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Strategies for egress from trains on fire in ventilated tunnels

Michael Winkler

Promoters: Dr Ricky Carvel and Dr Stephen Welch

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Michael Winkler

Contact: miwinkler@gmx.at

Abstract

This thesis focuses on strategies for egress from burning trains in tunnels for immediate stop situations where no rescue station can be reached. There is a general debate among fire engineers, fire service personnel and tunnel operators about different egress strategies and how to facilitate the tunnel ventilation in emergency situations.
The main goal was to rank different egress options and to provide qualitative guidance on feasible egress options in ventilated tunnels.
The analysis is based on CFD simulations and a toxicity model, capable of predicting the fire effluents data and its effect on passengers, respectively.
Based on this research's findings, forced airflows in combination with simultaneous evacuation should only be used when the fire is located on the power car or the first adjacent carriage. In case the fire is located in intermediate carriages or if the fire's location is unknown, no forced airflows should be introduced. No general recommendation could be made for phased evacuation processes, as tunnel specific decisions between tunnel operators and train manufacturers have to be made regarding the feasibility of these processes.

Zusammenfassung (German)

Diese Abschlussarbeit befasst sich mit Evakuierungsstrategien aus brennenden Personenzügen, die im Tunnel umgehend zum Halt kommen. Hierbei kann keine Rettungsstation erreicht werden.
Es gibt zurzeit eine Debatte zwischen Brandschutzingenieuren, den Feuerwehren und Tunnelbetreibern über verschiedene Evakuierungsstrategien, und wie man die maschinelle Tunnelbelüftung in solchen Situationen einsetzt. Das Ziel dieser Arbeit war es verschiedene Evakuierungssituationen nach deren Umsetzbarkeit zu reihen und qualitative Empfehlungen zu geben.
Die Analyse basiert auf numerischen Brand- und Strömungsberechnungen (CFD) in Kombination mit einem Toxizitätsmodell, wobei das CFD die entstanden Brandgase, das Toxizitätsmodell deren Effekte auf Passagiere prognostiziert.
Die Ergebnisse deuten darauf hin, dass maschinelle Belüftung bei gleichzeitiger Evakuierung aller Passagiere nur verwendet werden sollte, wenn der Antriebswagen oder der angrenzende erste Wagon in Brand steht. In Fällen, in denen der Brand sich in anderen Wagonen befindet oder der Brandort nicht genau feststeht, sollte keine maschinelle Belüftung eingesetzt werden.
Es konnten keine allgemeinen Empfehlungen zu phasenweisen Evakuierungsstrategien gemacht werden, da tunnelspezifische Entscheidungen zwischen Tunnelbetreibern und Zugherstellern bezüglich derer Durchführbarkeit gemacht werden müssen.

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1. Introduction

Egress strategies play a key role for every emergency incident on trains and careful planning is required to perform a controlled and efficient evacuation. Train fire incidents in tunnels need special consideration because of the limited presence of egress options. However, there has been done little research on the interaction between tunnel ventilation procedures and egress strategies. As ventilation procedures can direct smoke in directions which may be in favour of evacuating passengers or not, these two components are closely interdependent.

In general, burning trains can either drive out of a tunnel, drive towards a specific rescue station or immediately stop within the tunnel. This immediate stop scenario is the most challenging one in terms of passenger egress, as the evacuation location is not in the open or within a specially constructed rescue station. Passengers have to evacuate through cross passages into an adjacent tunnel or a refuge area. This thesis will focus on immediate stop situations and compare the tenability conditions for different scenarios. Fire and ventilation conditions will be varied and possible evacuation strategies will be analysed. The ultimate goal of this thesis is to rank different egress strategies in terms of hazardous exposure for passengers.

1.1 Definition of the problem

There is a general debate among fire engineers, fire service personnel and tunnel operators about different egress strategies for burning trains in tunnels and how to facilitate the emergency tunnel ventilation in these emergency situations (Kent Fire & Rescue Service, 2014).

In general, tunnel operators can make use of natural, unidirectional or bidirectional emergency ventilation procedures and choose between simultaneous or phased passenger evacuation.

'Natural ventilation' is the process in which no forced airflow is provided and smoke spreads to both sides of the fire. Natural ventilation is used in combination with simultaneous evacuations. The term 'unidirectional ventilation' is used within this thesis for scenarios with forced airflows in one direction only. When using unidirectional ventilation, simultaneous evacuation is carried out as well. 'Bidirectional ventilation' is used in respect to phased evacuation, in which one part of the train is evacuated while evacuation in the other part is temporarily put on hold. Once the first part of the train has been evacuated, the ventilation direction of the forced air flow is reversed. Hence, it is called bidirectional ventilation within this thesis.

In the past, when trains were powered by cars at the front and in the rear of the train, it was quite obvious how to set the ventilation direction for fires on those engines cars. Modern train development, however, has introduced the use of multi-traction units across the length of the train, which increases the number of potential fire locations, making the choice of ventilation direction less obvious. Passengers are now placed on both sides of the fire.

The question of whether to use simultaneous or phased evacuation strongly depends on the tenability within the tunnel and the train environment. The concept of phased evacuation requires passengers in carriages downstream of the fire to wait until the upstream part of the train has been evacuated and the ventilation direction is reversed (Kent Fire & Rescue Service, 2014). The build-up of smoke within the carriages in the downstream direction of the fire through gaps, cracks or other openings of the carriage could expose the passengers to a smoky environment for a considerable amount of time. Here, the fact that human behaviour plays a key role in evacuation strategies is somewhat neglected and, as a consequence, phased evacuation routines may not be the preferred solution for egress problems on trains.

An incident in the London Underground's Holland Park Station illustrates how people react when metro carriages start to fill up with smoke. A brake fault caused small amounts of smoke and fumes to enter the carriages and passengers desperately tried to open the doors and climb out of the carriages. The lack of real-time information on what was happening and the uncoordinated behaviour of the train staff had an additional impact on the passengers' behaviour (BBC, 2013) (YouTube, 2013).

This incident has shown that the presence of little smoke can cause a reaction of fear, which in turn can lead to a flight response of passengers. Therefore, phased evacuation procedures might not be the best option in many situations. Although human behaviour plays an important role as well, this thesis focuses on physical affects by fire effluents.

As the use of emergency ventilation procedures for facilitating egress strategies has not been studied thoroughly[1], this thesis aims to elaborate alternative approaches.

1.2 Objective

The objective of this thesis is to develop strategies for egress from burning trains in ventilated tunnels with or without help of emergency ventilation procedures. Conditions within the carriage and the tunnel enclosure will be assessed and compared for various fire scenarios. A final ranking should give qualitative guidance on different egress scenarios.

1.3 Organization of the thesis

Chapter 2 provides background information regarding tunnels, trains and fires in tunnels and important factors that come along with them.
Chapter 3 describes the factors that influence the egress situation, determines where the conditions in the tunnel have to be assessed and illustrates the modelling approach. Additionally, the post-processing of data is explained.
Chapter 4 presents the research results regarding fire effluent data and hazardous exposure of evacuees. A general ranking is established and variations in fire effluent data is analysed in respect to the ranking.
Chapter 5 summarizes the findings and presents the main conclusions for tunnel operators and train manufactures in regard to feasible egress strategies.
Chapter 6 contains acknowledgments to friends and professors who supported me along this thesis.
Chapter 7 lists all the references used.
In the **Annexes**, egress time estimates, additional fire data, a grid independence check and FDS input data can be found.

[1] To the best of the current knowledge, no information could be found in the literature on how to use emergency ventilation procedures for facilitating egress strategies.

2. Background and theory

After a consolidated overview of two tunnels and their ventilation systems, fire dynamics in tunnels and train technology, a brief summary of egress strategies will be given. Hereby, this theoretical part will describe the general topics of this thesis.

2.1 Tunnel and ventilation

Long transit tunnels, like the Channel Tunnel (50.45 km) or the Gotthard Base Tunnel (57 km), fall into the category of bored tube tunnels with an oval or circular profile (Carvel & Both, 2011).

Taking the Channel tunnel as an example, two single track running tunnels are separated by a smaller service tunnel. Figure 1 shows the typical tunnel set-up. The three bores are connected every 375 m via cross passages, which can be used during an evacuation. A walkway next to the train enables passengers to reach the cross passages. Apart from the normal ventilation system, which is used for the everyday provision of fresh air, a supplementary ventilation system is available to control smoke and heat. This system is reversible and can establish a longitudinal airflow of 100 m^3/s within the tunnel in either direction. In case of a fire, the normal ventilation system pressurizes the service tunnel in order to prevent smoke ingress from the incident tunnels to the evacuation route. Additionally, a ‘bubble effect’ around the cross passages is created which should clear the cross passages’ entrance area from smoke and make the exit visible. The rail control centre is able to remotely control the rail signalling system, the ventilation systems and the cross passage doors. Radio and telephone contact with the trains is provided as well (Channel Tunnel Safety Authority, 1997).

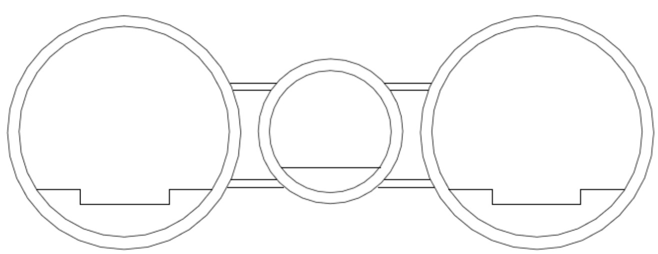

Figure 1 Tunnel cross section

The Gotthard Base Tunnel only has two running tunnels. In immediate stop situations, a safe location can be reached via cross passages. They are provided after every 325 m. A walkway of 2m in width runs next to the train exit doors and leads to the cross passages. The non-incident tunnel is supplied with fresh air in order to prevent smoke entering from the incident tunnel. In contrast to the Channel tunnel, where longitudinal air flow is used to direct the smoke into a certain direction, tunnel operators of the Gotthard Base Tunnel do not facilitate any ventilation in the incident tunnel and let the smoke stratify, a strategy often referred to as 'natural ventilation'. Once the evacuation phase is completed, smoke is guided into a specific direction for fire fighting purposes (Rudin, 2000) (Busslinger & Portmann, 2005) (Busslinger, et al., 2008).

2.2 Fire dynamics in tunnels

Generally speaking, fires behave differently in tunnels than in the open or in compartments such as flats. Due to the tunnel enclosure and other influencing factors, like ventilation systems, fires in tunnels require special consideration. Ingason (2011) explains in his research that an increased heat feedback from the tunnel and smoke to the fuel source leads to higher heat release rates of the fire. Compared to fires in the open, train carriage fires lack the availability of oxygen which leads to higher degrees of incomplete combustion. Natural or forced air flows can interact with the fire, which in turn can enhance the fire due to the supply of additional oxygen. On the other hand, airflows can direct heat and smoke from the fire area towards the downstream direction (Ingason, 2011).

Not only forced ventilation influences the airflow within a tunnel. Effects like the stack or piston effect are caused by different conditions at the tunnel portals and moving vehicles, respectively. Ventilation velocities fall into three groups, each with a different impact on egress procedures (Ingason, 2011).

- Low ventilation velocities (0−1 m/s) lead to the highest stratification of smoke in the tunnel environment and smoke spreads to both tunnel directions. The smoke cools down further down the tunnel and mixing with the cold layer is increased in this region.
- Medium ventilation velocities (1−3 m/s) direct the smoke mainly in one direction, but backlayering might exist. Moderate mixing occurs and limited stratification is seen.
- High ventilation with velocities higher than the critical velocity (>3 m/s) prevents backlayering of smoke. However, stratification of smoke is non-existent and smoke is likely to be well mixed across the tunnel cross section.

2.3 Trains

Many different types of trains are operated in long transit rail tunnels. In the Channel Tunnel, for example, there are tourist shuttles, heavy goods vehicles, passenger trains and freight rains (Channel Tunnel Safety Authority, 1997). As this thesis is about egress strategies, this section focuses on passenger trains. Trains that are operated within the Channel tunnel are seen as representative trains for long transit rail tunnels.

A typical train consists of two power cars in the rear of the train (PC1, PC2), two end carriages (C1 and C18) and several intermediate carriages (C2 to C17). The trains have a length up to 450 m and a capacity of about 800 passengers (Société nationale des chemins de fer français, 2012).

Figure 2 Typical half train set-up – TGV[2]

As explained in section 1.1, parts of the train, with passengers on board, could be exposed to smoke during a phased evacuation procedure. The condition inside the

[2] All graphics (trains) are reproduced with permission of the copyright owner (cadforum.cz).

carriage therefore mainly depends on its construction. Although the International Union of Railways (2012) recommends high speed rolling stock to be built airtight, it cannot be excluded that smoke enters the carriage through gaps, cracks and other openings. This could especially be a problem for train sets of an older generation. Since 1996, after a fire on a heavy good vehicle, during which smoke entered the amenity coach, the Channel Tunnel Safety Authority (1997), for example, recommends that all new carriages which are brought into service should be smoke-tight. However, there is no requirement for this in any statutory train construction standard, so that carriages have to be seen as non-airtight. Even new train construction standards, such as the British Standard BS EN 45545 (2013), require only specified parts of rolling stock vehicles to be fire-resistant. Long transit relevant rolling stock vehicles fall into the design category N of this standard. If these are operated in tunnels with an operation category 3 (OC3, long tunnels) they require the following fire-resistant parts (excerpt).

- Between various underfloor technical cabinets and the passenger area: E15, I15
- Between adjacent passenger areas and inside luggage containers E15

These criteria are assessed based on the principles in EN 13501-2 that allow for cracks, openings and even sustained flaming after the given required fire resistant time. In conclusion, carriages cannot be seen as airtight and have a tested fire resistance only in certain parts of the train. Any other areas are assumedly non-fire-resistant.

2.4 Current egress strategy

The following part summarizes current egress strategies from burning trains in tunnels. Here, the procedures of the Channel tunnel are seen as representative for long transit tunnels (Kent Fire & Rescue Service, 2014).

The channel tunnel adopts a drive-through policy for fires on board of passenger trains. Train drivers are advised to drive towards a rescue station or out of the tunnel, if possible. A running capability in emergency situations of 30 minutes is required for trains that operate within the Channel tunnel. This thesis, however, investigates immediate stop situations only. Trains could, among other possibilities, come to a forceful halt due to mechanical failure, rupture of brake lines or human error. In respect to this thesis, evacuation procedures of unconfined fires are presented. These represent situations in which the fire in not contained within the carriage and smoke ingresses into the tunnel environment. Only in these situations, tunnel operators make use of the ventilation system in order to direct the smoke in certain directions.

In general, passenger trains have a staff of at least five people to initiate and manage the evacuation. As the first line of response on the part of the fire services is not present within a considerable amount of time, the train's staff members make the decisions on how to carry out the evacuation. This is done according to regulations and in cooperation with the rail control centre which should cover all possible scenarios. As not all scenarios can be presented at this point, two fundamental egress strategies for controlled and uncontrolled stops are described.

If the train cannot reach a rescue station or reach the open, the primary goal is to stop the train in alignment with the cross passages (controlled stop). Train end exit doors are protected by the 'bubble effect' of the cross passages, which involves the provision of additional air into the incident tunnel. This should prevent smoke ingress into the cross passage and clear the area around the cross passage from any smoke. In controlled stop situations, simultaneous evacuation is carried out and evacuees exit the train and access the cross passages through the train end doors. Staff personnel facilitates 'push and sweep' techniques to direct passengers along the train into the desired direction.

If the train cannot stop in alignment with the cross passages, the egress scenario becomes more challenging, as this situation rules out the possibility of simultaneous evacuation in certain situations. An 'uncontrolled stop' would be possible for every full-length train (length of a cross passage span), as well as for trains with reduced length. Such events require a phased evacuation in which one part of the train is evacuated while evacuation in the other part is temporarily put on hold. Once the first part of the train has been evacuated, the ventilation direction of the forced air flow is reversed. In uncontrolled stop situations, it is necessary to consider an egress from other doors that are in the vicinity of a cross passage.

2.5 Acceptable conditions in tunnels

Conditions inside the tunnel environment and inside the train carriage can affect the passengers' ability to evacuate and even cause incapacitation or death. Therefore, tenability criteria have to be maintained and dose maxima have to be prevented during the evacuation process. Visual obscuration, temperature, radiation, as well as oxygen, carbon dioxide and carbon monoxide concentrations will serve as input parameters for a fractional effective dose model (section 3.3.8). This model estimates the physical effects on evacuees when they are exposed to a hazardous atmosphere inside of the tunnel or carriage. The individual effects and tenability criteria of these parameters are discussed below (Purser, 2002).

Visual obscuration affects the exit choice, the walking speed, as well as the ability to evacuate within the tunnel environment. A maximum smoke density of 0.08 OD/m should not be exceeded within buildings. This equals a visibility of 10 m. Charters (2011), however, claims that a visibility criterion of 5 m is appropriate for single track rail tunnels. Evacuees escape via a walkway − which is equipped with a handrail within the tunnel − until they reach a cross passage. It is considered easier for evacuees to reach the cross passage in a tunnel, compared to finding their way through a building.

Heat effects can arise in one or more ways, such as hyperthermia, skin burns and respiratory tract burns. These types can arise within tunnel environments as evacuees could have skin contact with or breath in hot smoke.

Hyperthermia, also known as heat stroke, is a result of exposure to raised temperatures for longer than 15 minutes. Evacuations carried out in high humidity tunnel environments have the potential to cause hyperthermia, as temperatures can exceed 80°C. Estimated egress times show that this time span of 15 minutes can be exceeded in certain situations (Annex A1). A temperature of 80°C could be exceeded, for example, if the fire is located close to a train exit door. Skin burns result when heat fluxes cause the skin to heat up above 44.8°C. During an evacuation, convective and radiative heat transfers are of importance and have tenability limits of 120°C and 2.5 kW/m², respectively. When evacuees breathe hot air, respiratory tract burns can arise when temperatures of humid air and smoke exceed 100°C. Mixing processes occur as evacuees escape further down the tunnel and when a layered smoke propagation is not maintained. As a result, evacuees could suffer from respiratory tract burns.

Low oxygen levels in the range of 14.4% to 11.8% harm evacuees physically and mentally during the evacuation progress. If the levels drop below that range, train

passengers can be severely impaired and lose consciousness. However, the effect as a dose over time has to be considered. As escaping passengers could be exposed to continuous small reductions of oxygen levels, this has to be taken into account as well.
The accumulation of CO as COHb in the body depends on the gas concentration, the breathing rate and the exposure time. Carboxyhaemoglobin (CoHb) is a product that forms in the blood of evacuees when carbon monoxide is breathe in and disturbs the delivery process of oxygen to the body (Stec & Hull, 2010). While escaping down the tunnel, evacuees are likely to lose consciousness when the COHb level in their blood reaches 30%.
The combustion product carbon dioxide causes dizziness and loss of consciousness in the range of 6 to 7%. The uptake as a dose over time has to be considered as well.
Further discussion on the fraction effective dose model is presented in section 3.3.8.

3. The egress challenge in tunnels

Based on different factors that can affect the egress situation, this chapter elaborates on various physical set-ups and conditions in immediate stop situations. Next, representative fire scenarios will be studied in detail. Finally, possible egress strategies will be formulated and the analysis method, including input parameters, will be presented.

3.1 Factors influencing the egress

Train, fire and tunnel characteristics affect either the conditions inside and outside of train carriages during a fire, the exposure times for passengers in poor conditions, or both. This section aims to identify the most influencing factors that affect the possibility to carry out an evacuation.

3.1.1 Train factors

Train characteristics exert a key influence on both the fire evolution and the egress progress. First, the final train location depends on the driver's possibility and ability to stop the train at a specific location in the tunnel. For immediate train stops this can be either with alignment of the train's end door with a cross passage, which is called 'controlled stop', or without alignment, which is named 'uncontrolled stop' (Capote, et al., 2012).

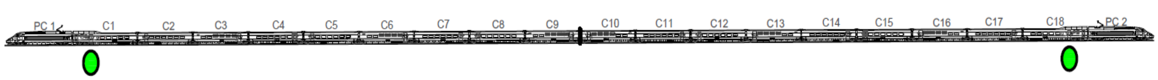

Figure 3 Controlled stop situation

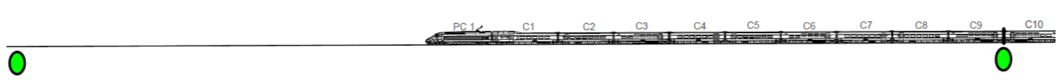

Figure 4 One possible uncontrolled stop situation

Next, the train length affects the potential fire load, the possible number of passengers and the ease of egress. Shorter trains could, depending on distances between cross passages, stop at locations where no train door is aligned with any cross passage. This affects the travel distance for passengers and subsequently the travel time under poor conditions.

Further characteristics which influence both fire evolution and the egress itself are the train's active and passive fire protection features. Train elements with a fire resistance can prevent smoke and fire spread inside the train. Moreover, active fire protection systems can shorten the detection time or even extinguish the fire.

3.1.2 Fire factors

The fire characteristics are primarily concerned with the fire's location, its size and the type of materials involved.

First, one needs to distinguish between a fire inside or outside of the train compartment. If the fire is inside, passengers are immediately affected and have to evacuate to adjacent carriages. Kumm (2010) points out that carried fire load, such as luggage and bags, can make up 50% of the train's total fire load.

On the other hand, if the fire is outside the train, passengers are unlikely to discover the fire soon and are less affected by it in its early stages. Possible external fire locations can involve traction units, electric brakes, transformers, auxiliary converters, batteries and their chargers. Generally, these components can be mounted over the entire length of the train under the carriages (Siemens AG, 2012).

Furthermore, the horizontal fire location plays a role for organisational matters in terms of egress procedures and in adjusting the direction of the tunnel's emergency ventilation system (if used), as shown in Figure 5.

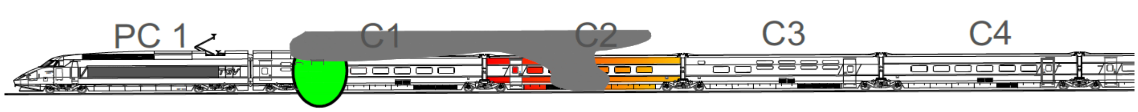

Figure 5 Fire on C2 affecting a cross passage in a controlled stop situation

The amount of materials, their properties and the supplied air determine the fire's size, its growth rate and the production of combustion gases. These are the dominant factors which determine the tenability conditions during the evacuation.

3.1.3 Tunnel factors

There are several tunnel characteristics which have both an influence on the fire development and the egress process.

The tunnel's geometry, its slope and the emergency ventilation system can affect the fire development, the smoke propagation and the possibility to facilitate certain egress strategies.

The available space between the cross passages determines the travel time for passengers and therefore also the time they are likely to be exposed to poor conditions.

3.2 What could happen?

As presented in the previous sections, there are many influencing factors, which vary from one incident to another. This section aims to choose representative factors for assessing the conditions inside of the carriages as well as the tunnel environment. In addition, the most influencing factors regarding the amount of time that passengers are exposed to poor conditions will be specified. Both the conditions and the exposure times are used in subsequent chapters to test egress strategies with regard to their feasibility.

3.2.1 Conditions in carriage and tunnel

It is difficult to account for every eventuality within this thesis, as time and resources are scarce. Therefore the most influencing factors are chosen and possible set-ups for immediate stop situations are determined. The following physical factors influence the conditions inside of the carriage and in the tunnel environment the most.

- Type of ventilation (natural, unidirectional, bidirectional) with its corresponding fire size
- Fire location horizontally (power cars or any carriage)

When choosing unidirectional ventilation, only the conditions in the tunnel downstream of the fire have to be assessed. For a given ventilation velocity, the conditions in the tunnel environment depend on the fire location and the fire size. As unidirectional ventilation is always connected to simultaneous egress procedures, the conditions inside of the carriage are not of major interest.

In case the ventilation system fails or if tunnel operators choose not to facilitate the use of the ventilation system, both train parts are affected by fire and smoke.
The conditions in the tunnel environment once again depend on the fire's location and size. This specific situation requires a simultaneous evacuation.
If the decision is to facilitate bidirectional ventilation with a phased egress strategy, tenable conditions inside of the carriage are important. Conditions in the tunnel environment are equal to those in case of unidirectional ventilation. This assumption can be made up until the point in time when the ventilation direction is reversed. Using information about the conditions during unidirectional ventilation, it is possible to evaluate the build-up of smoke inside of the carriage during the bidirectional waiting time for passengers.

Factors which have not been addressed, like some train and tunnel characteristics, will be defined as representative values in later sections. These include a representative train and tunnel set-up. A full set of scenarios is given in Figure 6. The tunnel can be operated with natural or unidirectional ventilation and the fire's location can be on one of the power cars or on any other carriage.

