Parameters that affect tenability conditions during fire emergency in metro tunnels

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Abstract. Underground spaces are characterized by special conditions and complexity, as well as by severe consequences in the event of an accident. Although the frequency of fire accidents in tunnels or metro stations is low, in worst cases they may lead to severe fatalities and damages. In order to have a more accurate prediction of fire impacts, most safety standards enforced worldwide suggest the development of special risk analyses. This needs to be made having in mind fire characteristics, geometrical and ventilation parameters so as to have an accurate view of the thermal and smoke propagation within the underground space. In this paper a parametric analysis is carried out, varying input values, crucial for fire risk analysis, like fire curve and heat release rate maximum (HRRmax), as well as ventilation and tunnel geometry. Key factors like visibility conditions, temperature and CO concentration are recorded through the fire dynamic simulation (FDS), in order to determine the conditions inside the metro tunnel. Furthermore, the fractional effective dose (FED) that occupants might receive in a period of time, in different positions inside the tunnel, is calculated. Based on the above, detailed data on the prevailing conditions are gathered and conclusions can be drawn regarding the influence of each parameter’s evolution on the tenability conditions inside the tunnel. Hence, the analysis can illuminate key issues to consider for performing an accurate risk analysis in an underground environment.

1. Introduction
The main goal of the fire management strategy is to avoid people interaction with fire hazards (smoke, toxic gases, thermal radiation etc.). An appropriate fire scenario will assist in developing reliable predictions concerning byproducts during numerical simulations, so that a realistic available safe escape time (ASET) can be estimated. The simulation of the phenomenon of fire is an extremely challenging procedure due to the combined influence of different parameters and the fact that minor variations of these parameters can be significant for the development of the fire. Nevertheless, the need for a realistic simulation of fire development is essential for the estimation of the environmental conditions and consequently of the available safe egress time (ASET). The estimation of ASET can lead to conclusions regarding the adequate measures that should be taken during the design of an underground space. According to the research programme UPTUN-WP2 [1] during the risk analysis various scenarios should be considered, so that the conditions that are created inside the tunnel can be thoroughly examined. Nevertheless, the analysis of the impact of each parameter that affects fire development is a time-consuming procedure and can lead to a large number of simulations, which could cause confusion regarding the final choice of the adequate parameters.
In this paper a parametric analysis is carried out, in order to identify the parameters that affect fire development and consequently the environmental conditions inside a tunnel. Parameters that are inserted during fire design and tunnel design are altered in order to examine their effect on visibility conditions, CO concentration and mainly on fractional effective dose (FED). FED constitutes the dose of toxic products of the fire that occupants receive in a period of time, which leads to incapacitation and death [2], as estimated by the following equation (1). Therefore, FED demonstrates the effect of fire and smoke to occupants and can be used as an indicator for the evolutions of the conditions inside the tunnel, regarding a safe evacuation.

\[
FED = \frac{\text{dose received in a period of time (Ct)}}{\text{dose Ct which leads to incapacitation and death}}
\]  

(1)

The calculation of FED used in the paper is made following the equations described in the SFPE Handbook of Fire Protection Engineering [3], and used in Pathfinder evacuation software, shown below. The equation uses only the concentrations of the narcotic gases CO, CO₂ and O₂ to calculate the FED [4].

\[
FED_{\text{tot}} = FED_{\text{CO}} + VCO_2 + FED_{O_2}
\]  

(2)

When FED reaches the value of 1 it indicates the incapacitation of the users. Through the fire dynamic simulation (FDS), the conditions inside the metro tunnel are determined, emphasizing on the tenability of the users and hence this provides direct linkage to the maximum available time for them to reach a point of safety out of the tunnel. Thus, a number of parameters are modelled and used in the analysis to assess the importance of each one in the whole system. Therefore, through the process described above, this paper provides valuable information on how various parameters affect tenability conditions, which could be taken into account when performing a fire risk analysis in a tunnel and an underground space.

2. Parametric analysis

The CFD code of FDS (Fire Dynamic Simulation) is used for the current study. FDS is a fully verified and validated CFD code that has been successfully used in simulations of fires in closed or open spaces. In current study, the Pyrosim software was used that is a graphical user interface of FDS [5]. The simulations of FED, its evolution though time, and, the assessment of FED that occupants receive in a period of time, in different positions inside the tunnel, is calculated through evacuation software named Pathfinder, which is an agent-based egress and human movement simulator [6].

