distributions, as shown in Figure 52.



(a) 1 Simulation



(b) 10 Simulations

Figure 52. Comparison of Predicted (Maroon) and Observed (Yellow) Exit to Low Platform Exit Traversal Times

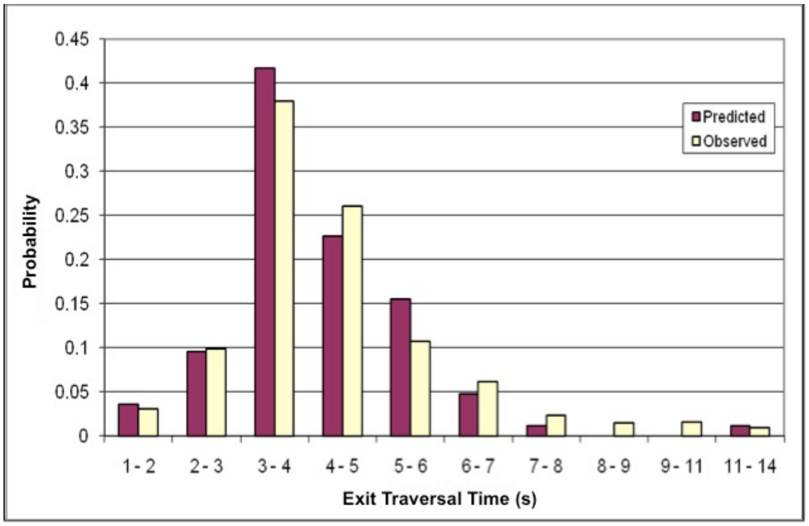
As each simulation comprised 84 agents, the results for one simulation (see Figure 52.a) correspond to the exit traversal times produced by 84 agents, while 10 simulations (see Figure 52.b) correspond to the exit traversal times produced by 840 agents.

Figure 52 shows that there is close agreement between the predicted and measured values. As the number of simulations increases and, thus, individual exit traversal times increase, so does the degree of agreement between the predicted and measured probability distributions. After 10 simulations (i.e., 840 agents (see Figure 52b.), the distribution of predicted exit traversal times closely matches that measured within the Volpe Center egress trials. As previously noted, this model scenario was run a total of 250 times. However, only the results for 1 and 10 simulations are shown since this was sufficient to obtain a very close match to the corresponding egress trial exit traversal time distribution.

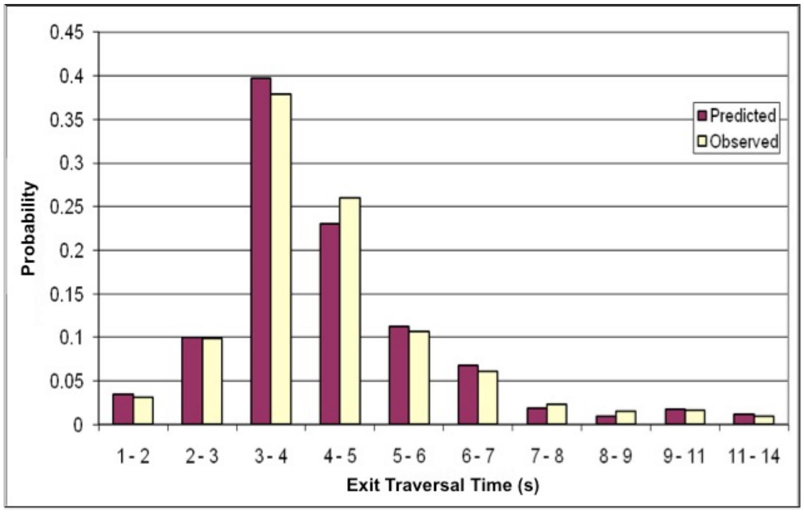
The close agreement between the shape of the predicted and measured exit traversal time probability distribution, even after a single simulation, demonstrates that the *Low Plat. Exit* transit node is functioning as intended. However, it is recommended that multiple simulations for any given model scenario be performed to ensure that small statistical variations in the exit traversal time probability distributions do not affect the overall results.

8.3.1.2 *Exit to R-O-W*

The verification process demonstrated that the predicted exit traversal time distribution matched the measured exit traversal time distribution for the Exit to R-O-W scenario. The software was run in precisely the same way as for the Exit to Low Platform scenario and the results are shown in Figure 53.



(a) 1 Simulation



(b) 10 Simulations

Figure 53. Comparison of Predicted (Maroon) and Observed (Yellow) Exit to R-O-W Exit Traversal Times

As with the Exit to Low Platform simulations, there is close agreement between the predicted and measured values. The close agreement between the shape of the predicted and measured exit traversal time probability distribution, even after a single simulation, demonstrates that the *R-O-W Exit* transit node is functioning as intended. However, as with the Exit to Low Platform scenario, multiple simulations for any given model scenario should be performed to ensure that small statistical variations do not affect the overall results.

8.3.2 Validating the Predicted Exit Time History Using Experimental Data

In addition to using the full-scale egress simulations to verify the exit traversal time distributions, additional model scenarios were run in order to validate that the movement of agents passing through the transit nodes matched the movement measured within the corresponding Volpe Center experimental egress trials. These model scenarios were designed to replicate the egress trials and, therefore, only involved the egress of a small group of agents from the passenger rail car. These simulations were intended to reproduce the group experimental egress trials described in Section 4.4. The Exit to Low Platform and Exit to R-O-W group scenarios involved the evacuation of 17 and 15 agents, respectively. Within these group egress trials, agents were required to exit the passenger rail car via one available exit and were initially located in the seats nearest to the exit. In each case, the predicted exit times of each agent (i.e., the exit time graphs) for the various simulations were directly compared with those measured within the corresponding egress trials.

8.3.2.1 *Exit to Low Platform*

A total of 250 simulations were run for the Exit to Low Platform scenario, with the position of agents being changed after every 10 runs. The window of results generated from the Volpe Center experimental egress trials is shown in Figure 24 of Section 4.4. Figure 54 shows the addition of the ±10 percent variation.

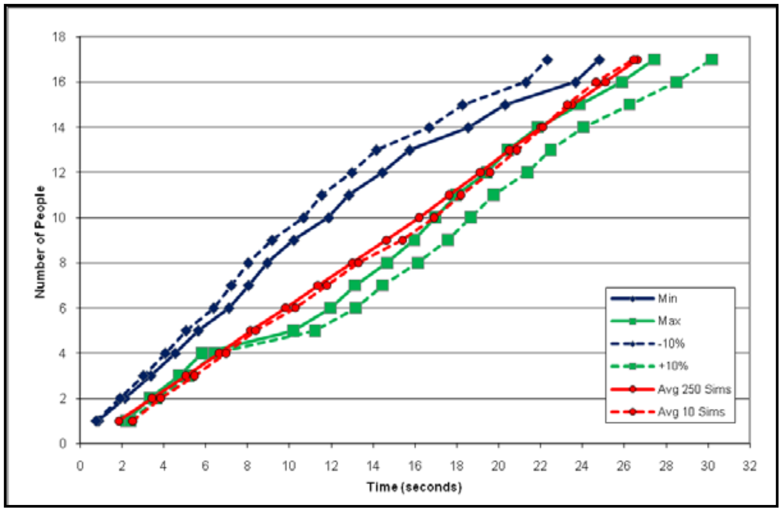


Figure 54. Exit Time Curves of Average Exit to Low Platform Prototype Software V2.1 Simulations Plotted Against Minimum and Maximum Envelope Curves Derived from Volpe Center Egress Trials

For the first 10 simulations, only one of the simulated egress trials involving 17 agents fell outside of the ±10 percent experimental envelope for the majority of the trial time. All of the other trials remained within the ±10 percent experimental envelope for the great majority of the trial time. The occasional variation from the ±10 percent experimental envelope is due to statistical anomalies that resulted from the inability of the relatively small number of experimental egress trials to generate the wide variation in possible exit time histories, as well as the inherent statistical variability produced by the simulations. Because of the statistical variability within individual simulations, it is more appropriate to compare the predicted average exit time curve with the experimentally derived envelope. A total of 250 repeat simulations were performed and the average exit time for each agent was determined and plotted with the experimental envelope. When comparing the predicted average curve from the first 10 repeat simulations with the curve produced from the full set of 250 repeat simulations, it is noted that the two average curves were almost identical, implying that 10 repeat simulations should be sufficient to produce meaningful results. Furthermore, the average exit time curves were well within the ±10 percent egress trial range of results (see Figure 55).

The predicted average flow rate for the Exit to Low Platform egress scenarios, generated from 10 and 250 simulations, was 40.2 ppm (0.67 pps) and 39 ppm (0.65 pps), respectively. The average exit flow rate measured from five repeat egress trials was 39 ppm (0.65 pps).

8.3.2.2 *Exit to R-O-W*

A total of 250 simulations were run, with the position of agents being changed after every 10 runs. The window of results generated from the experimental egress trials are shown in Figure 20 of Section 4.4. The ±10 percent variation was added, as shown in Figure 55.

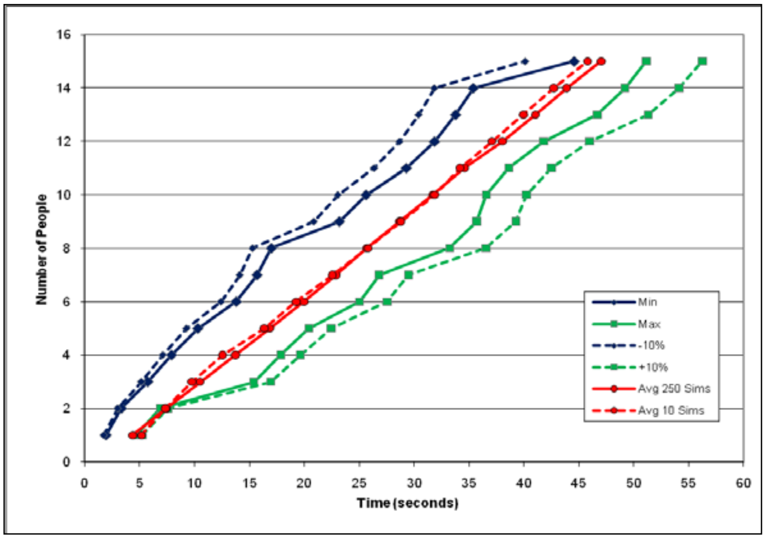


Figure 55. Exit Time Curves of Average Exit to R-O-W, Prototype Software V2.1 Predictions; and Minimum and Maximum Envelope Curves Derived from 2006 Egress Trials

As with the Exit to Low Platform scenario, the great majority of the first 10 of the 250 simulated egress trials, involving 15 agents, produced exit time histories that were within the ±10 percent experimental envelope. As with the Exit to Low Platform scenario, the occasional variations from the ± 10 percent experimental envelope were due to statistical anomalies resulting from the inability of the relatively small number of experimental egress trials to generate the wide variation in possible exit time histories, as well as the inherent statistical variability produced by the simulations. Due to the statistical variability within individual simulations, it is more appropriate to compare the predicted average exit curve with the experimentally derived envelope. A total of 250 repeat simulations were performed and the average exit time for each agent was determined and plotted with the experimental envelope. When comparing the predicted average curve from the first 10 repeat simulations with the curve produced from the full set of 250 repeat simulations, it is noted that the two average curves were almost identical, implying that 10 repeat simulations should be sufficient to produce meaningful results. Furthermore, the average exit curves fall well within the ±10 percent egress trial range of results (see Figure 55).

The predicted average exit flow rate for the Exit to R-O-W Exit scenarios, generated from 10 and 250 simulations, was 21 ppm (0.35 pps) and 19.8 ppm (0.33 pps), respectively. The average exit flow rate measured from five repeat trials was 19.2 ppm (0.32 pps).

8.3.3 Software Verification for Model Scenarios Involving Exit to Low Platform and Exit to R-O-W

In addition to comparing the predicted time required for agents to traverse each of the *Low Plat. Exit* and *R-O-W Exit* transit nodes with the Volpe Center egress data, a series of comparative simulations were conducted to demonstrate the impact of the use of one or two side doors in the various model scenarios: Exit to High Platform, Exit to Low Platform, and Exit to R-O-W.

In these scenarios, the passenger rail car population consisted of 84 agents and the model parameters were set to their default values for non-competitive, normal lighting model scenarios. Six model scenarios were considered. In the first series of three model scenarios, only one side-door exit was available and three cases were examined: Exit to High Platform, Exit to Low Platform, and Exit to R-O-W. Each model scenario was repeated 250 times, with the agents changing seat locations after every 10 runs. Therefore, the differences within the three model scenarios were due to the nature of the exit types. In the second series of three model scenarios, these scenarios were repeated using two side-door exits.

8.3.3.1 *One Side-Door Exit*

The average exit times for the one side-door egress involving 84 agents for the Exit to High Platform, Exit to Low Platform, and Exit to R-O-W scenarios were 102 s, 133 s, and 254 s, respectively (see Table 19). The Exit to R-O-W scenario exit times were 2.5 times longer than the Exit to High Platform scenario, while the Exit to Low Platform was 1.3 times longer than the Exit to High Platform scenario. The exit time differences between these simulations are a result of the average flow rate achieved in each case. For the Exit to High Platform scenario, the average exit flow rate was 52 ppm (0.87 pps), while for the Exit to the R-O-W scenario, the average exit flow rate was 20.6 ppm (0.34 pps).

The differences in egress performance for the use of one side-door exit between the three model scenarios can be more clearly seen by comparing the exit graph for each, as shown in Figure 56.

Table 19. Mean and Range of 250 Simulations: Exit Times and Flow Rate for Each One Side-Door Exit Model Scenario

MODEL SCENARIO	TIME OF FIRST AGENT OUT (s)	TIME OF LAST AGENT OUT (s)	EXIT FLOW RATE (ppm)
One Side-Door Exit to High Platform	4.55 [3.96–5.85]	101.5 [100.8–103.2]	52.0 [51.6–52.1]
One Side-Door Exit to Low Platform	5.50 [4.18–9.94]	133.1 [121.4–148.3]	39.6 [35.2–43.6]
One Side-Door Exit to R-O-W	8.22 [4.21–16.76]	253.6 [230.4–284.6]	20.6 [18.3–22.6]

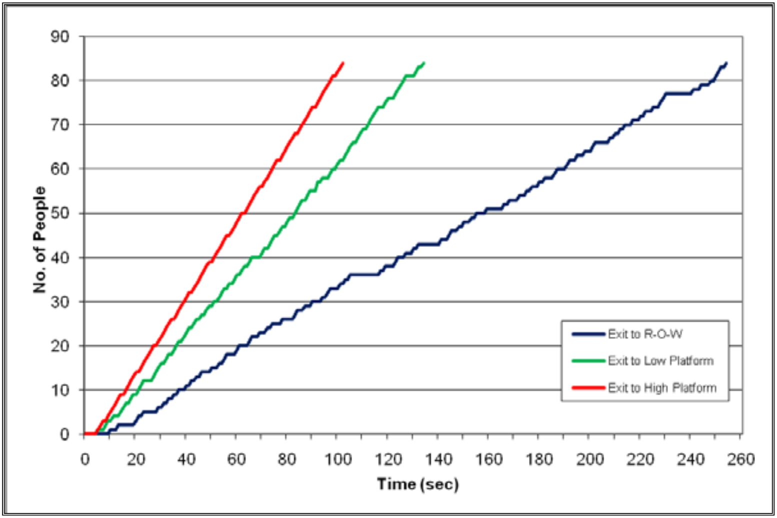


Figure 56. Exit Time Curves for One Side-Door Exit Model Scenarios – Normal Lighting

Each of the exit time curves displayed corresponds to the exiting behavior observed within a single representative simulation within each of the model scenarios. In each case, the single simulation was selected that most closely matched the mean overall egress time for the model scenario. The differences in the average exit flow rates achieved in each model scenario can clearly be seen by comparing the gradients of the three curves. It is noted that while the Exit to Low Platform scenario produces marginally slower exit times compared with the Exit to High Platform scenario, the Exit to the R-O-W scenario produces longer exit times (approximately 25 seconds longer). While the Exit to Low Platform scenario produces marginally slower exit times compared with the Exit to High Platform scenario, the Exit to R-O-W scenario produces significantly longer exit times. The relative ordering of these software predictions is consistent and reasonable, with the Exit to R-O-W scenario through one side-door exit taking longer than the Exit to Low Platform scenario and the Exit to Low Platform scenario taking longer than the Exit to High Platform scenario.

