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RAIL CAR OPERATIONAL ENVIRONMENT EVACUATION STUDY

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ABSTRACT

Jensen Hughes has performed a research study to understand egress from a rail car, which has unique requirements such as tight aisles, and operational environment differences from typical commercial buildings. Pathfinder was used to model egress from rail cars in tunnels and stations, based on NFPA 130, 2023 edition (Standard for Fixed Guideway Transit and Passenger Rail Systems) requirements. A sensitivity analysis was performed using the Monte Carlo method to run 25 unique simulations for varying occupant characteristics/parameters of interest. The occupant characteristics studied include walking speed, occupant diameter, which represents the shoulder width of an occupant, height, and boundary layer. A literature review based on work performed by John J. Fruin in 1971 (Fruin, 1971) and typical industry guidance informed the numeric inputs.

This report provides practical guidance for modeling egress in intercity trains. It is recommended to perform a sensitivity analysis to better understand the impact of input parameters on the overall egress time. Consideration should be given to the operational environment impacts on total egress time. Varying occupant speed played a more significant role in the station geometry due to occupant collision handling, queuing at the entrance to egress components and reductions in walking speed on stairs. Congestion within the train was the primary driver for the egress times seen in the tunnel, as there was minimal queuing and primarily free movement once egressing through the tunnel corridor. The results of this study also showed that the NFPA 130 walking speed, which takes into account the slowing down of the occupants in a congested environment, should not be used as an input for unimpeded walking speed in Pathfinder. In addition, when modeling egress within a station, the current room distance penalty should be set to zero in Pathfinder to avoid unrealistic occupant behavior on long platforms.

INTRODUCTION AND BACKGROUND

Jensen Hughes' research effort focused on quantifying the impact of the operational environment during egress from a rail car, utilizing the Pathfinder software, developed by Thunderhead Engineering. An egress analysis was performed at a high level to consider how long it takes able-bodied occupants that do not require assistance, to egress from a rail car when loaded at maximum capacity. When performing a life safety analysis, consideration should be given to the population set, fire size and location to determine the impact on the occupants' egress path. Pathfinder is an appropriate choice to further analyze egress within the transportation space because it was proven to incorporate a more complex trend of collision response and conflict resolution (Datta et al., 2024). The operational environment considers the composite of conditions that influence the capabilities and decision making of an occupant. In this study, the environments or geometries of interest include a rail car in a tunnel and a station. A Monte Carlo analysis was used to perform multiple simulations and quantify the sensitivity of the egress time to numerous inputs. The chosen inputs consider the expected demographic differences for occupants within intercity trains and are based on common design bases used in the industry for egress modeling. These inputs include varying occupant speed, diameter, height, and boundary layer (measured as the distance between the occupant and an obstacle).

LITERATURE REVIEW

This research study evaluates the impact of various input parameters on the total egress time for distinct operational environments. There was minimal information in the literature that directly correlated to the validation of Pathfinder inputs in train car operational environments, so a more detailed literature review was conducted to inform the input parameters utilized throughout this research. The following resources were identified as common design bases in the industry for egress modeling inputs:

- SFPE Handbook of Fire Protection Engineering, Chapter 59, Employing the Hydraulic Model in Assessing Emergency Movement (Gwynne and Rosenbaum, 2016)
- NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, Chapter 5, Stations (NFPA, 2023)

Following a review of the SFPE Handbook, Chapter 59 and NFPA 130 it was identified that the data utilized in both references is based on an egress study performed by Fruin, documented in the Pedestrian Planning and Design Guide (Fruin, 1971). Chapter 59 in the SFPE Handbook is comprised of over 50 sources, including Fruin's study, while Fruin's study is the primary source for NFPA 130 Chapter 5.

Chapters 1 through 3 of The Pedestrian Planning and Design Guide (Fruin, 1971) provides a comprehensive background of occupant movement in cities and pedestrian planning strategies over time. Additionally, these chapters provide an overview of human characteristics related to pedestrian design. The overview includes physical body dimensions based on a large number of human factor studies at the time. The physical dimensions identified in this document are used as the basis of design for many transportation systems and pedestrian planning in cities. It is important to highlight that the human dimensions identified in this report are outdated and are based on a representative population from the 1970's and not the current day. Research has shown that the average size of occupants has increased over time and results in new occupant size and movement.

Chapter 4 proposes the level of service concept for pedestrian planning. This concept was first developed for traffic engineering in recognition that capacity design resulted in planned congestion. Fruin applies this concept to capacity design and planned congestion for pedestrian planning.
Figure 1 describes level of service A through F. Level of service A corresponds to free circulation and the level of service increases based on the occupant density up to Level of service F.

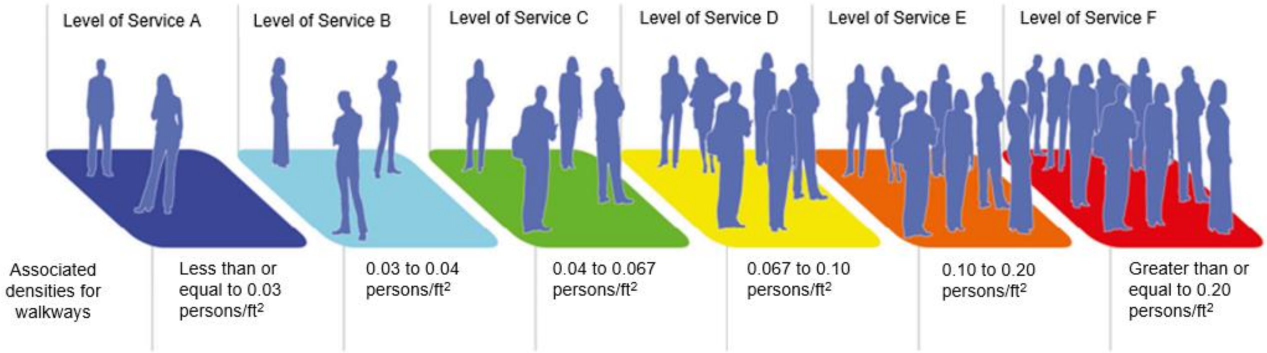


Figure 1. Illustration of increased occupant density with increased Fruin's level of service

The densities, flow rates, and walking speeds for different levels of services were published by Fruin based on an egress study of 1,000 occupants during normal traffic conditions at NYC Port Authority and Penn Station. This information is similarly published in the SFPE Handbook Chapter 59 (Gwynne and Rosenbaum, 2016), represented in a graph of density versus movement speed. This relationship shows that the average occupant walking speed decreases proportionally to the local increase in occupant density. The maximum unimpeded walking speed corresponding to an optimal density of 0.05 persons/ft^2 or less (i.e. level of service A-C) is 235 ft/min.

NFPA 130 publishes walking speed values to use for egress calculations. These walking speed values are based on Fruin's level of service concepts E and F, considering the high density of transportation stations, and align with the information published in the SFPE Handbook of Fire Protection Engineering based on an assumed density (i.e. level of service E/F).

The simplified distribution of walking speed considers two distinct speeds, each assigned to 50% of occupants. assigns 50% of the occupants. Though the female speed was reported by Fruin to be 254 ft/min, the default walking speed of 235 ft/min was used to create a greater contrast in the walking speeds.

The key takeaway is that utilizing data from any of these resources is essentially using data from Fruin's work; however, the presentation of the data in each reference is geared toward specific uses. It is important to understand the basis of design inputs and how the data was collected and used in a model. The walking speed inputs considered in this analysis are summarized in Table 1.

Table 1. Walking Speed Summary from different literature sources utilized in this research study

Source	**Walking Speed**	**Additional Information**
NFPA 130 – corridor/ platform	124 ft/min	Based on level of service F, very congested high-density area
NFPA 130 – concourse	200 ft/min	Based on level of service E, congested high density area
Pathfinder Default / SFPE Handbook	235 ft/min	Corresponds to level of service A through C
Pedestrian Planning and Design	Normal Distribution Min/max: 114-354 ft/min μ = 235.8 ft/min σ = 39 ft /min	Based on single normal distribution used for six population groups, based on age and gender
	Simplified Distribution, Male = 270 ft/min Female = 235 ft/min	Male speed - Average free flow walking speed based on data for males for 1,000 non-luggage carrying occupants in Port Authority Bus Terminal and Penn Station in NYC. Female speed - utilizes default Pathfinder walking speed to create greater contrasts in walking speed

Additional Occupant Characteristic Data

Relevant resources were also evaluated for guidance on the input parameters for occupant diameter, height, and boundary layer using the sources identified above. A summary of available guidance is provided in Table 2.

Note, the boundary layers in Table 2 for NFPA 130 are larger than the boundary layers that were modeled and validated in Pathfinder. Validation was performed to simulate the experiments performed by RISE Research Institute of Sweden and Lund University (Carlson et al., 2019) which identified the boundary layer between the train and the open track to be between 0.1 and 0.2 m (measured as the distance from the edge of the platform to the edge of the occupant's foot compared to the boundary layer measurement in Pathfinder). A boundary layer of 0.1 m was validated to most closely align with the experimental data, which is less than the NFPA 130 guidance.