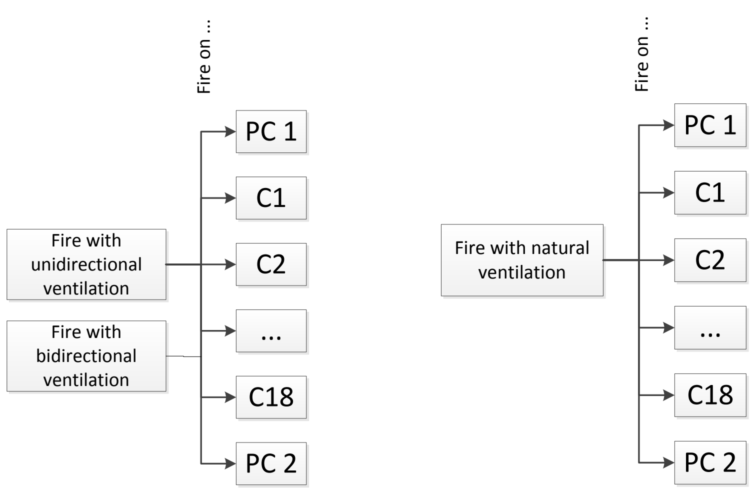

Figure 6 Possible scenarios for assessing conditions in the tunnel environment

In terms of assessing the conditions inside of the tunnel, unidirectional and bidirectional scenarios can be grouped together, since the same fire development and smoke spread can be expected (20 scenarios in total). Natural ventilated cases have to be treated separately (20 scenarios). As those forty scenarios for assessing the ventilation conditions cannot be addressed in the timescale of this project, a small subset of interesting and representative scenarios has been chosen for further study. In order to compare the conditions in the tunnel between the different ventilation scenarios, the same fire places are assessed in all cases. As mentioned previously, findings from the unidirectional scenarios are used in order to assess conditions inside the carriage during the bidirectional waiting time.

Fires inside of the carriage are likely to be reported via the train's internal emergency communication system. Additionally, the driver could make use of CCTV cameras to confirm the fire's location. A fire in one of the traction units is located by a fire detection system and the location of the activated detectors is communicated to the train staff (BS EN 45545, 2013). As the fire's location is likely to be known, this information can be used to determine the initial ventilation direction for uni- and bidirectional ventilation scenarios. It is assumed to be started in a direction that exposes fewer passengers to smoke. This means that fires on power car 1 (PC 1) up until carriage number 9 (C9) result in an airflow in driving direction. Fires on carriage number 10 (C10) up until power car 2 (PC2) result in an airflow against driving direction, as shown in Figure 7. PC1 is assumed to be the front power car.

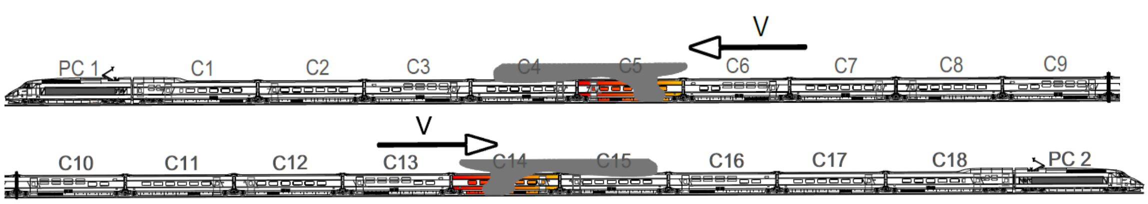

Figure 7 Choice of initial ventilation direction with mirror effect between C9 and C10

The initial ventilation direction is therefore independent of a controlled or uncontrolled stop. Hence, the train can be mirrored between carriages 9 and 10, and the total amount of scenarios, in order to assess the conditions in the tunnel, is reduced by half.

Next, scenarios which involve the power cars and the first adjacent carriages (C1 and C18) can be left out, as they can be seen as easy and obvious fire scenarios. Smoke emerging from the power car is kept away from passengers by means of the emergency ventilation system when facilitating unidirectional ventilation. If no ventilation is switched on, smoke spreads to both sides of the tunnel. Fires involving the first adjacent carriages, C1 and C18, are seen as similar scenarios. A fire on carriage 1 (C1) is shown in Figure 8. Passengers are likely to be evacuated towards the second carriage during the early stages of the fire. As there are more challenging scenarios, fires on PC1, PC 2, C1 and C18 are excluded and seen as non-representative.

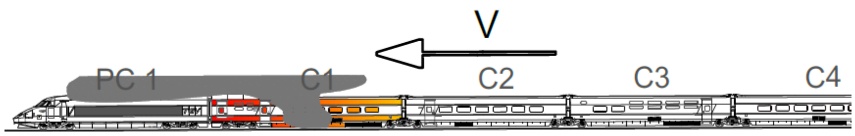

Figure 8 Fire on carriage 1 with a unidirectional ventilation direction

Three characteristic fire locations on the remaining part of the train are chosen. This is seen as reasonably accurate to assess conditions from the train exits to the cross passages. Figure 9 shows the set of representative scenarios which is used to assess conditions in the tunnel environment.

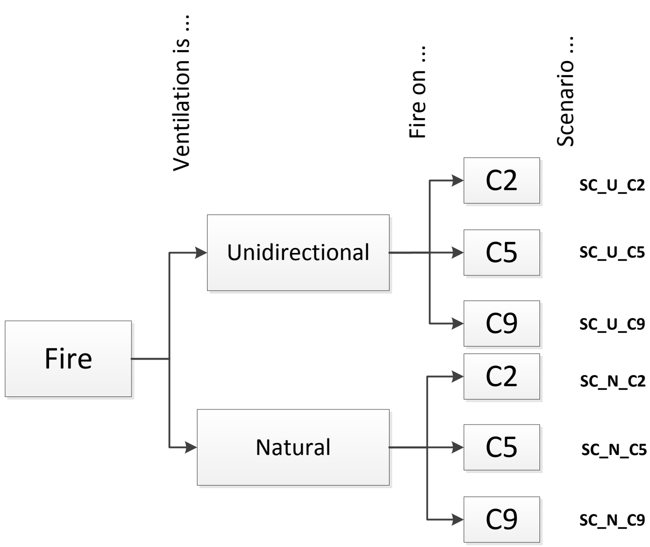

Figure 9 Representative fire scenarios

A fire originating from carriage 2 (C2) is seen as the first challenging scenario as it confines passengers on carriage 1 (C1). Although this scenario affects a limited number of passengers, the vicinity to the fire with high smoke concentration might be challenging. A direct smoke plume contact with the train exit door could expose evacuees to high temperatures and high combustion gas concentrations. On the other hand, there is a possibility that the smoke flows above the train exit door. Figure 10 shows fires on carriage 2 (C2) with unidirectional and natural ventilation.

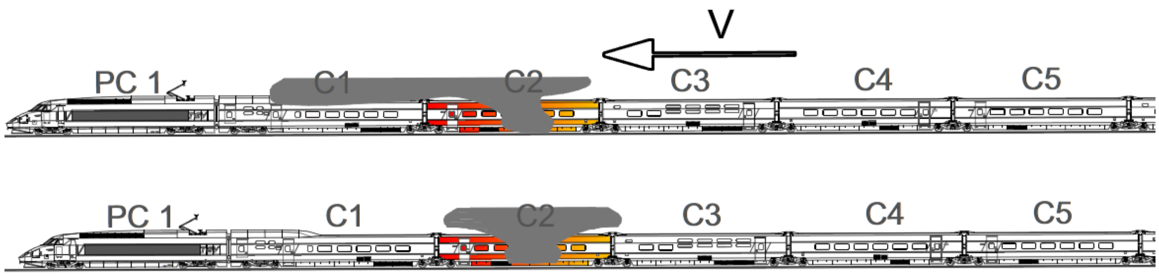

Figure 10 Fire on carriage 2; unidirectional ventilation (top), natural ventilation (bottom)

Next, a fire on carriage 5 (C5) is considered as a representative fire location. It encloses passengers in four carriages in the downstream direction of the fire, in case of unidirectional ventilation, and spreads to both sides when using natural ventilation. This is visualized in Figure 11. The difference between a fire on carriage 2 (C2) and carriage 5 (C5) is that the exit door at carriage 1 (C1) is not directly adjacent to the fire and the smoke can mix until it reaches the door. To sum up, this scenario places more passengers at risk but the smoke at the exit door at carriage 1 (C1) is likely to be more mixed as the fire source is more distant to the train exit. However, the mixing process might take more than several carriages to occur completely.

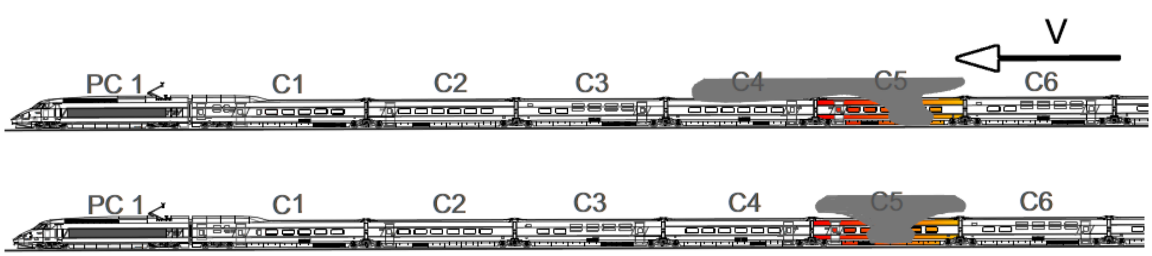

Figure 11 Fire on carriage 5; unidirectional ventilation (top), natural ventilation (bottom)

Finally, a fire on carriage 9 (C9) is chosen as a representative scenario as it places the highest number of passengers at risk. However, smoke concentrations are likely to be the lowest among the three scenarios at the exit doors in carriage 1 (C1) and carriage 18 (C18), since the exit doors are most remote from the fire origin and smoke can mix over the whole distance. Figure 12 shows the scenarios for the unidirectional and natural ventilation configuration.

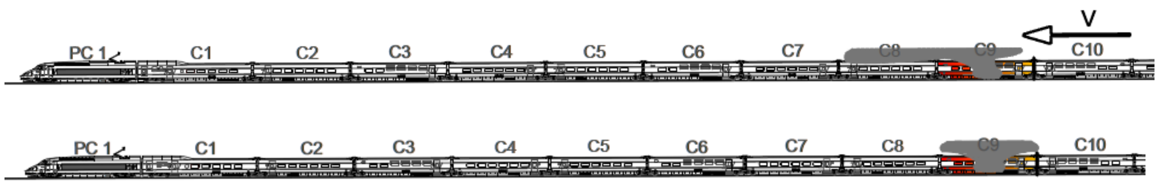

Figure 12 Fire on carriage 9; unidirectional ventilation (top), natural ventilation (bottom)

3.2.2 Egress paths and exposure times

This section presents factors which can affect the amount of time that passengers are exposed to conditions containing combustion products. Although not all factors influence the time in every scenario, the following factors are found to be influencing the egress path, the exposure time or both.

- Type of ventilation (natural, unidirectional, bidirectional)
- Train location (controlled vs. uncontrolled stop)
- Fire location horizontally (power car or any carriage)
- Conditions in the tunnel environment

In general, one can distinguish between exposure time inside of the carriage and exposure time in the tunnel environment. This next part elaborates on the three ventilation procedures in the context of exposure times.

For unidirectional ventilation the exposure time inside of the carriage is less important than the exposure time in the tunnel environment. Although smoke can ingress the carriage through door openings, concentrations in the tunnel environment are of major concern as passengers have to walk in the smoke logged tunnel environment. The time spent within the carriage depends on the location of the fire, as it determines how many passengers are affected. An illustration of the set-up inside of the carriages is shown in

Figure 13. Here, the train's position in the tunnel becomes irrelevant, as this only affects the travel time in the tunnel and not in the train.

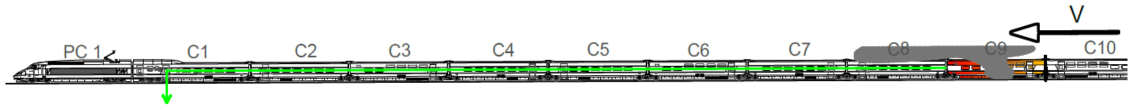

Figure 13 Unidirectional ventilation – egress path inside the carriage

For unidirectional ventilation, the time spent in the tunnel environment depends on the stop location of the train and the conditions inside of the tunnel, which can be seen in Figure 14. Jin (2002) points out that the walking speed in a smoke-logged environment slows down depending on the smoke's density and irritancy.

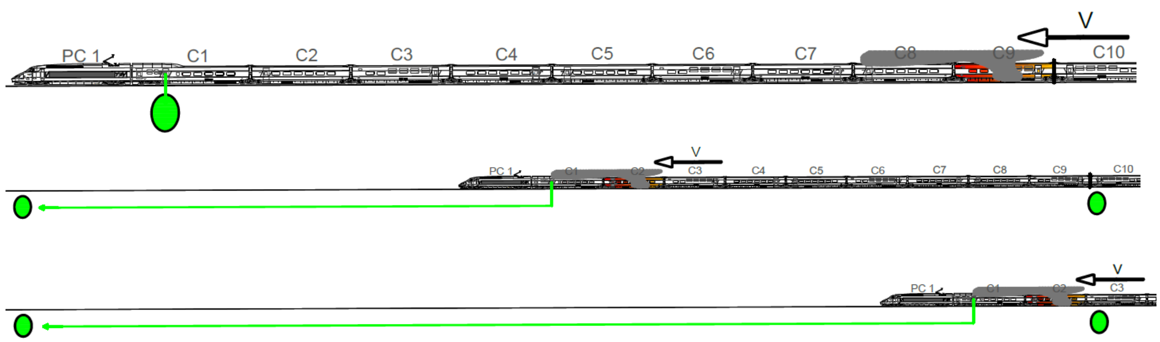

Figure 14 Unidirectional ventilation – egress path in the tunnel environment for controlled stop (top) and uncontrolled stops (middle and bottom)

When facilitating a natural ventilation procedure, smoke spreads in both directions of the fire. Consequently, both sides of the fire have to be evaluated. However, the same factors as in the previous case of unidirectional ventilation are of importance. The egress time within the carriage is affected by the location of the fire.

Figure 15 gives an overview of the egress path within the carriage, in direction of both train end doors at C1 and C18.

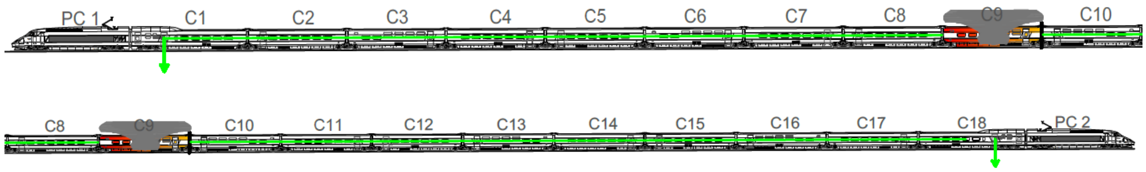

Figure 15 Natural ventilation – egress path inside the carriage

Once evacuees have reached the train exit doors, their egress path is continued in the tunnel environment. The egress time in the tunnel environment depends on the location of the train and the conditions. For a controlled stop, the train's exit doors are in alignment with the cross passages, resulting in short egress paths. Longer egress paths exist in uncontrolled stop situations for the other part of the train (C11-PC2), if the fire is located on carriages C2, C5 or C9, as presented in Figure 16.

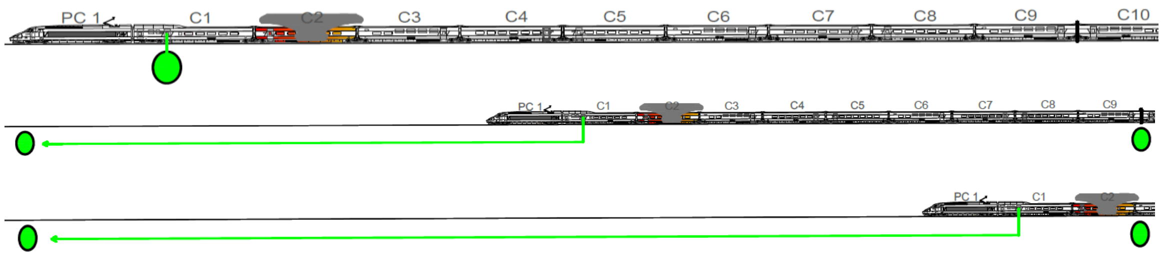

Figure 16 Natural ventilation – egress path in the tunnel environment for controlled stop (top) and uncontrolled stops (middle and bottom)

If the fire is located in carriages C10, C14 or C17, the egress path can be longer from the train's rear exit door, if the train stops in an unfortunate position. This can be explained by the mirror effect.

Although this analysis considers egress options from only the front and rear doors of the train, further investigation into using alternative exit doors should be carried out. In uncontrolled stop situations the end doors may not always be the best solution to facilitate the evacuation, as the egress path can be reduced in opening alternative exit doors.

When facilitating a phased evacuation with bidirectional ventilation, passengers do not exit the train into a smoke logged tunnel environment. Therefore, only the exposure time inside of the carriage is relevant. Passengers have to wait until the ventilation direction is reversed and tenable conditions in the tunnel environment have established. How long this takes depends on the fire's location, as passengers in the upstream part of the train have to evacuate first, but also on the capacity of the emergency ventilation system. Figure 17 shows the phased evacuation process when facilitating bidirectional ventilation.

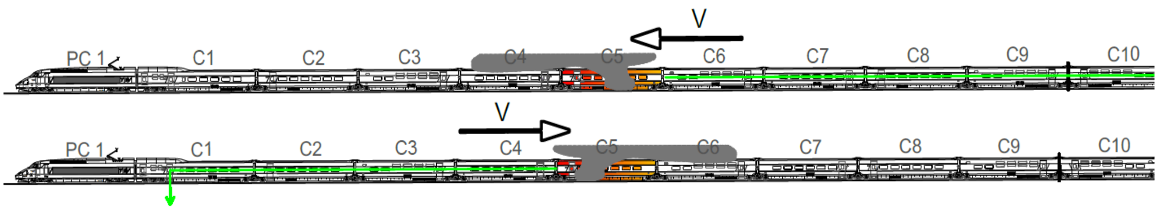

Figure 17 Bidirectional ventilation – egress path inside the carriage

3.3 Modelling approach

The following sections focus on the modelling objective, the choice of software and geometry configurations. Furthermore, the computational domain, the grid size and boundary conditions are defined.

Input files for the Fire Dynamics Simulator are presented in Annex A4 and Annex A5.

3.3.1 The flow problem

As mentioned in previous sections, a train inside of the tunnel with natural and forced airflows has to be modelled in order to assess the conditions in the tunnel. Hereby, the type of ventilation, the fire's location and its size affect the conditions both inside the carriage and the tunnel environment. In order to develop strategies for egress and to compare conditions for different fire scenarios, the following parameters have to be assessed in the tunnel enclosure (Purser, 2002).

- Carbon monoxide, carbon dioxide and oxygen concentrations
- Radiant heat flux
- Smoke temperature
- Optical density of the smoke

Once predictions for these time-dependent parameters are known, the toxicological effects on evacuees can be estimated. The physical set-up of a train inside of a tunnel in combination with forced ventilation is, in terms of modelling, challenging, as highly turbulent air flows are likely to occur. However, it is not necessary to model detailed fire dynamics to assess the desired approximate conditions. It is sufficient to use a model that provides time-dependent information on smoke mixing and smoke movement.

CFD models, and in this case Large Eddy Simulations (LES), allow to assess the desired time-dependent parameters and can cope with high velocity and temperature gradients (Rhodes, 2011). However, using a fine grid for the entire tunnel section is impossible in terms of the available computational power. Despite this limitation, it might be possible to achieve reasonable accurate values for assessing the desired parameters. A 25 cm grid size is implemented. Its use will be discussed in later sections of this thesis. A grid independence check is presented in Annex A3. The Fire Dynamics Simulator (FDS) is chosen as an appropriate (LES) simulation tool, as it is highly validated within the fire community and able to model the 3D and turbulent smoke movement (Rhodes, 2011) (Hu, et al., 2007). However, it has to be noted that this engineering tool has also its shortcoming. For example, FDS only accounts for one specific fuel type within the finite rate combustion model, which restricts the user's wish to represent the various fuel types involved in real fires (National Institute of Standards and Technology, 2013). Once the fire goes into a ventilation-controlled regime, the prediction of CO, for example, is highly uncertain, even when more sophisticated combustion models are used (Floyd & McGrattan, 2008). Further on in this thesis, an engineering approach to achieve more reliable CO data will be presented. Another limitation involves the fact that only once soot yield can be specified over a wide range of combustion regimes. However, this is not seen as a key limitation for this thesis. In further sections, this thesis will provide an extensive analysis of how these uncertainties involving fire simulation affect the general findings of this research.

Other engineering models, such as control volume and multi-scale models, are not capable of achieving the desired parameters because of the following reasons:

Control volume or zone models assume uniform conditions in each control volume (Charters, 2011). This means that the tunnel is divided into separate control volumes both in horizontal and vertical direction. When modelling a train inside the tunnel, high velocity gradients and highly turbulent flows are present. Hence, this kind of model cannot provide reasonable predictions regarding smoke mixing and smoke diluting processes. Moreover, this model does not work well with forced ventilation velocities.
Multi-scale models combine a computational fluid dynamic (CFD) model, set up in the fire region, and a one-zone model, which represents the fully mixed region in the far field (Colella, et al., 2011). This approach is appropriate in situations with a fully-mixed tunnel section. As one of the scenarios in this thesis includes the use of natural ventilation in which the smoke is likely to stratify, the one-zone assumption is not suitable, as it assumes uniform conditions within the zone further down the tunnel.

3.3.2 Geometry – a representative train and tunnel

In order to model the scenarios, a representative train and tunnel is chosen. This simulation aims to achieve a rough prediction of the conditions inside of the tunnel. Comparing the diameters of the Gotthard Base tunnel (7.76 m) and the Channel tunnel (7.6 m), there is only a diameter difference of 0.16 m. Both tunnels have walkways on both sides of the train, operate on the same track gauge system and have similar cross passage intervals of 375 m for the Channel tunnel and 325 m for the Gotthard Base Tunnel (Pompée, 1995) (Channel Tunnel Safety Authority, 1997).
A comparison of the San Francisco County Transportation Authority (2014) on standard width configuration trains − which includes Siemens, Alstom and Bombardier trains − shows that a train width of 2.9 m and a train height of 3.9 m can be treated as average values.

Rather than simulating a very specific geometry, a more generic tunnel set-up is chosen. It is hoped that findings of this research can be applied to a wide range of tunnels and the acquired knowledge can lead to a direct real world contribution.

A generic tunnel with a diameter of 7.6 m is chosen as a representative tunnel set-up. Within this tunnel, a representative train − 350 m long, 3.8 m high and 2.75 m wide − has been selected. Figure 18 shows the representative tunnel and train set-up, as modelled in FDS.

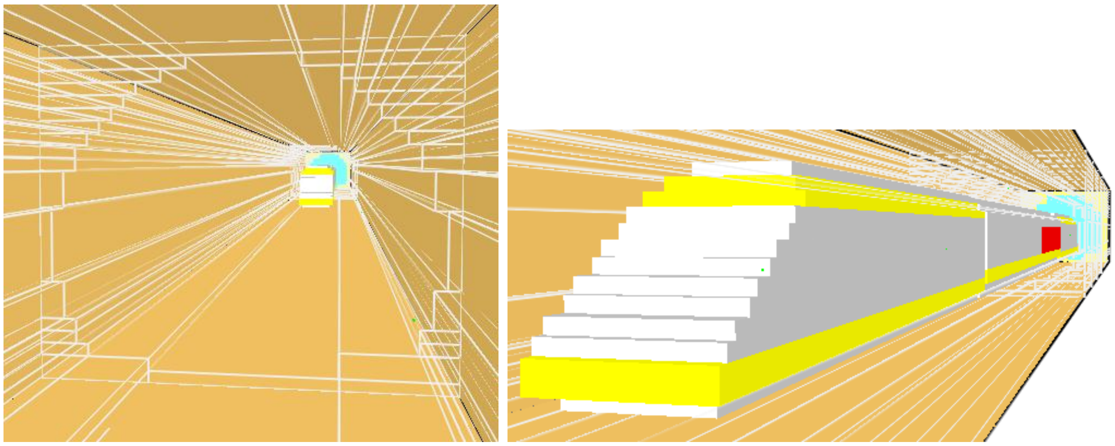

Figure 18 Tunnel and train geometry

3.3.3 Computational domain

For unidirectional ventilation, conditions upstream of the fires are not of major interest, as passengers are not affected in those scenarios. However, the airflow within the model has to be established before it meets the fire's location. Therefore a small tunnel section in the upstream direction is modelled as well. Once the smoke passes the end of the power car, it can mix across the entire tunnel section and is likely to reach uniform values in terms of smoke and toxic species concentrations. The computational domain of unidirectional ventilation scenarios has to capture the fire's location until the most distant location of cross passages for any stop situation of the train.

