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# Evaluation of Egress Models for Passenger Rail Cars for Emergency and Non-Emergency Scenarios

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# METRIC/ENGLISH CONVERSION FACTORS

## ENGLISH TO METRIC

### LENGTH (APPROXIMATE)

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

### AREA (APPROXIMATE)

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

### MASS - WEIGHT (APPROXIMATE)

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

### VOLUME (APPROXIMATE)

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

### TEMPERATURE (EXACT)

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## METRIC TO ENGLISH

### LENGTH (APPROXIMATE)

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

### AREA (APPROXIMATE)

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

### MASS - WEIGHT (APPROXIMATE)

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

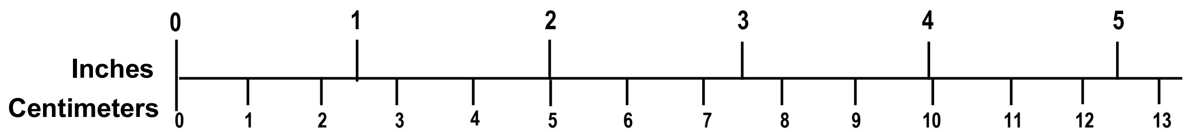
### VOLUME (APPROXIMATE)

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

### TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

## QUICK INCH - CENTIMETER LENGTH CONVERSION




## QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

| °F | -40° | -22° | -4° | 14° | 32° | 50° | 68° | 86° | 104° | 122° | 140° | 158° | 176° | 194° | 212° |
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| °C | -40° | -30° | -20° | -10° | 0° | 10° | 20° | 30° | 40° | 50° | 60° | 70° | 80° | 90° | 100° |

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

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## Executive Summary

The ability to accurately predict and analyze passenger evacuations from rail cars is an important component of the Federal Railroad Administration's (FRA) mission to enable the safe, reliable, and efficient movement of people and goods throughout the United States. Multiple commercial software packages are available for modeling pedestrian behavior in both non-emergency and emergency conditions. Between September 18, 2019, and September 17, 2020, Jensen Hughes conducted this study at its facility in Baltimore, MD, that focuses on two programs, railEXODUS and Pathfinder, and performs a detailed analysis of both programs with respect to their performance and features. In addition, the research team performed the analysis using both egress models to assess the impact of fire conditions on the egress times. Although this report does not recommend one program over the other, it is intended to serve as an informational resource to assist in determining which program is more suited to FRA's requirements.

Thunderhead Engineering developed Pathfinder, was developed by Thunderhead Engineering and is a general-purpose pedestrian modeling software package, while the University of Greenwich in collaboration with FRA developed railEXODUS specifically for egress modeling of passengers in rail cars. This study discusses the unique aspects and challenges of rail car egress modeling along with the capabilities an egress model would need to have to be effective in rail car scenarios. The research team discusses the general features and sub-models of both programs in the context of rail car evacuations. An overview of the egress considerations also includes analyses of previous emergency events and full-scale experiments involving rail car evacuations. Quantitative data from these events have been incorporated into the software modeling strategies.

To compare the performance and user experience of railEXODUS and Pathfinder, a series of example cases have been simulated using both programs and the results have been analyzed. The example cases are based on fully loaded Massachusetts Bay Transportation Authority (MBTA) bi-level rail cars which have a layout that is generally representative of many passenger rail vehicles. The example cases include single-car and three-car setups with emergency (i.e., with fire) and non-emergency scenarios within a rail car. The cases also include evacuation to a high platform (i.e., which is the typical situation for this train style), evacuation to a low platform, and evacuation directly to the ground level (i.e., the right-of-way) that covered variety of operating environments. For every example case, researchers used both railEXODUS and Pathfinder to create a model with inputs that were either identical or as similar as possible. Both programs have different sub-models with different parameter sets. Therefore, while equivalent scenarios can be modeled in railEXODUS and Pathfinder it is not possible to use the exact same inputs in both programs.

In the example cases involving non-emergency evacuations, both programs predicted similar evacuation times for each scenario. The difference in evacuation time between railEXODUS and Pathfinder was mostly within 20 percent of the total evacuation time. However, the differences between the two programs were more pronounced in the emergency scenarios. These scenarios involved multiple simulations with different delay times before the occupants begin evacuating. In these scenarios, railEXODUS consistently predicted that the time the occupants spent moving to the exit (i.e., the total evacuation time with the delay subtracted) is strongly correlated with the delay time. However, the Pathfinder models predicted much less correlation between the delay and the movement time and for most cases predicted a constant movement time regardless of the

delay time. The reasons for this difference are not fully known, but this report discusses potential explanations. It is also unclear which program's results more closely match the real conditions, since experimental or historical data for non-emergency scenarios are not available.

The study concludes with a summary of the potential benefits of both railEXODUS and Pathfinder. RailEXODUS has some rail-specific capabilities and a more detailed toxicity sub-model, but it has not been updated since 2009. The parent software on which railEXODUS is based on is called buildingEXODUS and was updated in 2017. On the other hand, Pathfinder is a user-friendly general-purpose software that is prevalent in many industries and is in active development with frequent updates. In addition, the research shows that the impact of fire conditions on egress times can be significant and a further research effort is required to assess realistic fire scenarios and passenger behavior specific to rail cars. Based on the information obtained during this study, Pathfinder is a capable software package for modeling rail car evacuations and is a potential alternative to railEXODUS for simulating non-emergency evacuations. However, caution must be applied if FRA considers the use of Pathfinder for emergency evacuation scenarios. Additional investigation of Pathfinder is recommended if intended to be used to simulate emergency evacuation.

# 1. Introduction

The Federal Railroad Administration's (FRA) mission is to enable the safe, reliable, and efficient movement of people and goods throughout the United States. To this end, the capability to analyze passenger evacuations from rail cars is of interest to FRA. In addition, industry standards in use in the United States have requirements for rolling stock that relates to the amount of time it needed to evacuate a rail car. Consequently, a method of predicting evacuation times from rail cars would be relevant to both FRA and the passenger rail industry.

## 1.1 Background

A common standard for passenger rail systems in the U.S. is National Fire Protection Association (NFPA) 130 – Standard for Fixed Guideway Transit and Passenger Rail Systems [1]. The standard contains fire protection and life safety requirements for passenger rail systems, including stations, trainways, and vehicles. The chapter regulating vehicles contains requirements for the materials that passenger cars are constructed of as well as fire performance of materials and assemblies. Note the requirement in Section 8.5.1.3.1 related to test assemblies used for establishing fire performance is provided below:

***NFPA 130 (2020) Section 8.5.1.3.1****: Test assemblies shall be representative of the vehicle construction and shall be tested in a configuration to demonstrate that a fire will not extend into the passenger and crew areas during the fire exposure duration.*

Further requirements (e.g., including those specifying the "fire exposure duration") indirectly reference the time required for a vehicle to be evacuated, and indirectly requires a method of determining the evacuation time of a vehicle described in the NFPA requirement below:

***NFPA 130 (2020) Section 8.5.1.3.2****: The minimum fire exposure duration shall be the greatest of the following:*

- *Twice the maximum expected time period under normal circumstances for a vehicle to stop completely and safely from its maximum operating speed, plus the time necessary to evacuate a full load of passengers from the vehicle under approved conditions.*
- *15 minutes for Automated Guideway Transit (AGT) vehicles and low floor vehicles, 30 minutes for all other passenger-carrying vehicles.*
- *15 minutes for all roof assemblies.*

***NFPA 130 (2020) Section 8.5.2****: A fire hazard analysis shall be conducted to demonstrate that fires originating outside the vehicle shall not extend into the passenger and crew areas before the vehicle is evacuated.*

In the fire protection industry, simulation software is routinely used to estimate the evacuation times of buildings and vehicles. Two commercially available programs for simulating pedestrian movement are railEXODUS, developed by the University of Greenwich, and Pathfinder, developed by Thunderhead Engineering. The purpose of this study is to compare both programs and evaluate their effectiveness in simulating the passenger evacuation of rail vehicles along with understanding the impact of fire conditions on the evacuation times.

## 1.2 Objectives

The main objectives of this work are as follows:

- Compare railEXODUS and Pathfinder with respect to their performance and features necessary for modeling rail car evacuation
- Provide information to FRA regarding the suitability of each program for rail car evacuation modeling
- Understand the impact of fire conditions on the evacuation times as predicted by each model

## 1.3 Overall Approach

Researchers performed a literature review to obtain the background information and context necessary for conducting the analysis. The goal of this review was to understand the state of the art of rail car evacuation modeling, ensure that the study is consistent with the current standard of care, and identify differences in approach compared to building evacuation modeling. A review of available data regarding rail car and tunnel evacuation took place, with a particular focus on the following topics:

- Challenges particular to rail car evacuation
- Considerations and standard of care for rail car evacuation models compared to building egress models
- Identification of quantitative egress data (e.g., flow rates, travel speeds, etc.) for use in the example modeling effort

A comparison of the features and capabilities of both programs focused on the necessary features that are unique to the modeling of rail car evacuations, while usability was also commented on.

To evaluate the performance of each program, multiple rail car evacuation scenarios were modeled in both railEXODUS and Pathfinder. To the extent possible, the same geometry, population, and hazard data were used in both programs. Single-car and multiple-car evacuation scenarios were modeled in both non-emergency and emergency settings. The non-emergency simulations were performed with no fire effects data imported into the model. The intention of the non-emergency simulation is to simulate the evacuation of a train in a normal condition or a condition which does not affect the interior environment of the car. The emergency simulations are performed with fire data imported into the model. The difference between the emergency and non-emergency scenarios is the presence of fire effects data in the emergency scenarios. The results were then compared between both models to determine the difference between the two. Non-emergency full scale evacuation data from egress experiments [1] used by the Volpe National Transportation Systems Center (Volpe), FRA, and the University of Greenwich in the development of railEXODUS was used to define the model input parameters but not to validate the models.

## 1.4 Scope

The scope of this effort is limited to the two programs (i.e., railEXODUS and Pathfinder) in the form of their current commercial releases in August 2020. Researchers evaluated the programs in the context of evacuation of rail cars (i.e., typical passenger-rail rolling stock used in the US), with and without consideration of fire effects. Features and capabilities that are unrelated to rail car evacuation are outside the scope of this study, as are pricing/licensing details.

This report is intended as an informational resource that contains objective feature comparisons, results from side-by-side testing, and the authors' opinions as users of both programs. The report does not contain, and is not intended to provide, a definitive statement of which program best fits FRA's needs.

### 1.5 Organization of the Report

The report is divided into six sections based on the different aspects of the research. Section 1 introduces the work performed and what researchers did not include in the research. Section 2 provides an overview of the egress considerations regarding rail car evacuations and quantitative movement data from egress experiments. Section 3 provides a high-level description of the railEXODUS and Pathfinder software packages and introduces concepts that will be important for understanding the detailed comparisons later in the report. Section 4 contains an in-depth comparison of the features in railEXODUS and Pathfinder from the perspective of a user. Section 5 contains a summary of the example egress scenarios that were modeled in both railEXODUS and Pathfinder and a discussion of the results. Section 6 states the overall findings and recommendations.

# 2. Overview of Egress Considerations

The following section summarizes the overview of egress considerations related to evacuation of rail cars. This includes results from experiments, evacuation modeling techniques, and reviews of information from past emergency events.

## 2.1 Challenges Particular to Railway Evacuation

In many ways, simulation of a rail car evacuation is similar in nature to simulation of a building evacuation. However, there are many aspects of a rail car evacuation that are generally not present in buildings. These factors must be considered when performing a modeling analysis, and the software used for modeling should have the capability to support these features in some way.

Many situations common in rail car evacuations are not present in a typical building evacuation. Fridolf, Nilsson, and Frantzich (2013) discuss the major differences between building evacuation and rail car evacuation [2]. For example, typical building evacuation, and typical boarding/exiting of a rail car, involves exiting the structure though a doorway that leads directly to the outdoors at grade level. However, this is frequently not the case during an emergency evacuation of a rail car, as the need to evacuate a train while it is not at a platform is a common occurrence. In this case passengers may need to evacuate to an internal location within the train, to the right-of-way (ROW) or ground level via the exits, or through the windows with or without the aid of a ladder. Use of these non-typical exit elements requires more time than a simple exit door and may not be possible for mobility-impaired passengers. Additionally, operating doors and windows may require special knowledge or tools which the occupants may not possess.

Another situation unique to rail cars is the effect that an accident or derailment could have on the evacuation process. While buildings are also subject to damage that could affect an evacuation, typical building egress modeling is performed with the assumption that the egress systems will remain intact for the time required to evacuate the building (i.e., with an exception to fire blocking certain exits). In rail car egress, an accident that could alter the normal evacuation process is very likely. Such an event could block certain means of egress, injure passengers, de-couple cars such that inter-car travel is impossible, or change the orientation of the rail car such that egress is only possible through one side or the ceiling. An accident could also disrupt the lighting and/or communication systems, affecting both passengers and staff.

## 2.2 Egress Modeling State of the Art

According to Bettelini and Rigert (2012), egress simulations can be generally grouped into either macroscopic or microscopic models [3]. Macroscopic are based on the principles of fluid dynamics and calculate the bulk movement of occupants based on walking speeds, distances, and maximum flow rates. These models are generally the simplest, but do not always provide accurate results in complex scenarios. In contrast, microscopic models calculate the movement of individual occupants through space and can be capable of simulating complex behavior patterns. Both Pathfinder and railEXODUS are examples of microscopic models. Markos and Pollard (2013) reviewed various existing egress models for their capability to predict the time necessary to evacuate U.S. passenger rail cars under various emergency conditions [4].

Egress models are generally validated using data from experiments, since data from actual emergency events is not available in sufficient detail. A comparison of multiple simulation methods showed that the predicted evacuation times were similar when occupant density was low, but varied significantly with the increase of occupant density.

Based on full-scale evacuation experiments performed by Bettelini and Rigert (2012) of inter-city and local trains used in Switzerland, the dominant factors that affected the evacuation time were the distance to the nearest exit, width of the exit path, and the occupant density of the train [3].

## 2.3 Necessary Capabilities of Rail Car Evacuation Models

Due to the unique situations that are frequently present during rail car evacuations, features always necessary when modeling building egress would be necessary for any program used to model rail car evacuations.

To be useful, the rail car evacuation model would need the capability to represent the different types of egress from a rail car: internal egress from car to car, egress to either a high platform or low platform, and egress to the right-of-way (i.e., ground/track level). The model would also need the ability to predict the impact of environmental conditions, such as the impact that fire hazard will have on passenger survivability and mobility, the change in occupant visibility due to fire conditions or lighting failures, and the changes in exit usage due to a partially or fully overturned rail car.

In situations where egress outside of the train itself is being considered (i.e., through a tunnel or station), the model should also have an ability to simulate occupant exit choice. In experiments involving a full-scale evacuation test inside of a tunnel, Fridolf et al. (2016) found that the occupants' choice of exit was influenced by a variety of factors including the exit choice of others, instructions given to them, and their proximity to the exit [5]. Since evacuation scenarios within tunnels often involve large distances between exits, occupant exit choice could have a significant effect on the evacuation and therefore should be considered when traveling in a tunnel. Note that the example cases in this study only consider egress within a rail car itself (i.e., where the exits are much closer together) and therefore are not primarily focused on exit choice.

## 2.4 Quantitative Modeling Data

Both railEXODUS and Pathfinder are based on literature data regarding typical travel speeds when navigating egress elements such as corridors, stairs, and doors. While many of these are applicable to building evacuations, there are also situations in which rail car-specific data is needed. For example, exiting a rail car to a low platform or to the ROW involves taking a large step down which is not common in building evacuations.

FRA and Volpe conducted a series of experimental egress trials in 2005 and 2006 to obtain human factors data relating to the amount of time necessary for passengers to exit from a rail car [1]. The research team conducted these trials on a single level commuter rail car and the experimental data was used as an input for the development of railEXODUS.

In additional full-scale experiments performed on overturned rail cars, a full carriage load of 62 passengers could take between 3 and 14 minutes to fully evacuate depending on the number of available exits and the presence of non-toxic smoke [6]. In the same study, Galea and Gwyne (2000) concluded that there is no fundamental reason that building evacuation models like

EXODUS could not be adapted to model the situations and behaviors critical in rail car evacuations.

As discussed earlier, the width and capacity of egress elements is critical to the modeling of rail car egress scenarios. For railway specific elements like egress to low platforms and ROW, data from egress experiments has been incorporated into the models [1]. Exits can be defined by a flow rate of passengers that can pass through the exit (i.e., persons/minute) and the amount of time it takes for a single passenger to navigate the exit. Since navigating a large step down can take a significant amount of time relative to walking through a doorway, the exits to low platforms and ROW are represented by a maximum flow rate through the exit as well as a delay time applied to each occupant that uses the exit.

# 3. Description of Software

The following section presents a high-level overview of the two software packages. This introduces the basic concepts of each model and provides context for more detailed comparisons in the later sections. In addition, the authors provide information on the fire model used for this work.

## 3.1 railEXODUS

The Fire Safety Engineering Group (FSEG) at the University of Greenwich developed the EXODUS suite of software. The most common program developed by the FSEG is buildingEXODUS with its latest version released in 2017, is an agent-based evacuation simulation software primarily for use in simulating building evacuation. railEXODUS is a variant of EXODUS developed specifically for rail rolling stock and makes use of rail specific human performance data [7]. Both buildingEXODUS and railEXODUS share much of the fundamental calculations and user interface.

The evacuation model in the EXODUS software is comprised of five core sub-models: the Occupant, Movement, Behavior, Hazard, and Toxicity sub-models. A set of rules define the function of each sub-model, and the sub-models interact with one another to predict the results given the inputs.

The spatial domain is represented by a two-dimensional grid, which maps out the geometry of the structure (i.e., including exits, internal compartments, obstacles, etc.). Domains consisting of multiple floor levels are represented by multiple grids connected by staircases. Each grid is made up of nodes and arcs, where a node is a small region of space that an individual can occupy, and an arc is a route by which an individual can travel between two nodes.

The occupant sub-model contains the attributes and variables that define an occupant (i.e., gender, age, walking speed, etc.). These attributes can either be fixed or can change throughout the simulation based on information from other sub-models.

The movement sub-model controls the physical movement of individuals from their current position to a neighboring location. This may include interactions with other individuals or with the environment, such as overtaking, side stepping, or evasive actions.

The behavioral sub-model informs the movement sub-model and is responsible for determining an individual's response to the current situation. This response is affected by an individual's personal attributes and affects both local behavior (e.g., response to local conditions) as well as global behavior (i.e., overall strategy such as exit choice).

The hazard sub-model contains information regarding the physical environment. This includes fire hazard data such as heat, smoke, and toxicity values throughout the spatial domain as well as the status of exits (i.e., open or closed) throughout the duration of the simulation.

The toxicity sub-model uses information from the hazard sub-model to determine the effects on an individual exposed to toxic products and then communicates this information to the behavior sub-model.

## 3.2 Pathfinder

Thunderhead Engineering Consultants, Inc. developed the Pathfinder software package. Like railEXODUS, it is an agent-based egress model. The description in this section is summarized from the Pathfinder Technical Reference released by Thunderhead [8].

Pathfinder has two main modes for simulating occupant motions: Society of Fire Protection Engineering (SFPE) mode and steering mode. The SFPE mode implements the concepts in chapter 58 of SFPE Handbook of Fire Protection Engineering [9], and determines occupant movement speeds in rooms and flow through doors based on occupant density and door width. In steering mode, the effect of density or queue length on movement speed is modeled but interactions between occupants do not occur. For example, an occupant's travel through a doorway can be delayed by a queue, but the occupants queued at the door will overlap each other and do not interact. Examples of the graphical results for steering mode and SFPE mode are shown below in Figure 1 and Figure 2, respectively.