NFPA 130 and the SFPE Handbook Chapter 5 do not provide guidance on the occupant height nor occupant diameter because these two resources are geared towards the hydraulic model, which simplifies egress behavior to use hand calculations based on occupant speed and flow, which does not require the occupant diameter or height.

Table 2. Occupant characteristic published guidance from different literature sources utilized in this research study

Source	**Diameter**	**Height**	**Boundary Layer**
NFPA 130	No guidance	No guidance	1 ft – sidewalls/ corridor 1.5 ft – edges open to trainway
SFPE Handbook Chapter 59	No guidance	No guidance	0.66 ft – corridor < 1.5 ft – wide concourse
Pathfinder	17.9 inches	6 ft	0.49 ft
Fruin Pedestrian Planning	18-inch x 24-inch ellipse	No guidance	0.66 ft

MODEL DEVELOPMENT BACKGROUND

The computer-based egress model, Pathfinder was used to evaluate rail car passenger egress time prediction in this report. The steering simulation mode was used for this study.

Pathfinder

Pathfinder is an agent-based emergency evacuation simulator developed by Thunderhead Engineering Consultants Inc. that considers a continuous mesh that encompasses all the movement space. Because originally Pathfinder was used to model building evacuation, the continuous navigation mesh is called a room. Passengers are allowed to move anywhere in the room except overlapping with another passenger. However, unlike a room in a building, movement in an actual railcar is limited to aisles between the seats. The train car configuration is captured by drawing individual rooms to represent the seat location and aisle width and is explained in more detail in the Rail Car Configuration section of this report.

Pathfinder Version Information

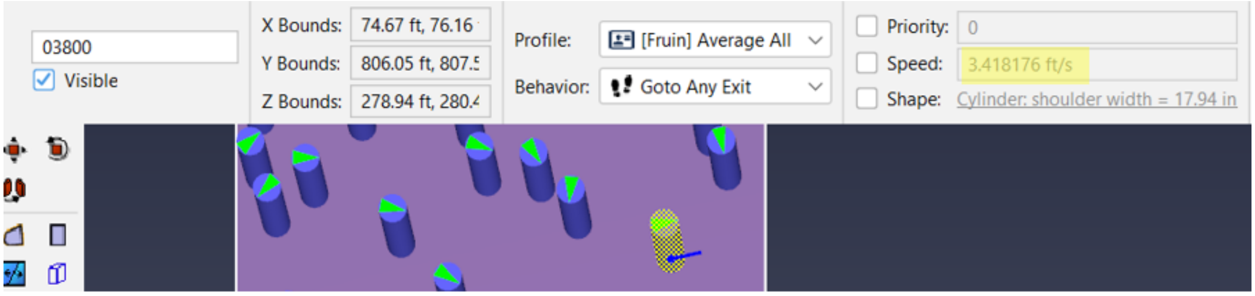
Pathfinder version 2023.2.0816 was used for this analysis. In this current version, occupants in the aisle have priority over occupants merging from their seats in the rail car. It is acknowledged that there are newer versions of Pathfinder to be released that incorporate a change in the collision handling model and occupant priority assignments for tight geometries, such as rail cars, theoretically resulting in less variation and decreased evacuation times. Therefore, the current model used in this analysis yields more conservative results. This updated version was not available at the start of this research effort and was therefore not used for this analysis.

Monte Carlo Method

The Monte Carlo method was utilized throughout this research project to evaluate the sensitivity of the total evacuation time to various model input parameters. The Monte Carlo Method is a mathematical technique used to estimate the possible outcomes of an uncertain event.

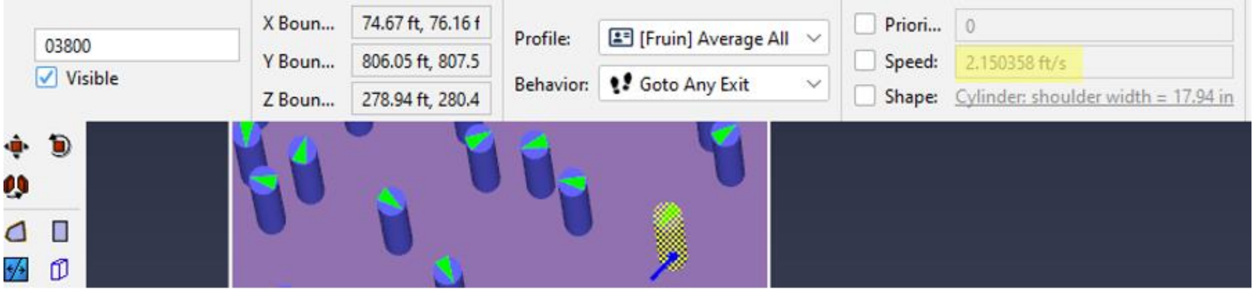
Pathfinder is a deterministic model; therefore, if the same input file is run multiple times, the same results will be obtained. In reality, occupant characteristics, location, behavior, and decisions are stochastic and will impact evacuation results. The Monte Carlo method allows occupant input parameters used in Pathfinder to be varied within a defined range for multiple simulations to evaluate the impact on the total evacuation time. A total of 25 simulations were performed to quantify the variation in egress times for each selected input parameter. For example, in Figure 2 and Figure 3, the same occupant in the same location is selected but the speed is approximately 3.4 ft/s for Run 1 and 2.2 ft/s for Run 16. The occupant location remained constant for both the tunnel and the station geometry, due to the high density of occupants in the train. Additionally, keeping occupant location the same allowed for the effect of the chosen variables to be isolated.

To utilize the Monte Carlo Method, the user develops a single Pathfinder input file varying the desired parameter. Based on the input file, a specified number of unique input files are generated using the Monte Carlo Method. The input files can be run automatically in series to provide comprehensive results for analysis. (Thunderhead Engineering, 2023a)



03800
☑ Visible
X Bounds: 74.67 ft, 76.16
Y Bounds: 806.05 ft, 807.5
Z Bounds: 278.94 ft, 280.4
Profile: [Fruin] Average All
Behavior: Goto Any Exit
☐ Priority: 0
☐ Speed: 3.418176 ft/s
☐ Shape: Cylinder: shoulder width = 17.94 in

Figure 2. Monte Carlo Run 1 of 25



03800
☑ Visible
X Boun... 74.67 ft, 76.16 f
Y Boun... 806.05 ft, 807.5
Z Boun... 278.94 ft, 280.4
Profile: [Fruin] Average All
Behavior: Goto Any Exit
☐ Priori... 0
☐ Speed: 2.150358 ft/s
☐ Shape: Cylinder: shoulder width = 17.94 in

Figure 3. Monte Carlo Run 16 of 25

Simulation Modes

Pathfinder supports two simulation modes - steering mode and SFPE mode. Each simulation mode uses a unique set of algorithms/equations to model people movement and determine egress times. The simulation mode impacts the occupant density calculation and associated calculated occupant walking speeds. SFPE Mode utilizes the assumptions in the Engineering Guide to Human Behavior in Fire (SFPE, 2019), and occupant density is based on total room density rather than localized occupant density, producing results similar to hand calculations, while steering mode attempts to mimic human behavior and movement as much as possible. In steering mode, the occupant density is calculated using local occupant spacing and determines an associated density based on the spacing density relationship developed by Fruin (Thunderhead Engineering, 2023b).

Simulations utilizing each simulation mode were conducted to model rail car evacuation onto an elevated platform in a rail tunnel. The results of the simulations found that SFPE mode is not able to accurately model tight geometries inside rail cars and consequently underpredicts the evacuation time. Steering mode is generally utilized and should be used for all models including tight rail car geometries.

EGRESS MODEL DEVELOPMENT AND INPUTS

Pathfinder models include key, user-defined inputs such as occupant profiles, input parameters, Pathfinder geometry, and occupant loading. The following section outlines key inputs which make up the occupant profiles.

Model Inputs

Occupant characteristic inputs are an important aspect of egress models; however, the available data for these types of inputs is lacking for many different populations. This analysis is focused on egress from intercity trains which includes a diverse range of occupants including age, gender, body dimensions, and demographics.

The following occupant parameters were identified to be evaluated during this research study: walking speed, diameter, height and wall boundary layer. After a review of the published guidance outlined above, the following input ranges were identified to be modelled. Where literature guidance was deemed insufficient to develop these parameters, additional references were utilized as listed in Table 3.

Table 3: Selected Pathfinder Input Parameters

Pathfinder Input Parameter	Modeled Range	Reference
Walking Speed	Normal Distribution [1.9-5.9 ft/s] µ: 3.93 ft/s σ: 0.65 ft/s	Fruin, 1971
	Simplified Distribution [3.9 ft/s, 4.5 ft/s]	Fruin, 1971
Diameter	17.9 – 24 in.	From airport study of occupant demographics – anticipated to be similar for train transportation (Goodhead and Strege, n.d.)
Height	5 ft 3 in – 6 ft	CDC data on body measurements (CDC, 2021)
Wall Boundary Layer	0.0-0.66 ft	Internal boundary layer validation

Scenarios

The scenarios outlined in Table 4 were analyzed for both the tunnel and station geometry. The values highlighted in green are varied for each of the Monte Carlo runs. Analyzing the impact of the same parameters allows for conclusions to be drawn about the operational environment.