8.3.3.2 *Two Side-Door Exits*

When two side-door exits are used, the mean exit times for the Exit to High Platform, Exit to Low Platform, and Exit to R-O-W model scenarios were: 54 s, 71 s, and 136 s, respectively (see Table 20). The results follow similar trends to the one side-door exit, with the Exit to the R-O-W scenario 2.5 times longer than Exit to High Platform scenario, while Exit to Low Platform scenario was 1.3 times longer than the Exit to High Platform scenario. The differences in **exit** time performance between the three model scenarios using two side-door exits were compared for each scenario, as shown in Figure 57. The Exit to R-O-W scenario produces significantly longer overall exit times and lower exit flow rates.

Table 20. Mean and Range of 250 Simulations: Exit Times and Exit Flow Rates for Each Two Side-Door Exit Model Scenario – Normal Lighting

MODEL SCENARIO	TIME OF FIRST AGENT OUT (s)	TIME OF LAST AGENT OUT (s)	EXIT 1 FLOW RATE (ppm)	EXIT 2 FLOW RATE (ppm)
Two Side-Door Exits to High Platform	4.44 [3.97–5.22]	53.8 [53.1–55.0]	52.6 [52.1–52.8]	52.5 [50.9–52.8]
Two Side-Door Exits to Low Platform	5.16 [4.15–7.06]	70.7 [64.9–83.9]	40.0 [34.2–46.7]	40.2 [33.0–44.2]
Two Side-Door Exits to R-O-W	7.35 [4.52–13.15]	135.8 [119.7–164.9]	20.7 [17.1–24.2]	20.8 [16.3–25.2]

The average overall exit times within each of the two side-door exit model scenarios were approximately 47 percent faster than those measured within the corresponding one-door exit model scenarios (see Table 20). This reduction in overall exit times is the result of the additional available exit within these model scenarios, which effectively doubled the egress flow rate of agents from the passenger rail car. These model scenarios did not observe an exact 50 percent reduction in their overall exit times, since the numbers of agents using each door exit were not evenly balanced. Therefore, one-door exit would always have slightly more than half the agent population use the exit (i.e., 43 of the 84 agents). Since the side-door exits were not used in a perfectly balanced manner, the more highly utilized exit would have its clearance extended in comparison to the other exit.

These model predictions are as expected, with the Exit to R-O-W model scenario using two side-door exits taking significantly longer than the Exit to High Platform model scenario using two side-door exits.

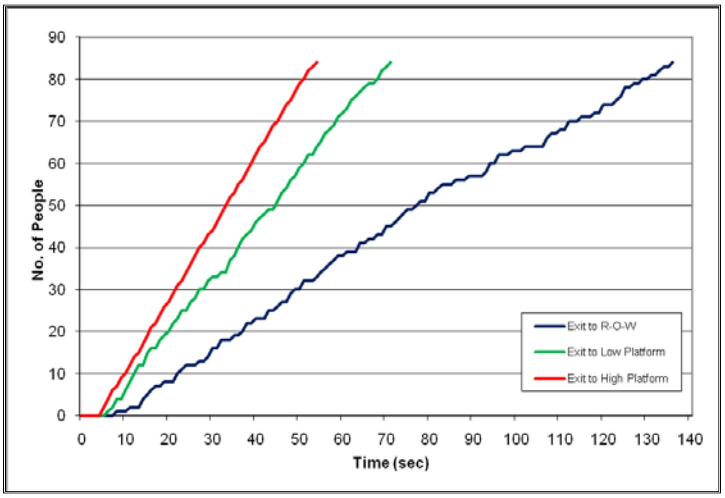


Figure 57. Exit Time Curves for Three Two-Side-Door Exit Model Scenarios – Normal Lighting

It is noted that 250 repeat simulations were performed for each model scenario to produce these results. This was considered necessary due to the wide variation in predicted total exit times produced by the Exit to Low Platform and Exit to R-O-W scenarios. In the Exit to Low Platform scenario, the maximum exit time is 22 percent greater than the minimum exit time, while in the Exit to R-O W scenario the maximum egress time is 24 percent greater than the minimum exit time. This result compares with only a 2 percent difference in the Exit to High Platform scenario. The reason for the wide spread in total exit times is the corresponding wide spread in exit times among participants as measured in the Volpe Center egress trials (see Section 4.4).

To be confident of producing the full range of likely exit times in simulations, given the wide distribution in transit times for individuals exiting to the low platform and the R-O-W, between 100 and 250 repeat simulations may be required.

8.4 Summary

The results from these verification and validation simulations demonstrated that both the *Low Plat. Exit* and *R-O-W Exit* transit nodes are functioning properly, each closely replicating the corresponding experimental data. This demonstrates that the Prototype Software V2.1 is capable of accurately modeling both the time individuals take to exit from the passenger rail by descending to either a low platform or to the R-O-W and the dynamics of non-competitive egress, under normal lighting conditions.

9. PROTOTYPE railEXODUS SOFTWARE V2.2 DEVELOPMENT

The first two phases in the development of the new Prototype Software extended the capabilities of the prototype railEXODUS software V1.0 to include: (1) the simulation of passenger egress to high platforms using passenger rail car side-door exits and egress to an adjacent car using inter-car end-door exits, in both normal and emergency lighting conditions (see Chapter 5 and Chapter 6); and (2) egress to low platform and R-O-W locations, using car side-door exits (see Chapter 7 and Chapter 8). These modifications to the prototype railEXODUS software V1.0 resulted in the Prototype Software V2.0 and V2.1.

The third and last phase in the development of the new Prototype Software involved extending the capabilities of the Prototype Software V2.1 to include the capability to model the movement of individuals within passenger rail cars subjected to adverse angles of roll. These modifications resulted in the development of the Prototype Software V2.2.

Before these capabilities could be incorporated within the new Prototype Software, detailed data describing the performance and behavior of individuals under appropriate egress conditions were required. Since data relating to the egress of participants from passenger rail cars subjected to angles of roll were not available, the data incorporated into the model were derived from the maritime industry because of the availability of the data set and the similarity between the experimental conditions in which the marine data were generated and the target passenger rail car conditions.

The Prototype Software V2.1 was systematically modified to incorporate the required changes. To make the modifications easier to understand, the changes to the software are described in terms of how the User would encounter these changes in using the software (i.e., by describing the changes to the core modes of software operations). Since no modifications were made to either the *Geometry* Mode or the *Population* Mode, as part of the third development phase, only two of the four EXODUS modes are outlined: *Scenario* Mode and *Simulation* Mode.

This chapter summarizes Prototype Software V2.2 development.

9.1 *Scenario* Mode

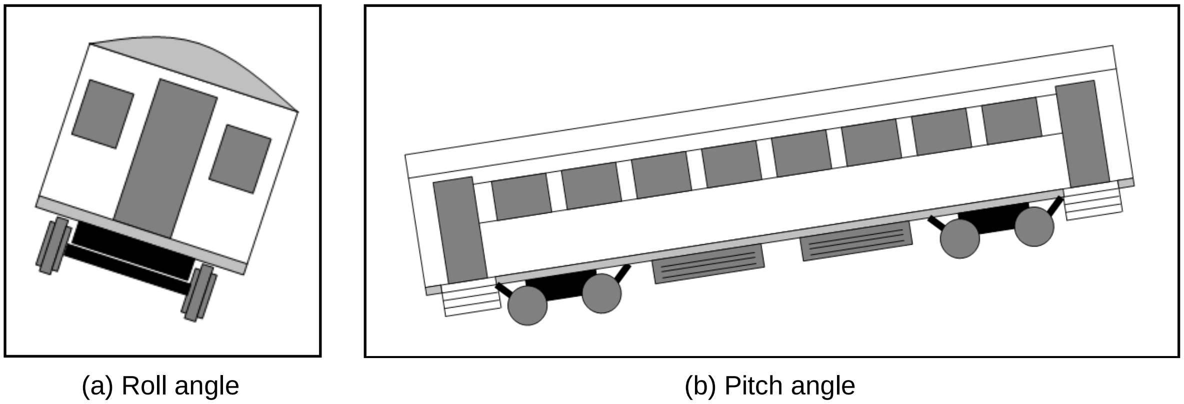
Several new developments were implemented within the Prototype Software V2.2 to enable the representation of inclined passenger rail cars and individuals moving along the car aisle. These modifications implemented within the *Scenario* Mode are:

- Defining regions (representing an entire passenger rail car or part of a rail car) at different angles of roll. This is achieved using the *Car Zone* specification capability initially developed for the Prototype Software V2.0 (see Section 5.4.) to represent regions of different lighting and extended for the Prototype Software V2.1 to enable the defining of rail car (zone) heights for the specification of egress to a low platform and to the R-O-W (see Section 7.2). The *Car Zone* specification capability is further extended to enable the angle of roll of each zone to be defined.

- Modeling the effect of angles of inclination on agent mobility. The movement sub-model was extended to enable the effect of given angles of roll and pitch on agents to be determined, thus enabling the agent corresponding mobility values (and thus travel speeds) to be adjusted to simulate the overall effect of such exposure.
- Loading and saving performance characteristics (i.e., flow rate and travel speed distributions) for the new transit nodes (i.e., *Inter-Car Conx*, *High Plat. Exit, R-O-W Exit*, and *Low Plat. Exit*).

9.1.1 Defining Roll Angles for Individual Passenger Rail Cars

As part of the third development phase of the railEXODUS Prototype Software, the Prototype Software V2.1 has been extended to include additional functionality to represent the movement of persons within a passenger rail car at adverse angles of inclination (see Figure 58). Rail car inclination is limited to angles of roll, as depicted in Figure 58a. As a result, other car orientations, such as nose-up or nose-down (i.e., pitch angles, see Figure 58b), were not considered. In addition, the angles of roll implemented within the software were also restricted to static angles of roll. The angle of roll within individual passenger rail cars was assumed to be fixed, and was not changed throughout the course of the simulation.


(a) Roll angle

(b) Pitch angle

Figure 58. Various Inclination Configurations for a Passenger Rail Car

Within the Prototype railEXODUS Software V2.2, the ability to define the angle of roll of individual passenger rail cars has been implemented by extending the existing functionality of *Car Zones*. Typically, *Car Zones* correspond to individual cars (but may also represent part of a car) and allow the specification of *Attributes* associated with the nature of the lighting condition and the physical height of the *Car Zone*. Within the Prototype Software V2.2, the *Car Zone Attributes* have been expanded to enable the specification of the roll angle for the *Car Zone* to be defined. Within each *Car Zone,* it is possible to specify roll angles between -90 and +90 degrees (see Figure 59). In each case, defining roll angles of plus or minus 90 degrees effectively corresponds to the car tipping completely over and thus lying on either one of its sides.

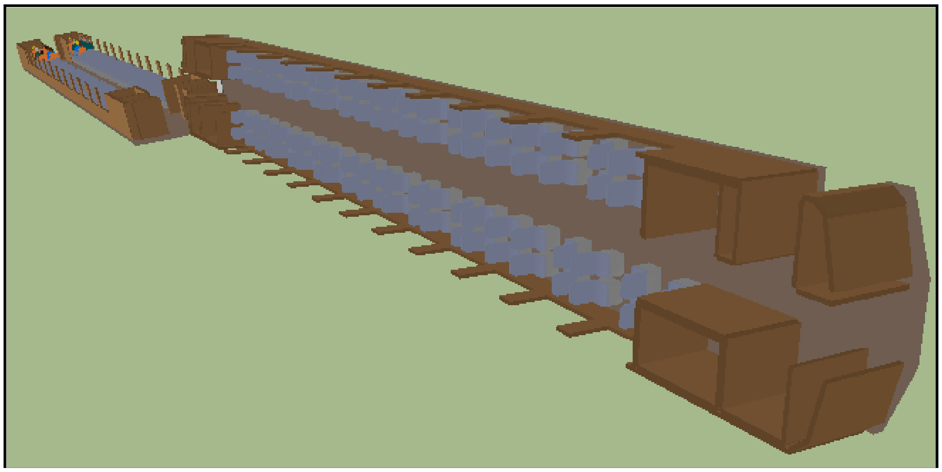
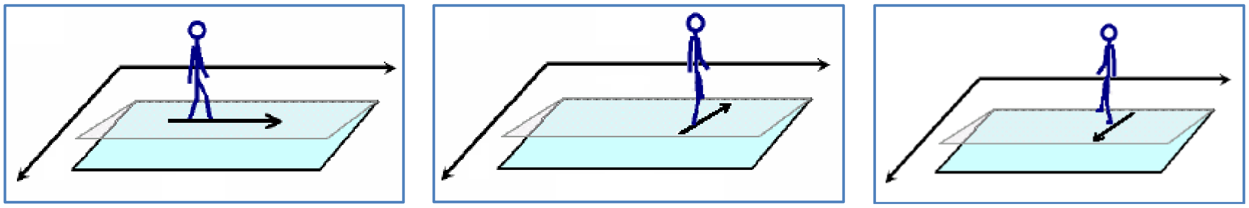


Figure 59. Representation of Different Roll Angles within vrEXODUS

9.1.2 Impact of Passenger Rail Car Roll Angle on Agent Mobility

Since no relevant data regarding the movement of individuals within passenger rail cars at different angles of roll was available, the Prototype Software V2.2 uses maritime industry egress experiment data (see Appendix D). FSEG considered two maritime industry egress data sources: TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Dutch Organization for Applied Scientific Research)) [23] and the Ship Evacuation Behavior Assessment (SHEBA) [24] to be the most appropriate for use to simulate the passenger rail car environments and so they were implemented within the Prototype Software V2.2.

The orientation of *Car Zone* regions was limited to angles of roll. However, this does not mean that agents subjected to an angle of roll will only experience the effects of roll. Figure 60 shows the various different angle effects experienced by an agent traversing a car subjected to a positive angle of roll (+ 10 degrees).



(a) Roll

(b) Negative Pitch

(c) Positive Pitch

Figure 60. Roll and Pitch Angles Experienced when Exposed to Positive Roll

Figure 60a shows an agent walking the length of the passenger rail car along the aisle (in the direction of the arrow); in this case, the agent only experiences the impact of roll. Figure 60b shows the agent moving along a negative pitch (perhaps towards an exit) while subjected to the same roll as in Figure 60a. In contrast, Figure 60c shows the agent moving along a positive pitch while attempting to move in the opposite direction to that shown in Figure 60b.

