The Safety in Tunnels-An Example of Simulated Evacuation from a Railway Tunnel

Abstract: Railway tunnels, as special structures in terms of design and construction always present an open and current topic. A particularly important aspect related to railway tunnels is evacuation, because of their structural and physical properties and inability to predict potential catastrophes, when it is important to reach and evacuate people possibly captured inside the tunnel in as short a time as possible. The possibilities for evacuation in tunnels significantly decrease due to the narrowness of the tunnels, faster spreading of fire and smoke than in open space, tunnel length and many other reasons. It is therefore obvious that prediction of potential evacuation situations could be very difficult and complex. Beside many theoretical calculations and partial experiments, one of the safest ways for prediction and realization of evacuation is the usage of software for evacuation, such as Pathfinder, Evac Tunnel, Exodus and similar. The purpose of this paper is to show the obtained simulation results for evacuation in software Pathfinder, in the case of a 6100m-long railway tunnel with emergency exits on every 500 m and without emergency exits.

Keywords: Evacuation, simulation, tunnels.

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Introduction

The term ‘evacuation’ can be defined in different ways, but generally, it alludes to organized and planned moving of people, animals and material, cultural and other properties from an endangered object, location or area to a secure object, location or area. Evacuation can be complete or partial depending on the degree of danger and potential consequences. Evacuation can be caused by different events, including the following: thunder strikes, earthquakes, storm winds and ice, snow, flood, drought, fire, technical disturbances etc. (Jevtić, 2014).

The term ‘tunnel’ can also be defined in different ways, but it refers to underground facilities with two openings, with horizontal or with a slightly gradient position related to the ground that serves for different purposes: railways, roads, underground airports, water ways, storage, etc. The main role of the tunnel is to connect two or more different points separated by obstacles that could not be overcome in any other way. The highest numbers of built tunnels were definitely railway tunnels. Much lower numbers of built tunnels were for road traffic or some other purpose. There were also examples of tunnels deep in the mountains being used as protection facilities for airplanes (tunnels in Sweden, Željava near Bihać (destroyed in 1992), Slatina near Priština, Divulje near Split, Šipčanik near Podgorica and similar ones).

It is obvious that the construction of tunnels demand engaging of specialist from different scientific fields, usage of modern equipment and huge financial expenses. The factors that influence a tunnel’s price are: the tunnel length, altitude, geological contents of the terrain, strength and arrangement of ground waters, terrain deformation, etc. It is obvious that tunnels present structures where the geological environment presents part of the building’s construction. Although the construction of tunnels demands usage of the latest technique and equipment, the corrections during the construction are very frequent. Some examples of tunnels are shown in Figure 1.
The tunnels can also be divided in several ways, with reference to different factors. For example, according to the tunnel length, tunnels could be classified in small tunnels (up to 50 m), short tunnels (50-500 m), medium-length tunnels (500-2200 m), long tunnels (2200-
According to the number of carriageways, tunnels could be classified in tunnels with one carriageway, tunnels with two carriageways and more carriageways tunnels. According to the tunnels position related to the ground, tunnels could be classified in hill tunnels, underwater tunnels and city tunnels. According to the structure, tunnels could be classified in completely constructed tunnels, partly constructed tunnels and non-constructed tunnels. There are also many other different divisions of tunnels (Grgić, 2008), (Jevtić, 2016).

The railway tunnels present a special type of tunnels where, beside the construction of the tunnel itself, there is a need to construct the complete infrastructure for railway needs. These structures are very complicated and demanding for evacuation in the case of some disaster, such as an explosion, earthquake, flood and similar emergencies. They could have emergency exits, but there are also lots of them without these exits because of specific features on the terrains where the tunnels were built. Some of the longest railway tunnels are presented in Table 1 (Jevtić, Blagoević, 2014), (Jevtić, 2014:19-20), (Davidović and others, 2013), (https://en.wikipedia.org).