Table 4: Pathfinder Scenario Run Matrix

	Scenario Identification	**Maximum Walking Speed**	**Diameter**	**Height**	**Wall Boundary Layer**	**# of runs**
Base Scenario	Pathfinder Default (D)	3.9 ft/s	17.9 in	6 ft	0.49 ft	25
Walking Speed	Fruin Distribution	**Normal Distribution [1.9-5.9 ft/s]** **µ: 3.39 ft/s** ***σ:* 0.65 ft/s**	17.9 in	6 ft	0.49 ft	25
	Simplified Distribution (SD)	**3.9 ft/s (50%), 4.5 ft/s (50%)**	17.9 in	6 ft	0.49 ft	25
	NFPA 130 Default[1]	**2.06 ft/s**	17.9 in	6 ft	0.49 ft	25
Additional Parameters	Diameter (D)	3.9 ft/s	**17.9 – 24 in**	6 ft	0.49 ft	25
	Height (D)	3.9 ft/s	17.9 in	**5 ft 3 in – 6 ft**	0.49 ft	25
	Boundary Layer (D)	3.9 ft/s	17.9 in	6ft	**0-0.66 ft**	25
	Diameter (SD)	3.9 ft/s (50%), 4.5 ft/s (50%)	**17.9 – 24 in**	6 ft	0.49 ft	25
	Height (SD)	3.9 ft/s (50%), 4.5 ft/s (50%)	17.9 in	**5 ft 3 in – 6 ft**	0.49 ft	25
	Boundary Layer (SD)	3.9 ft/s (50%), 4.5 ft/s (50%)	17.9 in	6 ft	**0 – 0.66 ft**	25
All	All Parameters	**Normal Distribution [1.9-5.9 ft/s]** **µ: 3.39 ft/s** ***σ:* 0.65 ft/s**	**17.9 – 24 in**	**5 ft 3 in – 6 ft**	**0-0.66 ft**	25

[1] Was not analyzed for station geometry or for additional parameters

Geometry and Occupant Loading

Rail Car Configuration

The train in the tunnel and station both consist of at least one, six-car length train (Figure 4), which is based on a rail car used by Massachusetts Bay Transportation Authority (MBTA). Figure 5 highlights the geometry of a single train car, with occupants represented by blue cylinders The opening into the train car seating is represented by a door to capture the effect of occupants squeezing through narrow geometry. The width is larger when one row of occupants is facing another. Note, that "reduce diameter to move through narrow geometry" was enabled in Pathfinder and set to 11 inches to accommodate this movement. The key parameters are found in Table 5.

Figure 4. Train Car Geometry

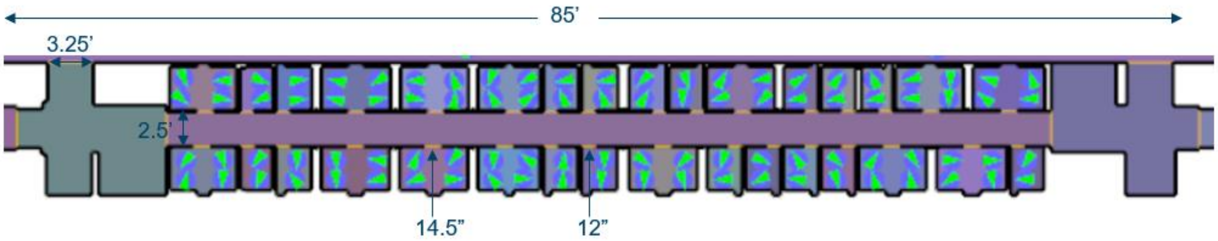


Figure 5: Single train car geometry

Table 5: Train Car Parameters

Model Parameter	**Value**
Length of single car	85 ft
Total train length	510 ft
Aisle width	2.5 ft
Door/opening width between aisle and seats	12 in or 14.5 in
Exit door width	3.25 ft
Number of occupants in single train car	92 persons
Total number of occupants in train	552 persons

Tunnel

The tunnel consists of a six-car length train, as described above. The tunnel geometry aligns with NFPA 130 requirements, but it should be noted that many tunnels in the US were built before the development of NFPA 130 and therefore do not comply with these requirements. The train and tunnel geometry parameters are highlighted in Figure 6, Figure 7, and Table 6.

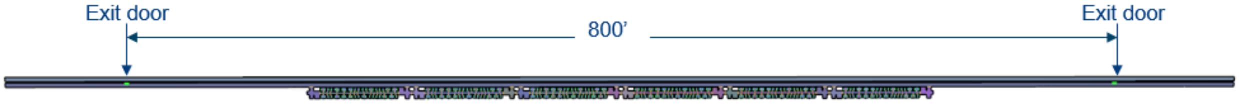


Figure 6: Tunnel Geometry

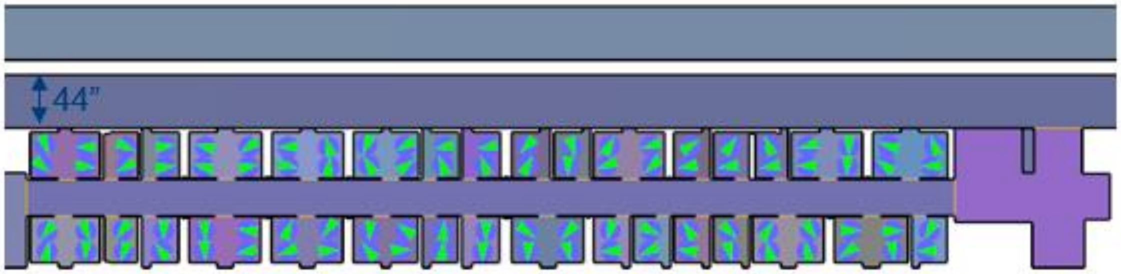


Figure 7. Train Car Geometry and Tunnel Width

Table 6: Tunnel Model Parameters

Model Parameter	**Value**
Distance between exits	800 ft
Exit door width	44 in
Width of tunnel platform	44 in
Total number of occupants	552 persons

Station

The representative geometry for a side platform station is based on NFPA 130 requirements and common geometries of railroad passenger stations in the United States. The station consists of eight stair/escalator sets and four elevator sets from the platform to the concourse level as shown in Figure 8. The maximum travel distance (distance from most remote point to nearest exit) is 100 ft, and the common path of travel (travel path before two separate and distinct paths of travel to two exits are available) is 70 ft on the platform level.

There are two tracks on the side platform level that can support two trains at a time, shown in Figure 9. It is assumed that there are 552 occupants waiting on each platform for boarding, based on the entraining load per §5.3.2 of NFPA 130. Additionally, there are an additional 552 occupants waiting on a platform 2 (adjacent to track 2) due to missed train headway based on disruptions and delays per §5.3.2.5 of NFPA 130. There are a total of 2,760 occupants within the model located in the train and on the platform, which assumes maximum occupant loading for worst-case conditions during a fire scenario. There are no occupants initially located on the concourse level for the model.