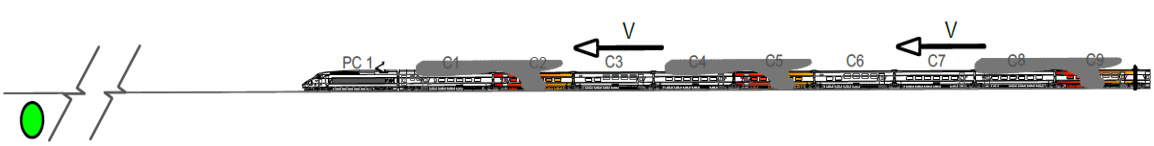

Figure 19 Area of interest - unidirectional ventilation

For scenarios with natural ventilation, conditions on both sides of the fire are of interest. As the stratification of smoke may affect escape capabilities of evacuees, conditions over a distance of two cross-passage spans have to be assessed. In doing so, every possible stop situation can be assessed. Figure 20 shows a stop situation with the longest possible walking distance from a certain end door to the cross passage.

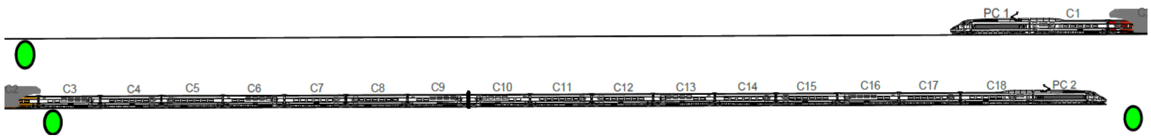

Figure 20 Area of interest - natural ventilation

For bidirectional ventilation scenarios, the findings of unidirectional ventilation scenarios can be used to assess the build-up of smoke inside of the carriage. Therefore, no additional scenarios are modelled.

3.3.4 Boundary and initial conditions

Since the majority of today's tunnels are built with concrete lining segments (Carvel & Both, 2011) (Pompée, 1995), concrete is chosen as a boundary condition within the tunnel tube. A conductivity k of 0.8 W/m·K, a specific heat capacity c_p of 880 J/kg·K and a density ρ of 1900 kg/m³ are chosen (Drysdale, 2011).

For unidirectional ventilation scenarios, a forced airflow has to be modelled. In general, ventilation velocities affect the horizontal smoke spread and degree of stratification inside of the tunnel. These values vary from one tunnel to another. A representative volumetric ventilation of the Channel Tunnel has been chosen here. The supplementary ventilation system of the Channel tunnel provides 100 m³/s of air in case of a fire (Channel Tunnel Safety Authority, 1997).

HBI Haerter (2013) carried out a study on temperatures and humidity in a long transit tunnel in Switzerland. It has to be mentioned that those values vary from one tunnel to another, but the study gives some insights into possible values. Temperatures and humidity were 29°C and 70%, respectively. These values are implemented in the model.

The location of the upstream boundary for simulations with unidirectional ventilation has negligible effect on the backlayering of the smoke. However, the upstream length has to be chosen wisely as the flow has to establish across the train (Jia, et al., 2010). Two carriages in the upstream direction are modelled in order to establish a stable flow.

3.3.5 Design fires

Design fires represent one of the most influencing factors regarding carriage and tunnel conditions. Therefore, the choice of the design fires requires careful consideration. The fire will turn from a fuel-controlled to a ventilation-controlled stage in tunnels with a high fuel load (Ingason, 2011). Therefore it can be stated that the amount of available air has a significant influence on the fire growth and peak heat output. As this thesis distinguishes between scenarios with unidirectional − which also include bidirectional scenarios in terms of design fires − and natural ventilation, respectively two design fires have to be evaluated. Subsequently, a short review on the chances to reach flashover inside a carriage and full scale experiments is presented. This is the basis for establishing the design fires.

Inside the carriage, fire loads such as bags, luggage, seats and possibly combustible wall and ceiling linings can be expected. SP Sweden (Claesson, et al., 2012) carried out a series of experiments with a 1/3 train carriage mock-up (1/3 of the length of a full carriage) in order to investigate the fire growth and possibility to cause flash-over inside a train carriage. Two of the six experiments resulted in a flashover of the carriage. The ignition source, the fire load at the place of fire origin, the fire load distribution and the vertical fire spread over the wall linings could be identified as the most influencing parameters regarding fire growth and flashover. Besides that, the findings showed that seats as the only fuel load are not enough to cause the carriage to flash over. Additional luggage must be present. Moreover, it was found that trains without combustible wall linings are very sensitive to a favourable disposition of luggage in the area of the fire's origin in order to reach flashover. The chances of reaching flashover dependent greatly on the fire growth near the fire's source. In the cases which resulted in flashover, an initial heat release of 700 to 900 kW was present. A maximum heat release of 3.5 MW was achieved during the flashover of the 1/3 length mock-up, which occurred between 2 and 14 minutes after ignition.

Since luggage as a fire load seems to be a key factor in evaluating a design fire, further research has been consulted. Kumm (Kumm, 2010) carried out a study on luggage in Stockholm's Metro and Commuter trains. The study concluded that large bags, luggage and prams contributed to the train's overall fire load the most. 87% of the passengers brought luggage with them, which had an individual average weight of 4.65 kg. This value represents an additional fire load of 85 GJ on a 1200 passenger train. Furthermore, fire experiments were carried out and pointed out that single luggage pieces can burn with a peak heat release rate in the range of 60 to 831 kW.

In contrast to the experiments conducted by SP Sweden (Claesson, et al., 2012), White (2010) concluded from his large-scale corner ignition experiments that a heat release rate of 100-170 kW is sufficient to reach a fire spread within the entire carriage.

After establishing that it is possible to cause a flashover in the carriage with relatively small initial fires, the decision has been made to use full-scale heat release curves as a design fire within this thesis. It has to be noticed that a representative full-scale set-up with a similar ventilation velocity in a tunnel environment is the most reliable and justifiable way of choosing a design fire curve. It is important to investigate the full-scale train itself and the conditions under which the experiment was carried out. In particular, the ventilation conditions seem to have a large influence. Furthermore, an outdated train is unlikely to cause a similar fire development and peak heat release rate compared to modern trains used nowadays. Modern train standards such as the BS EN 45545 (2013) set out requirements for the fire behaviour of materials, fire resistance for fire barriers and fire control systems.

Up until today, only a limited number of full-scale tests with rail cars have been carried out. Design fire curves of rail cars which have been assessed in different fire research projects are used at this point to determine a realistic design fire. The rail cars, the ignition mode, and the ventilation conditions are described below. A distinction between low and medium ventilation velocities is made and two representative design fires are chosen.

The EUREKA research project FIRETUN (Studiengesellschaft Stahlanwendung e.V., 1995) carried out a series of full-scale fire tests with a range of transport vehicles. Among them, two representative rail carriages in fire tests FS2 and F11 have been tested under restricted ventilation velocities of about 0.4 m/s. These experiments serve as an input to determine a design fire curve for the natural ventilation scenarios in this thesis. The fire test FS2 involved a steel carriage with interiors similar to a modern ICE car with a total fire load of 62 MJ. It must be noted that the experiments were carried out in the year 1995 and materials do not comply with modern standards which regulate maximum values for flame spread, toxicity of combustion gases and heat release (BS EN 45545, 2013). The fire origin was 6.2 kg of isopropanol, which was ignited inside of the carriage. The same ignition was used in the test F11 with a German IC train carriage. Interior material characteristics correspond to an ‘old’ design, as reported in 1995. The fire load of the carriage was estimated to be 76 GJ and one window was opened by 30 cm.

In order to represent a design fire for natural ventilation conditions, growth rates and peak heat release rates are averaged and a generic design fire is formed for the purpose of this thesis. In the cases of the EUREKA project, FS2 and F11 have a growth rate of about 0.5 MW/min with a peak heat release rate of 6 and 14 MW, respectively. After forming an average, a representative design fire for natural ventilation with a growth rate of 0.5 MW/min and a peak heat release rate of 10 MW is defined.
Figure 21 shows a comparison between the heat release rate curves of tests FS2 and F11 with the resulting representative design fire.

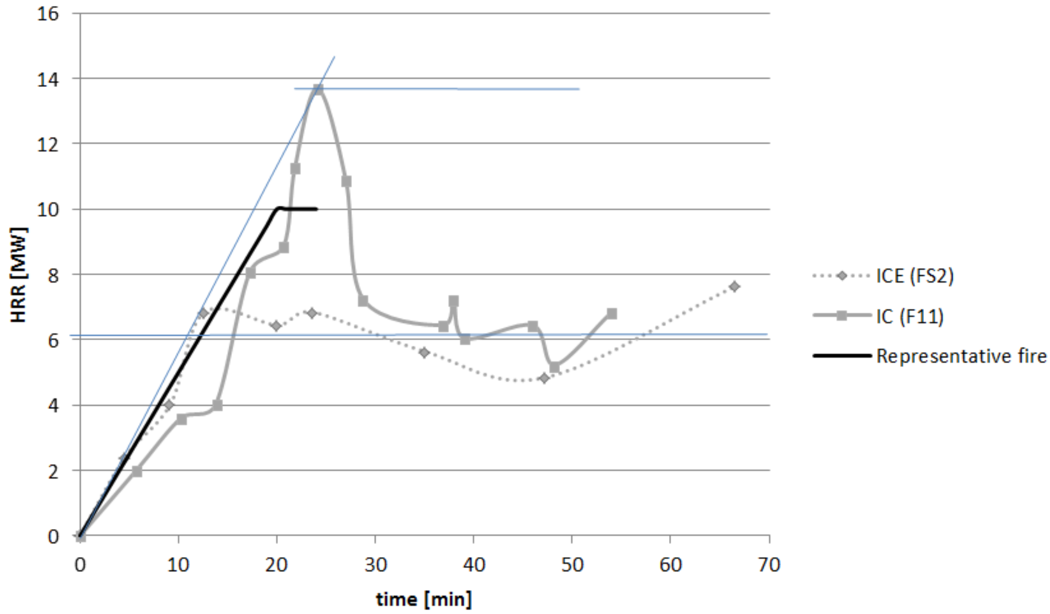

Figure 21 EUREKA FIRETUN tests FS2 and F11 with representative design fire, restricted ventilation

After establishing a design fire for natural ventilation conditions, a design fire for unidirectional ventilation conditions is assessed in the subsequent part. Findings from the METRO experiments and experiments carried out by Carleton University represent the basis for a design fire in the unidirectional ventilation scenarios of this thesis, as the ventilation velocity, as used in the experiments, is characteristic for these scenarios.

In 2012, SP Sweden carried out a series of full-scale tunnel fire experiments with a commuter train used in Stockholm's public transport (Lönnermark, et al., 2012). These experiments were part of the METRO project. A total of three tests was carried out: a fire under the train (Test 1) and two fires inside the train carriage (Tests 2 and 3). To achieve a realistic fire development, a luggage load of 79 pieces, corresponding to Kumm's research (2010), was placed in the carriage for tests 2 and 3. The total fire load was estimated to be 42.6 GJ. The tunnel was ventilated with a mobile fan with a capacity of 60.3 m^3/s, which induced (together with natural wind flows) a ventilation velocity of about 2-3 m/s for tests 2 and 3.

During the experiments, exceptionally high heat release rates have been achieved. In order to compare the fire behaviour of materials with those used in modern trains, a classification according to CEN/TS 45545-2:2009 has been carried out in the METRO experiments. BS EN 45545 (2013) divides the performance materials that were used into three hazard classification categories: HL1 (lowest), HL2 and HL3 (highest requirements). Herewith, different requirements are set. A representative train with a vehicle classification N (standard vehicle) – used in tunnels, allowing side evacuation and enabling long escape distances – falls under the operational category 3 (OC3). This combination of vehicle classification (design category N) and operational category 3 requires a HL2 performance of materials according to BS EN 45545 (2013). Table 1 shows a comparison between the materials used in the fire experiments and the materials required for modern trains (HL2).

Table 1 Commuter train carriage - material comparison

	Test 2 (X1)	Test 3 (C20/X10)
Wall linings	HL2	HL3
Complete seat	HL3	HL3
Seat upholstery	HL1	HL1

Besides the seat upholstery, materials are likely to perform in a similar way as materials used in modern trains. Findings (Lönnermark, et al., 2012) showed that a fire underneath the carriage, as in test 1, could not spread and then self-extinguished after 13.5 minutes. The original train in test 2 was ignited with one litre of petrol and resulted in a fast fire development, which was supported by luggage that was left behind. A fire in test 3, which was set in the same train with a refurbished interior fitting, slowed down after ignition and additional luggage had to be ignited in order to reach the desired fire development. However, once the fire was spreading, a heat release curve similar to one in test 2 was observed. Three doors were opened during the test.

To sum up the experiments of the METRO project: most materials used in the commuter train carriage fire correspond to modern long transit rail sets which operate in tunnels. Furthermore, moderate ventilation conditions are similar to the ventilation conditions for the unidirectional ventilation scenarios in this thesis. The use of luggage presents a realistic additional fuel load in long transit trains.

Similar ventilation conditions have been used in experiments at Carleton University (Hadjisophocleous, 2012). A mechanical ventilation system with an exhaust rate of $132m^3/s$ established an airflow over an intercity rail car. The fuel load was estimated at 50GJ. Four side doors were opened during the experiments, but no information on the train set-up in terms of materials is available. Despite the scarce information, the findings from this experiment serve as an additional input parameter in assessing a design fire for unidirectional ventilation conditions.

The same methodology in assessing the design fire for the natural ventilation conditions is used for the representative unidirectional design fire. In the cases of the METRO project experiments and experiments carried out by Carleton University, a growth rate of about 2 MW/min and 18 MW/min are existent. Hereby, peak heat release rates of about 55 MW and 30 MW have been achieved. After averaging those values, a representative design fire for unidirectional ventilation with a growth rate of 10 MW/min and a peak heat release rate of 45 MW is defined. The decision for averaging the values was considered necessary for the following reasons. As only two sets of data are available for the desired ventilation flow, certain fires are not more likely to occur in reality than others. The reason why the worst case is not taken here is because new rail carriages take fire safety issues more into account (BS EN 45545, 2013) and lower heat release rates can be expected from the carriage itself. However, the luggage places additional fire load in the carriage (Kumm, 2010), which is hard to regulate. As there are reasons not to choose one particular curve as design fire, the values are averaged. There is an urgent need to carry out full scale fire tests with modern rail carriages in order to reference justifiable heat release curves.

Figure 22 shows a comparison between the heat release rate curves of the METRO and Carleton University experiments with the resulting representative design fire.

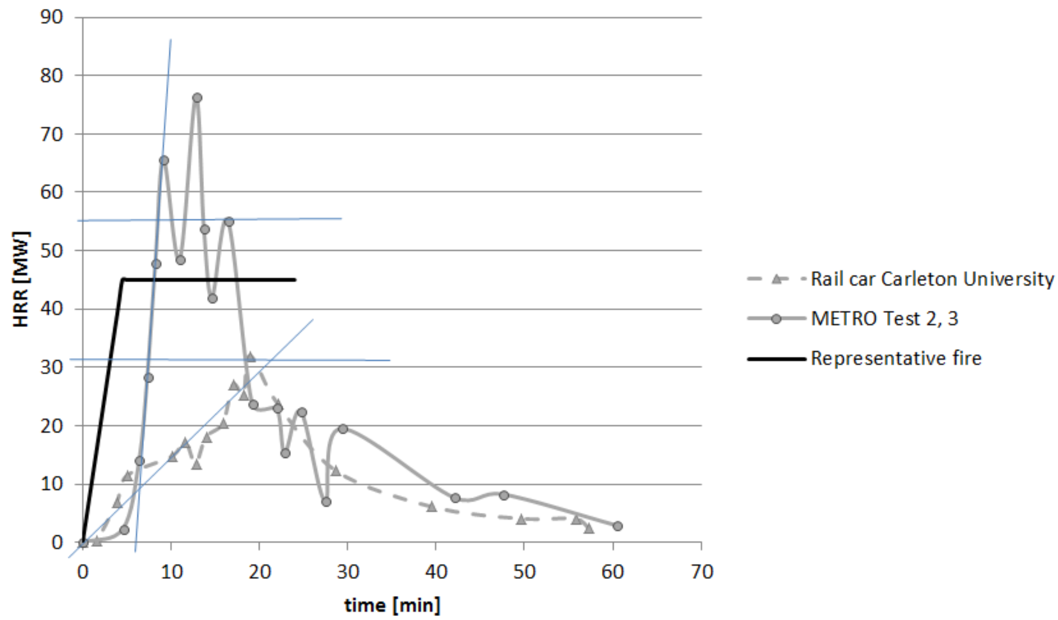

Figure 22 METRO project tests test 1 and 2 / Carleton University experiments, both moderate ventilation

Both representative design fires are modelled as boundary conditions with a specified heat release output history across the windows of the train at both sides.

3.3.6 Preliminary egress time estimation

In order to determine the required simulation time for assessing the conditions in the tunnel, preliminary movement time calculations are carried out. Table 2 shows findings for the different scenarios. A more detailed analysis is provided in Annex A1.

Table 2 Simulation time estimation

Ventilation	Fire on	Travel distance [m]	Affected passengers	Travel time [s]	Simulation time [s]
Unidirectional ventilation	Carriage 2	**Left Side: 335**	**104**	**872**	**940**
	Carriage 5	**Left Side: 275**	**272**	**1077**	**1140**
	Carriage 9	**Left Side: 195**	**375**	**1116**	**1180**

	Carriage 2	**Left Side: 335**	**104**	**872**	**1430**
		Right Side: 55	**646**	**1361**	
Natural ventilation	Carriage 5	**Left Side: 275**	**272**	**1077**	**1220**
		Right Side: 115	**478**	**1156**	
	Carriage 9	**Left Side: 195**	**375**	**1116**	**1180**
		Right Side: 195	**375**	**1116**	

3.3.7 Choice of fuel

Besides the simulation time, the heat release curve, the boundary and initial conditions, further variables regarding the fuel have to be defined within the fire model FDS. In order to choose representative values, the train, used during the EUREKA project is studied in more detail (Studiengesellschaft Stahlanwendung e.V., 1995). Table 3 lists the five most dominant fuels in terms of mass involved (Tewarson, 2002) (Karlsson & Quintiere, 2000). Having specified a certain heat release rate in the FDS code, the heat of combustion determines the fuel's mass loss. The lower the heat of combustion, the higher the mass loss and hence, the higher the production of combustion gases for a specific heat release (Drysdale, 2011).

$$\dot{Q} = \dot{m} \cdot \Delta Hc$$

Table 3 Material comparison for representative train, well-ventilated

Fuel	Equivalent fuel	ΔHc (kJ/g)	$Y_{CO,WV}$ (kg/kg)	$Y_{Soot,WV}$ (kg/kg)
Polyurethane foam	PU-foam GM25	24.6	0.028	0.194
GD-UP	Polyester-1	32.5	0.07	0.091
Core board	Particle board	17.7	0.005	0.015
Linoleum	PVC-1	16.4	0.1	0.076
Heave mat	Nylon	30.8	0.038	0.075
Average		**24.4**	**-**	**-**

The yields of CO and soot, as shown in Table 3, provide information on how much CO/soot is produced per kg of consumed fuel. The subscript WV (well-ventilated) indicates that these values vary depending on the available oxygen that is present (Tewarson, 2002). As the specified design fires are likely to change into a ventilation-controlled state, varying CO and soot yields are accounted for. It has to be emphasized that the values, as presented in Table 3, serve as additional information and represent the well ventilated case only. Especially CO values and soot values, as used in this thesis, highly depend on the combustion regime and the presence of external flaming, in which the listed values do not apply. An engineering approach for assessing the CO and soot concentration in post-processing is established. This is presented in section 3.4.
By averaging the heat of combustion of the most dominate fuels, it is shown that the heat of combustion of PU-foam represents the average heat of combustion best. A single step combustion model is selected within FDS. This model accounts for one fuel type only. Hereby, the stoichiometric combustion reaction of the most dominant fuel, polyurethane foam, is specified (Gottuk & Lattimer, 2002).

$$Fuel + Air \rightarrow Products$$

$$CH_{1.74}O_{0.323}N_{0.07} + 1.2735(O_2 + 3.76N_2) \rightarrow 1.0CO_2 + 0.87H_2O + 4.823N_2$$

3.3.8 Toxicity model

The concept of Fractional Effective Dose (FED) is used as an engineering approach to rank the different egress scenarios in terms of passengers' exposure to hazardous conditions (Stec & Hull, 2010) (Purser, 2002). It predicts the possible incapacitation of evacuees as a result of time-varying exposure to different smoke properties. It should be noted that values, as used in this approach, only serve as a guidance to establish a ranking of different scenarios. These values should not be used as input parameters in a quantitive risk assessment of further projects, keeping in mind that the scope of this thesis is to give qualitative guidance on different egress strategies. The FED values are not hard and fast

and are only used to attain general findings within this thesis. Do not take these values as a measure for any project that goes beyond the scope of this thesis.
The FED model, however, is seen as a reasonably accurate model to achieve a ranking. Nonetheless, the values themselves may include errors and uncertainties. An analysis of the variation of input parameters is carried out from sections 4.4 onwards.

The input parameters of the simplified form of Purser's (2002) FED model include the optical density, gas concentrations for CO, CO_2, O_2, the temperature of the combustion gases and the heat flux. The time- and location-varying quantities are assessed for different evacuees and the FED values are calculated.

The individual FED values can be calculated according to the method explained below (Stec & Hull, 2010).
Fractional effective concentration for smoke with tenability conditions for visibility of 5 m:

$$FEC_{smoke} = \frac{smoke\ OD/m}{0.2}$$

A fractional smoke concentration above the value of unity indicates to which extent evacuees would be impaired in case the visibility for an easy egress is not maintained. However, this value is not an indicator of whether or not passengers would lose consciousness or whether a successful escape along the tunnel wall would still be possible.

Fractional effective dose for asphyxiant:

$$F_{IN} = F_{I,CO} \cdot V_{CO2} + FED_{I,O2}$$

where:

$$F_{I,CO} = 3.317 \cdot 10^{-5} \cdot [CO]^{1.036} \cdot 25 * t/30$$

$$V_{CO2} = exp([CO_2]/5)$$

$$FED_{I,O2} = \frac{t}{exp\big(8.13 - 0.54 \cdot (20.9 - [\%O_2])\big)}$$

The fractional effective dose for asphyxiants takes into account the effects of high carbon monoxide, high carbon dioxide and low oxygen concentrations. F_{IN} values above unity are an indicator of whether or not evacuees lose consciousness and thus become incapacitated – meaning that they cannot escape on their own anymore.

Fractional heat dose (Purser, 2002):

$$FED_{heat} = \sum_{t1}^{t2} \left(\frac{1}{t_{I,rad}} + \frac{1}{t_{I,conv}} \right) \Delta t$$

where:

$$t_{I,rad} = \frac{133}{q^{1.33}} \quad (T > 200°C)$$

$$t_{I,conv} = 5 \cdot 10^7 \cdot T^{-3.4}$$

A fractional heat dose above unity is an indicator of whether the convective and radiative heat exposure for passengers evacuating along the tunnel is large enough to cause incapacitation.

Although the fractional effective doses mentioned above indicate that incapacitation would only occur when values exceed unity, it has to be emphasised that each individual reacts differently to a certain hazardous exposure. More sensitive evacuees, for example, are likely to be affected by fire effluents from FED values of 0.3 onwards (Stec & Hull, 2010). Furthermore, a graduate exposure would cause problems long before the FED reaches unity and would not cause incapacitation instantly.

Although the fractional smoke concentration is an important concept to evaluate whether the evacuee might be impaired, it has to be noted that the formula mentioned above is based on a 5 m visibility criterion. This value can hardly be maintained. The METRO Project (Ingason, et al., 2012) carried out evacuation experiments in a smoke-logged tunnel with visibility ranging from 1.5 to 3.5 m. Average walking speeds of 0.9 m/s could be maintained. One has to distinguish between an escape in a tunnel and other structures. Whereas evacuees might have difficulties to escape from a building with visibility under

5 m, evacuees in tunnels have to escape on a straight walkway along the tunnel wall. The channel tunnel, for example, provides a handrail for further guidance. Furthermore, the cross sections are pressurized and a ‘bubble effect’ establishes around the exit as fresh air is introduced (Channel Tunnel Safety Authority, 1997). Due to these reasons, the overall ranking of scenarios in this thesis is determined by the two factors which would cause incapacitation: fractional asphyxiant dose and fractional heat dose.