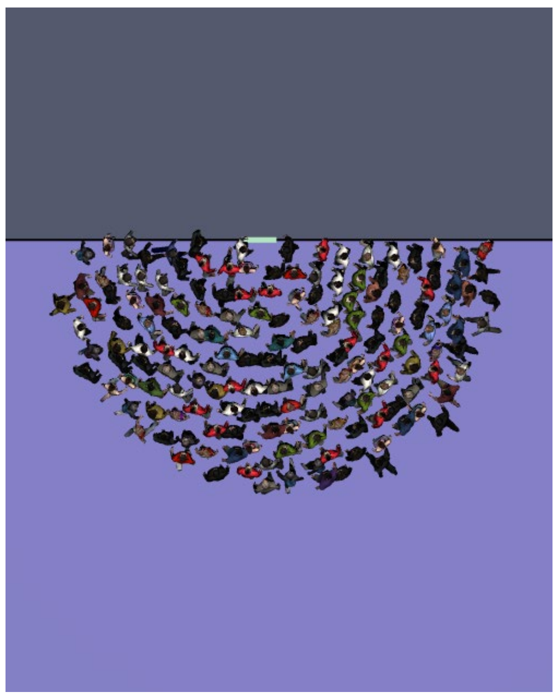

**Figure 1. Example of Pathfinder steering mode results**

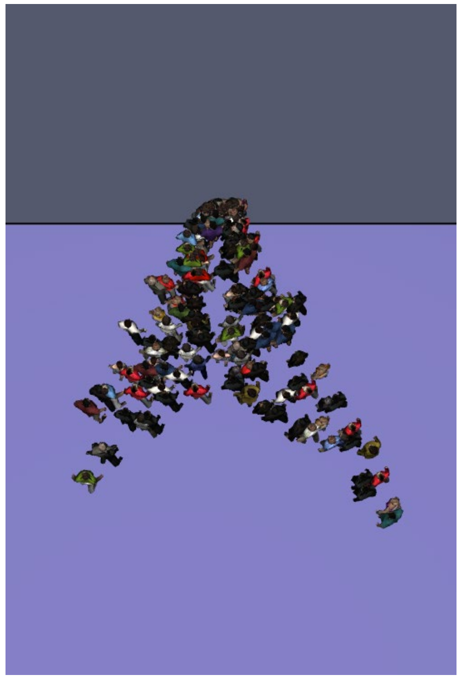

**Figure 2. Example of SFPE mode results**

The steering mode is based on the idea of inverse steering behaviors, which calculates the optimal action for each occupant to take utilizing cost-based heuristics to evaluate each potential action. Steering mode does not rely on explicit door queues or density calculations, but does rely on movement algorithms from which complex behaviors can naturally emerge. In this study, steering mode will be used exclusively when performing egress modeling with Pathfinder.

### 3.3 CFAST

The Consolidated model of Fire and Smoke Transport (CFAST) is a multizone model that predicts conditions within a structure resulting from a user-specified fire. CFAST Version 6 can accommodate up to 30 compartments or zones with multiple openings between them and to the outside. The required program inputs are the geometry data describing the compartments and connections; the thermophysical properties of the ceiling, walls, and floors; the fire as a rate of mass loss; and the generation rates of the products of combustion. The program's outputs are temperature, thickness, and species concentrations in the hot, upper layer and the cooler, lower layer in each compartment. CFAST also includes very limited mechanical ventilation capabilities, a ceiling jet algorithm, capability of multiple fires, heat transfer to targets, detection and suppression systems, and a flame spread model. National Institute of Standards and Technology (NIST) developed and maintains the CFAST model. Researchers modeled the simulations with emergency scenarios involving fire in CFAST and the fire effects were coupled to egress models.

# 4. Comparison of Features

The following section describes in detail the features and capabilities of railEXODUS and Pathfinder. The methods each software uses to model occupant behavior are also discussed.

## 4.1 Basic inputs

Both programs have a graphical user interface to create, modify, run, and view the results of simulations. The graphical interfaces are different in each program, but both include a geometry window for viewing the model and/or results, a navigation window for selecting different elements/modes within the model, and multiple toolbars/menu bars for accessing specific features of the software.

In general, Pathfinder allows the user to select and edit an element of any type (e.g., a room or occupant) from either the navigation window or the geometry window. In railEXODUS, the elements that can be selected and edited are grouped into "modes." The program can be in one of four different modes (i.e., Geometry Mode, Population Mode, Scenario Mode, and Simulation Mode), each of which allow a subset of the model's elements to be selected and edited. Geometry mode allows editing of the spatial domain and elements like the exits and floor levels. Population mode allows editing of the occupants and their parameters. Scenario mode allows for defining fire conditions and assigning portions of the spatial domain affected by the conditions. Simulation mode runs and displays the results of the simulation.

## 4.2 Geometry

Both programs allow the user to either create the simulation geometry manually or to import data from third-party sources.

railEXODUS can import geometry data from four different types of files: computer-aided design (CAD) -based DXF files, BIM/IFC files, Fire Dynamics Simulator (FDS) geometry files, and SMARTFIRE geometry files. The import from FDS is limited to geometry information only, and not the fire effects data and results as described in Section 4.5. After importing the geometry file into railEXODUS, post-processing is required to define the simulation domain. This includes defining the nodes and arcs over which the occupants travel as well as features such as exits, stairways, and the initial location of occupants as shown in Figure 3 and Figure 4 for a single car and a three-car geometry respectively. In the example simulations, CAD drawings of each level were imported into the model and used as the basis for defining the spatial domain. A representative geometry of a single Massachusetts Bay Transportation Authority (MBTA) bilevel rail car along with the nodal locations as modeled in railEXODUS is shown in Figure 3. This setup is extended and is used to represent a three-car MBTA model in railEXODUS, as shown in Figure 4.

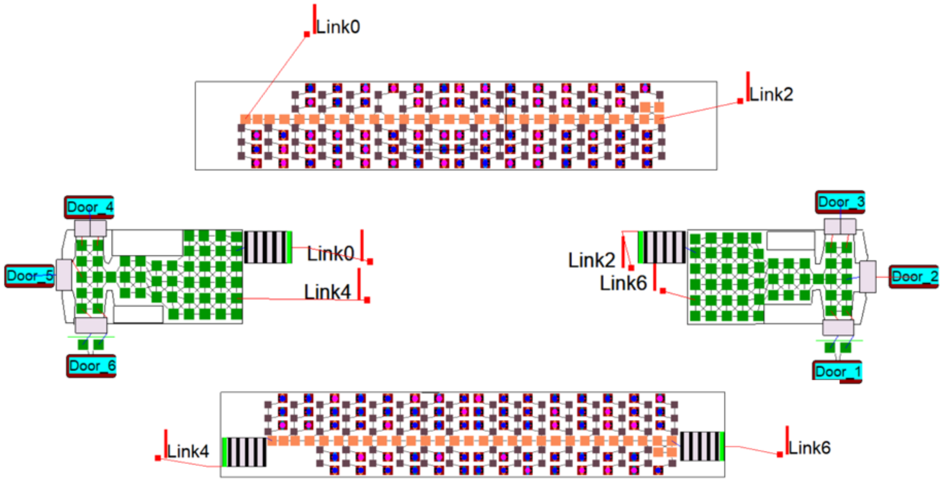


**Figure 3. railEXODUS single-car model**

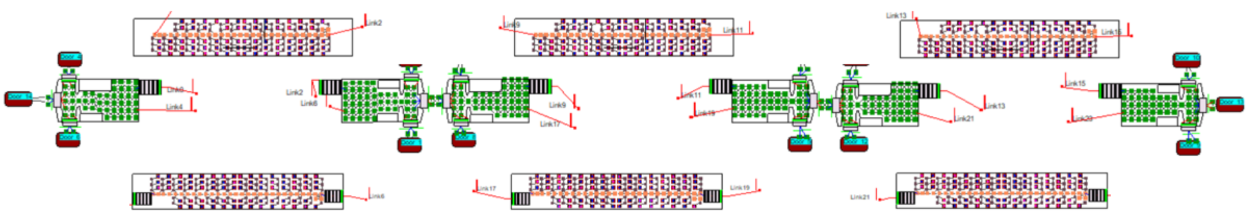

**Figure 4. railEXODUS three-car model**

Pathfinder can import geometry CAD-based DXF and DWG files, FDS geometry files, and multiple image formats (e.g., GIF, JPG, and PNG). Geometric data can be extracted directly from the CAD and FDS files, while the image files can be used as an overlay to assist the user in drawing the building geometry manually. Like railEXODUS, Pathfinder required additional processing to define features such as stairways and exits. Since Pathfinder does not utilize a grid-based spatial domain, the user is not required to define nodes or arcs for occupant movement. Spaces imported into or created within Pathfinder are continuous areas over which occupants can travel in any direction.

CAD drawings of each level were imported into the model and used as the basis for defining the spatial domain for the scenarios modeled in this work. A representative geometry of a single MBTA bilevel rail car along with the occupant locations as modeled in Pathfinder is shown in Figure 5. This setup is extended and is used to represent a three-car MBTA model in Pathfinder, as shown in Figure 6.

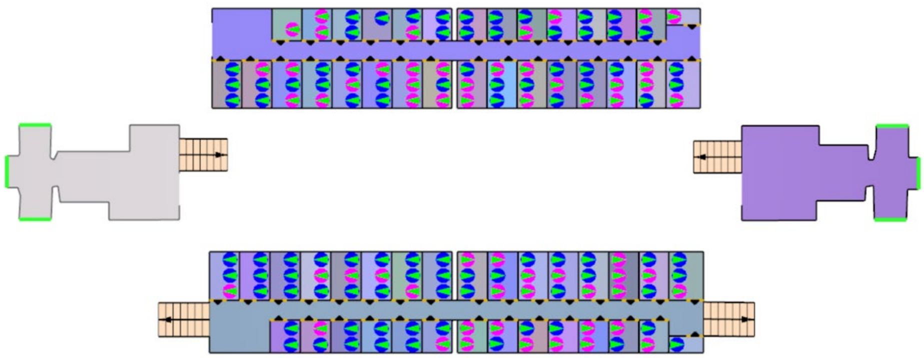

**Figure 5. Pathfinder single-car model**

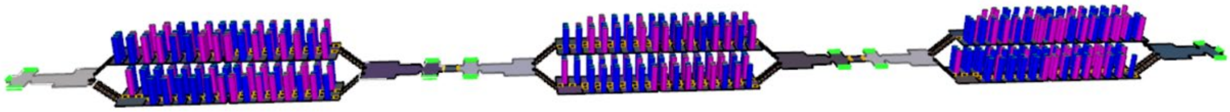

**Figure 6. Pathfinder three-car model**

### 4.3 Occupant Profiles

Both programs allow customization of the parameters that drive occupant behavior. However, the parameter sets are different in both programs due to the differences in their behavioral sub-models.

The occupant characteristics that can be edited by the user in railEXODUS are summarized in Table 1. Parameters that are not specified by the user are left at their default values.

In the example cases described later in this report, attributes such as gender, age, weight, and height (e.g., as well as parameters that are influenced by weight and height) were varied to create a distribution of occupant characteristics. Attributes that were varied are indicated with asterisks in Table 1. The remaining attributes were generally left at their default values.

**Table 1. Summary of railEXODUS occupant parameters**

| Parameter | Description | Range | Default Value |
|---|---|---|---|
| Gender* | Gender of occupant, used in the definition of travel speed and other characteristics | Male or Female | None |
| Age* | Age of occupant, used in the definition of travel speed and other characteristics | 1–100 years | 25 Years |
| Weight* | Weight of occupant, does not directly influence any other | 1–200 kg | 80 kg |

| Parameter | Description | Range | Default Value |
|---|---|---|---|
| | variable but can be used as a guide for correlations | | |
| Height* | Height of occupant, used when fire hazards at specific heights are defined | 1.0–2.0 m | 1.8 m |
| Response Time* | Time that occupant waits before starting to evacuate | 0–10,000 s | 0 s |
| Mobility | Factor multiplied by maximum travel speed to determine actual speed of travel. An occupant with a disability or exposed to fire conditions will have a lower mobility value. | 0.0–1.0 | 1.0 |
| Agility* | Represents ability of occupant to navigate obstacles such as moving over seat backs | 0.0–7.0 | 5.0 |
| Fast Walk Speed* | Speed of occupant when in an aisle | 0.0–10.0 m/s | 1.5 m/s |
| Walk Speed* | Speed of occupant when moving to/from/between seats | 0.0–10.0 m/s | 90% of Fast Walk Speed |
| Leap Speed* | Speed of occupant when moving between rows of seats | 0.0–10.0 m/s | 80% of Fast Walk Speed |
| Crawl Speed* | Speed of occupant when crawling due to environmental conditions | 0.0–10.0 m/s | 20% of Fast Walk Speed |
| Up-Stair Speed* | Speed occupant travels upstairs | 0.0–10.0 m/s | Varies by age and gender |
| Down-Stair Speed* | Speed occupant travels downstairs | 0.0–10.0 m/s | Varies by age and gender |

| Parameter | Description | Range | Default Value |
|---|---|---|---|
| Up-Escalator Speed* | Speed occupant travels up escalators | 0.0–10.0 m/s | Varies by age and gender |
| Down-Escalator Speed* | Speed occupant travels down escalators | 0.0–10.0 m/s | Varies by age and gender |
| RMV* | Respiratory Minute Volume – the volume of air an occupant breathes per minute | 0.0–50.0 l/min | Varies by gender and activity level |
| PID* | Personal Incapacitation Dose – measure of carboxyhemoglobin (COHb) to cause incapacitation | 0–100% | Randomly assigned based on a distribution |
| Drive* | Represents assertiveness of an occupant and is used to resolve conflicts between occupants | 1.0–15.0 | 10.0 |
| Patience* | Amount of time an occupant will wait stationary before considering an alternative action | 1–1,000 s | 1,000 s |
| Target Exit | If enabled, occupants will seek a specified exit instead of following the potential map | N/A | None |
| Itinerary | List of actions that an occupant is required to perform prior to evacuation | N/A | No actions |
| Gene | Represents "identity" of an individual for specifying groups of related occupants. A value of zero indicates that an occupant is not related to any other occupant. | Greater than 0 | 0 |
| Leader | Influences priority of information shared within a | Yes or No | No |

| Parameter | Description | Range | Default Value |
|---|---|---|---|
| | group (i.e., information from a leader is of higher priority) | | |
| Gas-Specific Toxicity Response Values* | Factors that affect movement speed and other aspects of occupant behavior based on gas exposure | Varies | Varies |

Table 2 summarizes the occupant characteristics that can be edited by the user in Pathfinder. Parameters that are not specified by the user are left at their default values.

**Table 2. Summary of Pathfinder occupant parameters**

| Parameter | Description | Default Value |
|---|---|---|
| Priority Level | Represents priority of occupant, used in resolving conflicts | 0 |
| Speed | Maximum walking speed | 1.19 m/s |
| Shoulder Width | Diameter of the cylinder representing the occupant | 45.58 cm |
| Ignore One-way Door Restrictions | Whether or not an occupant can ignore the direction specified for one-way doors | No |
| Walk on Escalators | Whether or not the occupant will walk on escalators and moving walkways | No |
| Current Room Travel Time | A cost factor that affects the cost of traveling to a door in the occupant's current room | 1.0 s |
| Current Room Queue Time | A cost factor that affects the cost of waiting in a queue at a door in the occupant's current room | 1.0 s |
| Global Travel Time | A cost factor that affects the cost of traveling from a door to an exit in the occupant's next goal | 1.0 s |
| Current Door Preference | A value used to make occupants stick to their currently chosen doors to prevent excessive door switching | 35% |

| Parameter | Description | Default Value |
|---|---|---|
| Current Room Distance Penalty | A value used to exponentially increase the cost associated with traveling based on how far the occupant has traveled in the current room | 35.0 m |
| Height | Height of the occupant | 1.83 m |
| Acceleration Time | The amount of time it takes for the occupant to reach maximum speed from res or to reach rest from maximum speed | 1.1 s |
| Reduction Factor | Factor by which an occupant can reduce their width to squeeze past others in tight corridors | 0.7 |
| Persist Time | Amount of time an occupant will maintain an elevated priority when trying to resolve movement conflicts | 1.0 s |
| Collision Response Time | Factor that controls the distance at which an occupant will start recording a cost for colliding with other occupants | 1.5 s |
| Slow Factor | The fraction of an occupant's speed which is considered as slow | 0.1 |
| Boundary Layer | The distance that an occupant will try to maintain with walls and other static obstructions | 0.15 m |
| Comfort Distance | The distance that an occupant will try and maintain from others | 0.08 m |

## 4.4 Behavior Modeling

In railEXODUS, the movement sub-model and the behavioral sub-model controls the general occupant movement. The movement sub-model controls the physical movement of individuals from their current position to a neighboring location, while the behavioral sub-model informs the movement sub-model and is responsible for determining an individual's response to the current situation.

While the behavioral sub-model selects the direction of travel and most other movement choices, the movement sub-model is responsible for actually moving the occupant. The primary function is to determine the speed at which the occupant moves, which is dependent on the terrain type (e.g., climbing over a row of seats or walking through open space) and on occupant attributes (e.g., whether or not they have the agility to travel over certain obstacles). The movement sub-model also determines if an occupant will wait and for how long.

The core of the behavioral sub-model is a potential map for each occupant, which assigns attractiveness values to every node in the spatial domain and influences each occupant's global movement. Exits are assigned a high attractiveness, and occupants move from their current location to a node with a higher attractiveness. Occupants can also be assigned to a specific exit, in which case they will move from this current node to one closer to the assigned exit. While navigating a route to an exit, occupants can also be assigned an itinerary of tasks (e.g., waiting or navigating to a waypoint) to accomplish before exiting. The local behavior of occupants is affected by their interaction with other occupants. If two occupants are attempting to move to the same node, a conflict arises which is resolved by their Drive values. The outcome of the conflict is that one occupant will move to the node and both occupants will incur a time penalty. This time penalty has the effect of reducing overall travel speeds in situations where there are a lot of occupant interactions.

In Pathfinder, the behavior of each occupant is controlled by the behavior that is assigned to them by the user. The behavior is a sequence of goals that is assigned to them and can include actions like waiting, traveling to a room or waypoint, and navigating to an exit. When an occupant's current goal is navigating to an exit or location, the model calculates an ideal path to the goal location which minimizes the travel distance while avoiding obstacles. A process called inverse steering determines the occupant travel along the path. Inverse steering evaluates a set of discrete movement directions for each occupant and chooses a direction that minimizes a cost function. This allows the occupants to deviate from their ideal path to respond to their environment (e.g., to avoid collisions with other occupants). Goals such as maintaining a distance from walls, maintaining a distance from other occupants, and maximizing their travel speed in a crowded area are weighed against remaining on the ideal path by a cost function and the direction which minimizes the cost is chosen.

## 4.5 Fire Effects Data

Fire effects data in railEXODUS can either be defined manually within the program or imported from a third-party modeling software. Data from the University of Greenwich's developed SMARTFIRE models can be imported directly into railEXODUS, and data from CFAST models can be converted into the SMARTFIRE format by a utility included with railEXODUS. Section 5.4 documents this process. After the data is read, the user must specify zones in the egress model and then associate these zones with regions of the fire model data.

Fire effects data in Pathfinder must be imported from an FDS fire model. This data is applied to each occupant individually based on their location in the three-dimensional space, so the user is not required to define any zones. However, the origin and orientation of the FDS and Pathfinder models must be the same for the fire data to be imported correctly. Currently, Pathfinder does not support the manual definition of fire effects data.