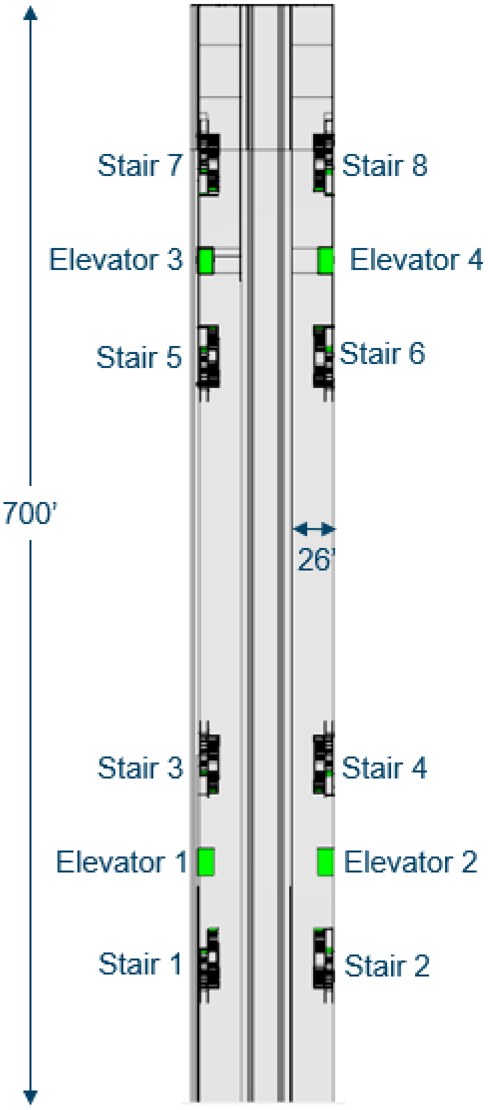


Figure 8. Platform Level, Plan View

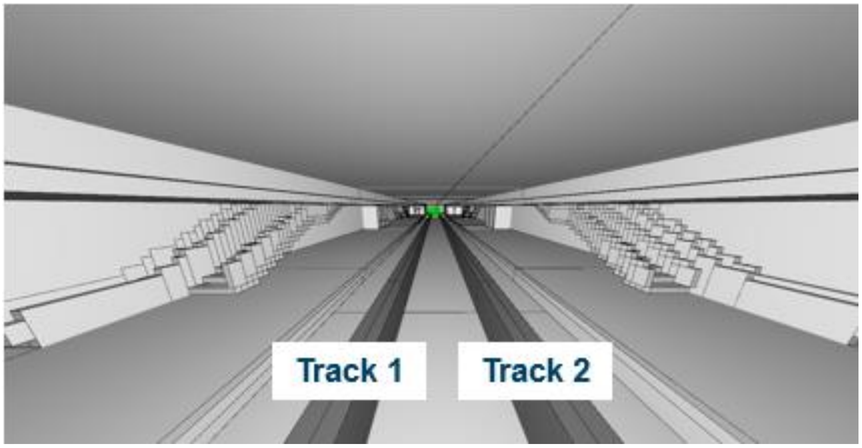


Figure 9: Platform Level Front View

There are two main egress escalator/stair sets from the concourse level to the ground level, that are spaced 690 ft apart. The width of the north and south main egress components are shown in Figure 10 and Figure 11 respectively. The minimum concourse level width is 13.67 ft.

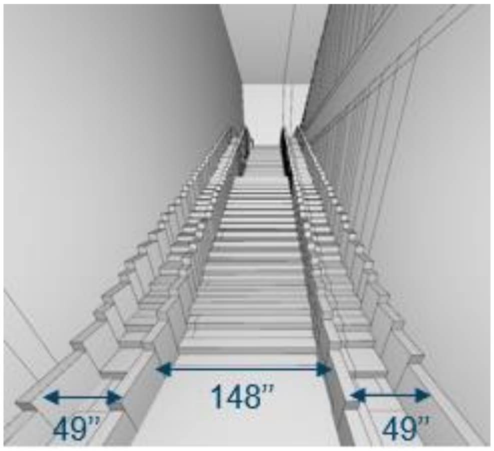


Figure 10: Main egress stair, North Exit, Main egress stair 2

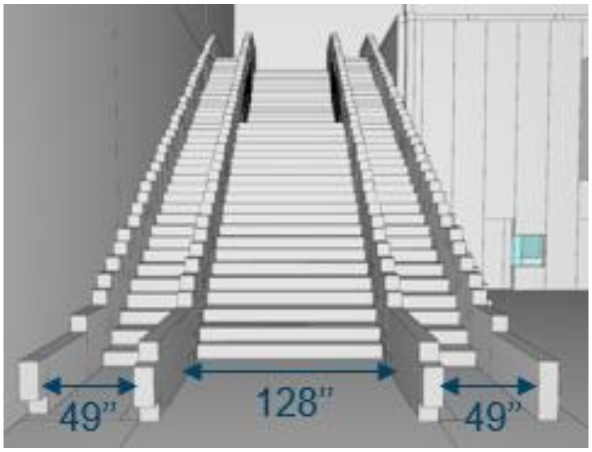


Figure 11: Main egress stair, South Exit, Main Egress Stair 1

The overall station parameters and model configuration in Pathfinder are summarized in Table 7 and shown in Figure 12 through Figure 14.

Table 7: Station Model Parameters

Model Parameter	**Value**
Platform Length	700 ft
Platform width [minimum, maximum]	13.9 ft, 26 ft
Escalator width	49 in
Stair width (Platform)	69 in
North exit stair width	148 in
South exit stair width	128 in
Concourse level width [minimum]	13.67 ft (164 in)
Total number of occupants in trains	1,104 persons
Total number of occupants on platform	1,656 persons
Total number of occupants	2,760 persons

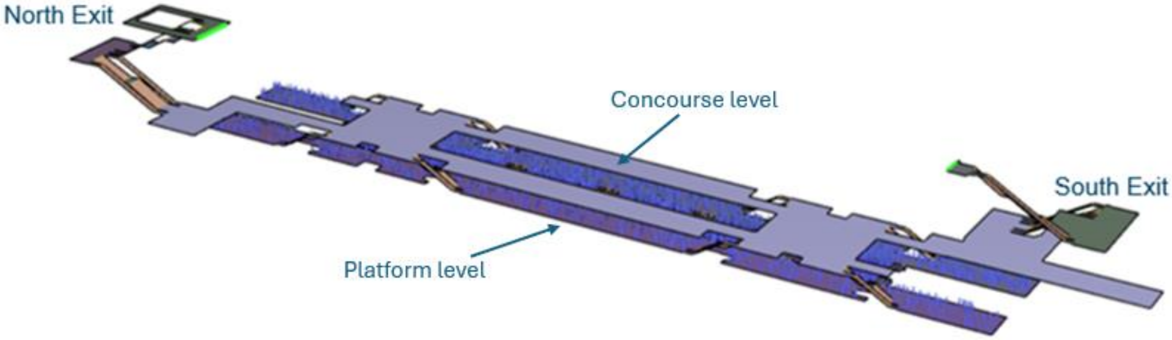


Figure 12. Overall Station Configuration in Pathfinder

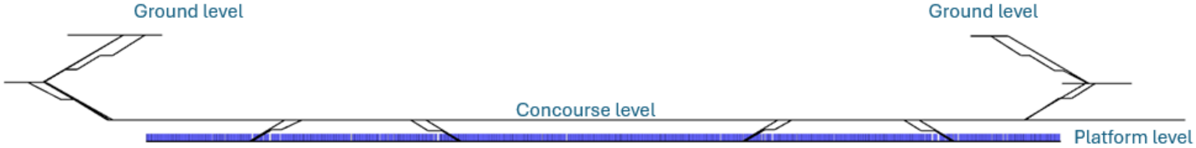


Figure 13. Station Profile in Pathfinder

Figure 14. Platform Plan View in Pathfinder, with stair/escalator combinations circled in red

EGRESS MODEL RESULTS

The results for both the tunnel and station geometry analyze the impact of walking speed and less commonly altered input parameters like occupant diameter, height and boundary layer on total evacuation time. A Monte Carlo Analysis using 25 unique input files was completed for each of the scenarios identified in Table 4.

NFPA 130 Speed

The NFPA 130 walking speed results are not presented in the following section and were not analyzed further because the reduced walking speed yields unrealistic results when modeled in Pathfinder, as the average egress time utilizing a walking speed of 2.06 ft/s is 117% greater than the average walking speed when using the default speed of 3.9 ft/s.

Pathfinder considers an unimpeded walking speed when occupant density is below a critical threshold value, as highlighted in Figure 15. As density increases, the occupant speed decreases which is captured by the slope of the curve that represents the corridor walking speed. The NFPA 130 walking speed does not take into account population characteristics, but instead considers a high density of occupants in the corridor, which equates to Fruin's level of service E or F, as indicated by the star in Figure 15.

Egress in the tunnel was modeled in Pathfinder for both speeds to further analyze this impact. The corridor is not densely populated when occupants exit the train car, as is considered with the NFPA 130 walking speed (Figure 16). The density of occupants in the corridor utilizing the NFPA 130 walking speed is less than the density when using the Pathfinder default. This is indicated by the distance measured between occupants in Figure 16 and Figure 17 respectively.

Pathfinder considers local density of occupants and reduces the speed in the model accordingly, shown with the specific occupant colors and seen in the range of speed for a particular occupant (2.62 to 3.28 ft/s) shown in Figure 17. Therefore, including a walking speed that already considers a reduction in speed based on density is overly conservative when modeling egress in Pathfinder.