The parameters that are examined are the geometry of the tunnel (width, height), the intensity and evolution of the fire as given by the heat release rate (HRR) curve and \(HRR_{\text{max}}\), the time period until the \(HRR_{\text{max}}\) is reached, as well as the tunnel ventilation characteristic, as denoted by the airflow velocity attained. The values of the examined parameters are chosen based on guidance for fire emergency data in rail tunnels. Each parameter as well as the values selected for the assessment is analyzed hereinafter:

- **Tunnel geometry**: the length of the tunnel is chosen to be 300 meters for the purposes of the analysis, so that the simulation time is reduced. The width and the height of the tunnel vary from 4 to 8 meters. According to NFPA the maximum tunnel length between metro stations or station and a ventilation shaft should be 700 meters. The height dimensions of the tunnel in the Athens metro vary from 4.5, 6 and 7 meters for single, double and triple rail respectively. The width dimensions vary from 5, 8.5 and 14 meters for single, double and triple rail as well [7].

- **HRR\(_{\text{max}}\)**: HRR is considered by many researchers as the most important parameter when defining the severity of an accident [8]. The estimations of HRR\(_{\text{max}}\) is based on previous accidents in metro stations, large scale experiments on railway carriages, small scale experiments and dynamic simulations. When analyzing evacuation efficiency in self-rescue what interests most is the maximum value of HRR within a refrained time period, since the users have to evacuate the underground space within minutes. From the research conducted it can be said that the maximum HRR could reach the value of 30MW within this time frame [9] [10]
Therefore, scenarios of 5, 10, 15 and 20 MW were created, which are considered values possible to be achieved in a small period of time (Figure 1). The same curve proposed by Gao et al. [15] with different values of HRR maximum is inserted in the fire dynamics software, so that the effect of the HRR maximum is examined.

Figure 1. HRR curves used in the analysis.

- **Time until HRR$\text{max}$ is reached - fire growth rate**: for the purposes of the analysis the time when the maximum HRR is reached is considered between 3 and 5 minutes. From the majority of test results, it can be concluded that a maximum value of 5, 10, 15 and 20 MW can be achieved within this time frame [1] [16] [17] [18]. The fire growth rate defines the time when HRR$\text{max}$ is reached which is usually time squared dependent and therefore the $t^2$-fire growth model is used [19] where the fire growth rate alters and the value of HRR$\text{max}$ of 10 MW is reached in different points of time. Ingason [18] proposes for the growth rate the value of 0.01 for rail and 0.3 for metro train. UPTUN-WP2 [1] proposes the value $a=10$ MW/min for fires under 30 MW.

- **Ventilation – airflow velocity**: according to the NFPA 130 [20] the airflow velocity as given by the ventilation system may vary among 0.75 and 11 m/sec. Beard et al. [21] have studied the impact of ventilation on HRR for airflow values ranging from 0 to 12 m/sec. The NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways 2020 [22] includes a new Annex D Critical Velocity Calculation for a tunnel with a height of 5 m, and width of 12 m, for a range of heat release rates from 5,000 kW to 30,000 kW. In order to estimate air velocities for smoke control in emergency situations, a typical critical airflow velocity ranges approximately between 2-2.5 m/sec [23]. According to the above, for the parametric analysis three different values of airflow velocity were used, taking the values of 1 m/s, 2 m/s and 3 m/s.

- **Burning Material**: as burning material is chosen the FRP Polyester, which is present often in rail vehicles and its properties are described in Table 1. Furthermore, the fire source is situated in the middle of the tunnel, which constitutes the worst-case scenario of an emergency event. Also, the burning area is assumed to be whole area of a typical carriage (18 m length, 2.8 m-width and 2.5 m-height), or approx. 50 m$^2$.

Table 1. Thermodynamic parameters of the FRP material used as the main burning source.

| Parameter of FRP polyester material | value          |
|------------------------------------|----------------|
| Energy per unit mass O$_2$ (kJ/kg of O$_2$) | 11,900         |
| Effective heat of combustion (kJ/kg)    | 12,870         |
| Fraction of CO from fuel (kg/kg)       | 0.0705         |
| Fraction of Soot from fuel (kg/kg)     | 0.062          |
| Radiative fraction (%)                | 0.35           |
Based on all the above, a total of 21 scenarios were used in the parametric analysis. The characteristics and details of each one are presented in Table 2.