3.4 General post-processing

As mentioned above, the output values of a modified version of the FED model (Stec & Hull, 2010) are used in order to rank the scenarios. This model considers the time-varying quantities of optical density (OD/m), concentrations of CO (ppm v/v), CO_2 (%) and O_2 (%), as well as temperature (°C) and incident heat flux (kW/m²). Evacuees are tracked along the tunnel and the quantities mentioned above serve as input parameters for the FED model.

Concentrations for CO_2 and O_2, the temperature and the incident heat flux are assessed by means of the Fire Dynamics Simulator. As presented in section 3.3.5, this thesis accounts for transient fires which grow linearly to a ventilation-controlled state within the train compartment.

In order to make estimates of product yields of combustion gases, the combustion regimes of both the tunnel and the train compartment have to be determined. This is done by means of hand calculations of the equivalence ratio Φ, which is an indicator of the combustion regime (Drysdale, 2011). Values above unity stand for an under-ventilated regime, whereas values below unity imply a well-ventilated combustion regime. In case of unidirectional ventilation, the fire will be supplied with a volumetric flow rate of fresh air of 100 m³/s. Assuming a supply-air temperature of 29°C, an air supply of 85 kg/s is theoretically available for combustion. Taking into account that not all of the air is used for combustion, the equivalence ratio for the unidirectional and bidirectional ventilation cases for the tunnel can be calculated (Ingason, 2011).

$$\Phi = \frac{\dot{Q}}{\dot{m}_a \cdot 3000} = \frac{45000\ kW}{85\ \frac{kg}{s} \cdot 3000} = 0.17$$

The results show that even for the peak heat release rate of 45 MW, the fire is very well ventilated within the tunnel.

In order to estimate the combustion regime for the natural ventilated case, preliminary simulations regarding the air supply are carried out. Figure 23 shows the velocity of the supplied air within the combustion region to be roughly 0.7 m/s. The smoke layer height can be identified conservatively at the half-height of the tunnel. Hence, the air is supplied from the left and the right at the half-cross section of the tunnel. The oxygen level of the supplied air is not reduced. With an overall cross section area of 45 m² and a peak heat release rate of 10 MW, the equivalence ratio for the natural ventilated case can be calculated (Ingason, 2011).

$$\Phi = \frac{\dot{Q}}{\dot{m}_a \cdot 3000} = \frac{10000\ kW}{26\ \frac{kg}{s} \cdot 3000} = 0.12$$

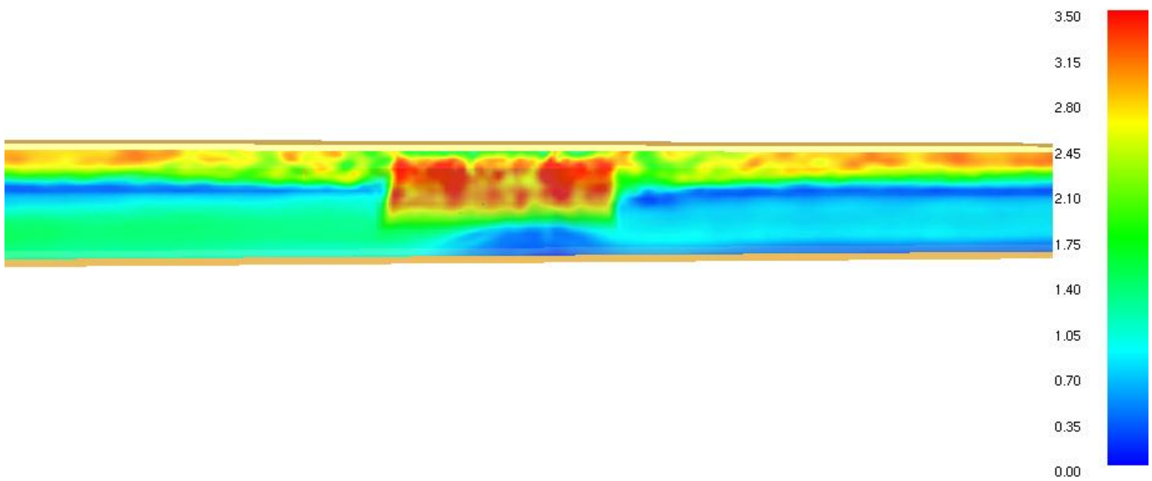

Figure 23 Ventilation velocity below the interface height from both sides, natural ventilation

To conclude, the tunnel environment can be described as well-ventilated for bi-, uni- and natural ventilation cases. However, this is not the case for combustion within the train carriage. This represents a specific type of enclosure where the equivalence ratio (Φ), expressed by the ratio between actual fuel-to-air ratio and the stoichiometric fuel-to-air ratio, changes to values larger than unity, since air for combustion is limited (Drysdale, 2011). Quantities of CO and soot concentration, for instance, will therefore vary significantly from well-ventilated to under-ventilated fire regions within the train compartment (Gottuk & Lattimer, 2002).

As the Fire Dynamics Simulator only allows for one specific soot and/or CO yield, which would not account for the varying equivalence ratio, the assessment of CO and soot concentration is performed in post-processing. This approach allows for varying yield, which would also be present in reality. Therefore, the combustion conditions in terms of fuel excess are estimated by means of hand calculations and the approximate equivalence ratio is established as well. Next, empirical evidence is used in order to make estimates of the CO and soot yield. Knowing the stoichiometric combustion equation of polyurethane-foam and the CO/soot yields, the CO and soot concentrations in the fire plume can be calculated. Subsequently, ratios of the rise of CO_2 to CO and the rise of CO_2 to soot concentrations are used in order to make conclusions about CO and soot concentrations at different locations along the tunnel. The ‘rise of CO_2’ is implemented in order to take into account the offset of the atmospheric CO_2 content of 0.038%. This engineering approach will be described in more detail below.

One has to consider two combustion regions for train carriage fires. Firstly, the main combustion takes place inside the carriage with limited air supply. Secondly, not all fuel can react inside and external flaming with an excess of oxygen is present. Air for internal combustion is supplied by the carriage openings. The METRO project report (Lönnermark, et al., 2012) states that train carriage windows fall out or break within 6 minutes after ignition. Observations by the EUREKA project (Studiengesellschaft Stahlanwendung e.V., 1995) show that window shattering and external flaming occurs from minute 2 onwards. It is very unlikely that the train stops and that evacuation can be started within that time span (pre-movement time). Hence, the assumption is made that major openings exist once the egress is started.

Once the fire within the train compartment is large enough, the supplied air from the openings is no longer sufficient to allow clean combustion condition: the fire is ventilation-controlled. To make an estimate of the equivalence ratio within the train compartment, hand calculations are carried out. The Fire Dynamic Simulator provides information on the amount of fuel which is lost at each time-step: the burning rate (kg/s). As the heat output data was measured by oxygen consumption calorimetry in the full-scale tests (Lönnermark, et al., 2012), the under-ventilated combustion regime is presented in the burning rate. Using this information in combination with an estimate of the amount of air that enters the carriage, the equivalence ratio can be calculated (Drysdale, 2011).

$$\dot{m}_{air} = 0.5 \cdot A_w \cdot H^{1/2}$$

The area of broken windows and their height respectively represent the ventilation area A_w and the window height H. After taking measurements from the representative train, 14 openings with an area of 1.5 m by 0.6 m are chosen.

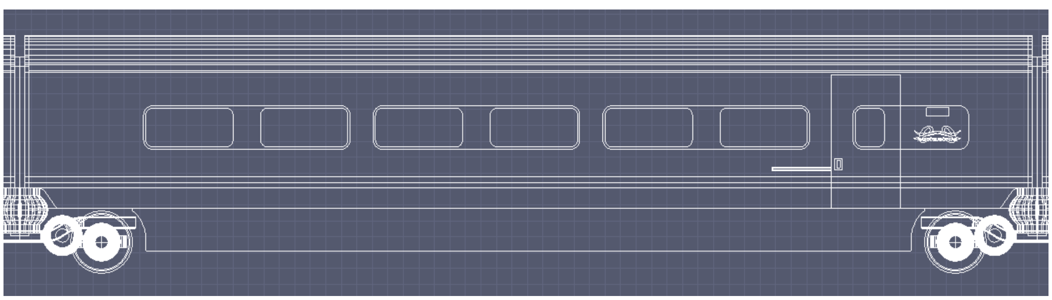

Figure 24 Representative Train, ventilation openings

$$\dot{m}_{air} = 0.5 \cdot 12.6 \cdot 0.6^{0.5} = 4.9\ kg/s$$

As described earlier, Polyurethane foam is used as the most dominant fuel in the train fire. Based on its stoichiometric equation (cf. section 3.3.7), further analysis can be carried out.

Knowing the molecular weight of PU-foam (19.888 g/mol) and air (137.28 g/mol), their respective masses of 19.888 g and 174.826 g can be calculated. Next, the stoichiometric fuel-to-air ratio *r* can be formed.

$$r = \frac{19.888\ g}{174.826\ g} = 0.1138$$

$$r\ gram\ fuel + 1\ gram\ air\ \rightarrow (r + 1)\ gram\ products$$

Using the fuel-to-air ratio r and the approximate inflow of air $\dot{m}_{air}$, the equivalence ratio Φ can be calculated (Karlsson & Quintiere, 2000). Values larger than unity indicate a ventilation-controlled fire.

$$\Phi = \frac{\frac{\dot{m}_{fuel}}{\dot{m}_{air}}}{r}$$

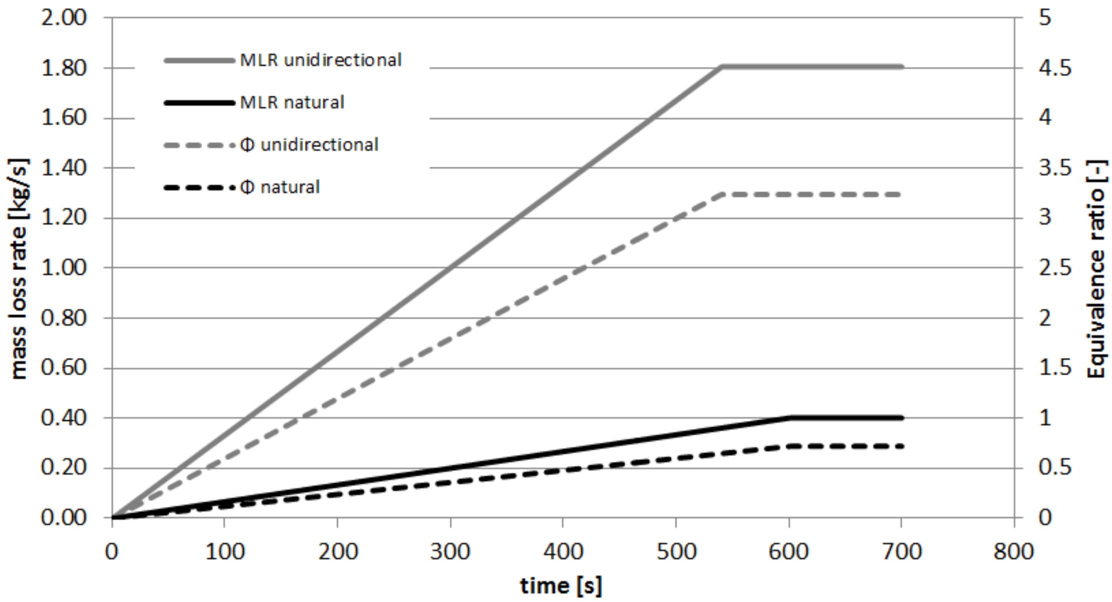

Figure 25 Mass loss rate and equivalence ratio; uni/bidirectional and natural ventilation

Figure 25 shows that scenarios with natural ventilated fires are well-ventilated in respect to air supply into the carriage, whereas scenarios with unidirectional ventilation are under-ventilated.

Once the equivalent ratio Φ is known, empirical correlations can be used to determine the regarding CO and soot yield per gram of fuel burned. This approach overestimates the equivalence ratio in assuming that all combustion takes place inside of the carriage and no external flaming is present. Gottuk (1992) reports that the CO yield in combustion gases depends on the flow dynamics and the upper layer temperature within the compartment. He states that, when estimating yields outside of the compartment, the plume yields can be used, if one takes into account external flaming. External flaming reduces the amount of CO to 10 to 25% of its original values.

An equivalence ratio correlation for describing the CO and soot yield of polyurethane foam ($CH_{1.74}O_{0.323}N_{0.07}$) could be found at the end of this project only (Purser & Puser, 2003). This could not be implemented in the thesis due to time constraints. Gottuk and Lettimer (2002) developed CO yield correlations based on hexane fires and suggested to consider these values as minimum CO yields for compartment fires. In order to achieve general findings on egress strategies, this is also seen as an appropriate method to investigate approximate trends. It was found that the upper layer temperature has an effect on the CO yield. In the case of the train compartment, the plume temperature is expected to be above 900 K in which the following correlation can be applied.

$$Y_{CO} = (0.22/180) \cdot \tan^{-1}(X) + 0.11$$

where

$$X = 10 \cdot (\Phi - 1.25)$$

For demonstration purposes, a CO yield of 0.3 g/g for polyurethane foam is assumed at this point. Afterwards, the mass of CO per reaction step can be calculated, using the molecular weight of PU-foam of 19.888 g/mol. This mass represents 0.21 mol CO.

$$19.888\ g\ PU \cdot 0.3\ g/g = 5.97\ g\ CO$$

The FED model requires a CO concentration input with a unit of ppm v/v at 20°C. Assuming atmospheric pressure, the volumetric concentration of CO in the fire plume gives:

$$V_{CO} = R \cdot \frac{T}{P} \cdot n = 8.314\ \frac{J}{K} mol \cdot \frac{293\ K}{101325\ Pa} \cdot 0.21\ mol = 5.05 \cdot 10^{-3} m^3$$

$$V_{Products} = R \cdot \frac{T}{P} \cdot \sum n_{products} = 8.314 \ \frac{J}{K} mol \cdot \frac{293\ K}{101325\ Pa} \cdot 6.693 = 0.16\ m^3$$

$$\frac{V_{CO}}{V_{Products}} = \frac{5.05 \cdot 10^{-3}\ m^3}{0.16\ m^3} \cdot 10^6 = \ 31562\ ppm\ v/v$$

Regarding the soot yield, Tewarson (2002) provides correlations for several other materials which are used in train construction, more specifically Nylon, PVC, wood, and PMMA. Subsequently, the correlation of Polymethylmethacrylate (PMMA) is presented, which is a complex hydrocarbon and is in some ways analogous to PU-foam. Yields with an infinity symbol represent the yields in well-ventilated conditions.

$$y_{soot} = y_{soot,\infty}\left[1 + \frac{1.6}{exp(\Phi/4.61)^{-0.6}}\right]$$

Following the above procedure, the soot concentration in the fire plume can be calculated. Taking a soot yield of 0.2 g/g as an example:

$$19.888\ g\ PU \cdot 0.2\ g/g = 3.98\ g\ soot$$

Assuming atmospheric pressure and a plume temperature of 800 K, the concentration of the smoke aerosol in the fire plume gives:

$$V_{Products} = R \cdot \frac{T}{P} \cdot \sum n_{products} = 8.314 \frac{J}{K} mol \cdot \frac{800\ K}{101325\ Pa} \cdot 6.693 = 0.44\ m^3$$

$$\frac{m_{soot}}{V_{Products}} = \frac{3.98\ g}{0.44\ m^3} = 9.05\ g\ soot/m^3$$

Until this point, CO and soot concentrations have been assessed in the fire plume adjacent to the fire source. In assuming the concentration ratios of (the rise of) CO_2 to CO and concentration ratios of (the rise of) CO_2 to soot being constant, concentrations along the tunnel can be predicted.

$$\left.\frac{rise\ in\ [CO_2]}{[CO]}\right|_{Point\ A} = \left.\frac{rise\ in\ [CO_2]}{[CO]}\right|_{Point\ B}$$

This concept assumes that CO_2 and CO/soot are equally mixed with fresh air.

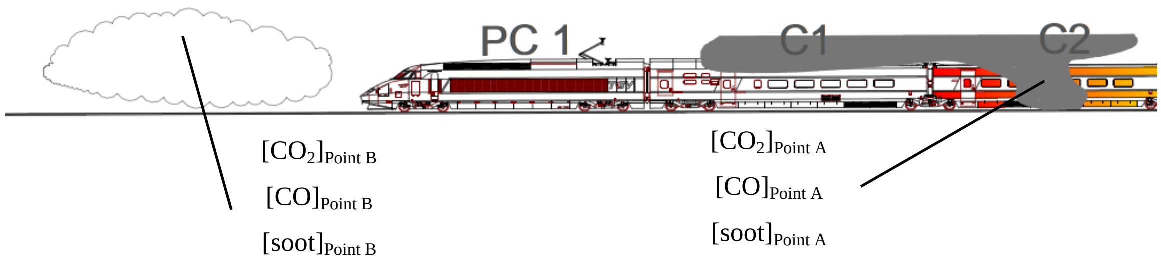

Figure 26 Concentration ratios

The Fire Dynamics Simulator provides the CO_2 concentration at point A and B as an output quantity. As presented earlier in this section, the concentration of CO and the rise in concentration of CO_2 are known. Therefore, the ratio of (the rise of) CO_2 to CO can be calculated.

$$\frac{rise\ in\ [CO_2]}{[CO]} = ratio_{CO}$$

The same procedure can be followed for determining the (rise in) CO_2 to soot ratio. The mass of soot has been calculated earlier. The density of soot is between 1 to 2 g/cm^3 (Hamins, 1993) and an average is chosen at this point.

$$V_{soot} = \frac{m}{\rho} = \frac{3.98\ g}{\frac{1.5 \cdot 10^6\ g}{1\ m^3}} = 2.65 \cdot 10^{-6}\ m^3$$

$$\frac{V_{soot}}{V_{Products}} = \frac{2.65 \cdot 10^{-6} m^3}{0.44 m^3} = 6.02 \cdot 10^{-6}$$

$$\frac{rise\ in\ [CO_2]}{[soot]} = ratio_{soot}$$

The following prediction can be made for point B in terms of CO and soot concentration.

$$[CO]_{Point\ B} = \frac{rise\ in\ [CO_2]_{Point\ B}}{ratio_{CO}}$$

$$[soot] = \frac{rise\ in\ [CO_2]_{Point\ B}}{ratio_{soot}}$$

As the FED model requires soot concentration inputs in the unit of optical density OD (1/m), a simple correlation between the extinction coefficient per unit mass K_M and the mass concentration of the smoke aerosol m for wood and plastics (4.4 m^2/g) is used (Mulholland, 2002).

$$K = K_M \cdot m$$

$$OD = \frac{K}{2.3}$$

It has to be mentioned that this engineering approach contains many assumptions which can introduce uncertainties and errors in the calculations. However, it represents an attempt to include the transient fire behaviour with its varying CO and soot yields. It is seen as more appropriate than specifying single yield parameters for the entire simulation time, which would not capture the transient combustion gas concentrations. An extensive variation of parameters is carried out later in section 4.4, which explores the effects of varying CO and soot yields on the final ranking of egress scenarios.

3.5 Post-processing for bidirectional ventilation scenarios

Based on the assessed data of unidirectional ventilation scenarios, the smoke ingress into the carriage for the bidirectional waiting time is estimated. Combustion gas concentrations and pressure differences across the carriages are assessed with CFD. The aim is to predict the physical effects for passengers during the time when the other part of the train is evacuated until the ventilation is reversed. Based on Annex A1, the longest evacuation time for a bidirectional scenario is about 20 minutes. Afterwards, the ventilation is reversed and a different flow field is established. The concentration of combustion products changes as well, when new supply air is provided. Although the time span which is needed to reverse the ventilation flow is part of the waiting time, no analysis on smoke ingress within that time is made. Varying flow fields and combustion products cannot be estimated without detailed computer simulations. However, it is estimated that it takes about 20 minutes to reverse the ventilation and establish a smoke-free atmosphere in the tunnel. This time span is based on the egress time estimates, as presented in Annex A1.

In order to predict the smoke ingress into the carriage, flow fields across the carriages for the first 20 minutes are analyzed and pressure differences are assessed. The following engineering approach assumes the carriage to be a control volume in which the conversation of mass can be applied. The mass efflux from the carriage minus the mass flow into the carriage equals zero (Welty, et al., 2008). Destruction of gaseous mass occurs in the lungs of passengers when they breathe in oxygen. However, an accumulation or destruction of mass is seen as negligible. The effect of transformation of oxygen to carbon dioxide by passengers is investigated.

In general, carriages are surrounded by hotter smoke at the top of the carriage, whereas colder smoke/air appears at the bottom of the carriage. Furthermore, the dynamic pressure is higher at the top, due to the ventilation flow. To make a conservative estimation, the maximum pressure difference between the top of the carriage on one side and the bottom of the carriage on the other side is assessed. Equal leakage areas on both sides are assumed. Gas concentrations at the top of the carriage provide information on the composition of combustion gases entering the carriage. Knowing the leakage area, the pressure difference across the carriage, and the temperature of combustion gases, the mass flow through the carriage can be estimated (Karlsson & Quintiere, 2000).

$$\Delta p = \frac{1}{2} \cdot v^2 \cdot \rho$$

$$\dot{m} = C_d \cdot A \cdot v \cdot \rho$$

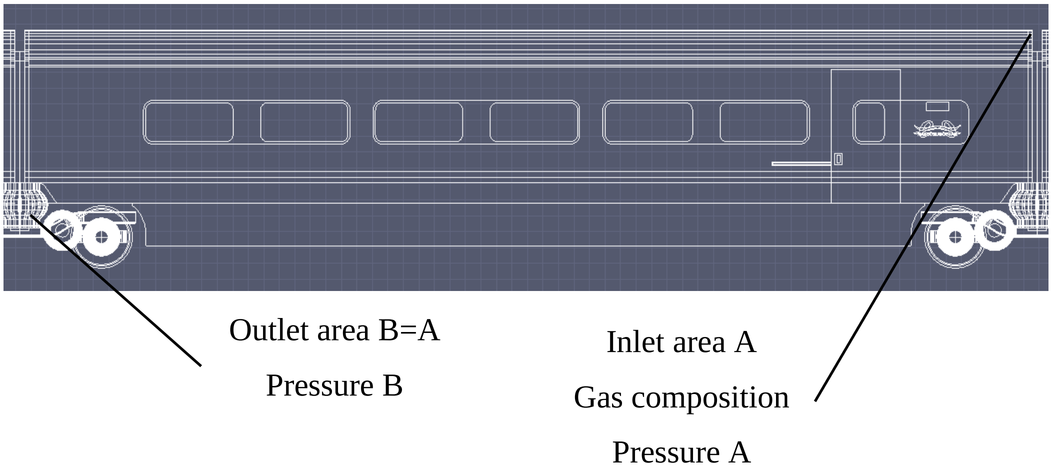

Figure 27 Assessment of smoke leakages and combustion gas compositions

An accumulation of combustion gases is assumed within the carriage. To maintain the conversation of mass, the mass of air (composition of fresh air) leaving the carriage equals the mass of smoke entering the carriage. A uniform composition and mixing within the carriage is assumed. Calculations are carried out on a mole basis. An influence on the smoke ingress for a carriage adjacent to the fire and for carriages further away is investigated.

It has to be noted that this approach only aims at giving a rough prediction of the smoke ingress. To achieve detailed information, a more accurate flow field analysis needs to be carried out. The leakage area of the carriage remains the biggest uncertainty. Whereas Siemens states that a very well-sealed carriage has a leakage area of 645 mm² (Parsons Brinckerhoff Group Inc, 2013), this value is likely to vary from one manufacturer to another. Also, a deviation of that value with the carriage's deterioration can be expected. Furthermore, there is a possibility that new leakage areas are produced, when the carriage is surrounded by high temperature smoke. Window and door seals made of EPDM (ethylene propylene diene monomer rubber) with a maximum functioning temperature of 150°C are likely to fail at higher temperatures (All Seals Inc., 2008).

4. Results and discussion

This chapter aims in presenting the findings of CFD simulations. A modified version of Pursers' toxicity model (Purser, 2002) is used to estimate the Fractional Asphyxiant Dose, the Fractional Heat Dose and the Fractional Smoke Concentration, as described in section 3.3.8. Figures with FED values are shown with ranges, representing the first and last evacuees based on simple egress time estimates (Annex A1). Fire effluent data are presented for evacuees only. Additional fire data can be found in Annex A2.

The following sections are divided into the two possibilities of having controlled and uncontrolled stop situations. Within each section, results from the three ventilation types (unidirectional, natural ventilation and bi-directional) are presented and discussed for the different fire locations on the train (fire on carriage 2, 5 or 9). People evacuate, as mentioned in previous sections, from the train end doors only. Subsequently, the uncertainties regarding input parameters are discussed.