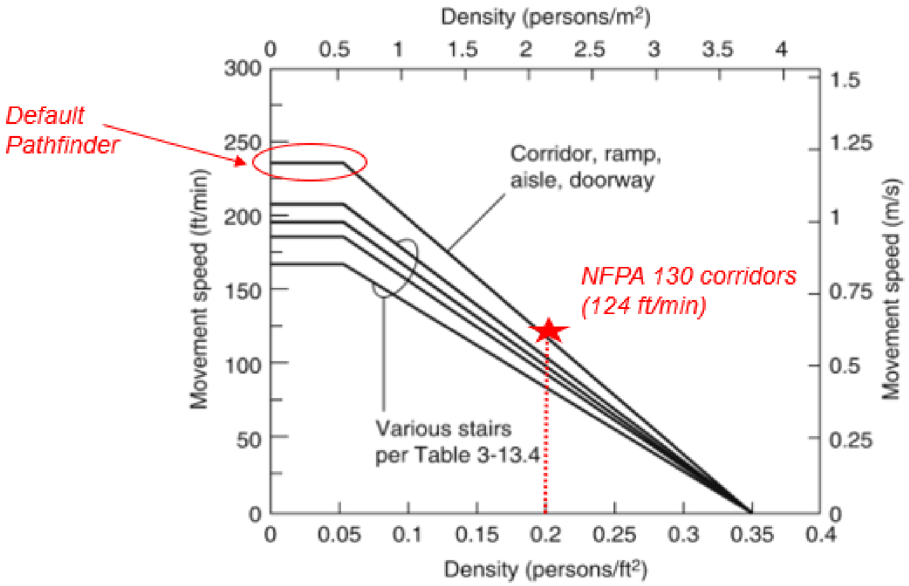


Figure 15. Speed versus density graph from SFPE Handbook

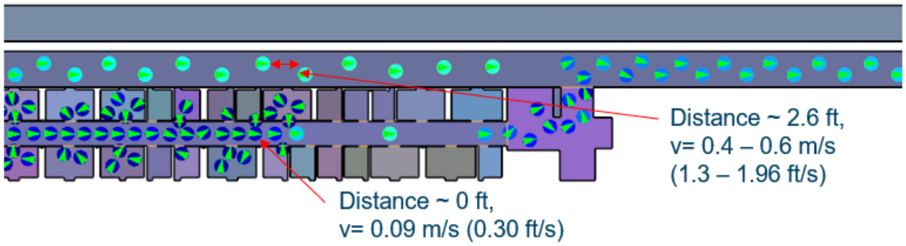


Figure 16. NFPA 130 walking speed

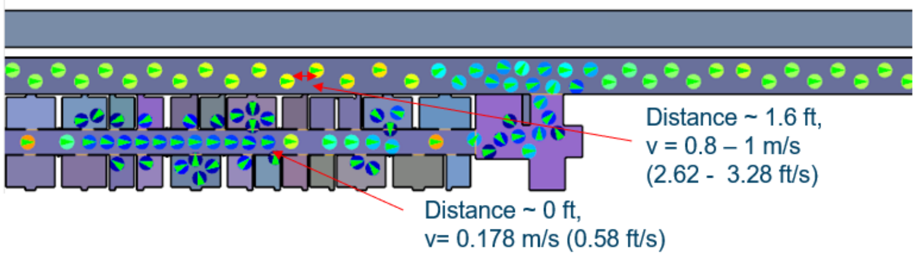


Figure 17. Pathfinder default walking speed

Operation Environment Analysis

The results for the simulations shown in Table 4 illustrate the importance of performing a sensitivity analysis when analyzing the impact of specific parameters.

The following results are presented for each scenario evaluated:

- Minimum egress time for occupants to evacuate the tunnel (minimum out of the 25 simulations)
- Average egress time for occupants to evacuate the tunnel (average of the 25 simulations)
- Maximum egress time for occupants to evacuate the tunnel (maximum out of the 25 simulations)

The total evacuation time data was analyzed in the following two ways and are presented in Table 8.

1. Determination of the variance in Pathfinder evacuation when varying a single parameter. This highlights the impact of the Monte Carlo analysis.

$$\% = \frac{t_{max} - t_{min}}{t_{min}} * 100$$

2. Determination of the variance in Pathfinder evacuation time for a single parameter compared to the corresponding average value. This highlights the overall impact of a specific parameter. The walking speed variations are all compared relative to the Pathfinder default average and calculated using the %D formula. For the “Additional Parameters” the %D variation is calculated relative to the Pathfinder default average ($t_{avg,D}$) when utilizing the Pathfinder default speed, and the %SD variation is calculated relative to the simplified distribution average ($t_{avg,SD}$) when utilizing the simplified distribution of speed. “All Parameters” is calculated using the %D formula.

$$\%D = \frac{t_{avg,X\ scenario} - t_{avg,D}}{t_{avg,D}} * 100$$

$$\%SD = \frac{t_{avg,X\ scenario} - t_{avg,SD}}{t_{avg,SD}} * 100$$

Table 8. Modeled Scenario Results

Scenario	Environment	Minimum	Average	Maximum	% Variation between min and max egress time	% Variation relative to default value
Walking Speeds						
Pathfinder Default (D)	Tunnel	334	359	392	17	N/A
	Station	892	906	918	3.0	N/A
Fruin Distribution	Tunnel	345	366	398	15	1.9
	Station	1125	1145	1165	3.5	26.4
Simplified Distribution (SD)	Tunnel	303	332	367	21	-7.5
	Station	855	864	877	2.6	-4.6
Additional Parameters						
Diameter (D|SD)	Tunnel	341|325	348|331	355|345	4.1|6.1	-3.1|-0.3
	Station	968|917	983|926	999|940	3.2|2.5	8.5|7.2
Height (D|SD)	Tunnel	326|310	358|333	390|357	19.6|15.2	-0.27|0.3
	Station	898|853	910|863	922|876	2.6|2.8	0.49|-0.09
Boundary Layer (D| SD)	Tunnel	305|285	346|315	444|356	46|16.7	-3.6|-5.1
	Station	853|805	864|822	884|832	3.6| 3.4	-4.5|-4.9
All Parameters	Tunnel	349	367	402	15.0	2.1
	Station	977	995	1019	4.2	9.8

Individual Variation – Walking Speed

The results show that there is up to a 17% variation in total egress time with the default Pathfinder inputs for tunnel geometry, while there is an expected 3.0% variation for the station geometry. The differences in the tunnel are due to variations in occupant decision making and collision handling between the simulations. In simulations with shorter egress times occupants more effectively utilize train exit doors. Additionally, the congestion effects in the train car propagate to the tunnel where occupants walk in a single file. The station however has multiple levels and egress components, which minimizes the rail car effects because of queuing and congestion that occurs in other areas of the station. A similar conclusion can be made regarding the variation in total egress times for two operational scenarios utilizing Fruin and Simplified distributions.

Default vs Scenario Average – Walking Speed

The station geometry has a much larger variation for the Fruin walking speed distribution compared to default than the tunnel geometry (26.4% versus 1.9% respectively) as shown in Figure 18 and Figure 19. The total egress time is driven by the slowest person in the group and 50% of occupants are moving at speeds less than 3.93 ft/s for the Fruin distribution. It was hypothesized that the minimum walking speed impacts the station more than the tunnel.

