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Model predora in simulacija prezračevanja v primeru požara

A Model of a Tunnel and a Simulation of Ventilation in the Case of Fire

Jurij Modic

Uničujoči požari v nekaterih predorih od leta 1999 naprej, ter vrsta hudih nesreč v nekaterih predorih poleti leta 2000 spodbujajo resne pogovore in predloge o potrebni povečani varnosti v predorih. Če v predoru izbruhne požar in se pri tem pojavi pomanjkanje svežega zraka, nastajajo velike količine dima, ki onemogočajo vidljivost in možnost gibanja z vozili in okrog njih. Nastaja močan tok dimnih plinov, ki se pomika v vseh smereh. Če je hitrost zračnega toka majhna, se dim dalj časa zadrži pod stropom v obliki plasti, s tem omogoča umik udeležencev v prometu po vnaprej določenih poteh. Prispevek prikazuje model predora in rezultate računalniške simulacije: hitrosti in temperature zraka ter površinske temperature sten v primeru požara. Simulacija zajema stanje pred vključitvijo prezračevalnega sistema in prikazuje tudi nadaljevanje požara in vključevanje prezračevalnega sistema.

(Ključne besede: predori cestni, požari, prezračevanje, simuliranje)

The catastrophic tunnel fires that have occured since 1999 and the series of accidents in some tunnels in the summer of 2001 have triggered extensive discussions and proposals relating to tunnel safety. When a fire occurrs in a tunnel, and in the absence of sufficient air supply, large quantities of smoke are generated, filling the vehicles and any space availabile arround them. Unless a strong flow is created and maintained, hot gases and smoke migrate in all directions. With a weak airflow, smoke forms a layer along the tunnel ceiling and can flow against the direction of forced ventilation, interfering with the evacuation of people from the tunnel. This paper describes a model of a tunnel and the results of a fire simulation in the tunnel. The model takes into account air velocity, air temperature and wall temperature during the fire. The simulation starts before the emergency ventilation system is activated and continues with the fans activated to control the smoke.

(Keywords: road tunnels, fires, ventilation, simulation)

0 UVOD

V vseh cestnih predorih potrebujemo prezračevanje, da lahko odstranimo onesnažene snovi, ki nastajajo kot izpuh motorjev vozil pri normalnem obratovanju. Prezračevanje je povzročeno po naravni poti, z gibanjem vozil povzročenim "batnim učinkom", ali pa z mehansko opremo. Izbrani način prezračevanja mora biti gospodaren, tako z vidika opreme in porabe energije kakor tudi z vidika pogona in vzdrževanja. Način prezračevanja mora torej biti pravilno izbran, da lahko zagotovimo ustrezen nadzor nad različnimi plini, vključno z dimom, in s tem zagotavljamo znosne razmere in vidljivost tudi v primeru požara ter s tem omogočimo umik ljudem z ogroženega področja. Pri tem lahko uporabljamo naravne zakonitosti, pri katerih izkoriščamo s

0 INTRODUCTION

All road tunnels require ventilation to remove the contaminants produced by vehicle engines during normal operation. Ventilation may be provided by natural means, by the traffic-induced piston effect, or by mechanical equipment. The method selected should be the most economical in terms of construction and operating costs. Ventilation must also be considered for road tunnels in order to provide the necessary control of smoke and hot gases resulting from a fire taking place in a tunnel so as to provide an environment suitable for emergency evacuation and rescue along the evacuation path. Emergency ventilation can be provided by utilizing natural means, by taking advantage of the buoyant forces generated by the povišano temperaturo in dimom povzročen vzgon in podobne učinke, ali pa uporabimo mehansko opremo, torej prisilno prezračevanje.

Poznamo tri načine prisilnega prezračevanja cestnih predorov: normalno prezračevanje, interventno prezračevanje in začasno prezračevanje.

Interventno prezračevanje uporabljamo zato, da nadzorujemo in odstranjujemo dim in vroče pline v primeru požara. Zagotoviti moramo najmanjše pogoje, potrebne za umik z ogroženega območja, kar pomeni zadostno vidljivost in primerno nizko temperaturo vročih plinov po poti, načrtovani za umik udeležencev v prometu in tudi varen dostop reševalnim ekipam v predor, nazadnje pa tudi zaščito nosilne konstrukcije predora.

S prezračevanjem v normalnih razmerah redčimo koncentracijo škodljivih snovi, v primeru požara pa nadzorujemo dim. Pri tem moramo upoštevati vse značilnosti predora, geometrijske, prometne, okoljske in ostale. To so dolžina predora, njegov prerez in nagib, njegovo okolico, gostoto prometa, smer prometa (enosmerni, dvosmerni), sestav prometa in investicijske stroške.

Če imamo naravno prezračevanje, se dim, ki nastaja ob požaru, dviga pod strop predvsem zaradi vzgona. Pri večji hitrosti zraka pa se dim zaradi mešanja z zrakom hitreje ohlaja in spušča navzdol, poslabša vidljivost posledica tega je panika, slabo počutje, s tem otežuje umik, kar je samo uvod v katastrofo.

Če v predoru izbruhne požar, vstopajoči sveži zrak redči dimne pline. V primeru polprečnega prezračevanja moramo tok zraka obrniti v nasprotno smer tako, da sveži zrak vstopa skozi vhode in je s tem omogočeno dihanje reševalcem. Če imamo pri tem izvedbo z dvojnim stropom in obrnljivimi ventilatorji, pa sesamo dim skozi dvojni strop. Običajno povečamo tudi količino odsesovanega zraka, n.pr. s pomočjo nastavljivih loput. Tako vzdržujemo v predoru razmeroma čist zrak.