Furthermore, agents exposed to an angle of roll experience the same effects irrespective of its given direction (i.e., positive or negative). Since each of the TNO and SHEBA data sets considered the effects of roll and pitch in isolation, no experimental data were available for agents exposed to both effects simultaneously. As a result, the roll and pitch effects that an agent is exposed to at any given time within the Prototype Software V2.2 are calculated separately; the factor with the largest impact on the agent travel speed is used for the calculations.

The impact of roll angle on an agent's travel speed is introduced through the *Mobility* attribute of the EXODUS software. Within the EXODUS software, the *Mobility* is an agent attribute which defines that agent's reduction in travel speed resulting from physical disability or the impact of physical environmental factors, such as fire. A *Mobility* of 1.0 indicates that the agent has no mobility impairment and there are no environmental factors impacting his or her ability to walk. *Mobility* values less than 1.0 indicate that the agent has some mobility impairment or is experiencing adverse environmental factors, which will reduce his or her maximum travel speed. The *Mobility* attribute is used in conjunction with the agent *Initial Travel Speed* to calculate the agent travel speed as a result of exposure to the adverse environmental factor, as shown in Equation (9):

Travel Speed = Initial Travel Speed x Mobility **(9)**

Within the Prototype Software V2.2, a *Mobility Inclination Factor* is determined based on the angle of roll that the agent experiences at any point during egress. After the *Mobility Inclination Factor* is determined, this factor is used with the agent's *Initial Mobility* value (defining his or her specific level of impairment) to define the overall level of mobility impairment. The overall level of mobility impairment is calculated by multiplying the mobility impairments that result from the assumed initial level of impairment (i.e., initial mobility) and that resulting from the roll angle experienced, as shown in Equation (10):

Mobility* = *Initial Mobility* x *Mobility Inclination Factor **(10)**

As already noted, for a given passenger rail car angle of roll, it is also possible for the agent to experience the impact of pitch. In situations where the agent is subjected to non-zero values of roll and pitch angle, the roll and pitch effects that an agent is subjected to at any specific time are calculated separately, with the factor having the largest impact on the agent's travel speed (i.e., the greatest reduction factor) being adopted as the *Mobility Inclination Factor,* as shown in Equation (11):

Mobility inclination Factor = Min (*Roll Factor, Pitch Factor*) **(11)**

The *Roll Factor* in Equations (11) and (12) is determined using the SHEBA data [24]. The impact of a given angle of roll (i.e., Heel) on travel speed was determined to be a function of the participant's age and gender and the nature of the terrain he or she was traveling over (e.g., flat corridor, stairways going up or going down). A *Roll Age Factor* and a *Roll Gender Factor* were determined for a given terrain type. The *Roll Factor* for a given terrain type is determined using Equation (12):

Roll Factor* = *Roll Age Factor* x *Roll Gender Factor **(12)**

Within this calculation, the *Roll Age Factor* is dependent upon the angle of roll that the agent is subjected to, the type of terrain being traversed (i.e., stairway or flat corridor), and the corresponding age category. Figure D1 in Appendix D shows the impact of *Age* on the *Roll Age Factor* for traveling on stairways.

Similarly, the *Roll Gender Factor* is dependent upon the angle of roll to which the agent is subjected, the terrain being traversed (i.e., flat corridor or stairways), and the corresponding gender category. Figure D2 in Appendix D shows the impact of *Gender* on the *Roll Gender Factor* for travelling on stairways.

The *Pitch Factor* in Equations (11) and (13) is determined using the TNO data [23], since the SHEBA trials did not produce pitch data. (Unlike the SHEBA roll data, the TNO data does not include data relating to gender.) Therefore, the only factors to influence the mobility are age and pitch angle. For a given angle of pitch, the *Pitch Factor* is specified by Equation (13):

$$\textbf{\textit{Pitch Factor}} = \textbf{\textit{Pitch Age Factor}} \qquad \textbf{(13)}$$

The *Pitch Age Factor* within this calculation is dependent upon the angle of pitch to which the agent is subjected, the terrain being traversed (i.e., flat corridor or stairways), and the corresponding age category.

The data collection within the SHEBA egress trials [24] was restricted to 0, 10, and 20 degrees of roll, while the TNO [23] data collection was restricted to 0, 5, 10, 15, and 20 degrees of pitch. Within the Prototype Software V2.2, angles of roll and pitch between these measured values are determined using linear interpolation, while roll and pitch angles outside this range are determined using extrapolation.

Exposure of agents to angles of roll and the resulting modifications to both *Mobility* and *Travel Speeds* apply in all lighting conditions (i.e., normal and emergency) and behaviors (competitive and non-competitive). Therefore, an agent exposed to a specific angle of roll will encounter the same *Roll* and *Pitch Factors* in both normal and emergency lighting conditions, and thus the effect on the agent's mobility (i.e., the factor by which the mobility travel speed will be multiplied) will be the same.

It is noted that agents within a given inclined region will only have their *Mobility* (and thus *Travel Speed*) modified to reflect the effect of roll angle on their movement when they are traversing conventional EXODUS node types (i.e., *Free Space, Boundary, Car Aisle,* etc.). In contrast, agents traversing the newly developed transit nodes used in the Prototype Software V2.2 (i.e., *Inter-Car Conx*, *High Plat. Exit, Low Plat. Exit*, and *R-O-W Exit*) will not have their movement directly affected, even if the new transit node is subjected to an angle of roll since no data relating to exit behavior of occupants to high or low platforms, adjacent rail cars, or the R-O-W from passenger rail cars subjected to angles of roll is available. Therefore, the effect on agents traversing the new nodes is a simplification because actual exiting behavior may be greatly affected, particularly for significant roll angles."

In addition to data that enabled the effects of static roll on mobility (and thus travel speed) to be calculated, the SHEBA data [24] also enabled the impact of static roll and smoke density to be determined. This data allows the impact of reduced visibility (due to a fixed smoke density) to be measured and represented within the mobility factor. If the *Hazard* sub-model is disabled within the Prototype Software V2.2, the agent will not be exposed to heat, smoke, or toxic gases during egress. As a result, the calculation of roll effects is based on Equations (9) to (13). If the *Hazard* sub-model is enabled, the calculation of angle effects is based on the SHEBA experimental data set that considered the combined effects of both roll and smoke density [24].

9.1.3 Defining Mobility Limits within Passenger Rail Cars Subjected to Angles of Roll

In addition to defining the mobility effect on agents exposed to specific angles of roll, it is also possible to define a range of roll angles within which adverse inclination conditions make movement along the car aisle or side wall extremely difficult, if not impossible for the majority of persons. If individuals were to attempt to move along the passenger rail car in such situations, they would be forced to climb on or walk over the seats. The potential behavior associated with this type of movement is expected to be dependent on individual personal characteristics (e.g., age, gender, weight, level of mobility impairment, physical strength, etc.). Given this dependence, this movement is likely to be restricted to only a small subset of the population. Furthermore, movement under such conditions is likely to be subject to considerable variability and is expected to be extremely slow. Moreover, passenger rail car experimental data relating to movement rates under these conditions are not available. In order to be conservative, within the Prototype railEXODUS Software V2.2, agent movement under these extreme angles of roll conditions is assumed to be impossible.

Within the Prototype Software V2, the range of angles where agent movement is not possible is specified in the definition of both minimum and maximum critical angles (see Figure 61).

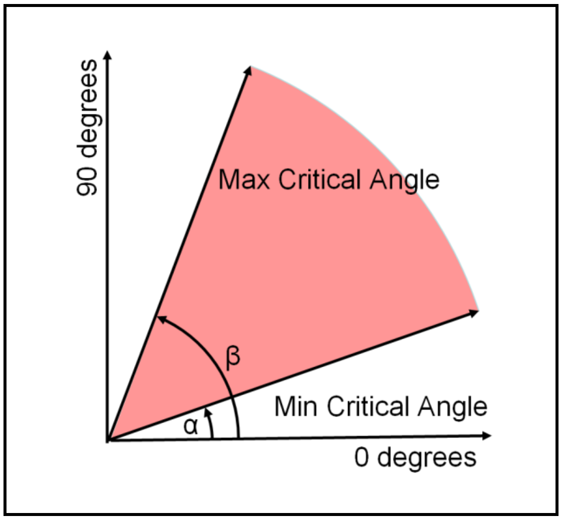


Figure 61. *Minimum (α)* and *Maximum (β)* Critical Angles

Accordingly, any *Car Zones* subjected to roll angles greater than the ***minimum critical angle (α)*** and less than the ***maximum critical angle (β)*** are considered to be impassable within the simulation (i.e., the agents will not be able to move along the rail car). Agents within cars subjected to roll angles between the minimum and maximum critical angle are considered trapped and unable to egress. This applies to both positive and negative angles of roll.

Within the Prototype Software V2.2, agents within a *Car Zone* subjected to a roll angle less than the minimum critical angle are assumed to egress in the conventional manner, by traversing the car aisle. In contrast, agents within a *Car Zone* subjected to a roll angle greater than the maximum critical angle are assumed to egress by traversing the walls or windows of the overturned passenger rail car, just above the seat back tops. By default, agents within a *Car Zone* subjected to roll angles between the two critical angles are considered to be unable to move without assistance and so are treated as if they are trapped within the car. In cases where this occurs, a warning message will automatically be displayed indicating that the simulation cannot run because of the roll angle. Within the Prototype Software V2.2, the minimum and maximum critical angles can be specified and have default values of 20 and 80 degrees, respectively.

Within the Prototype Software V2.2, the *Roll Factor* and *Pitch Factor* are both assumed to be zero for angles of roll between 20 and 80 degrees. For roll angles less than 20 degrees, the *Roll Factor* and *Pitch Factor* are determined, as described in Section 9.1.2. For roll angles greater than 80 degrees, *Roll Factor* is arbitrarily taken as 0.8, while the *Pitch Factor* is assumed to be zero. The *Roll Factor* of 0.8 represents the difficulty in walking along the windows of the overturned passenger rail car.

9.1.4 Defining Car Door Exit Performance within Passenger Rail Cars Subjected to Angles of Roll

When agents travel through one of the new exit types defined in the Prototype Software V2.2 (i.e., *Inter-Car Conx*, *High Plat. Exit*, *Low Plat. Exit*, and *R-O-W Exit*), their passage through these exits will be impacted by the roll angle. Subjecting passenger rail cars to roll angles could directly affect individual ability to exit the rail car since the steeper the roll angle, the greater the difficulty, and thus the greater the time taken to safely travel through the exit. The time to travel through the exit is also expected to be dependent on whether the car door exit is effectively located at the top end or the bottom end of the sloping rail car floor. As a result, the performance of each new transit node would change when subjected to different angles of roll. Therefore, new data defining the performance (i.e., flow rate limits/travel speed/travel time distributions, etc.) would be required. For example, a previous FSEG experiment conducted in 1999 suggests that the flow rate for a rail car end door (equivalent to the *Inter-Car Conx*) in an overturned passenger rail car (i.e., 90 degrees of roll) could be as low as 9.2 ppm under normal lighting conditions and 5 ppm in a smoke-filled environment [25].

While this type of passenger rail car movement data is not currently available, the data could potentially be derived from future rail car experimental trials. Therefore, the software was modified to enable the adoption of data defining the performance of these exits as a function of roll angle. These transit nodes typically either enable the maximum flow rate of agents through the transit node to be restricted (i.e., *Inter-Car Conx* and *High Plat. Exit* transit nodes), or alternatively enable travel speeds to be imposed on agents traversing the transit node, in accordance with User-defined distributions (i.e., *Low Plat. Exit* and *R-O-W Exit* transit nodes). This new feature enables the User to specify his or her own data-sets characterizing exit performance, allowing the development of User libraries for exit performance.

9.2 *Simulation* Mode

To enable the impact of the roll angle defined within *Car Zones* within the Prototype Software V2.2, the *Behavior Control* was expanded to allow the activation of the *Roll & Pitch Factor* switch. Failure to enable the *Roll & Pitch Factor* option within the *Behavior Control* will result in no mobility factors being applied to agents within *Car Zones* subjected to roll angles. In addition, the data output capability of the Prototype Software V2.2 was expanded to accommodate the roll angle associated with each *Car Zone.*

9.3 Summary

The third phase in the new railEXODUS software development resulted in the Prototype Software V2.2. In addition to the capabilities inherited from the Prototype Software V2.1, the Prototype Software V2.2 has the capability to simulate the movement of individuals within passenger rail cars subjected to predefined angles of roll. Since data relating to participant egress from passenger rail cars subjected to angles of roll were not available, the data incorporated into the model were derived from maritime industry ship egress experiments.

10. Verification of Prototype railEXODUS Software V2.2

Since passenger rail car experimental data concerning the egress performance of individuals subjected to various roll angles were not available, it was not possible to perform a detailed software validation analysis. Accordingly, verification of the Prototype Software V2.2 focused on ensuring that the movement rates (i.e., *Mobility* and *Travel Speed*) of a single agent were correctly adjusted when subjected to specified conditions of roll angle (and corresponding pitch angle), agent gender and age, and smoke concentration. A total of four model scenarios were evaluated. Within each model scenario, and at each location, hand calculations were performed in order to obtain both the predicted mobility and travel speed of the agent resulting from the imposed conditions. The model was then configured to simulate comparable model scenario conditions. The hand calculations and the simulated results were then compared.

This chapter summarizes the verification analysis of the Prototype Software V2.2.

10.1 *Geometry, Population*, and Software Set-up

For each of the verification scenarios, a single passenger rail car, identical to the type of rail car described in Chapter 5, was modeled. In total, the passenger rail car comprises 92 seats, 56 arranged in facing blocks of 4, and the remaining 36 arranged in blocks of 2.

Four model scenarios were investigated to verify that the software functioned as intended. Each model scenario was designed to check that the specified *Car Zone* could be subjected to the specified roll angle and that the movement rates of agents within the *Car Zone* were modified correctly. For each model scenario, the entire passenger rail car was defined as a single *Car Zone*, to which differing roll angles were applied. Each model scenario involved the movement of a single agent that would exit from the passenger car to a high platform. In each case, the agent was initially seated towards the middle of the passenger rail car and was assumed to move via the shortest route to the nearest available exit. Normal lighting conditions were assumed for each of the scenarios modeled. Since *Non-Competitive* behavior was also assumed, the agent was assumed to exit in a *Non-Competitive* manner, using only the defined non-emergency routes (i.e., a single lane).

10.2 Results

A total of four model scenarios were evaluated. Three scenarios involved subjecting the passenger rail car to roll angles of: +10 degrees, -12.5 degrees, and -22.5 degrees. These angles were selected since they fall on either side of critical thresholds that require the model to access different data sets. The fourth scenario involved subjecting the passenger rail car to both +15 degrees of roll and a smoke-filled environment. Within each of these scenarios, four separate checks on the agent's mobility and travel speed were performed. The location of each of these checks were carefully chosen, since at each location the agent was subjected to different angles of both roll and pitch, which would thus affect mobility differently. These checks were conducted when the agent was:

- Moving along the car aisle (agent only experiences the effect of roll),

- Moving into the vestibule (agent experiences the effect of both roll and pitch),
- In the vestibule (agent only experiences the effect of pitch), and
- Outside the passenger rail car on the high platform (agent experiences no roll or pitch).