For the purpose of this thesis, only the egress options from the train end doors are considered. Multiple exit doors are not taken into account because of the following reasons. Based on the possibilities of having controlled and uncontrolled stops, further distinction for an alignment to a cross passage would have to be made for all scenarios. Within a train set, for example, the first part could be aligned to a cross passage, whereas the second part could not. In order not to complicate the scenarios and set-ups, evacuation from the train end doors is assumed, which is a limitation of this project.

4.1 Uncontrolled stop situations

This section presents findings of uncontrolled stop situations where the fires (C2, C5, C9) are located adjacent to one cross passage which renders them unavailable. This represents the worst case scenario in terms of travel length for passengers close to the fire (one cross passage separation distance).

4.1.1 Unidirectional ventilation

Figure 28 shows the different set-ups for fires on carriages 2, 5 and 9 with unidirectional ventilation. The green lines represent the egress paths in the tunnel.

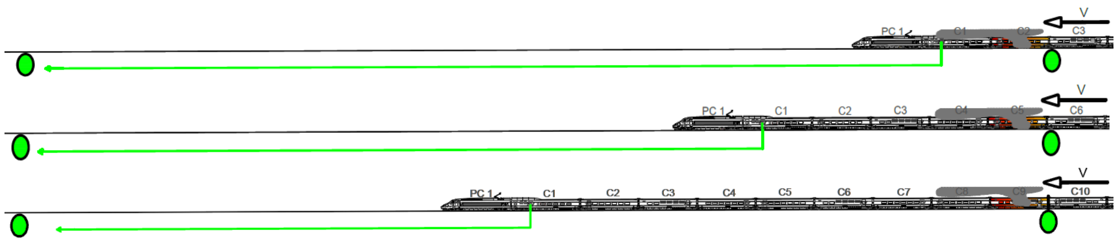

Figure 28 Uncontrolled stops with fires on C2, C5 and C9, unidirectional ventilation

Depending on where the fire is located, more or fewer passengers are affected by smoke. Furthermore, the travel distance to the next cross passage varies as well. An overview of the physical and chronological conditions is given in Table 4 (based on Annex A1).

Table 4 Uncontrolled stop - unidirectional ventilation, physical and chronological data

Fire on	Train exit door location [m]	Cross Passage location [m]	Affected passengers	Last evacuee exiting train [s]
C2	0	-340	104	201
C5	0	-290	272	526
C9	0	-220	375	725

The first evacuees who exit the train are affected by time- and location- varying temperature, radiation and gas concentrations. An overview is presented in Figure 29.

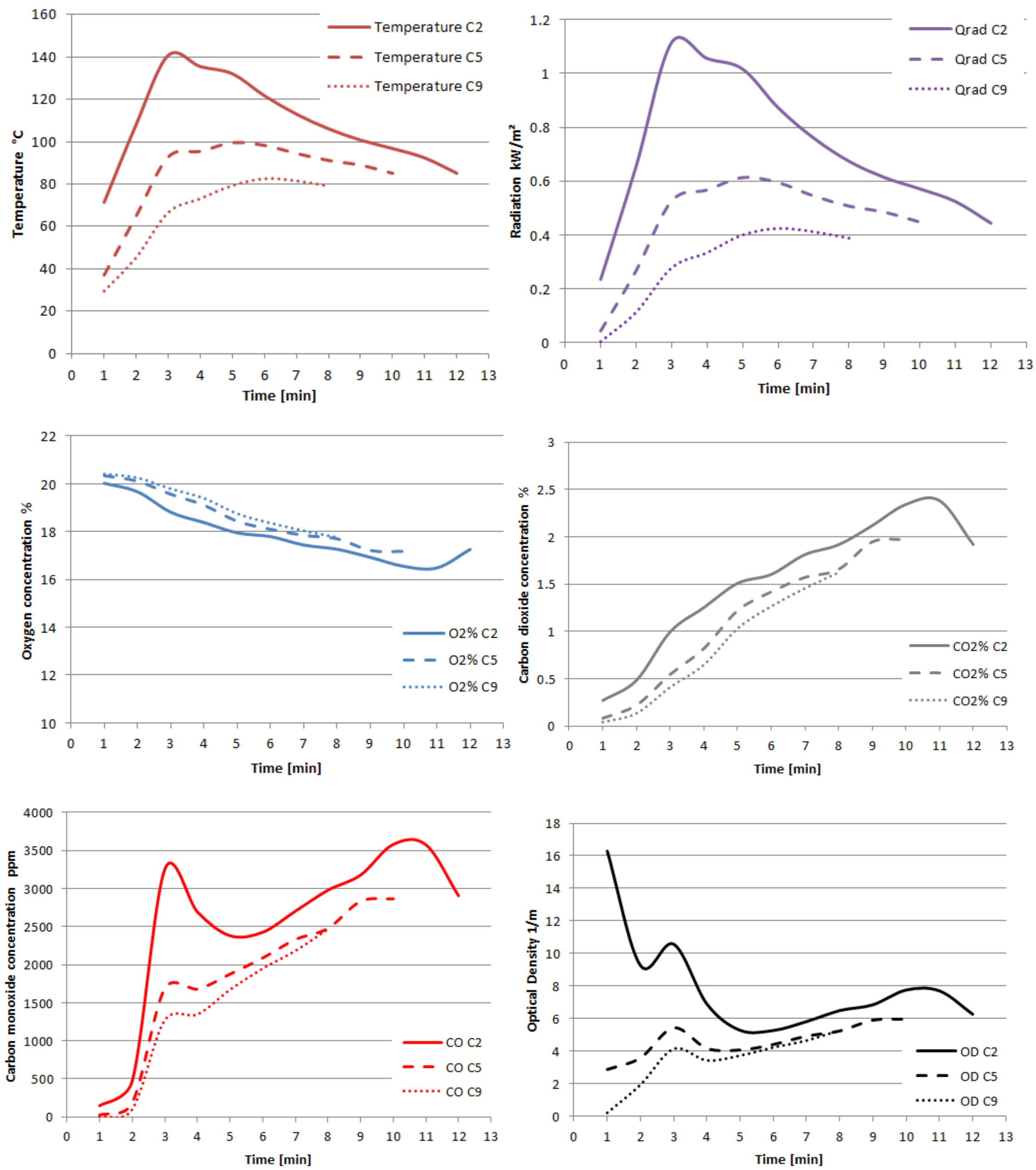

Figure 29 Uncontrolled stop – first evacuee, time concentration curves and temperature at 2m height, unidirectional ventilation

As the evacuee starts to escape, the temperature generated by the fire growth is more dominant than the dilution provided by the ventilation system. This leads to an increase in temperature within the first three minutes. As the evacuee moves further down the tunnel, mixing processes increase, which in turn leads to a temperature reduction.

During the first evacuee's escape time, the fire starts its growth phase and is therefore producing less combustion gases. As the ventilation flow is faster than the walking speed of the evacuee, increasing gas concentrations are present at the evacuee's position as well. The production of combustion gases seems to be more dominant than the mixing processes, leading to increasing combustion gas concentrations over the entire escape length.

Furthermore, poorer conditions can be identified, when the fire is close to the train's exit door. This is not only valid for the starting position of the evacuee, but also for the entire escape length.

A discussion on the physical effects of the evacuee is carried out later in this section.

It has to be noted that high values of combustion gas concentrations and temperatures are observed for unidirectional ventilation scenarios, which leads to high FED values. More reasonable values in terms of evacuation feasibility are found for natural ventilated scenarios in later sections.

Having determined the conditions for the first evacuees, Figure 30 presents conditions for the last evacuee. It should be pointed out that evacuees in different scenarios exit into the tunnel at different times, as various numbers of evacuees are affected.

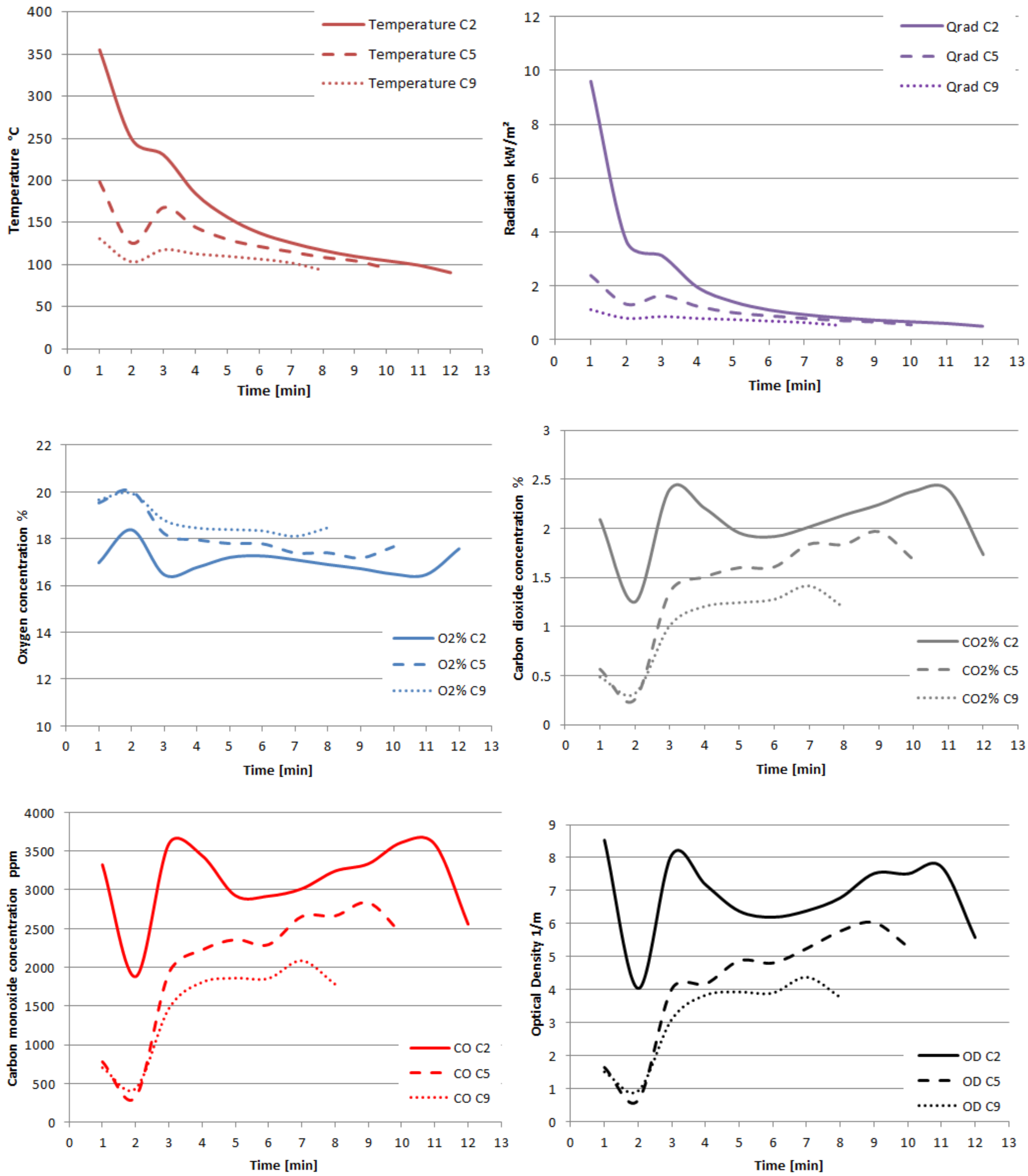

Figure 30 Uncontrolled stop – last evacuee, time concentration curves and temperature at 2m height, unidirectional ventilation

When the last evacuee exits into the tunnel, the fire has not yet reached its peak value for all scenarios. However, the temperature drops significantly as mixing occurs along the escape route. One would assume that for fires on C5 and C9 (same peak fire peak values for the last evacuees), the conditions are already well mixed when the passengers exit into the tunnel. Nonetheless, the results show that more constant gas concentration values, indicating a well-mixed atmosphere, occur only from minute 3 onwards. One reason for this could be that mixing is increased when the smoke passes the front/rear end of the train. Before this, a more layered propagation occurs adjacent to the train. Furthermore, one would expect the single gas concentrations to converge to the same value at the end of the evacuation times, as the gases might be fully mixed. The results show that this is not the case and a difference for fires on C2, C5 and C9 can be seen. One explanation for this could be that a distinctive layer for a fire on C2 is longer maintained than for fires on C5 or C9, which leads to higher gas concentrations at 2 m head height.

Based on the data presented above, the physical effects on the evacuees are estimated by means of the FED concept.

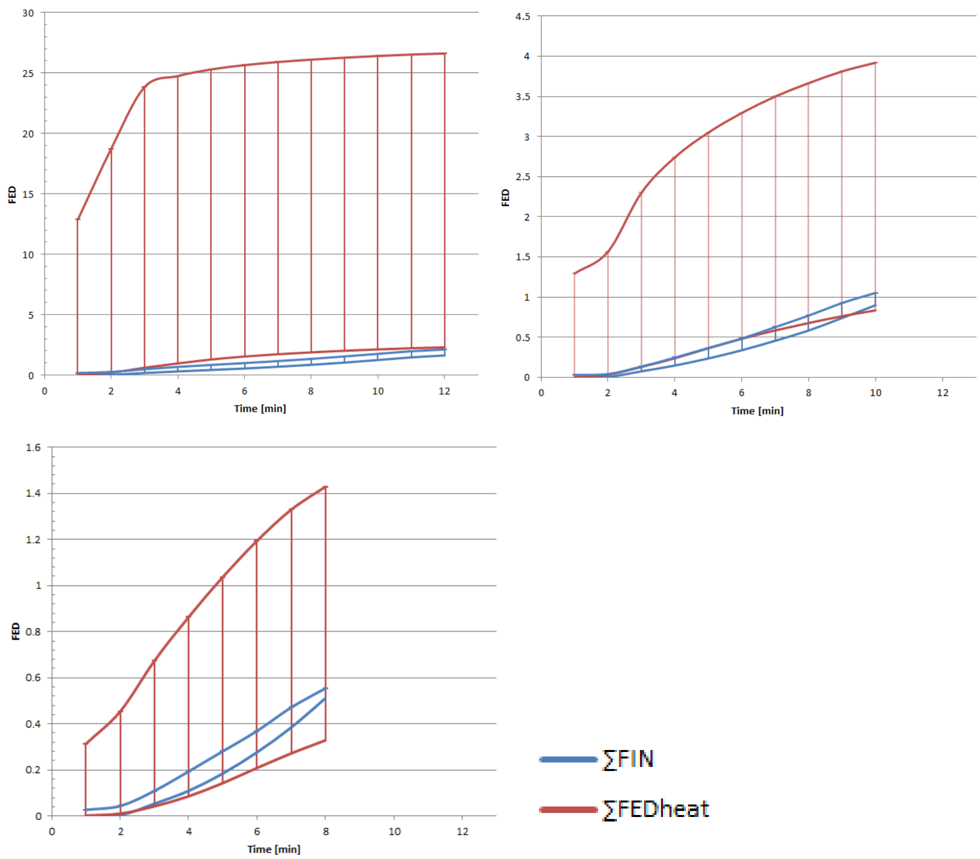

Figure 31 Uncontrolled stop - unidirectional ventilation, FED analysis for a fire on C2 (top left), C5 (top right), C9 (bottom)

In general, heat and radiation effects seem to have a much higher influence on evacuees than effects of asphyxiants.
Whereas an escape in terms of heat exposure might be possible for the first evacuees in case of fires on C5 and C9, it is not an option for the first evacuees in case of a fire on C2. The first evacuees exit into a less contaminated atmosphere, leading to low sloping FED values, whereas the last evacuees exit into the tunnel when the fire has already reached its peak value. This leads to steep gradients of FED values.
An evacuation for the last evacuees of all scenarios is not possible for a worst-case uncontrolled stop with unidirectional ventilation. The analysis for a fire on C2, for example, shows that FED values (heat exposure) of 13 are reached within a single minute for the last evacuees. The heat is such that the last evacuees cannot escape. This can be explained by the direct effects of the unmixed fire plume and the evacuee. This influence continues for three minutes, as indicated by a high dFED/dt value, representing the gradient of the FED curve. Although passengers are not able to continue their evacuation on their own in case a FED value of unity is reached, the graph is continued for further analysis. It can be seen that the slope decreases, indicating a more mixed, tenable atmosphere.
Compared to heat and radiation effects, less difference is seen for the uptake of asphyxiant gases between the first and last evacuee.

4.1.2 Natural ventilation

As mentioned in section 2.2, fires in tunnel develop differently if no mechanical ventilation is facilitated. Furthermore, one would expect a higher degree of stratification as the mixing process is not evoked compulsive.

Figure 32 shows the different set-ups for fires on carriages 2, 5 and 9 with natural ventilation. The green lines represent the egress paths in the tunnel. As mentioned in section 3.2.1, the mirror effect applies for the regarding carriages on the other part of the train. Table 5 presents physical and chronological data, as used for the natural ventilation set-ups (based on Annex A1).

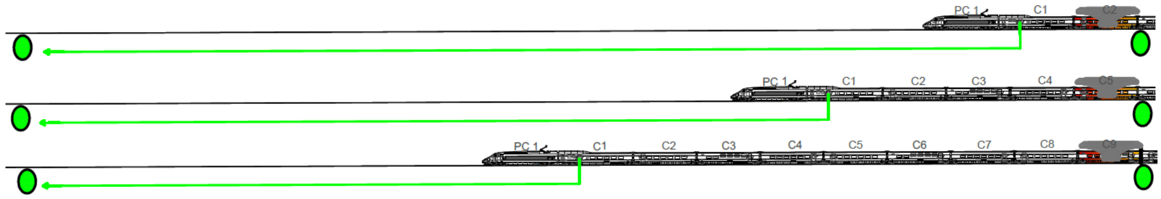

Figure 32 Uncontrolled stops with fires on C2, C5 and C9, natural ventilation

Table 5 Uncontrolled stop - natural ventilation, physical and chronological data (exit from C1 at 0m, exit from C18 at 290m)

Fire on	Train exit door location [m]	Cross Passage location [m]	Affected passengers	Last evacuee exiting train [s]
C2	**0**	**-340**	**104**	**201**
	290	410	646	1250
C5	**0**	**-290**	**272**	**526**
	290	450	478	925
C9	**0**	**-220**	**375**	**725**
	290	520	375	725

When exiting into the tunnel, evacuees are affected by time- and location-varying temperature, radiation and gas concentrations. Subsequently, only data for passengers evacuating from carriage 1, as shown in Figure 33 and Figure 34, are presented. The proximity to the fire location, longer travel distances and hence longer exposure times in the tunnel make them more interesting than evacuees from carriage C18. However, FED values are presented for both train exit doors at C1 and C18.

Figure 33 shows data for the first evacuee. Smoke propagates at much lower velocities and, depending on the fire location, reaches the first evacuee at different times. Practically no rise in temperature is seen for the first evacuee for a fire on C9. However, in case of a fire on C2, a rise in temperature can almost immediately be seen. This trend is noticed more clearly when investigating radiation and gas concentration data. The first evacuees are immediately affected by radiation if the fire is in close proximity, like a fire on C2. If the fire is more distant, like a fire on C9, it takes about 5 minutes for the smoke to catch up with the first evacuee. Comparing combustion product concentrations shows that higher values are found for fires in the proximity of the train's exit. This indicated that a complete stratification of the smoke layer cannot be maintained and that smoke mixes significantly before reaching the train exit door. Concentrations are initially low for all three scenarios, because the fire is small and still in its growth phase for the first evacuees.

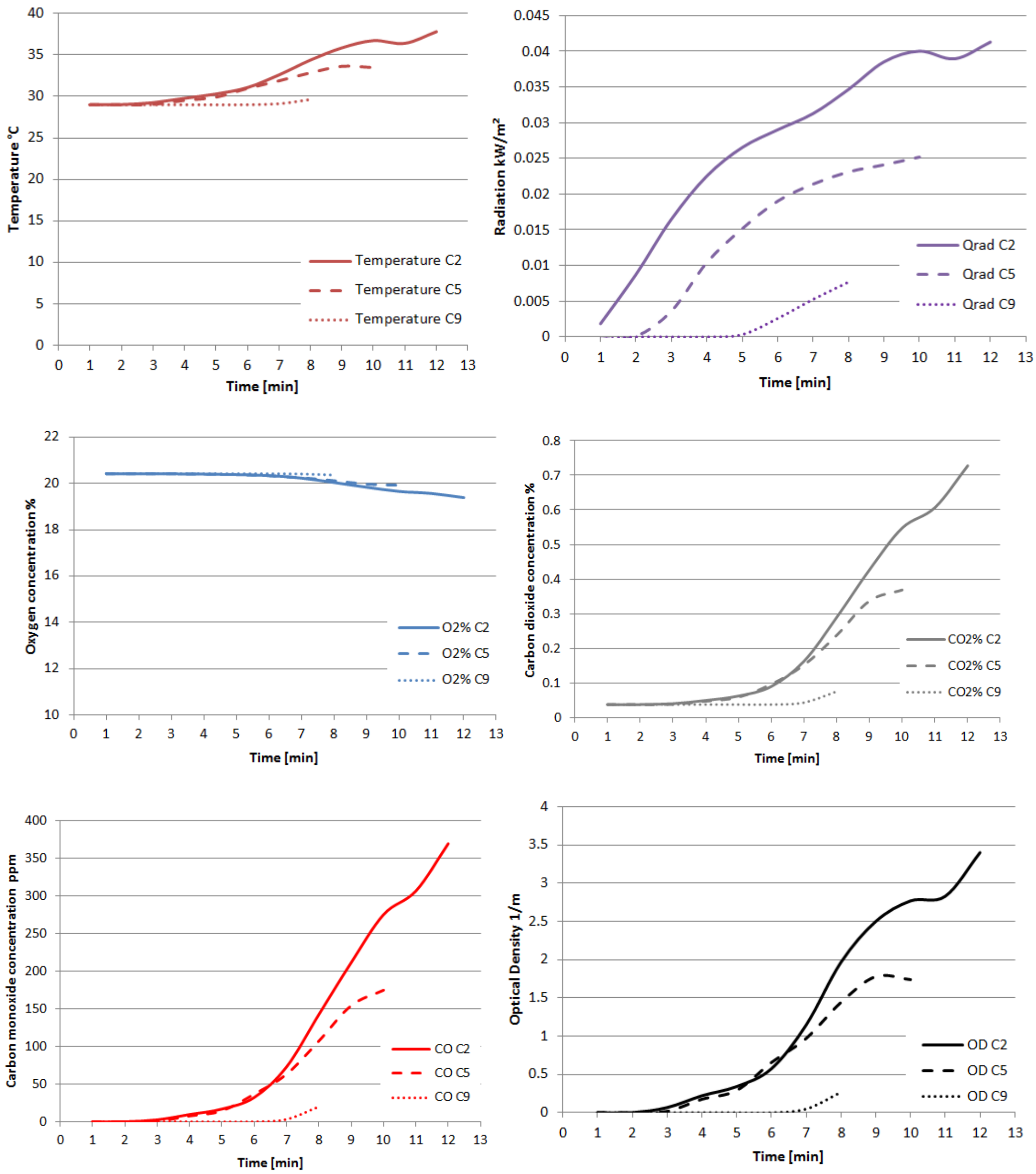

Figure 33 Uncontrolled stop – first evacuee, time concentration curves and temperature at 2m height, natural ventilation

Compared to smoke originating from a fire on C9, combustion product concentrations are higher for evacuees in case of a fire on C2, because the smoke is less diluted. This is not only valid for the evacuee's starting position, but also for the entire escape length. A discussion on the physical effects on the evacuee is carried out later in this section.

After the conditions for the first evacuees are known, Figure 34 presents the conditions for the last evacuees. It should be pointed out that evacuees for the different scenarios exit into the tunnel at different times because the total number of evacuees is affected by the fire's location. The fire is still in its growth phase for the last evacuees for a C9 fire. Hence, the magnitude of the fire's size is different.