V primeru požara moramo pognati ventilatorje s polno močjo. S tem preprečimo preveliko mešanje zraka in dima. Dim ostaja pod stropom dalj časa, tako vzdržujemo tik nad cestiščem razmeroma čisto področje, ki olajša umik udeležencem v prometu in vstop reševalnim ekipam.

V daljših predorih moramo predvideti posamične odseke ali cone. Tako v cono, v kateri so vozila ujeta, torej pred cono s požarom, dovajamo največjo količino svežega zraka ter sesamo malo dima, iz cone za požarom, kjer promet še poteka, pa sesamo največjo količino dima in vročih plinov ter dovajamo najmanjšo količino svežega zraka. Tako lahko z dobro zasnovanim prezračevalnim sistemom ugodno vplivamo na razmere v predoru v primeru požara.

smoke and hot gases generated by the fire or by mechanical means.

Three types of mechanical ventilation are considered for road tunnels: normal ventilation, emergency ventilation and temporary ventilation.

Emergency ventilation is required during a fire emergency to remove and control smoke and hot gases. The primary objective of emergency ventilation is to provide an evacuation-path environment that is sufficiently clear of smoke and hot gases and at a sufficiently low temperature to permit the safe evacuation of motorists, to allow relatively safe access for firefighters, and to protect the structure.

Any ventilation must dilute contaminants during normal tunnel operations and control smoke during emergency operations. Factors that determine the system selected include the following: tunnel length, cross-section, and grade; surrounding environment; traffic volume; traffic direction (unidirectional vs. bi-directional); traffic mix; and construction costs.

Smoke from a fire in a tunnel with only natural ventilation moves up a grade, driven primarily by the buoyant effect of the hot smoke and gases. The steeper the grade the faster the smoke will move, thus restricting the ability of motorists that are trapped between the incident and the portal at the higher elevation to evacuate the tunnel safely.

If a fire occurs in the tunnel, the supply air initially dilutes the smoke. The supply semi-transverse ventilation should be operated in reverse mode for the emergency so that fresh air enters the tunnel through the portals to create a respirable environment for fire-fighting efforts and emergency evacuation. Therefore, the ventilation configuration for a supply semi-transverse system should preferably have a ceiling supply (in spite of the disadvantage this impases during normal operations), and reversible fans so that smoke can be drawn up to the ceiling in an emergency.

During a fire emergency, the exhaust system should be operated at the maximum available capacity, while the supply should be operated at a somewhat lower capacity. This operation allows the smoke that has stratified towards the ceiling to remain at that higher elevation and to be extracted by the exhaust without mixing. This helps to maintain an irrespirable environment at the roadway and allows fresh air to enter through the portals and create a respirable environment for fire-fighting and emergency evacuation.

In longer tunnels, a means should be provided to control the individual sections or zones, so that the section with traffic trapped behind the fire is provided with maximum supply and no exhaust; and the section on the other side of the fire, where traffic has driven away, is provided with maximum exhaust and minimum or no supply.

1 HITROST ZRAKA, MOČ POŽARA IN TEMPERATURA

1 AIR VELOCITY, FIRE SIZE AND TEMPERATURE

1.1 Hitrost zraka [1]

Predor si zamislimo kot cev in skupino togih teles, ki se gibajo skozi njo.Gibanje zraka je povzročeno s tlakom, višinsko in temperaturno razliko med vstopom in izstopom, prerezom, gibanjem vozil in delovanjem ventilatorjev.

V splošnem primeru si zamislimo predor z enosmernim prometom. Tako je hitrost zraka na koncu predora po [1]:

1.1 Air velocity [1]

A tunnel can be illustrated by a pipe and a group of stiff bodies moving through it. The air movement is caused by the pressure, the height, the temperature difference between the inlet and outlet cross section, the movement of vehicles and the effect of fans.

In the general case we assume a tunnel with unidirectional traffic. So the air velocity u at the end of tunnel is [1]:

$$u^2\left\{\frac{1}{2LA}\left[\left(1-\frac{p_t}{100}\right)\frac{M}{L}l_o c^*_{wo}A_{vo}+\frac{p_t}{100}\frac{M}{L}l_t c^*_{wt}A_{vt}\right]-0,50\left(\frac{\lambda}{D_h}+\frac{1,35}{L}\right)\right\}-$$
$$-u\left\{\frac{1}{L\,A}\left[\left(1-\frac{p_t}{100}\right)\frac{M}{L}l_o\,c^*_{wo}\,A_{vo}+\frac{p_t}{100}\frac{M}{L}l_t\,c^*_{wt}\,A_{vt}\right]v\right\}+ \qquad (1).$$
$$+v^2\left\{\frac{1}{2\,L\,A}\left[\left(1-\frac{p_t}{100}\right)\frac{M}{L}l_o\,c^*_{wo}\,A_{vo}+\frac{p_t}{100}\frac{M}{L}l_t\,c^*_{wt}\,A_{vt}\right]\right\}\pm\frac{\Delta p}{L\rho}=0$$

Enačba (1) velja za predor z enosmernim prometom, pri polni obremenitvi, za tekoč promet. Omogoča izračun hitrosti zraka na koncu predora z enosmernim prometom kot funkcijo dolžine in prereza predora ter lastnosti (koeficienta zračnega upora in čelne površine) vozil, števila in hitrosti vozil ter koeficienta trenja ob stenah predora.

From Equation (1) we can compute the air velocity u at the end of a single-bore tunnel with two lanes of unidirectional traffic as a function of the tunnel length, the cross section, the characteristics and numbers of vehicles, and the friction coefficient.