**Table 1. The longest railway tunnels in the world**

<table>
<thead>
<tr>
<th>Name of the tunnel</th>
<th>Location of the tunnel</th>
<th>Length of the tunnel</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gotthard Base Tunnel (GBT)</td>
<td>Switzerland</td>
<td>57 km</td>
<td>expected to be completed in 2016</td>
</tr>
<tr>
<td>Brenner Base Tunnel</td>
<td>Austria</td>
<td>55 km</td>
<td>to be completed in 2025</td>
</tr>
<tr>
<td>Seikan Tunnel</td>
<td>Japan</td>
<td>53.85 km</td>
<td>1988</td>
</tr>
<tr>
<td>Channel Tunnel</td>
<td>United Kingdom</td>
<td>50.5 km</td>
<td>1994</td>
</tr>
<tr>
<td>Lötschberg Base Tunnel</td>
<td>Switzerland</td>
<td>34.57 km</td>
<td>2007</td>
</tr>
<tr>
<td>Koralm Tunnel</td>
<td>Austria</td>
<td>32.9 km</td>
<td>to be completed in 2022</td>
</tr>
<tr>
<td>New Gunjiao Tunnel</td>
<td>Tibet</td>
<td>32.64 km</td>
<td>2014</td>
</tr>
<tr>
<td>Guadarrama Tunnel</td>
<td>Spain</td>
<td>28.4 km</td>
<td>2007</td>
</tr>
<tr>
<td>West Qinling Tunnel</td>
<td>Gansu Province, north-west China</td>
<td>28.236 km</td>
<td>2014</td>
</tr>
<tr>
<td>Taihang Tunnel</td>
<td>China</td>
<td>27.848 km</td>
<td>2007</td>
</tr>
</tbody>
</table>
Disasters that could happen in railway tunnels could have unforeseen consequences on human lives and could cause material damage. In the past, there were lots of accidents in railway tunnels (train wrecks, brake malfunction, explosion and similar). One of the worst was on 03/01/1944 in the tunnel near Tore del Bierzo, in the Leon mountains in Spain, where, according to the estimated figures, over 500 people lost their lives in the train wreck. These and similar facts show the importance of analysing potential accident scenarios in order to prevent damage and protect human lives and material property.

Similar research of possible fire and evacuation scenarios in road and railway tunnels was carried out in many countries, although for different purposes, focusing on the time necessary for a tunnel evacuation, safety criteria for tunnel occupants, heat transfer for different fire scenarios in tunnels, fire and smoke propagation in road and railway tunnels, smoke visibility in tunnels during fire, modelling crowd evacuation from road and railway tunnels, occupant movement and behaviour under panic and stress and many other issues. There were a lot of important results noted as the result of research (the usage of evacuation routes, evacuation under the influence of toxic and other dangerous materials, movement models of occupants under evacuation in tunnels and a lot of others), but of course one of the most important facts is that a great number of those researches were realized by simulations and with the usage of simulation software, which was absolutely safe-on the other hand, it would be necessary to test evacuation simulations with humans in real conditions which could be very dangerous and could have unforeseen consequences. Similar results for evacuation times from tunnels were obtained for the road tunnel Straževica in Serbia. The methodology of evacuation from fire endangered areas in Serbia was regulated by Technical reference TP 21 from 2002. This regulation still does not apply to all types of objects (Persson, 2002), (Norén and others, 2003), (Directive 2004/54/EC, 2004), (Yang and others, 2006), (Yang and others, 2006), (Nilsson and others, 2009), (Ronchi and others, 2012), (Caliendo and others, 2012), (Mu and others, 2014), (Jevtić, 2016).

According to the aforementioned, the benefits of the simulation software usage for evacuation are obvious. One of the safest, as well as the most successful, most economic, most correct and most frequently
used ways for potential occupant evacuation in different accident scenarios is the usage of the simulation software designed for these purposes. The research and results in this paper were obtained using Pathfinder 2012 software. This software presents an agent based on egress and human movement simulator and it provides a graphical user interface for simulation design and execution as well as 2D and 3D visualization tools for result analysis. Pathfinder can provide two different simulation models: one, where occupants are moving to their goals with avoiding other occupants and obstacles (Steering model) and other, where the occupants speed and the doors flow rates are included (SFPE model). An example of evacuation situation in a particular object at a particular time moment, in Pathfinder, is presented on Figure 2 (Thunderhead, 2012), (Jevtić, 2016).

