Pathfinder

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Technical Reference

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Users are warned that Pathfinder is intended for use only by those competent in the field of egress modeling. Pathfinder is intended only to supplement the informed judgment of the qualified user. The software package is a computer model that may or may not have predictive capability when applied to a specific set of factual circumstances. Lack of accurate predictions by the model could lead to erroneous conclusions. All results should be evaluated by an informed user.

Acknowledgements

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We would like to thank Rolf Jensen and Associates for their assistance with testing and other suggestions that helped guide the development of the simulator.

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Overview

Pathfinder is an agent-based egress simulator that uses steering behaviors to model occupant motion. It consists of three modules: a graphical user interface, the simulator, and a 3D results viewer.

Pathfinder provides two primary options for occupant motion: an SFPE mode and a steering mode. The SFPE mode implements the concepts in the SFPE Handbook of Fire Protection Engineering [Nelson and Mowrer, 2002]. This is a flow model, where walking speeds are determined by occupant density within each room and flow through doors is controlled by door width.

The steering mode is based on the idea of inverse steering behaviors. Steering behaviors were first presented in Craig Reynolds' paper "Steering Behaviors For Autonomous Characters" [Reynolds, 1999] and later refined into inverse steering behaviors in a paper by Heni Ben Amor [Amor et. al., 2006]. Pathfinder's steering mode allows more complex behavior to naturally emerge as a byproduct of the movement algorithms - eliminating the need for explicit door queues and density calculations.

Example Problem IMO Test 10

In the following discussions, it is often useful to have an example with which to illustrate particular points. One frequently referenced example is Test 10 from the International Maritime Organization (IMO) [IMO, 2002].

This test problem represents a cabin corridor section as shown in Figure 1. The cabins are populated as indicated. The population consists of males 30-50 years old with a minimum walking speed of 0.97 m/s, a mean speed of 1.30 m/s, and a maximum speed of 1.62 m/s. There is no delay in response and the walking speeds are distributed uniformly between the minimum and maximum to the 23 occupants. The passengers in cabins 5 and 6 are assigned the secondary exit; all the remaining passengers use the main exit. The expected result is that the allocated passengers move to the appropriate exits.

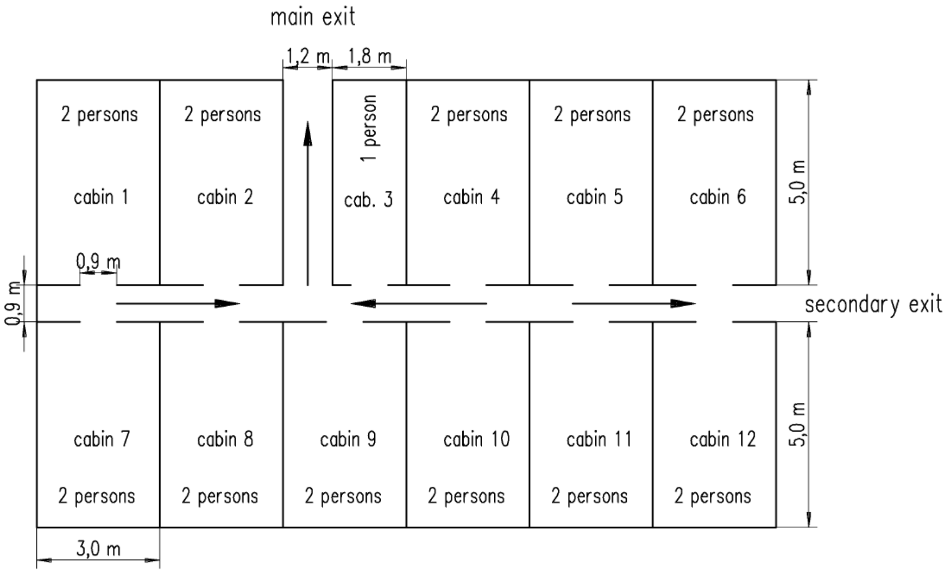


Figure 1: Cabin area (from IMO, 2002)

The display of occupant movement, Figure 2, does show that occupants have selected the assigned exits. In this display, the paths of all occupants are displayed, with selected occupants and their paths highlighted. For the steering mode analysis, all occupants exited the corridor in 18.0 seconds.

The results for SFPE mode are illustrated in Figure 3. In SFPE mode, the passengers form a queue at the main exit and the flow through this door controls the exit time. For the SFPE analysis, all occupants exited in 21.2 seconds. In SFPE mode, occupants can overlap in space during movement and when the queue forms.

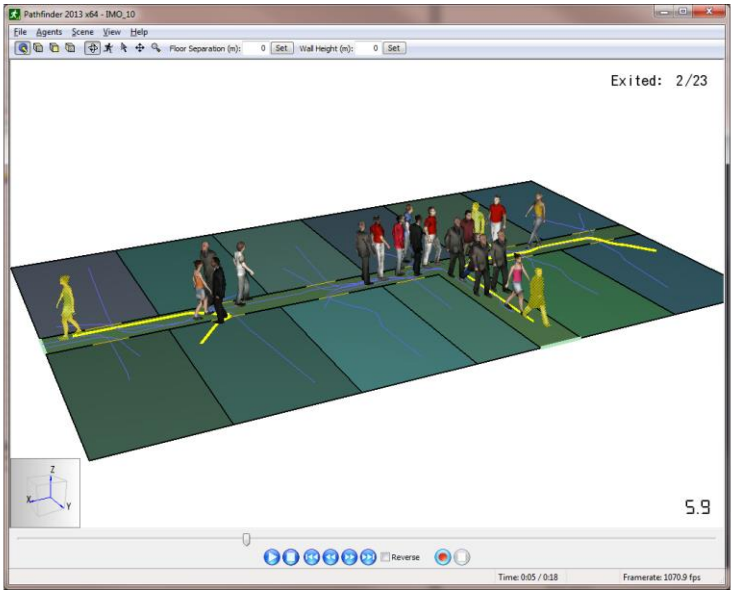


Figure 2: Steering mode results for IMO 10 problem showing occupant movement. Note how highlighted occupants move to their assigned exits.

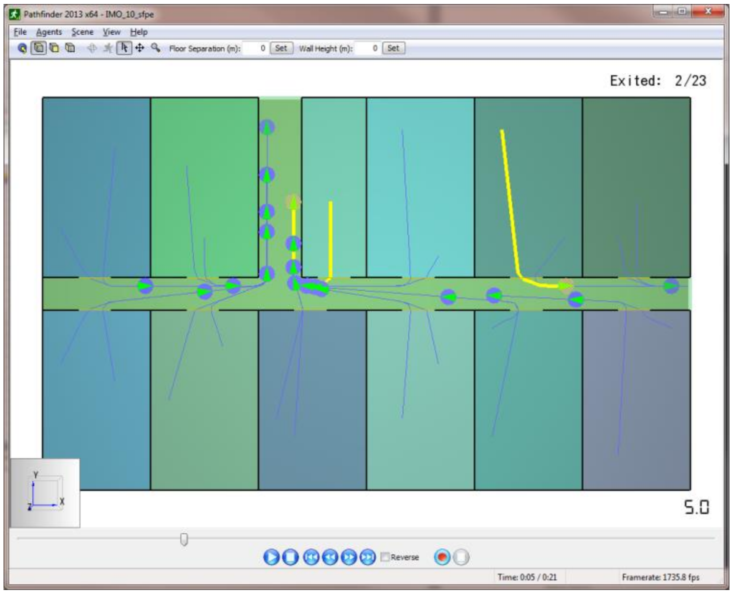
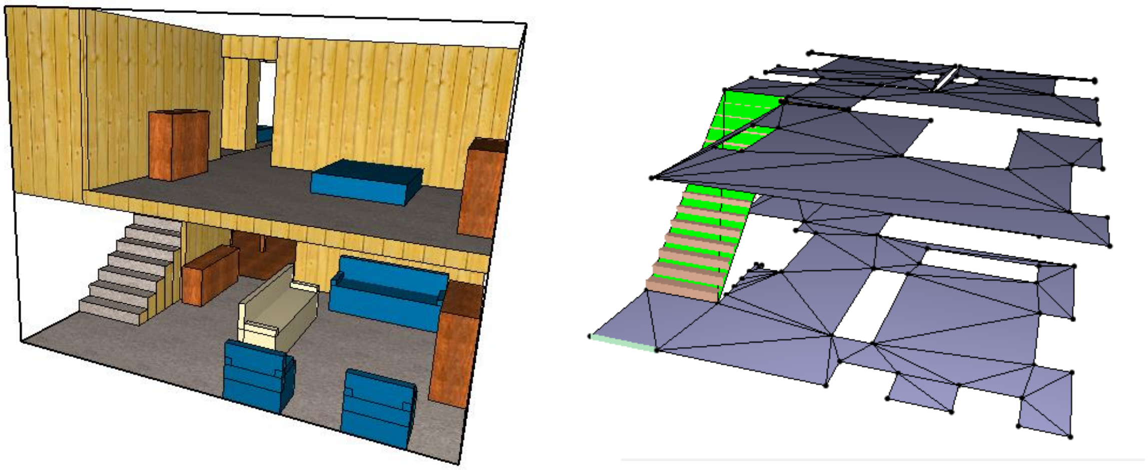


Figure 3: SFPE mode result for IMO 10 problem. Note that multiple occupants can occupy the same space.

Geometry

Pathfinder uses a 3D geometry model. Within this geometric model is a navigation mesh defined as a continuous 2D triangulated surface referred to as a "navigation mesh." Occupant motion takes place on this navigation mesh. The navigation mesh is an irregular one-sided surface represented by adjacent triangles.

Figure 4 shows a townhouse model and the corresponding navigation mesh. Pathfinder supports drawing or automatic generation of a navigation mesh from imported geometry – including Fire Dynamics Simulator files [McGrattan et al., 2007], PyroSim files, and Autodesk's Drawing Exchange Format (DXF) and DWG files.



a. 3D geometry

b. Navigation mesh

Figure 4: A simple building model and the corresponding navigation mesh

As can be seen in Figure 4, obstructions in Pathfinder are represented implicitly as gaps in the navigation mesh. Since occupants can only travel on the navigation mesh, this technique prevents the overhead of any solid object representation from affecting the simulator. When the navigation mesh is generated by importing geometry, any region of the mesh blocked by a solid object is automatically removed. For overhead obstructions, the mesh generator considers any obstruction within 1.8 meters (6 feet) of the floor to be an obstacle.

Geometry Subdivision

The navigation geometry is organized into *rooms* of irregular shape. Each room has a *boundary* that cannot be crossed by an occupant. Travel between two adjacent rooms is through *doors*. A door that does not connect two rooms and is defined on the exterior boundary of a room is an *Exit door*. There can be multiple exit doors. When an occupant enters an exit door in SFPE mode, they are queued at the door and removed at the flow rate defined by SFPE. Occupants that enter an exit door in reactive steering mode are removed from the simulation immediately.