1.2 Moč požara

Oblika in moč požara močno vplivata na kritično hitrost zraka, potrebno za preprečitev povratnega gibanja dima in vročih plinov. V [2] so podane smernice za značilne vrste požarov, ki jih povzročajo cestna vozila. Običajno upoštevamo, da je moč požara 100 MW, njegova dolžina pa 10 m.

1.2 Fire size

The size of the design fire size selected has a significant effect on the magnitude of the critical air velocity necessary to prevent back layering. The data in [2] provide a guideline to the typical fire size for a selection of road vehicles. Usually, we take into account a fire with a power of 100 MW and 10 m length.

1.3 Temperatura zraka [2]

Zaradi požara se močno poviša temperatura zraka v predoru ali v morebitnih zračnih kanalih. To pomeni, da sta celotna konstrukcija , pa tudi oprema, izpostavljeni visokim temperaturam dima in vročih plinov. Prav tako se poveča tudi količina: dim + zrak. Tako je količina zraka po [8]:

1.3 Air temperature [2]

A fire in a tunnel significantly increases the air temperature in the tunnel roadway or duct. This means that the structure and equipment are exposed to high gas and smoke temperatures, which increases the quantity: smoke + air. So the air quantity is [8]:

$$m = C\cdot q_c^{1/3}\cdot(h-d)^{5/3} \qquad (2)$$

in temperaturna razlika med povprečno temperaturo dimnih plinov in temperaturo okolice:

and the difference between the average temperature of the smoke gases and the indoor temperature is:

$$\Delta\Theta_m = \frac{q_c}{m\ .\ c_p} \qquad (3).$$

.

Pri tem moramo vedeti, da je: $\Delta\Theta_m = f\left(\tau, L\right)$.

Spremembo temperature vzdolž predora računamo s funkcijo, ki opisuje, kakšno je razmerje

But we must know that $\Delta\Theta_m = f\left(\tau, L\right)$.

The temperature variations along the tunnel are calculated using a function that describes how med naraščajočo temperaturo v predoru in površinsko temperaturo sten v odvisnosti od časa po izbruhu požara.

Tako vidimo, da običajno reševanje enačb in računanje posameznih vrednosti terja veliko časa, zato je bolj smotrna uporaba računalniškega programa.

2 RAZPOLOŽLJIVI RAČUNALNIŠKI PROGRAMI

Znanih je več testiranih računalniških programov, kot so

– TUNNEL – Slovenija [8]
– IDA – Švedska [3]
– RVS – Avstrija [4]
– SOLVENT – ZDA [6]

Načelo računanja z računalniškimi programi je utemeljeno na predstavitvi mreže predorov s poljubno geometrijsko obliko. Uporabnik vnaša geometrijske podatke predora, kot npr. nagib, velikost prereza vzdolž predora, nato meteorološke podatke, vključno s tlakom vetra na obeh vhodih, gostoto in strukturo predmeta, emisijo vozil, koeficient trenja itn.

Večina programov je izdelana in testirana za vzdolžno naravno ali prisilno prezračevanje, z upoštevanjem v predoru nameščenih ventilatorjev, predvsem za dolžino predora do 4000 m. Možna je tudi analiza polprečnega prezračevanja.

Požar v predoru simuliramo tako, da v posamične odseke predora vstavimo podatke o toplotnem toku, ki je posledica požara določene moči in dolžine. Na ta način dobimo povprečne hitrosti in temperature zraka v vseh prerezih predora.

3 MODEL PREDORA

Predor je dolg 800 m, z enosmernim prometom. Uporabljen je program IDA [3], ki ponuja največ možnosti. Na sredini predora je prečni rov za povezavo s sosednjo predorsko cevjo, ki je namenjena za umik v primeru požara. Tako je najdaljša pot za umik dolga 400 m. Čas, v katerem pešec prehodi to razdaljo, je okoli 3 minute. Če upoštevamo še čas izstopa iz vozila 2 minuti, je možen čas umika 5 minut.

Pomembno je, da ovrednotimo celotno dogajanje v predoru, kadar izbruhne požar. Na obnašanje dima v tem primeru vplivajo:

- hitrost naraščanja požara, kar je odvisno od vrste vozila, tovora itn.;
- hitrost zraka v predoru. Na to vpliva hitrost vozil pri normalnem prometu, sistem prezračevanja, vpliv okolice (npr. vzgon, ki ga povzročata višinska in temperaturna razlika med vhodi), zunanja temperatura itn.;
- hitrost, s katero nadzorno osebje ugotovi požar in ustrezno ukrepa;
- hitrost odzivanja prezračevalnega sistema;

the relation between the increase of temperature in the air and in the tunnel walls varies with the time since the start of the fire.

It is clear that solving the equations and calculations in a classical way would take a lot of time, so it is convenient to use a computer program.

2 COMPUTER PROGRAMS AVAILABLE

There are a several, tested computer programs:

– TUNNEL – Slovenia [8]
– IDA – Sweden [3]
– RVS – Austria [4]
– SOLVENT – USA [6]

The calculations are performed for a network of tunnels with an arbitrary geometry. The user enters a geometrical description of the tunnels, i.e. height and cross-sectional area along the length of the tunnel. Other input data are the atmospheric conditions, including wind pressure at the entrance of the tunnels, the amount of traffic through the tunnels, the emission of pollution, and the coefficients of friction.

The ventilation is assumed to be longitudinal, driven by the traffic, with additional installations of air-supply and exhaust-terminal devices distributed along the tunnel as well as the momentum jet fans at specific locations along the tunnel. The software can be customized to include transverse ventilation.

