A modified approach to walking speed within smoke-filled rail tunnels

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ABSTRACT

Lighting and walkway configuration have a clear impact on movement in a smoke-filled rail tunnel. During design, analysis and evacuation modelling, occupants' walking speed should be adjusted according to the visibility and the configuration of the tunnel. The walking speeds proposed in standards and default values in evacuation modelling tools are often based on an environment which does not fully correspond to environments as seen in today's newer rail tunnels.

Newer rail tunnels are often equipped with adequate lighting, walkways free from obstructions and handrails providing guidance and support. If the walking speed used during design and analysis can be increased to reflect a more beneficial environment in new tunnels, it could lead to distances between exits being extended leading to fewer escape routes being needed. Hence, refined analysis can provide large cost-savings.

This paper presents a case study where walking speed reduction due to visibility is varied within egress simulations. This given varied lighting configurations. The constant K, used for calculating visibility, is varied to illustrate impact of sufficient lighting. The paper also studies the impact of an increased minimum walking speed given a more preferable egress environment. For this part, the usage of wayfinding aids, e.g. handrails, is focus. Based on these aspects, the effect in terms of toxic exposure on the evacuees in case of fire will be studied.

Using CFD for fire modelling coupled with evacuation modelling, this study aims to highlight the shortcomings in current knowledge and provide a greater understanding for important input parameters when conducting egress analysis. Results show that an enhanced lighting configuration and tunnel environment can lead to significantly lower smoke exposure during egress. However, it is clear that a refined analysis approach equals greater challenges for the engineer conducting the analysis.

KEYWORDS: Walking speed reduction, rail tunnels, tunnel environment, evacuation, light configuration

PURPOSE

This case study investigates the impact of lighting configuration on walking speed, focusing on the constant K used for visibility calculations. The paper also studies the impact of an increased minimum walking speed given more preferable egress environments, e.g. use of continuous handrail. Using Computational Fluid Dynamics (CFD) and evacuation simulations, the toxic impact of smoke under varied conditions is analyzed. Findings aim to refine egress modeling, ensuring safety while optimizing design and cost efficiency.

DESIGN STANDARDS

The driving factor for conducting fire and egress analysis within rail tunnels is often optimizing distance between emergency exits.

The governing standard for subway systems in Sweden (Swedish Transport Agency) states that:

> *"If the distance between two escape routes is greater than 300 meters in one tunnel, the developer must determine threshold values for critical impact for evacuation. These limit values must not be exceeded during the required time for the evacuation."*

The standard outlines threshold values which should not be exceeded during evacuation. Criterias include smoke and heat exposure and are listed below. These limits can be considered acceptable conditions to determine whether self-evacuation is possible or not. Within this study, the focus is on exposure to toxic gases. Based on experience, the threshold values for toxic gases are often exceeded earlier than the threshold values for heat and temperature exposure.

Toxic gases	The last group to evacuate can reach a point of safety before the toxic gases cause unconsciousness. A fractional incapacitation dosis (FID) of maximum 0.3 (excluding effects of Hydrogen Cyanide, HCN) is used as a criteria. *Note: A fractional incapacitation dose (FID) of 0.3 corresponds to approximately the most vulnerable 11% of the population being susceptible to compromised tenability, and an FID of 1.0 corresponds to 50% of the occupants experiencing compromised tenability.* Toxic gases 2.0 meters above walkways should contain at least 15% oxygen by volume, no more than 5% carbon dioxide by volume and no more than 0.2% carbon monoxide by volume.
Heat exposure	Prolonged exposure < 2,5 kW/m^2
Temperature	Air temperature should be below 80 degrees celsius.

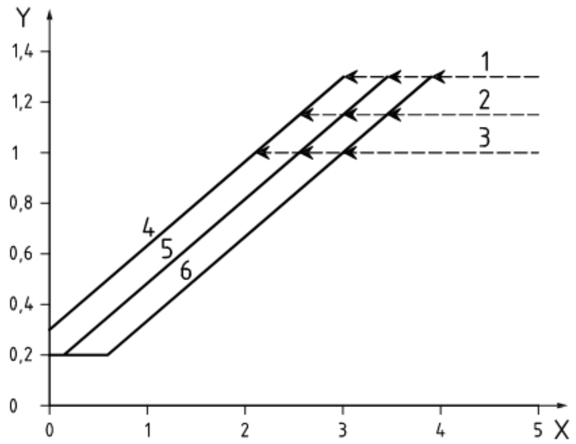
Similar type of design standards, highlighting a need for fire and evacuation analysis, exists in other parts of the world.

ISO/TS 21602:2022

Walking speed reduction due to a decreased visibility can be found in some design standards.

ISO/TS 21602:2022 (ISO/TS 21602:2022, 2022) provides correlation between movement speed and smoke characteristics. However, the document does not consider the effects of smoke on way-finding behaviour.