## 4.6 Fire Effects Modeling

The fire effects sub-model in railEXODUS (i.e., referred to as the toxicity sub-model in the documentation) can track multiple gas species and their effects on occupant behavior. The fire effects calculations employ a Fractional Effective Dose (FED) model and consider the effects of elevated temperature, hydrogen cyanide (HCN), carbon monoxide (CO), carbon dioxide ($CO_2$), and low oxygen ($O_2$). For each condition, a Fractional Incapacitating Dose (FID) is calculated. If the sum of these FID values reaches a value of one during a simulation, the occupant has become incapacitated. FID value greater than one would correspond to dosage exceeding the threshold limit leading to incapacitation. In the simulation, an incapacitated occupant does not move and blocks their location from other occupants. The fire effects model also calculates a Mobility Degradation Factor based on an occupant's exposure to toxic gases, irritant gases, and low visibility due to smoke. The mobility degradation factors slows down an occupant's walking speed by a fraction of their normal walking speed.

The fire effects calculations in Pathfinder records the temperature, CO, $CO_2$, low $O_2$, and low visibility conditions from the fire model that each occupant is exposed to and outputs this information after a simulation is complete. The CO, $CO_2$, and $O_2$ values are also used to calculate an FED value for each occupant which is also output from the model. Currently, the only factor that affects occupant behavior is low visibility due to smoke. In areas with a visibility distance of 3 meters or lower, an occupant's walking speed will decrease by a fraction of their maximum walking speed based on the visibility distance. All data related to temperature, CO, $CO_2$, and $O_2$ is for informational purposes and does not affect occupant behavior.

Table 3 shows a summary of the fire effects models in railEXODUS and Pathfinder. Note that in the example cases described later in this report only CO, $O_2$, $CO_2$, visibility, and temperature were imported into the railEXODUS and Pathfinder models.

**Table 3. Summary comparison of fire effects models**

| Program | railEXODUS | Pathfinder |
|---|---|---|
| Smoke Obscuration | | |
| Model | Based on data from [10] [11] | Based on data from [12] |
| Effect | Reduce walking speed to 0.3–0.5 m/s minimum at high extinction coefficient (i.e., low visibility)<br>Travel speed is affected between 10 m and 2 m of visibility | Reduce walking speed linearly (to 0.2 m/s minimum at low visibility)<br>Travel speed is affected between 3 m and 0 m of visibility |
| Toxic Gases | | |
| Program | railEXODUS | Pathfinder |
| Model | Purser SFPE FED model [14]: CO, $O_2$, $CO_2$, HCN, HCl, HBr, HF, $SO_2$, $NO_2$, Acrolein, Formaldehyde | Purser SFPE FED model [9]: CO, $CO_2$, and $O_2$ |

| Program | railEXODUS | Pathfinder |
|---|---|---|
| Effect | Reduce walking speed to 80% at FED>0.95<br>Incapacitation at FED>1.0 | None on walking speed,<br>Incapacitation at FED>1.0 |
| Irritant Gases | | |
| Program | railEXODUS | Pathfinder |
| Model | Purser SFPE FIC model [9]<br>HCl, HBr, HF, $SO_2$, $NO_2$, Acrolein, Formaldehyde | None |
| Effect | Reduces walking speed, incapacitation | N/A |

### 4.7 Output and Display of Results

Both railEXODUS and Pathfinder output summary and diagnostic data from the simulation in the form of text files and allow for a visual representation of the occupant movement. The visualization of the evacuation is similar in form to each program's geometry editor interface: railEXODUS shows a series of two-dimensional floors with icons representing occupants while Pathfinder shows a full three-dimensional representation of the geometry with realistic models of occupants. VREXODUS can be used to display a three-dimensional representation of the model results from railEXODUS. Pathfinder's three-dimensional visualization is built into the base software.

# 5. Comparison of Example Cases

In order to examine the differences in the two simulation algorithms and their potential effects on the results of an egress study, multiple example cases were run in railEXODUS and Pathfinder and the results were compared. While differences in features do not allow for the exact same parameters to be used in both programs, the model inputs in both programs were the same or equivalent to the maximum extent possible.

## 5.1 Rail Car Layouts (Single-car and Multi-car)

For all comparison simulations, the geometry layout was chosen to match a MBTA bi-level rail car. This style of car is used extensively by the MBTA, and the general layout is typical of many passenger rail vehicles. The car consists of an upper level and a lower level which are used primarily for seating and have identical seating layouts. Each end of the car has an intermediate level which contains side exits and inter-car connections. Each car has a total of four exits, where passengers can exit either to an elevated platform—if available—or directly to the ground (i.e., the ROW). Cab control cars are rail cars with passenger seating and a compartment for the train crew to control the trainset. These cars have three primary exits with an engineer control station that also have passenger seating. The fourth exit would be blocked with a permanently attached engineer's seat or one that can be folded out of the way to operate the trap. This analysis considered all coaches as trailer coaches with four door exits. Figure 7 shows a drawing of the MBTA rail car.

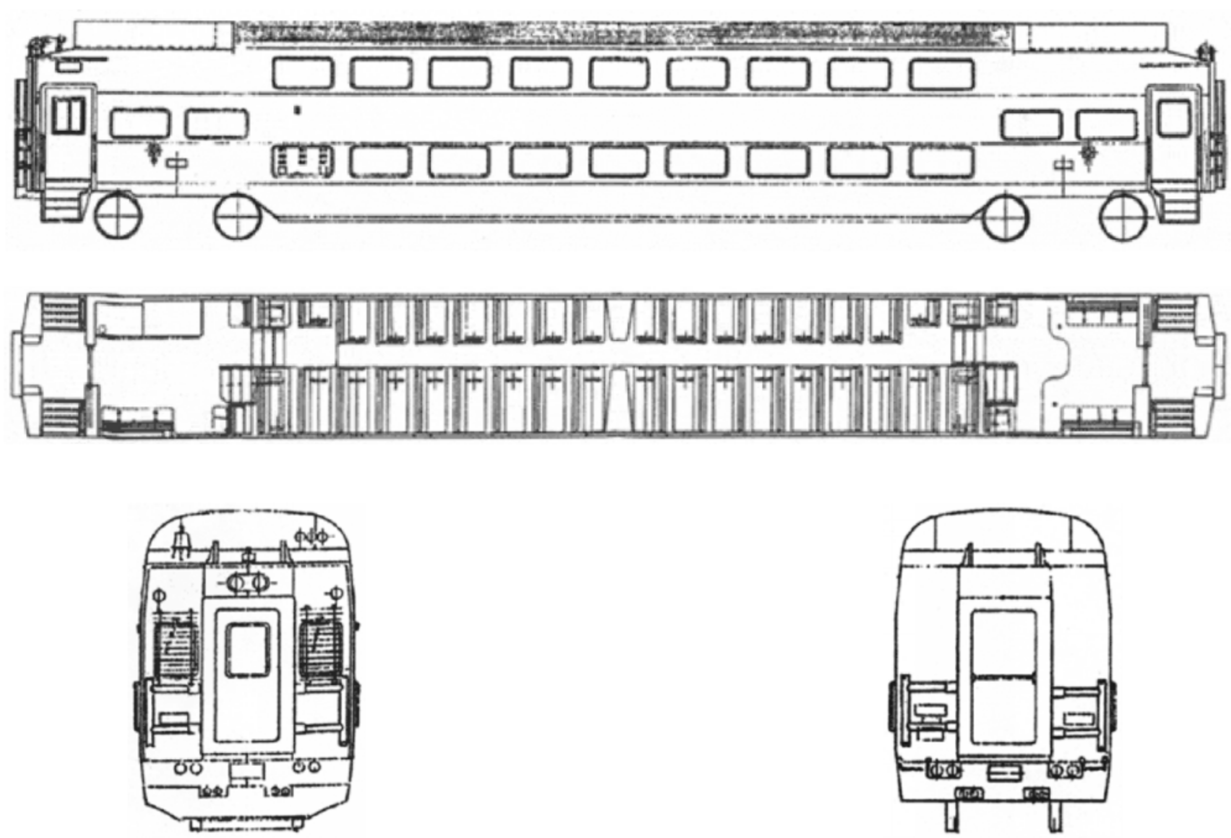

**Figure 7. MBTA bi-level rail car drawings**

## 5.2 Door Flow Rates and Exit Configurations

Interior movement within the car and movement from the car to the outside is influenced by the maximum allowable flow rates at the doorways, which is set as a parameter in the models. In the example cases, the exit door flow rates are set to simulate exiting to a high platform, exiting to a low platform, and exiting directly onto the ROW.

When exiting to a high platform, the inside of the rail car is at the same level as the platform and occupants pass through the exit like a normal doorway. When exiting to the low platform or to the ROW, occupants must first travel down steps to reach the outside. In railEXODUS, this was simulated by modeling the exit as a single node defined as Low Platform exit Node or ROW Exit node, which considers the combined impact of traveling through a doorway and a short stairway. In all cases, the doorway was modeled with a maximum flow rate of 1.33 occupants per second per meter of door width. In the low platform and ROW models, the stairway was modeled with statistical distribution of travel speeds. The travel speeds used in railEXODUS is based on the experiments conducted by Volpe using a single level commuter rail [1]. Figure 8 shows the travel speed distributions.

In pathfinder, this is no egress component, which can consider the combined impact of traveling through a doorway and a short stairway. To have the same egress behavior as railEXODUS, the low platform and ROW exits in Pathfinder were modeled as a doorway with a maximum flow rate and a delay time in which occupants must wait at the door before traveling through it. The statistical distribution of delay times was calculated based on the travel speeds and length of the stairs in railEXODUS [7] such that the exits would be equivalent in both programs. Note that the delay times and travel speeds used in railEXODUS is based on the experiments conducted by Volpe using a single level commuter rail [1]. Figure 9 shows the calculated delay times in the Pathfinder model.

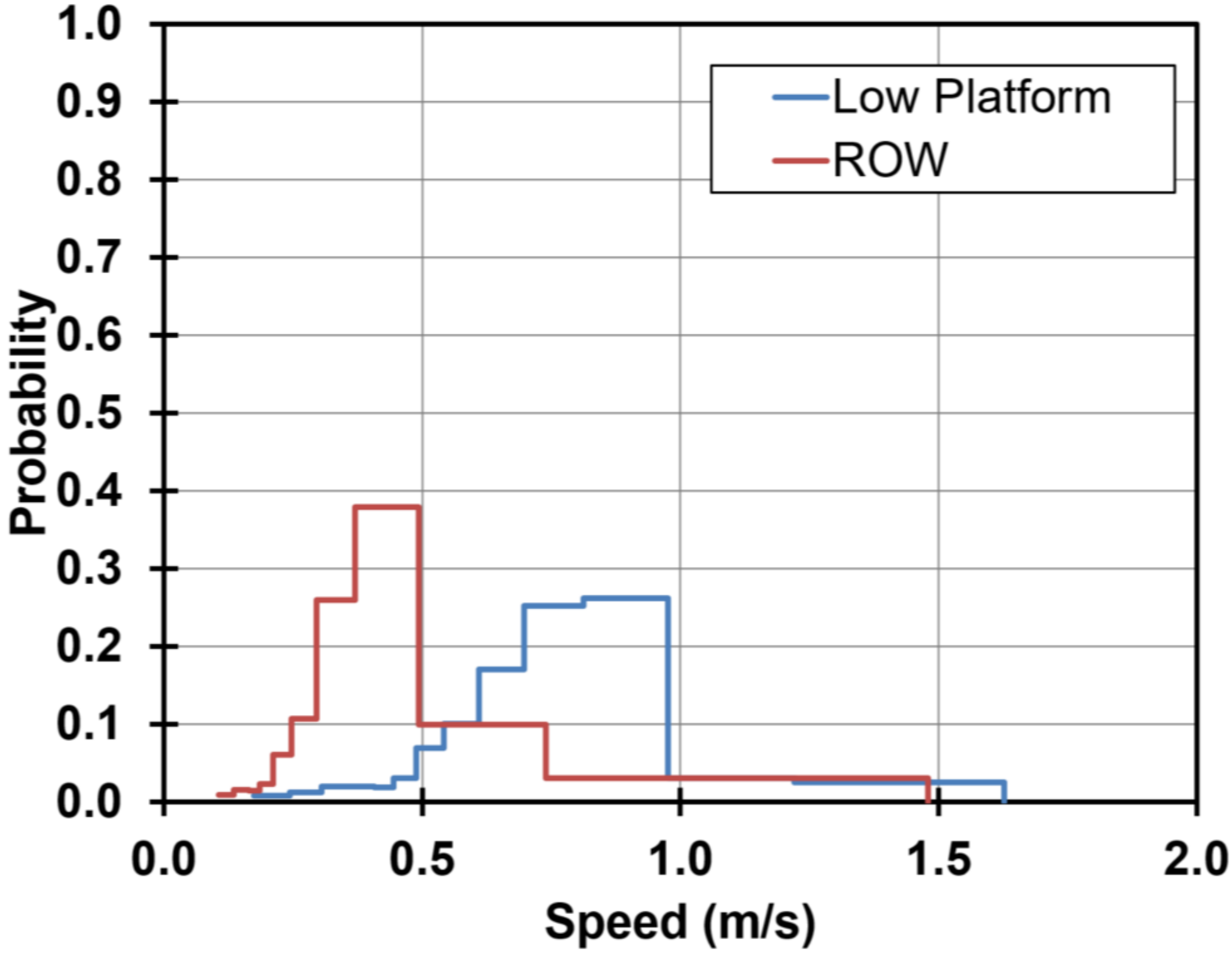


**Figure 8. Travel speeds for railEXODUS low-platform and ROW exits**

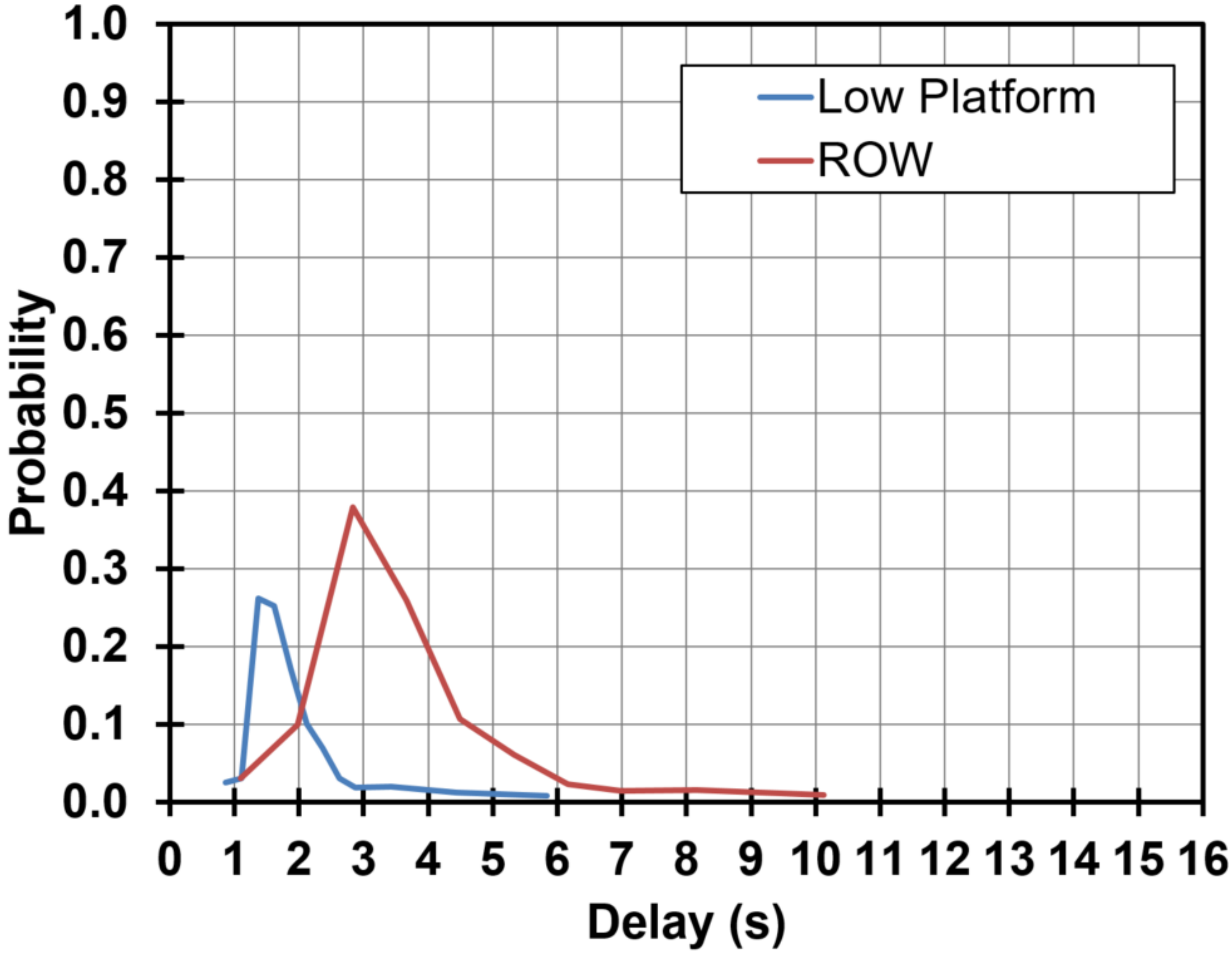


**Figure 9. Delay time for Pathfinder low-platform and ROW exits**

## 5.3 Population Parameters

In all simulated scenarios, each rail car was modeled as fully loaded with 149 passengers per rail car. Therefore, the 3-car scenarios contained a total of 447 passengers.

Occupant parameters were set to be as consistent as possible between the railEXODUS and Pathfinder models. However, not all occupant characteristics have analogous parameters in both programs, and not all parameters that can be edited in one program can be edited in the other (e.g., the "agility" parameter only exists within the railEXODUS model, and the "wall boundary layer" only exists within the Pathfinder model). The occupant walking speed, which exists in both models and has a significant impact on the model results, was set to be the same in both models. In railEXODUS, the range of free flow or unencumbered walking speeds in the male passengers was defined with a maximum of 1.98 m/s and a minimum of 1.22 m/s [1]. The distribution of free flow walking speeds in the female passengers was defined with a maximum of 1.77 m/s and a minimum of 1.0 m/s [1]. In Pathfinder, the range of free flow or unencumbered walking speeds in the male passengers was defined with a maximum of 1.98 m/s and a minimum of 1.22 m/s, a mean of 1.6 m/s, and a standard deviation of 0.38 m/s. The distribution of free flow walking speeds in the female passengers was defined with a maximum of 1.77 m/s and a minimum of 1.0 m/s, a mean of 1.385 m/s, and a standard deviation of 0.385 m/s.

Figure 10 shows a typical range of free flow walking speeds of 149 occupants for both railEXODUS and Pathfinder simulation. The distribution varies as railEXODUS uses random distribution opposed to the normal distribution used in Pathfinder.