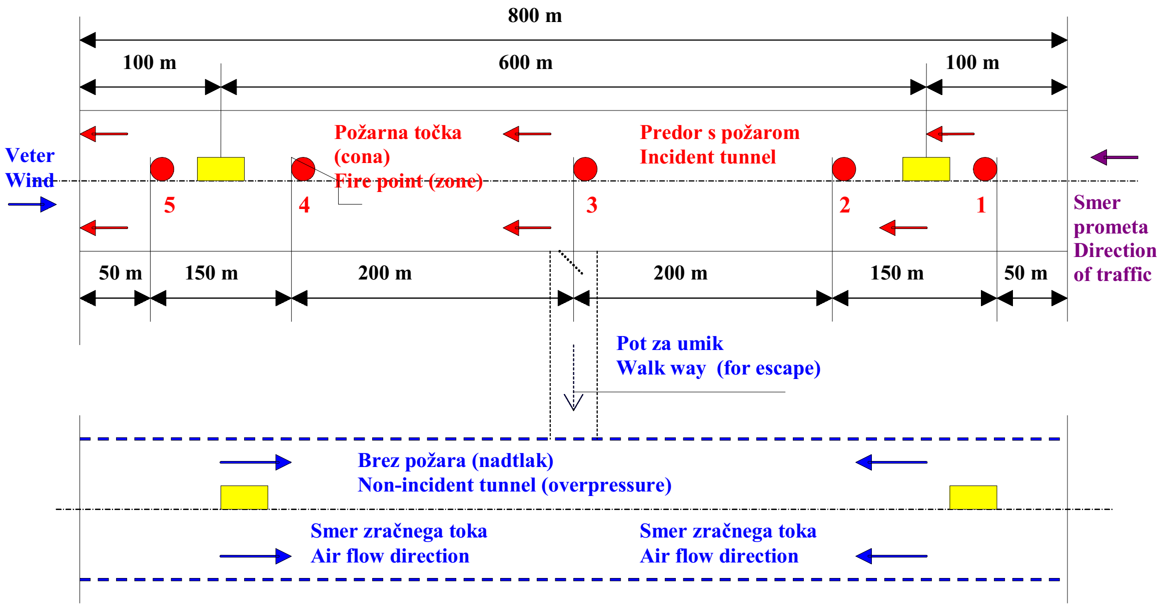
A fire in the tunnel can also be simulated, in which case a specified heatflux is added in a limited section (350-m long) of the tunnel. The program also uses average air velocities in all cross sections in the case of a fire simulation.

3 MODEL OF THE TUNNEL

The tunnel is 800-m long. In the middle of the tunnel is a walk-way to provide an escape route in the case of fire. The IDA program [3] was used. The longest distance to escape in the incident tunnel is 400 m. The time it takes for a pedestrian to walk this distance is approximatly 3 minutes. If we add another two minutes to get out of the car, the time for the escape from the incident tunnel is about 5 minutes.

The smoke behaviour in a tunnel fire can be affected by:

- The growth rate and the ultimate size of the fire; this would depend on the type of vehicle involved in the fire, its load, etc.
- The tunnel air velocity; this would be affected by the initial traffic speed, the ventilation design and the environmental effects, such as wind or buoyancy effects due to the difference between the tunnel temperature, the ambient air temperature and the slope of the tunnel.
- The speed with which the operator can identify the fire location and take appropriate action.
- The speed of response of the tunnel-ventilation system.



Sl. 1. *Model predora*
Fig. 1. *Model of tunnel*

Glavna cilja uporabe opreme za prezračevanje med požarom v predoru sta:
- hitrost zraka, manjša od 1,50 m/s povzroča razslojevanje, dim ostaja dalj časa pod stropom;
- omejevanje difuzije ostankov zgorevanja vzdolž predora, ki olajša delo reševalnim ekipam.

Ko v predoru izbruhne požar, mora prezračevalni sistem nadzorovati širjenje dima. V primeru vzdolžnega ali polprečnega prezračevanja je najpomembneje ohraniti naravno razslojevanje dima in zraka tako, da se dim zadrži pod stropom, spodnji predel predora pa ostaja razmeroma čist. Tako olajšamo umik do reševalnih poti vsem tistim, ki se znajdejo na kraju požara, pa tudi odsesovanje dima je učinkovitejše.

Poglavitni razlog, ki preprečuje razslojevanje dima in zraka, je medsebojni vpliv med vzdolžnim zračnim tokom in dvigovanjem vročega dima. Na širokem območju se razvijajo vrtinci, ki povzročajo intenzivno mešanje zraka in dima. V tem primeru so vzgonske sile razmeroma šibke v primerjavi s turbulenco, postopek mešanja se nadaljuje, mešanica dima in zraka se ohlaja in pada navzdol. Zato je smotrno, da določimo mejno vrednost vzdolžne hitrosti zraka, ki še zagotavlja zadostno razslojevanje.

Glede hitrosti gibanja ljudi med umikom je na voljo vrsta podatkov. Običajna hitrost pešca v predelu, kjer ni dima, je od 1,00 m/s do 2,00 m/s (standardna hitrost vojakov pri hoji: 5 km/h → 1,40 m/s). Na sliki 2 je prikazana hitrost hoje v predelu z dražečim in nedražečim dimom.