The standard provides correlations for walking speed reduction to be used for deterministic analyses. For Method II within the standard, the first step is to define three different movement speeds in smoke free environments (unimpeded walking speed). The movement speeds should reflect the population evacuating. During the second step, correlations describing the reduction of movement speed as a function of visibility distance shall be selected. *Figure* 1 below shows the correlation of three groups and how walking speed is reduced based on visibility.



Key

X visibility distance, *V* (m)
Y movement speed, *v* (m/s)
1 medium
2 slow
3 very slow
4 medium reduction
5 early reduction
6 very early reduction

Figure 1 Example of correlation between movement speed and visibility according to Method II

The movement speed starts to reduce once low visibility prohibits free movement, i.e. when people are no longer able to move at their unimpeded speed without risking injury due to a collision or fall. The lower visibility distance typically corresponds to smoke-filled conditions, which create a situation similar to moving in complete darkness. Below the lower visibility distance, people move at a constant low movement speed at which collisions or falls lead to limited injuries.

The standard highlights that handrails along a wall can lead to a higher minimum movement speed in smoke. It also highlights that a continuous visual way-guidance system (e.g. light strip) can lead to a higher minimum movement speed. Uneven or coarse floor surfaces along with geometry requiring decision making leads to lower unimpeded movement speed and a more rapid reduction of movement speed in smoke. The impact of these factors are however not quantified and are therefore not explicitly included within the standard.

The standard also highlights the need of taking irritans species into consideration during analysis.

PREVIOUS STUDIES AND EXPERIMENTS

Research focusing on walking speed within smoke-filled rail tunnels is scarce. In Sweden, a minimum walking speed of 0,3 m/s have historically been used in analysis when evacuating through heavy smoke. The basis for this goes back to experiments conducted during the 1980s. In the upcoming sections some more recent research deemed suitable for the study herein is summarised.

Fridolf et al. (2016)
The report investigates how reduced visibility in smoke-filled environments affects walking speeds, based on data from several full-scale experiments conducted in different settings. The studies mentioned in the literature review include experiments where participants navigated through smoke with varying visibility distances.

One of the key findings is that the current state of research shows that there are major uncertainties linked to the movement of people in smoke. A recommendation to represent occupants' walking speed in smoke is however presented, handling some of the these uncertainties. Three different methods are presented within the recommendation. Independent of method, the recommendation is that peoples' walking speed in smoke should be dependent on the unimpeded walking speed in a smoke-free environment. Hence, an individual assumed to move faster than another individual in a smoke-free environment will always be assumed to do so in a smoke-filled environment as well.

Method 2 in the report splits the population into the different categories; medium, slow and very slow. The figure below shows the walking speed for the different categories. It is up to the designer to choose the distribution of occupants for each category.

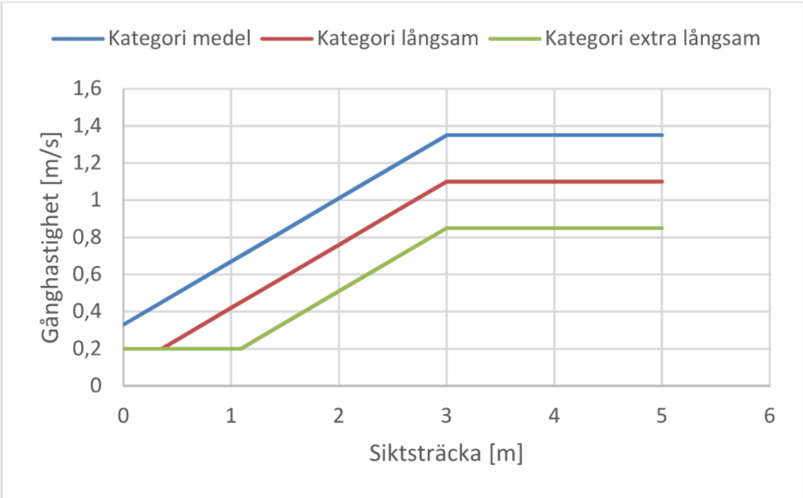


Figure 2 Diagram showing the applied relationship between walking speed (y-axis) and visibility (x-axis) for the three categories.

The minimum walking speed is 0,2 m/s, corresponding to situations where visibility is extremely limited. Note that walking speeds below 0,4 m/s have only been observed in environments containing obstacles in the form of cars in a road tunnel.

The literature review also contains an experiment in a complex environment representing a ferry or a hotel including stairs. In this experiment walking speeds below 0,4 m/s, including pauses for wayfinding decisions, were observed in low visibility. These experiments included different smoke environments and wayfinding aids with or without a handrail. It could be observed that a combination of wayfinding aids in form of handrail and reflective strips on the floor, or a reflective strip on the handrail (scenario 10,11 and 13), was significantly more effective than having only visual wayfinding aids (scenario 2-8) or only handrail (scenario 9 and 12).