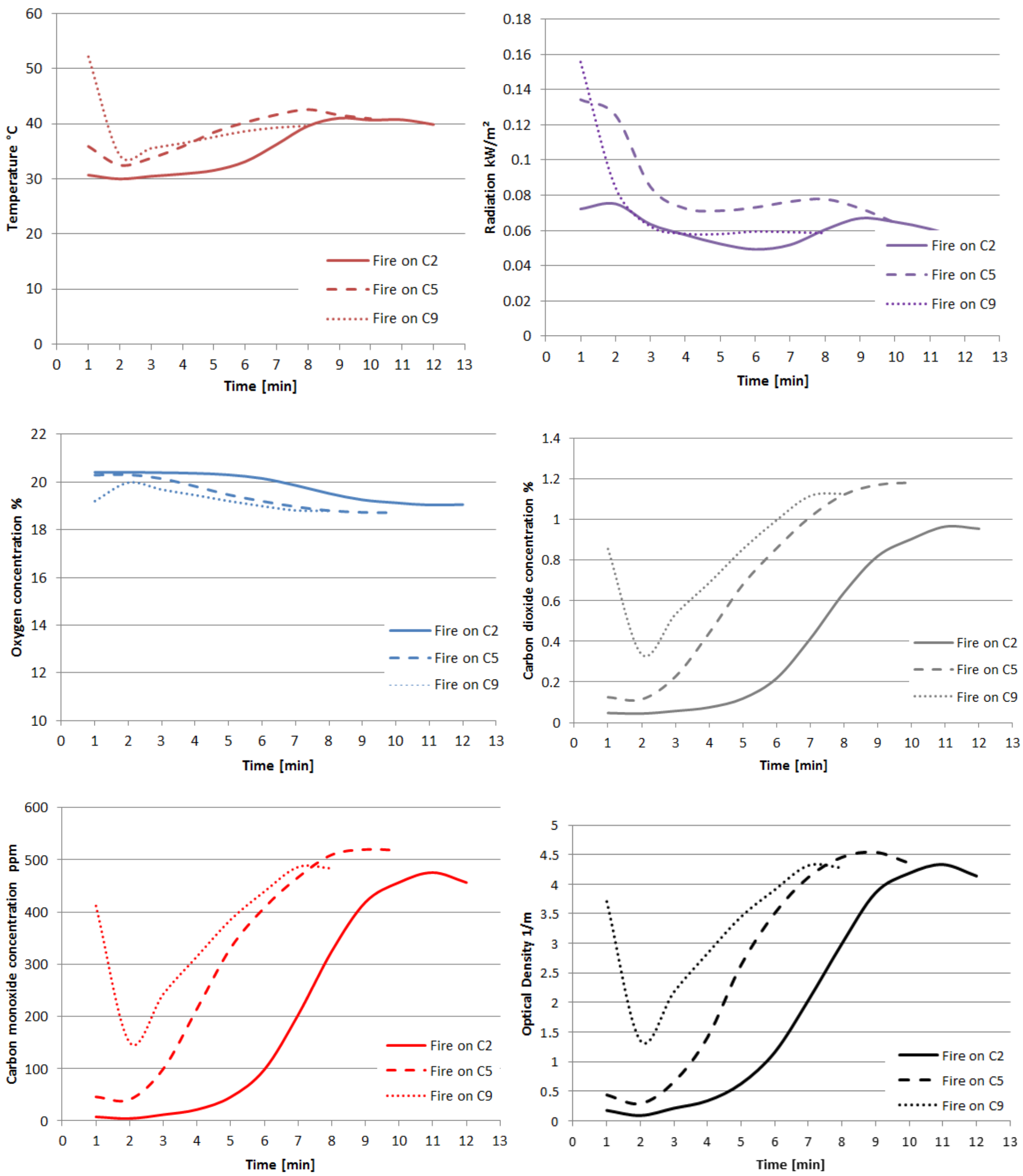

Figure 34 Uncontrolled stop – last evacuee, time concentration curves and temperature at 2m height, natural ventilation

It can be seen that fire growth has a higher influence on temperature, radiation and combustion product concentrations than the dilution processes. The last evacuees exit later for a C9 fire than for a C2 fire. At this time, the fire's size is higher and evacuees exit into a tunnel environment with higher combustion gas concentrations.
The peak combustion gas concentrations for a C9 fire within the first minute is an indicator for dense smoke flowing next to the train. Once the train end has been reached, mixing is increased, which in turn leads to a drop in gas concentrations. Due to further growth of the fire and the mixing processes, which take place with air that is no longer fresh but contaminated, the combustion concentrations keep increasing along the evacuation route. This effect is not seen for C2 and C5 fires, because these fires are possibly too small at those times to evoke this outcome. A growth in combustion products is identified only for those two cases as the evacuee escapes along the tunnel.

In all cases of natural ventilation, the increase of combustion products over time can be explained by a combination of a dissolving stratified smoke layer and a general increase of concentration in the smoke layer caused by the growing fire.

Based on the data presented above, the physical effect on the evacuees is estimated by means of the FED concept. As the goal of this thesis is to provide at a qualitative ranking, the following discussion is based on trends.

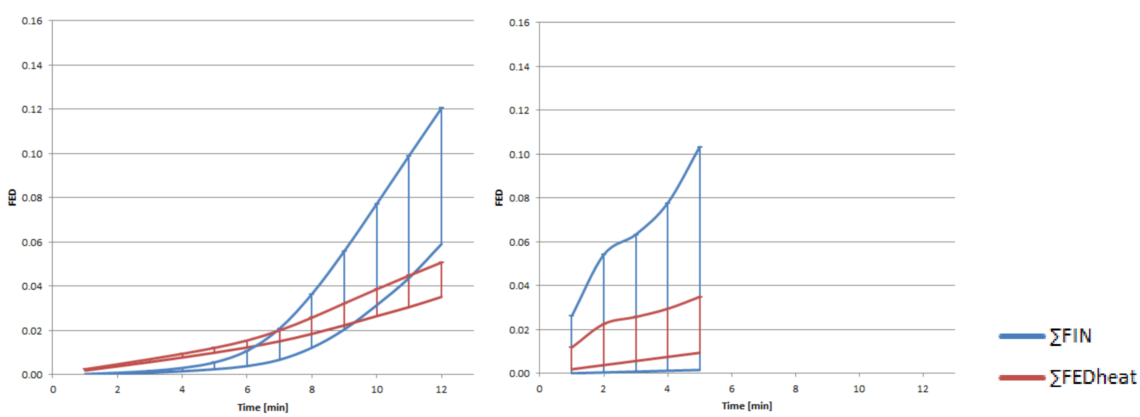

Figure 35 Uncontrolled stop - natural ventilation, FED analysis for a fire on C2

Figure 35 presents FED ranges for the first evacuees (lower range) to the last ones (upper range) for train exit doors C1 (left) and C18 (right). The fire is located on C2.

It is obvious that the first evacuees exiting from C1 are affected by smoke faster than evacuees from C18. Although last evacuees from C18 get off about 1050 seconds later than passengers from C1, the uptake of combustion gases is smaller due to a combination of higher mixing processes along the way and a shorter overall egress time.

The analysis shows that FED values are dominated by asphyxiant gases rather than by radiation and heat effects, as seen in scenarios with unidirectional ventilation.

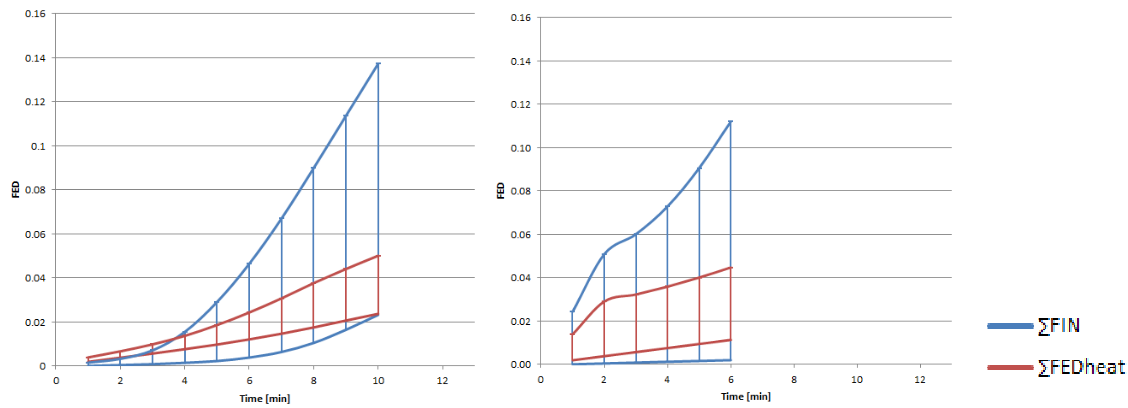

Figure 36 Uncontrolled stop - natural ventilation, FED analysis for a fire on C5

Figure 36 presents FED ranges for the first evacuees (lower range) to the last ones (upper range) for train exit doors C1 (left) and C18 (right). The fire is now located on C5.

A slower increase for the first evacuees exiting from C1 can be seen as the fire is more distant. In general, FED values are slightly higher than for C2 fires, as the number of passengers has increased. However, comparing this trend to the one seen for unidirectional ventilation, the increase is negligible.

FED values for people exiting at C18, are still lower for the same reasons as mentioned for a fire on C2.

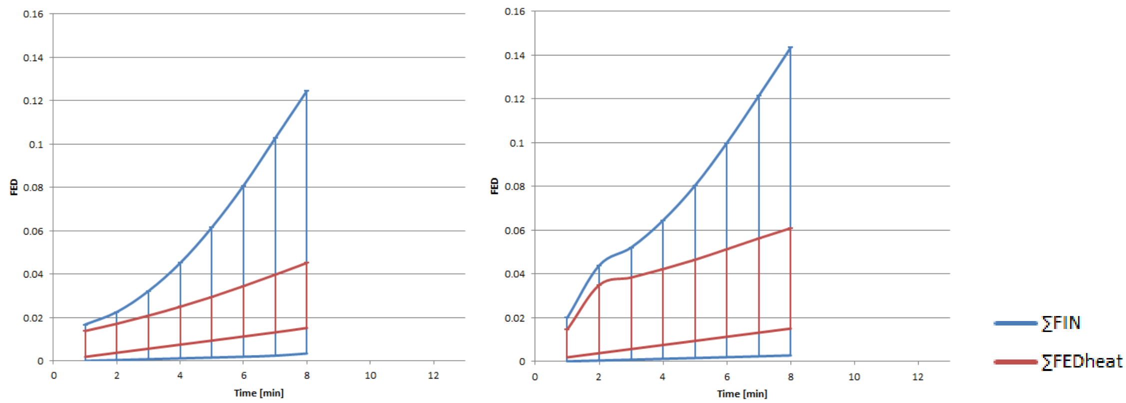

Figure 37 Uncontrolled stop - natural ventilation, FED analysis for a fire on C9

Figure 37 presents FED ranges for the first evacuees (lower range) to the last ones (upper range) for train exit doors C1 (left) and C18 (right). The fire is now located on C9. One would expect to find slightly lower FED values for passengers evacuating from C18, as the exit is one carriage further away from the fire than for evacuees exiting from C1. However, the opposite is found. This is a small error induced by the post-processing of data as values are only assessed every 10 m and FED values are calculated up to full minutes.

Comparing all natural scenarios, it can be seen that the further away the fire is located from the train exit, the higher the difference between FED values for the first and last evacuees. This trend can be identified for both asphyxiants and the heat effect, but is more distinctive when it comes to heat exposure.

FED values of natural ventilated fires are found to be about two orders of magnitude smaller than for ventilated fires, as presented in section 4.1.1.

4.1.3 Bidirectional ventilation

When facilitating a phased evacuation, people in the downstream part of the tunnel have to wait until the upstream part has been evacuated and the ventilation is reversed. Here, the fire behaves in the same way as in the unidirectional scenarios, as the ventilation flow and fire behaviour are the same as well.

Figure 38 indicates the pressure differences across the carriages. The different lines show the carriage-differences from the fire. Number 1 represents the carriage adjacent to the fire. It can be seen that the pressure difference drops along the train. The combustion gases are less diluted for carriages next to the fire, leading to higher mass flows with high concentrations of combustion gases flowing into the carriage.

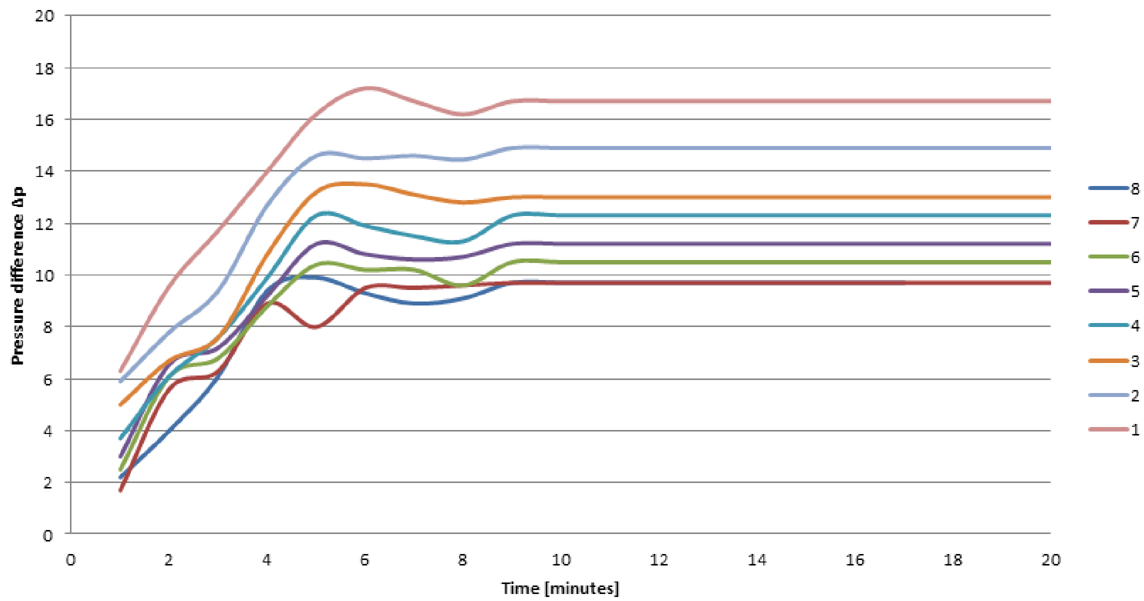

Figure 38 Pressure differences (in Pa) across the carriages in carriage-distances from fire (1=carriage adjacent fire)

As mentioned earlier, the leakage area is trainset-dependent and is likely to increase when the carriages are surrounded by hot smoke. Common sealing materials have a maximum functioning temperature of 150°C (All Seals Inc., 2008). Figure 39 shows the temperature at the top of the carriage, measured in carriage-distances. The highest temperatures − above 800°C − are reached at the carriage adjacent to the fire. Temperatures are lower at the windows, as they are not directly located within the fire plume. However, temperatures are likely to be above 150°C and affect the sealing capacities of the carriage. Investigating the effect of temperature on the increasing sealing area is not within the scope of this thesis. Further research has to be carried out regarding this topic. Therefore, only rough estimates regarding physical effects on passengers by asphyxiants entering the carriages are made. Heat and radiation effects cannot be assessed accurately within the scope of this thesis.

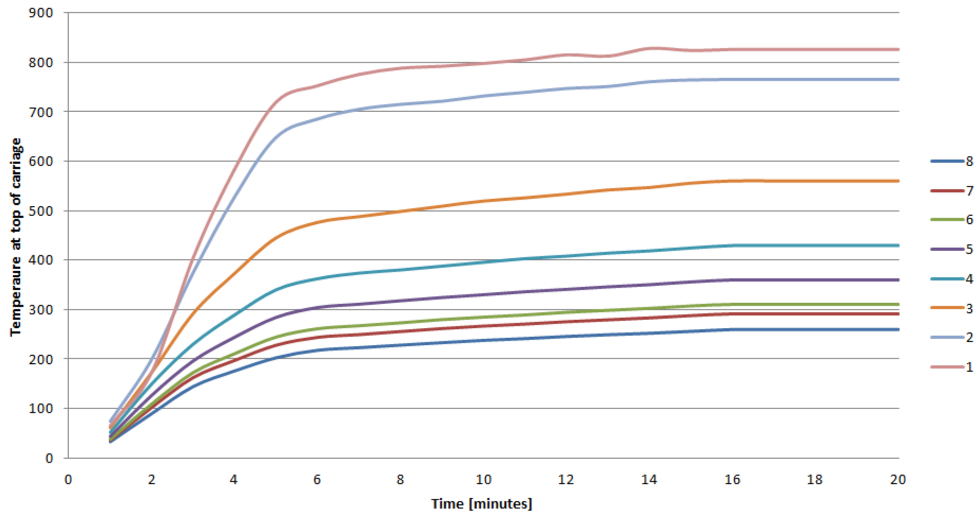

Figure 39 Temperatures at the top of carriages in carriage-distances from fire (1=carriage adjacent fire)

As the leakage area is train-set dependent, the problem is turned around and the leakage area, which causes incapacitation (fractional asphyxiant dose equals 1), for each carriage is calculated within the waiting time of 20 minutes. Thanks to this information, tunnel operators can, in cooperation with train manufacturers, evaluate whether the train-set fulfills the requirements for a phased evacuation with bidirectional ventilation. Train manufacturers can provide adequate information on train-specific leakage areas and behavior of sealing materials when they are exposed to high temperatures. Figure 40 shows the maximum leakage areas in cm^2.

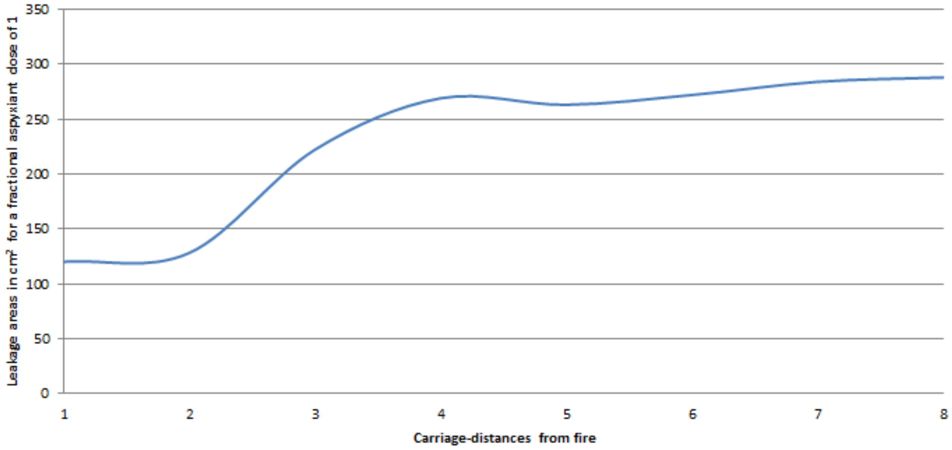

Figure 40 Leakage areas to achieve a fractional asphyxiant dose of 1 within 20 minutes (1=carriage adjacent fire)

It can be seen that the closer the respective carriage is located to the fire, the smaller the leakage area can become. This can be explained by the increasing pressure differences. Although the calculated values are about 20 to 40 times higher than the leakage areas of a very-well sealed carriage (Parsons Brinckerhoff Group Inc, 2013), these areas could be reached when sealing material fails due to the high temperatures, as shown in Figure 39. Additionally, heat and radiation through the windows and the carriage-chassis also affect the passengers. This lies outside the scope of this thesis.

It was found that the depletion of oxygen and creation of carbon dioxide, caused by the breathing of passengers, has a negligible effect on the FED values. Oxygen was reduced by 2 mol per minute. The overall oxygen content is about 1,000 mol within the carriage. In general, FED values of unity are reached when the oxygen concentration within the carriage drops to about 18%. The carbon dioxide and carbon monoxide concentration rose to 1.4% and 0.21%, respectively. As mentioned earlier, heat and radiation effects through the windows and other parts of the chassis have not been investigated.

Human behaviour during the waiting time has to be taken into account as well. An incident in the London Underground's Holland Park Station showed an example of how people react when metro carriages start to fill up with smoke (BBC, 2013) (YouTube, 2013). Another example, where smoke entered a train carriage, was the incident of Heavy Goods Vehicle shuttle No 7539 in the Channel tunnel in 1996. The amenity coach was already filled with smoke after a short time and passengers suffered from smoke inhalation (Channel Tunnel Safety Authority, 1997). It lies outside the scope of this thesis to investigate differences in the passengers' behaviour during the phased evacuation waiting time. Further research has to be carried out regarding human behaviour and other organisational aspects of phased evacuations.

In general, scenarios with a change of ventilation direction highly depend on the construction of the carriages and the willingness of passengers to wait. As presented in the examples above, people are likely to react with fear when the carriage is surrounded by black smoke, which enters through small opening and cracks. The tunnel operator might provide guidance on how to react in emergency situations and give instructions via loudspeakers. However, this does not guarantee that passengers will stay on the train and they might exit into a smoke-logged tunnel.

4.2 Controlled stop situations

Controlled stop situations present the ideal evacuation case, as both train exit doors are closest to the cross passages. Travel distances for evacuees are minimized to 38 m. Cross passages are separated by 375 m, whereas the train exit doors lie 300 m apart. Conservatively, another 10 m travel length is assumed to reach a smoke-free atmosphere within the cross-passage tunnel. In total, passengers are exposed to combustion products, raised temperatures and radiation over a travel distance of about 50 m. Assuming a conservative walking speed in a smoke-laden environment of 0.5 m/s, evacuees are exposed for 2 minutes (rounded up from 1.7).

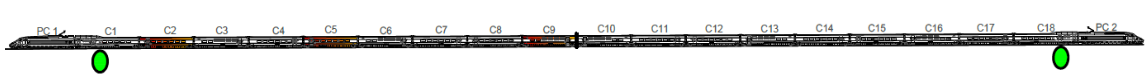

Figure 41 Controlled stop situation

Table 6 Uncontrolled stop - unidirectional and natural ventilation, physical and chronological data

Fire on	Train exit door location [m]	Cross Passage location [m]	Affected passengers	Last evacuee exiting train [s]
C2	0	-50	104	201
C5	0	-50	272	526
C9	0	-50	375	725

In general, evacuees are affected by the same temperatures, levels of radiation and combustion gas concentrations as discussed in section 4.1.1 for unidirectional ventilation and in section 4.1.2 for natural ventilation. Therefore, no additional data is presented at this point, except for FED values, which are accumulated within the first two minutes exposure. Table 7 shows a comparison on the FED for controlled stop situations for unidirectional and bidirectional ventilation scenarios with different fire locations.

Table 7 Controlled stop situations - exposure for 2 minutes

Ventilation	Fire on	Evacuee	Exposure	
Unidirectional	C2	First	$\sum FIN$	0.024
			$\sum FED_{heat}$	0.205
		Last	$\sum FIN$	0.276
			$\sum FED_{heat}$	31.6
	C5	First	$\sum FIN$	0.008
			$\sum FED_{heat}$	0.03
		Last	$\sum FIN$	0.043
			$\sum FED_{heat}$	1.57
	C9	First	$\sum FIN$	0.004
			$\sum FED_{heat}$	0.011
		Last	$\sum FIN$	0.044
			$\sum FED_{heat}$	0.454

Natural (C1 exit)	C2	First	∑FIN	0.000
			$\sum FED_{heat}$	0.004
		Last	∑FIN	0.001
			$\sum FED_{heat}$	0.004
	C5	First	∑FIN	0.000
			$\sum FED_{heat}$	0.004
		Last	∑FIN	0.003
			$\sum FED_{heat}$	0.007
	C9	First	∑FIN	0.000
			$\sum FED_{heat}$	0.004
		Last	∑FIN	0.023
			$\sum FED_{heat}$	0.017

Based on the data presented above, it can be stated that natural ventilation in combination with simultaneous evacuation is most feasible for controlled stop situations with limited exposure times. The first passengers experience slightly raised heat exposure due to the elevated temperature in the tunnel. The last evacuees are exposed to low concentrations of combustion gases which raise the fractional asphyxiant dose slightly.

When facilitating unidirectional ventilation, heat exposure remains the most important hazard for evacuees. Only if the fire is located far away from the train exit doors, like a fire on C9, a safe egress might be possible.

At this point, it can be said that it is not feasible to facilitate a phased evacuation in controlled stop situations. Passengers would reach the same FED values, as presented in section 4.1.3 for uncontrolled stops, as the 20 minutes waiting time does not change. The carriages would be surrounded by high temperature smoke, which in turn would affect their construction materials. No reasonable recommendation can be made regarding phased evacuations until there has been further research on leakage areas and the effect of high temperatures on sealing products.

To conclude, for controlled stop situations with limited travel distances, natural ventilation in combination with simultaneous evacuation leads to the lowest FED values.

4.3 Ranking of scenarios

Based on the previously presented results, the following ranking can be established. The ranking is independent of the final stop location of the train.

For fires on the two power cars (PC1, PC2) and on the end-carriages (C1, C18):

1.) Unidirectional ventilation (simultaneous evacuation)
2.) Natural ventilation (simultaneous evacuation)
~~3.) Bidirectional ventilation (phased evacuation)~~

Fires at the two end carriages represent special cases, as only few passengers are placed on one side and all the other passengers on the other side. It is reasonable to assume that passengers within the incident carriage can escape to adjacent carriages during the initial phase of the fire. The same can be assumed for the driver. Hence, the preferable method is to direct the smoke away from the majority of passengers with unidirectional ventilation. All passengers evacuate through the opposite train end door. As an alternative, natural ventilation can be used. Based on the fact that few or no occupants are placed on one side of the fire, bidirectional ventilation with a phased evacuation is not worth considering.