The agent within each model scenario was initially located towards the center of the car and was assumed to have a *Fast Walk* travel speed of 4.9 ft/s (1.5 m/s) and be able-bodied (i.e., have an initial *Mobility* value of 1.0). The agent was also assumed to respond instantly to the call to egress (i.e., did not experience delays prior to commencing his or her egress).

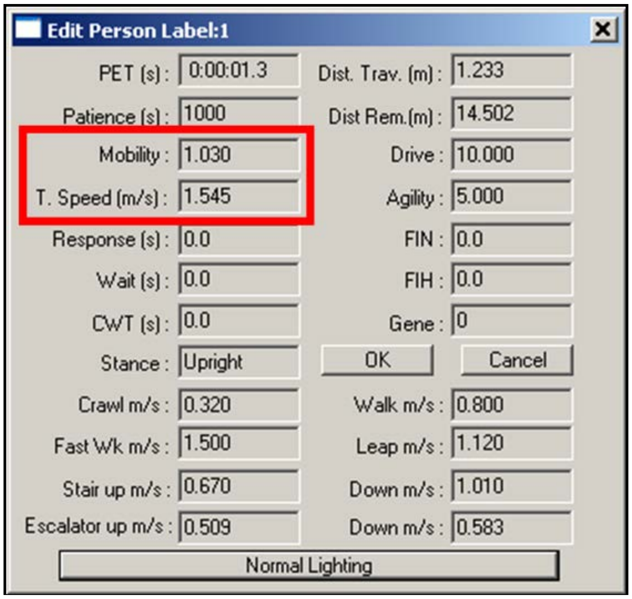
Each model scenario was run only once, as the purpose of the scenarios was purely to verify that the exposure of an agent to a given roll angle results in their corresponding mobility and travel speed being correctly modified which can be ascertained from running and interrogating a single simulation for each scenario.

In order to calculate the respective *Roll* and *Pitch Factors*, and thus determine the agent's adjusted *Mobility* and *Travel Speed*, it is first necessary to determine the effect that each individual variable (i.e., age, gender, etc.) has on the agent's *Mobility* at each given roll angle. A representative example is shown for Scenario 1 to determine the effects of roll at a roll angle of 10 degrees.

As described in Chapter 9, the overall effect of roll angle on an agent is a combination of both the effects of age and gender. According to the gender mobility factor tables (derived from analysis of the maritime experiment egress trials, the effect on a male (i.e., the *Roll Gender Factor*) when traversing a flat terrain at 10 degrees of roll is 1.020. This indicates that the horizontal travel speed is actually slightly higher than it is at zero angle of roll. Similarly, according to FAA-developed age mobility factor tables (see Appendix E), the effect on a 25-year old agent (i.e., the *Roll Age Factor*), as categorized within the $15 < \text{age} \leq 65$ years old age group when traversing a flat terrain at 10 degrees roll is 1.010.

At 10 degrees of roll, the combined effect of age and gender results in a *Roll Factor* of 1.03 (using Equation (12) from Chapter 9, 1.020 x 1.010). The mobility of the agent is then determined to be 1.03 (using Equation (10) from Chapter 9, where the initial mobility is given as 1.0). The modified travel speed for this agent at this roll angle is thus 5.1 ft/s (1.54 m/s) (using Equation (11) of Chapter 9, 1.03 x 1.5 m/s). This result is then compared with the results produced by the Prototype railEXODUS Software V2.2 when simulating the same scenario (see Figure 62). Figure 62 shows the simulation results and correctly shows that the mobility of the agent is 1.030 and the travel speed is 1.54 m/s.

This analysis was conducted for each of the four roll angle scenarios for each of the four agent locations and demonstrated that the Prototype Software V2.2 functions as intended.



PET (s) : 0:00:01.3
Dist. Trav. (m) : 1.233
Patience (s) : 1000
Dist Rem.(m) : 14.502
Mobility : 1.030
Drive : 10.000
T. Speed (m/s) : 1.545
Agility : 5.000
Response (s) : 0.0
FIN : 0.0
Wait (s) : 0.0
FIH : 0.0
CWT (s) : 0.0
Gene : 0
Stance : Upright
Crawl m/s : 0.320
Walk m/s : 0.800
Fast Wk m/s : 1.500
Leap m/s : 1.120
Stair up m/s : 0.670
Down m/s : 1.010
Escalator up m/s : 0.509
Down m/s : 0.583

Figure 62. Scenario 1 (+10 degrees): Observed Mobility and Travel Speed at Location 1

10.3 Summary

Since passenger rail car experimental data concerning the egress performance of individuals subjected to various roll angles were not available, it was not possible to perform a detailed software validation analysis.

However, the results from these verification simulations demonstrate that the movement speeds of agents exiting from a passenger rail car subjected to prescribed angles of roll and pitch and smoke density are correctly adjusted and are consistent with the maritime industry ship egress experiment data sets used. These results verified that the Prototype Software V2.2 functions as intended.

11. Summary

The FRA-sponsored research study to develop a new Prototype railEXODUS Software capable of simulating time-based egress performance of U.S. passenger rail cars has been successfully completed. Each of the objectives of the contract has been met, resulting in the development of the Prototype Software V2.2.

The Prototype Software V.2.2 is currently in “alpha” version, since that it has only undergone in-house testing by FSEG and has been subjected only to limited external third-party (Volpe Center) “beta” testing.

11.1 New Prototype railEXODUS Software V2.2 Development

The new Prototype Software V2.2 was developed based on modifications to the prototype railEXODUS software V1.0 that have been implemented to permit its use to predict egress times from U.S. passenger rail cars.

FSEG analyzed the results of the series of single-level passenger rail car egress experiments conducted by the Volpe Center in 2005 and 2006 [4]. Volpe Center egress trials provided data for the following scenarios:

- Exit flow rates for egress from a rail car for Exit to High Platform station using one or two side-door exits and for egress from a car door Exit to Adjacent Car using inter-car end-door exits;
- Exit time frequency distributions for Exit to Low-Platform and Exit to R-O-W locations; and
- Participant travel speeds within the rail car.

The Volpe Center egress trial data and other data, as available, were incorporated within the EXODUS evacuation model environment. Since data for egress of participants from passenger rail cars subjected to angles of roll were not available, the data incorporated into the model were derived from the maritime industry for passenger ships. These data were selected because of the availability of the data set and the similarity between the experimental conditions in which the maritime data were generated and the target rail conditions. These data have also been used to verify and validate the new Prototype Software, where appropriate.

The new Prototype railEXODUS Software development was implemented in three phases.

- The first phase of the development extended the prototype railEXODUS software V1.0 by incorporating the Volpe Center 2005 and 2006 experiment egress data and appropriate behaviors associated with participant use of side-door exits to move onto high platforms and inter-car end-door exits to move to an adjacent high platform, in non-competitive conditions, with normal and emergency lighting conditions. Since egress under emergency conditions may be expected to be more urgent (i.e., competitive), the capability to represent competitive evacuation behavior was included, albeit without a corresponding comprehensive data set. This development resulted in the Prototype Software V2.0.

- The second development phase involved the extension of the capabilities of the new Prototype Software V2.0 by incorporating data and appropriate behaviors for passenger car egress, using side-door exits to low platform and to R-O-W locations. This further development resulted in the Prototype Software V2.1.
- The third development phase involved extending the capabilities of the new Prototype Software V2.1 to include the capability to model the movement of individuals within passenger rail cars subjected to adverse angles of roll (e.g., overturned). These modifications resulted in the Prototype Software V2.2.

11.2 Model Verification and Validation

In addition to developing the new Prototype railEXODUS Software V2.2, an extensive verification and validation study was completed to demonstrate that each version of the new software functioned as intended and was capable of producing indicative numerical predictions of passenger egress performance. The study included the comparison of:

- Numerical predictions produced by the new Prototype Software with numerical data derived from the Volpe Center egress trials (e.g., total egress times, exit time histories, etc.);
- Emergent agent behaviors produced by the new Prototype Software, with behaviors observed in the Volpe Center egress trials (e.g., degree of bunching in car aisle, single-file movement in the car aisle, etc.); and
- Performance parameters assigned to agents or objects by the new Prototype Software with expectations (e.g., mobility factors resulting from roll angle, maximum exit flow rates, etc.).

11.2.1 Verification Analysis

11.2.1.1 *Exit to High Platform and Exit to Adjacent Car*

In all but one case, the average exit flow rates produced by the Prototype Software for the Exit to Exit to Adjacent Car and Exit to High Platform in normal and emergency lighting scenarios were within the range measured in the 2005 Volpe Center egress trials:

- In the Exit to Adjacent Car in emergency lighting scenario, the predicted average exit flow rate was 1 percent lower than that measured in the Volpe Center egress trials.
- While just outside the range of measured values, the discrepancy is small and is within 10 percent of the measured values.

Agent behaviors observed in the simulation of the one side-door Exit to High Platform in normal lighting scenario closely match the observed behaviors within the corresponding egress trial video. These behaviors include the:

- Spacing between free walking agents;
- Manner in which the free walking region eventually moves down the car with time; and

- Manner in which agents standing between seat rows gain entry to the aisle as the free walking region extends to their location.

11.2.1.2 *Exit to Low Platform and Exit to R-O-W*

There is good agreement between the predicted and measured exit travel time probability distribution for the Exit to Low Platform scenario:

- It is noted that as the number of simulations increases, and thus individual travel times, increase, so does the degree of agreement between the predicted and measured probability distributions.
- After 10 simulations (i.e., 840 agents passing through the Exit to the Low platform), the distribution of predicted travel times closely matches that measured in the egress trials.

There is good agreement between the predicted and measured exit travel time probability distribution for the Exit to R-O-W scenario:

- It is noted that as the number of simulations increases, and thus individual travel times increase, so does the degree of agreement between the predicted and measured probability distributions.
- After 10 simulations (i.e., 840 agents passing through the exit to low platform), the distribution of predicted travel times closely matches that measured within the egress trials.

11.2.1.3 *Movement in Overturned Cars*

The movement speeds of agents subjected to prescribed angles of roll and pitch and smoke density are correctly adjusted and are consistent with the maritime industry ship data set used.

11.2.2 Validation Analysis

11.2.2.1 *Exit to Adjacent Car and Exit to High Platform*

The predicted time for a fully loaded passenger rail car for the Exit to Adjacent Car and Exit to High Platform scenarios, in normal or emergency lighting conditions, under non-competitive egress conditions, was within 11 percent of the exit times measured in the 2005 Volpe Center egress experiment trials.

- While the time for the first agent to exit was predicted to within 20 percent of the measured egress times, this parameter is highly dependent on the response time distribution used in the simulations and that which occurred in the trial. In the simulations, an instant response time was used, while in the egress trials, participants had a small but non-zero response time. As a result, the predicted time for the first agent to exit is expected to be faster than the measured value.

- Furthermore, the average predicted time for the last agent to cross the rail car mid-point was between 2 and 11 percent of the time measured in the Volpe Center egress trials for the Exit to High Platform and Exit to Adjacent Car scenarios in normal and emergency lighting conditions.

The exit time history curves for the inter-car end-door Exit to Adjacent Car scenarios;, and the Exit to High Platform (one and two side-door exits), in normal and emergency lighting conditions, as predicted by the Prototype Software V2.2, is similar to the experimental curves produced from the 2005 Volpe Center egress data. In all cases, the software predictions are within the ±10 percent experimental variation window:

- The average predicted time for the agents to commence free walking in the aisle was between 7 and 21 percent of the time measured in the Volpe Center egress trials for the Exit to Adjacent Car scenarios and Exit to High Platform, in normal and emergency lighting conditions.
- This average predicted time is within the range of acceptability given the uncertainties in personal attributes of the participants and demonstrates that the new prototype railEXODUS software is capable of providing a reasonably accurate representation of the detailed behavior of occupants for egress from passenger rail cars under different exiting conditions.
- Furthermore, the trends in the Volpe Center egress experimental results in which the longest times to commence free walking by participants who are located furthest away from a working exit are also reproduced by the simulations.
- The average aisle population density in the Exit to Adjacent Car in normal lighting conditions trial was over-predicted by 12 percent.
    - It is noted that the determination of aisle density from the experimental trial video is difficult and subject to error.
    - As a result, the estimated population density derived from the egress trial video data, especially in high density regions, is only approximate.

11.2.2.2 *Exit to High Platform and Exit to R-O-W*

- All but one of the first 10 exit time history curves for the Exit to Low Platform scenario predicted by the Prototype Software fall within the ± 10 percent variation experimental envelope for the majority of the trial time.
    - The occasional variations from the ± 10 percent experimental variation envelope are due to statistical anomalies that resulted from the inability of the relatively small number of experimental egress trials to generate the wide variations in exit time histories that are possible.
    - Because of the statistical variability within individual simulations, it is more appropriate to compare the predicted average exit curve with the experimentally derived envelope. The predicted average exit curve for 10 and 250 repeat simulations both fall within the ±10 percent experimental variation envelope.

  - The predicted average exit flow for the Exit to Low Platform scenario, generated from 10 and 250 simulations, was 40.2 ppm and 39.0 ppm, respectively. The average exit flow rate measured from five repeat egress trials was 39.0 ppm.
- The majority of the first 10 exit time history curves for the Exit to R-O-W scenario predicted by the Prototype Software fall within the ±10 percent variation experimental envelope for the majority of the egress trial time.
  - The occasional variation from the ±10 percent experimental variation envelope are due to statistical anomalies that resulted from the inability of the relatively small number of experimental egress trials to generate the wide variation in exit time histories that are possible.
  - Because of the statistical variability within individual simulations, it is more appropriate to compare the predicted average exit curve with the experimentally derived envelope. The predicted average exit curve for 10 and 250 repeat simulations both fall within the ±10 percent experimental variation envelope.
  - The predicted average egress flow rate for the Exit to R-O-W scenario, generated from 10 and 250 simulations, was 21.0 ppm and 19.8 ppm, respectively. The average exit flow rate measured from five repeat egress trials was 19.2 ppm.

11.2.2.3 *Angle of Roll*

Since passenger rail car experimental data concerning the egress performance of individuals subjected to various roll angles were not available, it was not possible to perform a detailed software validation analysis.

11.2.3 Summary

The results from this study verify that the Prototype Software V2.2 functions as intended and produces simulated egress behavior, which is consistent with that observed in the 2005 and 2006 Volpe Center egress trials. Furthermore, the study validates that detailed numerical predictions of quantifiable egress parameters, such as total exit times, exit time histories, aisle population density, etc., as produced by the Prototype Software V2.2 for an upright single level passenger car, are a reasonably accurate representation of those parameters, as measured in the Volpe Center egress trials.

11.3 New Prototype railEXODUS Software V2.2 Capabilities

Additional modeling capabilities were incorporated into the prototype railEXODUS software V1.0 to permit the new Prototype Software V2.2 to provide a reasonably accurate representation of occupant egress behavior under different passenger rail car exiting conditions. The new Prototype Software V2.2 software addresses the egress scenarios identified in Reference 16, as summarized in Table 21.