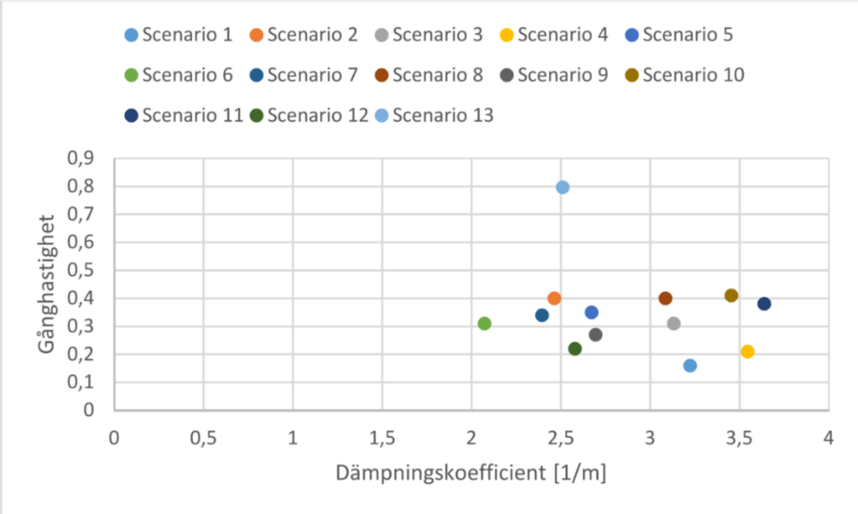


Figure 3 Correlation between walking speed (y-axis) and extinction coefficient (x-axis)

The report emphasizes the need for further research. Explicitly movement within environments with a visibility <3 metres is deemed important to study further. In addtion, the study recommends that future research aim to quantify the effect of other parameters and variables than visibility itself, both in relation to the behavior of people as well as their walking speed. Within this context, the use of handrails and light installation are mentioned.

Fridolf et al. (2013)
The report examines how smoke density affects evacuation speed, based on full-scale experiments. In total, 146 participants navigated smoke-filled tunnels, with extinction coefficients ranging from 1.2 to 7.5 m^{-1}. The tests included both a road tunnel setup and a rail tunnel setup.

At lower smoke levels, the average walking speed was 1.02 m/s, but it dropped to 0.42 m/s at higher densities. Factors like age, gender, and tunnel slope had no significant effect, but it was clear that most participants used the walls for guidance.

Ronchi et al. (2012)
The report focuses on how smoke density affects walking speeds in evacuation simulations and examines the role of different experimental data sets and model interpretations. The study compares two primary data sets being Jin's experiments and Frantzich and Nilsson's tunnel trials. It analyzes six evacuation models, including STEPS, to assess how embedded assumptions and default settings influence simulation outcomes.

The study underscores the importance of understanding how evacuation models interpret smoke-related data to avoid misinterpretations and emphasizes the need for the designer to re-evaluate the appropriateness of the default values for a certain evacuation model.

Fridolf et al. (2019)
The article provides an in-depth analysis regarding how walking speed is affected by smoke in tunnels and suggests methods for incorporating this data into fire safety design. Many of the findings presented inherit from (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2016).

The document highlights the importance of visibility rather than extinction coefficient to represent walking speed, as people adjust their speed based on what they can see in the environment rather than theoretical smoke metrics.

The report emphasizes the importance of tactile or visual guidance, noting that people tend to follow walls in smoke to maintain direction and stability. This aligns with our interest in investigating whether e.g. illuminated handrails can help evacuees maintain higher walking speeds in smoke-filled tunnels.

Additionally, the report reference to real-life incidents, such as the Gudvanga Tunnel, in which a fire occurred in a truck in Norway 2013. During this incident, a family of two adults and a 10 year old child managed to evacuate a distance corresponding to approximately 8 km in 90 minutes. The relatively high walking speeds observed in the Gudvanga tunnel fire could be linked to the limited irritating effects of the smoke due to the large air volme within the tunnel. However, the fire crew reported visibility as low as 0-2 m within the tunnel (Accident Investigation Board Norway, 2015). Hence, the incident indicates that a high minimum walking speed is possible even in smoke-filled environments. It also highlights how environmental conditions, such as ventilation and smoke irritancy, can affect walking speeds.

Yamada T. & AkiZuki Y. (Yamada T., 2016)
The correlation between soot density and visibility is described in the SFPE Handbook. The human eye can distinguish a sign from the background in smoke only when the difference between the luminance of the sign and the background luminance is larger than some threshold value of luminance contrast. Visibility therefore depends on the intensity of luminous flux from the background, the luminous flux from the sign and the properties of smoke.

In the range of visibility of 5–15 m, the constant K, of the visibility, V, at the obscuration threshold and the smoke density, Cs, is almost constant as expressed in equation below.

$$V = k\frac{I}{C_s}$$

Where:

V	Visibility of signs at the obscuration threshold [m]
k	Constant K
I	The intensity of light through smoke [cd]
C_s	Smoke density expressed by the extinction coefficient [1/m]

For reflecting signs, the product of the visibility and smoke density is almost constant as well. The product depends mainly on the reflectance of the sign and the brightness of illuminating light. The constant K varies between 2 and 4 for reflective signs and between 5 and 10 for light emitting signs. The visibility of other objects such as walls, floors ,doors, stairways, and so forth in an underground shopping mall or a long corridor varies depending on the interior and its contrast condition; however, the minimum value for reflecting signs may be applicable.