For fires on any other carriage (C2 to C17):

1.) Natural ventilation (simultaneous evacuation)
~~?.) Unidirectional ventilation (simultaneous evacuation)~~
~~?.) Bidirectional ventilation (phased evacuation)~~

The CFD simulations have shown that natural ventilation is the preferred ventilation strategy when the fire is located somewhere between carriages C2 and C17. When facilitating unidirectional ventilation, the fire grows to peak values, making an evacuation unlikely to be successful. Although all data presented in this thesis is used only to establish a qualitative ranking of scenarios, there is clear indication that unidirectional ventilation procedures with simultaneous evacuation are not feasible. Up to this point, a justifiable conclusion about bidirectional ventilation with phased evacuation cannot be drawn, as there is not enough evidence to make an informed judgment about the feasibility of this method. Furthermore, this evacuation strategy cannot be generalized, as it always depends on the construction materials of the carriage.

If the fire’s location − for any reason whatsoever − is not known, natural ventilation should be preferred over other strategies.

4.4 How to treat uncertainties and assumptions

Up to this point, initial output data was used as input parameters for the FED model in order to estimate the effects on evacuees. It can be said that CFD simulations never represent reality and are prone to uncertainties and errors. Among others, the numerical solutions of the Navier Stokes Equations, human factors, the grid size and physical assumptions introduce uncertainties and errors in the CFD code. An over- or under-prediction of input parameters for the FED model is therefore possible. A grid independence check for the CFD simulation is presented in Annex A2. These questions remain: What effect does this have on the overall ranking of egress scenarios? Does the ranking of scenarios change, if higher or lower input values of the FED model are introduced?

To answer those questions, the effect on the rankings of egress scenarios in varying input parameters of the FED model is investigated. Up to this point, FED values for unidirectional ventilation scenarios are higher than for natural ventilation scenarios. This is the case for all fire locations on the train. It needs to be investigated whether or not varying input parameters could change this ranking. In order to do so, reasonable ranges in carbon dioxide and carbon monoxide yields, oxygen concentrations and temperature and radiation levels have to be found. Within the groups of uncontrolled and controlled stops, the above mentioned input parameters of the FED model are changed in disfavour regarding the ranking of scenarios. This means, for example, that temperature is decreased for a scenario with a fire on C2 with unidirectional ventilation, whereas the temperature is increased for the same scenario with natural ventilation. This approach investigates whether reasonable temperature variations have an effect on the ranking. If the ranking by means of FED values is still the same, it can be said that temperature errors, which originate from the CFD simulations, have no effect on the overall ranking of scenarios.

Relevant literature (Karlsson & Quintiere, 2000) reports that carbon dioxide yields of 1.5 g/g can be expected for well-ventilated fires. The stoichiometric maximum yield is 2.2

g/g. Therefore, the carbon dioxide yield for natural ventilated fires is raised by 47% in order to challenge the overall ranking.

Carbon monoxide represents a key factor in egress situations, as small doses can affect egress capabilities (Stec & Hull, 2010). As presented in earlier sections, the carbon monoxide yield varies strongly depending on the ventilation conditions. An engineering assumption was made that the carbon monoxide yield is determined by the equivalence ratio inside of the carriage. External flaming was taken into account by reducing the yield to 25% of its original value, as found by Gottuk (1992). In order to challenge the rankings, carbon monoxide yields for natural ventilated fires are raised to the same values as for scenarios with unidirectional ventilation. Yields for scenarios with unidirectional ventilation are maintained.

The lowest oxygen concentrations for scenarios with unidirectional ventilation are 16% (decrement of 4.9%), whereas lowest oxygen concentrations with natural ventilations drop to 19% (decrement of 1.9%). In order to challenge the ranking, additional 18% (rel.) oxygen concentrations of its original value is introduced for unidirectional ventilation, whereas natural ventilation values are reduced by 18% (relative) of its original values.

Temperatures differ significantly between unidirectional and natural ventilated scenarios. When neglecting the direct plume interaction of fires at C2 with the train exit door (350°C), maximum temperatures of about 200°C are achieved for scenarios with unidirectional ventilation (45 MW fire). On the other hand, scenarios with natural ventilation reach only 40°C as evacuees escape under the stratified smoke layer of the relatively small 10 MW fire. In order to challenge the scenarios, temperatures of unidirectional ventilation scenarios are lowered by 25% (200 °C to 150 °C), whereas temperatures of natural ventilation scenarios are raised by 25% (40 °C to 50 °C).

In order to maintain the temperature to the forth power relationship between for radiation, radiation is changed according to the ± 25% temperature ranges. That means that radiation levels for scenarios with unidirectional ventilation are lowered by 56% (200 °C to 150 °C), whereas levels for natural ventilated fires are raised by 13% (40 °C to 50 °C).

The values mentioned above represent maxima. The variations are introduced for each time step with their respective values within the above mentioned regions in per-cent.

The parameter variation is carried out for uncontrolled stop situations in which the last evacuees are compared.

4.4.1 Variation in carbon dioxide concentrations

Carbon dioxide affects the evacuee's breathing rate and therefore increases the uptake of other combustion gas products like carbon monoxide (Stec & Hull, 2010). However, Table 8 shows that when varying the carbon dioxide concentration, the overall ranking of scenarios does not change. A minor effect on the fractional asphyxiant dose is seen. Therefore, inaccurate carbon dioxide data on the part of CFD simulations and other engineering assumptions have no effect. Scenarios with natural ventilation are still preferable.

Table 8 Carbon dioxide variation

Variation	Scenario	∑FIN original	New ∑FIN	Change in ranking
CO_2 not changed	Uni C2	2.14	Already stoichiometric values	No change
	Uni C5	1.05		
	Uni C9	0.55		
CO_2 raised by 47%	Nat C2	0.12	0.13	
	Nat C5	0.13	0.14	
	Nat C9	0.13	0.14	

4.4.2 Variation in carbon monoxide concentrations

In order to challenge the ranking regarding carbon monoxide uptake, CO yields are varied in the following manner. Scenarios with unidirectional ventilation (high CO concentrations) include already a conservative reduction of 75% of CO due to external flaming (Gottuk, 1992). Therefore, carbon monoxide yields for unidirectional ventilation are not changed.

Carbon monoxide yields for natural ventilated fires are raised to the same values as seen in unidirectional ventilation to 5% (raised by 200%). This approach can be seen as conservative, as the natural ventilated fires do not reach a heavy under-ventilated combustion region. A fire in this region does not lead to high production rates of carbon monoxide (Gottuk & Lattimer, 2002).

Table 9 Carbon monoxide variation

Variation	Scenario	∑FIN original	New ∑FIN	Change in ranking
CO yield lowered	Uni C2	2.14	Already conservative values	No change
	Uni C5	1.05		
	Uni C9	0.55		
CO yield raised	Nat C2	0.12	0.49	
	Nat C5	0.13	0.51	
	Nat C9	0.13	0.51	

Although the carbon monoxide yields for the natural ventilated fire are raised (by 200%) to the same yields as used in scenarios with unidirectional ventilation, no change in the overall ranking can be observed. However, the fractional asphyxiant doses for fires on C9 almost converge.

4.4.3 Variation in oxygen concentrations

When comparing the lowest oxygen concentrations of scenarios with unidirectional ventilation and scenarios with natural ventilation, a relative difference of 18% can be noticed. In order to challenge the scenarios' rankings, oxygen of unidirectional ventilation scenarios are raised by 18% (to absolute 21.0%) and those with natural ventilation lowered by 18% (to absolute 15.5%).

Table 10 Oxygen variation

Variation	Scenario	∑FIN original	New ∑FIN	Change in ranking
O_2 level raised	Uni C2	2.14	2.12	No change
	Uni C5	1.05	1.04	
	Uni C9	0.55	0.55	

O_2 level lowered	Nat C2	0.12	0.16	
	Nat C5	0.13	0.16	
	Nat C9	0.13	0.16	

The results of Table 14 show, that the fractional asphyxiant dose is affected insignificantly by changing oxygen concentrations in the mentioned range.

4.4.4 Variation in temperature

Both temperature and radiation levels serve as input parameters for the fractional heat dose. As mentioned above, temperatures are lowered by 25% of their initial values for scenarios with unidirectional ventilation, whereas the temperature of scenarios with natural ventilation is raised by 25%. As a reminder, the FED value for a fire on C2 and unidirectional ventilation arises due to direct plume contact at the train exit door at C1.

Table 11 Temperature variation

Variation	Scenario	$\sum FED_{heat}$ original	New $\sum FED_{heat}$	Change in ranking
T level raised	Uni C2	40.2	21.7	No change
	Uni C5	3.71	1.4	
	Uni C9	1.43	0.54	
T level lowered	Nat C2	0.05	0.11	
	Nat C5	0.05	0.1	
	Nat C9	0.05	0.1	

Table 11 indicated that temperature variations of 25% do not change the overall ranking of scenarios. However, additional tests are carried out. It is assumed that the CFD code can accurately predict temperature for the 45MW fire, as used in unidirectional ventilation. For the same grid, it is reasonable to assume that higher uncertainties arise in the smaller 10 MW fire, as used for natural ventilated fires. Therefore, the temperature of scenarios with unidirectional ventilation is kept constant while temperatures of natural ventilated fires are raised to the same level of $\sum FED_{heat}$. The results show that temperatures of natural ventilated fires on C2 have to be raised by 610%, temperatures of C5 fires by 260% and temperatures of a C9 fires by 175%. To conclude, despite possible temperature uncertainties, natural ventilated scenarios are preferable in terms of temperate effects.

4.4.5 Variations in radiation levels

In general, evacuees are mostly affected by radiation originating from particles in the smoke. The intensity is hereby dependent on the smoke temperature, the smoke particle concentration and the view factor, which describes geometrical aspects of the set-up (Drysdale, 2011). As the CFD software uses a fixed soot yield, the soot concentration cannot be varied in post-processing. However, the values, as chosen in the CFD code, are seen as conservative for the fire's peak values. The view factor does not change as the geometrical set-up is the same. Hence, the radiation is changed according to a temperature to the forth power dependence between radiation and temperature. Possible variations in radiation are calculated based on the ±25% variation in temperature (°C) based on section 4.4.4. This leads to a reduction of radiation by 56% for scenarios with unidirectional ventilation and a rise of 13% for scenarios with natural ventilation.

Table 12 Radiation variation based on temperature

Variation	Scenario	$\sum FED_{heat}$ original	New $\sum FED_{heat}$	Change in ranking
Q_{rad} level raised	Uni C2	40.2	29.95	No change
	Uni C5	3.71	3.71	
	Uni C9	1.43	1.43	
Q_{rad} level lowered	Nat C2	0.05	0.05	
	Nat C5	0.05	0.05	
	Nat C9	0.05	0.05	

The reason why only one fractional heat dose changes is because the FED model only takes into account radiation when the smoke temperature is above 200°C (Purser, 2002). Temperature values above this are only present in scenario C2 with unidirectional ventilation. Radiation levels are below the common tenability criteria (Stec & Hull, 2010) of 2.5 kW/m² for all scenarios, except for a fire on C2 with unidirectional ventilation. In this latter scenario, evacuees are – for a short time − directly affected by radiations from flames and smoke.

To conclude, if the exit is not adjacent to the source of the fire, radiation levels do not affect the fractional heat dose.

4.5 Summary of assumptions

This section provides an overview of the assumptions/limitations of this thesis. Specific justifications can be found in the respective sections.

- In choosing a representative tunnel and train set-up it is hoped that the findings of this thesis can be applied to a wide range of tunnels (section 3.3.2).
- The initial ventilation direction for unidirectional ventilation scenarios is assumed to be set in a direction that exposes fewer passengers to smoke (section 3.2.1).
- The design fires are based on full-scale test of slightly outdated but still representative trains. Additionally, PU-foam is assumed to be the dominant fuel (section 3.3).
- Smoke ingress into the end carriage through the open door is not considered (section 3.1).
- Equivalence ratio correlations are used in post-processing in order to estimate the transient generation of CO and soot (section 3.4). This concept assumes that CO_2 and CO/soot are mixed equally with fresh air when flowing further down the tunnel.
- The engineering approach for phased evacuation with bidirectional ventilation assumes a waiting time of 20 minutes and that the carriage is a control volume with uniform gas content. Furthermore, equally sized leakage areas on both ends of the carriage are assumed (section 3.5).
- An evacuation from the train end doors is assumed (chapter 4).
- Passengers’ egress time estimates are based on a general walking speed of 0.5 m/s (Annex A1).

5. Conclusion and recommendations for further research

This thesis aimed to develop strategies for egress from burning trains in ventilated tunnels as well as rank different scenarios to give qualitative guidance for various ventilation and egress procedures.

In order to achieve these goals, CFD simulations were carried out for three ventilation strategies and different fire locations on representative train models within a representative tunnel environment. Two different train stop locations within the tunnel and three different egress strategies have been analysed. A qualitative ranking of preferable egress strategies has been developed on the basis of hazardous exposure of evacuees by combustion gases and heat effects.

- Findings from a toxicity assessment (FED) suggest that fires on the power cars and train end-carriages require a simultaneous evacuation with a forced ventilation flow (with unidirectional ventilation) to direct the smoke away from passengers. Alternatively, natural ventilation (without forced airflow) could be used.
- If the fire is located somewhere else in the train, natural ventilation in combination with simultaneous evacuation should be preferred.
- In case the fire's location is unknown, natural ventilation should be preferred.
- An evacuation for the last evacuees is not possible for worst-case escape lengths when facilitating unidirectional ventilation. If tunnel operators do not use natural ventilation in such cases, the last evacuees cannot escape.

Due to limited resources for conducting research on carriage leakage areas and performance of sealing materials when exposed to high temperature smoke, general guidance on phased evacuation with a reversed forced airflow (bidirectional ventilation) could not be given.

Apart from the qualitative ranking, the results show that the first three recommendations, as stated above, do not depend on the stop location within the tunnel. The effects of fire effluents within each ventilation scenario are the same for controlled (train exit doors in alignment with emergency exits) and uncontrolled stops. However, the exposure time for evacuees is longer for uncontrolled stops. Hence, the aim should always be to stop the train in a controlled stop position.

The fire's location determines the number of affected passengers, the combustion gas concentrations and temperature and radiation effects over the entire escape length. Generally, it can be stated that, the further away the fire is located from the train exit doors, passengers are exposed to lower fire effluents concentrations. This observation is valid for all ventilation and egress strategies.
Heat effects on evacuees are found to be more dominant in controlled as well as uncontrolled stop situations when facilitating forced ventilation flow (unidirectional ventilation). In contrast, the effects of asphyxiants are more dominant than heat effects in uncontrolled stop situations when using natural ventilation (no forced airflow).
The fire's size mainly depends on the type of ventilation used. When facilitating forced ventilation flow (unidirectional ventilation), the fire growth is larger and peak values reach higher levels. This is seen as the dominant factor why natural ventilation is preferred in most scenarios. The increased dilution process of forced ventilation cannot compensate the increased combustion gas concentrations.

It has to be highlighted that values, as used in this thesis, aim to draw general conclusions and offer a qualitative ranking regarding ventilation and egress procedures. By no means should the values be used in risk assessment for further projects. The numbers are not hard and fast and have only been used to attain general findings within this thesis. Although this thesis aimed to choose representative tunnel and train set-ups, all deviations in respect to real tunnels have to be considered and general findings of this thesis may have to be re-evaluated.

More research is necessary to fully understand the fire development in modern rail carriages. There is a lack of knowledge in the field of full-scale testing for rail carriages that comply with current fire safety standards. The implementation of flame spread, heat output and toxicity limits in current train construction standards (BS EN 45545, 2013) are likely to influence the overall fire behaviour of modern trains. As long as no full-scale tests have been carried out, there is no way to justify lower heat release rate curves other than those used within this thesis.

Furthermore, it is necessary to test phased evacuation procedures with reversible forced airflows regarding the following two aspects: Firstly, full-scale tests need to be carried out in order to see the effects of high temperature smoke on leakage areas and sealing products. It is essential to determine whether or not leakage areas would increase and how sealing materials would perform under these conditions. Secondly, the influence of human behaviour in phased evacuation procedures has to be further examined. More particularly, human behaviour in the presence of smoke ingress into the carriage through gaps and smaller openings has to be studied.

Although this thesis offers useful insights and trends regarding evacuation from burning trains in ventilated tunnels, further research is recommended to obtain strategies that can improve the safety of passengers even further.

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Annex A1. Estimation of the egress time

In order to determine the required simulation time for assessing the conditions in the tunnel, preliminary movement time calculations are carried out. Hence, the scenario with the longest movement time determines the simulation time. The movement time calculations are based on following equation (Nelson & Mowrer, 2002).

$$t_m = \frac{N}{W \cdot F_s} + \frac{L}{S}$$

Where:

t_e is the movement time [s]

N is the total population [-]

W is the width of the exit [m]

F_s is the specific flow of the exit [P/(m·s)]

L is the travel length [m]

S is the movement speed [m/s]

The first part of the equation indicates the time needed in order to pass N people through the train exit door, whereas the second part stands for the travel time of the last passenger from the exit door to the cross passage. In end of train evacuations, passengers have to overcome a vertical distance from the train to the walkway. Fridolf (2010) shows that this distance affects the flow rate through exit doors. However, suitable bridging between the train and the tunnel walkway can be expected, as for example required in the Channel Tunnel (Channel Tunnel Intergovernmental Commission, 2013). Therefore a low vertical distance can be expected. Based on a collection of intercity and international train egress data made by Fridolf (2010), a specific flow in the range of 0.574 to 0.935 P/(m·s) for vertical distances from 0.3 to 0.7 m is realistic. The exit widths varied hereby between 0.9 and 1.4 m. In order to carry out a conservative estimation of the overall movement time, an exit width of 0.9m and a specific flow of 0.574 P/(m·s) is chosen. As mentioned in section 2.3, a passenger train with a length of 450 m can have a capacity up to about 800 passengers. Depending whether the train stops in a controlled or uncontrolled state, the number of affected passengers and their travel length vary significantly.

Representative numbers of passengers are taken from the Eurostar seating plan (Eurostar (U.K.) Ltd, 2013). Table 13 shows the distribution of passengers along the train.

Table 13 Passenger distribution Eurostar train

Car description	Number of passengers
Power car (PC)	-
Carriage 1 (C1)	48
Carriage 2 (C2) to Carriage 5 (C5)	56 each
Carriage 6 (C6)	Variable (Bar-Buffet)
Carriages 7 and 8 (C7 and C8)	39 each
Carriages 9 and 10 (C9 and C10)	25 each
Carriages 11 and 12 (C11 and C12)	39 each
Carriage 13 (C13)	Variable (Bar-Buffet)
Carriage 14 (C14) to Carriage 17 (C17)	56 each
Carriage 18 (C18)	48
Power car (PC)	-
	Total: 750 passengers

Depending on the type of ventilation and the fire's location, different numbers of passengers are affected. Table 14 shows an overview.

Table 14 Overview affected passengers

Ventilation	Fire on	Affected passengers
Unidirectional ventilation	Carriage 2	48+56 Left side: **104 passengers**
	Carriage 5	48 + 4·56 Left side: **272 passengers**
	Carriage 9	48+4·56+2·39+25 Left side: **375 passengers**

Natural ventilation	Carriage 2	Left side: **104 passengers** Right side: **646 passengers**
	Carriage 5	Left side: **272 passengers** Right side: **478 passengers**
	Carriage 9	Left side: **375 passengers** Right side: **375 passengers**

Assuming an average car/carriage length of 20 m, different egress path lengths for uncontrolled stops are identified. A distinction between unidirectional and natural ventilation directions must be made. Based on a 375 m cross passage separation, Table 15 shows worst case travel lengths of passengers. The values represent the travel length from the train end exit doors to the cross passage. Passengers are hereby assumed not to travel adjacent the fire.

Table 15 Maximum travel distance estimation

Ventilation	Fire on	Cross passage at	Travel distance
Unidirectional ventilation	Carriage 2	Carriage 3	**Left Side:** 375 m – (2·20 m) **335 m**
	Carriage 5	Carriage 6	**Left Side:** 375 m – (5·20 m) **275 m**
	Carriage 9	Carriage 10	**Left Side:** 375 m – (2·20 m) **195 m**
Natural ventilation	Carriage 2	Carriage 3	**Left Side: 335 m** **Right Side:** 375 m – (16·20 m) **55 m**
	Carriage 5	Carriage 6	**Left Side: 275 m** **Right Side:** 375 m – (13·20 m) **115 m**
	Carriage 9	Carriage 10	**Left Side: 195 m** **Right Side:** 375 m – (9·20 m) **195 m**

Findings by the METRO Project (Ingason, et al., 2012) recommend an average walking speed of 0.9 m/s in smoke filled environments. This value was determined experimentally in a smoke logged tunnel with visibility ranges from 1.5 to 3.5 m. As it is not guaranteed that a visibility of 1.5m can be maintained, a conservative walking speed of 0.5 m/s is chosen.

Table 16 summarized the data which is used to assess the total simulation time. An additional 60 s prior to the start of the travel time is given to establish the flow conditions within the tunnel.