Ob pomanjanju podatkov o hitrosti hoje pri umiku v cestnem predoru predpostavljamo, da je ta od 0,50 m/s do 1,50 m/s, odvisno od vidljivosti v predelu z dimom, razsvetljave, oblike in tipa obvestil

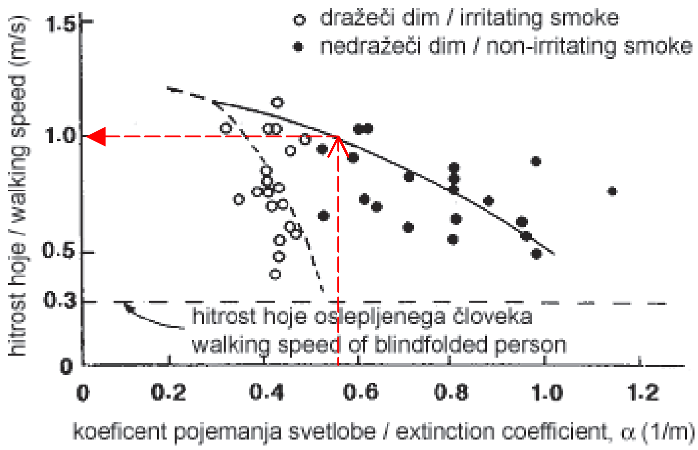
Ventilation equipment is used during a fire event in a tunnel to achieve two main aims:
- To kepp the air velocity lower than 1.5 m/s, to ensure the smoke extraction is near the fire position.
- To limit the diffusion of the combustion product along the tunnel to allow the fire brigades to operate.

When a fire occurs in a tunnel, the existing ventilation system has to be able to control the fire-induced smoke propagation. In the case of longitudinal or transverse ventilation systems, one of the main aspects deals with the preservation of the smoke's natural stratification. So a clean-air layer must be preserved in the lower part of the tunnel, which is crucial in order to facilitate the evacuation of people in the tunnel and to increase the extraction efficiency of the vents located in the ceiling.

The major cause of the non-stratification of smoke downstream of the fire is the interaction between the longitudinal airflow and the thermal plume. Large eddies develop and then mix both the air and the smoke. In the case of a strong interaction, the buoyant forces become too weak in comparison with the turbulence being convected within the longitudinal flow. The mixing process continues and no stratification can appear downstream. From a practical point of view, it might be quite useful to be in a position to define a boundary value for the longitudinal velocity, which would thus allow us to preserve a suitable stratification.

There is a lot of information about walking speeds under different conditions in various facilities and buildings. Usually, walking velocity in a smoke-free environment varies between 1.0 and 2.0 m/s (military walking speed: 5.0 km/h →1.40 m/s). In Fig. 2, walking speed is shown for non-irritating and irritating smoke.

There is no data on the evacuation speed in a road tunnel, but a good guess is that it would be of the order of 0.5 to 1.5 m/s, depending on visibility, illuminance and the design of the exit signs, among



Sl. 2. *Hitrost hoje v dražečem in v nedražečem zraku [7]*
Fig. 2. *Walking speed in irritating and non-irritating smoke [7]*

in znakov za umik itn. V skladu s sliko 2 izberemo povprečno hitrost pri hoji 1,00 m/s.

Času, potrebnem za hojo na varno mesto, moramo dodati še čas, ki definira hitrost izstopa iz vozila, vključno z odzivnim časom. Če je hitrost hoje 1,00 m/s, je čas, v katerem prehodimo razdaljo 400 m (največja razdalja):

other things. So we have taken into account an average walking speed of 1.0 m/s (see Fig. 2).

It is also necessary to add the times for detection and alerting and the times to react and leave the vehicle to the walking time to a safe place, in order to know if people can escape the fire safely. If the walking speed is 1.0 m/s, the time for walking a distance of 400 m (maximum) is:

$$t = \frac{400}{1,0} \quad \frac{m}{m/s} = 400 \quad s = \frac{400}{60} = 6,7 \quad \text{min}$$

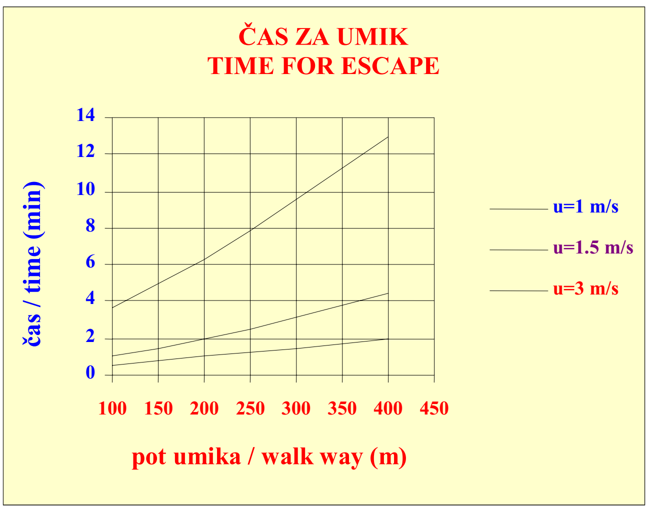
Čas, v katerem ljudje zapustijo, npr. poln avtobus, je po [7] približno 5 minut. Tako je potreben čas za umik po 400 m dolgi poti, vključno s časom, potrebnim za zapustitev avtobusa:

The leaving time for a bus [7] is 5.00 min. So in this case the time for escape is (for 400 m, including leave time for a bus):

$$t = 6,7 \; + \; 5,0 = 11,7 \quad \text{min}$$

To je tudi čas, v katerem mora “peš cona”, torej spodnji del predora, ostati brez dima. Tako dobimo za vzdolžne hitrosti od 1,00 m/s do 3,00 m/s rezultate, prikazane na sliki 3.