Note that the presented relation between the visibility of self-illuminated signs at the obscurity threshold and smoke density (extinction coefficient) from the experiments performed in Japan indicates that the constant K does not decrease at lower visibilities. The equation is used in FDS User's guide for all visibilities with a recommendation for constant K of 3 at light reflecting signs and 8 for light emitting sign. The equation is also used in ISO ISO/TS 21602:2022 for all ranges of visibility and a recommended range of constant K between 2 and 10.

METHODOLOGY

This paper presents a case study. It couples fire simulations with egress simulations to understand the impact on egress given the following two parameters:

- Lighting configuration along the walkway. This is conducted by varying the constant K, used for calculating visibility distance.
- Built environment along the walkway, e.g. continuous handrails. This is conducted by varying the minimum walking speed in smoke.

A quantitative approach is used studying the fractional incapacitation dose (FID) of toxic gases (excluding effects of Hydrogen Cyanide, HCN) experienced during evacuation. The calculation of FID is based on equations given in the SFPE Handbook (SFPE Handbook of Fire Protection Engineering, 5th edition, Society of Fire Protection Engineers , 2016). The FID values experienced are compared against the threshold previously explained (mainly a toxic FID < 0.3).

MODEL CONFIGURATION

Fire and smoke simulations were initially conducted using CFD. The results from the CFD simulation were thereafter input for egress simulations using the software STEPS. Further explanation regarding the modelling setup in given in the upcoming sections.

Fire simulations

A geometry representative of a generic single bore tunnel was used as a basis. The model consisted of a tunnel with a width of 5,6 m and a height of 4,8 m. A train with two cars was modelled within the tunnel. Each car was approximately 30 m. A walkway on one side of the trains was modelled within the tunnel. The walkway was modelled without elevation. Hence, the difference in elevation between the floor of the train cars and the walkway was 0,8 m.

The totalt length of the tunnel within the study was 800 m. The fire was located inside the train car closest to the North tunnel portal. The incident car was placed 200 m from the North Portal. A wind was applied from north as a pressure boundary. During cold condition, the airflow within the tunnel was around 1,2 m/s. See below for configuration.

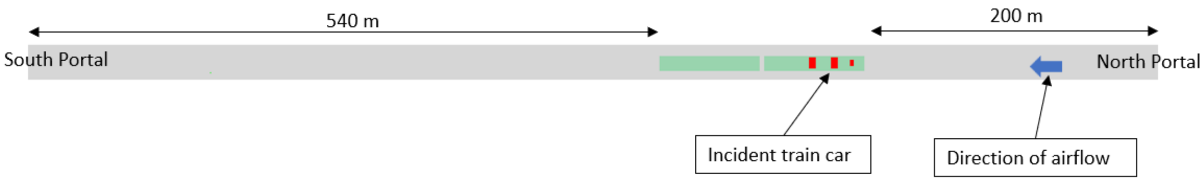


Figure 4 Fire simulation configuration

The incident car was equipped with three doors leading to the walkway. Each door was 1.4 x 2.2 meters (width x height). Doors facing the walkway were all modeled as open throughout the simulation enabling smoke to reach the walkway early on. Doors on the other side of the train were modeled as closed throughout the simulation.

Windows in the incident car were modelled to break at different times depending on proximity to the fire sources. The windows have been estimated to brake at around 450 °C. The times for when windows fail are shown in Table 1. Note that these times are estimates and have been taken slightly earlier than when the temperature reaches 450 °C at window level, in order to avoid the risk of the fire becoming ventilation-controlled.

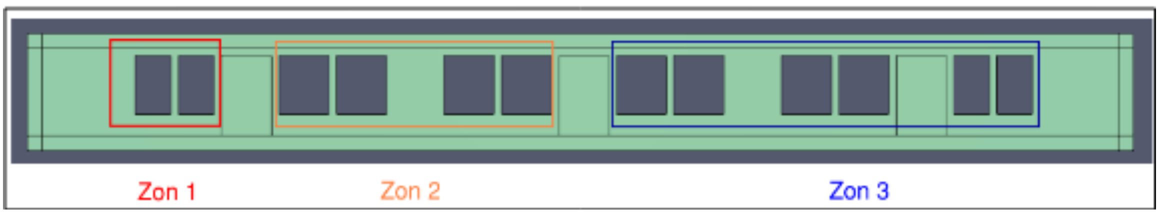


Figure 5 Window zones in the incident train car

A single fire size was simulated within this study. This includes a 20 MW fire with a medium growth rate. The fire was deemed suitable based on experience and similar fire sizes are often used in Sweden to study egress. Three different burners were used as indicated in *Figure 4*.