Where “sufficient data available” is highlighted a sufficient amount of rail specific data are available, enabling a reasonable amount of confidence in the predictive capability of the new Prototype Software V2.2. When “additional data desirable” is highlighted, while some data are

Table 21. Prototype Software V2.2 Passenger Rail Car Egress Scenarios

EGRESS CONFIGURATION	NORMAL LIGHTING	EMERGENCY LIGHTING	NON-COMPETITIVE	COMPETITIVE	MULTI-LEVEL	FIRE CONDITIONS	CAR WITHIN TUNNEL	INCLINED CARS
Car—Car	√√√	√√	√√√	√	√√	√√√	√√	√
Car Door Exit—High Platform	√√√	√√	√√√	√	√√	√√√	√√	√
Car Door Exit—Low Platform	√√√	√√	√√√	√	√√	√√√√	√√	√
Car Door Exit—R-O-W	√√√	√√	√√√	√	√√	√√√	√√	√

Table Key:

√ : Capability exists within software, appropriate data required
√√ : Capability exists within software, additional data desirable
√√√ : Capability exists within software, sufficient data available

currently available that can be used to undertake simulations, additional data would be required in order to have a reasonable amount of confidence in the predictive capability of the simulations produced by the new software.

Finally, when “appropriate data required” is highlighted (i.e., competitive and inclined car situations), while the modeling capability exists within the Prototype Software V2.2, no passenger rail car-specific data are currently available. Accordingly, while the Prototype Software V2.2 can be used to simulate the indicated scenario, there is low confidence in the reliability and accuracy of the simulation results.

While much important data were generated in the Volpe Center egress experiment trials (see Chapter 4), additional data are still required to fully utilize the capabilities of the Prototype Software V2.2 (see Section 4.6 for recommendations for further experimental data).

11.4 New Prototype railEXODUS Software V2.2 Applications

Nevertheless, notwithstanding the restrictions identified above, a wide range of potential applications of the Prototype Software V2.2 to U.S. passenger rail cars exists, including:

- **Design Applications**. Passenger rail car design engineers could use the software in early stage design to optimize the level of evacuation safety built into new passenger rail car designs. For example the location, type, and number of exits could be evaluated.
- **Regulating Applications**. Regulatory agencies, in consultation with industry groups, could use the software to define performance-based evacuation requirements for different types of railroad operating environments.
- **Certification Applications**. Industry groups could use the software to determine whether new passenger rail car designs comply with performance-based egress requirements.

- **Passenger Train Crew Training and Emergency Management Aid**. Passenger train operating agencies could use the software (with its virtual reality graphical capabilities) as an aid in the evacuation safety training of train crews. The software could also be used to assist operating agencies in the development of operating procedures in the event of emergency situations. The software could also assist emergency response organizations to plan their response.
- **Accident Investigation**. Accident investigators could use the software to assist in the analysis of accidents and other emergency situations.
- **Normal Operations**. Passenger rail car design engineers, train operating agencies, and station managers could use the software to simulate normal operations, including the train-station interface and the efficiency of loading and disembarkation.

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APPENDIX A. Literature Review Summary

FSEG completed a detailed review of the literature relating to emergency egress from passenger trains, as well as aviation and maritime passenger transportation systems. The primary purpose of this review was to identify publicly available data relating to the performance of both individuals and transportation vehicle systems during emergency egress, to support the development of the new Prototype Software.

This appendix summarizes the key findings of the review. Chapter 3 of the FSEG-prepared technical report contains additional extensive explanation relating to accident data and data bases; egress experiment results; and evacuation model development and historical use to predict egress time [1]. (Note: References for this appendix are contained in Section A5.)

A.1 ACCIDENT DATA

A1.1 Passenger Trains

Information reviewed was obtained from U.S. National Transportation Safety Board (NTSB) [2] and the United Kingdom (UK) Rail Accident Investigation Board (RAIB) accident reports [3], as well as journal papers, accident inquiry reports, independent studies and related press articles. The majority of the NTSB reports focus on factors relating to the cause of the accident and recommendations for future accident prevention. The UK approach is similar, addressing engineering factors and causes and liability, rather than evacuation. Many accident reports contain little or no data relevant to evacuation. A second limitation, particularly within the UK system, is the delay time between the accident and full inquiry report. In their review of accident reports from 1988–2003, Cokayne and Whiteman [4] noted that very little information about consequences to passengers, including evacuation, was included. Furthermore, some data are not published in a form that is amenable to use in egress modeling. (The technical report prepared by FSEG for this contract contains additional information relating to passenger rail accidents [1].

Although the review of the accident data determined that the majority of passenger train accident reports contained little or no details of passenger behavior in relation to egress or emergency evacuation, several common issues were identified:

- Since emergency egress situations seldom occur when the train is at a platform, it is important to consider alternate egress routes.
    - Internal egress, in which passengers move from a place of danger to a place of relative safety within the train or from car to adjacent car, often occur.
    - External egress routes to the R-O-W, using the side doors or wind.
- Structural deformation damage resulting from the incident can eliminate normal means of egress, such as side-door exits, car to car egress routes, and interconnecting stairways in multi-level cars.
- Passengers may be thrown about in an accident and injured. These injuries may make self-evacuation impossible.

- Passenger rail cars may overturn in accident situations making evacuation difficult in accidents in which the rail car has overturned; it may be difficult or impossible for passengers to travel between cars even when the cars have not decoupled.
- Passenger rail cars may be inclined at an adverse angle in accident situations. The angle of orientation at which the cars come to rest and their decoupling may make evacuation routes difficult.
- The external physical environment in which the accident takes place can have an impact on the ability to evacuate a passenger rail car.
- In some circumstances, fire may spread rapidly through the passenger rail car, exposing survivors to fire hazards such as smoke, heat, and toxic gases, making rapid egress essential.
- Low visibility due to smoke, dust, and obscured windows may hamper rapid egress of survivors even in daylight conditions.
- In accidents that occur at night, emergency lighting may assist passengers to assess their circumstances and find suitable exit routes, which may positively affect the evacuation efficiency.
- Passenger rail car windows may be used as an egress route by passengers, and ladders may be necessary to reach passengers trapped in multi-level cars or when the car s overturned at an angle.
- In some accidents, a significant number of passengers may be forced to exit through windows;
  - Of those exiting through windows, a significant number may exit from the high side of the overturned car;
  - Access to and egress through windows may be made more difficult due to the orientation and position of the car. If the car has overturned, the only way to exit the car may be through the windows that are now in the ceiling area;
    - Use of emergency windows can be very difficult when located on an upper level of a multi-level car; and
    - Multilayer windows make it difficult for passengers and even emergency crew to evacuate passengers via windows (as the windows are more difficult to break);
- Low levels of visibility due to smoke, dust, and failure of emergency lighting may hamper movement.
- Fire may spread rapidly through the car, exposing survivors to fire hazards;
- Egress from an upright or partially or fully overturned car (s) environment:
  - Internal egress from car to adjacent car using an end door,
  - External egress using:
    - Side doors to a high or low platform, or the R-O-W, or
    - Car windows.

Since data were limited or non-existent, the following specific scenarios were selected for incorporation into the new Prototype Software for passenger car egress time prediction:

- One or two side-door exits onto a high platform in normal or emergency lighting conditions,
- One or two side-door exits in normal lighting conditions to:
  - Low platform or
  - R-O-W;
- Inter-car end door-exit into the adjacent car in normal or emergency lighting conditions; and
- Passengers subjected to adverse angle of roll.

A1.2 Aircraft and Passenger Ships

A considerable amount of potentially relevant evacuation data is available from other forms of transportation, in particular aviation and maritime data. The data available from these sources concern both accident analysis and experimental egress trials. The technical report prepared by FSEG for this contract contains additional extensive descriptions of aircraft and maritime egress experiments [1].

A.2 TRANSPORTATION VEHICLE EGRESS EXPERIMENTS

A.2.1 Passenger Trains

The collection of passenger rail car experimental data is essential to address the human factors issues related to passenger rail car egress. For U.S. passenger rail cars, data involving aisle movement rates, flow rates through exits onto high platforms, low platforms and the R-O-W, and inter-car end door exits to an adjacent car were generated in the Volpe Center egress experiments conducted in 2005 and 2006.

However, with the exception of the Volpe Center egress experiments [5], the majority of the other publicly available documents describing rail car evacuation experiments contain limited information relating to detailed experimental results. While it is difficult to generalize conclusions relating to egress human factors from the available information, to ensure a high level of model reliability for the new Prototype Software, sufficient data to characterize human performance in passenger rail car-specific environments is necessary. For example, data are required relating to flow rates achieved by a representative population in traversing passenger rail car side-door exits: Where the vertical drop may vary from no distance (high platform) to several ft (m) down to the R-O-W:

- Through inter-car door exits to an adjacent car; and
- During low levels of visibility due to smoke, dust, and failure of emergency lighting, which may hamper individual and group movement.

In addition, data for car design-specific features, such as aisle and exit widths; movement rates along passenger rail car aisles; passenger exiting behaviors, etc., are required. Since the majority of the passenger car experimental data were not intended for the development of a rail egress model, that data lacks the majority of this detailed information. Furthermore, except for the

Volpe Center 2005 and 2006 experiments, available experimental data does not relate to U.S.-specific passenger train operating environments.

While this type of data can be used to characterize passenger performance, more rail car-specific data are required for different situations, such as participant behavior in multi-level cars, adverse vehicle orientations, smoke environments, and exiting via emergency windows. Until passenger rail-specific human factors data are collected, similar data derived from aviation and maritime evacuation experiments were identified that may be used in the development of a rail-car-specific egress model. For example, in the maritime environment, data have been collected for participant movement in corridors and on stairways, while at adverse orientations and in different smoke conditions [6] [7]. However, caution must be used when interpreting results produced using these data since these data sets are limited in size and focus only on certain aspects of human performance and behavior; additionally, the passenger rail car environment is different from ship and aircraft environments.

It may be necessary for individuals in actual passenger train emergencies to:

- Travel through cars that are oriented at adverse angles;
- Use windows to exit the car; and
- Exit through smoke-filled environments.

Data relating to human performance under these conditions must also be collected if the new Prototype Software can be reliably used in these more realistic accident scenarios.

While some of this data are beginning to be collected, more is required to increase the reliability of the new model software predictions.

Finally, it is noted that evacuation experiments introduce an artificial element to the behavior of participants since they are often specially selected and usually forewarned of the nature of the experiments. Furthermore, it is not practical or ethical to submit participants to the full range of situations that may be encountered in real accident situations. Despite these shortcomings, egress experiments offer the best opportunity to quantify human performance in emergency situations.

The technical report prepared by FSEG for this contract contains additional extensive descriptions of passenger rail egress experiments [1].

A.2.2 Aviation and Marine

There are two major facilities capable of conducting large-scale aircraft evacuation experiments that are located at the FAA Civil Aerospace Medical Institute (CAMI) in the United States and Cranfield University in the United Kingdom. The primary purpose of these facilities has been to address operational or regulatory issues associated with aircraft evacuation.

Real-scale experiments have been used in the maritime industry to collect data on human performance at adverse angles of orientation or under dynamically changing conditions. The majority of this data is proprietary and has been used in the development of ship evacuation models.

Several full-scale ship evacuation experiments are reported in the publicly available literature. Full-scale experimental egress trials are rare due to the difficulties involved in conducting such trials at sea.

The technical report prepared by FSEG for this contract contains additional extensive descriptions of aircraft and maritime egress experiments [1].

A3. EGRESS MODELS

A.3.1 Overview

Attempts to model evacuation fall into two main categories of models, those which consider only human movement, the so-called “ball-bearing” models, and those which attempt to link movement with behavior. The first category of model concentrates solely on the carrying capacity of the structure and its various components. The “ball-bearing” model (also referred to as environmental determinism [8] has individuals treated as unthinking objects that automatically respond to external stimuli while evacuating. Furthermore, the direction and speed of egress is determined only by physical considerations (e.g., population densities, exit capacity, etc.). The second category of model considers not only the physical characteristics of the structure but treats the individual as an active agent, taking into consideration response to stimuli, such as the various fire hazards, individual behavior, exit preference, etc.

A variety of modeling methodologies are available to represent these different categories of evacuation model. Within the modeling methodologies, there are also a number of ways in which to represent the geometry, population, and behavior of the individuals. These different approaches have led to the development of a wide variety of different evacuation models which can be categorized according to the underlying methodologies used to represent:

- Nature of model application – optimization, risk assessment, or simulation;
- Enclosure representation – coarse network, fine network, and continuous approach;
- Population perspective – individual or global; and
- Behavioral perspective – functional analogy behavior, implicit behavior, rule based behavior, artificial intelligence based behavior, or no behavioral component.

Further details relating to this description of evacuation model structure can be found in [1] [9] [10] [11].

A3.2 Model Application to Passenger Rail Car Egress

The majority of current literature concerning evacuation modeling relates to the simulation of evacuation from the building environment, with a small number relating to aircraft and maritime evacuation models.

Building evacuation model applications extend to include evacuation from transportation infrastructures such as airport terminals, rail stations, subway stations, and tunnels. Readers are referred to one of the several published reviews of building evacuation models for further information [10] [11] [12] [13] [14]. Only one of these reviews [14] discusses the application of building evacuation models to the rail infrastructure. Some of the building egress models have been used to simulate evacuation from passenger rail cars. However, none of these building-specific models have the necessary human performance data or capabilities to address the passenger rail car-specific egress environment.

Evacuation models have been developed for aircraft and ship applications. From a modeling perspective, several of the currently available aircraft and maritime evacuation models may have a number of features in common with passenger rail car egress; however, the passenger train operating environment is significantly different.

A more recent review completed for FRA describes egress variables and computer models [15] as they could be applied to passenger rail car evacuation. (The technical report prepared by FSEG for this contract contains an extensive review of building, aircraft, and maritime models [1].)

With the exception of the prototype railEXODUS V1.0 software, very little information has historically been publicly available for passenger rail car-specific egress. The prototype railEXODUS software V1.0 has been under development since the early 2000s and, as noted in Chapter 2 of this report, has been adapted from the buildingEXODUS software to incorporate many capabilities of that software, such as the ability to consider egress to high platforms, multi-level car design, and impact of fire on passengers.

However, neither the prototype railEXODUS software V1.0, nor the building, aircraft, and maritime-specific EXODUS models can characterize and quantify human performance and the nature of the passenger rail car environment to permit accurate prediction of passenger rail egress times. For example, the prototype railEXODUS software V1.0 does not possess data that characterizes and quantifies human performance in passenger rail car-specific operating environments. These egress environments can include egress to low platform locations and the R-O-W, as well as egress from passenger rail cars that are inclined at an adverse angle (overturned).

A4. SUMMARY

The literature review identified issues associated with passenger rail car egress resulting from past rail accident human factors data derived from passenger rail, aircraft, and maritime vehicle egress experiments, as well as computer models to simulate evacuation from rail, aircraft, and maritime environments.

Analysis of past passenger train accidents identified several issues in emergency evacuation situations which influence the way individuals will behave and the resulting human dynamics. Emergency evacuation scenarios include: internal egress from one car to another; external egress to the R-O-W; egress from overturned cars; all under potential low levels of visibility due to smoke, dust and failure of emergency lighting; which all may hamper individual movement.

Accordingly, to accurately simulate passenger rail car evacuation for a variety of emergency scenarios, the new Prototype Software must have the capabilities to address how passengers behave and the resulting human dynamics, and to represent the unique passenger train operating environment in order to accurately predict passenger rail car egress time.