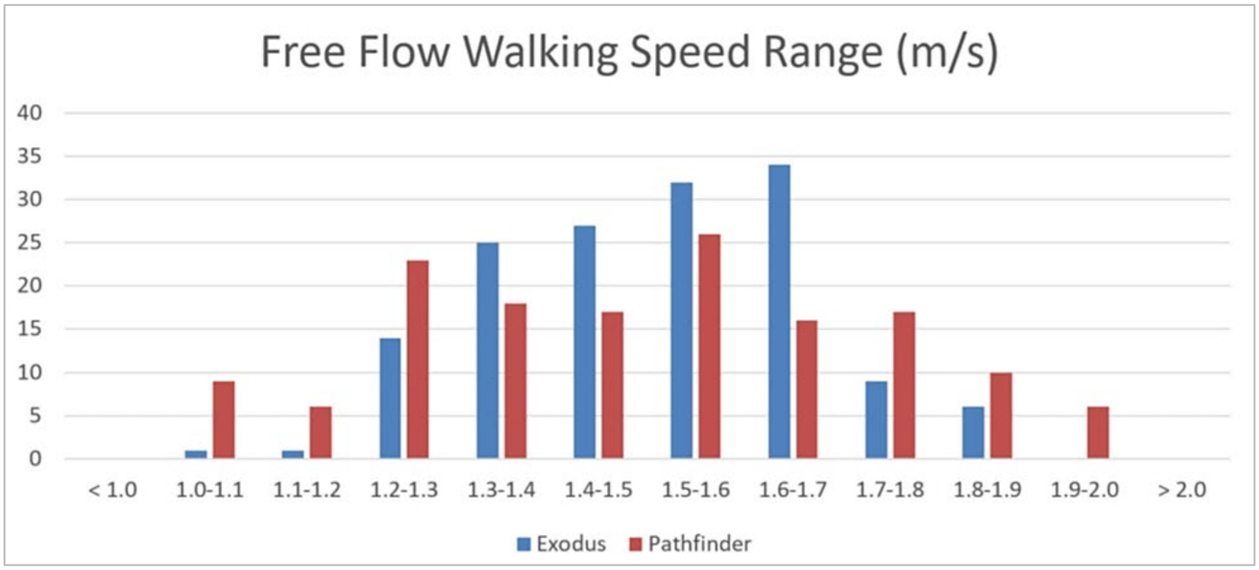


**Figure 10. Range of occupant free flow walking speeds (railEXODUS vs. Pathfinder)**

## 5.4 Fire Scenarios

Researchers used CFAST, a software package developed by NIST for evaluating the impact of fire and smoke in a building environment, to generate fire effects data. It utilizes a two-zone fire model, which simulates a compartment fire as an upper layer and a lower layer that each have uniform properties such as temperature, soot density, and oxygen concentration. The rail car geometry was modeled in CFAST and an exemplar design fire was simulated.

The selection of a design fire was performed in accordance with the guidelines in ASTM E2061-15, *Standard Guide for Fire Hazard Assessment of Rail Transportation Vehicles* [13]. Multiple potential initiating fire scenarios were considered for the example simulation. The assumption was that all fires occurred inside the rail vehicle, as this would result in more severe conditions for occupants than an exterior exposure fire. Experimental data and standard heat release rate (HRR) curves were used to characterize a variety of potential fuel packages which are realistic and plausible inside of a rail car [14]. In general, the considered fires can be grouped into two broad categories: fires with a high peak HRR and last for a relatively short duration, and fires with a lower peak HRR but a longer total duration. Figure 11 and Figure 12 show a summary of the design fires considered.

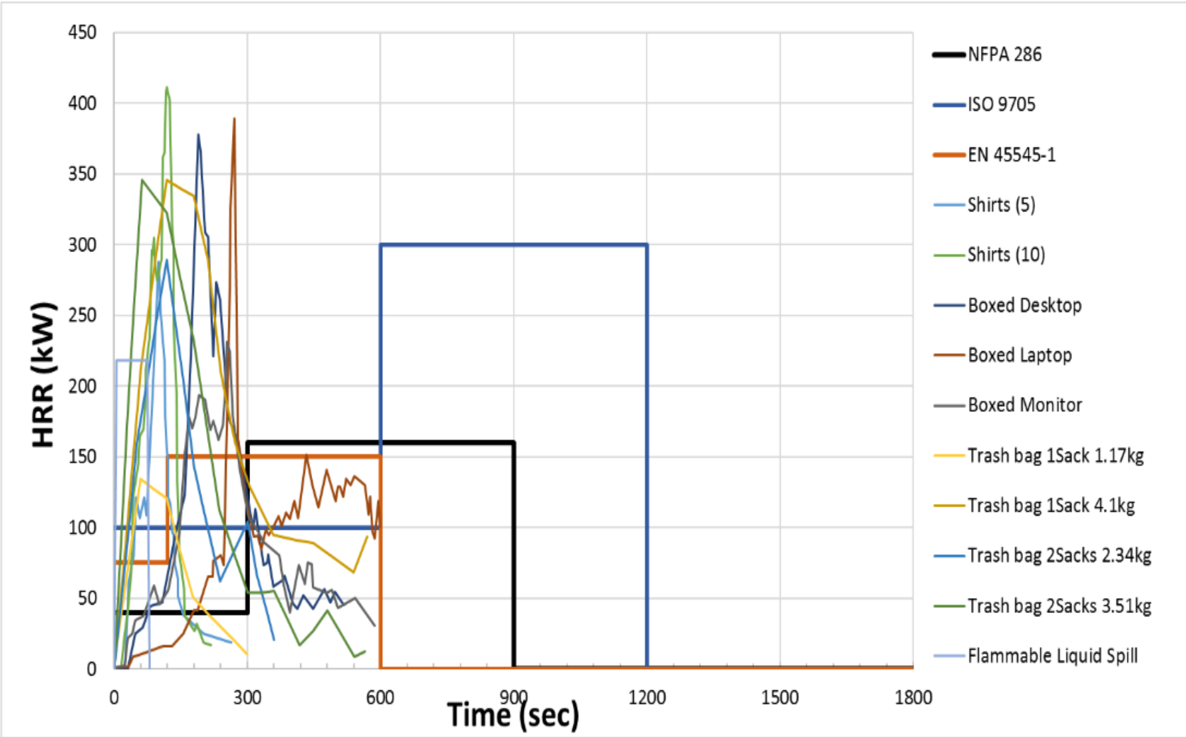


**Figure 11. High-HRR, short-duration design fires [14]**

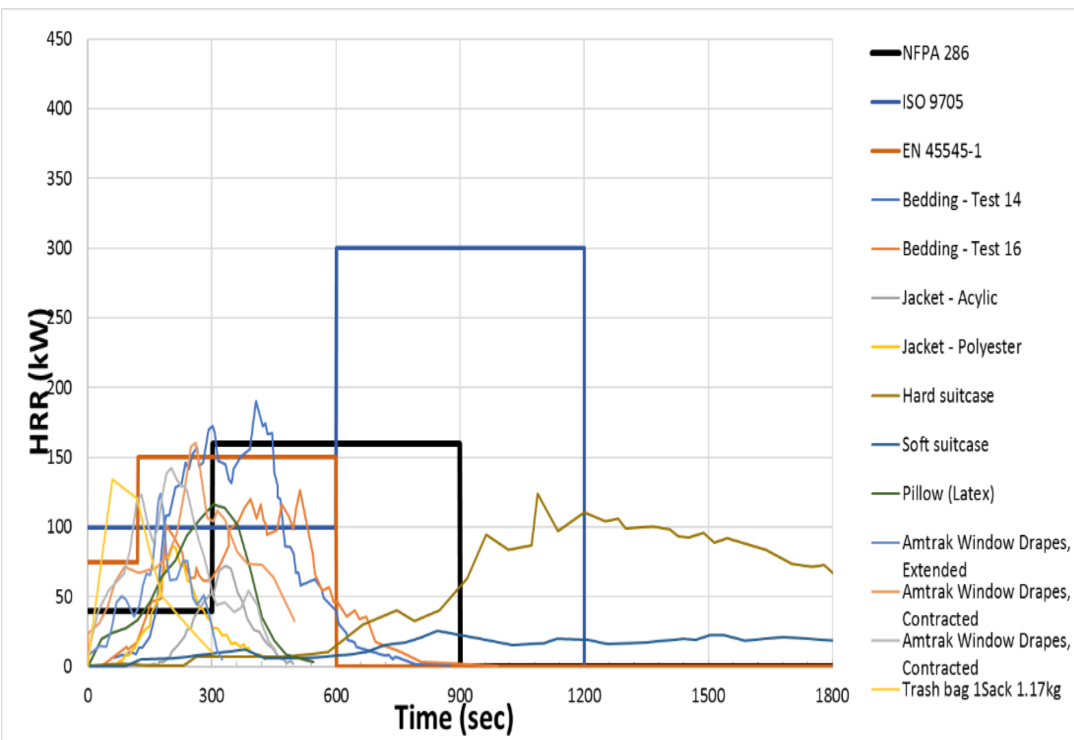


**Figure 12. Low-HRR, long-duration design fires [14]**

The design fire was chosen to be similar to the initiating fire specified in NFPA 286 [15]. It consists of a 40-kW HRR for 5 minutes, followed by a 160-kW HRR for 10 minutes. Note that the purpose of choosing the design fire was to provide a reasonable fire scenario to illustrate the process and results of incorporating fire data into the railEXODUS and Pathfinder models. It is not intended to be an estimate of the likely fire hazards present in an actual rail car and should not be used for design purposes.

Table 4 shows the fire fuel properties that are modeled as polyurethane foam, with properties from the SFPE Handbook [9].

**Table 4. Design fire fuel properties**

| Parameter | Value |
|---|---|
| Fuel Chemistry | $CH_{1.7}O_{0.32}N_{0.07}$ |
| Heat of Combustion ($\Delta H_C$) | 24.6 MJ/kg |
| CO Yield | 0.028 g/g |
| Soot Yield | 0.194 g/g |
| HCN Yield | 0.0 g/g |

The location of the fire was in the center of the rail car (i.e., the middle rail car in the three-car scenarios), either in the upper level or the lower level depending on the specific scenario. CFAST model divides each compartment into an upper and a lower gas zone with the height of interface separating two zones as the layer height. The fire drives combustion products from the lower to the upper layer via the plume. The temperature within each layer is uniform, and its evolution in time is described by a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. The transport of smoke and heat from zone to zone is dictated by empirical correlations. The CFAST model geometry and examples of the CFAST modeling results depicting temperature, visibility, CO and $CO_2$ concentrations and layer interface heights are shown in Figure 13 through Figure 17.