This is also the time in which the “walking zone” of the tunnel must remain free of smoke. So we obtain from [4] the data in Fig. 3.



Sl. 3. *Čas “brezdimne cone” v odvisnosti od vzdolžne hitrosti zraka*
Fig. 3. *Time of the “smoke-free” zone, depending on the air velocity*

Na temelju podatkov iz [4] dobimo za različne hitrosti zraka:

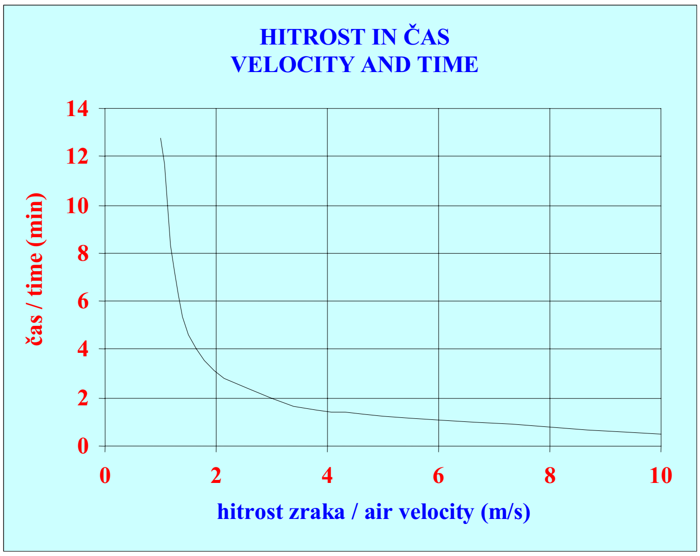
From the data in [4] we obtain, for various air velocities:

v = 1,00 m/s:	$\tau = 0{,}0315\ .\ l\ +\ 0{,}25$	$r^2 = 0{,}997$
v = 1,50 m/s:	$\tau = 0{,}0116\ .\ l\ -\ 0{,}25$	$r^2 = 0{,}993$
v = 3,00 m/s	$\tau = 0{,}005\ .\ l$	$r^2 = 0{,}998$

Tako je čas, potreben za 400 m dolgo pot v odvisnosti od hitrosti zraka (sl. 4):

So the time of escape for a walkway 400-m long, depending on the air velocity is (Fig. 4.):

1,00 m/s	τ = 12,80 min
1,50 m/s	τ = 4,40 min
3,00 m/s	τ = 2,00 min



Sl. 4. *Čas, v katerem ostane dim pod stropom predora*
Fig. 4. *Time for which the smoke remains under the ceiling*

4 REZULTATI SIMULACIJE

Kot primer je bila izdelana simulacija za točko 3 (sl. 1 in 5).

S slike 6 vidimo, da je največja vzdolžna hitrost zraka v predoru manjša od 1,00 m/s. V skladu s [4] to pomeni, da ostane dim pod stropom v višini nad 2,00 m okrog 8 minut. To je dovolj, da se ljudje umaknejo iz predora, v katerem je izbruhnil požar. Umikajo se v sosednji predor, kjer mora biti s prezračevalnim sistemom zagotovljen nadtlak. Ko pa v predoru, v katerem je požar, po umiku ljudi poženemo ventilatorje, se hitrost zraka poveča na 3,60 m/s, kar zadošča za uspešno odstranjevanje dima in vročih plinov.

Analogno temu so na sliki 7 prikazane temperature zraka, na sliki 8 pa površinske temperature sten v točki požara.

Na sliki 9 je prikazano temperaturno polje, dobljeno s simulacijo, med dolžinama predora 350 m in 450 m, torej zaradi požara v točki 3. Podobna temperaturna polja so izračunana tudi za preostale požarne točke, prav tako tudi za površinske temperature.

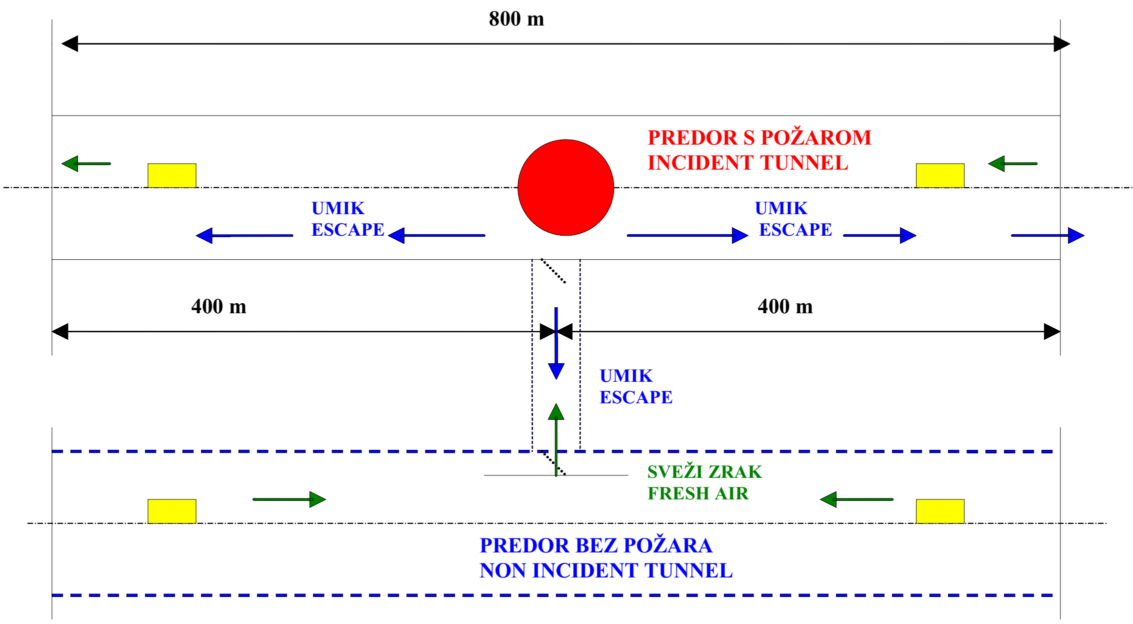
4 RESULTS OF THE SIMULATION

As example, a fire simulation at point 3 was made (Fig. 1 and Fig. 5).