Table 2. Scenarios of parametric analysis.

| Scenario id | Burning Material | Tunnel Width (m) | Tunnel Height (m) | Tunnel Length (m) | HRR\(_{\text{max}}\) (MW) | Time to HRR\(_{\text{max}}\) (s) | Airflow velocity (m/s) |
|-------------|------------------|------------------|-------------------|-------------------|---------------------------|-----------------------------|------------------------|
| 1           | FRP poly         | 4                | 4                 | 300               | 10                        | 180                         | -                      |
| 2           | FRP poly         | 4                | 4                 | 300               | 15                        | 180                         | -                      |
| 3           | FRP poly         | 4                | 6                 | 300               | 10                        | 180                         | -                      |
| 4           | FRP poly         | 4                | 8                 | 300               | 10                        | 180                         | -                      |
| 5           | FRP poly         | 4                | 8                 | 300               | 15                        | 180                         | -                      |
| 6           | FRP poly         | 4                | 6                 | 300               | 15                        | 180                         | -                      |
| 7           | FRP poly         | 4                | 8                 | 300               | 10                        | 180                         | -                      |
| 8           | FRP poly         | 6                | 4                 | 300               | 20                        | 180                         | -                      |
| 9           | FRP poly         | 4                | 6                 | 300               | 20                        | 180                         | -                      |
| 10          | FRP poly         | 6                | 4                 | 300               | 20                        | 180                         | -                      |
| 11          | FRP poly         | 4                | 6                 | 300               | 5                         | 180                         | -                      |
| 12          | FRP poly         | 8                | 6                 | 300               | 10                        | 180                         | -                      |
| 13          | FRP poly         | 4                | 4                 | 300               | 15                        | 180                         | -                      |
| 14          | FRP poly         | 8                | 6                 | 300               | 15                        | 180                         | -                      |
| 15          | FRP poly         | 8                | 4                 | 300               | 10                        | 180                         | -                      |
| 16          | FRP poly         | 4                | 8                 | 300               | 20                        | 180                         | -                      |
| 17          | FRP poly         | 4                | 4                 | 300               | 10                        | 250                         | -                      |
| 18          | FRP poly         | 4                | 4                 | 300               | 10                        | 320                         | -                      |
| 19          | FRP poly         | 4                | 6                 | 300               | 15                        | 180                         | 1 m/s                  |
| 20          | FRP poly         | 4                | 6                 | 300               | 15                        | 180                         | 2 m/s                  |
| 21          | FRP poly         | 4                | 6                 | 300               | 15                        | 180                         | 3 m/s                  |

3. Results and Discussion

Initially the effect of the tunnel geometry on tenability conditions, as modeled by the FED, inside the tunnel is examined, with respect to the fire intensity (as modeled with the use of HRR). The analysis is held for a tunnel height of 4, 6 and 8m (tunnel width of 4 m) and HRR of 10, 15 and 20 MW, respectively. The control points for the measurements of fire products are placed at intervals of 50 m inside the tunnels, and the same intervals are used for FED measurements. The carbon monoxide (CO) concentration is also modelled, as it can be seen in Figure 3, allowing for accurate measurements at the level of the user’s height. In Figure 3 the CO concentration is presented for the cases of HRR\(_{\text{max}}\) having values of 10 and 20 MW, respectively. Indicative limit values of CO concentration and time of exposure for tenability are given below [SFPE, 2016]:

- 6,000 to 8,000ppm for a 5 min exposure
- 1,400 to 1,700ppm for a 30 min exposure

The results from the modelling of soot visibility are presented in Figure 4, for the case of 3 selected tunnel heights (4, 6 and 8) and 2 particular HRR of 10 and 15 MW, respectively. For the case of the lower HRR some differentiation in the conditions can be experienced, however the deterioration of the situation is quite fast. In largest fires, the visibility conditions experience almost the same behavior within a matter of seconds.

The results of FED shown in Figure 5 below and refer to the area 50-100m from fire position, where the highest values of FED are traced inside the tunnel.
Figure 2. Visualization of CO concentration (mol/mol) in the FDS Software for HRR$_{\text{max}}$=20 MW at t=489.5s.

Figure 3. Effect of tunnel height on CO concentration (ppm) for HRRmax 10 (a) and 20 (b) MW.