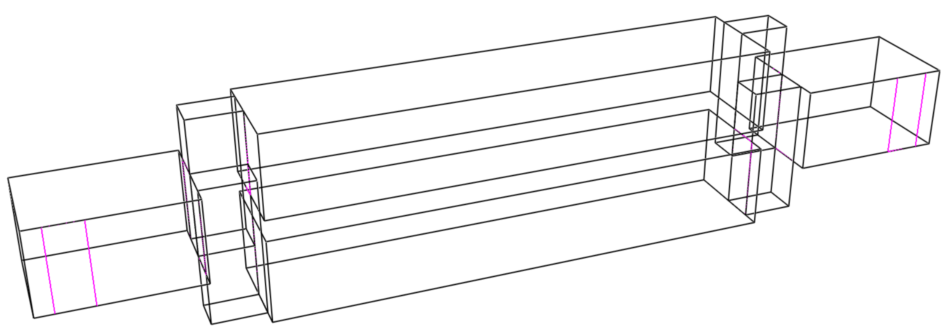

**Figure 13. Rail car geometry as modeled in CFAST**

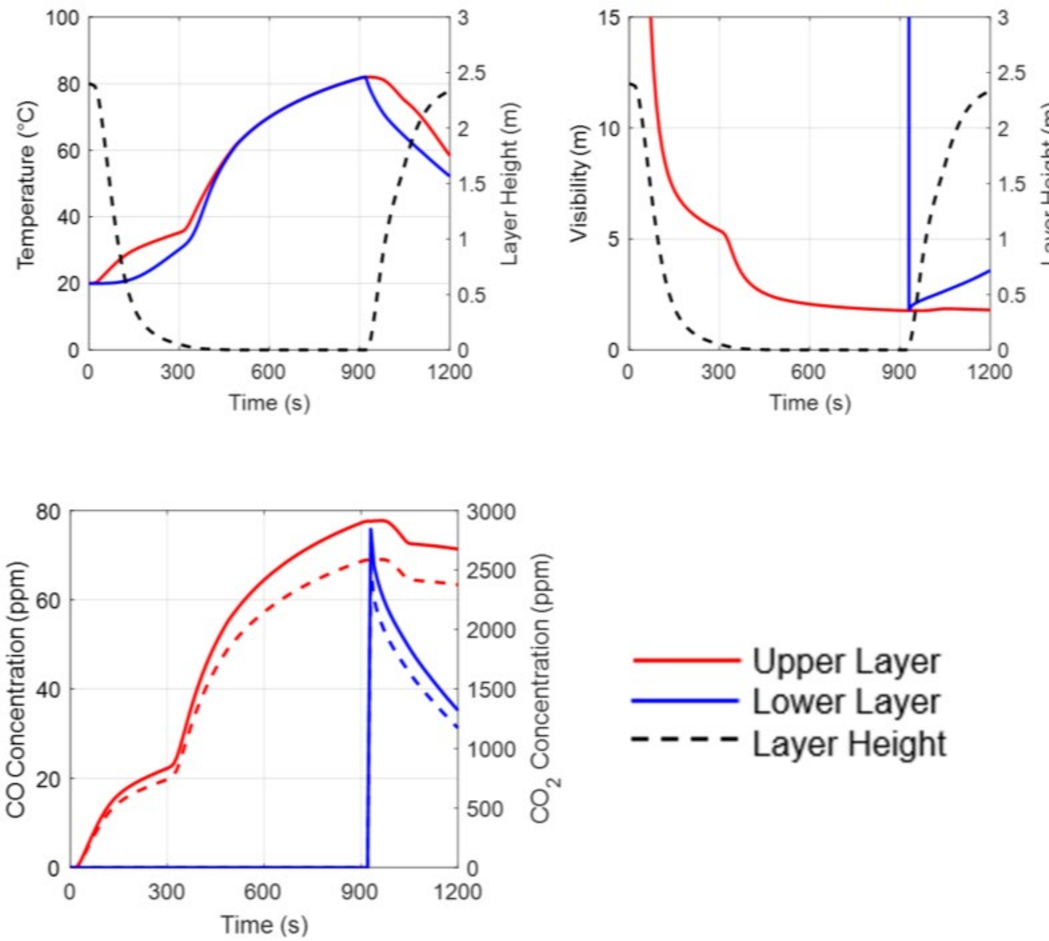


**Figure 14. Upper-level temperature and visibility results for lower-level fire**

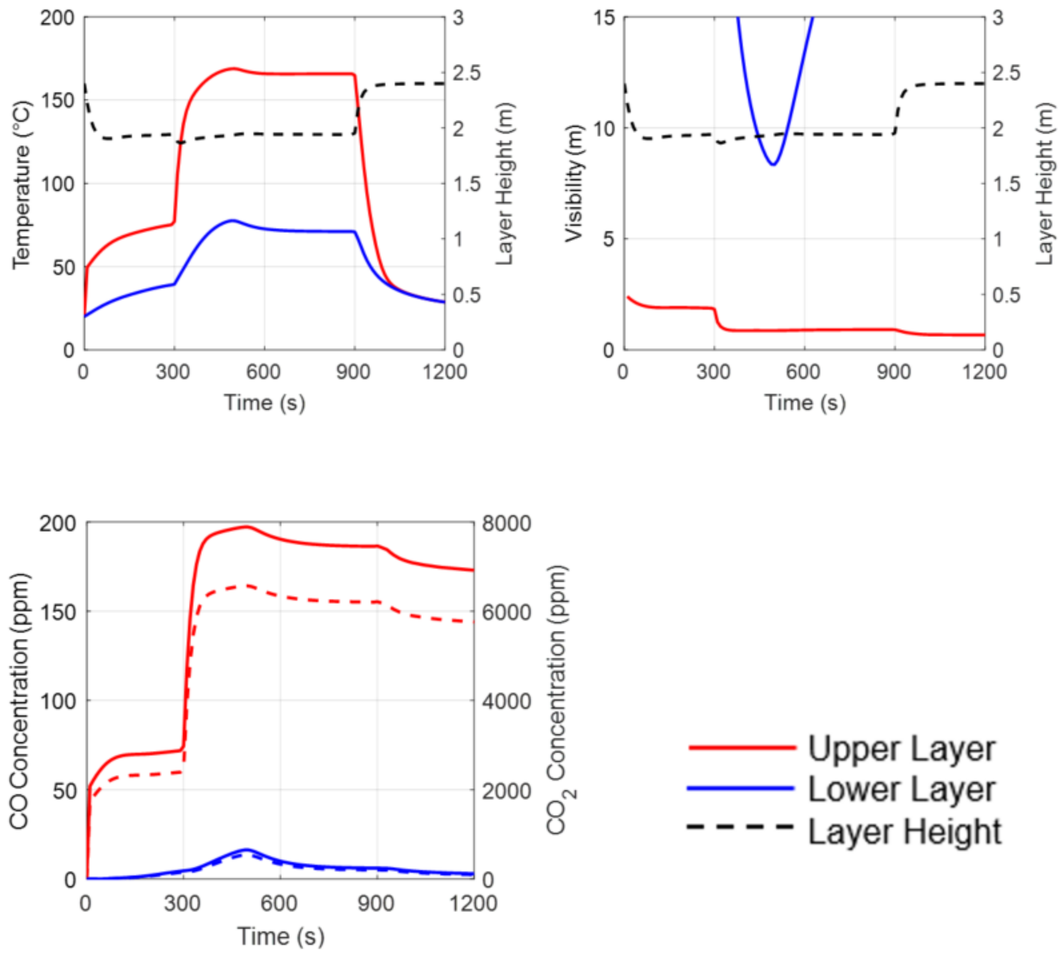


**Figure 15. Lower-level temperature and visibility results for lower-level fire**

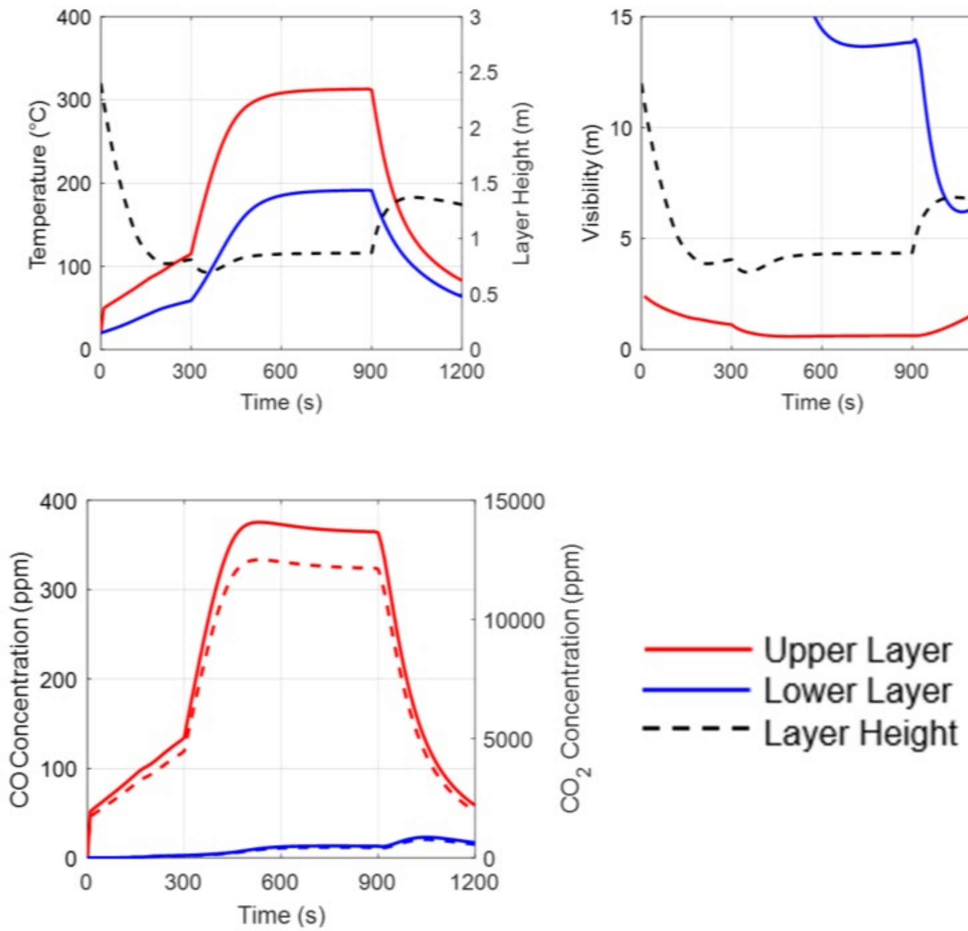


**Figure 16. Upper-level temperature and visibility results for upper-level fire**

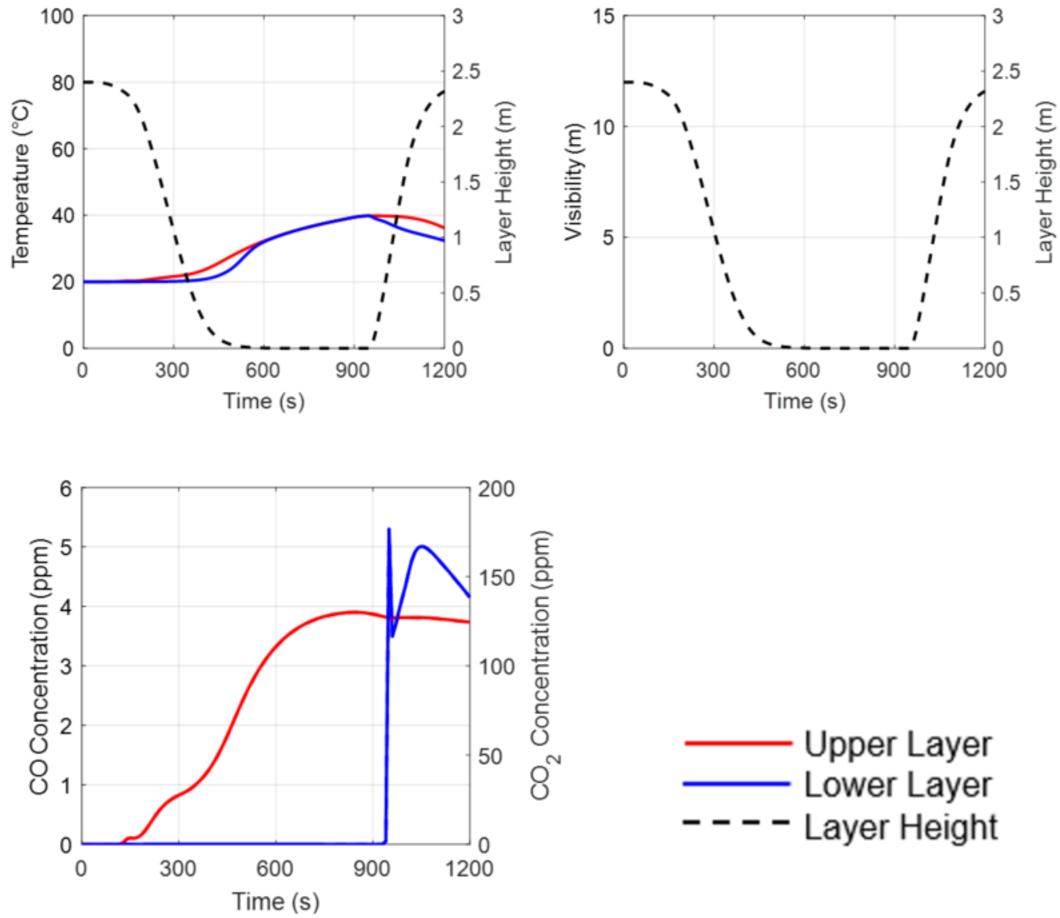


**Figure 17. Lower-level temperature and visibility results for upper-level fire**

To import the fire effects data into the egress model, railEXODUS provides a utility which converts the CFAST output into a .DAT file which can be read by railEXODUS. After the data is read, zones must be defined in the spatial domain which correspond to the compartments in the CFAST model. Then, the fire effects data from each CFAST compartment are assigned to the zones in the egress model. Figure 18 shows a diagram visualizing this process.

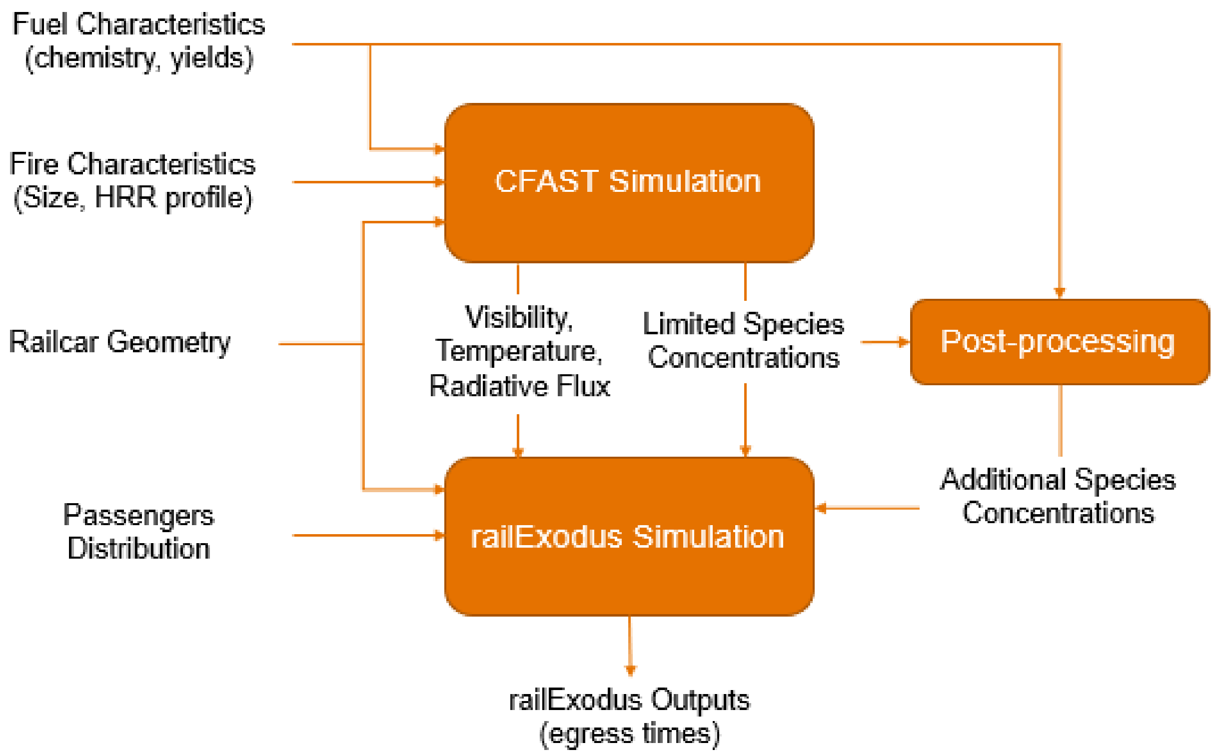


**Figure 18. Coupling of railEXODUS and CFAST data**

Since Pathfinder does not natively support CFAST files, a custom tool was developed to convert the CFAST data into a .SMV file representing a data format that can be read by Pathfinder. Pathfinder applies the fire effects data to occupants based on their position in a three-dimensional space, so defining zones is not necessary. However, the origin and orientation of the CFAST and Pathfinder models must be the same for the fire data to be imported correctly. Note that while data imported into Pathfinder can describe fire effects with a much higher resolution than a zone model, the .SMV file used in this study matches the zone data from the CFAST file.

## 5.5 Summary of Simulations

A variety of simulations were performed in railEXODUS and Pathfinder with different layouts and conditions. The main categories are non-emergency vs. emergency and single-car vs. three-car train consist.

Researchers performed the non-emergency simulations with no fire effects data imported into the model. This is intended to simulate the evacuation of a train in a normal condition or a condition which does not affect the interior environment of the car. The emergency simulations are performed with fire data imported into the model. Note that Pathfinder cannot model whether occupants perceive a situation to be an emergency or non-emergency—and effect that it may have on their behavior. In the railEXODUS model, drive attribute is used that can be interpreted as representing the individual's motivation to escape in relation to the rest of the population. However, the attribute was not used specifically to differentiate between emergency scenarios from non-emergency.  Therefore, the difference between the emergency and non-emergency scenarios is the presence of fire effects data in the emergency scenarios.

The single-car simulations are performed with one MBTA bi-level rail car.  The number and location of open doors is dependent on the specific scenario.  In most operating situations, the end doors (i.e., located at the end of each car and are normally used for inter-car travel) in a multi-car train are kept closed, but unlocked, when the train is in motion.  The end door on the control coach is secured with latches but can be open if needed.  In the single car models, availability of end doors varied between scenarios.  In the three-car simulations, the end doors connecting the cars are assumed to be open (i.e., travel between cars is allowed) while the end doors at the end of the three-car train are not available for egress.

Since both the railEXODUS and Pathfinder models are non-deterministic (i.e., running the same model twice will yield slightly different results), many of the models were run 10 times each and then the results were averaged to account for the variation in results.  The model variation in terms of door availability was made to ensure the maximum possible variations.  Some of the configurations analyzed may not be likely in the real world.  For example, egress to a possible live adjacent track would not be recommended.  Figure 19 and Figure 20 shows an explanation of the naming convention for the single-car and three car consist simulations.  In each example, the open doors are shown in green.

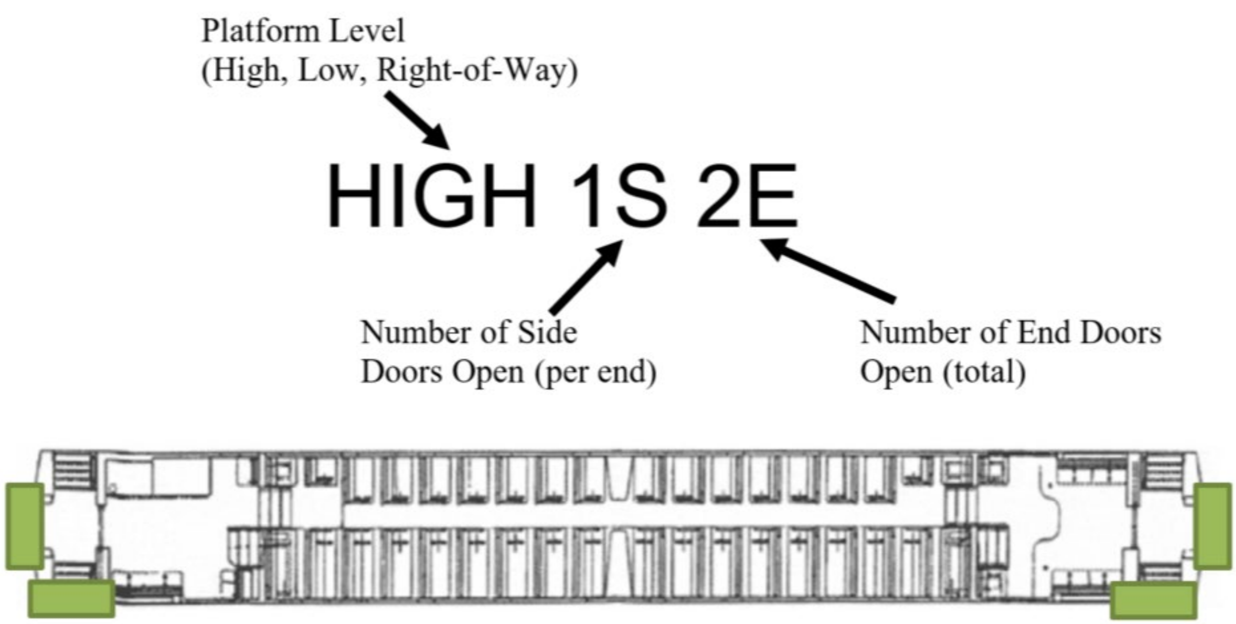


**Figure 19. Naming convention for single-car simulations**

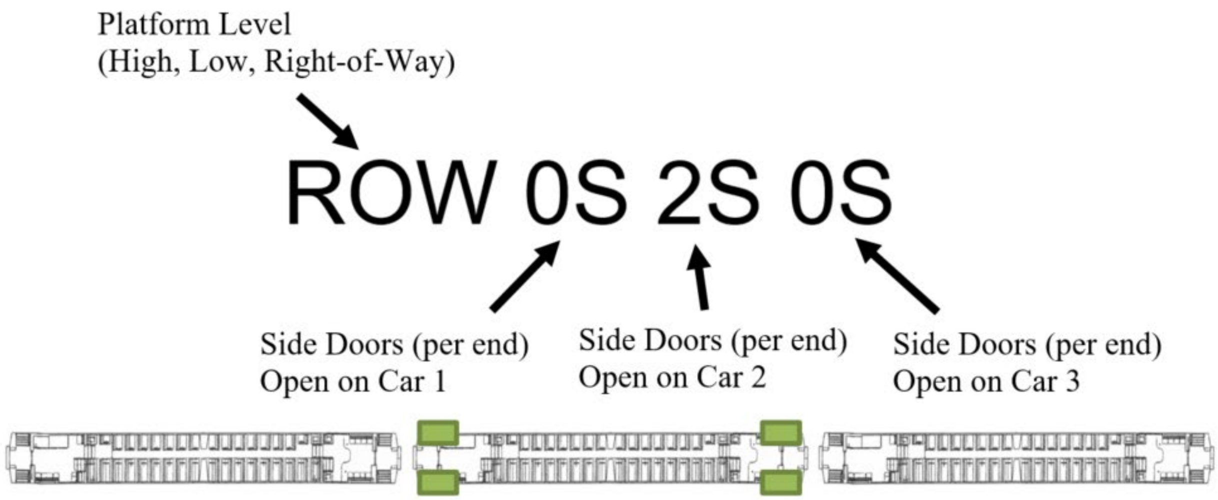


**Figure 20. Naming convention for three-car simulations**

Table 5 through Table 8 summarizes all simulations performed, and the number of iterations performed. Section 5.6 discusses the results in the order of these tables.

**Table 5. Summary of single car non-emergency simulations**

| Name | Platform Type | Side Doors | End Doors | # of Iterations |
|---|---|---|---|---|
| High 1S | High | 1 Side | - | 10 |
| High 2E | High | - | 2 Ends | 10 |
| High 2S | High | 2 Sides | - | 1 |
| High 2S 2E | High | 2 Sides | 2 Ends | 1 |
| Low 1S | Low | 1 Side | - | 10 |
| Low 2S | Low | 2 Sides | - | 1 |
| ROW 1S | Right-of-Way | 1 Side | - | 10 |
| ROW 1S 2E | Right-of-Way | 1 Side | 2 Ends | 1 |
| ROW 2S | Right-of-Way | 2 Sides | - | 1 |

**Table 6. Summary of three-car non-emergency simulations**

| Name | Platform Type | Side Doors | | | End Doors | # of Iterations |
|---|---|---|---|---|---|---|
| | | Car 1 | Car 2 | Car 3 | | |
| ROW 0S 1S 1S | Right-of-Way | - | 1 Side | 1 Side | Inter-car only | 10 |
| ROW 0S 2S 0S | Right-of-Way | - | 2 Sides | - | Inter-car only | 10 |
| ROW 0S 0S 2S | Right-of-Way | - | - | 2 Sides | Inter-car only | 10 |

**Table 7. Summary of single car emergency simulations**

| Name | Platform Type | Side Doors | End Doors | Fire Location | Delay | # of Iterations |
|---|---|---|---|---|---|---|
| High 1S | High | 1 Side | - | Upper Level | 0, 60, 180, 300 s | 10 |
| High 1S | High | 1 Side | - | Lower Level | 0, 60, 180, 300 s | 10 |
| ROW 2S | High | 2 Sides | - | Upper Level | 0, 60, 180, 300 s | 1 |

**Table 8. Summary of three-car emergency simulations**

| Name | Platform Type | Side Doors | | | End Doors | Fire Location | Delay | # of Iterations |
|---|---|---|---|---|---|---|---|---|
| | | Car 1 | Car 2 | Car 3 | | | | |
| ROW 0S 0S 2S | Right-of-Way | - | - | 2 Sides | Inter-car only | Upper Level | 0, 60, 180, 300 s | 10 |

## 5.6 Comparison of Results

For all the example cases, the time for all occupants to exit the car(s) was compared between the railEXODUS and Pathfinder simulations. In general, the non-emergency evacuation times were similar. The emergency evacuation times showed some significant divergence in the results. The evacuation is considered complete when all passengers capable of self-preservation have escaped.

### *5.6.1 Single Car Non-emergency Simulations*

Figure 21 through Figure 23 shows the non-emergency simulations with a single car. Although for these scenarios only a single simulation per scenario was performed, all the results agree to within approximately 15 percent of the total egress time. In the analysis shown below, Pathfinder and railEXODUS predicted the calculation of the evacuation time differences:

Difference (s) = Evacuation time from Pathfinder (s) – Evacuation time from railEXODUS (s)

For the high-platform scenarios, the evacuation times are not very sensitive to the number and arrangement of available exit doors. This suggests that when the train is at a high-level platform, the evacuation time is limited by the available travel space within the car and queues near the doorways are not significant enough to limit egress speed. The results for the low-platform and ROW scenarios suggests that these results are more sensitive to the exit door arrangement. For example, when occupants must egress to the ROW, having two side doors available instead of one side door available reduces the evacuation time by roughly 40–50 percent. This is not surprising, since exiting to the ROW is much slower than exiting to a high platform and therefore is a significant factor in the evacuation time.