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APPENDIX B. Volpe Center Commuter Rail Car Egress Experiments

This appendix contains a more complete summary description of the 2005 and 2006 Volpe Center commuter rail egress experiment trials, as discussed in Chapter 4 of this report. A complete description of the Volpe Center-conducted passenger rail car experiment egress trials is contained in the original Volpe Center report.*

B.1 2005 HIGH PLATFORM/INTER-CAR EGRESS TRIAL SUMMARY

Volpe Center staff conducted an experiment consisting of a series of 12 experimental egress trials to obtain human factors data related to exit from a single-level passenger rail car. Three basic egress scenarios were conducted relating to egress from a commuter rail car:

- Egress from a commuter rail passenger car (# 1531) through one side-door exit onto a high-level train platform,
- Egress from a car (# 1531) through two side-door exits onto a high-level train platform, and
- Egress from one car (# 1531) to an adjacent passenger car (also referred to as inter-car end-door exit egress).

All three passenger rail car egress trials were conducted under normal and emergency lighting conditions. In addition, each egress trial was repeated using the same participant population, resulting in a total of 12 experimental egress trials. The egress trial sequence is summarized in Table B1. All 12 egress trials were conducted on the same day and within a 1-hour time period.

A total of 84 participants were recruited from the population of passengers who traveled regularly to the North Station commuter rail station (see Table B2). All 84 participants took part in each of the egress trials (with the exception of the first egress trial in which 81 participants were involved).

Table B2 contains demographics of the participants in term of age, weight, and gender.

Each participant wore a vest with an ID number on its front and back and was assigned to different seats during each of the 12 egress trials, providing a total of 81–84 participants during all one-door exit egress trials (i.e., one side-door exit and inter-car door exit) and 41–43 participants during the two side-door exit egress trials (i.e., approximately half the population using each of the doors).

Figure B1 shows the schematic arrangement of the two commuter rail cars and the platform used for the high platform egress experiments at North Station.

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* Markos, S.H. and J. K. Pollard. *Passenger Train Emergency Systems: Single Level Commuter Rail Car Egress Experiments*. Prepared by Volpe Center/U.S. DOT for FRA/U.S. DOT. Final report. In FRA report approval process. 2014.

Table B1. Volpe Center Passenger Rail Car Experiment Egress Trial Sequence

EGRESS TRIAL #	DESTINATION	LIGHTS
1	Platform—1 side door exit	Emergency
2	Adjacent car—end door exit	Normal
3	Platform—2 side door exits	Emergency
4	Platform—2 side door exits	Normal
5	Platform—side door exit	Normal
6	Adjacent car—end door exit	Emergency
7	Platform—1 side door exit	Emergency
8	Adjacent car—end door exit	Normal
9	Platform—2 side door exits	Emergency
10	Platform—2 side door exits	Normal
11	Platform—1 side door exit	Normal
12	Adjacent car—end door exit	Emergency

Table B2. Participant Demographics

GENDER	MALE	FEMALE			
	52%	48%			
Age	30 yrs and below	31–50yrs	Over 50 yrs		
	30%	40%	30%		
Height	5 ft and below	5 ft–5 ft, 6 in	5ft, 6 in–6 ft	Over 6 ft	
	1%	47%	39%	13%	
Weight	100 lb and below	100–149 lb	150–199 lb	200–249 lb	250 lb and above
	1%	29%	55%	12%	3%

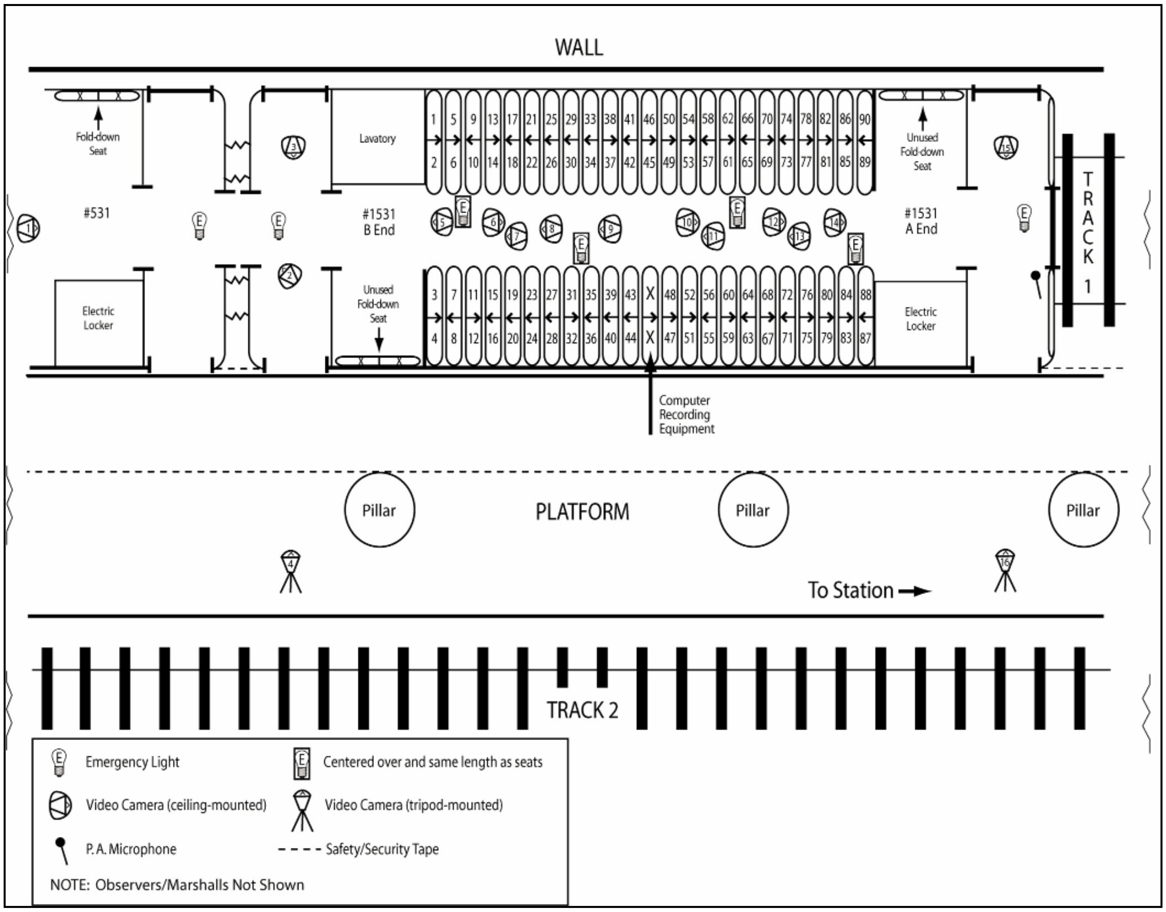


Figure B1. Volpe Center 2005 Experiment Passenger Rail Car Configuration Showing Seat Numbering and Camera Locations

The performance of the participants during the egress trials was recorded using 13 video cameras positioned on the interior ceiling of the passenger rail car and three tripod-mounted cameras located just outside each operating door on the platform (see Figure B1 and Figure B2). After each of the egress trials, each participant also completed a questionnaire (see Chapter 4).

(a) Interior Ceiling

(b) Exterior Platform

Figure B2. Video Cameras Used in Egress Trials

B.2 2006 EGRESS TRIALS SUMMARY

A series of two experimental egress trials were conducted at the Boston Maintenance Facility in Somerville, MA, by Volpe Center staff in 2006 to obtain human factors data related to the egress from a passenger rail car. The first series of egress trials (conducted on April 19, 2006) involved the egress of a group of 15 participants to a location simulating the R-O-W, and the second series of egress trials (conducted on May 31, 2006) involved the egress of a group of 17 participants to a location simulating a low platform station. Each series of egress trials were conducted for about 1 hour during daylight hours.

B.2.1 Exit to R-O-W

During the first series of egress trials, participants were asked to exit from the commuter rail car via an open side-door exit and step down onto the R-O-W using the car's door integral stairway. Due to health and safety concerns, an additional small yellow step was placed on the ground beneath the last step from the passenger rail car. This step box reduced the distance that participants had to descend and therefore reduced the risk of injury. Figure B3 shows the interior of the passenger rail car, the exit with side door integral stairway used by each participant to exit from the car, and the yellow step box used to decrease the distance of the final step to ground (via a pallet placed for stability).

Figure B3. Exit to R-O-W: Passenger Rail Car Interior View and Yellow Step Box / Wooden Pallet and Ballast / Ground Step Area

The single-level passenger rail car used in these egress trials was different from the one used in both the Exit to Low Platform egress trials and the 2005 egress trials. In particular, the seating configuration with the passenger rail car was 3-2, with the aisle off center (see Figure B4). The car interior configuration did not play a role in these exiting trials, but it is noted that the side door was narrower. This can be seen clearly in Figure B5.

(a) Exit to R-O-W Egress Trials (b) Exit to Low Platform (and 2005) Egress Trials

Figure B4. Passenger Rail Car Internal Seating Configurations

(a) Exit to R-O-W (b) Exit to Low Platform

Figure B5. Passenger Rail Car Side-Door Exit Used in the Egress Trials

The car side-door stairway consisted of four steps, producing a total stairway step distance (from the side-door sill threshold to the bottom step) of 33 in (83.8 cm). The drop from the bottom step to the R-O-W (without the step box/pallet) was 25 in (63.5 cm), and the bottom step to step box was 16 in (40.6 cm).

To collect the egress trial data, video cameras were set up to record the participants as they exited from the passenger rail car. The entire exiting process, from start to finish, was captured using three tripod-mounted video cameras (see Figure B5 and Figure B6).

Two series of egress trials were conducted. The first series of egress trial involved 15 participants who individually exited from the commuter rail car, one at a time. Each of these egress trials was repeated five times, with participants requested to take different seating positions. The exiting order changed for each trial, providing a total of 75 individual data points. The second series of egress trials involved the same 15 participants exiting from the rail car (from seated positions) as a group. Each of these egress trials was also repeated five times, with participants again requested to take different seating positions so that the exiting order changed for each trial. (See Table B3 through Table B5 for participant demographic data.)

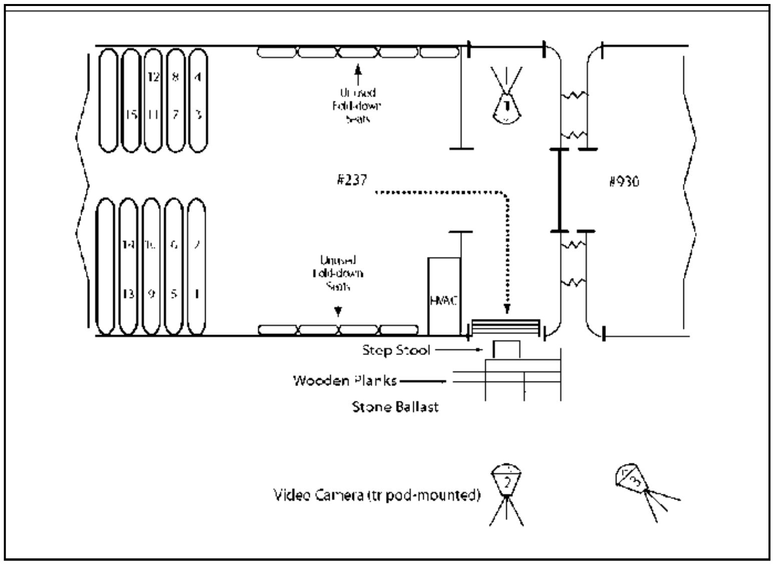


Figure B6. Exit to R-O-W: Video Camera Locations

Participants again requested to take different seating positions so that the exiting order changed for each trial. (See Table B3 through Table B5 for participant demographic data.)

Five participants were over the age of 50, one female participant weighed more than 250 lbs, and one participant had a mobility impairment. One person also participated in the May 2006 egress trials and another person participated in the August 2005 egress trials.

Table B3 shows the percentage of individuals in each age group.

Table B3. Exit to R-O-W: Participant Age Distribution

AGE BAND	PERCENTAGE (NUMBER)
Less than 30 years	13.33% (2)
Between 30 and 50 years	53.33% (8)
Greater than 50 years	33.33% (5)
TOTAL	15

Table B4 shows the percentage of individuals in each weight group.

The data in Table B5 show the specific demographic information for each participant.

Table B4. Exit to R-O-W: Participant Weight Distribution

WEIGHT BAND	PERCENTAGE (NUMBER)
100–149 lb (45.4–68.0 kg)	33.3% (5)
150–199 lb (68.0–90.7 kg)	40.0% (6)
200–249 lb (90.7–113.4 kg)	20.0% (3)
Greater than 250 lb (>113.4 kg)	6.7% (1)
TOTAL	15

Table B5. Exit to R-O-W: Participant Demographics

VEST	GENDER	AGE	HEIGHT (ft)	WEIGHT (lb)	COMMUTER
1	F	30–50	5.0–5.6	200–249	Y
2 *	F	> 50	5.7–6.0	200–249	N
3	M	30–50	5.7–6.0	200–249	Y
4	F	> 50	5.0–5.6	100–149	N
5	M	< 30	5.7–6.0	100–149	Y
6	M	30–50	6.0	150–199	Y
7	M	> 50	5.7–6.0	150–199	N
8	F	> 50	5.0–5.6	> 249	N
9	M	30–50	5.0–5.6	150–199	Y
10	F	30–50	5.0–5.6	150–199	Y
11	M	< 30	5.7–6.0	100–149	N
12	F	30–50	5.0–5.6	100–149	Y
13**	M	30–50	6.0	150–199	N
14	F	> 50	5.0–5.6	150–199	Y
15	M	30–50	5.0–5.6	100–149	N

* Participated in 5-31-06 egress trial.

** Participated in 8-25-05 egress trial and in 5-31-06 egress trial.

B.2.2 Exit to Low Platform

The second series of egress trials, conducted on May 31, 2006, used 17 participants and were for passenger rail car egress to a low platform station location. Participants were directed to exit from the rail car via a side-door and step down onto a low platform using the car door integral stairway. Figure B7 shows the car interior, as well as the side-door integral stairway used by participants to exit from the car. The type of passenger rail car used in these egress trials was identical to the car used in the 2005 Volpe Center experiment. (See Figure B5 for a view of the participant exiting the car to the low platform.

Figure B7. Exit to Low Platform: Passenger Rail Car Interior and Side-Door Exit

The car side-door stairway consisted of four steps, producing a total stairway step distance (from side-door sill threshold to bottom step) of 33 in (83.8 cm). The drop from the car stairway bottom step to the low platform was 15 in (38.1 cm). The car side-door stairways' vertical dimensions were identical to those in the R-O-W trials, with the only difference being in the final drop. As in the R-O-W egress trials, this distance was 16 in (40.6 cm) from the bottom of the side-door stairway step to the safety step box, 25 in (63.5 cm) from the bottom of the car side-door stairway step to the safety step box, and 25 in (63.5 cm) from the bottom of the car side-door integral stairway step down to the ballast via the pallet. In contrast, the drop from the last side-door integral stairway step from the car to the low platform was 15 in (38.1 cm).

As done for the R-O-W egress trials, three tripod-mounted video cameras were used to collect the exiting data (see Figure B7 and Figure B8).