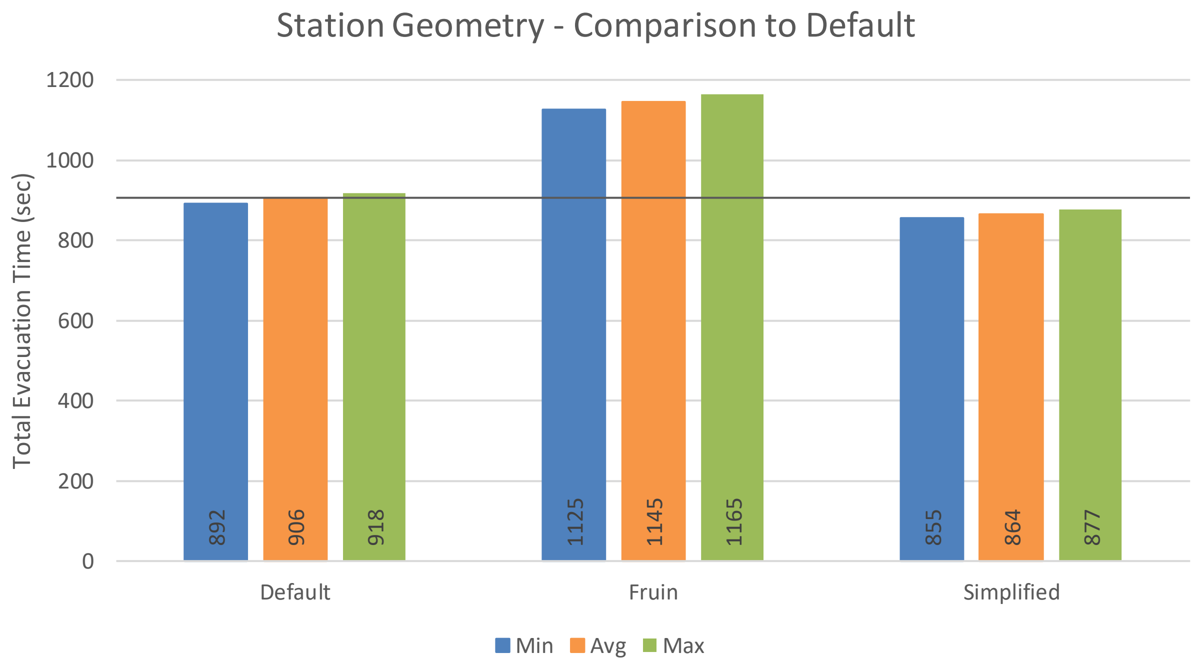


Figure 18. Station Comparison to Default - Walking Speeds

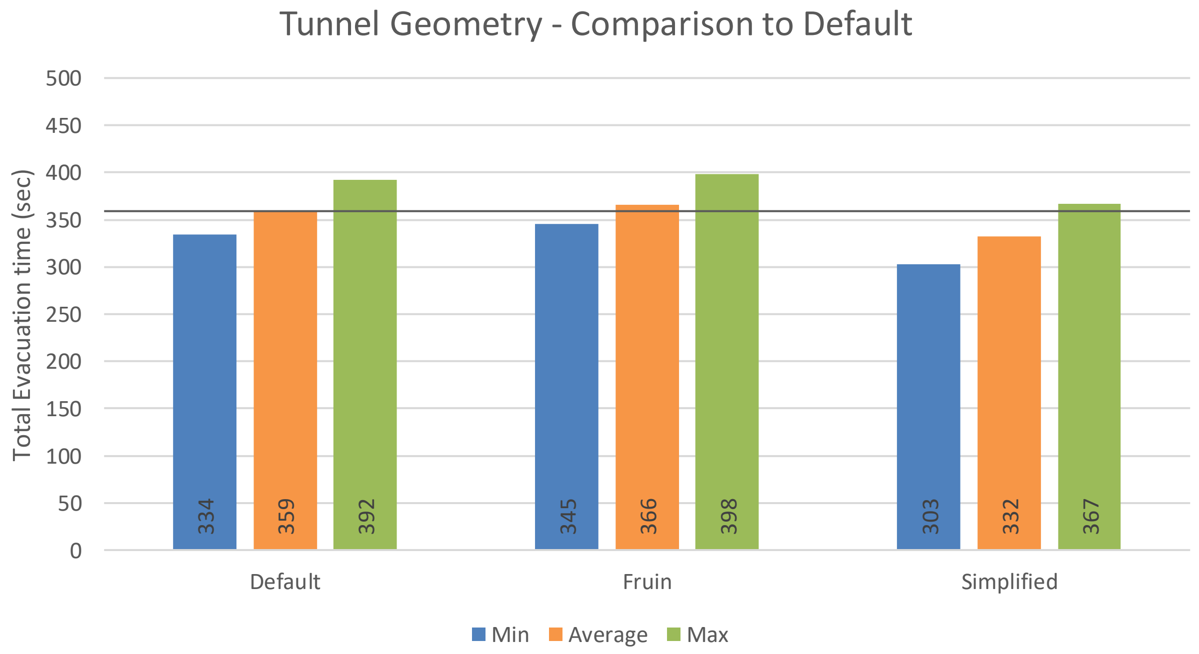


Figure 19. Tunnel Comparison to Default - Walking Speeds

The magnitude of the variation in Fruin walking speed versus default can be attributed to the station geometry. There is a steady flow of occupants walking up the stairs using the default walking speed since they are all moving at the same reduced speed. This translates to a steady flow of occupants on the concourse level, which can be seen in the uniform spacing of occupants moving towards the station exit on the concourse in Figure 20. However, when the Fruin normal distribution of speed is applied to occupants, there are "fast" occupants that can get stuck behind "slow" occupants, resulting in increased egress times. The only time that the "faster" occupant is able to make up for this excessive reduction in speed up the stairs is when they are on a level walking surface (concourse) and can maneuver around the "slower" occupants. The impact of the slowing on the stairs is shown in Figure 21, represented by the staggered occupants moving towards the station exit on the concourse level.

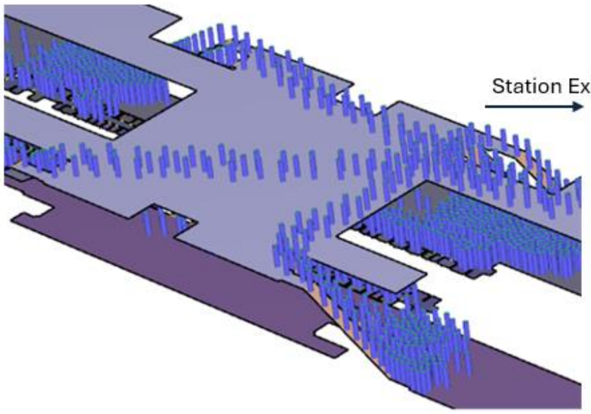


Figure 20. Occupant movement on concourse level - default speed

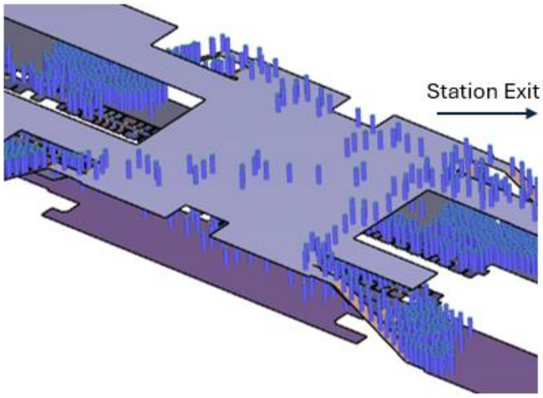


Figure 21. Occupant movement on concourse level - Fruin normal distribution of speed

This difference in variation seen in the station versus the tunnel geometry can also be explained by the impact of egress components. Queuing occurs in other regions of the station once occupants leave the rail car, specifically at the entrance to stairs, as shown in Figure 22, while occupants that exit the train in the tunnel are essentially able to experience unimpeded walking speeds once they pass the train exit doors as shown in Figure 23.

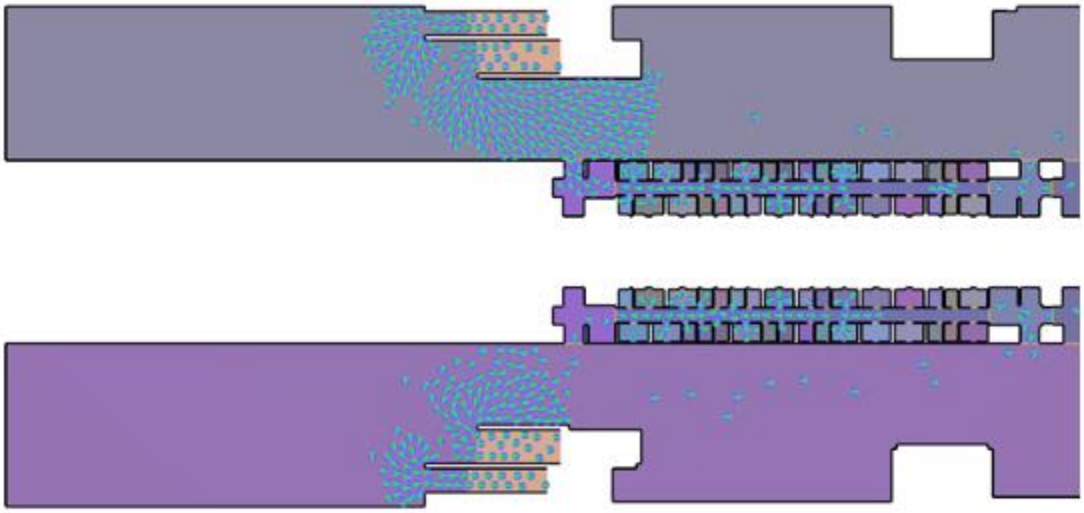


Figure 22. Occupant distribution on platform level when out of the rail car in the station

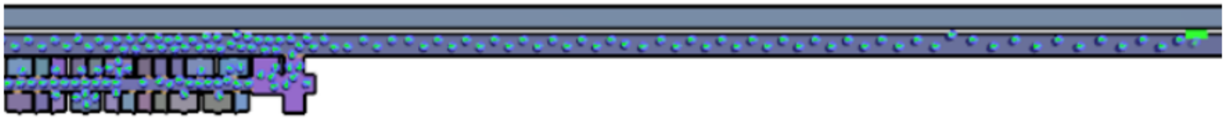


Figure 23. Occupant distribution when out of the rail car in the tunnel

The impact of different occupant speeds is not seen until the occupants are outside of the rail car, since the congestion within the rail car has the same impact on both operational environments. Occupant movement within the train is represented before the vertical dashed lines that show when occupants leave the rail car (Figure 24 and Figure 25), where the speed for both environments remains relatively constant, below 0.6 ft/s. Occupants within the station are not able to reach a continuous constant walking speed when they leave the train car due to the congestion and queuing previously mentioned, which is further illustrated with the stochastic nature of the walking speed shown in Figure 24. When the last occupant leaves the railcar in the tunnel, they are able to walk at the maximum unimpeded walking speed. Additionally, most of the egress time for tunnel scenarios occurs in the train car, therefore the tunnel is driven by the environment and the variation in station is driven by speed. There are greater deviations between default and Fruin averages in the station because congestion in the train car isn't driving and the impact of speed can be realized.