Fire parameters were based on general recommendation within Swedish guidelines (Boverket, 2013) and the SFPE handbook (SFPE Handbook of Fire Protection Engineering, 5th edition, Society of Fire Protection Engineers , 2016).

Slice files were placed in the fire model to study results. The most eminent slice file being soot density at a height of 2 meters above the walkway. This was later to be used as an input in egress calculations.

Table 1 presents the parameters used for the fire simulation.

Table 1 Parameters for the fire simulation

Parameter	Value	Comment
Area of tunnel	27 m^2	Height 4,8 m Width 5,6 m
Length of tunnel	800 m	Deemed satisfactory for the current study.
Heat release rate	20 MW	Note that this fire size and growth rate is often not used strictly as a design fire. However, it is a common fire size used to study egress.
Fire growth rate	0,012 kW/s^2	
Window breakage (after fire start)	Zon 1 – 600 s Zon 2 – 900 s Zon 3 – 1200 s	See Figure 5 for applicable zones.
Simulation time	3600 s	This extent of time was modelled after the start of the fire. An extensive simulation time was modelled to ensure sufficient inputs for egress studies.
Slope	-	The tunnel was modelled without slope.
Surface roughness	250 mm	Based on experience and deemed suitable for the study.
Software	FDS 6.7.9.	
Fire parameters		
Yields	Soot – 0,09 g/g CO – 0,10 g/g CO_2 – 2,5 g/g	Deemed suitable based on Swedish guidelines (Boverket, 2013) and SFPE handbook (SFPE Handbook of Fire Protection Engineering, 5th edition, Society of Fire Protection Engineers , 2016).
Heat of combustion	20 000 MJ/kg	Based on Swedish guidelines (Boverket, 2013).
Constant K	8	Constant K, used for calculating visibility distance (slice files). This was later varied within STEPS as part of the purpose of the study.

The output from the fire simulation where used as input parameters for the evacuation simulations.

Evacuations simulations

It was assumed that the first egress point was 150 m into the tunnel (from the North portal), hence 50 m upstream from the incident train car. The second egress point was placed 600 m into the tunnel (from the North portal). Hence, there is a significant distance between the two egress points, see *Figure 6*. Note that the figure below does not show the entire length of the tunnel used in the fire simulation and shown in *Figure 4*.

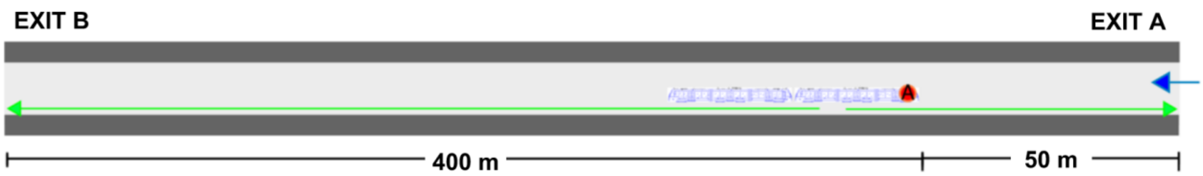


Figure 6 Distance from the fire-affected train car to the evacuation routes

The main principle is that passengers move away from the fire during evacuation. Hence, occupants within the non-incident train car were modelled to evacuated downstream, towards Exit B.

The train in the egress simulations had 1,35 m wide doors, with three doors per train car leading to the walkway.

The flow rate from the train cars to the walkway has been set at 0,52 p/s per door. The flow rate is based on experiments and recommendations (Niclas Åhnberg, 2017) regarding the flow capacity of the Swedish railway system for different door widths and height differences between the door and the walkway.

The walkway was 1,2 m wide in the evacuation simulations. For the walkway, a flow rate of 1,2 p/sm was assumed, corresponding to Swedish guidelines (Boverket, 2013), allowing two people to walk side by side.

The tenability criterias allow for movement in a smoke-filled environment, and walking speeds must therefore be adapted depending on the specific visibility. The unimpeded walking speeds and the walking speed reduction along the walkway used in the simulations can be linked to the research presented by Fridolf et al. (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2016). The walking speed reduction due to a decreased visility is more significant for the slowest individuals than the reductions specified in ISO/TS 21602:2022 (ISO/TS 21602:2022, 2022). However, ISO/TS 21602:2022 includes correlations which do not cover individuals without full mobility, such as children (covering only the 80^{th} percentile), whereas the proposal from Fridolf et al. (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2016) includes the 97^{th} percentile. *Figure 7* presents the applied walking speeds relative to the visibility distance in this case study. Note that the minimum walking speed presented in the figure is 0,4 m/s and that for some of the simulations the minimum walking speed was set to 0,2 m/s.

Individuals in the simulations are assigned one of the three representations of unimpeded walking speeds according to the distribution in *Table 2*.

Table 2 Distribution of representations of walking speeds in the evacuation scenarios.