![Figure 2. The example of evacuation situation in the tunnel simulation model after 242.3 seconds from the start of the simulation](image)

**Simulation model**

The first task in the simulation realization is to create the simulation model of the desired object- in this case, the tunnel and train with the specific dimensions. Beside Pathfinder software, it is possible to create a simulation model in some other program, such as Auto Cad or PyroSim and insert it into Pathfinder program, which could significantly decrease complete design time. Pathfinder
simulation software used methodology that was developed by NFPA-National Fire Protection Association.

The simulation model of the railway tunnel was designed with the following dimensions: 6100 m length, 12 m width and 5 m height. The simulation model was designed without emergency exits, for the first scenario, and with emergency exits on every 500 m, for the second scenario. The main reason for that was to compare evacuation times in both cases and conclude the potential advantages or disadvantages. Also, it could be possible to analyse some other parameter on evacuation in some other program, such as air flow or heat transfer, in PyroSim. In that case, the simulation model in Pathfinder must be changed into the adequate form and extension appropriate for PyroSim. For both scenarios, there were four different cases, for the occupant’s speeds of 1.25 m/s, 2 m/s, 2.5 m/s and 3 m/s. The whole train composition was located in the middle of the tunnel. The train had maximum passengers load, which meant that the passengers number was 1604 (20 carriages with 80 passengers per carriage and four personal members in the locomotive) (Galea, 2013), (Valasek, Glas, 2013).

It is very important to note the main limitations of this kind of simulation experiment. It was implied that the train was used for passengers transport; it was not cargo train, which would make the simulation much more complicated. Different cargo types, with their own fire, explosion, toxic, smoke or other properties could have significant influence on evacuation times and evacuation routes. For example, an explosion of a tanker with oil, gas or similar could cause the blocking in tunnels and a completely different epilogue. Passengers were designed according to the Pathfinder form and all of them were the same size while in reality, the passengers are completely different in the sense of dimensions. Noted fact also implies that the speeds of passengers must be different while in the simulation every passenger has the same speed like any other passenger.

The train was simulated according to its real dimensions, with 20 passengers’ carriages and a locomotive. The carriage itself is presented on Figure 3 while the dimensions of the passenger carriage are presented in Table 2 (http://www.zeljeznice.net/forum/index.php?/topic/12787-beemt-vagoni/).
Figure 3. The Beemtc carriage (figure source: http://www.zeljeznice.net/forum/index.php?/topic/12787-beemt-vagoni/)

Table 2. The specification of the passenger carriage (data source:)

<table>
<thead>
<tr>
<th>Letter sign of carriage</th>
<th>Beemt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number sign of carriage</td>
<td>61 78 20-70</td>
</tr>
<tr>
<td>Carriage type</td>
<td>UIC-Z1</td>
</tr>
<tr>
<td>The place and the year of production</td>
<td>GOŠA, SmederevskaPalanka, Serbia, 1991.</td>
</tr>
<tr>
<td>Mass of the carriage</td>
<td>50-51000 kg</td>
</tr>
<tr>
<td>Drive speed</td>
<td>160 km/h</td>
</tr>
<tr>
<td>Carriage class</td>
<td>2</td>
</tr>
<tr>
<td>Number of compartment</td>
<td>No compartment</td>
</tr>
<tr>
<td>Number of seats</td>
<td>80</td>
</tr>
<tr>
<td>Maximal length</td>
<td>26400 mm</td>
</tr>
<tr>
<td>Box width</td>
<td>2825 mm</td>
</tr>
<tr>
<td>Maximal height</td>
<td>4050 mm</td>
</tr>
</tbody>
</table>
### Simulation and simulation results

Every simulation software with visualization possibilities demands strong computer machine, with strong processor and a lot of RAM memory. Limited size of paper makes it impossible that every simulation result should be presented and for that technical reason, only some evacuation situations that presented a small part of the obtained simulation results from the first scenario are presented on figures from 4 to 10 as examples.

