NEED FOR FIXED FIRE FIGHTING SYSTEMS IN ROAD TUNNELS

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ABSTRACT. Road tunnels with heavy traffic are expected to have in place specific emergency measures for prevention and mitigation of effects of road accidents and other critical events associated with fires which might endanger human life, tunnel structure and facilities or cause environmental pollution. It is known that risk management in the event of road tunnel fire cannot be ensured solely by means of emergency ventilation. Fire control systems can save human lives and maintain acceptable environment for evacuation of tunnel users. Fire impact mitigation and reduction of heat release rates are essential also for preservation of tunnel facilities. The purpose of this work is to assess fire dynamics in road tunnels taking into account response time of Fire & Rescue Services and to provide rationale for the use of fixed firefighting systems therein as well as for the need of training of Fire & Rescue personnel involved in suppression and rescue operations in these underground sites.

Keywords: tunnels, fire dynamics, FFFS

НЕОБХОДИМОСТ ОТ СТАЦИОНАРНИ ПОЖАРОГАСИТЕЛНИ СИСТЕМИ В ПЪТНИ ТУНЕЛИ

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РЕЗЮМЕ. В пътните тунели с голям трафик се очаква предприемането на конкретни аварийни мерки с цел да се предотвратят и ограничат последиците от пътнотранспортни произшествия и други критични събития, свързани с пожари, които могат да застрашат човешкия живот, конструкцията и съоръженията в тунела или да предизвикат замърсяване на околната среда. Известно е, че управлението на риска при възникване на пожар в пътен тунел не се осигурява в необходимата степен само с използване на аварийна вентилация. Системите за контрол на пожари могат да спасят човешкия живот, като запазят ниско нивото на мощността на пожара и поддържат приемлива среда за евакуация на пътниците в тунела. Ограничаването на размера на пожара и на темпа на нарастване на неговата мощност имат значителна полза и за опазване на техническите системи в тунела. Целта на настоящата работа е да се проследи динамиката на пожарите в пътни тунели, като се отчете времето за реакция на службите за ПБЗН и се обоснове необходимостта от използването на стационарни пожарогасителни системи в тях, както и за провеждането на обучение за поддържане и актуализиране на тактическата подготовка на състава от РСПБЗН, осъществяващ пожарогасителна и аварийно-спасителна дейност в тези подземни обекти.

Ключови думи: тунели, динамика на пожари, стационарни пожарогасителни системи

Fire dynamics in road tunnels

Fire dynamics is essential for the design of emergency ventilation mode, fire alarm and fire suppression in tunnels. It is described by the time of growth tg, until reaching of stable burning at maximum rate tmax, and time of decay td, associated with fire load of design fires as detailed in Table 1. Fires where no fuel spills are involved could reach high heat release rates as well. For instance, a fully loaded heavyweight vehicle catching fire may reach a heat release rate of 100 MW, albeit in longer growth time (Fig. 1) until reaching the maximum heat release rate HRRmax (Michaylov, Makedonska, 2017).

Table 1. *Fire dynamics scenarios*

HRRmax [MW]	Duration of fire stages [min]			Fire load [MJ]
	tg	tmax	td	
8	5	25	20	18 000
15	5	60	15	63 000
30	5	0	45	50 000
30	10	50	30	125 000
100	10	60	20	450 000
200	10	60	30	960 000

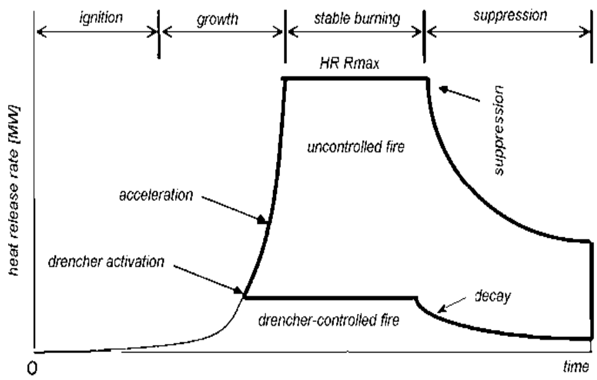

Fig. 1. Fire development stages

There are several methods of calculation of heat release rate of a material. It may be defined by the formula:

$$Q = m''\Delta Hc_{eff}(1-e^{-k\beta D})A_{dike} \quad (1)$$

where: Q – heat release rate [kW]
m" – mass fuel burning rate per unit area [kg / m^2.s]

ΔHc,eff – effective fuel burning heat [kJ/kg]

$A_f = A_{dike}$ -fire area (area where evaporation occurs)) [m^2]

k_β – empiric constant [m^{-1}]

D – fire diameter (diameter involved in evaporation, assumed to be a circle), [m].