Figure 4. Effect of tunnel height on visibility for HRRmax 10 (a) and 15 (b) MW.
Based on the data acquired through the modelling it becomes obvious that the tunnel height plays an important role on the tenability conditions. Moreover, its role seems to become more crucial when a more intense fire is encountered. This is depicted in Figure 2c \(|\text{HRR}_{\text{max}} = 20 \text{ MW}\) where it can be seen that if the tunnel height is increased from 4 to 6 m, this delays the development of critical conditions for the users \((\text{FED}=1)\) for almost 200s, a critical window of opportunity for the users to attain self-rescue. A more comprehensive picture of the attained conditions is given in Table 3, where more details are given on the results. The \(\text{FED}_{\text{max}}\) value is also presented, along with the \(\text{ASET}\) time attained in each scenario, which depicts the time when the \(\text{FED}\) value reaches the critical threshold of 1.

| Tunnel height (m) | HRR\(_{\text{max}}\) (MW) | \(\text{FED}_{\text{max}}\) | ASET (s) \((\text{FED}=1)\) |
|-------------------|--------------------------|----------------|-----------------|
| 4                 | 10                       | 0.7            | \(\text{Not reached}\) |
| 6                 | 10                       | 0.5            | \(\text{Not reached}\) |
| 8                 | 10                       | 0.3            | \(\text{Not reached}\) |
| 4                 | 15                       | 1.5            | 450             |
| 6                 | 15                       | 1.0            | 720             |
| 8                 | 15                       | 0.5            | \(\text{Not reached}\) |
| 4                 | 20                       | 3.0            | 380             |
| 6                 | 20                       | 1.5            | 600             |
| 8                 | 20                       | 1.0            | 720             |

It can be seen that for the 10MW fire critical \(\text{FED}\) values are not reached within the time of the simulation \((720s)\). This is the case for the 15MW fire in the 8-m height tunnel, where the max \(\text{FED}\) value measured was 0.5. In the case of the 20MW fire if the tunnel height is increased from 4 to 6m this results in a delay of about 200s in reaching critical values – as discussed previously – a delay time that is reduced to 100s if the height was increased from 6 to 8m. Also, in the 20MW fire the max \(\text{FED}\) value for the 8-m tunnel is almost one third of the one attained for the 4-m height tunnel.

The effect of the tunnel geometry in the \(\text{FED}\) evolution is also proved based on the data obtained with respect to the \(\text{FED}\) values taken with respect to the tunnel width. These data, for the same HHR\(_{\text{max}}\) values of 10, 15 and 20MW, as in the case of tunnel height, are presented in Figure 6 and in Table 4. In the cases modelled the tunnel height is set to 4 m, while the width takes the values of 4, 6 and 8 meters. The \(\text{FED}\) evolution is also greatly affected, perhaps more, than of the height impact. The changes are also witnessed in the fire of 15MW, where the geometry of 6m width provides a delay in reaching critical \(\text{FED}\) values for over 220s. For the fire of 20MW the respective delay is aprox. 340s. Nevertheless, the data also indicate that when tunnel width falls below 6 meters, \(\text{FED}\) increases significantly and tenability conditions deteriorate, especially when fires of greater HRR values are experienced.
Figure 6. Effect of tunnel width on FED evolution for HRRmax 10 (a), 15 (b) and 20 (c) MW.

Table 4. ASET estimation with respect to HRRmax and tunnel width

| Tunnel width (m) | HRRmax (MW) | FEDmax | ASET (s) (FED=1) |
|------------------|-------------|--------|------------------|
| 4                | 10          | 0.7    | Not reached      |
| 6                | 10          | 0.4    | Not reached      |
| 8                | 10          | 0.1    | Not reached      |
| 4                | 15          | 1.4    | 500              |
| 6                | 15          | 0.5    | 720              |
| 8                | 15          | 0.3    | Not reached      |
| 4                | 20          | 2.8    | 380              |
| 6                | 20          | 1.0    | 720              |
| 8                | 20          | 0.5    | Not reached      |

The effect of HRRmax on FED is examined as HRR is considered by many researchers one of the most important parameters that affect the conditions inside the tunnel. The following Figures 7a and b, depict the FED’s evolution over time with respect to various HRRmax values (5, 10, 15 and 20MW) for 2 tunnel geometries of 4m x 4m and 4m x 6m, respectively.

Figure 7. Effect of tunnel section (a) 4x4m (b) 4x6m tunnel on FED evolution for various HRRmax values.