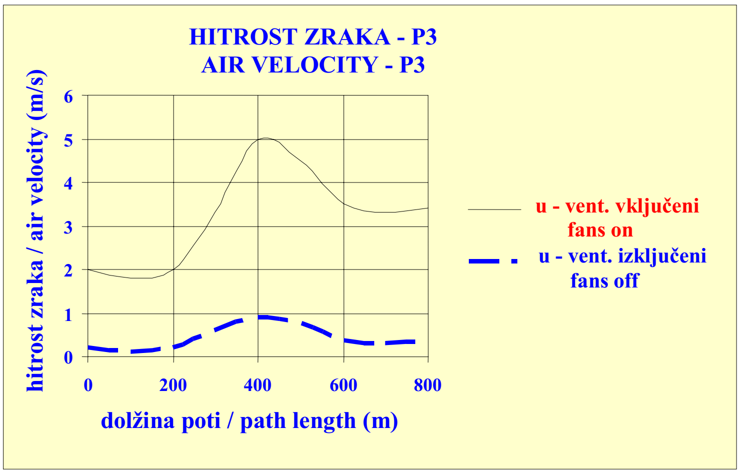
From Fig. 6 it is clear that the highest air velocity is lower than 1.0 m/s. Refering to [4], this means that the smoke remains on the level of the upper 2.00 m for about 8 minutes. This is enough to be able to rescue the people from the incident tunnel. In the mean time there is an air over-pressure in the non-incident tunnel. When the fans are on, the lower air velocity behind the fire zone is about 3.6 m/s, which is enough to clean the tunnel.

Fig. 7 shows the air temperatures, and Fig. 8 shows the wall temperatures.

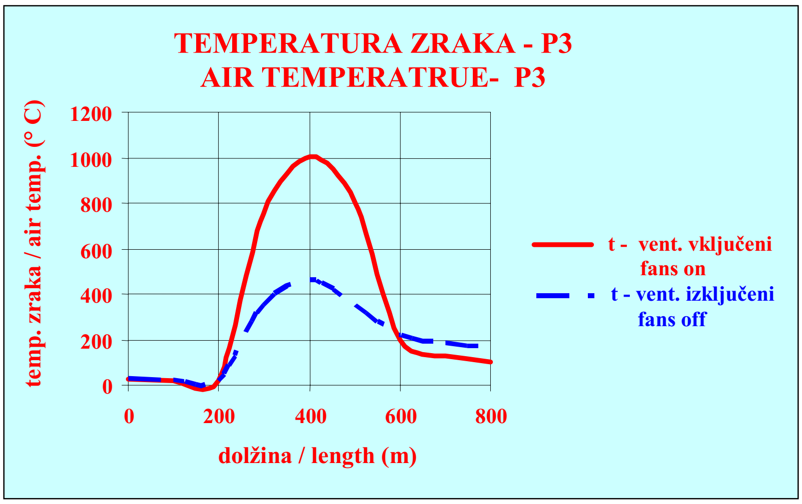
Fig. 9 shows the temperature field on the basis of the simulation between 350 m and 450 m of the tunnel's length (in the fire point 3). It is possible to make such a field for all the temperatures in the tunnel and for the wall temperatures.



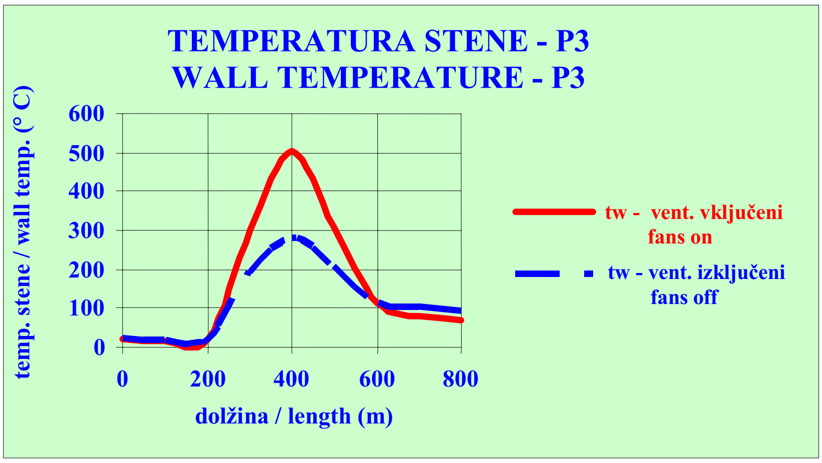
Sl. 5. *Požar v točki 3*
Fig. 5. *Fire in point 3*