The heat release rate, HRR is a major characteristic of fire dynamics. It predicates generation of undesired effects of the fire and its products which increase as HRR increases. This means that toxic gases, smoke and other fire hazards increase in parallel with heat release rate (table 2).

Comprehensive study of dynamics (HRR in time) of design fires may help prevent human life hazards and property damage.

Table 2. *Burning data of different fuels*

Fuel	m'' [kg/m^2.s]	ΔHc,eff [kJ/kg]	k_β [m^{-1}]
Benzene	0.055	43 700	2.1
Kerosene	0.039	43 200	3.5
Diesel	0.045	44 400	2.1
Transformer oil	0.039	46 000	0.7
Crude petroleum	0.0335	42 600	2.8
Lubricant	0.039	46 000	0.7

Tunnel fire risk is evaluated on the basis of representative statistical data about the frequency of road tunnel fires and modelling of consequences of each individual design fire. Design fire development and effects thereof constitute the fire scenario.

It is known that any scenario of design tunnel fire is a unique combination of events and is the result of certain set of circumstances associated with passive and active fire protection measures (Chochev, 2003). Design fire scenario is defined in consideration of the following factors:

a) Tunnel geometry (cross sections, gradients, tube connections, evacuation and service workings);
b) Type, size, dimensions, and location of ignition source;
c) Fuel type in the vehicle;
d) Fuel quantity and distribution thereof in vehicle structure;
e) Type of combustible material – liquid, solid or gaseous fuel;
f) Fire growth rate and time (Fig. 1, Table 1);
g) Maximum heat release rate of design fire (HRRmax) – please refer to Table 3 and Fig.1;

Table 3. *Dimensional severity of design fires*

Vehicle type on fire	Maximum fire severity, [MW]	Fire load [GJ]
One car	5	11
2-3 cars	8	18
One van	15	63
One bus or light commercial vehicle	20	50
Heavyweight truck without dangerous load	30	125
Heavyweight truck or cistern with dangerous load	100	450
Cistern with hydrocarbons or trailer	200	960

h) Tunnel ventilation system and design fire ventilation mode for the scenario;
i) Weather conditions at tunnel inlet and outlet;
j) Fire alarm activation – manual and/or automatic;
k) Firefighting installations (type, distribution), fire water supply, foamer, and primary extinguishers (Häggkvist, 2009);
l) Human intervention for fire suppression and emergency ventilation control.

Response time of Fire & Rescue Services

Table 4 presents information about tunnels of length > 100 m on the territory of Bulgaria and their specific characteristics: length, distance to the responsible Regional Fire & Rescue Service, and travel time of fire vehicles to each tunnel.

Response time of Fire & Rescue Services is correlated to the time of free fire development which is defined by the equation (Stojanov, 2016):

$$t_{св} = t_{д.с} + t_{из} + t_{дв} + t_{б.р} \qquad (2)$$

where:

$t_{д.с}$ – time to fire detection – assumed to be 2-3 [min] for fire alarm installations, and 6 min for manual alarm;

$t_{из}$ - departure time of fire vehicle– 1 [min];

$t_{дв}$ – travel time of fire vehicle to the tunnel (Table 4);

$t_{б.р}$ – deployment time – from 3 to 5 [min] depending on deployment area, fire location in the tunnel, and type of vehicles and extinguishing agents used.

Fire detection time is essential for the start of evacuation of tunnel users and the response of Fire & Rescue Services. Major characteristics of fire alarm equipment include reliability and accuracy of fire site localisation.

Smoke detectors fail to meet these requirements due to the smoke spreading mode within the tunnel. Smoke spreading may render difficult even for CCTV cameras to detect fire location and follow vehicle travel in dense smoke environment.

In such circumstances, application of thermal cables with semi-conductor maximum-differentiated sensors installed along the entire tunnel length is successful. The distance between addressable sensors may be selected from 7 m to 10 m. Dire detection reliability is achieved by simultaneous reaction of two sensors. The threshold value is set at two alarm levels: maximum- for instance up to 50-600°C, and differential – 30°C/20s. Thus, fire detection time of 120-150 s can be achieved. Thermal-cable- based systems also allow for setting of one pre-alarm level of maximum temperature and of temperature rise rate. Reliability and accuracy of fire localisation render thermal cables particularly suitable for automatic switching of the ventilation system in emergency mode and activation of drencher-type fire suppression system. This is mandatory for tunnels without operative management on site.