HRRmax has an important effect on FED and tenability conditions inside the tunnel as expected. As tunnel height decreases the effect of HRRmax is even more crucial, as seen by directly comparing Figure 7a...
versus Figure 7b. When the same HRR$_{\text{max}}$ is compared, the FED values are almost 1.5 times higher in the smallest tunnel. For example, for an HRR$_{\text{max}}$ value of 15, the FED reaches the point of 1.4 at the end of the simulation for the 4m x 4x tunnel, while it hardly reaches the threshold value of 1 for the largest tunnel section. Furthermore, the tenability conditions are quickly deteriorated in the small section tunnel even for cases of smallest intensity fire when compared to the ones obtained in the large cross-section.

The time until HRR$_{\text{max}}$ is reached is examined by altering the fire growth rate ($a_g$) which defines how fast the HRR$_{\text{max}}$ is reached and is expressed as $a_g = \frac{\text{HRR}_{\text{max}}}{t^2}$. Three different fire curves were created for the CFD simulation, where the HRR$_{\text{max}}$ of 10 MW is reached within 180, 250 and 320 seconds with fire growth rates 0.3MW/min, 0.16 MW/min and 0.1MW/min respectively. The tunnel dimensions are 4*4 meters. As seen, the effect of fire growth rate on FED, which is not as important as the value of HRR$_{\text{max}}$ itself. Nevertheless, for the determination of ASET for a safe evacuation it should be examined, and properly defined, because large deviations could lead to wrong assumptions regarding the time frame available to achieve a safe evacuation.

![Figure 8](image)

Figure 8. Effect of the fire growth on FED’s evolution.

Finally, the effect of ventilation conditions and the understanding in their impact to the tunnel’s tenability conditions and the resulting FED values are carried out for three different values of ventilation (air-flow) velocity. The values of ventilation velocity modelled are 1m/sec, 2m/sec and 3 m/sec, respectively. The tunnel dimensions used in the evaluation are 4m x 6m while the HRR$_{\text{max}}$ selected is 15 MW. The results obtained are presented in Figure 9.

It can be seen that ventilation has a critical impact on tenability conditions inside the tunnel and decreases FED significantly. This is evidently shown throughout the cases examined, where the FED values in all case does not reach the threshold value of 1 until the end of the simulation. Contrary to the ventilated tunnel section, the no-ventilation case actually reached this value at t=400s. Of course, a more thorough analysis is required to fully decode the issue of the limited impact of the air-flow velocity in the overall conditions.
4. Conclusions

In this paper, a parametric analysis is carried out focusing on the effect of tunnel geometry, heat release rate, fire growth rate and ventilation on the attained tenability conditions. The latter is examined through the calculation of Fractional Effective Dose (FED) through a combined Fire Dynamics Simulation and evacuation analysis, for various scenarios. This can be further used to the safe determination of the Available Safe Egress Time (ASET) as shown in Tables 3 and 4.

Regarding the parameters analyzed, the following conclusions can be concluded:

- Initially, one can say that the value of FED is highly depended on CO concentration inside the tunnel. This comes to an agreement with the fact that carbon monoxide affects the users more than any other product of fire.

- The tunnel height plays an important role on tenability conditions inside the tunnel. Its role seems to become more crucial when the \( HRR_{\text{max}} \) increases. Furthermore, it seems that when the tunnel height is reduced below a specific threshold value, this may lead to an important increase on FED’s value and the responding deterioration of tenability conditions.

- The tunnel width has also an important effect on FED and therefore on ASET, and, perhaps even more crucial than the tunnel height. Also, as in the case of tunnel width, when tunnel width falls below a specific value, FED increases significantly and tenability conditions deteriorate.

- The \( HRR_{\text{max}} \) has the most important effect on FED and tenability conditions inside the tunnel; therefore, this a parameter that should be carefully selected for performing an evacuation analysis. Especially, as tunnel height decreases, the effect of \( HRR_{\text{max}} \) is even more crucial.

- Only relatively large deviations of fire growth rate could have a significant impact on tenability conditions leading to wrong assumptions regarding the time frame for a safe evacuation. The fire growth rate may play a significant role when the analysis results in values of FED close to the value 1.

- The existence of ventilation (air-flow) has a critical effect on tenability conditions and the attained FED values; therefore, during an emergency event it can play a major role for a successful evacuation.

The parametric analysis reveals that all these factors play an important role on tunnel conditions and should be taken into account during of an underground space design, in order to provide a safe environment for the users of the underground space. Of course, more research is required especially for individual cases where special requirements or conditions are in effect, so to provide accurate assessment of the tenability conditions and the ASET for its users for a safe evacuation.
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