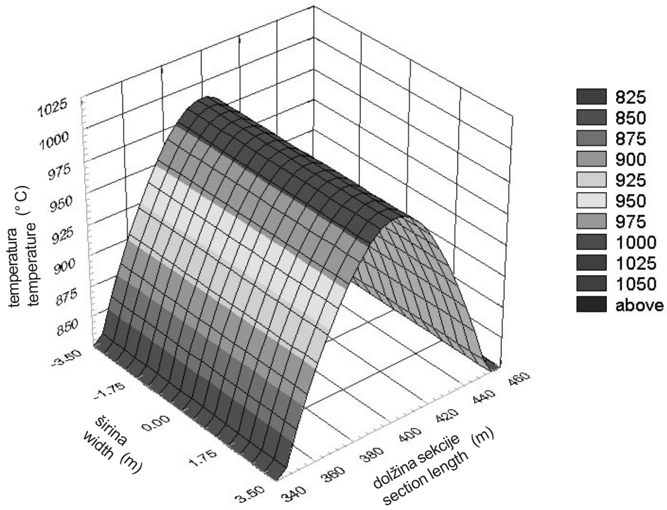
Sl. 6. *Požar v točki 3 – hitrost zraka (m/s), čas 30 minut*
Fig. 6. *Fire at point 3 – air velocity u (m/s), time 30 minutes*



Sl. 7. *Požar v točki 3 – temperatura zraka, čas 30 minut*
Fig. 7. *Fire in zone 3 – air temperature t, time 30 minutes*



Sl. 8. *Požar v coni 3 – površinske temperature, čas 30 minut*
Fig. 8. *Fire in zone 3 – wall temperature t_w, time 30 minutes*



Sl. 9. *Temperaturno polje pod stropom predora med 350 m in 450 m (točka 3)*
Fig. 9. *Temperature field under the ceiling of the tunnel between 350 m and 450 m (zone 3)*

5 SKLEP

Vsak potek temperatur vzdolž predora je odvisen od požarnega scenarija in je od primera do primera različen. Analize in simulacije kažejo znatne razlike za posamezne predore. Temperature zraka se gibljejo v mejah od 800 °C pa do prek 1300 °C.

V začetni fazi požara mora imeti absolutno prednost reševanje ljudi iz ogroženega območja. Vendar je čas, v katerem je umik še možen, zelo omejen. Ko enkrat temperatura doseže 1000 °C in se temu pridruži še gost dim, možnosti preživetja v takšnih razmerah praktično ni. Obodne stene predora, posebej še zaradi močnih vzdolžnih toplotnih tokov, zelo hitro višajo temperaturo v celotnem območju v nekaj minutah.

Podrobni problemi, razrešeni na temelju simulacije, dajejo odgovore na številna vprašanja. Tako npr. lahko določimo optimalne razdalje med prečnimi, za reševanje pomembnimi povezavami med obema

5 CONCLUSION

Any temperature curve is the result of a fire scenario and cannot act as a basic design requirement unless a worst-case-based fire curve is chosen. The analyses and simulations show remarkable differences for the different tunnels. The temperature range can be between 800 °C and more than 1300 °C.

The initial phase offering the possibility of escape is very limited. Temperatures exceeding 1000 °C together with the smoke concentration provide conditions where the chances of survival are close to zero. The surrounding walls in a tunnel together with the lack of heat escape in the vertical direction, lead to a large temperature increase in just a few minutes.

The evacuation times computed by a computer program can be used to evaluate the alternative distances and widths of cross-passages and to provide comparisons of alternative walkway predorskima cevema, njihovo širino in dolžino. Za dosego izhodnega časa okoli 6 minut obstaja več možnosti. Če večamo razdaljo med vmesnimi prehodi, morajo umikajoči se ljudje prehoditi daljšo pot do naslednjega izhoda iz predora s požarom, tam pa morajo na izhod čakati dalj časa. Z razširitvijo prečnih povezav narašča število ljudi, ki se lahko umikajo, ter se čas, potreben za umik, tudi zaradi večje pretočnosti skrajša.Toda upoštevati moramo, da z razširitvijo čas, potreben za izhod, skrajšamo, čas za prehojeno enako dolžino pa ostaja enak [5].

heights and widths. To achieve an evacuation time of 6 min, there are various options. As the distance between cross-passages increases, people have to walk a longer distance to the nearest cross-passage and wait longer periods to get out of the incident tunel. Widening the cross-passage increases the people flow rate and reduces the evacuation time. However, only the waiting time at the cross-passage is reduced, the walking time to the cross-passage remains the same [5].

6 OZNAČBE
6 SYMBOLS

prerez predora	A	m^2	cross-section of tunnel
čelna površina	A_v	m^2	front section
koeficient zračnega upora	c_w		air-resistance coefficient
specifična toplota	c_p	kJ/kgK	specific heat
konstanta	C		constant
debelina plasti plina	d	m	thickness of gas layer
hidravlični premer	D_h	m	hydraulic diameter
geodetska višina predora	H	m	geodetic height of tunnel
višina	h	m	height
dolžina predora	L	m	length of tunnel
dolžina	l	m	length
pretok	m	kg/s	flow rate
število vozil	M	h^{-1}	number of vehicles
število vozil v predoru	N	h^{-1}	number of vehicles in tunnel
hitrost zraka	u	m/s	air velocity
hitrost vozila	v	km/h	velocity of vehicles
konvekcijska toplota	q_c	kJ/s	convective heat
tlak	p	Pa	pressure
čas umika	τ	min	time for escape
tlačni padec	Δp_k	Pa	local pressure difference
čas	t	s	time
temperaturna razlika	$\Delta\Theta_m$	K	
koeficient trenja	λ		coeff. of friction
gostota zraka	ρ	kg/m^3	density of air

Indeksi in potence		*Indexes and powers*
tovorni	T	truck
osebni	o	personal
stenski	w	wall
povprečni	*	average

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