Figure 5 illustrates these concepts for the IMO Test 10 problem. The rooms (and corridors) are shaded different colors. Doors from individual rooms to the corridor (just another room in the model) are indicated by a thick orange line. Exit doors are indicated by a thick light green line. Occupants are shown by the blue dots. Superimposed on the geometry is the navigation mesh.

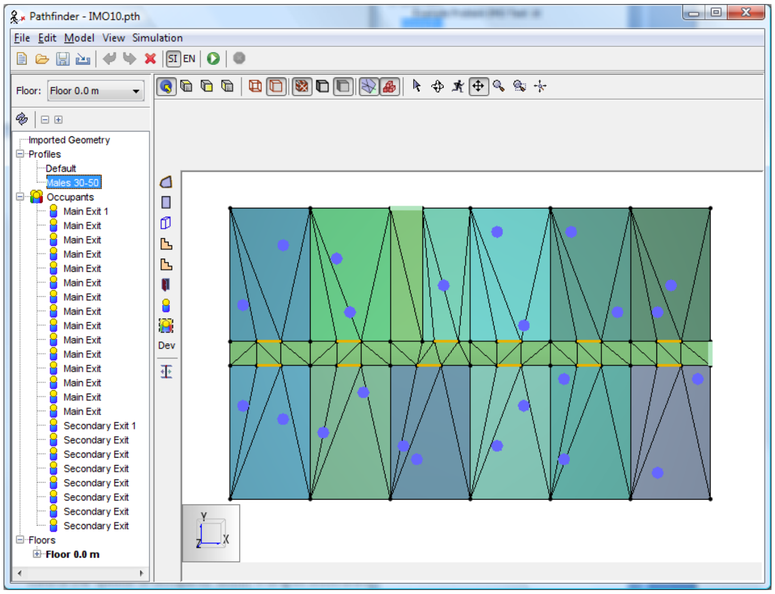


Figure 5: Rooms, doors, exits and the navigable mesh in the IMO Test 10 problem

Any location on the navigation mesh can be categorized as one of four terrain types: open space, doors, stairs, and exit. Ramps and rooms are classified as open space. Each terrain type has an effect on the behavior of occupants on that section of the mesh.

Open Space (Room and Ramps)

Open space provides no explicit constraints on movement. Rooms creating in the user interface using the room drawing tools are all considered open space having level terrain, even if rotated so that they have slope. In SFPE mode, the maximum walking speed of occupants becomes a function of the occupant density in the room.

Doors (Connecting)

Doors connect two adjacent rooms together. In SFPE mode they act as the main flow control mechanism, as discussed in Movement through Doors on page 22, but in steering mode, doors merely record the flow between rooms for results viewing unless explicitly set to limit flow.

Normally, occupants can travel through doors in either direction; however, in the user interface the door can be marked as one-way. This limits occupants to travelling through the door in only the indicated direction unless the occupant's profile dictates otherwise.

Stairs

Stairways connect rooms on different levels. They denote areas where the maximum occupant velocity is controlled by an alternate calculation specific to stairways. The specific velocity calculation is given in the stairway section for each simulator mode.

At the top and base of each stairway, there are two doors. While the user can edit the width and activation events for the doors, the doors cannot be directly moved or deleted independently of the stair. These doors connect the stairway mesh to the adjacent rooms' meshes and function identically to ordinary connecting doors.

Like doors, stairs can normally be traversed in either direction, but they can also be marked as one-way. The simulator models this by making both doors on the ends of the stair one-way.

Each stair has associated step rise and step run properties, which are settable in the user interface. This rise/run does not have to match the geometric slope of the stair. This is important as it relates to the calculation of an occupant's speed on stairs as discussed in Velocity on page 19.

Ramps

Ramps are created and represented very similarly to stairs in a Pathfinder model, but they are treated very differently in the simulation. Like stairs, ramps have two doors at either end and can be made to be one-way. Unlike stairs, however, ramps do not affect the speed of occupants when using the default SFPE ramp speed calculations. When using a custom ramp speed function, the input slope is geometric and cannot be entered by the user.

NOTE: While a room may be rotated such that it resembles a ramp, it is still a room and is considered to be level terrain in the speed calculations. The only way to create a ramp in the user interface is to use one of the ramp drawing tools.

Doors (Exit)

Exits are a special case of doors that mark building exits.

Behaviors and Goals

Each occupant has a *behavior* assigned to them in the user interface. A *behavior* dictates a sequence of *goals* that the occupant must achieve in the simulation. There are two main types of goals in Pathfinder: *idle goals* and *seek goals*. *Idle goals* are ones in which an occupant must wait at a location until an event occurs, such as a time-interval elapses or an elevator reaches a discharge floor. *Seek goals* are ones in which an occupant moves toward a destination, such as a waypoint, room, elevator, or exit.

Seek Goals

When an occupant seeks, they are trying to find a destination on the mesh. The occupant uses *path planning*, *path generation*, and *path following* to reach the destination as discussed in Paths on page 14. The types of seek goals that can be defined in the user interface and the criteria for an occupant reaching them are defined as follows:

- **Waypoint** – a point is defined on the mesh along with a radius. The occupant attempts to reach the point. The waypoint is reached once the occupant is within the radius of the point.
- **Room** – a room or set of rooms is defined that the occupant should seek. This goal is reached once the occupant crosses a door leading into one of the rooms.
- **Elevator** – an elevator or set of elevators is defined that the occupant should use. This goal is implemented in Pathfinder through a combination of a room-seek goal and an idle goal (the idle goal is discussed in the next section). As discussed in Elevators, there is a virtual pickup room representing the elevator at each floor to which the elevator attaches. The room-seek portion of the elevator goal points to one or more of these virtual rooms. The virtual rooms are selected based on the location of the previous seek goal. If the previous seek goal is attached to the elevator on the same floor, the elevator's room on this floor is selected as the target room. If not, the next floor down is tested. This continues until the bottom floor is reached. If no elevator connection is found, the search continues with the next floors up from the previous seek goal. This continues until an elevator pickup room is found that connects to the previous seek goal.
- **Exit** – a door or set of doors is defined that the occupant seeks. The goal is reached once the occupant crosses one of the exit doors. Additionally, the occupant is removed from the simulation.

Idle Goals

When occupants idle, they wait until an event occurs. While the occupant is waiting in SFPE Mode, they stand still until the event occurs. While the occupant is waiting in Steering Mode, they use *separation* to maintain a distance from other occupants (see Idle Separate on page 26).

Because the occupant may move in Steering Mode, they are assigned a containment area that depends on the previous seek goal in the occupant's behavior. If the occupant leaves this area because of separation, they create and use a temporary *seek goal* to return to the area. The areas are defined as follows:

- If the previous seek goal was a *waypoint*, the occupant tries to stay in the radius of the waypoint.
- If the previous seek goal was a room (including an elevator), the occupant tries to stay in the room, away from the doors, allowing other occupants to enter.
- If there was no previous seek goal, the occupant can move anywhere along the mesh.

There are currently two types of events that can trigger an idle goal to finish:

- A time interval elapses.
- An elevator that the occupant is in reaches its discharge floor and the doors open. This type of idling is implicit when an occupant is instructed to use an elevator.

Paths

When an occupant has a destination to seek, they need a plan for how to reach the destination, a path to follow, and a way to follow the path while accounting for dynamic obstacles along the path, such as other occupants.

Path Planning (Locally Quickest)

Path planning is the process of determining a plan for moving toward a destination.

Given an occupant seeking a destination, there may be multiple paths to reach the destination, each with differing lengths, numbers of occupants along the way, and various hazards. A naïve path planning approach to choosing a route would be to take the shortest route. This may not be the fastest or best route to the destination for a particular occupant, however.

Locally quickest is the path planning approach used in Pathfinder to solve this problem. It plans the route hierarchically, using local information about the occupant's current room and global knowledge of the building. It is assumed that an occupant knows about all doors in their current room as well as queues at those doors. It is also assumed that the occupant knows how far it is from one of those doors to the current destination (seek goal). Locally quickest then uses this information to choose a door in the current room based on a calculated cost of that door. A path is then generated to the door, which the occupant can follow.

More formally, the occupant uses the following steps to plan a path.

1. Generate a list of *local targets*. By default, the local targets include the doors attached to the occupant's current room that can lead to the seek goal.[1] If the seek goal is in the current room, it is added to the list of local targets.
2. Choose a local target based on local and global knowledge of the model and occupant preferences. This is discussed further below.
3. Move toward the local target using *path generation* and *path following*, periodically repeating these steps until the final seek goal is reached.

Door Choice

As mentioned in step 2 above, the occupant chooses a local target by calculating a cost for the target and choosing the target with the lowest cost. The cost for each target is based on multiple criteria and the occupant's preferences. The criteria are as follows:

- **current room travel time, t_{lt}** – the time it would take the occupant to reach the target at maximum speed, ignoring all other occupants.
- **current room queue time, t_q** – if the target is a door, this is an estimate of the time the occupant will have wait in the queue at the door based on the occupant's position in the queue and the flowrate of the door. If the target is not a door, the queue time is 0. The flowrate through doors is calculated using a bi-quad low-pass filter with a cut-off frequency of .05 Hz. In addition, the flowrate as seen by the occupant is clamped so that it will never be less than 10% of the nominal flowrate of the door as calculated by SFPE unless there is counterflow at the door.
  NOTE: neither the flowrate filter cutoff frequency nor the minimum clamp are currently settable in the user interface.
- **global travel time, t_{gt}** – the time it would take the occupant to travel from the target to the current seek goal at the occupant's maximum speed, ignoring all other occupants. If the target is the current seek goal, this time is 0.
  NOTE: if two targets have global travel times within 10% of the longer time, the global travel time is treated as the lower of the values. This causes occupants to prefer the closer door if two targets have similar global travel times.
- **distance travelled in room, d_t** – the distance the occupant has travelled since entering the current room.

Each occupant also has a set of door choice preferences that are settable in the user interface. These preferences are:

- **Current Room Travel Time Cost Factor, k_{lt}** – a cost factor associated with the current room travel time.

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[1] A door leads to a seek goal if the shortest path from that door to the goal goes immediately outside the current room or a path exists from the door to the goal that does not pass through any rooms more than once and does not go through the current room.

- **Current Room Queue Time Cost Factor, k_q** – a cost factor associated with the current room queue time.
- **Global Travel Time Cost Factor, k_{gt}** – a cost factor associated with the global travel time.
- **Current Door Preference**, $\mathbf{p}$ – a value that gives preference to the occupant's most recently chosen target. This value also helps to prevent occupants from frequently switching local targets.
- **Current Room Distance Penalty**, $\mathbf{k}_{dd}$ – a doubling distance that is turned into a cost factor. This factor causes the travel time costs to increase as the occupant travels further in a room. It has the effect of causing occupants to prefer doors with shorter overall distances to shorter times the further they travel in a room. This is a simplistic way to model fatigue and helps to dampen the frequency at which occupants switch local targets.