![Evacuation situation for the first scenario after 3.7 seconds from the start of the simulation](image)

*Figure 4. Evacuation situation for the first scenario after 3.7 seconds from the start of the simulation*

![Evacuation situation for the first scenario after 14.8 seconds from the start of the simulation](image)

*Figure 5. Evacuation situation for the first scenario after 14.8 seconds from the start of the simulation*
The presented figures showed the train passenger movement and direction of their movement in different time intervals from the simulation start for the first simulation scenario which implied a tunnel without emergency exits. The fact that the tunnel length was 6100 m
was the reason for figures presentation. The figures actually present screenshots in the determined time moment from simulation. During the simulation, it was possible to see, in every moment of simulation, the number of passengers that left the tunnel and the number of the remaining passengers.

**Discussion**

The complete simulation results, which included total time needed for evacuation of all passengers, for both scenarios, are presented in Figures 11 and 12, although every simulation was performed separately.

![Figure 11. Simulation results for the first scenario without emergency exits](image-url)
The simulation results mostly showed the expected directions, ways and times for complete tunnel evacuation for both scenarios, with and without emergency exits. But, it is a known fact that every tunnel could not have emergency exits for many reasons, for example, because of its geographic position and location, because of its purpose, because of ground contents, ground waters presence, etc. It is obvious, according to the simulation results that the higher speed of occupants could lead to congestions, because, in that case, occupants cannot get out from the carriage quickly. Even in the case where there were fewer emergency exits, the complete evacuation times had been shorter than in the case without any emergency exits. This simulation of the evacuation example implied only a simple leaving of the train that was stopped in the middle of the railway tunnel, but, it is very important to note, that this and similar software could analyse much more complicated situations, such as fire influence on occupants evacuation, air flow influence on smoke in the tunnel or some other closed space and many other potential situations that could happen and on which all information is needed for saving human lives (Netcu and others, 2011), (Jevtić, Blagojević, 2013), (Jevtić, 2015), (Jevtić, 2016).

It is a well-known fact that in tunnels there are, more or less, air flows that could have significant effects on the fire development in a tunnel or on smoke and toxic material distribution in a tunnel. There
are different factors that could have influence on air flow movement in railway tunnel: train movements, natural or mechanical ventilation, piston effect, different gases emissions, buoyancy and similar ones. Fire, explosion, smoke and toxic material could be made by different train accidents in the tunnel, for example. According to the obtained simulation results, it is important to know many different parameters to know potential effects on passenger evacuation from tunnel. For example, a tunnel of 6656 m in length, with natural ventilation velocity of 1 m/s and density of 1.30 kg/m$^3$ contains 400 tons of air. In that kind of tunnel, for example, when the fire source is about at the middle of the tunnel (the firepower of fire source being 20 MW), heat transfer does not bear effect on the flow rate and the maximum temperature is about 60°C – it is the temperature that people can stand without protection (Daeron, Ruffin, 2000). The development of smoke and toxic material can be different according to their type - for example, chlorine and ammonia could be transported in truck tankers as liquefied gases under pressure and it is assumed that 30 m$^3$ of product are transported in a container 2.5 m in diameter and 7 m in length. According to some results obtained in road tunnel, chlorine, which is heavier than air, progressively accumulated towards the floor while the dispersion of ammonia, which is lighter than air, appeared to be more influenced by diffusivity than by gravity, which could be particularly important for the first scenario of this paper where emergency exits did not exist (Bubico and others, 2014). The noted facts also showed the great significance of evacuation scenario simulations aimed at solving a very complicated problem of evacuation dependent on many different parameters.