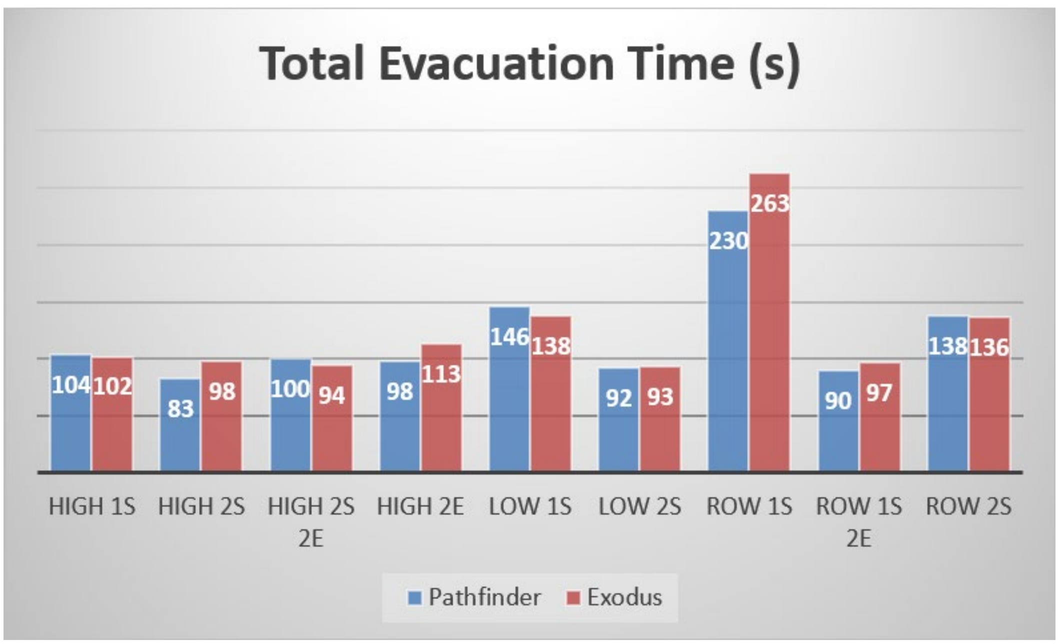


**Figure 21. Evacuation time for single-car non-emergency simulation (one simulation per scenario)**

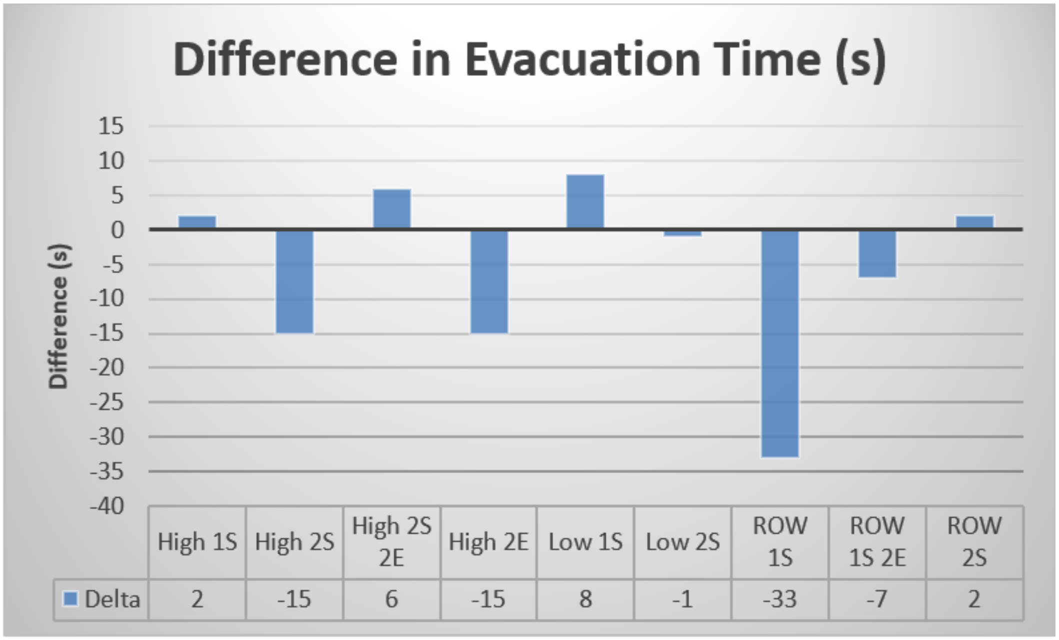


**Figure 22. Difference in evacuation time between Pathfinder and railEXODUS for single-car non-emergency simulation (one simulation per scenario)**

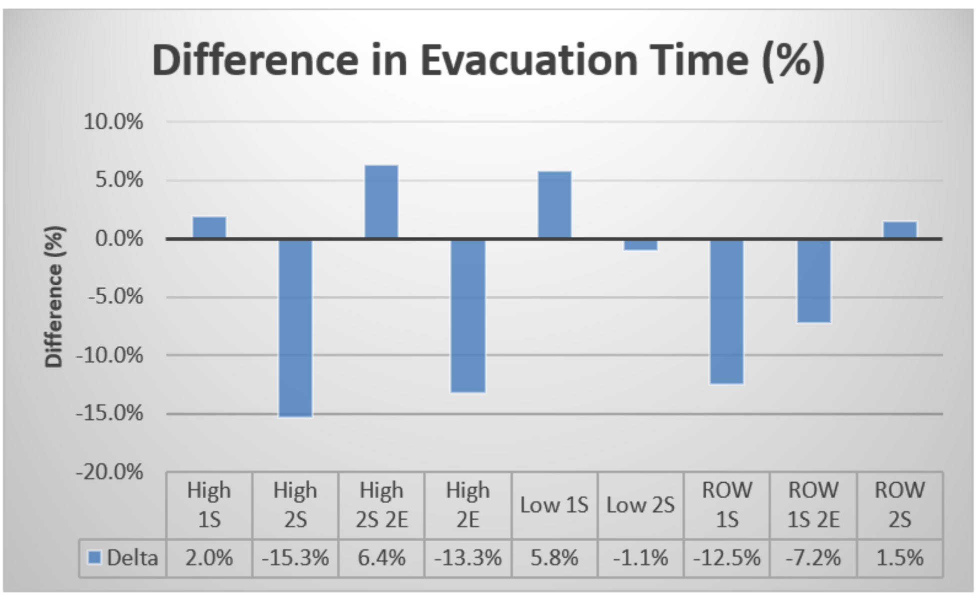


**Figure 23. Percentage difference in evacuation time between Pathfinder and railEXODUS for single-car non-emergency simulation (one simulation per scenario)**

Figure 24 through Figure 26 show the results of a subset of the non-emergency single-car scenarios, for which 10 simulations per scenario were performed and the results were averaged. In this case, the conclusions are similar: the maximum difference between the evacuation times is slightly lower (10% vs. 15%), but the results of both the railEXODUS models and Pathfinder models follow the same trend.

Like in the previous simulations, the effect of the exit arrangement is clear. Exiting to the high-level platform is the fastest method, exiting to a low-level platform increases the evacuation time, and exiting to the ROW is the slowest method. Since railEXODUS predicts a lower evacuation time in some scenarios and Pathfinder predicts a lower time in some scenarios, it is not clear at this time if one model is inherently more conservative than the other.

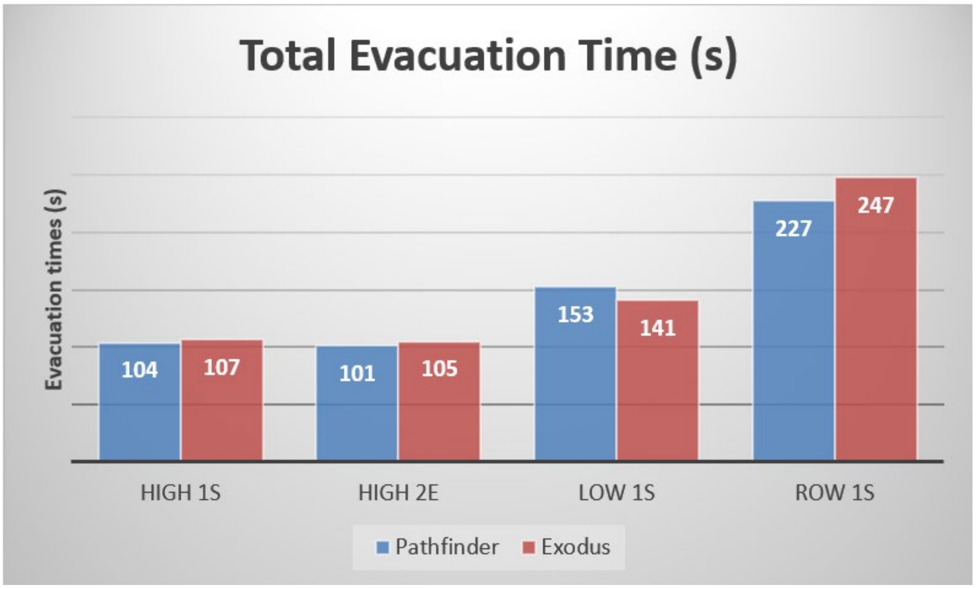


**Figure 24. Evacuation time for single-car non-emergency simulation (10 simulations per scenario)**

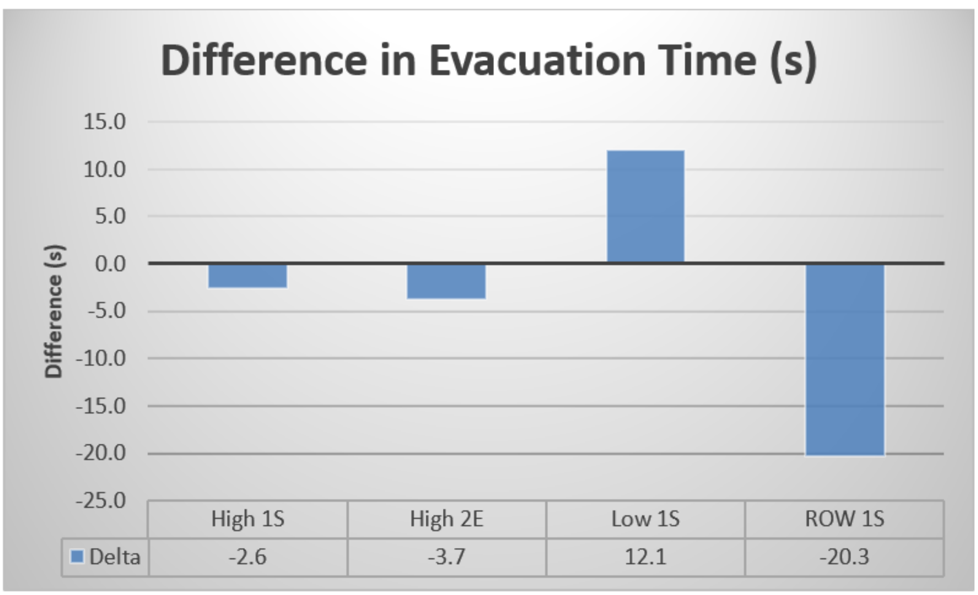


**Figure 25. Difference in evacuation time between Pathfinder and railEXODUS for single-car non-emergency simulation (10 simulations per scenario)**

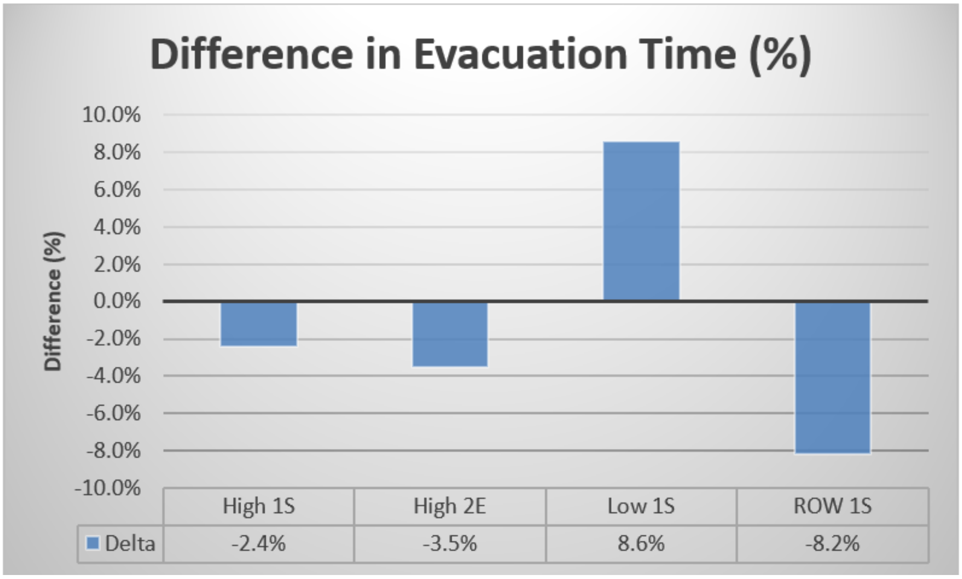


**Figure 26. Percentage difference in evacuation time between Pathfinder and railEXODUS for single-car non-emergency simulation (10 simulations per scenario)**

### *5.6.2 Three-car Non-emergency Simulations*

For the three-car non-emergency scenarios, three simulations were run 10 times each and the resulting evacuation times were averaged. The results are shown in Figure 27 through Figure 29. The railEXODUS and Pathfinder results for egress times agree to within 20 percent of each other. In all three scenarios, railEXODUS predicted higher total evacuation times than Pathfinder. Overall, the non-emergency evacuation times for three cars are two to three times higher compared to the single car evacuation times.

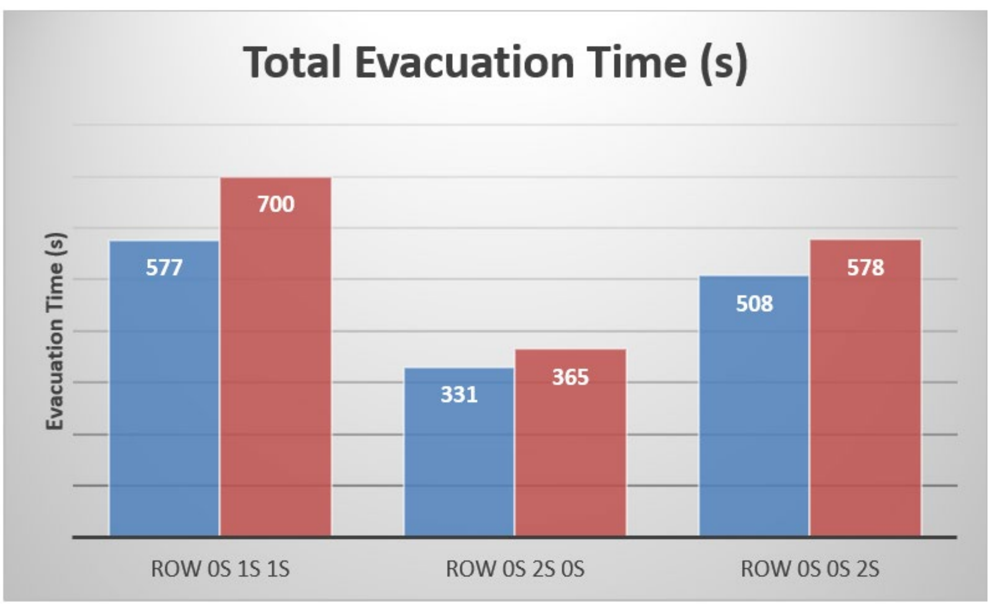


**Figure 27. Evacuation time for 3-car non-emergency simulation (10 simulations per scenario)**

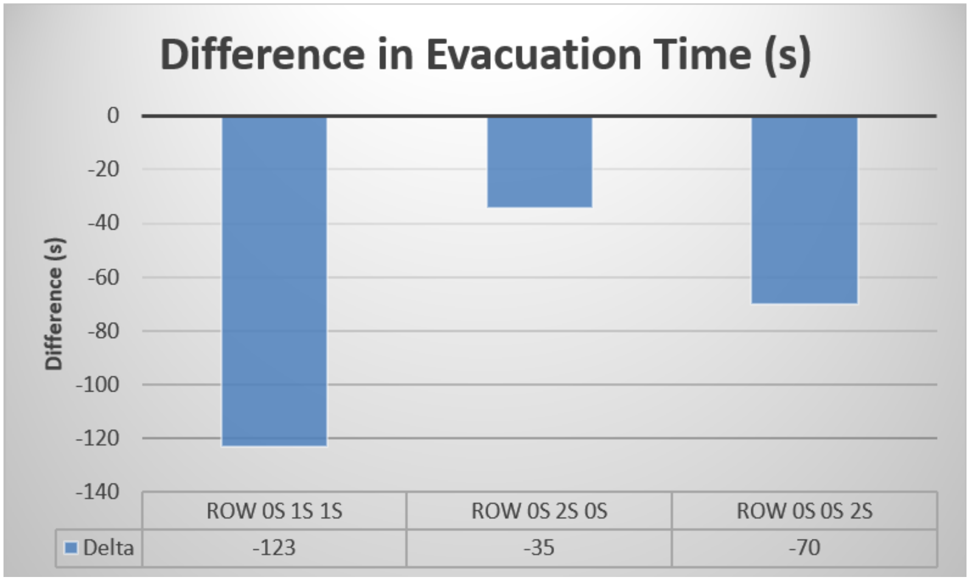


**Figure 28. Difference in evacuation time between Pathfinder and railEXODUS for 3-car non-emergency simulation (10 simulations per scenario)**

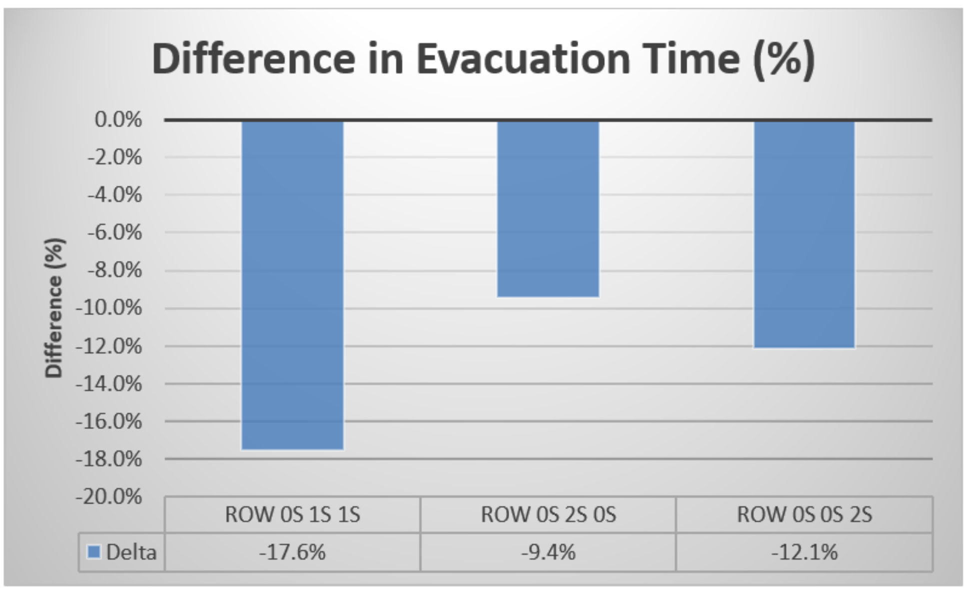


**Figure 29. Percentage difference in evacuation time between Pathfinder and railEXODUS for 3-car non-emergency simulation (10 simulations per scenario)**

### *5.6.3 Single Car Emergency Simulations*

For the emergency simulations, three single-car scenarios were performed. Two scenarios were performed with egress to the high-level platform via one side door on each end of the car ("High 1S"), with the fire located on the upper level in one scenario and on the lower level in the other scenario. Both scenarios were modeled 10 times each. Based on the results of these scenarios, the upper-level fire had a more significant impact on evacuation times. Therefore, the third scenario was performed with egress to the ROW with two side doors open on each end of the car ("ROW 2S") and a fire on the upper level. This scenario was modeled only once. This was intended to represent a severe-case scenario both in terms of egress layout and fire effects. Each scenario was simulated with a delay of 0, 60, 180, and 300 seconds as well as with no fire data to establish a baseline for comparison.

For the emergency scenarios, the delay time was subtracted from the total evacuation time to yield the movement time. This allowed for the comparison of simulations with different delay times to evaluate their effect on occupant movement.

The railEXODUS results show a clear increase in movement time as the delay time increases (Figure 30). This was expected, as the fire conditions will have a negative effect on occupant movement with conditions becoming worse over time. Therefore, delaying the start of evacuation will cause the occupants to be exposed to more severe conditions which are expected to have a greater impact on travel speeds. Note that the 300-second delay results in a lower movement time than the 180-second delay as shown in Figure 31. However, this is likely since 36 occupants (see Figure 32) become incapacitated in the 300-second delay simulation in railEXODUS. Pathfinder cannot model incapacitation of the passengers. Since incapacitated occupants are not seeking an exit, a high number of incapacitations will reduce the total number of occupants exiting the train and therefore lower the required evacuation time. No occupants were incapacitated when the delay was 180 seconds or less.