The cost of a particular target is then calculated as follows:

$$\begin{aligned}C_{target} &= C_l + C_g\\ C_g &= p_d k_{gt} t_{gt}\\ C_l &= \max\left(p_d k_{lt} t_{lt} \middle| k_{qh} k_q t_q\right)\\ p_d &= e^{k_d d_t}\\ k_d &= \frac{\log 2}{k_{dd}}\end{aligned}$$

In the equation above, k_{qh} is set to $1 - p$ for the most recently chosen target and 1.0 for all other targets.

Each occupant chooses a door using this technique when they first enter a room. The second door choice in the room is randomized per-occupant between 0 to 1 second later. The third and subsequent door choices occur at intervals of 1 second from the second door choice. NOTE: This is currently not settable in the user interface.

Backtrack Prevention

Occupants are only aware of queue sizes and door flowrates in their current room. When they enter a new room, knowledge about the last room is replaced by knowledge about the current room. Without any sort of backtrack prevention in place, large queues could lead to occupants walking back-and-forth between two rooms, potentially for long periods of time (until the previous room emptied). In Pathfinder, once an occupant manages to exit a room using a particular exit door, they are committed to that routing decision using the following rules:

1. The next local door the occupant selects may not lead back into any previous rooms. If this rule eliminates all options (e.g. the occupant went through an unplanned door), then
2. Backtrack prevention is disabled, the occupant can choose from any valid local door.

Path Generation

Once a local target has been chosen through path planning, a path is needed to reach the target. Pathfinder uses the *A** search algorithm [Hart et al., 1968] and the triangulated navigation mesh. The resulting path is represented as a series of points on edges of mesh triangles. These points from A* create a jagged path to the occupant's goal.

To smooth out this jagged path, Pathfinder then uses a variation on a technique known as *string pulling* [Johnson, 2006]. This re-aligns the points so the resulting path only bends at the corner of obstructions but remains at least the occupant's radius away from those obstructions. Examples of these final points, called *waypoints,* are shown in .

shows the projected path of an occupant in a simple rectangular room. The occupant is standing in the lower-left corner and plans to exit out the lower-right corner. The navigation mesh is shown by the thin lines that form triangles inside the rectangular area. An obstruction prevents the occupant from walking straight to the exit. The planned path of the occupant is shown as the dark line and the waypoints are shown as circles. A waypoint is generated for each edge that intersects the path.

Once these waypoints are found, Pathfinder removes intermediate points that lie between two others in a straight line. This creates a series of waypoints only where the direction of travel will change.

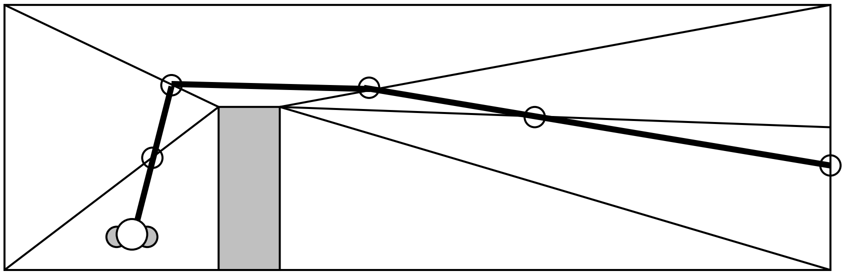


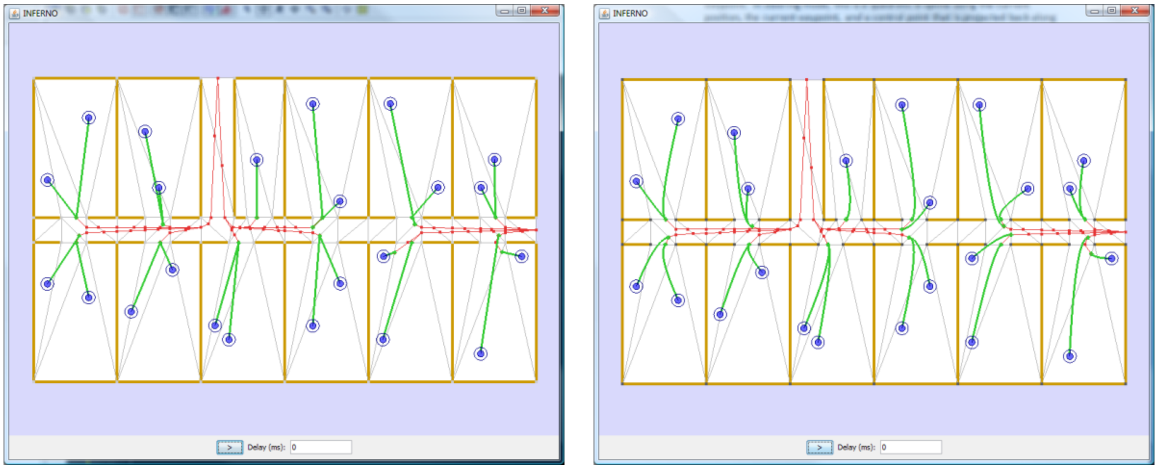
Figure 6: An occupant's planned path with waypoints shown

Once a path is generated, the occupant needs a way to follow the waypoints. The occupant performs the following:

1. Two waypoints are tracked: (1) a *current waypoint* that is initially the furthest waypoint on the path that defines a bend in the path, and (2) a *next waypoint* that defines the next bend in the path.
2. The occupant checks if the next waypoint should become the current. This is determined by checking if the occupant crossed an infinite line connecting the current waypoint with the next waypoint. If the line is crossed, the next waypoint becomes the current and a new next waypoint is determined.
3. The occupant checks for the need to re-path. Occupants must re-path if they cannot see a straight line to their current waypoint or if it is time to re-evaluate the current door choice according to locally quickest.

4. A *seek curve* is generated to define the desired motion. In SFPE mode, this curve is merely a straight line segment from the current position to the current waypoint. In steering mode, this is a quadratic B-spline using the current position, the current waypoint, and a control point that is projected back along the direction from the current waypoint to the next waypoint.
5. The occupant attempts to move along the tangent to the current seek curve. This movement is strongly influenced by the movement mode (SFPE or steering) and is discussed in the next sections.

Figure 7 shows the paths and waypoints for the IMO Test 10 problem for both SFPE and steering modes. The green lines indicate the current seek curves for each occupant. The red lines and points indicate future paths and waypoints. Notice the straight seek curve in the SFPE mode as compared to the spline used in steering mode.



a. SFPE mode b. Steering mode

Figure 7: Paths and waypoints for the IMO Test 10 analysis

Path Following in SFPE Mode

Pathfinder provides the option to calculate motion in an *SFPE Mode*. This mode implements the flow-based egress modeling techniques presented in the *SFPE Handbook of Fire Protection Engineering* [Nelson and Mowrer, 2002] and the *SFPE Engineering Guide: Human Behavior in Fire* [SFPE, 2003]. The SFPE calculation as described in the handbook is a flow model, where walking speeds and flow rates through doors and corridors are defined.

In Pathfinder, navigation geometry can be grouped into three types of components; doors, rooms, and stairs. Rooms are open space on which occupants can walk. Stairs can be thought of as specialized rooms in which the slopes of the stairs limit the speed of the occupants. Doors are flow limiters that connect rooms and stairs. There is no specialized corridor type as in the SFPE guide. Instead, corridors are modeled as rooms with doors on either end. In this manner, corridors are handled in the same manner as rooms, with the flow being controlled by the doors.

In SFPE mode, multiple occupants can occupy the same space.

SFPE Mode Parameters

In SFPE Mode, the following parameters are used.

Max Room Density (0.0 < D_{max}*, default=3.55 pers/*m^2*)* – This parameter controls how many occupants will be allowed to enter a room via doors and stairways. Pathfinder uses room density to determine movement speed and door flowrate. When occupants queue at doors, they will not be able to leave the queue on their turn unless doing so will keep the density in the next room below this value.

Boundary Layer (0.0 <= BL) – This value controls the effective width of every door in the simulation – including doors associated with stairs. The effective width of a door is *W - 2*BL* where *W* is the actual width of the door. The effective width of a door controls the rate at which occupants can pass through the door.

Door Flow Rates at High Density, Use a Calculated Specific Flow (on/off, default=on) – This flag controls the calculation of door specific flow with respect to density. If this flag is enabled, specific flow for doors is calculated based on the occupant density in adjacent rooms. This calculation is explained in Movement through Doors on page 22.

Door Flow Rates at High Density, Always Use Max Specific Flow (on/off, default=off) – This flag controls the calculation of door specific flow with respect to density. If this flag is enabled, doors always use maximum specific flow.

Velocity

The velocity, *v*, at which an occupant moves depends on several factors, including the occupant’s maximum velocity (v_{max}) specified in the user interface, the type of terrain being travelled on, speed modifiers and constants associated with the terrain, and occupant density in the current room.

Base Speed, v_b

The occupant's base speed, v_b, is defined as a function of density, terrain, and a speed fraction curve based on the SFPE fundamental diagram. It does not take terrain speed modifiers or constants into account.

$$v_b = v_{max} * v_f(D) * v_{ft}$$

v_{max} is the occupant's maximum speed as entered in the user interface as **Speed**.

$v_f(D)$ is a speed fraction as a function of density as follows:

$$v_f(D) = \begin{cases} 1, & D < .55\, pers/m^2 \\ max\left[v_{fmin}, \frac{1}{.85}(1 - .266D)\right], & D \geq .55\, pers/m^2 \end{cases}$$

v_{fmin} is a *minimum speed fraction* as defined in the user interface (default=.15), and D is the occupant density in the current room.

v_{ft} is a speed fraction that depends on the type of terrain being traversed by the occupant. It is defined as

$$v_{ft} = \frac{k}{1.4}$$

For level terrain (rooms) and ramps, *k* = 1.40 m/s. For stairs, k depends on the step slope of the stairway. The SFPE handbook defines k only for a limited set of known step slopes as follows:

Stair Riser (inches)	Stair Tread (inches)	k
7.5	10.0	1.00
7.0	11.0	1.08
6.5	12.0	1.16
6.5	13.0	1.23

Pathfinder uses this information to determine *k* values for any stairs by constructing a piece-wise linear function that maps step slope to k values using these known data points. The step slope of a stair is defined as:

$$step\ slope = \frac{Stair\ Riser}{Stair\ Tread}$$

For step slopes above .75 (the maximum in the table), the values are extrapolated down to a minimum k of .034. This ensures that very steep stairs do not cause occupants to become excessively slow. For step slopes below .5 (the minimum in the table), k is linearly interpolated to 1.4 at a step slope of 0 (while not realistic, this would correspond to a flat stairway). This produces a k function as shown in Figure 8.