Two types of egress trials were conducted. The individual egress trials were each repeated five times followed by the group egress trials repeated five times. In total, 85 individual egress trials and five group egress trials were conducted.

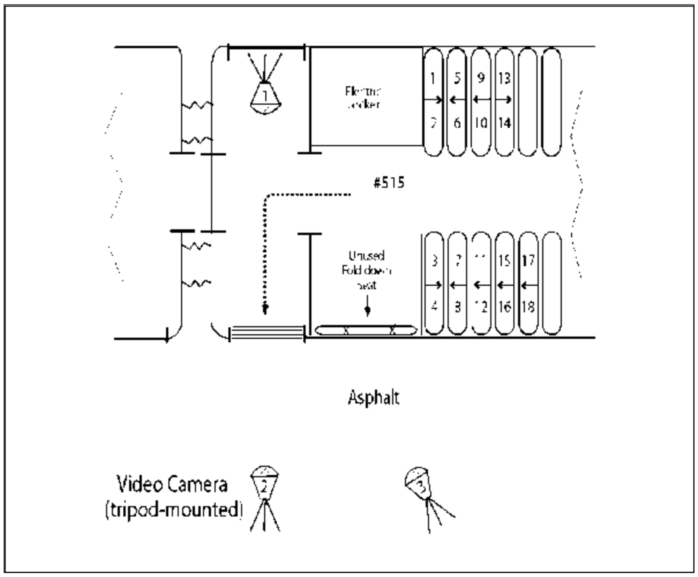


Figure B8. Exit to Low Platform: Video Camera Locations

Table B6 shows the percentage of the individuals in each age group.

Table B6. Exit to Low Platform: Participant Age Distribution

AGE BAND	PERCENTAGE (NUMBER)
Less than 30 years	41.2% (7)
Between 30 and 50 years	35.3% (6)
Greater than 50 years	23.5% (4)
Total	17

Table B7 shows the percentage of the individuals in each weight group.

Table B7. Exit to Low Platform: Participant Weight Distribution

WEIGHT BAND	PERCENTAGE (NUMBER)
100–149 lb (45.4–68.0 kg)	17.7% (3)
150–199 lb (68.0–90.7 kg)	47.1% (8)
200–249 lb (90.7–113.4 kg)	35.3% (6)
Greater than 250 lb (>113.4 kg)	0.0% (0)
Total	17

The data in Table B8 show the specific demographic information for each participant.

Table B8. Exit to Low Platform: Participant Demographics

VEST	GENDER	AGE	HEIGHT (ft)	WEIGHT (lb)	COMMUTER
1*	F	30–50	5.0–5.6	150–199	Y
2	M	30–50	>6.0	200–249	N
3*	F	> 50	>6.0	200–249	Y
4	F	< 30	5.0–5.6	100–149	
5	M	30–50	5.7–6.0	150–199	Y
6	M	> 50	5.0–5.6	150–199	Y
7	M	< 30	>6.0	200–249	N
8	M	30–50	5.7–6.0	150–199	N
9	M	< 30	>6.0	150–199	Y
10	F	< 30	5.0–5.6	100–149	Y
11 **	F	> 50	5.7–6.0	200–249	N
12	F	30–50	5.0–5.6	150–199	Y
13	M	> 50	5.7–6.0	200–249	N
14	M	30–50	>6.0	150–199	Y
15	M	< 30	5.0–5.6	100–149	N
16	M	< 30	5.0–5.6	150–199	N
17 ***	F	< 30	5.7–6.0	200–249	N

* Participated in 8-25-05 egress trials.

** Participated in 9-19-06 egress trials.

*** Observer for 8-25-05 egress trials.

APPENDIX C. Volpe Center Egress Experiment Quantitative Data

Chapter 4 of this report describes the FSEG review and analysis of the 2005 and 2006 Volpe Center-conducted egress experiment trial data. This appendix contains certain data generated from that review as discussed in that chapter, but presented in table format.

C1. 2005 EGRESS EXPERIMENT TRIALS

C.1.1 Seat To Aisle Movement Times

Table C1 presents a summary of the 226 data points measured from the Volpe Center provided-egress trial video for the seat to aisle movement analysis. The primary purpose of this analysis was to determine the time required to enter the aisle and to start free movement in a crowded or fully occupied situation. In several cases, where the cells are shaded, the required data could not be obtained from the video recording due to poor lighting, camera angles, or obscuration of the participant vest numbers. Furthermore, in a number of cases (shown in gray), the data were determined to be unrepresentative.

Table C1. T1, T2 and T3 for Various Seat Locations, Various Door Locations –Emergency and Normal Lighting—2005 Volpe Egress Trials

ORDER	DOORS	LIGHTS	TRIAL T1/T2/ T3	ROW									
				2 (A)	2 (W)	6 (A)	6 (W)	12 (A)	12 (W)	17 (A)	17 (W)	22 (A)	22 (W)
First	One (side)	Emer	1:T1	3.3	11.6	3.3	23.0	2.2	40.7	4.7	58.8	☒	3.2
			1:T2	1.2	1.3	20.2	1.0	39.1	6.5	52.7	1.8	☒	75.0
			1:T3	4.5	12.8	23.5	24.0	41.3	47.2	57.4	60.6	☒	***78.2***
		Non-Emer	5:T1	8.0	13.9	3.8	20.7	5.2	38.2	4.7	55.8	2.9	6.7
			5:T2	1.2	0.8	16.3	0.9	32.2	0.7	46.1	0.8	66.8	64.7
			5:T3	9.1	14.7	20.1	21.6	37.4	38.9	50.8	56.6	69.7	***71.4***
	One (inter-car)	Emer	6:T1	1.8	2.6	2.4	13.3	2.3	5.9	1.9	☒	3.5	72.8
			6:T2	0.6	0.8	13.8	4.8	34.8	31.4	51.3	☒	65.7	0.8
			6:T3	2.4	3.4	16.2	18.1	37.1	37.3	53.2	☒	69.2	***73.6***
		Non-Emer	2:T1	6.0	12.8	2.1	6.1	3.1	6.0	3.9	56.9	4.1	75.9
			2:T2	2.8	0.7	10.9	12.5	33.6	32.5	47.0	1.2	65.7	1.1
			2:T3	8.9	13.5	13.0	18.6	36.7	38.5	50.8	58.1	69.9	***77.0***
	Two	Emer	3:T1	7.3	9.2	5.1	23.0	3.5	6.7	2.5	4.2	2.7	4.0
			3:T2	1.3	2.3	14.5	0.9	34.3	31.8	15.7	21.0	1.0	0.7
			3:T3	8.6	11.5	19.6	24.0	37.8	***38.5***	18.2	25.2	3.7	4.7
		Non-Emer	4:T1	2.8	5.0	2.4	6.5	3.0	6.2	2.3	22.3	2.2	6.5
			4:T2	2.8	0.2	10.6	10.0	32.8	27.2	15.3	1.3	1.7	0.8
			4:T3	5.5	5.2	13.0	16.5	***35.9***	33.4	17.6	23.6	3.9	7.2
Second	One (side)	Emer	7:T1	2.8	6.0	3.8	6.5	1.5	☒	3.5	6.6	2.9	69.3
			7:T2	1.4	0.9	13.3	11.1	26.3	☒	41.6	40.4	63.8	1.3
			7:T3	4.1	6.9	17.1	17.7	27.8	☒	45.0	47.0	66.8	***70.5***
		Non-Emer	11:T1	2.8	5.0	1.4	2.6	2.2	3.8	4.8	48.0	5.6	65.5
			11:T2	1.6	4.9	14.1	17.2	35.0	34.8	46.3	1.9	59.7	1.0
			11:T3	4.4	9.9	15.5	19.7	37.2	38.6	51.1	49.9	65.3	***66.5***
	One (inter-car)	Emer	12:T1	2.2	4.9	2.8	16.0	1.5	4.0	1.6	☒	9.7	69.6
			12:T2	1.6	2.9	12.8	1.0	28.8	29.4	44.7	☒	57.0	1.0
			12:T3	3.8	7.8	15.6	17.0	30.3	33.3	46.3	☒	66.7	***70.6***
		Non-Emer	8:T1	3.6	10.0	3.1	21.7	2.8	43.9	4.0	51.8	4.5	72.5
			8:T2	2.7	0.6	17.2	0.9	38.9	1.1	46.8	0.9	65.3	3.9
			8:T3	6.3	10.7	20.4	22.6	41.7	45.0	50.8	52.7	69.8	***76.4***
	Two	Emer	9:T1	2.6	7.3	2.5	22.4	☒	8.3	1.6	27.2	3.3	5.5
			9:T2	4.2	3.5	17.8	1.3	☒	29.8	16.2	1.2	1.1	1.0
			9:T3	6.8	10.8	20.3	23.7	☒	***38.1***	17.8	28.4	4.4	6.5
		Non-Emer	10:T1	1.7	10.5	2.0	4.0	1.8	3.0	1.6	5.7	☒	☒
			10:T2	7.9	1.2	16.5	15.8	35.7	34.8	19.5	23.2	☒	☒
			10:T3	9.6	11.6	18.5	19.8	37.5	***37.8***	21.1	28.9	☒	☒

Note: The maximum value for each trial is in bold/italics.

C2 2006 R-O-W AND LOW PLATFORM EGRESS TRIALS

C2.1 R-O-W

Table C2 shows the exit times in seconds for participant o step down from the passenger rail car and onto the R-O-W for the individual Exit to R-O-W egress trials.

Table C2. Exit to R-O-W: Individual Egress Trials – Exit Times

PARTICIPANT	EGRESS TRIAL 1 (s)	EGRESS TRIAL 2 (s)	EGRESS TRIAL 3 (s)	EGRESS TRIAL 4 (s)	EGRESS TRIAL 5 (s)	MEAN (s)
1	6.00	6.13	5.97	6.73	6.07	6.18
2	13.70	11.53	11.63	11.17	9.97	11.60
3	4.47	4.43	4.47	4.50	5.40	4.65
4	3.47	4.50	4.20	3.97	3.97	4.02
5	1.73	* N/D	* N/D	2.03	1.90	1.90
6	2.57	2.03	2.47	2.03	2.60	2.34
7	3.17	3.10	3.17	3.30	3.37	3.22
8	5.30	6.50	7.80	7.73	6.73	6.81
9	3.03	3.00	3.27	3.40	3.30	3.20
10	3.90	3.97	3.73	3.80	3.47	3.77
11	3.50	3.27	3.33	3.07	3.13	3.26
12	4.67	4.00	4.53	4.57	4.50	4.45
13	4.47	4.73	4.23	4.37	*N/D	4.45
14	3.80	4.87	4.50	4.10	4.07	4.27
15	10.37	12.33	9.17	9.40	9.83	10.22
MIN	1.73	2.03	2.47	2.03	1.90	
MAX	13.70	12.33	11.63	11.17	9.97	
MEAN	4.94	5.31	5.18	4.94	4.88	
STANDARD DEVIATION	3.13	3.05	2.61	2.66	2.50	

* N/D are discarded data points.

Table C3 shows the exit time data compiled for the group Exit to R-O-W egress trials.

Table C3. Exit to R-O-W: Group Egress Trials – Exit Times

PARTICIPANT	EGRESS TRIAL 1 (s)	EGRESS TRIAL 2 (s)	EGRESS TRIAL 3 (s)	EGRESS TRIAL 4 (s)	EGRESS TRIAL 5 (s)	MEAN (s)
1	4.97	6.07	5.47	6.57	4.70	5.55
2	9.30	10.07	10.10	9.37	8.60	9.49
3	3.63	3.27	3.60	2.90	3.30	3.34
4	5.67	4.73	4.23	3.90	4.40	4.59
5	2.73	5.83	3.40	3.07	2.80	3.57
6	3.47	3.83	3.37	4.13	1.93	3.35
7	2.53	3.23	6.47	2.93	1.90	3.41
8	8.53	6.90	5.37	5.10	4.73	6.13
9	4.00	6.50	4.30	3.30	3.13	4.25
10	3.20	4.87	4.43	3.60	4.57	4.13
11	4.27	5.17	3.63	3.10	6.00	4.43
12	3.60	4.57	4.20	3.93	3.97	4.05
13	7.97	4.57	3.87	3.23	4.13	4.75
14	2.80	6.87	3.97	3.97	3.07	4.13
15	9.17	8.73	9.17	10.27	9.93	9.45
MIN	2.53	3.23	3.37	2.90	1.90	
MAX	9.30	10.07	10.10	10.27	9.93	
MEAN	5.06	5.68	5.04	4.62	4.48	
STANDARD DEVIATION	2.46	1.92	2.06	2.32	2.25	

Table C4 shows the Exit to R-O-W exit flow rates for the group egress trials.

Table C5 shows the exit time probability distribution as it is used in the new Prototype Software.

Table C4. Exit to R-O-W: Group Egress Trials – Exit Flow Rates

EGRESS TRIAL #	AVERAGE FLOW RATE (ppm)
1	19.8
2	17.4
3	18.6
4	19.2
5	20.4
MIN	17.4
MAX	20.4
AVERAGE	19.2

Table C5. Exit to R-O-W: Exit Time Probability Distribution

TIME (s)	PROBABILITY
1–2	0.031
2–3	0.099
3–4	0.379
4–5	0.260
5–6	0.107
6–7	0.061
7–8	0.023
8–9	0.015
9–11	0.016
11–14	0.009
TOTAL	1.000

C.2.2 Egress to Low Platform

Table C6 shows the exit times in seconds for each participant to step down from the passenger rail car side-door exit and onto the low platform for the individual egress trials. A total of 85 data points were collected but three data points were discarded because of the participants incorrectly exiting the passenger rail car (according to the procedural definitions in Section 4.4.1).

Table C7 shows the exit time data collected for the Exit to Low Platform egress trials.

Table C8 shows the egress flow rates for the Exit to Low Platform group egress trials.

Table C9 shows the combined individual and group Exit to Low Platform exit times and probability distribution.

Table C10 shows the exit time probability distribution for the Exit to Low Platform exit times as used in the Prototype Software V2.1.

Table C6. Exit to Low Platform: Individual Egress Trials – Exit Times

PARTICIPANT	EGRESS TRIAL 1 (s)	EGRESS TRIAL 2 (s)	EGRESS TRIAL 3 (s)	EGRESS TRIAL 4 (s)	EGRESS TRIAL 5 (s)	MEAN (s)
1	1.97	2.13	2.00	2.03	1.93	2.01
2	0.87	1.43	1.27	1.50	1.47	1.31
3	2.23	2.13	2.37	2.23	2.20	2.23
4	1.50	1.77	*N/D	1.83	1.73	1.71
5	1.73	1.73	1.60	1.57	1.57	1.64
6	2.63	2.53	2.43	2.50	2.37	2.49
7	1.30	1.33	1.20	1.33	1.37	1.31
8	1.40	1.37	1.63	1.90	1.43	1.55
9	1.60	2.07	1.97	1.80	1.67	1.82
10	*N/D	1.27	1.40	1.53	1.27	1.37
11	6.80	7.27	6.30	5.50	5.03	6.18
12	1.73	1.70	1.60	1.57	1.70	1.66
13	2.43	2.77	*N/D	2.87	2.53	2.65
14	1.43	1.47	1.20	1.73	1.63	1.49
15	1.37	1.17	1.40	1.50	1.30	1.35
16	1.73	2.00	1.63	1.53	1.57	1.69
17	1.40	2.07	2.17	2.10	1.80	1.91
MIN	0.87	1.17	1.20	1.33	1.27	
MAX	6.80	7.27	6.30	5.50	5.03	
MEAN	2.01	2.13	2.01	2.06	1.92	
STANDARD DEVIATION	1.35	1.40	1.25	0.97	0.88	

* N/D are data points that were discarded.