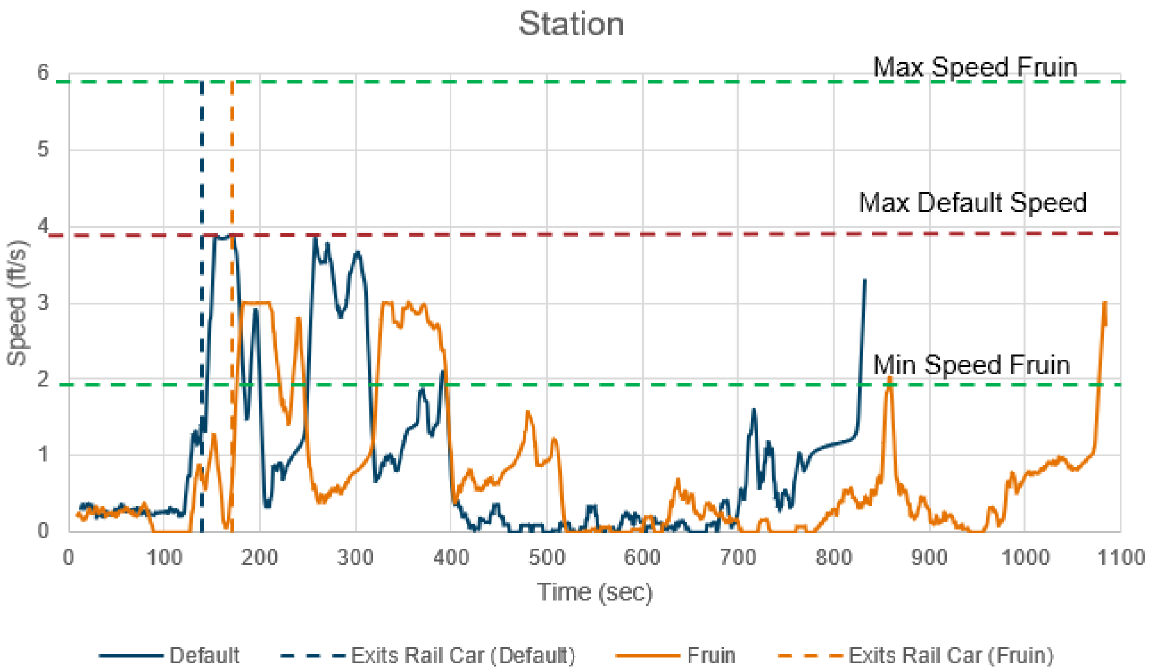


Figure 24. Comparison of default and Fruin distribution of occupant speed in station

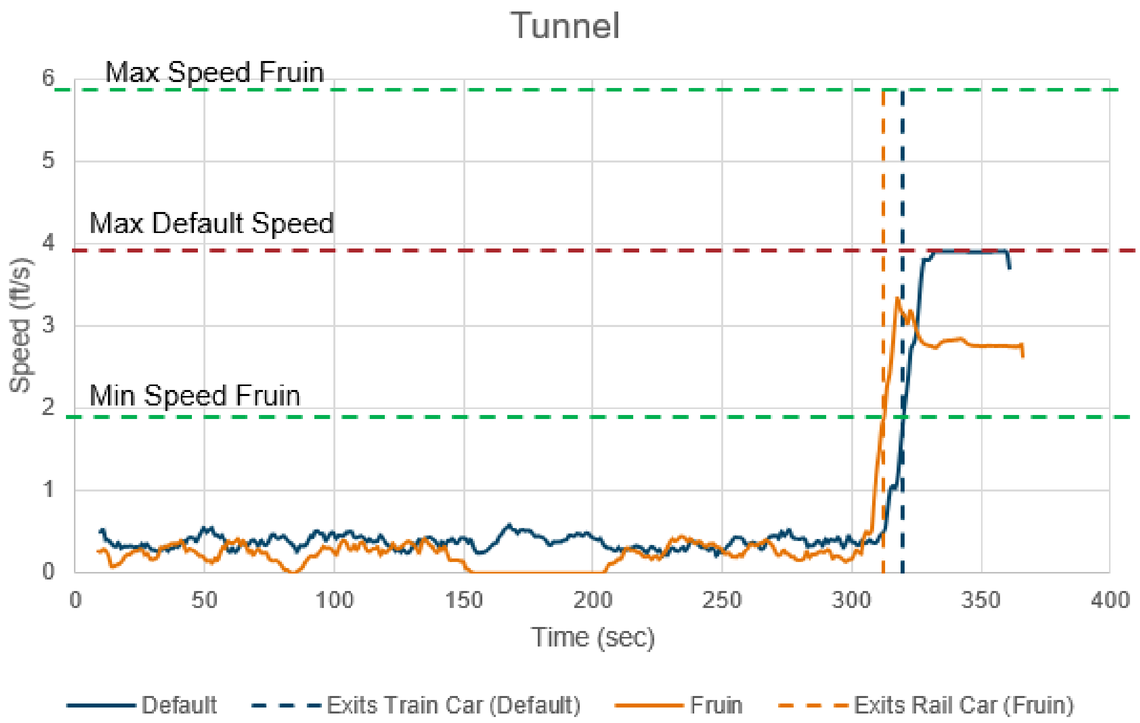


Figure 25. Comparison of default and Fruin distribution of occupant speed in tunnel

Additional Parameters

The variation seen in other parameters is more intuitive. The average diameter of occupant is increased, which impacts collision handling and increases the overall evacuation time. The egress time when varying the boundary layer is less than the default egress times because 75% of the occupants have a smaller boundary layer. The overall decrease in the boundary layer increases the walking space and allows occupants to egress more efficiently. Lastly height does not impact occupant egress in the environments that were studied. Similar conclusions can be drawn for diameter, boundary layer and height when using simplified distribution.

Varying All Parameters

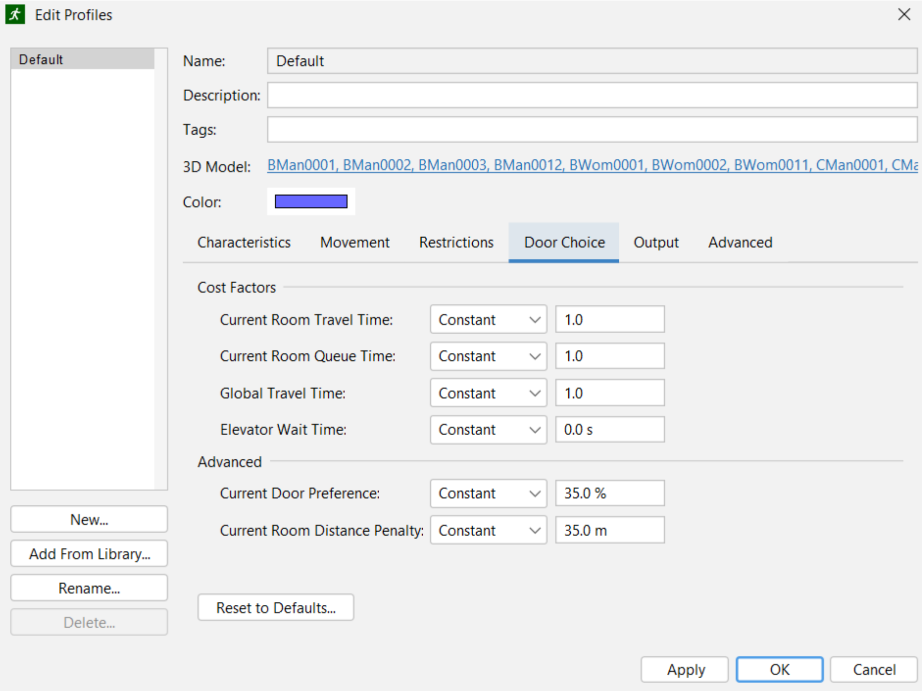
In reality, diameter, height, boundary layer and walking speed will vary simultaneously for each occupant, which is representative of intercity train demographics. The variation when applying the normal distribution of occupant speed based on Fruin and the range of the additional parameters are isolated in Table 9. The order of magnitude of the variation between the minimum and maximum egress time is similar to the variation when parameters were isolated, though the variation relative to the default value is more telling. The variation in the tunnel ha the same order of magnitude as presented above. However, the impact of the increased diameter plays a bigger role in the station geometry when combined with the normal distribution of walking speeds, resulting in a 9.8% variation.

Table 9. Impact of Varying All Input Parameters at Once

Environment	**Minimum**	**Average**	**Maximum**	**% Variation between min and max egress time**	**% Variation relative to default value**
Tunnel	349	367	402	15.0	2.1
Station	977	995	1019	4.2	9.8

Station Specific Inputs

If used as a means of egress, escalators must be capable of being stopped locally and remotely per NFPA 130, therefore it was assumed that escalators shut down upon fire alarm activation to yield conservative total evacuation times. The escalators were modeled as stairs in Pathfinder. Occupants did not equally distribute between the main means of egress on the concourse level when utilizing the default Pathfinder parameters, shown in Figure 26. The far-most escalator is not being utilized to its maximum capacity as shown highlighted in red in Figure 27 and Figure 28. This is not realistic, so a sensitivity analysis was performed to further study the parameters that impact occupant decision making by analyzing total egress time, occupant distribution over escalators and stairs and occupant decision making across the concourse level.