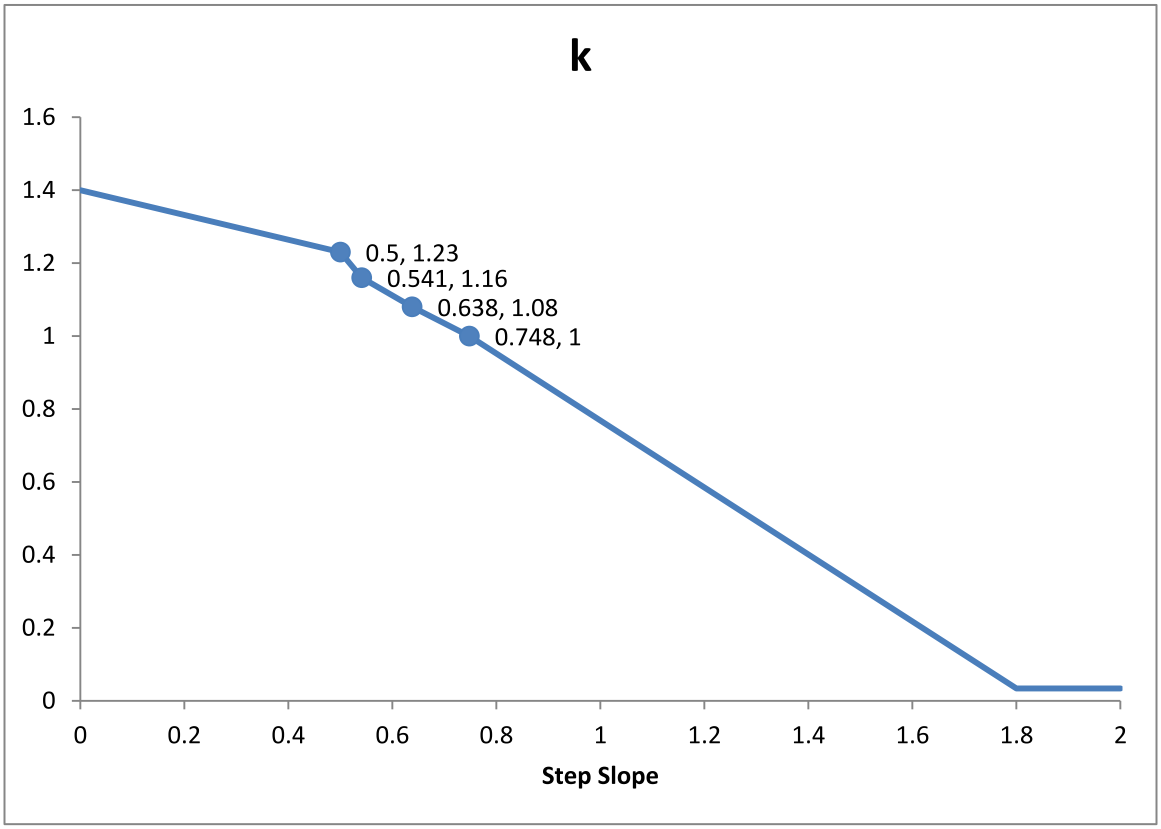


Figure 8: k as a function of step slope

Density, D

In SFPE mode, density is considered uniform throughout a single room. It is calculated as follows:

$$D = \frac{n_{pers}}{A_{room} - A_{blayer}}$$

n_{pers} is the number of occupants in the room, A_{room} is the area of the room, and A_{blayer} is the area of the boundary layer, which is calculated by multiplying the total length of the boundary edges in the room by the *boundary layer* as set in the user interface.

Speed Modifiers and Constants

Egress components, such as rooms, stairs, and ramps, can be assigned speed modifiers and speed constants in the user interface, which can be used to emulate environmental effects, such as smoke, and specialized navigational geometry such as escalators and moving walkways. By default, all egress components have a speed modifier of 1.

When an occupant enters an egress component with a speed modifier, the occupant's speed on that component is calculated as follows:

$$v = k_v v_b$$

where k_v is the speed modifier for the component, and v_b is the occupant's base speed on the component.

If the component has a speed constant instead of a speed modifier, the occupant's speed depends on the occupant's profile parameter, *Walk on Escalators*, and the speed constant value. If *Walk on Escalators* is turned on or the speed constant's value is 0, the occupant's speed is:

$$v = v_c + v_b$$

where v_c is the speed constant for the component. Otherwise, the occupant's speed is:

$$v = v_c$$

Movement through Doors

When using Pathfinder in *SFPE Mode*, the occupant flow rate through the door is specified by the SFPE guidelines. This is implemented using a delay timer that controls how quickly occupants are allowed to pass through the door. This timer is initially set at zero. When an occupant passes through the door, the simulator calculates a delay time based on the specific flow of the door. That delay time is added to the door and must elapse before another occupant is allowed to pass through.

Each door may have a different specific flow depending on the direction occupants are going through the door and the type of terrain connected to the door. The specific flow for a particular direction through a door is

$$F_s = (1 - .266 * D) * k * D$$

The evacuation speed constant, k, depends on the terrain of the previous room, and D is the maximum of the occupant densities in the rooms attached to the door. Because the flow equation is quadratic, the value of D is clamped to the range [1.9, 3.0] pers/m^2. This range ensures that low densities do not slow the flowrate and that high densities do not reduce the flowrate to zero.

In the user interface, if *Door Flow Rates at High Density, Use a Calculated Specific Flow* is selected, the density is calculated as described above. Otherwise, it is set to 1.88 pers/m^2 to maximize the flowrate.

The time it takes *n* occupants to pass through a door with effective width W_e is

$$T = \frac{n-1}{F_s}$$

The *n* value is reduced by 1 because the first occupant through a door does not have to wait for a time delay.

In counter-flow situations, an occupant from R_1 may be waiting at a queue to enter R_2 while an occupant from R_2 may be waiting to enter R_1. In this case, the queues evenly exchange their next occupant and both occupants are allowed through the door. The delay time placed on the door queue becomes the sum of the delay times from each occupant's passage, which maintains the correct flow rate for the simulation.

Collision Handling/Response

In SFPE mode, while occupants cannot collide with other occupants, they can still collide with walls. Collision handling is applied in two steps. The first step occurs before movement is attempted for a time step, and the second occurs during movement. For the pre-movement step, the travel velocity is adjusted to force the occupant to slide along any nearby walls. After the travel velocity is adjusted, the occupant attempts to move using this new velocity. During the movement stage, wall collisions are still possible, so the occupant will simply halt at the earliest collision.

Path Following in Steering Mode

In steering mode, Pathfinder uses a combination of steering mechanisms and collision handling to control how the occupant follows their seek curve. These mechanisms allow the occupant to deviate from the path while still heading in the correct direction toward their goal.

Velocity

As an occupant moves along their path, they calculate a modified maximum velocity, $\acute{v}_{max}$, that depends on the occupant's current terrain, specified maximum velocity, v_{max}, and the spacing of surrounding occupants. The spacing of surrounding occupants is used to estimate an occupant density, *D*, as described below. These parameters are then used in the equations to calculate *v* in SFPE mode (see Velocity on page 19), which becomes $\acute{v}_{max}$.

In steering mode, both $v_f(D)$ and v_{ft}, which are used to calculate $\acute{v}_{max}$, may either be left at the SFPE default or may be user-defined in the occupant profile as piece-wise linear functions. $v_f(D)$ is entered as a function of occupant density and v_{ft} is entered as a function of either stair step slope or ramp slope, depending on the terrain type. Stair step slope is entered in the user interface by specifying a stair's *riser* and *tread*. Ramp slope is determined by the normal of the triangle that belongs to a ramp node and cannot be entered directly by the user. A triangle's slope is calculated as follows:

$$slope = \frac{\sqrt{{n_x}^2 + {n_y}^2}}{n_z}$$

n_x, n_y, and n_z are the components of the triangle's normal. In addition, different $v_f(D)$ and v_{ft} functions may be defined for when the occupant goes up or down stairs or ramps. This is in contrast to SFPE calculations, which use the same functions for both up and down.

Once $\acute{v}_{max}$ is calculated, it is then used by the steering system to calculate a desired velocity vector as described in Steering on page 26.

Acceleration

An occupant's acceleration is split into multiple components depending on the desired velocity vector calculated by the steering system. A tangential forward component of acceleration is calculated as:

$$a_{fmax} = \frac{v_{max}}{t_{accel}}$$

where t_{accel} is the occupant profile parameter, *Acceleration Time*. The tangential reverse component of acceleration is:

$$a_{bmax} = 2 * a_{fmax}$$

The radial component of acceleration is:

$$a_{rmax} = 1.5 * a_{fmax}$$

These components are combined to determine the final acceleration vector.

Estimation of Occupant Density, *D*

To calculate $\acute{v}_{max}$ for an occupant, the occupant density *D* at that occupant's location must be known. Pathfinder estimates the density by using the spacing of the near occupants and the average longitudinal and lateral spacing density relationship demonstrated in Chapter 3 of (Fruin, 1987) as shown in Figure 9.

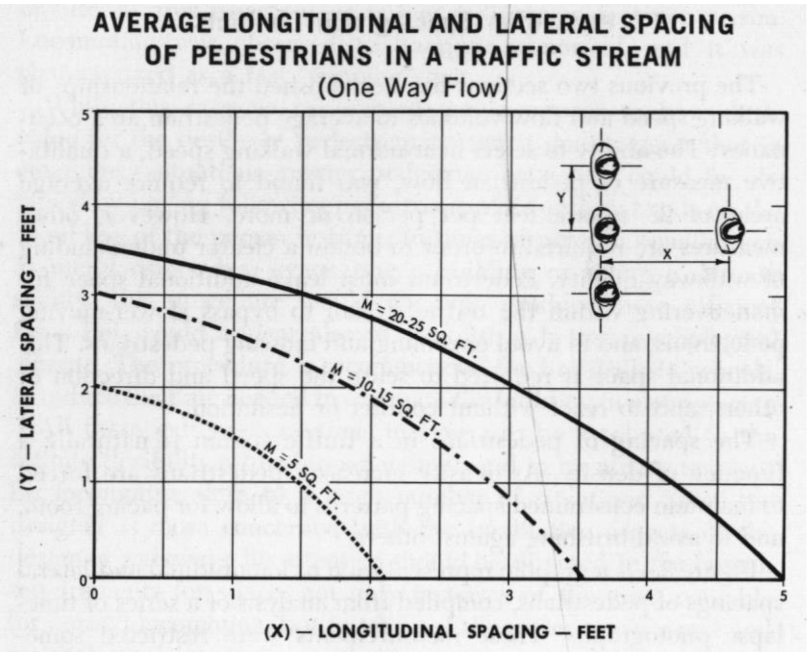


Figure 9: Average Longitudinal and Lateral Spacing of Pedestrians in a Traffic System (Figure 3.4 of Fruin's *pedestrian planning and design*)

In Pathfinder, the density lines in the figure are treated as contours, each being estimated as an ellipse. The contours are mirrored about Y=0.

To calculate the density for an occupant, the X axis in the figure is aligned with the occupant's current velocity and the origin is set to the occupant's location, forming a local coordinate system. Then for each other near occupant, their location is transformed to this local coordinate system. If the local coordinate for the other occupant has an x value less than 0, the occupant is ignored. This prevents an occupant's speed from being affected by occupants behind them. For occupants with local x >= 0, the density is interpolated or extrapolated from the density contours. The maximum of these densities is then used as the density for the occupant.