Representation of walking speed	Distribution
Average	80 %
Slow	15 %
Extra slow	5 %

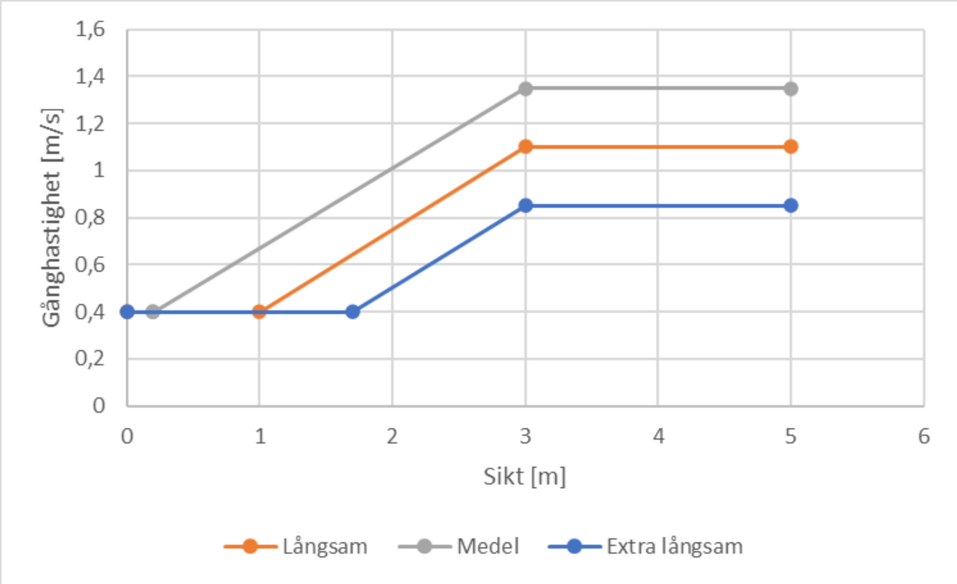


Figure 7 Diagram showing the applied relationship between walking speed (y-axis) and visibility (x-axis) for three groups.

Visibility distance which affects the walking speed of evacuees, is calculated using the soot density from the fire simulations according to the following equation:

$$V_s(t,x) = \frac{K}{\sigma * \rho_{sm}}$$

Where:

$V_s(t,x)$	Visibility as a function of time and distance from the fire [m]
ρ_{sm}	Soot density from the fire simulations [kg/m^3]
K	Constant K
σ	Mass extinction coefficient, 8700 [m^2/kg] (Mulholland)

The soot density, used to calculate visibility, is taken at the height of 2 m above the walkway, in line with the perspective of a standing adult. The visibility is generally better at lower heights, even if the smoke layer is not clearly defined.

Within the simulations, visibility affects the movement of individuals, while doses of various gases are recorded for the evacuees. This is possible because output data from the fire simulations is imported into the evacuation simulation model.

Table 3 Parameters for the evacuation simulations

Parameter	Value	Comment
Constant K	Base value = 3 Alternative value = 8	For the scenarios with a value of 8, continuous light emitting LED handrails (1 m above ground) with sufficient light intensity are assumed.
Minimum walking speed	Base value = 0,2 m/s Alternative value = 0,4 m/s	For scenarios with a minimum walking speed of 0,4 m/s, a flat walkway, level with its surrounding is assumed, with handrails to follow a path without any obstacles along the way.
Occupant load	145 occupants per train car	The simulations were conducted with 2 train

		cars. Hence, a total of 290 occupants were simulated.
Time to initiation of evacuation	Fire-affected train car: 2 min Second train car: 4 min	Based on time to untenable conditions in the car and travelling time between safe areas.
Distance between evacuation routes	450 m	

Toxic exposure

The evacuation simulations generates output in the form of accumulated doses per individual. To calculate toxic exposure during evacuation, a so called fractional dose model is used. This model describes the combined effects of the toxic gases carbon monoxide (CO) and carbon dioxide (CO_2), as well as the impact of reduced oxygen concentration (O_2). The model indicates the sum of contributions to the dose an individual can tolerate for each gas at a given concentration and exposure time. The total fractional dose is calculated in time steps and then accumulated. When the sum of the doses exceeds a certain value, self evacuation can no longer be assumed for all individuals. In this case a FID value of 0,3 is used the threshold value. ISO-13571:2012 have been used for calculation the number of fatalities depending on the FID value. (SS-ISO 13571:2012 Livshotande parametrar i händelse av brand - Vägledning för bedömning av tiden till kritiska förhållanden vid brand,, 2012)

Simulation descriptions

A totalt of four different egress simulations were conducted as described below in *Table 4*. Except for the parameters outlined in *Table 4*, the inputs followed parameters shown in *Table 3*.