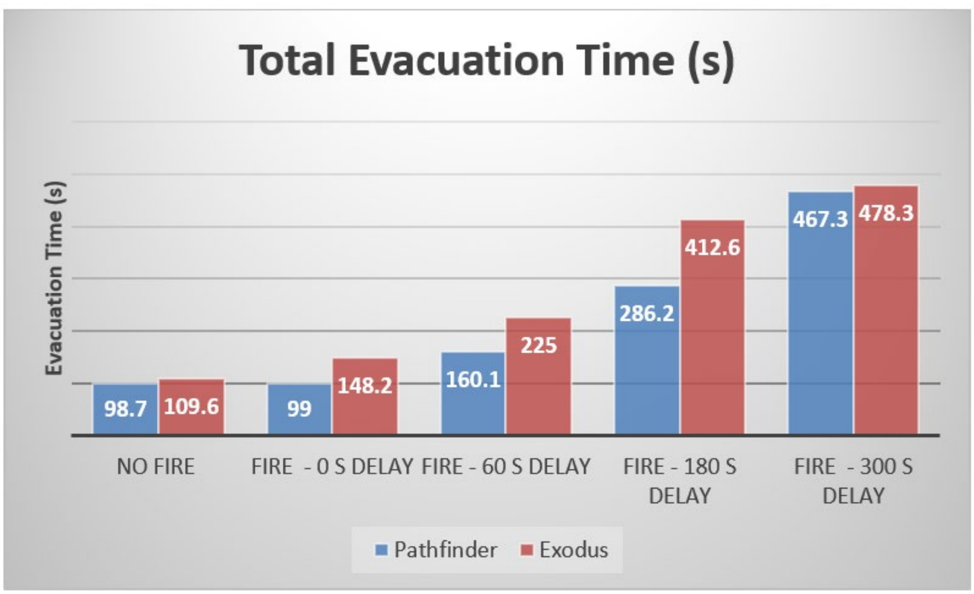


**Figure 30. Evacuation time for single-car emergency simulation (High 1S / Upper Level Fire)**

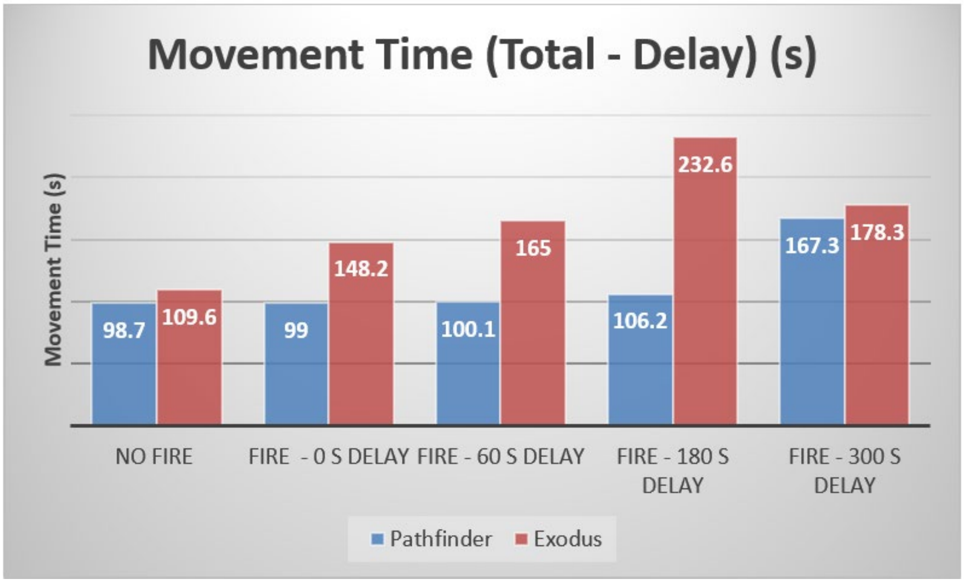


**Figure 31. Movement time for single-car emergency simulation (High 1S / Upper Level Fire)**

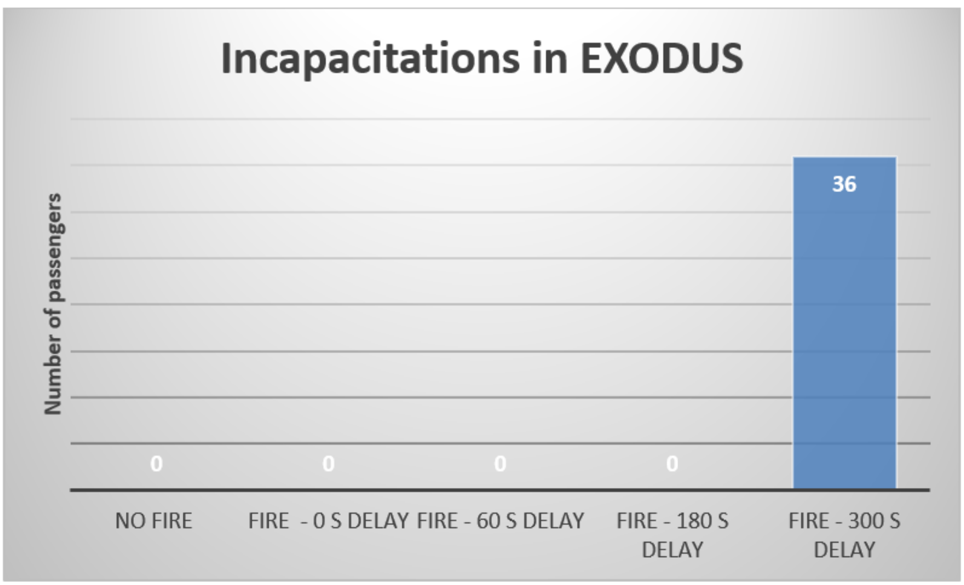


**Figure 32. Incapacitations for single-car emergency simulation (High 1S / Upper Level Fire)**

The Pathfinder results suggest that the movement time is not significantly affected by the fire conditions until the delay reaches 300 seconds as shown in Figure 31, which is different than the railEXODUS results. A potential reason for this is the difference in the fire effects models. The fire effects model in railEXODUS slows the occupant walking speeds due to toxic gases as well as low visibility. In Pathfinder, only low visibility affects the walking speed of the occupants. In addition, railEXODUS and Pathfinder calculates the speed reduction due to low visibility differently, and therefore the same visibility conditions could lead to different occupant walking speeds even if toxic gas effects are not considered.

For the High 1S Upper Level Fire scenario, researchers examined the detailed time-dependent data from the simulation. Figure 33 shows visibility and walking speeds over time through Figure 36 for an occupant initially located in the center of the upper level. As shown in Figure 33, the visibility conditions in both railEXODUS and Pathfinder are well within the range of affecting occupant walking speed (i.e., 10 m in railEXODUS and 3 m in Pathfinder). The walking speeds for the occupant in the Pathfinder simulation for 0 and 180 second delays are shown in Figure 34. For a 180 second delay, the walking speeds are lower than the occupant's maximum speed (1.43 m/s) even during high visibility at times greater than 260 second (see Figure 34) indicating that the limit of movement of the occupant is by internal queuing as reduction of walking speed in Pathfinder starts at a visibility value of three and reduces linearly to 0.2 m/s at low visibility as described in the Section 4.6. Similar walking speed vs time graph was not available as part of railEXODUS model output.

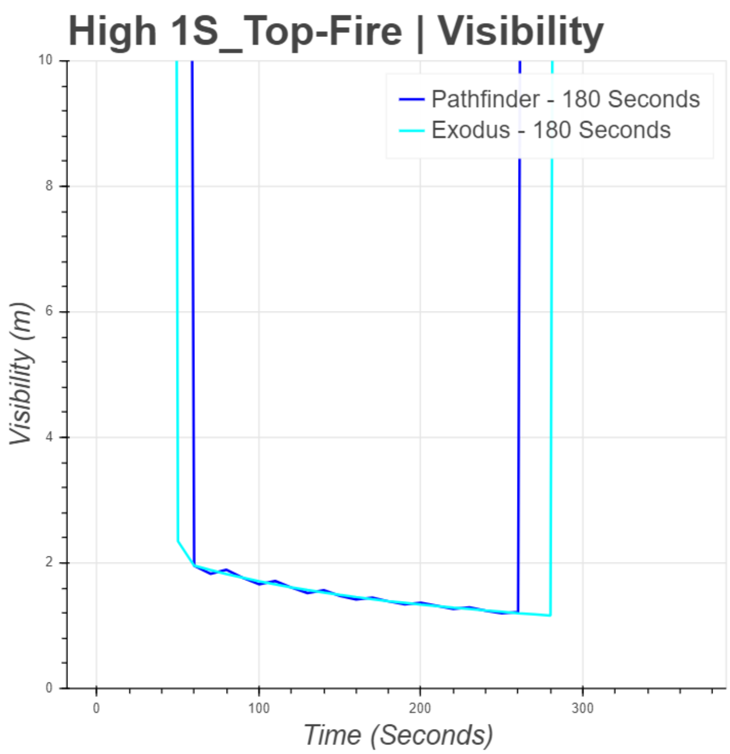


**Figure 33. Occupant visibility history, High 1S_Top Fire, 180-second delay**

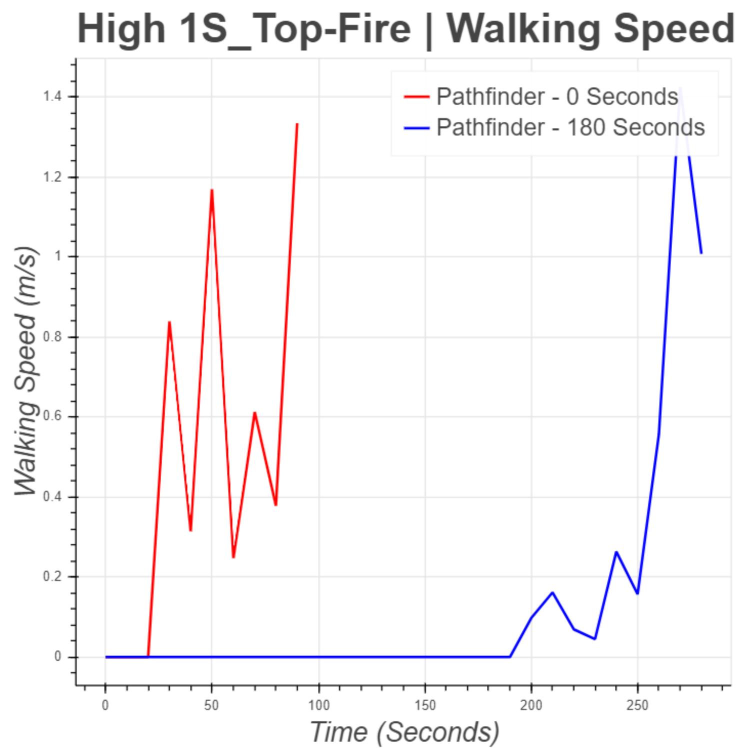


**Figure 34. Occupant walking speed history, High 1S_Top Fire, 0 and 180-second delay**

The same general observations were made for the simulation with a 300-second delay, as shown in Figure 35 and Figure 36. The 180-second delay led to a movement time almost equal to the non-emergency scenario while the 300-second delay led to a movement time approximately 60 seconds longer than the non-emergency scenario. Since the movement of individual occupants can vary significantly between simulations and the walking speed varies within a simulation over time, it is difficult to determine how much of an effect the fire conditions would have on the occupant evacuation.

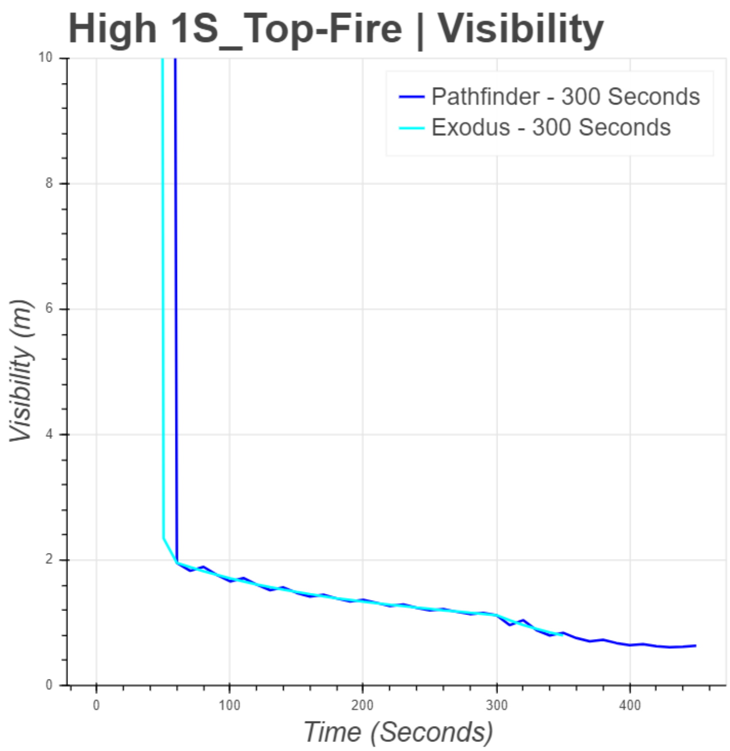


**Figure 35. Occupant visibility history, High 1S_Top Fire, 300-second delay**

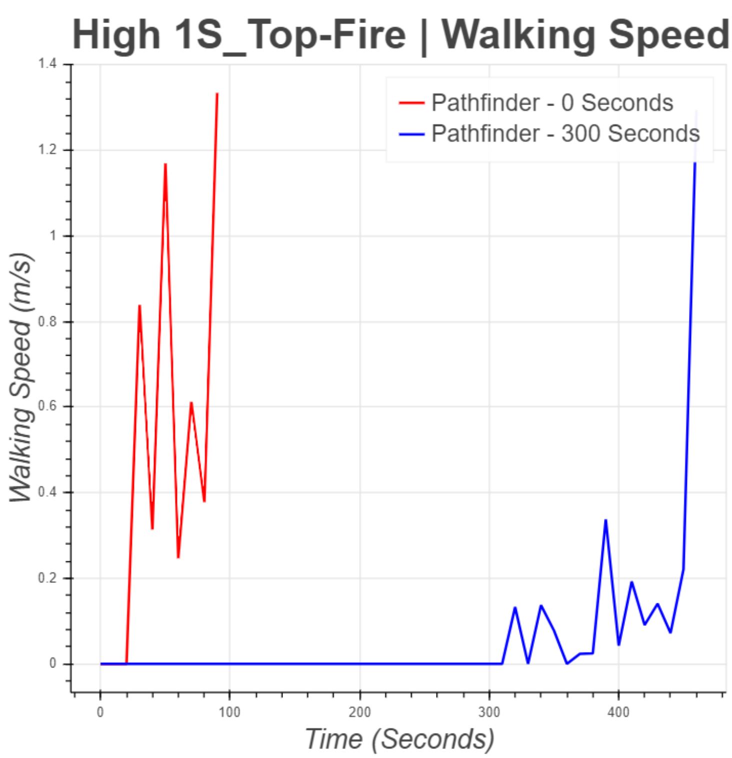


**Figure 36. Occupant walking speed history, High 1S_Top Fire, 0 and 300-second delay**

The same exit layout was used in the next simulation, but with the fire located on the lower level instead of the upper level. Overall, the lower-level fire leads to less severe conditions since the smoke spreads out through both levels of the rail car and is therefore more diluted than the upper level scenario, which concentrates the fire products on the upper level.

In the railEXODUS simulations, the fire clearly influences the movement times, but the evacuation time is less sensitive to the delay than the previous (i.e., upper-level fire) scenario (Figure 37 and Figure 38). This is due to the less severe environmental conditions. Unlike the railEXODUS simulations, the Pathfinder simulations show no significant changes in the evacuation due to the environmental conditions. A further analysis should be done by considering a smaller number of occupants to better understand the effect of fire on both models. This exercise will help to differentiate the delays due to fire effects from the delays due to queuing.

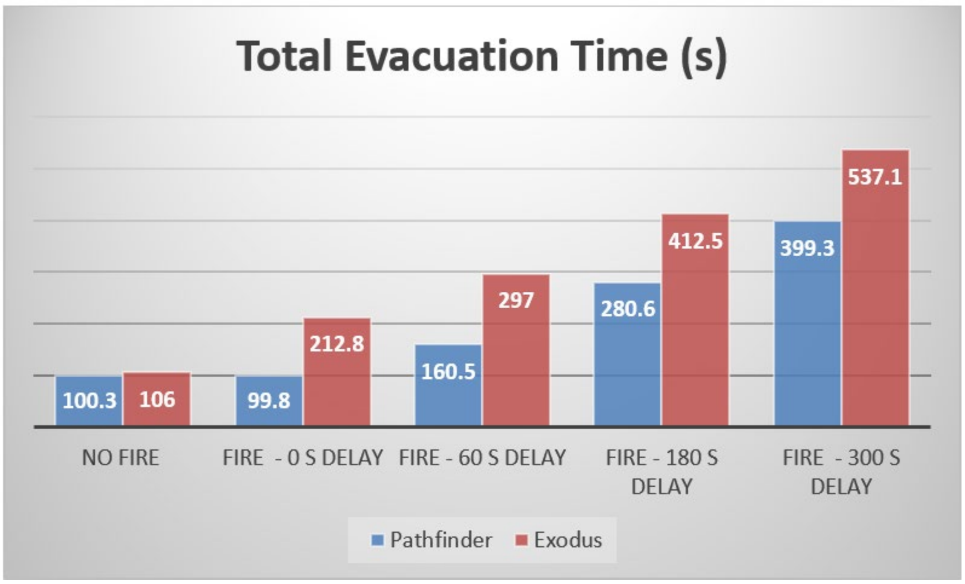


**Figure 37. Evacuation time for single-car emergency simulation (High 1S/lower level fire)**

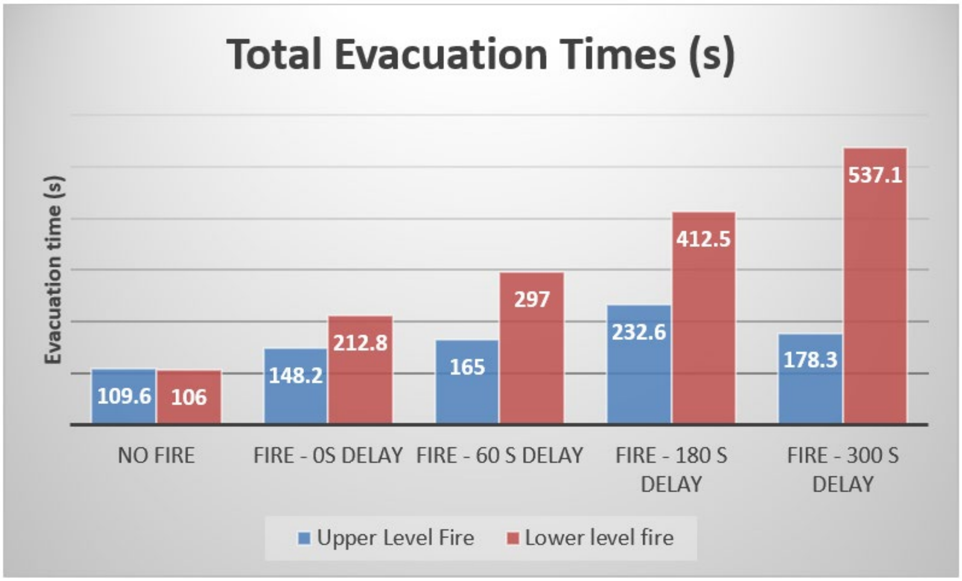


**Figure 38. Evacuation time comparison between upper and lower level fire scenarios in railEXODUS**

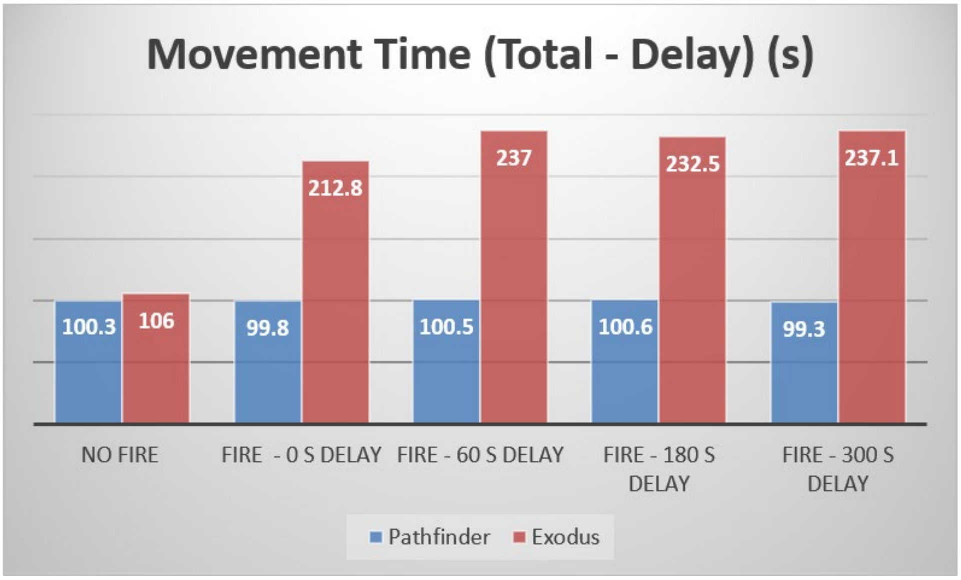


**Figure 39. Movement time for single-car emergency simulation (High 1S / lower level fire)**

An emergency simulation was also performed with occupants exiting to the ROW using two side doors on each end of the car. For this layout, the fire was located on the upper level since this produced the most severe conditions. The results are shown in Figure 40 through Figure 42.