Steering

The steering system in Pathfinder moves occupants so they roughly follow their current seek curve and can respond to a changing environment. Inverse steering, used in Pathfinder, is the process of evaluating a set of discrete movement directions for an occupant and choosing the direction that minimizes a cost function. See Figure 10 for an example of sample directions. The cost function is evaluated by combining several types of steering behaviors to produce a cost. The types of steering behaviors used are determined by the occupant’s current state, and the number of sample directions is controlled by the occupant’s state and current velocity. For more information on states, see Occupant States on page 31.

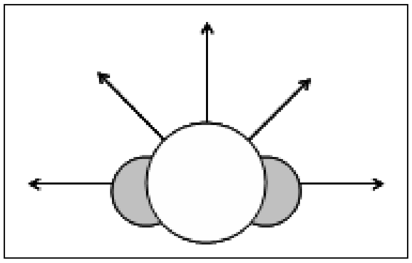


Figure 10: Sample inverse steering directions

Pathfinder defines several steering behaviors: *seek*, *idle separate*, *seek separate, seek wall separate, avoid walls*, *avoid occupants*, *lanes*, and *cornering*. Most behaviors award a cost between 0 and 1 for each sample direction. The net cost for a direction is a weighted sum of these values.

Seek

The *seek* behavior steers the occupant to travel along a seek curve. Given the sample direction v, and a seek curve sc, the seek behavior bases its cost on the magnitude of the angle between v and the tangent to sc. The cost is calculated as follows:

$$C_{seek} = \frac{\theta_t}{2\pi}$$

Where θ_t is the angle between v and the tangent vector to sc.

Idle Separate

The *idle separate* behavior steers occupants to maintain a desired distance away from other occupants and is used when occupants are in an *idle* state. This behavior works somewhat outside the inverse steering system, in that before considering sample directions, the separation behavior calculates a desired absolute movement vector (direction and distance). This movement vector is calculated as the average of occupant separation vectors as follows:

$$\overline{m} = \frac{1}{n_{occ}} \sum_{i=1}^{n_{occ}} \overline{m_i}$$

Where n_{occ} is the number of occupants by which the occupant would like to separate.

If the ith occupant is idle, $\overline{m_i}$ is calculated as:

$$D_{gap} = |\overline{p} - \overline{p_i}| - r - r_i$$
$$\overline{m_i} = (D_{gap} - D_{sep}) \frac{\overline{p} - \overline{p_i}}{|\overline{p} - \overline{p_i}|}$$

Where $\overline{p}$ is the position of an occupant, r is the radius of an occupant, and D_{sep} is the desired separation distance of the occupant (settable via the input parameter, comfortDist).

If the ith occupant is seeking, $\overline{m_i}$ is instead calculated such that it is perpendicular to the ith occupant's direction of travel and its magnitude is defined as:

$$|\overline{m_i}| = \mathrm{r} + r_i + D_{sep} - D_{path}$$

Where D_{path} is the occupant's distance to the nearest point on the line tangent to the ith occupant's seek curve.

Once the movement vector is defined, the *separation* behavior works like other inverse steering behaviors. The cost is calculated as follows:

$$C_{isep} = 1 - (\overline{m_i} \cdot \overline{d_s})$$

Where $\overline{d_s}$ is the sample direction.

Avoid Walls

The *avoid walls* behavior detects walls and steers the occupant to avoid collisions with them. This behavior projects a moving cylinder ahead of the occupant in the direction of the projected point. The cost reported by this behavior is based on the distance the occupant can travel in the direction of the projected point. It is also affected by the angle at which the occupant hits the wall. The cost is decreased if the agent will hit the wall at a shallow angle to the desired direction.

$$D_{min} = \frac{\acute{v}_{curr}{}^2}{2a_{bmax}}$$
$$D_{max} = D_{min} + \max\left[\frac{\acute{v}_{max}{}^2}{2a_{bmax}}, \acute{v}_{curr} t_{wcr}\right]$$
$$C = 1 - \frac{D_{coll} - D_{min}}{D_{max} - D_{min}}$$
$$C_{aw} = \begin{cases} 1, & \overline{d_{slide}} \cdot \overline{d_{des}} \le 0 \\ C * (1 - \overline{d_{slide}} \cdot \overline{d_s}), & \overline{d_{slide}} \cdot \overline{d_{des}} > 0 \end{cases}$$

t_{wcr} is the maximum time at which an occupant will react to a wall collision (fixed at 2 s), a_{bmax} is the maximum tangential deceleration, D_{coll} is the collision distance, $\overline{d_{slide}}$ is the direction the agent would slide if they hit the wall, $\overline{d_{des}}$ is the desired travel direction, and $\overline{d_s}$ is the sample direction. The resulting cost is clamped from 0 to 1.

Avoid Occupants

The *avoid occupants* behavior steers an occupant to avoid collisions with other occupants. This behavior first creates a list of occupants within a frustum whose size and shape is controlled by the velocity of the occupant. Then the behavior projects a moving cylinder ahead of the occupant in the sample direction. This cylinder is tested against another moving cylinder for each nearby occupant. If none of the moving cylinders collide the cost is zero, otherwise the cost is based on how far the occupant can travel prior to the collision. The closer this collision point, the higher the cost of the steering behavior.

The cost is based on the earliest collision with another occupant along the sample direction and is evaluated as follows:

$$
\begin{aligned}
D_{min} &= D_{sep} + \frac{{\acute{v}_{curr}}^2}{2a_{max}} \\
D_{max} &= D_{min} + \max\left[\frac{{\acute{v}_{max}}^2}{2a_{max}}, \acute{v}_{curr} t_{cr}\right] \\
C_{ao} &= 1 - \frac{D_{coll} - D_{min}}{D_{max} - D_{min}}
\end{aligned}
$$

Where D_{sep} is the desired separation distance between the occupant and the collision occupant (settable via the input parameter, *comfortDist*), t_{cr} is the maximum time at which an occupant will react to a collision (settable via the input parameter, *collisionResponseTime*), and D_{coll} is the collision distance. The resulting cost is clamped from 0 to 1.

Seek Separate

The *seek separate* behavior spreads out occupants to maximize their travel speed as calculated by the occupant's speed-density curve and Fruin's spacing-density relationship (see Figure 9).

For a sample direction, the occupant's future location along that direction is predicted using $\acute{v}_{max}$ and the *steering update interval*, settable in the user interface. In addition, the locations of the surrounding occupants are predicted using their current velocity and the *steering update interval*. From these predicted locations, the density is estimated as described in Estimation of Occupant Density, *D* on page 25. The speed is then predicted at that location from the density and the occupant's speed-density curve. The predicted speed is then used to calculate the cost.

$$
C_{ssep} = 1 - \left(\frac{v_{pred}}{v_{max}}\right)^2
$$

v_{max} is the occupant's maximum speed ignoring occupant density, and v_{pred} is the predicted speed.

Seek Wall Separate

The *seek wall separate* behavior steers occupants such that they want to main a *boundary layer* distance away from walls. Like the *seek separate* behavior, the occupant's location is predicted along the sample direction using $\acute{v}_{max}$ and the *steering update interval*. The nearest wall to this location is then used calculate the cost.

$$C_{swsep} = 1 - \frac{d_w - r - bl}{bl}$$

Where d_w is the distance to the nearest wall (walls more than 90° from the sample direction are ignored), r is the occupant's radius, and bl is the *boundary layer* set in the occupant profile. The cost is clamped from 0 to 1.25.

Lanes

The *lanes* behavior steers occupants into lanes when they detect that they are in counterflow with other occupants. It works by steering an occupant towards the center of mass of the occupants in front who are not in counterflow. Other occupants are considered to be in front if their center is within 60° of the tangent to the occupant's seek curve. For these in-front occupants, the vector to their center of mass is calculated as the following:

$$\overline{v_{cen}} = -\overline{p_{occ}} + \frac{1}{n_{occ}} \sum_{i=1}^{n_{occ}} \overline{p_\imath}$$

$\overline{p_{occ}}$ is the location of the occupant, n is the number of occupants in front, and $\overline{p_\imath}$ is the location of the ith occupant in front.

The cost, C_{lanes}, for the *lanes* behavior is determined in the following order:

1. If the occupant is considered to be a lane leader, the cost is 0. An occupant is a lane leader if there are no occupants in front who are not in counterflow.
2. If a test direction does not lead to counterflow, the cost is 0. A test direction leads to counterflow if at least one vector from the occupant to a counterflow occupant has an angle less than 36° to the test direction.
3. The cost is calculated as the angle between the test direction and $\overline{v_{cen}}$.

Cornering

The *cornering* behavior seeks to steer agents so that they can take wide turns as part of a group without cutting in front of each other. This allows them to better utilize wide hallways/ramps with turns. To a certain extent, the *avoid occupants* and *seek separate* behaviors already achieve this, but the *cornering* behavior improves this.

The *cornering* behavior works similarly to *avoid occupants*, but it treats the size and positions of the nearby occupants differently when calculating intersections between occupant paths. The size of a nearby occupant is expanded by 50% and their position is moved by a distance of 150% of the occupant's radius along their most recent steering direction. In addition, a flow direction is calculated from nearby occupants who are in front of the occupant as follows:

$$\overline{v_{flow}} = \sum_{i=1}^{n} \overline{d_{\iota f}}$$

n is the number of nearby occupants in front, and $\overline{d_{\iota f}}$ is the direction that the ith occupant is facing.

The cost, C_{cnr}, is calculated as follows:

1. If any intersections are found, the cost is calculated the same as in *avoid occupants* except with the expanded occupant radius and adjusted positions.
2. If the test direction's angle with the tangent to the seek curve is greater than 60° and the test direction's angle with $\overline{v_{flow}}$ is greater than 90°, the cost is 1.0.
3. Otherwise, the cost is 0.

Final Direction Cost

The final cost for a sample direction is a weighted sum of the individual behavioral costs:

$$C_{ds} = .5C_{seek} + w_{isep}C_{isep} + w_{ao}C_{ao} + w_{aw}C_{aw} + w_{ssep}C_{ssep} + w_{swsep}C_{swsep} + w_{lanes}C_{lanes} + w_{cnr}C_{cnr}$$

The weights depend on the occupant's current state, and are defined in the following table.

Weight	**State=Idle**	**State=Seeking**
w_{ao}	1	1
w_{aw}	1	1
w_{isep}	1	0
w_{ssep}	0	2
w_{swsep}	0	1
w_{lanes}	0	1
w_{cnr}	.2	.2

Evaluating Movement

Once the lowest cost direction has been determined, the steering velocity and acceleration are calculated that will move the occupant in the steering direction.