Table 4 Evacuation simulation descriptions

Evacuation simulation	Constant K	Minimum walking speed
Sim_A_1 (Base scenario)	3	0,2 m/s
Sim_A_2	8	0,2 m/s
Sim_A_3	3	0,4 m/s
Sim_A_4	8	0,4 m/s

RESULTS

The results from the fire simulations show that smoke spread is extensive downstream throughout the simulation. Once the fire grows in intensity, the backlayering increases. However, smoke does not reach the North portal.

Exposure to toxic gases

The maximum toxic gases FID, average egress time, number of individuals with FID over 0,3 and number of fatalities for each of the four egress cases are shown in *Table 5*.

Table 5 Analysis results

Scenario	Description	Avg. egress time [min][1]	Max toxic exposure FID	Number of personens FID > 0,3	Max time with visibility < 3m [min]	Consequence (Fatalities)
Sim_A_1	Constant K: 3 Minimum walking speed: 0,2 m/s	26	1,64	8	18	5
Sim_A_2	Constant K: 8 Minimum walking speed: 0,2 m/s	13	0,06	0	5,5	0
Sim_A_3	Constant K: 3 Minimum walking speed: 0,4 m/s	18	0,28	0	11	0
Sim_A_4	Constant K: 8 Minimum walking	13	0,07	0	5,5	0

	speed: 0,4 m/s						
[1] Average egress time according to the evacuation simulations							

Radiation and temperature exposure
For prolonged exposure, which can be equated to queuing for more that a few minutes, a threshold value of 2,5 kW/m^2 is applied as previously described. This corresponds to the radiation from fire gases at approximately 200 °C.

Results from fire simulations indicate that ceiling temperatures approaching these levels only occus after approximately 15 minutes into the fire development and above the fire affected train car. At this point, high radiation levels from the fire are localized, and the evacuees have already left the area near the fire.

Results also indicate that a temperature of 80 °C at a height of 2 m above the walkway is only evident beyond the proximity of the incident car after approximately 20 minutes. At this time, occupants have left this area and are therefore not exposed to temperatures above 80 °C.

DISCUSSION

The results from the egress simulations shows the significant impact the constant K can have. This highlights the importance that lighting configuration can have on evacuation. By changing the constant K , used for calculating visibility, to 8 instead of 3, the FID values are significantly lower (see Sim_A_1 vs. Sim_A_2, and Sim_A_3 vs. Sim_A_4). This emphasizes the importance of the engineer understanding the prerequisites for lighting and other visual way-finding aids within each tunnel project.

The results also indicate that an increased minimum walking speed can have a great impact on evacuation. When increasing the minimum walking speed from 0,2 m/s to 0,4 m/s, for simulations with a constant K of 3, the maximum toxic FID is significantly lower (Sim_A_1 vs. Sim_A_3). This highlights the importance of having an environment where navigation is possible with a limited risk for collisions or falls that lead to injuries.

The impact of the increased minimum walking speed is however not evident when comparing simulations with a constant K of 8. This since the visibility that evacuaees experience remains above 2 metres due to the relatively short evacuation times. If a greater occupant load was modelled, leading to an extended evacuation time, the impact of increasing the minimum walking speed is expected to be greater.

Based on the results, it is clear that the designer is faced by several challenges when analyzing egress. These challenges are both connected to inputs to use for evacuation simulations but also regarding which requirements to be set for the tunnel environment. Some of these challenges are deeper discussed below.

- **How should the constant K (used for calculating visibility) be assessed?**
  A constant K is chosen based on the lighting within the tunnel. A constant K of 3 is typically used for light-reflecting surfaces and a constant K of 8 is used for light-emitting surfaces. In many existing rail tunnels, the lighting configuration consists of light-emitting items placed approximately 25 m apart. Hence, within a heavy smoke-filled environment, e.g. visibility <3 m, these items will not be seen. Therefore, a constant K of 3 has historically been used when conducting egress analysis. Based on newer rail tunnels often being equipped with more sufficient lighting, e.g. continuous light strip, it is important that the designer takes this into account when selecting constant K. It can also be mentioned that contrasts have an impact on how a human eye distinguish a sign. Hence, a handrail, or walkway, being in clear contrast to a tunnel wall impose usage of a greater constant K. Also a greater illumination flux directed at the walkway, handrail or directly at the evacuee is of importance.

- **How should the walking speed be assessed based on the occupants' trust for the tunnel environment?**
  The answer to this question is not fully given in current research. The main aspect affecting this is the configuration of the walkway and a tactile guidance. Occupants are expected to walk faster if being comfortable with the layout of the walkway without fear for serious injury from fall or collision. Factors expected to lead to a greater walking speed includes;

  - walkway being straight throughout the tunnel,
  - no height differences between the walkway and the surroundings being present,
  - the walkway being even,
  - no obstacles narrowing the walkway being present, e.g. signaling systems,
  - and a continuous handrail being provided.