Name: Default
Description:
Tags:
3D Model: BMan0001, BMan0002, BMan0003, BMan0012, BWom0001, BWom0002, BWom0011, CMan0001, CMa
Color: 🟦

Cost Factors

Current Room Travel Time: Constant 1.0
Current Room Queue Time: Constant 1.0
Global Travel Time: Constant 1.0
Elevator Wait Time: Constant 0.0 s

Advanced

Current Door Preference: Constant 35.0 %
Current Room Distance Penalty: Constant 35.0 m

Figure 26. Default Door Choice parameters

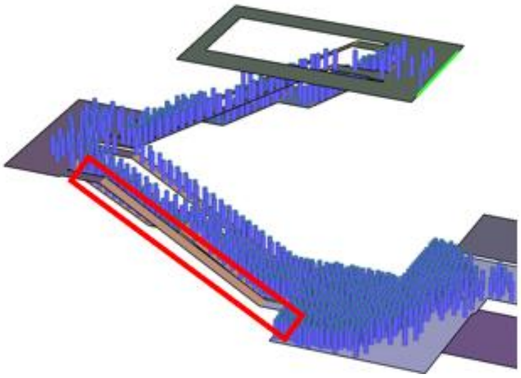


Figure 27. North Exit

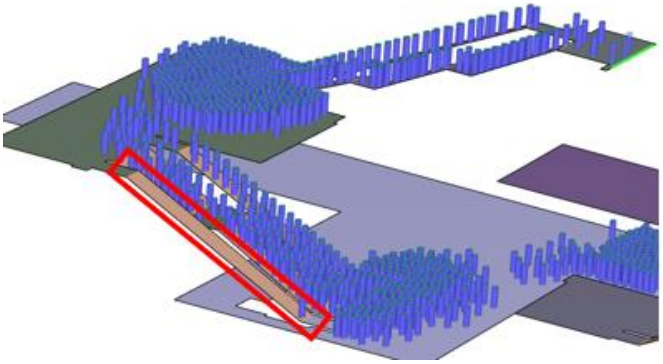


Figure 28. South Exit

Occupants choose the target with the lowest cost, which is based on multiple criteria and occupant's preference and is a function of both distance and time, detailed further in the Pathfinder Technical Reference Manual. (Thunderhead Engineering, 2023c) The "Current Room Distance Penalty" was isolated as the parameter that had the greatest impact on occupant decision making in the station. The current room distance penalty is a rudimentary implementation of fatigue, where occupants prefer shorter distances over shorter times the greater distance they travel within the room. The concourse level is modeled as one large room until the occupant reaches an egress element on one of the main exits and occupants already walked a long distance before reaching the stair or escalator, which leads to a large distance penalty. The associated cost exponentially increases based on how far the occupant has traveled on the concourse level, which results in a larger distance penalty for the far escalator when compared to the stair or near escalator.

It is recommended to change the current room distance penalty from the default of 35 m (114.83 ft) to 0. This recommendation is independent of station geometry and concourse length. This essentially eliminates the decision making as a function of concourse length and allows occupants to choose the quickest route out of the station. The occupant paths across the center of the concourse level are shown in Figure 29 and Figure 30. When using the default parameters, not all occupants fully commit to crossing the concourse and using the opposite exit, as seen in the occupant paths redirecting and turning around, highlighted in red in Figure 29. However, when the room distance penalty is set to 0, occupants travel to the opposite side of the concourse, and utilize the opposite exit as highlighted in red in Figure 30.

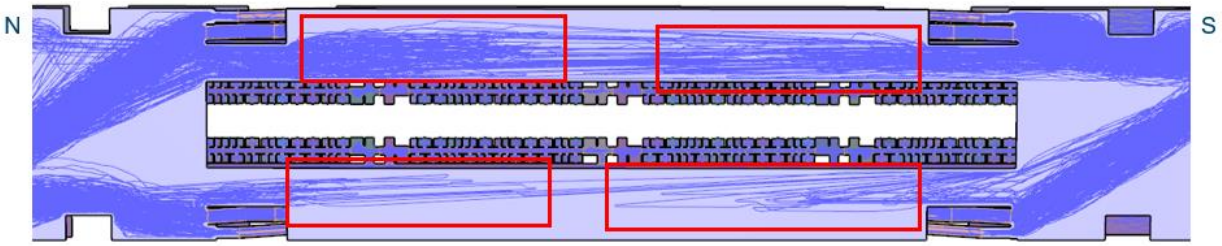


Figure 29: Occupant movement across concourse, default

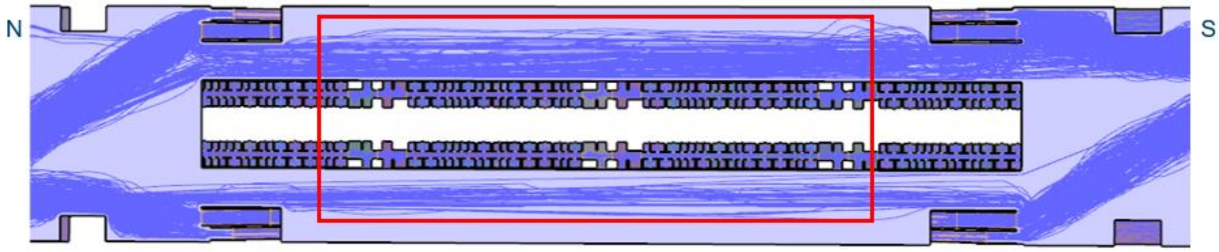


Figure 30: Occupant movement across concourse, room distance penalty = 0

The goal is to have an even distribution of occupants to the far (escalator 1) and near escalator (escalator 2) (Figure 31) to model realistic occupant movement and decision making. Table 10 outlines the percent distribution of occupants (relative to the total number of occupants using the escalators, excluding the central stair) using escalator 1 and 2. When changing the room distance penalty to 0, the distribution goes from a minimum of 9%/91% to 47%/53%, which is close to an even split. An additional benefit of changing this parameter is that the total evacuation time also decreases due to more efficient movement (Table 10).

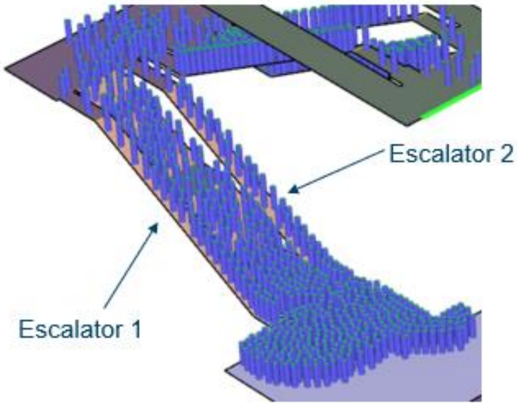


Figure 31: Escalator Distribution

Table 10: Escalator Usage

	North Escalator			South Escalator			
Parameter	Distribution 1 (%)	Distribution 2 (%)	Total usage (persons)	Distribution 1 (%)	Distribution 2 (%)	Total usage (persons)	Total evacuation time (s)
Default	9	91	358	30	70	524	1197.3
Room Distance Penalty = 0	47	53	543	47	53	568	1131.8

PRELIMINARY CONCLUSIONS

The preliminary conclusions from this research study can only be applied to the two distinct geometries analyzed – a tunnel and a station, both configured per NFPA 130 requirements. Though NFPA 130 provided guidance on the geometric configuration and other important considerations, the default walking speed provided in this standard is not recommended when using Pathfinder to model egress. The walking speed of 2.06 ft/s accounts for a high density of occupants. Pathfinder accounts for local density and adjusts the speed of occupants accordingly, so the reduced NFPA 130 speed essentially accounts for this density-driven reduction twice, which is overly conservative and unrealistic. This speed should only be considered for hand calculations.

A sensitivity analysis is important to perform when analyzing the impact of occupant characteristics in unique environments. It is recommended to perform a Monte Carlo analysis to capture the uncertainty in the assignment of occupant parameters, as was highlighted when looking at the individual variation of walking speed for both environments. A sensitivity analysis should be performed regardless of if the impact of a parameter seems intuitive.

The geometries influence the impact of the parameters on the egress time. As explained above, the egress times in the tunnel are more driven by the environment, as the congestion in the train car is the primary influence on the evacuation times, not the movement in the tunnel corridor. However, the impact of variability in speed, for example, is emphasized more in the station geometry because of the stairs and escalators in the space. Additionally, it is recommended to set the current room distance penalty equal to zero when modeling egress in a station. This gets rid of the dependency of distance traveled in occupant decision making and can be applied to stations of any size. This further emphasizes the importance of the consideration of the unique environment being studied as well as the occupants within that environment.

This research is ongoing, and the results are based on the level of completion at the time of the conference. Additional research should be performed on other tunnel and/or station configurations to confirm if the results presented in this study can be extrapolated. Further research can include but is not limited to gathering experimental data to have a more robust validation set for modern occupant egress in intercity trains.

ACKNOWLEDGEMENTS

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