Along with a cost, each steering behavior calculates a maximum distance that should be traveled along the sample direction. This maximum distance is then used to determine the magnitude of the desired velocity, $\overline{v}_{des}$, as follows:

$$D_{stop} = \frac{\acute{v}_{curr}{}^{2}}{2a_{max}}$$

$$|\overline{v}_{des}| = \begin{cases} 0, & D_{max} \leq D_{stop} \\ v_{max}, & D_{max} > D_{stop} \end{cases}$$

$$\overline{v}_{des} = |\overline{v}_{des}|\overline{d}_{des}$$

Where D_{max} is the maximum distance for the lowest cost sample direction, $\overline{d}_{des}$ is the lowest cost sample direction, and $\overline{v}_{curr}$ is the occupant's current velocity.

The acceleration is calculated as follows [Reynolds, 1999]:

$$\overline{a} = \frac{\overline{v}_{des} - \overline{v}_{curr}}{|\overline{v}_{des} - \overline{v}_{curr}|} a_{max}$$

Explicit Euler integration is then used to calculate the velocity and position of each occupant for the next time step from their steering acceleration. The velocity and position are calculated as follows:

$$\bar{v}_{next} = \overline{v}_{curr} + \overline{a}\Delta t$$
$$\bar{p}_{next} = \overline{p}_{curr} + \bar{v}_{next}\Delta t$$

Where Δt is the time step size, $\overline{p}_{curr}$ is the current position, and $\bar{p}_{next}$ is the position after the time step.

Occupant States

Depending on an occupant's current scripted behavior, they will be in one of two states:

a. **Seeking** – the occupant is trying to follow a path to some destination.
b. **Idling** – the occupant is waiting for a specified amount of time.

Effect on Steering Behavior

Occupant state has a direct effect on which steering behaviors are combined to determine the lowest cost steering direction.

When idling, the occupant combines *separation*, *avoid occupants*, and *avoid walls*. This allows the occupant to maintain a separation with other occupants, move away from others that might be trying to seek near them, and avoid other occupants and walls at the same time.

When seeking, the occupant combines *seek*, *avoid occupants*, *avoid walls, seek separation, seek wall separation*, *lanes*, and *cornering*. This allows the occupant to avoid collisions with other occupants and walls and follow their seek curve. To a limited extent, the avoid occupants behavior integrates separation, so a separate separation behavior is unnecessary. While seeking, the occupant may temporarily switch to an idle state if they sense another occupant of higher priority or they have moved in such a way that they are touching another occupant. By temporarily switching to the idle state, they are able to move away from the other occupant to maintain the desired separation.

Effect on Sample Directions

Occupant state also affects the number of sample directions used for inverse steering.

In an idle state, 8 sample directions are tested, 45° apart, along with a “null” direction that tests standing still. This allows the occupant 360° of movement so they can easily separate from others.

When seeking, the occupant tests a different set of directions depending on the occupant’s speed. A seed direction tangent to the occupant’s seek curve is used as the starting direction. If the occupant’s speed is relatively slow, they will consider 7 more sample directions, 45° apart as when idling. If their speed is faster, the sample directions are taken 15° apart, up to 75° to either side, creating 9 sample directions. The occupant’s speed is considered “slow” if the following is true:

$$v_{curr} \leq f_{slow}\acute{v}_{max}$$

Where f_{slow} is settable via the input parameter, slowFactor, and $\acute{v}_{max}$ is the occupant’s modified maximum velocity. In addition to the sample directions, the null direction is again considered for seeking.

Priority

Pathfinder provides a priority system that operates on discrete priority levels assigned to each occupant. When occupants encounter other occupants at the same priority level as their own, they behave as indicated above (the common case). If, however, they detect another occupant with a different priority nearby and in front of them, they will slightly alter the above behaviors.

If the other occupant is of lower priority, the occupant will not separate and will use a comfort distance of zero, effectively allowing them to push against the other occupant if necessary. Because there is no notion of occupants exerting force on one-another, the other occupant must respond accordingly.

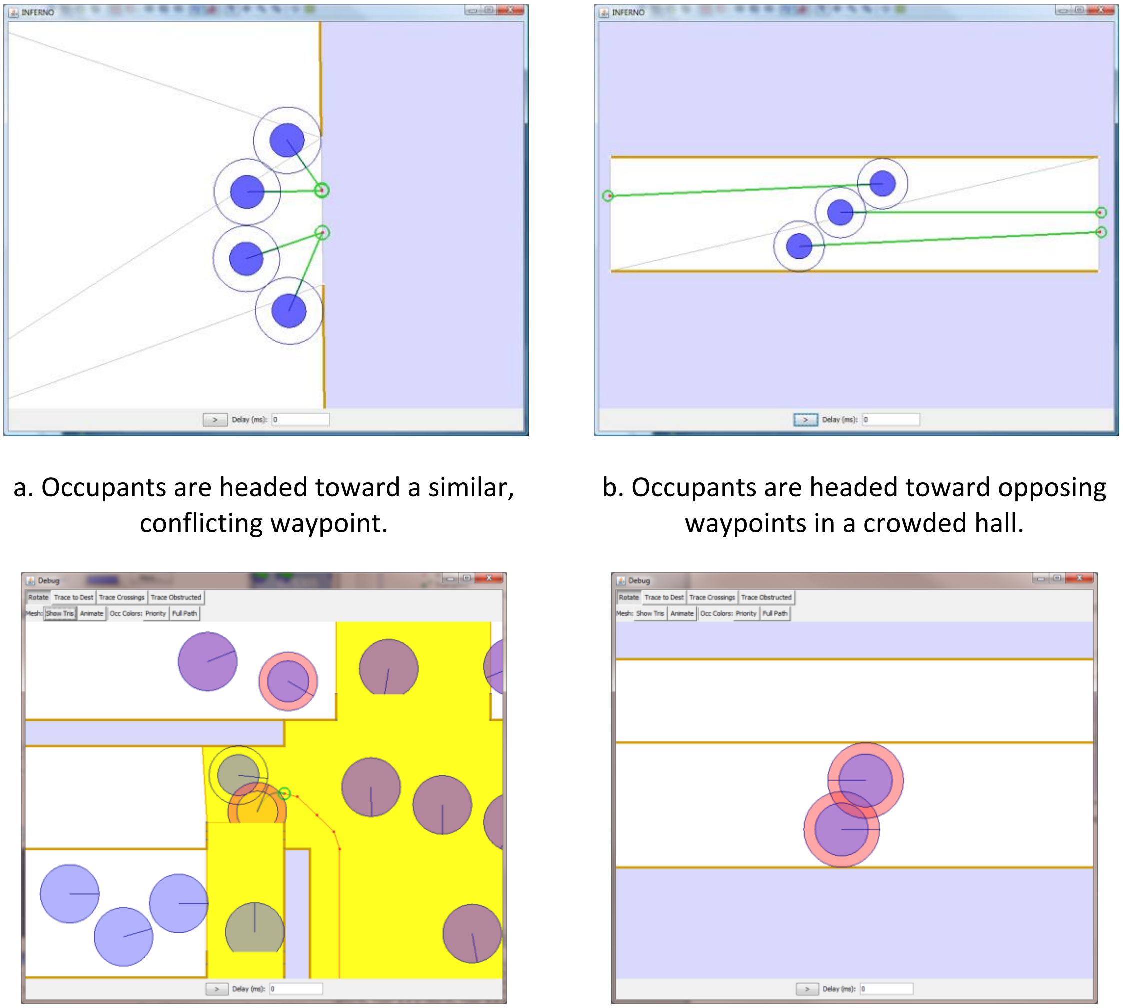
So in the inverse case of an occupant detecting another of higher priority within their comfort distance, they will ignore their seek behavior and instead use their separation behavior, even if their goal puts them in a seek state. This allows them to back away from the occupant of higher priority, giving the higher priority occupant a chance to move through.

Priority levels are completely relative. For example, if three occupants meet having priorities of 5, 7, and 12, their behavior toward one another would be exactly the same as if their priorities were 0, 1, and 2, respectively. Occupants with higher priority values have higher priority over other occupants.

Resolving Movement Conflicts

There are some scenarios where an occupant's movement conflicts with another occupant's movement due to limitations of the geometry. In these situations occupants must negotiate how to resolve these conflicts such that they can continue moving. The following examples illustrate how these situations can arise and are pictured in Figure 11:

a) Multiple occupants are simultaneously headed in a common direction and are approaching a physically tight area that will not allow all of them to pass at once (such as a narrow door or narrow hallway).
b) Occupants are headed in opposite directions in a crowded hallway (counterflow).
c) Occupants have squeezed into a tight area and cannot back up, due to a wall or one-way door.
d) Occupants are headed in opposite directions in a hallway that will not physically allow them to pass.



a. Occupants are headed toward a similar, conflicting waypoint.

b. Occupants are headed toward opposing waypoints in a crowded hall.

c. Merging occupants squeezed together

d. Counterflow occupants squeezed together

Figure 11: Potential conflict scenarios

Pathfinder employs special handling to resolve these movement conflicts and prevent occupants from becoming stuck. This is handled as part of each occupant's steering behavior as follows:

1. The occupant performs their steering behavior as described previously and determines that the lowest cost direction is to either stand still or to move counter to their desired steering direction because of another occupant.
2. The occupant performs a "free pass" test as discussed below. If the occupant obtains a free pass, they continue the next step. Otherwise, they return the no-progress steering direction.
3. The occupant recalculates steering with a *locally-elevated priority*. A locally-elevated priority is one that makes the occupant appear to have a higher priority

to others within the same priority level, but to other occupants with higher priority levels, the occupant still appears to have lower priority.

4. If the occupant makes progress with the newly calculated steering direction, the occupant raises their priority to this new locally-elevated priority (if not already raised) and returns the new steering calculation. If the occupant does not make progress, however, they skip to the next step. NOTE: When an occupant raises their priority, they also begin a count-down timer (settable via the input parameter, *Persist Time*) or extend a previous timer if priority was already raised. In addition, the occupant's radius is reduced by a reduction factor (settable via the input parameter, *Reduction Factor* in the pre-processor), allowing the occupant to squeeze past other occupants. If other occupants detect this occupant, they too will reduce their radii by their set reduction factors.
5. If the occupant has not yet set a timer, they will return the no-progress result. If they have set a timer, they skip to the next step.
6. If the occupant's timer has not yet expired from a previous steering calculation, the occupant remains stationary with a locally-elevated priority in hopes that other occupants will separate due to the elevated priority. If the timer has expired, however, they skip to the next step.
7. The occupant maintains raised-priority and enters a state in which they can pass through the other occupants that are immediately in their way.

Free Pass

In steering mode, an occupant obtains a free pass if at least one of the following conditions is true for all nearby occupants:

a. The other occupant is a lower priority.
b. The other occupant is the same priority and has a lower chance of reaching the intersection of their paths before the occupant being considered can.

Collision Avoidance/Response

While the wall and occupant avoidance behaviors will attempt to steer around obstacles, they might not always succeed. This often occurs in crowded situations when occupants cannot avoid being pressed tightly against walls and other occupants. In these situations, additional collision handling is necessary to prevent the simulation from entering an invalid state. There are two collision handling scenarios: one in which two or more occupants collide and another where an occupant collides with the boundary of the navigation mesh (i.e. a wall).