  The tunnel in the case study herein is assumed to be provided with the above. Therefore a minimum walking greater than 0,2 m/s, as suggested in ISO/TS 21602:2022 (ISO/TS 21602:2022, 2022) and Fridolf et al. (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2016), was used for some of the cases. A minimum walking speed of 0,4 m/s was deemed reasonable, as the factors above were assumed, and the walking speeds below 0,4 m/s have only been observed in experiments containing obstacles in the form of cars in a road tunnel or stairs. However, a scientific basis for a precise effect of the parameters above or the explicit use of walking speeds greater than 0,4 m/s does not exist. If comparing to the Gudvanga accident, where a family evacuated with a walking speed of approximately 1,5 m/s (8 km in 90 minutes), a walking speed of 0,4 m/s is still deemed conservative.

- **How should walkways and lighting be designed?**
  The answer to this question depends on who is deemed suitable for selecting walkway and lighting design. In the end, the AHJ (Authority Having Jurisdiction) will decide the minimum requirements. However, an engineer responsible for evacuation assessment, should have an idea of how improvements can be cost-effective.

It should be noted that no explicit impact of irritant smoke is studied within this paper. Limited data exists regarding experiments in irritant smoke due to ethical restrains. Therefore, the impact on occupants evacuating is uncertain.

CONCLUSION

During design of rail tunnels, focus is often around design fires. Design fires play a major role in the design of fire-life safety systems for a rail system and can be the principal factor responsible for the sizing of the ventilation system or distance between exit routes. However, factors affecting walking speed during evacuation is another important parameter with uncertainties in need of focused research and guidance on selecting design values.

It is clear from the literature review provided that data from evacuation tests performed within a rail tunnel environment are few. Therefore, many of the input parameters being used within evacuation calculations are based on test and research inheriting from buildings and road tunnels.

The study has shown that enhanced design and refined analysishave the potential of providing more preferable results in terms of smoke exposure. Meaning that the distance between egress points can be longer, leading to great cost-savings. However, it is also evident that a refined analysis gives the engineer greater challenges connected to selecting both inputs and requirements.

The study focuses on impact of toxic exposure, due to a varied constant K and increased minimum walking speed given more preferable egress environments. Many simplifications have been made within the analysis and the extent of the study is rather narrow, e.g. only one fire sizes has been studied. Hence, there is a clear need for sensitivity analysis and further research. Some parameters deemed suitable for sensitivity analysis include a varying walkway width and different fire parameters, e.g. heat release rate. Further research is needed regarding the impact on walking speeds in reduced visibility due to exposure of irritants, varying age of evacuees, functionality impairment and walkway surface.

REFERENCES

1. Swedish Transport Agency, ”Transportstyrelsens föreskrifter och allmänna råd om personsäkerhet i tunnlar och plattformsrum för tunnelbana och spårväg, TSFS 2017:119”.
2. ISO/TS 21602:2022, Fire safety engineering - Estimating the reduction in movement speed based on visibility and irritant species concentration, ISO, 2022.
3. K. Fridolf, D. Nilsson, H. Frantzich, E. Ronchi och S. Arias, ”Människors gånghastighet i rök: Förslag till representation vid brandteknisk projektering,” SP Sveriges Tekniska Forskningsinstitut, Borås, 2016.
4. K. Fridolf, K. Andrée, D. Nilsson och H. Frantzich, ”The impact of smoke on walking speed,” John Wiley & Sons, Ltd, Lund, Sweden, 2013.
5. E. Ronchi, P. Colonna, S. M. V. Gwynne och D. A. Purser, ”Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models,” Springer Science + Business Media, LLC, The United States, 2012.
6. K. Fridolf, E. Ronchi, D. Nilsson och H. Frantzich, ”The representation of evacuation movement in smoke-filled underground transportation systems,” Elsevier Ltd, Lund, Sweden, 2019.
7. Accident Investigation Board Norway, ”Report on Fire in a Heavy Goods Vehicle in the Gudvanga Tunnel on the E16 road in Aurland on August 2013,” Lilleström, 2015.
8. A. Y. Yamada T., ”Visibility and Human Behaviour in Fire Smoke,” i *Handbook of Fire Protection Engineering, Fifth ed*, New York, Springer, 2016.
9. SFPE Handbook of Fire Protection Engineering, 5th edition, Society of Fire Protection Engineers, 2016.
10. Boverket, ”Boverkets ändring av verkets allmänna råd (2011:27) om analytisk dimensionering av byggnaders brandskydd; BFS 2013:12 - BBRAD 3,” Boverket, 2013.
11. K. H. &. A. E. Niclas Åhnberg, ”Report 2017:243 Utrymningsdimensionering vid upphöjda gångbanor,” Swedish Transport Administration, Borlänge, 2017.
12. G. Mulholland, ”SFPE Handbook of Fire Protection Engineering, chapter Enclosure Smoke Filling and Fire-Generated Environmental Conditions, 5th edition,” New York, Springer, 2016..
13. ”SS-ISO 13571:2012 Livshotande parametrar i händelse av brand - Vägledning för bedömning av tiden till kritiska förhållanden vid brand,,” Swedish Standards Institute, Stockholm, 2012.