Table C7. Exit to Low Platform: Group Egress Trials – Exit Times

PARTICIPANT	EGRESS TRIAL 1 (s)	EGRESS TRIAL 2 (s)	EGRESS TRIAL 3 (s)	EGRESS TRIAL 4 (s)	EGRESS TRIAL 5 (s)	MEAN (s)
1	2.00	1.77	2.47	2.13	1.80	2.03
2	1.00	0.87	1.33	1.37	0.90	1.09
3	1.97	4.97	2.40	2.00	2.03	2.67
4	1.63	1.60	1.73	1.97	2.00	1.79
5	1.40	1.50	3.63	1.47	1.60	1.92
6	2.00	2.30	2.20	2.00	1.80	2.06
7	1.30	1.90	1.63	2.87	1.43	1.83
8	1.47	1.37	1.83	1.73	1.43	1.57
9	1.73	1.73	1.97	1.43	3.67	2.11
10	1.57	1.23	1.47	1.73	1.50	1.50
11	4.07	5.50	5.73	4.77	4.43	4.90
12	1.63	1.73	1.63	2.03	1.63	1.73
13	3.90	2.33	2.30	2.20	2.60	2.67
14	1.37	1.73	1.40	1.60	1.30	1.48
15	1.50	1.43	1.73	1.33	1.23	1.45
16	2.53	2.40	1.40	1.77	1.53	1.93
17	1.83	1.63	2.07	1.80	1.97	1.86
MIN	1.00	0.87	1.33	1.33	0.90	
MAX	4.07	5.50	5.73	4.77	4.43	
MEAN	1.94	2.12	2.17	2.01	1.93	
STANDARD DEVIATION	0.85	1.24	1.08	0.80	0.89	

Table C8. Exit to Low Platform: Group Egress Trials – Exit Flow Rates

EGRESS TRIAL #	AVERAGE FLOW RATE (ppm)
1	40.8
2	38.4
3	37.2
4	37.2
5	41.4
MIN	37.2
MAX	41.4
AVERAGE	39

Table C9. Exit to Low Platform: Combined Individual and Group Egress Trials – Exit Times

TIME (s)	FREQUENCY	PROBABILITY
0.00–0.75	0	0.000
0.75–1.00	4	0.025
1.00–1.25	5	0.031
1.25–1.50	42	0.264
1.50–1.75	40	0.252
1.75–2.00	27	0.170
2.00–2.25	16	0.101
2.25–2.50	11	0.069
2.50–2.75	5	0.031
2.75–3.00	3	0.019
3.00–3.25	0	0.000
3.25–3.50	0	0.000
3.50–3.75	2	0.013
3.75–4.00	1	0.006
4.00–4.25	1	0.006
4.25–4.50	0	0.000
4.50–4.75	0	0.000
4.75–5.00	1	0.006
5.00–5.25	0	0.000
5.25–5.50	0	0.000
5.50–5.75	0	0.000
5.75–6.00	0	0.000
6.00–6.25	0	0.000
6.25–6.50	0	0.000
6.50–6.75	0	0.000
6.75–7.00	1	0.006
TOTAL	159	0.999

Table C10. Exit to Low Platform: Exit Time Probability Distribution

TIME (s)	PROBABILITY
0.75–1.0	0.025
1.0–1.25	0.031
1.25–1.50	0.264
1.50–1.75	0.250
1.75–2.00	0.170
2.00–2.25	0.101
2.25–2.50	0.069
2.50–2.75	0.031
2.75–3.00	0.019
3.00–4.00	0.020
4.00–5.00	0.012
5.00–7.00	0.008
TOTAL	1.000

APPENDIX D. Maritime Egress Experiment Data

D.1 REAL-SCALE PASSENGER SHIP EGRESS EXPERIMENTS

Real-scale experiments have been used in the maritime industry to collect data on human performance at adverse angles of orientation or under dynamically changing conditions. The majority of this data is proprietary and has been used in the development of ship evacuation models, such as maritimeEXODUS [1] and EvacuShip [2]. Several attempts have been made to generate data under inclination conditions [3] [4] [5] and [6]. (Note: References for this appendix are listed in Section E.2.)

Of these data sources, the first has been published in a form that is not usable in evacuation modeling and the second was limited in size and considered groups of participants rather than individuals. The TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Dutch Organization for Applied Scientific Research)) [5] and SHEBA (Ship Evacuation Behavior Assessment) [6] data sources appear to be the most useful data currently available. However, both these data sets are also limited in size and only focus on certain aspects of human performance and behavior.

The TNO Human Factors group used the TNO Ship Motion Simulator (SMS) to generate data related to the impact of the inclination of a ship on participant travel speeds. Sixty subjects of various ages participated in the experiments, which examined the impact of both trim (pitch) and heel (roll) on movement in a corridor and on stairways. The factors examined in this data are the impact of trim, heel, the direction of travel, and the age of the participants. The TNO facility was rectangular in shape (a shipping container) and fitted with dividers to form three small passages approximately 6.6 ft (2 m) in length that required test subjects to turn at the end to enter the next leg of the passage. The facility also provided a very limited stairway capability, which was restricted by the size of the available space. The entire facility was placed on a hydraulic platform that allowed it to be tilted to various angles of heel and trim. The data should be viewed with caution as the facility does not allow the development of steady state speed in the participants. Furthermore, the stairway was limited so that only a few steps could be taken before the participant was forced to stop. The TNO analysis focused on the parameters of *age, angle of inclination,* and *direction of travel*. Factors such as gender and whether a life jacket was worn or not were not considered. Figure D1 shows the impact of *Age* on the *Pitch Age Factor* for ascending a stairway [8].

To acquire reliable data concerning human performance in static heel conditions, Fleet Technology of Ottawa and FSEG, with funding from the Canadian Transportation Development Centre, developed the SHEBA facility. The SHEBA facility allows measurements of human performance and behavior in a typical ship passageway and stairway.

SHEBA comprises a 23 by 13 ft (7 by 4 m) “cabin” attached to a 33 by 7 ft (10 by 2 m) passageway at the end of which is a stairway. This entire structure was mounted on hydraulic rams capable of tilting the facility to up to 21 degrees. The steel structure reproduces a ship’s corridor and stairway, with handrails (removable) and facilities to insert a doorway with sill, etc. (see Figure D2). Test participants enter the assembly “cabin” at the bottom left of the picture, while the facility is level and the facility is tilted to the test angle only after all participants are inside and have grabbed hold of the structure to secure themselves. Participants travel through

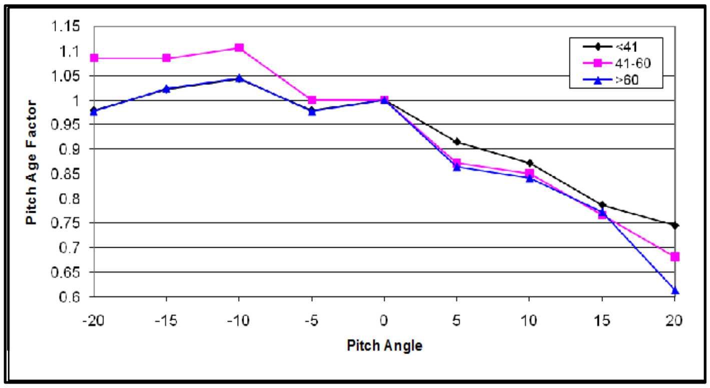
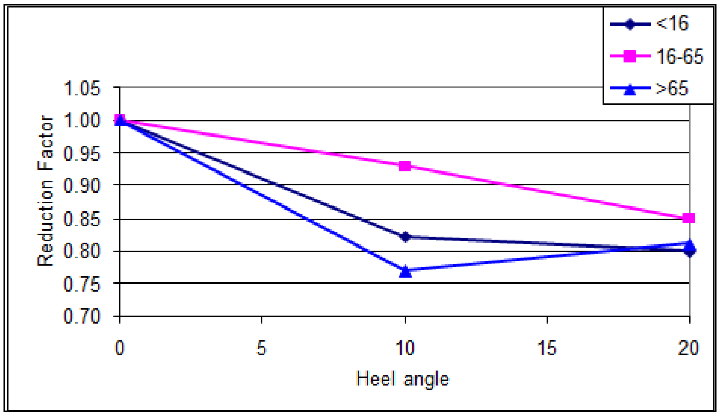


Figure D1. Pitch and Age Factors for Ascending a Stairway Subjected to Pitch Based on Data from the TNO Trials

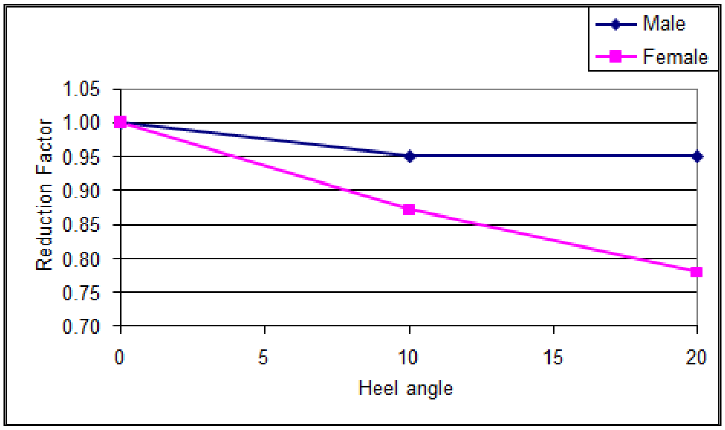
the passageway and the stairways, individually and in groups, and contra-flow conditions are also tested. Tests have been conducted with participants using life jackets and without life jackets.

Figure D2. SHEBA Facility Heeled at 20° with Group Evacuation (left) and with Wheelchair Participant Negotiating a 20° Heel

In addition, a ship-style doorway can be included in the middle of the corridor to allow flow rate calculations to be made under varying conditions of heel. The participant behavior is recorded on video and movement is timed along the passageway and up and/or down the stairways. Participants exit onto a fixed platform at the top of the stairways, designed to ensure that they clear the test area quickly and do not influence those participants still in the test area. Tests have been conducted in both directions. The stairway has been designed to allow its gradient to be varied and the passageway and stairway may be varied in width. An analysis of the raw data generated from the SHEBA experiments is shown in Figure D3 [7]. The linear graph of Figure D3 (a) shows the effect of heel angle on travel speeds for three different age groups < than 15, 16 - 65, and > than 65. The influence of the 10-degree heel slows non-elderly adult movement on the stairways by only about 6%, but children and the elderly are slowed by about 20%. At a 20-degree angle, non-elderly adults were slowed by about 15%, while the walking speed for children and the elderly were reduced by the same 20%. The linear graph of Figure D3(b) shows that at a 20-degree of heel, the walking speed of female participants was slowed to 78% of normal, while at both 10 and 20-degrees of heel, the walking speed of the male participants walking speed was slowed to 95% of normal.



(a) Age Influence on Descending Stairways



(b) Gender Influence on Descending Stairways

Figure D3. Travel Speed Reduction Factors Extracted from SHEBA Trials

While these data have been used for the Prototype Software V2.2 development for passenger rail cars, it is noted there are significant differences between a ship corridor inclined at an angle of heel and a passenger rail car inclined at the same angle. The passenger rail car aisle is separated from the walls of the car by the seats. The seats will make the movement dynamics more difficult than that found in a ship corridor. For example, movement of individuals along the length of the rail car aisle may be restricted to a discontinuous range of inclination angles (e.g., 0^o to Critical Angle 1 and Critical Angle 2 to 90^o). Up to Critical Angle 1, movement will be along the car aisle and at a progressively reduced travel speed as the angle approaches Critical Angle 1. Above Critical Angle 2, movement may be along the car wall, including the windows, which are now located in the floor region. Between Critical Angle 1 and Critical Angle 2, effective movement along the length of the car may be severely restricted. This type of situation cannot be represented in the existing maritime data set. The existing ship data provides an understanding of how individual travel speeds will degrade as the angle of heel increases (i.e., as it approaches Critical Angle 1).

However, whether the degradation in individual travel speeds as angle increases is the same in the rail and ship environment is currently unknown. To address these issues, it would be desirable to perform targeted egress experiments in an environment that simulates a full-scale passenger rail car environment, such as the FRA-funded rollover rig [8].

D.2 FULL-SCALE PASSENGER SHIP EGRESS EXPERIMENTS

Full-scale passenger ship experiment egress trials are rare because of the difficulties involved in conducting such trials at sea. Egress trials provide a means to obtain human factors data to characterize the performance of participants (e.g., response times), demonstrate suitability of evacuation equipment, or provide data for model validation purposes. However, these data are of limited use for passenger rail car egress applications since they are specific to the maritime environment.

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APPENDIX E. FAA Egress Experiment Mobility Factors Data

E.1. FAA CAMI

To address operational or regulatory issues associated with aircraft evacuation, the Federal Aviation Administration (FAA) Civil Aerospace Medical Institute (CAMI) developed a reusable large scale test facility to conduct aircraft evacuation experiments in order to address issues concerning seating density, exit size, passenger flow rates through different types of door and overwing (window) emergency exits, and interaction with cabin crew with passengers during evacuation. (Note: References for this appendix are listed in Section E.2.)

The original CAMI cabin simulator, built in 1968, consisted of a Douglas C124 fuselage section mounted on hydraulically controlled platforms so that various pitch and roll conditions can be simulated [1] [2] [3]. The simulator provides a typical narrow body aircraft style, six-across, economy-class seating configuration, with a 15-inch (38-inch)-wide central aisle and a maximum seating capacity of 80 persons. Some of the earliest studies to make use of the facility involved the investigation of the evacuation capabilities of mobility-impaired passengers from aircraft [1] and the impact of stairways on aircraft evacuation [2].

The work described in Reference 2 includes important data on rates of movement for persons with a variety of disabilities. This data were incorporated into the airEXODUS software using the concept of agent *Mobility*, derived from the mean mobility of the data and calculated by comparing the average rate of movement of persons with various disabilities with their unimpaired movement rate (as shown in Table E1).

E.2 REFERENCES

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Table E1. Mean Mobility as Used in airEXODUS [Derived from Reference 2]

CLASS OF MOBILITY IMPAIRMENT	MOBILITY IMPAIRMENT OR CAUSE OF MOBILITY IMPAIRMENT	NUMBER OF SUBJECTS	MEAN MOBILITY
Neurological	Blindness	21	0.41
	Deafness	5	0.58
	Mental Deficiency	21	0.46
Neuromuscular	Cerebral Palsy	7	0.20
	Old Age	10	0.45
	Paraplegia and Quadriplegia	20	0.20
	Hemiplegia	14	0.12
	Muscular Dystrophy, Multiple Sclerosis and Polio	7	0.30
Orthopedic	Arthritis	5	0.38
	Arm Cast	2	0.78
	Lower-Leg Cast and Amputee	3	0.30
	Congenital Birth Defects	5	0.35
Other	Obesity	9	0.49