If collision handling is turned on, the occupant will halt at the earliest collision with either a wall or another occupant for a given time step. If collision handling is off, the occupant will only halt at the earliest collision with a wall.

Movement through Doors

By default, Steering Mode simulations provide no additional constraints on occupants when they move through doors. Flow limiting can be turned on, however, either through the simulation parameter, *Limit Door Flow Rate*, or the *Flowrate* parameter on individual doors.

In Steering mode, flow limiting works similarly to that in SFPE mode. For more details, see Movement through Doors on page 22. The main differences between flow limits in the two modes are as follows:

- In steering mode, the flow limit can only be specified as a fixed value. It cannot be based on room densities as in SFPE mode.
- The actual achieved flowrate in steering mode will often be less than the specified limit. This is due to the acceleration model and occupant avoidance used in steering mode. When an occupant is stopped at a door, they have to accelerate again to leave the doorway and allow another occupant to enter.
- Occupants passing through a flow-limited door in steering mode may encounter a slight slow-down at the door threshold even if they do not need to be held at the door to achieve the flow limit. This is because each occupant always needs to be enqueued at the door when they cross the threshold in order for the limiting logic to progress properly. This enqueuing step stops the occupant completely. In situations such as these, the door will immediately release the occupant, but some of the occupant’s momentum will be lost. This slowdown effect is dependent on the simulation time-step size. It will be worse for large time steps.

Elevators

Elevators in Pathfinder are composed of a discharge node and any number of elevator levels. Rather than modeling elevators using dynamic geometric elements (i.e. a floor that moves up and down), Pathfinder represents elevators using ordinary rooms. There is a room at each level the elevator touches, with doors connecting the elevator rooms to each level. There is one discharge room at the discharge level. There are several pickup rooms, one at each pickup level. Occupants that have entered a pickup room are moved directly toward the discharge room, bypassing any geometry in-between. They still appear to move, however, as if they are in a moving room as they are moved toward the discharge room. Elevator rooms that are not currently being served by the elevator are blocked using closed doors.

Elevator operation can be split into three main stages:

1. Idling
2. Pickup
3. Discharge

Idling

At the start of a simulation, each elevator is idle. All doors connecting all levels to the elevator are closed, the elevator is at the discharge floor, and the elevator is waiting to be called from one of the pickup levels. Once called, it proceeds to the pickup stage.

Elevator Calling

In order for an occupant to call an elevator, they must be assigned an elevator goal. If the elevator goal specifies multiple elevators to choose from, the occupant uses a modified version of Locally Quickest to choose the best one. This version of Locally Quickest adds the elevator doors on the level closest to occupant's location to the list of door targets. The global travel time for each elevator door reflects an estimate of the time it will take for the elevator to reach the pickup level for that door as well as the time to travel in the elevator to the discharge level and walk to the nearest exit.

Once the occupant has chosen one of the elevator doors, the occupant walks to the door. When they are within .5 m of the chosen elevator door and the elevator is in the idle state, the elevator is called. If the elevator is part of a call group, all elevators in that group are called.

Pickup

When a pickup level calls an elevator, the elevator moves toward that level. If multiple pickup levels call the elevator at once, the elevator travels to the one with the highest priority as specified in the user interface. As the elevator travels toward the pickup level, it continues monitoring calls. If a call is received from a level with higher priority before the elevator reaches the current pickup level, the elevator switches pickup levels. The time to reach the pickup level is specified in the user interface.

When the elevator reaches a pickup level, it opens its doors and waits for a countdown timer to elapse. The elevator then closes its doors and proceeds to the discharge stage.

Countdown Timer

When the elevator doors open at a pickup level, the elevator begins a countdown timer, initialized to the time specified by the *Open Delay* input parameter. Once this timer reaches zero, the elevator doors close. While the timer is counting down and the elevator has room for more occupants, two events may occur that can affect the timer:

- An occupant enters the elevator.
- An occupant is outside the elevator desiring to enter it, is moving more than 10% of their maximum speed toward the elevator, and is within 7 m of one of the elevator doors.

If one of these events occurs, the countdown timer is reset to be the larger of its current value or the *Close Delay* input parameter.

Loading

The process of loading an elevator and achieving the user-specified nominal load is controlled by occupants and their movement behavior rather than elevator logic. Pathfinder provides different mechanisms for achieving the nominal load depending on the simulation mode.

In SFPE mode, achieving the nominal load is fairly trivial. Usually, a room is assigned a maximum occupant density from the simulation parameters. The doors leading to that room use a gating mechanism to prevent occupants from entering if doing so would exceed the maximum density in the room. For elevator rooms, the maximum occupant density is derived from the nominal load as nominal_load/area. Because occupants can overlap in SFPE mode, no additional work is needed to ensure that the nominal load can be met.

In steering mode, however, Pathfinder requires further action to ensure the nominal load. This is because each room has a physical loading limit due to room shape, occupant size, and avoidance behavior. To allow elevators to reach the nominal load, collisions are turned off, while still allowing occupants to avoid one-another.

Discharge

After the elevator is loaded at the pickup level, it moves toward the discharge level. The amount of time it takes to reach the discharge level is the same as travelling from the discharge to pickup level as specified in the user interface. Once the elevator reaches the discharge level, it opens its doors. When the elevator is empty, it closes its doors and enters the idle state again.

Solution Procedure

Pathfinder runs in a simulation loop that calculates movement at discrete time steps. For each time step, the following steps are carried out:

1. Update each occupant's current target point. This step takes the longest on the first time step because each occupant must find a path to their goal.
2. Calculate each occupant's steering velocity. The steering velocity will be calculated differently depending on whether SFPE or Reactive Steering mode is active.
3. Increment the current time step.
4. Move each occupant. This involves several sub-steps:
5. Calculate the velocity for the current time. If steering mode is on, this will calculate a desired steering force from the desired velocity, and then use integration to calculate the actual velocity. In SFPE mode, this will simply be set to the desired velocity.
6. If collision avoidance is turned on, detect potential collisions, and modify the desired velocity to avoid the collisions.
7. Integrate the final velocity to find the maximum travel distance, and travel along the mesh until this distance is reached or until the earliest collision.
8. Update output files.

File Format

The simulator portion of Pathfinder can optionally use an input file to run simulations. By default, this input file is written every time a simulation takes place. This section describes the input file including its format and all parameters.

NODES

Rooms, doors, and stairways are represented by nodes. At any given time during the simulation each occupant is either inside one of the following nodes or has exited the simulation.

`[nodes]`

name

...

name : string	Name of a node

VERTS

This section contains all of the vertices that will be used by the geometry (triangles and edges) in the input file.

`[verts]`

x y z

...

x : float	x-coordinate
y : float	y-coordinate
z : float	z-coordinate

NAVMESH << NODES, VERTS

This section defines the walkable space within a simulation.

`[navmesh]`

ixnode ttype ixverta ixvertb ixvertc

...

ixnode : int	Index of the node associated with this triangle
ttype : string	Terrain type: [`open`, `stair`]
ixverta : int	Index of first vertex
ixvertb : int	Index of second vertex
ixvertc : int	Index of third vertex

Note**:** The order of the three vertices is significant. Use CCW ordering (i.e. right hand rule) to define the top of the mesh element.

GEOMMESH (optional) << NODES, VERTS

The definition of this section is identical to the definition of the NAVMESH section. If present, the mesh defined in this section will be used for geometry searches during the simulation. This can improve performance if this mesh is coarser than the NAVMESH.

`[geommesh]`

ixnode ttype ixverta ixvertb ixvertc

...

(same as NAVMESH)

DOORS (optional) << NODES

This section defines the doors that will be used if the `use_door_queues` option is enabled. Associating a door entry with a node causes that node to be recognized by the simulator as a door node and prevents the density calculation from being used to control the speeds of occupants within triangles associated with that node. This section does not define the geometric edges that the door represents (see ***Note***).

Exit doors should define only one adjoining room and internal doors should define two such rooms. These entries are used to prevent overcrowding as occupants transition between rooms and to provide for more elaborate merge calculations.

`[doors]`

ixnode eff_width ixnodeA ixnodeB

...

ixnode : int	Index of the node corresponding to this door
eff_width : float	Effective width of this door
ixnodeA : int	Index of a room adjoining the door (use dash "-" for none)
ixnodeB : int	Index of a room adjoining the door (use dash "-" for none)

Note: Agents will not enter a door's queue unless they cross a special door edge (defined in the EDGES section).

EDGES (optional) << NODES, VERTS

The entries in this section represent the geometric portion of entities that are defined as edges in the NAVMESH.

`[edges]`

etype <depends on etype>

...

etype : string	Edge type: [`boundary, door, exit_door`]

`boundary` *ixverta ixvertb*

This edge type represents a boundary that occupants will not walk across.

ixverta : int	Index of the first vertex
ixvertb : int	Index of the second vertex

`door` *ixnode ixverta ixvertb*

This edge type represents an internal door. Doors of this type will not be included in the search for the nearest exit and should have two adjoining nodes defined in the corresponding door record.

ixnode : int	Index of the node corresponding to this door
ixverta : int	Index of the first vertex
ixvertb : int	Index of the second vertex

`exit_door` *ixnode ixverta ixvertb*

This edge type represents an exit door. Doors of this type will be included in the search for the nearest exit and should have one adjoining node defined in the corresponding door record.

ixnode : int	Index of the node corresponding to this door
ixverta : int	Index of the first vertex
ixvertb : int	Index of the second vertex

***Note*:** Edge definitions must match edge definitions in the NAVMESH. If a door is formed by the three vertices *A*, *B*, and *C*, it must be given as two edges: A-B and B-C. Edges that do not correspond to edges in the NAVMESH (e.g. A-C) are invalid and may cause the simulation to crash or otherwise behave unexpectedly.

PARAM (optional)

This section allows you to customize global simulation parameters. The format is a list of key value pairs.

`[param]`

key value

...

key : string	The name of a simulation parameter
value : mixed	The value for a simulation parameter (type depends on *key*)

max_time	0	Simulation time limit in seconds (0=infinite)
show_vis	0	Turn debugging visualization on/off (0=off, 1=on)
out_time_history	*vis.out*	Movie playback (time history) output
out_node_pop	nodes.csv	Node populations over time
out_clear_times	clear.csv	Clearing times for each node
dt_init	0.025	Simulation time step size (s)
dt_vis	0.25	Frequency of visualization output (s)
dt_wall_meta	0.5	Frequency of simulation progress meta data (s)
dt_csv_data	1.0	CSV data print time increment (s)
handle_collisions	1	Turn collision handling on/off (0=off, 1=on)
reactive_steering	1	Turn reactive steering on/off (0=off, 1=on)
inertia	1	Turn inertia on/off (0=off, 1=on)
vel_from_density	1	Turn density-based velocity calculation on/off (0=off, 1=on). Only applies when inertia is off.
use_door_queues	0	Turn door queues on/off (0=off, 1=on)
wall_slide	1	Turn wall sliding on/off (0=off, 1=on)
density_max	3.55	Maximum room fill density. Only applies when door queues are active.