The simulation results obtained in this paper were mostly in accordance with similar domestic or foreign researches. Of course, there are lots of different parameters and conditions that should be taken into account. The main task where the results were in accordance with similar earlier results is that the time needed for total evacuation from a railway tunnel with emergency exits is less than the time needed for total evacuation from a railway tunnel without emergency exits. Also, the speed of passengers is very important because jams could occur at higher speeds. Simulation results for the passenger speed of 1.25 m/s is particularly similar with earlier simulation results, while for simulation results for passenger speed of 3 m/s there were
some differences. This was expected because the conditions and parameters applied in this paper were original. It is also obvious that for different types of passenger carriage (different carriage dimensions, different arrangement of seats, different width of exit/enter doors and similar) simulation results would be different, as well as for different tunnel infrastructure (Howarth, Griffin, 2011), (Wang, Jacqueline, 2014), (Jevtić, 2016).

Some references related to future researches would concern different train position in the tunnel (close or far from exit/entrance, normally positioned or turned over and similar), different arrangement of passengers at the moment of evacuation start, evacuation scenarios under different fire load and different position of fire load and similar.

**Conclusion**

Real evacuation of some particular building and/or event can be very complex, hard to perform and, which is always the biggest problem, very unpredictable, although all the rules, plans and law regulations were taken into consideration. In order to provide maximum success for evacuation with minimal risk for humans, it is necessary to predict, as much as possible, all factors that can have influence on evacuation and their consequences. Usage of the simulation software allows for some evacuation situations and scenarios to be predicted and analysed. For example, one of above noted factors is an occupant’s speed. For different speeds, the evacuation time will be different and that can be calculated. Also, many occupants with higher moving speed (caused by panic, for example) can cause jams that can be crucial for evacuation time. By using the simulation software and their visual potentials, it is possible to note potential points where occupants can be jammed and eliminate them. It is possible to do all of the aforementioned without endangering the safety of occupants. The simulation results presented in this paper for a railway tunnel prove this fact.

Simulation software usage has many benefits for evacuation, especially for its safety aspect, and definitely presents the important, powerful and inevitable engineer’s tool for the successful analysis of the evacuation. Even in the situations when it is almost impossible to create an adequate evacuation scenario (for example, fan fight at a
football stadium or help to victims in an earthquake) usage of simulation software can give directions as to where the solution can be found.

References


27. Valasek, L. and Glas, J., (2013). *Simulation of the course of evacuation in tunnel fire conditions by FDS+Evac*, Institute of
Informatics, Slovak Academy of Sciences, Bratislava, Slovak Republic.


Bezbednost u tunelima-primer za simulaciju evakuacije železničkog tunela

Apstrakt: Železnički tuneli kao specijalni objekti u smislu projekovanja i realizacije predstavljaju uvek otvorenu i aktuelnu temu. Posebno važan aspekt vezan za železničke tunele je evakuacija, zbog njihovih građevinskih i fizičkih osobenosti i nemogućnosti predviđanja potencijalnih katastrofa, kada je važno dopreti do ljudi koji mogu biti zatvoreni u tunelu i evakuisati ih zašto je moguće kraće vreme. Mogućnosti za evakuaciju u tunelima značajno opadaju u zavisnosti od uskosti tunela, mnogo bržim širenjem vatre i dima nego na otvorenom prostoru, dužinom tunela i mnogim drugim razlozima. Pored mnogih teorijskih proračuna i nedovršenih eksperimenta, jedan od najsigurnijih načina za predviđanje i realizaciju evakuacije je korišćenje programa za evakuaciju, kao što su Pathfinder, Evac Tunnel, Exodus i slični. Ovaj rad je napisan sa ciljem da pokaže realizovane simulacione rezultate evakuacije u program Pathfinder u slučaju železničkog tunela dužine 6100 metara sa evakuacionim izlazima na svakih 500 m i bez evakuacionih izlaza.

Ključne reči: Evakuacija, simulacija, tunel