Table 16 Total simulation time assessment

Ventilation	Fire on	Travel distance based on Table 15	Affected passengers	Travel time	Simulation time
Unidirectional ventilation	Carriage 2	**Left Side: 335 m**	**104**	**872 s**	**940 s**
	Carriage 5	**Left Side: 275 m**	**272**	**1077 s**	**1140 s**
	Carriage 9	**Left Side: 195 m**	**375**	**1116 s**	**1180 s**
Natural ventilation	Carriage 2	**Left Side: 335 m** **Right Side: 55 m**	**104** **646**	**872 s** **1361 s**	**1430 s**
	Carriage 5	**Left Side: 275 m** **Right Side: 115 m**	**272** **478**	**1077 s** **1156 s**	**1220 s**
	Carriage 9	**Left Side: 195 m** **Right Side: 195 m**	**375** **375**	**1116 s** **1116 s**	**1180 s**

Annex A2. Additional fire data

						Fire location						Position of first evacuee		
Air supply carriage kg/s	Minute	Burning rate kg/s	Equivalence Ratio [-]	YCO kg/kg	Ysoot kg/kg	%CO ppm v/v at 20°C	Plume Temperate °C	%soot g/m³	%CO2 %	CO/(Rise CO2)	ratio CO2/soot	%CO ppm v/v at 20°C	%soot g/m³	OD 1/m
4.9	1	0.20	0.36	0.002	0.121	209.6	88.0	12.17	0.004	24.0	1.40	146.67	8.52	16.29
	2	0.61	1.09	0.010	0.151	1056.8	230.5	10.84	0.010	40.2	0.41	471.91	4.84	9.26
Window Opening	3	1.01	1.82	0.052	0.172	5543.7	390.5	9.41	0.017	129.3	0.22	3254.90	5.52	10.57
0.9	4	1.41	2.54	0.054	0.191	5725.5	628.6	7.66	0.026	84.2	0.11	2691.43	3.60	6.89
Window Height	5	1.76	3.17	0.054	0.205	5772.8	838.4	6.68	0.036	61.5	0.07	2380.50	2.76	5.27
0.6	6	1.81	3.26	0.054	0.207	5777.1	871.2	6.55	0.038	58.9	0.07	2426.26	2.75	5.26
Number Window	7	1.81	3.26	0.054	0.207	5777.1	881.3	6.49	0.038	57.9	0.07	2703.21	3.04	5.81
14	8	1.81	3.26	0.054	0.207	5777.1	866.8	6.58	0.037	60.3	0.07	2979.08	3.39	6.49
	9	1.81	3.26	0.054	0.207	5777.1	879.2	6.50	0.038	58.0	0.07	3177.85	3.58	6.85
	10	1.81	3.26	0.054	0.207	5777.1	873.7	6.54	0.038	59.0	0.07	3580.76	4.05	7.75
	11	1.81	3.26	0.054	0.207	5777.1	879.3	6.50	0.038	57.9	0.07	3574.63	4.02	7.70
	12	1.81	3.26	0.054	0.207	5777.1	878.1	6.51	0.038	58.7	0.07	2904.92	3.27	6.26
	13	1.81	3.26	0.054	0.207	5777.1	885.5	6.47	0.039	57.5	0.06			
	14	1.81	3.26	0.054	0.207	5777.1	878.9	6.51	0.038	58.6	0.07			
	15	1.81	3.26	0.054	0.207	5777.1	886.9	6.46	0.038	57.9	0.06			
	16	1.81	3.26	0.054	0.207	5777.1	887.8	6.46	0.039	57.3	0.06			

Figure 42 Raw fire data each minute - unidirectional ventilation, fire on C2

						Fire location						Position of first evacuee		
Air supply carriage kg/s	Minute	Burning rate kg/s	Equivalence Ratio [-]	YCO kg/kg	Ysoot kg/kg	%CO ppm v/v at 20°C	Plume Temperate °C	%soot g/m³	%CO2 %	CO/(Rise CO2)	ratio CO2/soot	%CO ppm v/v at 20°C	%soot g/m³	OD 1/m
4.9	1	0.02	0.04	0.006	0.098	614.3	63.2	10.54	0.003	107.5	1.84	0.02	0.00	0.00
	2	0.06	0.11	0.006	0.105	653.2	110.4	9.94	0.005	50.6	0.77	0.05	0.00	0.00
Window Opening	3	0.10	0.18	0.007	0.111	697.0	150.1	9.47	0.007	37.3	0.51	2.62	0.04	0.07
0.9	4	0.14	0.25	0.007	0.115	747.0	190.0	9.01	0.010	30.4	0.37	9.62	0.12	0.22
Window Height	5	0.18	0.32	0.008	0.119	804.7	233.3	8.54	0.012	25.9	0.27	16.88	0.18	0.34
0.6	6	0.22	0.40	0.008	0.123	872.1	274.0	8.15	0.015	23.4	0.22	32.23	0.30	0.58
Number Window	7	0.26	0.47	0.009	0.127	951.7	312.0	7.83	0.017	22.1	0.18	72.90	0.60	1.15
14	8	0.30	0.54	0.010	0.130	1047.2	348.8	7.56	0.019	21.5	0.16	142.51	1.03	1.97
	9	0.34	0.61	0.011	0.133	1163.8	395.8	7.20	0.022	20.7	0.13	211.51	1.31	2.50
	10	0.38	0.69	0.012	0.136	1309.3	440.9	6.89	0.025	20.5	0.11	275.21	1.45	2.77
	11	0.40	0.72	0.013	0.137	1394.6	465.4	6.73	0.026	20.5	0.10	306.67	1.48	2.83
	12	0.40	0.72	0.013	0.137	1394.5	467.1	6.72	0.026	20.4	0.10	369.36	1.78	3.40
	13	0.40	0.72	0.013	0.137	1394.5	470.9	6.68	0.027	20.1	0.10			
	14	0.40	0.72	0.013	0.137	1394.5	475.4	6.64	0.028	19.5	0.09			
	15	0.40	0.72	0.013	0.137	1394.5	478.8	6.61	0.028	18.9	0.09			
	16	0.40	0.72	0.013	0.137	1394.5	479.8	6.60	0.029	18.5	0.09			
	17	0.40	0.72	0.013	0.137	1394.5	484.2	6.57	0.030	18.0	0.08			
	18	0.40	0.72	0.013	0.137	1394.5	486.4	6.55	0.030	17.6	0.08			
	19	0.40	0.72	0.013	0.137	1394.5	487.6	6.54	0.031	17.4	0.08			
	20	0.40	0.72	0.013	0.137	1394.5	490.0	6.52	0.031	17.1	0.08			
	21	0.40	0.72	0.013	0.137	1394.5	493.0	6.49	0.032	16.9	0.08			
	22	0.40	0.72	0.013	0.137	1394.5	493.4	6.49	0.032	16.7	0.08			
	23	0.40	0.72	0.013	0.137	1394.5	494.6	6.48	0.032	16.5	0.08			
	24	0.40	0.72	0.013	0.137	1394.5	495.1	6.47	0.033	16.3	0.08			

Figure 43 Raw fire data each minute - natural ventilation, fire on C2

Annex A3. Grid independence check

In order to get a certain confidence in the simulation results, a grid independence check is carried out for one scenario (fire on C2). As the goal is to achieve grid independent results on evacuee's positions, temperature, radiation and carbon dioxide is compared at head height at the train exit door at C1. Other input parameters like carbon monoxide are not tested, as they are calculated in post-processing.

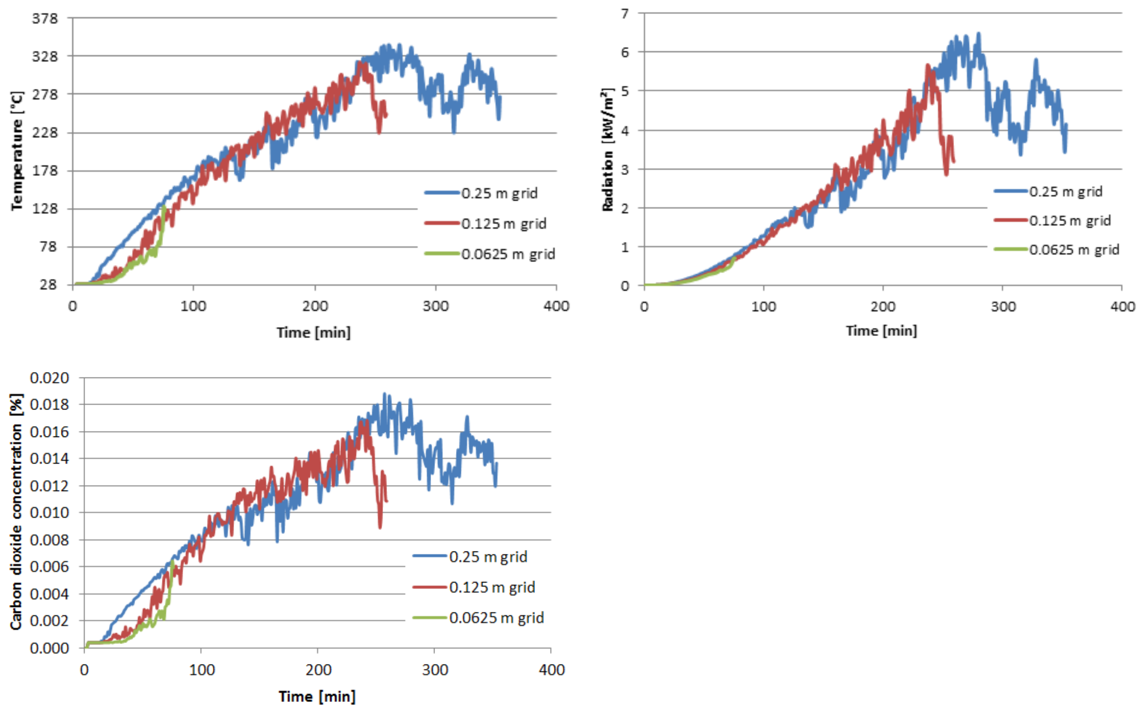

Figure 44 Grid independence check - unidirectional ventilation cases

The data shows good agreement with the medium and fine grid. A general overprediction by a coarse grid is likely because the grid cannot fully resolve the turbulence and the plume entrainment is not presented in a correct way. However, also the coarse grid gives reasonable results.

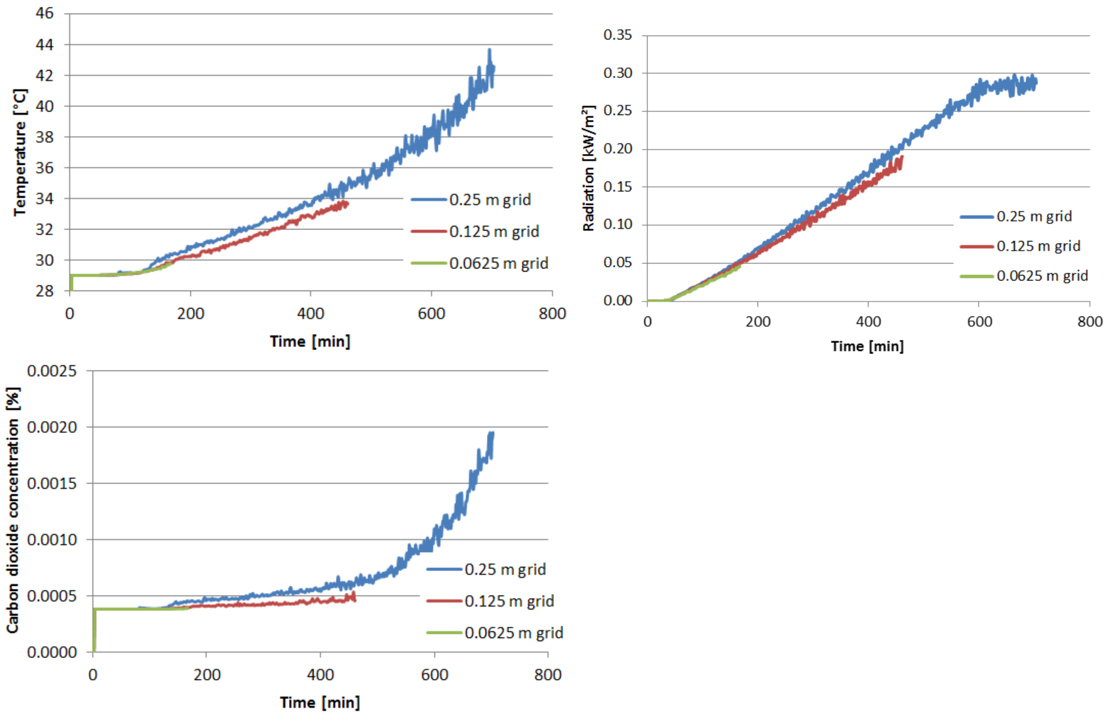

Figure 45 Grid independence check - natural ventilation cases

The same trend can be seen for cases of natural ventilation cases, as shown in Figure 45. Due to limitations regarding computational power available, the simulations are run on a coarse grid only. The variation of input parameters on the overall ranking of scenarios is studied in section 4.4. It has been found out that reasonable variations do not change the ranking.

The FDS manual suggests to use the expression D^*/δ for buoyant plumes in order to determine the mesh resolution. These calculations have been carried out, but are not presented at this point because it is an indication for plumes without interaction with forced air flows. Furthermore, it is not applicable for vertical fire boundaries, as used in this research project. Therefore, a grid independence check, as presented in this section, is seen as more appropriate.

Annex A4. FDS input files unidirectional ventilation

```
Sc_Bi_C2.fds
Generated by PyroSim - Version 2014.1.0110
25.03.2014 12:24:09

&HEAD CHID='Sc_Bi_C2'/
&TIME T_END=940.0/
&DUMP RENDER_FILE='Sc_Bi_C2.ge1', DT_DEVC=1.0, DT_RESTART=100.0/
&MISC HUMIDITY=70.0, TMPA=29.0, INITIAL_UNMIXED_FRACTION=0.0/
&RADI RADIATIVE_FRACTION=0.3/

&MESH ID='Mesh01-a-a-a-a', IJK=200,33,27, XB=-312.0,-262.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-a', IJK=200,33,27, XB=-262.0,-212.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-a', IJK=200,33,27, XB=-212.0,-162.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-b-a', IJK=200,33,27, XB=-162.0,-112.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-b-b-a', IJK=200,33,27, XB=-112.0,-62.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-b-b-b-a', IJK=200,33,27, XB=-62.0,-12.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-b-b-b-b-a', IJK=200,33,27, XB=-12.0,38.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-b-b-b-b-b-b-b', IJK=180,33,27, XB=38.0,83.0,-2.0,6.25,-0.25,6.5/

&SPEC ID='CARBON DIOXIDE', FYI='CO2'/
&SPEC ID='CARBON MONOXIDE', FYI='CO'/
&SPEC ID='OXYGEN', FYI='O2'/

&PART ID='Tracer',
      FYI='Tracer to invesitgate airflow',
      MASSLESS=.TRUE.,
      MONODISPERSE=.TRUE.,
      COLOR='BLACK',
      AGE=60.0,
      SAMPLING_FACTOR=10/

 &REAC ID='MaterialMix_REAC',
      FYI='PU-Foam, SFPE Handbook, GM25',
      FUEL='REAC_FUEL',
      C=1.0,
      H=1.7,
      O=0.32,
      N=0.07,
      SOOT_YIELD=0.2,
      HEAT_OF_COMBUSTION=2.49E4/
```

(Excerpt for devices)

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&DEVC ID='CO2_0m', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=28.75,-0.5,2.5/
&DEVC ID='CO2_10m', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=38.75,-0.5,2.5/

&DEVC ID='O2_0m', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=28.75,-0.5,2.5/
&DEVC ID='O2_10m', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=38.75,-0.5,2.5/

&DEVC ID='T_0m', QUANTITY='TEMPERATURE', XYZ=28.75,-0.5,2.5/
&DEVC ID='T_10m', QUANTITY='TEMPERATURE', XYZ=38.75,-0.5,2.5/

&DEVC ID='Qrad_0m', QUANTITY='RADIATIVE HEAT FLUX GAS', XYZ=28.75,-0.5,2.5, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='Qrad_10m', QUANTITY='RADIATIVE HEAT FLUX GAS', XYZ=38.75,-0.5,2.5, ORIENTATION=1.0,0.0,0.0/

&DEVC ID='CO2_Plume01', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=51.25,0.5,3.0/
&DEVC ID='CO2_Plume02', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=48.0,0.5,3.0/
&DEVC ID='CO2_Plume03', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=45.25,0.5,3.0/
&DEVC ID='CO2_Plume04', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=43.75,0.5,3.0/
&DEVC ID='CO2_Plume05', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=43.25,0.5,3.25/
&DEVC ID='CO2_Plume06', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=43.0,0.5,3.5/
&DEVC ID='CO2_Plume07', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=48.0,0.25,3.0/
&DEVC ID='CO2_Plume08', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=45.25,0.25,3.0/
```

```
&MATL ID='CONCRETE',
      FYI='Concrete - (Drysdale, 2011)',
      SPECIFIC_HEAT=0.88,
      CONDUCTIVITY=0.8,
      DENSITY=1900.0/

&SURF ID='ADIABATIC',
      COLOR='GRAY 80',
      ADIABATIC=.TRUE./
&SURF ID='TunnelLining',
      GEOMETRY='CYLINDRICAL',
      BACKING='EXPOSED',
      MATL_ID(1,1)='CONCRETE',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.5,
      LAYER_DIVIDE=0.0/
&SURF ID='Ventilation_Supply_Center',
      FYI='Ventilation Supply 70.4mÂ³/s',
      RGB=102,204,255,
      VOLUME_FLUX=-100.0,
      PART_ID='Tracer',
      DT_INSERT=0.1/
&SURF ID='Fire',
      FYI='Fire',
      COLOR='BLACK',
      HRRPUA=1071.0,
      RAMP_Q='Fire_RAMP_Q'/
&RAMP ID='Fire_RAMP_Q', T=0.0, F=0.0/
&RAMP ID='Fire_RAMP_Q', T=270.0, F=1.0/
```

(Excerpt for train obstruction)

```
&OBST XB=0.5,22.5,0.75,3.5,1.0,1.25, COLOR='YELLOW', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=0.5,22.5,0.75,3.5,0.75,1.0, COLOR='YELLOW', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=1.0,22.5,1.0,3.25,0.5,0.75, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=0.75,22.5,0.75,3.5,1.25,1.5, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=1.0,22.5,0.75,3.5,1.5,1.75, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
```

(Excerpt for tunnel obstruction)

```
&OBST XB=-312.0,83.0,4.0,6.25,-0.25,0.25, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,83.0,-2.0,4.0,-0.25,0.0, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,83.0,-2.0,0.25,0.0,0.5, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,83.0,-2.0,-1.25,0.5,0.75, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,83.0,-2.0,-1.25,0.75,1.0, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel

&VENT SURF_ID='Ventilation_Supply_Center', XB=83.0,83.0,-0.5,4.75,0.5,5.25/ Vent_Rear_Center
&VENT SURF_ID='OPEN', XB=83.0,83.0,0.25,4.0,0.0,0.5/ Vent_Rear_Bottom
&VENT SURF_ID='OPEN', XB=83.0,83.0,-1.25,-0.5,0.5,4.5/ Vent_Rear_Right
&VENT SURF_ID='OPEN', XB=83.0,83.0,4.75,5.5,0.5,4.5/ Vent_Rear_Left
&VENT SURF_ID='Fire', XB=44.0,58.0,0.75,0.75,1.5,3.0/ Vent_FIRE_Left
&VENT SURF_ID='Fire', XB=44.0,58.0,3.5,3.5,1.5,3.0/ Vent_FIRE_Right

&SLCF QUANTITY='TEMPERATURE', PBY=-0.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=-0.5/
&SLCF QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', PBY=-0.5/
&SLCF QUANTITY='VISIBILITY', PBY=-0.5/
&SLCF QUANTITY='OPTICAL DENSITY', PBY=-0.5/
&SLCF QUANTITY='PRESSURE', PBY=0.5/
&SLCF QUANTITY='TEMPERATURE', PBY=0.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=0.5/
&SLCF QUANTITY='DENSITY', PBY=0.5/
&SLCF QUANTITY='PRESSURE', PBY=0.75/
&SLCF QUANTITY='PRESSURE', PBY=1.5/
&SLCF QUANTITY='PRESSURE', PBY=2.25/
&SLCF QUANTITY='PRESSURE', PBY=2.75/
&SLCF QUANTITY='PRESSURE', PBY=3.5/
&SLCF QUANTITY='PRESSURE', PBX=23.0/
&SLCF QUANTITY='PRESSURE', PBX=42.25/


&TAIL /
```

Annex A5. FDS input files natural ventilation

```
1703_Sc_N_C2_25cm.fds
Generated by PyroSim - Version 2014.1.0110
18.03.2014 07:45:27

&HEAD CHID='1703_Sc_N_C2_25cm'/
&TIME T_END=1430.0/
&DUMP RENDER_FILE='1703_Sc_N_C2_25cm.ge1', DT_DEVC=1.0, DT_RESTART=300.0/
&MISC HUMIDITY=70.0, TMPA=29.0/
&RADI RADIATIVE_FRACTION=0.3/

&MESH ID='Mesh01-a-a-a-a-a', IJK=376,33,27, XB=-312.0,-218.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-a', IJK=376,33,27, XB=-218.0,-124.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-a', IJK=376,33,27, XB=-124.0,-30.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-b-a', IJK=376,33,27, XB=-30.0,64.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-b-b-a', IJK=376,33,27, XB=64.0,158.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-b-b-b-a', IJK=376,33,27, XB=158.0,252.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-b-b-b-b-a', IJK=376,33,27, XB=252.0,346.0,-2.0,6.25,-0.25,6.5/
&MESH ID='Mesh01-a-a-a-a-b-b-b-b-b-b-b', IJK=376,33,27, XB=346.0,440.0,-2.0,6.25,-0.25,6.5/

&SPEC ID='CARBON DIOXIDE', FYI='CO2'/
&SPEC ID='CARBON MONOXIDE', FYI='CO'/
&SPEC ID='OXYGEN', FYI='O2'/

&REAC ID='MaterialMix_REAC',
      FYI='PU-Foam, SFPE Handbook, GM25',
      FUEL='REAC_FUEL',
      C=1.0,
      H=1.7,
      O=0.32,
      N=0.07,
      SOOT_YIELD=0.09,
      HEAT_OF_COMBUSTION=2.49E4/
```

(Excerpt for devices)

```
&DEVC ID='CO2_0m', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=28.75,-0.5,2.5/
&DEVC ID='CO2_10m', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=38.75,-0.5,2.5/

&DEVC ID='O2_0m', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=28.75,-0.5,2.5/
&DEVC ID='O2_10m', QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', XYZ=38.75,-0.5,2.5/

&DEVC ID='T_0m', QUANTITY='TEMPERATURE', XYZ=28.75,-0.5,2.5/
&DEVC ID='T_10m', QUANTITY='TEMPERATURE', XYZ=38.75,-0.5,2.5/

&DEVC ID='Qrad_0m', QUANTITY='RADIATIVE HEAT FLUX GAS', XYZ=28.75,-0.5,2.5, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='Qrad_10m', QUANTITY='RADIATIVE HEAT FLUX GAS', XYZ=38.75,-0.5,2.5, ORIENTATION=1.0,0.0,0.0/

&DEVC ID='CO2_Plume01', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=54.25,0.5,3.0/
&DEVC ID='CO2_Plume02', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=51.0,0.5,3.0/
&DEVC ID='CO2_Plume03', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=48.25,0.5,3.0/
&DEVC ID='CO2_Plume04', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=46.75,0.5,3.0/
&DEVC ID='CO2_Plume05', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=46.25,0.5,3.25/
&DEVC ID='CO2_Plume06', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=46.0,0.5,3.5/
&DEVC ID='CO2_Plume07', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=51.0,0.625,3.0/
&DEVC ID='CO2_Plume08', QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE', XYZ=48.25,0.625,3.0/
&MATL ID='CONCRETE',
      FYI='Concrete - (Drysdale, 2011)',
      SPECIFIC_HEAT=0.88,
      CONDUCTIVITY=0.8,
      DENSITY=1900.0/

&SURF ID='ADIABATIC',
      COLOR='GRAY 80',
      ADIABATIC=.TRUE./
```

```
&SURF ID='TunnelLining',
      GEOMETRY='CYLINDRICAL',
      BACKING='EXPOSED',
      MATL_ID(1,1)='CONCRETE',
      MATL_MASS_FRACTION(1,1)=1.0,
      THICKNESS(1)=0.5,
      LAYER_DIVIDE=0.0/
&SURF ID='Fire',
      FYI='Fire',
      COLOR='BLACK',
      HRRPUA=238.0,
      RAMP_Q='Fire_RAMP_Q'/
&RAMP ID='Fire_RAMP_Q', T=0.0, F=0.0/
&RAMP ID='Fire_RAMP_Q', T=600.0, F=1.0/
```

(Excerpt for train obstruction)

```
&OBST XB=0.5,22.5,0.75,3.5,1.0,1.25, COLOR='YELLOW', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=0.5,22.5,0.75,3.5,0.75,1.0, COLOR='YELLOW', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=1.0,22.5,1.0,3.25,0.5,0.75, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=0.75,22.5,0.75,3.5,1.25,1.5, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=1.0,22.5,0.75,3.5,1.5,1.75, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
&OBST XB=1.5,22.5,0.75,3.5,1.75,2.0, COLOR='GRAY 80', SURF_ID='ADIABATIC'/ Obstruction
```

(Excerpt for tunnel obstruction)

```
&OBST XB=-312.0,440.0,4.0,6.25,-0.25,0.25, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,440.0,-2.0,4.0,-0.25,0.0, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,440.0,-2.0,0.25,0.0,0.5, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,440.0,-2.0,-1.25,0.5,0.75, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel
&OBST XB=-312.0,440.0,-2.0,-1.25,0.75,1.0, COLOR='GRAY 94', OUTLINE=.TRUE., SURF_ID='TunnelLining'/ Tunnel

&VENT SURF_ID='OPEN', XB=-312.0,-312.0,-0.5,4.75,0.5,5.25/ Vent_Front_Center
&VENT SURF_ID='OPEN', XB=-312.0,-312.0,0.25,3.75,5.25,6.0/ Vent_Front_Top
&VENT SURF_ID='OPEN', XB=-312.0,-312.0,0.25,4.0,0.0,0.5/ Vent_Front_Bottom
&VENT SURF_ID='OPEN', XB=-312.0,-312.0,-1.25,-0.5,0.5,4.5/ Vent_Front_Right
&VENT SURF_ID='OPEN', XB=-312.0,-312.0,4.75,5.5,0.5,4.5/ Vent_Front_Left
&VENT SURF_ID='OPEN', XB=440.0,440.0,-0.5,4.75,0.5,5.25/ Vent_Rear_Center
&VENT SURF_ID='OPEN', XB=440.0,440.0,0.25,3.75,5.25,6.0/ Vent_Rear_Top
&VENT SURF_ID='OPEN', XB=440.0,440.0,0.25,4.0,0.0,0.5/ Vent_Rear_Bottom
&VENT SURF_ID='OPEN', XB=440.0,440.0,-1.25,-0.5,0.5,4.5/ Vent_Rear_Right
&VENT SURF_ID='OPEN', XB=440.0,440.0,4.75,5.5,0.5,4.5/ Vent_Rear_Left
&VENT SURF_ID='Fire', XB=44.0,58.0,0.75,0.75,1.5,3.0/ Vent_FIRE_Left
&VENT SURF_ID='Fire', XB=44.0,58.0,3.5,3.5,1.5,3.0/ Vent_FIRE_Right

&SLCF QUANTITY='TEMPERATURE', PBY=-0.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=-0.5/
&SLCF QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN', PBY=-0.5/
&SLCF QUANTITY='VISIBILITY', PBY=-0.5/
&SLCF QUANTITY='OPTICAL DENSITY', PBY=-0.5/
&SLCF QUANTITY='PRESSURE', PBY=0.5/
&SLCF QUANTITY='TEMPERATURE', PBY=0.5/
&SLCF QUANTITY='VELOCITY', VECTOR=.TRUE., PBY=0.5/
&SLCF QUANTITY='DENSITY', PBY=0.5/


&TAIL /
```