PROFILES << NODES

These entries are descriptions of artificial intelligence for simulation agents.

```
[profiles]
goto [ixnode | nearest]
...
```

`goto`	Currently, the only form of AI allowed by the simulator.
Ixnode : int	The index of the goal node
`nearest`	This option causes the occupant to search for the nearest exit

OCCUPANTS << PROFILES, NODES (indirect), NAVMESH (indirect)

This section describes the occupants present at the beginning of the simulation. The starting node for each occupant is inferred based on the location of the occupant.

`[occupants]`

name ixprofile x y z

...

name : string	The name of the occupant
ixprofile : int	The index of the corresponding profile entry
x : float	The x-coordinate of the occupant
y : float	The y-coordinate of the occupant
z : float	The z-coordinate of the occupant

OTHER NOTES

Lines beginning with the comment character (“#”) will be ignored.

Lines are considered to be delimited by spaces and commas. Strings containing spaces and commas should be enclosed in double-quotes. The following three VERT definitions are identical to inferno.

```
1, 1, 0
1.0 1. 0.
1, 1 0
```

EXAMPLE INPUT FILE

```
# Sample 0
# Pathfinding with edge exits test case

[nodes]
"R1"
"e2"

[doors]
1 1.32 0 -

[verts]
0. 0. 0.
1. 0. 0.
1. 1. 0.
0. 1. 0.

[navmesh]
0 open 0 1 2
0 open 2 3 0

[geommesh]
0 open 0 1 2
0 open 2 3 0

[edges]
```

```
#type ixNode ixVert1 ixVert2
exit_door 1 1 2

[param]
show_vis 1
handle_collisions 1
reactive_steering 1
inertia 1
vel_from_density 0
use_door_queues 0

[profiles]
#goto <ixNode>
goto nearest

[occupants]
#name ixProfile x y z
"001" 0 0.25 0.75 0.
```

Results

Occupant Contours

The 3D results provide some post-processing capabilities, including the ability to generate contours that show dynamic occupant data overlaid on the navigation mesh or imported geometry as shown in Figure 12.

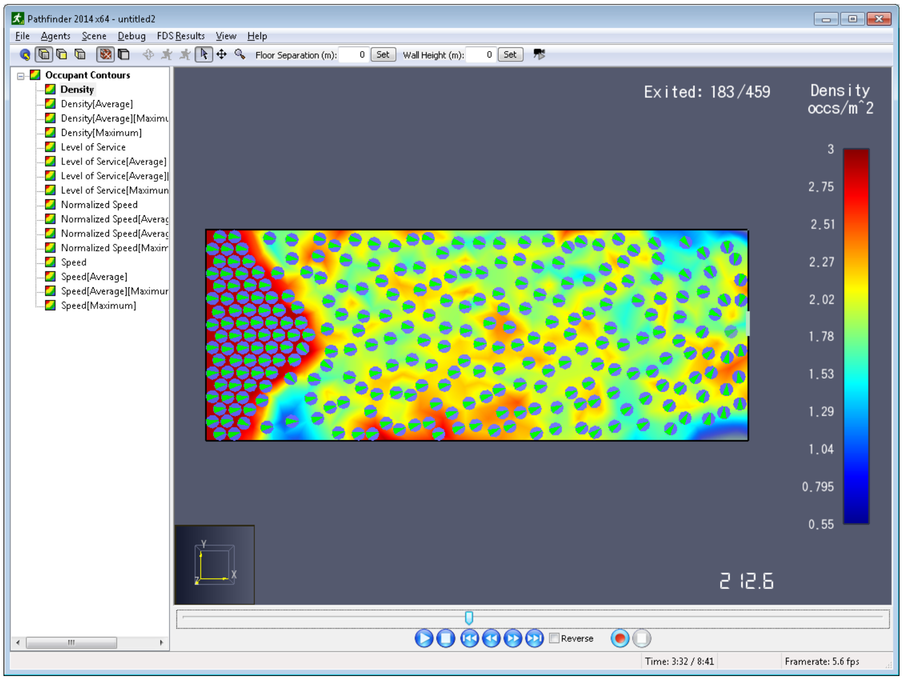
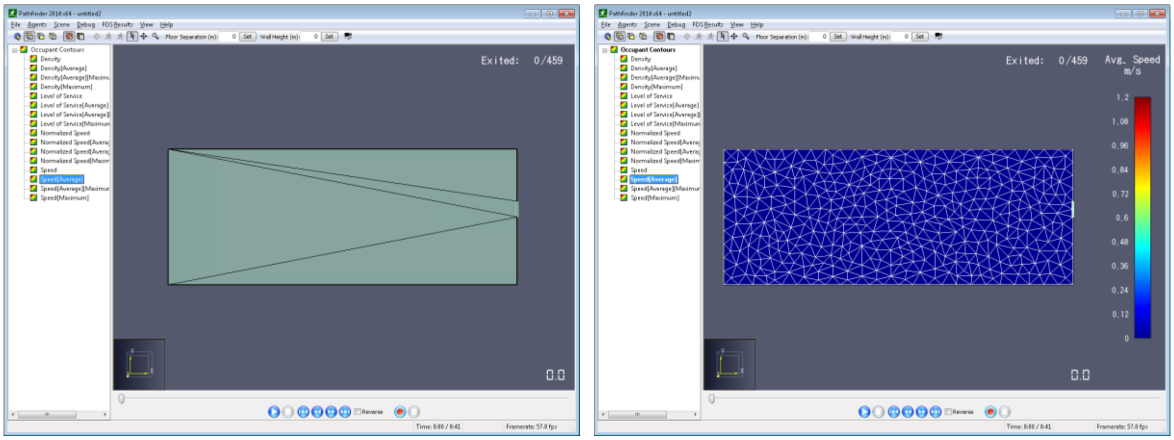


Figure 12: Occupant contours

Contours can either be calculated as results are played back or can be optimized and stored on disk for later retrieval. Optimization is discussed further in the User Manual. The calculation of the contours is described in this guide.

Contours are calculated using a sub-divided version of the navigation mesh as seen in Figure 13.



Navigation Mesh

Occupant Contour Mesh

Figure 13: Navigation Mesh vs. Occupant Contour Mesh

Contour values are calculated at the vertices of the triangles in the contour mesh and are linearly interpolated across triangles to produce the shading. The contour mesh is used only to display occupant contours and is independent from the navigation mesh used during the simulation. The spatial resolution of the contour mesh as well as the update frequency can be controlled using the **Occupant Contours Properties** dialog. Smaller values for space and time resolution offer smoother contours at the cost of greater calculation time and memory requirements.

Frames of contour data are produced throughout time depending on both the 3D results data frames and the time step specified in the **Occupant Contours Properties** dialog as discussed in the User Manual. Each contour frame lines up in time with a frame of occupant animation data, though there does not have to be a one-to-one correspondence. This ensures that contour data is only produced when occupants are at known positions rather than interpolated positions. To view contour data at times between contour frames, the data is linearly interpolated between frames.

Density

The density calculated at each vertex of the contour mesh is dependent on the location of nearby occupants and the value of the **Density Radius** parameter. Any occupant intersecting the circle around a vertex contributes to the density at that vertex. Occupants who partially fall within the circle around a vertex contribute partially based on intersection area.

Increasing the **Density Radius** parameter smooths out contours by eliminating peaks and valleys in the density calculation. This effect will tend to be more visible near the edges of dense flows and more stable within uniformly dense regions due to partial attribution of occupants intersected by the density measurement radius.

The following steps describe in detail how the density values that control contour colors are calculated.

1. For each vertex of the contour mesh, an area is calculated. The area is at most $\pi {r_d}^2$, where r_d is the user-settable parameter, **Density Radius**, as described in the User Manual. The area will be less if there are boundaries closer than r_d.
2. For each vertex, the mesh is traversed to find occupants whose bodies are at least partially within r_d.
3. The number of occupants within this radius are summed, with occupants fully within the radius counting as 1 and occupants partially within the radius counting as follows:
$$C = 1 - \frac{d - r_d + r_o}{2r_o}$$
where $r_o$is the occupant's radius and d is the 2-d distance from the vertex to the occupant's center.
4. The occupant count is then divided by the area at the vertex to produce the density value.

Level of Service

Level of Service is implemented the same as density but with three special color maps. Each color map represents a different type of terrain, including Walkway, Stairway, and Queuing [Fruin, 1987].

Speed

For each occupant, their speed is applied to the vertices of the contour mesh within a distance of r_i (see **Influence Radius** in the User Manual). The speed value at each vertex is calculated as follows:

$$s_v = \max_{1 \le x \le n} \left(s_x \frac{r_i - d_x}{r_i} \right)$$

where n is the number of occupants within a 2-d radius of r_i surrounding the vertex's position, s_x is the current speed of occupant x, and d_x is the 2-d distance from the vertex to the position of occupant x.

Normalized Speed

The normalized speed contour is calculated similarly to the speed contour, except that the speed value per vertex is the following:

$$s_v = \max_{1 \le x \le n} \left(\frac{s_x}{s_{xmax}} * \frac{r_i - d_x}{r_i} \right)$$

where s_{xmax} is the maximum speed of occupant x.

Usage [Instantanteous]

The usage value at each vertex is calculated as follows:

$$u_v = \max_{1 \le x \le n} \frac{r_i - d_x}{r_i}$$

Usage [Accumulated]

The accumulated usage contour is implemented as a time-integrated filter on top of an instantaneous usage contour. See Integrate below for more information about the integration filter.

Time to Exit

The Time to Exit contour value at each vertex is calculated as follows:

$$tte_v = \max_{1 \le x \le n} \left((t_{exit} - t_{curr}) \frac{r_i - d_x}{r_i} \right)$$

where t_{exit} is the occupant's exit time and t_{curr} is the current contour calculation time.

Average

Average contours are applied on top of other contours. They are calculated over a user-specified interval that is always trailing a particular time step. So if the averaging interval is 30 s long, then at t=120 s, the averaging interval is [90,120] s. The interval cannot go back in time, however, so at t=10 s, the interval is [0,10] s.

For each vertex, the vertex contour values of the base contour are averaged over this interval to produce the final vertex value as follows:

$$v_x = \frac{1}{n} \sum_{f=x-n+1}^{x} v_f$$

where x is the index of the contour frame for the current time step, n is the number of frames that intersect the calculation interval (see **Calculation Interval** in the User Manual), v_f is the vertex value of the base contour at frame f.

Maximum

Maximum contours are applied similarly to average contours. For each vertex, the final vertex value is the maximum of the vertex values of the base contour over the time interval as follows:

$$v_x = \max_{x-n+1 \le f \le x} v_f$$

Integrate

Currently, the integration filter is not exposed as a general contour filter – it is only available incorporated into the accumulated usage contour. The integration filter is implemented on a per-vertex basis as follows:

$$v_x = \sum_{f=x-n+1}^{x} v_f \left(t_f - t_{f-1}\right)$$

where t_f is the time of frame f, and t_{f-1} is the time at frame $f - 1$.

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