The railEXODUS results are similar to the other upper-level fire scenario. The movement time generally increases with increasing the delay time, and the 300-second delay involves a large number of incapacitations which decreases the movement time. The Pathfinder results show very little change in movement time until the delay time is increased to 300 seconds. Based on the non-emergency models, the evacuation to the ROW is mostly driven by the flow rate of the exits. Therefore, it is understandable that the conditions in the interior of the rail car have less of an effect on the evacuation time than the scenario in which occupants exit to the high-level platform. Note that in the Pathfinder model, flow rates through doors are not affected by fire conditions—other than the walking speed at which occupants reach the door. Therefore, a scenario in which occupants spend most of their time in a queue waiting to exit will not be significantly affected by a slowdown in walking speeds.

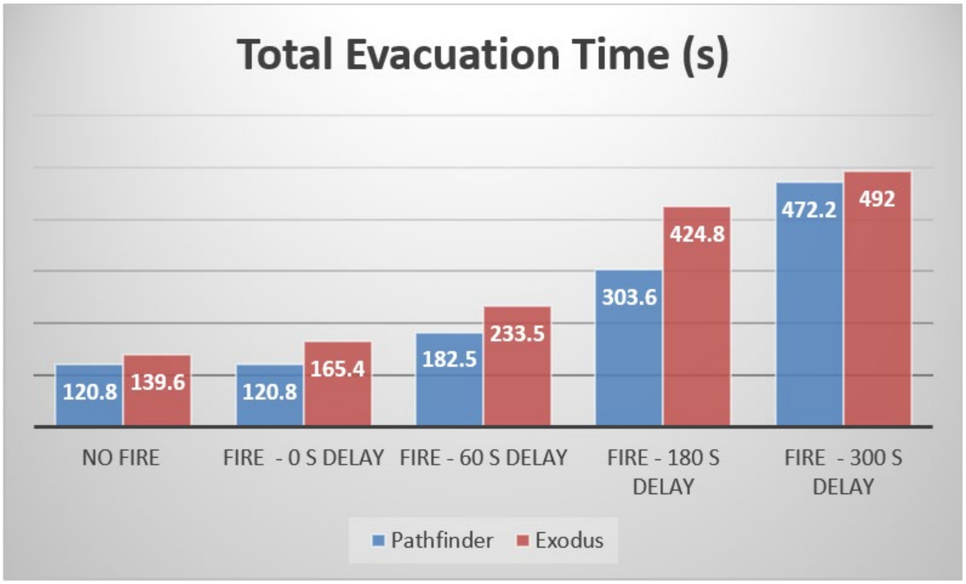


**Figure 40. Evacuation time for single-car emergency simulation (ROW 2S / Upper Level Fire)**

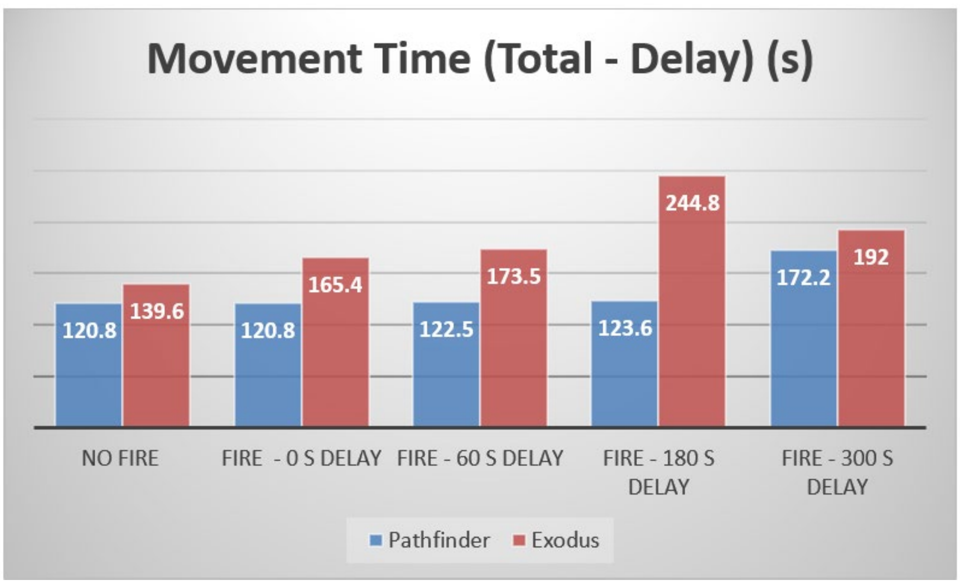


**Figure 41. Movement time for single-car emergency simulation (ROW 2S / Upper Level Fire)**

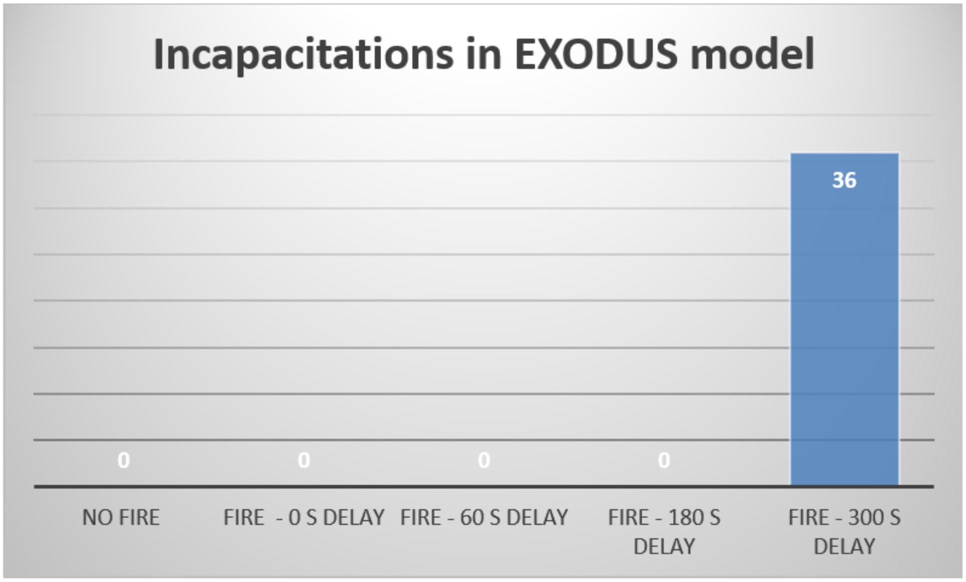


**Figure 42. Incapacitations for single-car emergency simulation (ROW 2S / Upper Level Fire)**

### *5.6.4 Three-car Emergency Simulations*

For the three-car emergency scenario, a ROW evacuation was simulated with all doors closed except for two side doors on the end of the train and a fire located on the upper level of the center car. This creates a scenario in which occupants must travel through the center car to reach an exit.

Figure 43 through Figure 45 shows the results of the three-car emergency simulation. In the railEXODUS models, the movement time initially increases with increasing delay time, and then starts to decrease. The number of incapacitated occupants also increases with increasing delay time, which based on the single-car simulations has the effect of decreasing the evacuation time. It is not known why the number of incapacitated occupants decreases between the 180-second delay and 300-second delay simulations, or why there is still a decrease in movement time in these simulations despite a decrease in incapacitated occupants.

In Pathfinder model, there is a slight (~4%) increase in movement times between the non-emergency scenario and the emergency scenarios, but once again the delay time appears to have almost no effect on the movement time. In addition, the 4 percent increase may not be significant since multiple iterations of the same model can vary by more than this amount.

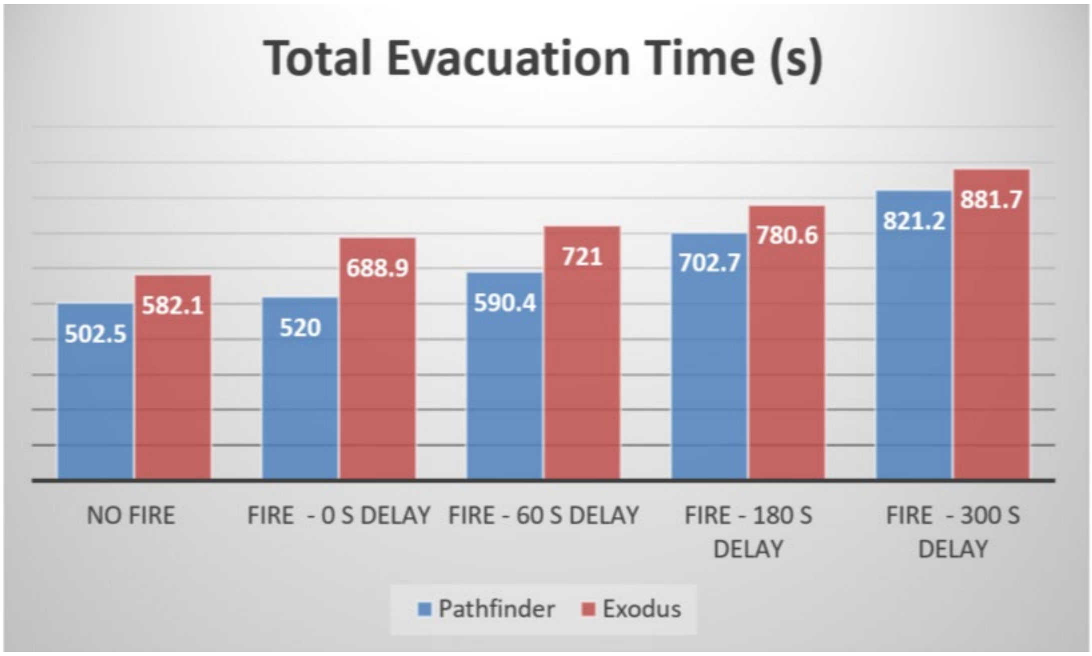


**Figure 43. Evacuation time for emergency three-car simulation (ROW 0S 0S 2S)**

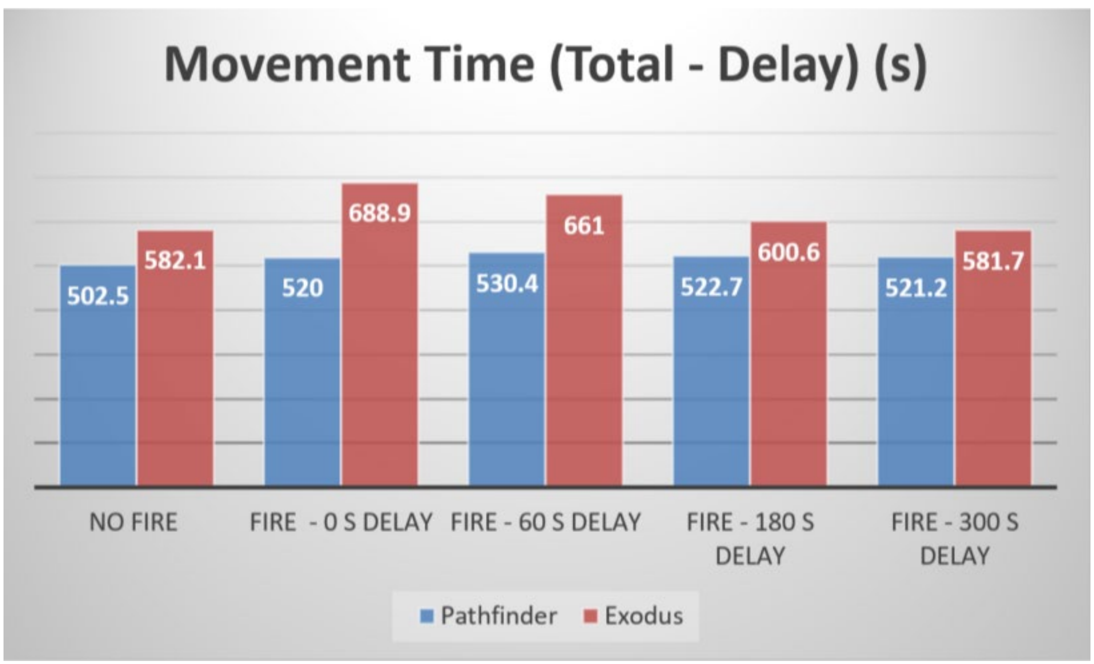


**Figure 44. Movement time for emergency three-car simulation (ROW 0S 0S 2S)**

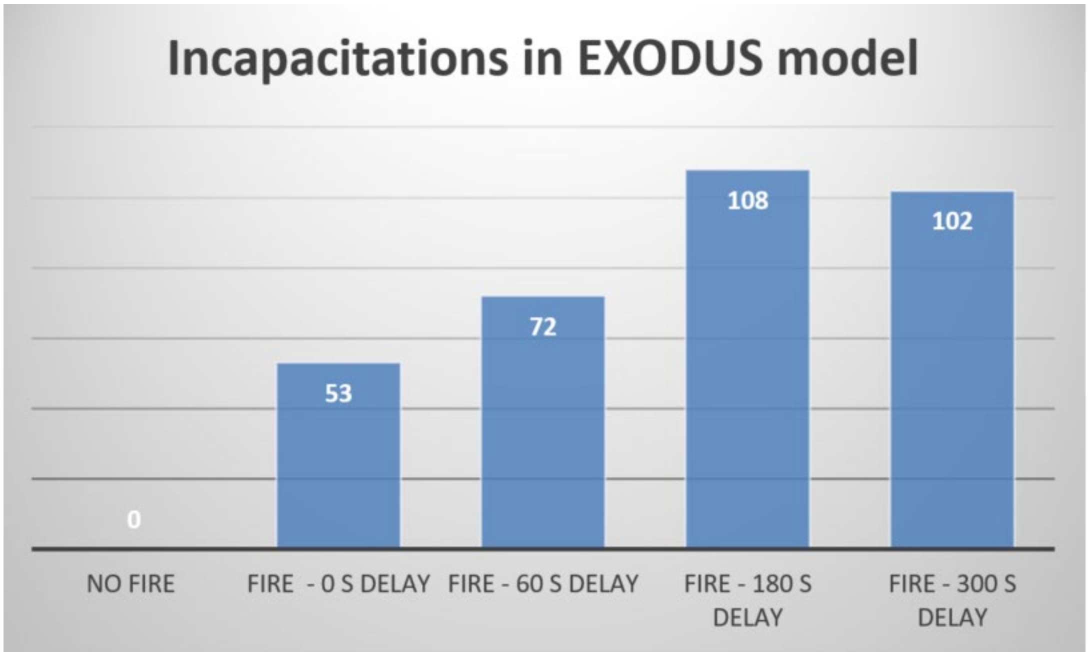


**Figure 45. Incapacitations for emergency three-car simulation (ROW 0S 0S 2S)**

# 6. Conclusion

After analyzing Pathfinder and railEXODUS in detail, both software packages were found to be adequate for simulating the evacuation of rail cars in non-emergency scenarios. The results of the example cases show that Pathfinder and railEXODUS predict similar results for non-emergency evacuations, but differ in their results for emergency scenarios. It appears that the Pathfinder model may not be as effective as railEXODUS' for emergency scenarios due to lack of a toxicity model that can capture the incapacitation of occupants during untenable conditions. A literature study to identify the egress data for an actual or simulated non-emergency scenario will help to assess whether Pathfinder or railEXODUS more closely predicts the evacuation time in an emergency scenario.

## 6.1 Benefits of railEXODUS

Since railEXODUS was designed specifically for simulations of rail vehicles, it does contain some features specific to rail cars (e.g., simulating travel in overturned cars) which are not included in the Pathfinder by default. However, many of railEXODUS' abilities to simulate rail-specific simulations can be replicated in Pathfinder using custom profiles and user-defined settings (e.g., defining door flow rates to simulate travel down to the ROW).

For the models available at the time of this research, the fire effects model in railEXODUS is more capable than in Pathfinder, as it can model the effect of multiple fire products on walking speeds while Pathfinder can only model the impact of low visibility.

## 6.2 Benefits of Pathfinder

In terms of general usability for this research, the Pathfinder user interface is easier to learn and more user-friendly. Specifically, the ability to view and edit geometry in a three-dimensional interface allows for a more intuitive understanding of the design process. In addition, the occupants' ability to move on a continuous two-dimensional plane instead of occupying discrete points in space creates a more realistic-looking result when visualized.

Pathfinder is also in active development, with updates being provided multiple times per year. While the authors have no specific knowledge of any planned features or updates, it is likely that many of the current features will be improved over time. In particular, the fire effects model is a relatively new feature in Pathfinder and potentially could be improved or expanded in the future.

## 6.3 Final Recommendations

While recommending which software best suits FRA's needs is outside the scope of this study, Pathfinder has been shown to be a capable software package for modeling rail car evacuations and is a potential alternative to railEXODUS for simulating non-emergency evacuations. However, caution must be applied if FRA considers the use of Pathfinder for emergency evacuation scenarios. Researchers recommend additional investigation and development of Pathfinder if intended to be used to simulate emergency evacuation. In addition, this future work is recommended in the following areas to understand egress from rail cars:

1. Conduct a literature review to collect movement speed data for rail specific geometries (i.e., exiting rail car by steep steps to track level, track level movement on uneven surfaces [e.g., gravel and track]), reduction in movement speeds/change in direction by

fire conditions (e.g., temperature, smoke visibility, and toxicity), and effects of carrying personal items on movement speeds

2. Validate the egress models using the available data on emergency and non-emergency scenarios [1].
    a. Determine whether both models predict the similar egress times for the non-emergency scenarios
    b. Determine whether both models predict the slowing of occupants by fire smoke accurately. Note that this will depend on Pathfinder's hazard sub-model being developed further.
    c. Determine the impact of irritants and toxicants on walking speed by comparing smoke only and smoke with toxicants, then toxicants and irritants
3. Develop custom scripts and tools to extract occupant specific information from both Pathfinder and railEXODUS
4. Include fire environment effects by working with Thunderhead Engineering to incorporate in Pathfinder the ability to import fire environment effects from external fire models (e.g., CFAST and FDS) and account for the effects of the fire environment on movement speeds / direction
5. Incorporate effects of personal items by working with Thunderhead Engineering to include this feature using a probabilistic approach
    a. Probabilistic selection of people that would be carrying a personal item, which would result in slowing their movement speed
    b. Probabilistic determination of a how many personal items would be in the floor area as well as a probabilistic selection of where these items would be located in the rail car
    c. Ability to perform numerous simulations and create an egress time distribution
6. Perform egress analysis during a fire event for rail cars with sleeping accommodations
7. Assess the impact of operating environment on egress out of rail car to the point of safety

## 7. References


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## Abbreviations and Acronyms

| ACRONYMS | EXPLANATION |
|---|---|
| ASTM | American Society of Testing and Materials |
| AGT | Automated Guideway Transit |
| $CO_2$ | Carbon Dioxide |
| CO | Carbon Monoxide |
| COHb | Carboxyhemoglobin |
| CAD | Computer-Aided Design |
| CFAST | Consolidated model of Fire And Smoke Transport |
| FRA | Federal Railroad Administration |
| FDS | Fire Dynamics Simulator |
| FSEG | Fire Safety Engineering Group |
| FED | Fractional Effective Dose |
| FID | Fractional Incapacitating Dose |
| HRR | Heat Release Rate |
| HCN | Hydrogen Cyanide |
| MBTA | Massachusetts Bay Transportation Authority |
| NFPA | National Fire Protection Association |
| NIST | National Institute of Standards and Technology |
| $O_2$ | Oxygen |
| ROW | Right-of-Way |
| SFPE | Society of Fire Protection Engineering |
| Volpe | Volpe National Transportation Systems Center |