In recent years a great deal of research has taken place internationally to ascertain the types of fire which could occur in tunnel and underground spaces. This research has taken place in real tunnels, in laboratory conditions, and via numerical modelling. As a consequence of the data obtained from these tests, a series of time/temperature curves for the various exposures have been developed as detailed.

Standard curve - Standard fire tests to which specimens of constructions are subjected, are based on the use of the Cellulosic time/temperature curve, as defined in various national standards, e.g. ISO 834, BS 476: part 20, DIN 4102, AS 1530 etc. This curve is based on the burning rate of the materials found in general building materials and contents.

Table 4. *Response time of Fire & Rescue*

№	REGION	TUNNEL ON ROAD №	Initial kilometer	Tunnel length [m]	Regional F& R Service	Distance b/n Regional FRS and tunnel [km]	Travel time [min]	Time t_{CB} [min]
1	SOFIA	Vitinya RT- Hemus Highway	32+260	1195	Botevgrad	20.50	27.33	33.33
2	SOFIA	Topli Dol RT - Hemus Highway	39+562.30	883	Botevgrad	23.3	31.07	37.07
3	PLOVDIV	RT RELOCATION OF EXISTING ROAD III-868 “DEVIN-MIHALKOVO”, tunnel at Lyaskovo Village		880	Devin	16	21.33	27.33
4	SOFIA	Praveshki Hanove RT - Hemus Highway	54+672	834	Pravets	3.4	4.53	10.53
5	SOFIA	Echemishka RT - Hemus Highway	41+904	820	Botevgrad	9	12.00	18.00
6	SOFIA	Trayanovi Vrata RT – Trakia Highway	53+297	685	Ihtman	15.3	20.40	26.40
7	GABROVO	III-5004 “Detour of Gabrovo, Stage Three, Tunnel № 1, size 9/10.5 from km. 12+420 to 13+020	12+420	540	Gabrovo	10	13.33	19.33
8	PERNIK	Golyamo Buchino RT - Lyulin Highway	14+680	490	Pernik	20.5	27.33	33.33
9	SOFIA	Malo Buchino RT - Lyulin Highway	7+712	440	06 Regional FRS	13.3	17.73	23.73
10	SMOLYAN	II-86	97+079	421	Smolyan	5	6.67	12.67
11	LOVECH	II-35 RT at Lovech	43+298	413	Pravets	23	30.67	36.67
12	SOFIA DISTRICT	Kashana RT – Pirdop-Etropole Road		380	Zlatitsa	15	20.00	26.00
13	BLAGOEV-GRAD	Zheleznitsa RT on Road I-1/E-79	370+430	360	Blagoevgrad	13	17.33	23.33
14	KYUSTENDIL	Levski RT- Struma Highway – KocherinovoTown	82+890	350	Rila	15	20.00	26.00
15	PERNIK	Middle RT - Lyulin Highway	10+562	350	Pernik	25.8	34.40	40.40
16	BLAGOEV-GRAD	Kresna RT on Road I-1/E-79	388+848	343	Blagoevgrad	30.8	41.07	47.07
17	GABROVO	III-5004 “ Detour of Gabrovo, Stage Five, Tunnel № 4, size 9/10.5 28+930 to 29+020 length – 90 m and tunnel № 5, size 9/10.5 from km 29+120 to 29+410	28+930	290	Kazanlak	n.a.		
18	KYUSTENDIL	Struma Highway	56+176	280	Dupnitsa	11	14.67	20.67
19	KYUSTENDIL	RT on Road I-1/E-79 - Dupnitsa	328+100	272	Dupnitsa	4	5.33	11.33
20	GABROVO	III-5004 “ Detour of Gabrovo, Stage Five, Tunnel № 3, size 9/10.5 from km. 27+800 to 28+040	27+800	240	Kazanlak	n. a.		
21	PLOVDIV	Konnika RT on Road II-86 Asenovgrad-Bachkovo	32+419	215	Asenovgrad	5.5	7.33	13.33

№	REGION	TUNNEL ON ROAD №	Initial kilometer	Tunnel length [m]	Regional F& R Service	Distance b/n Regional FRS and tunnel [km]	Travel time [min]	Time t_{CB} [min]
22	SMOLYAN	RT on Road III-35 Grohotno – Devin	83+488	178	Devin	10	13.33	19.33
23	VELIKO TARNOVO	RT №1 on Road I-5 Ruse-Veliko Tarnovo, Detour of Valiko Tarnovo	103+524	178	Veliko Tarnovo	3	4.00	10.00
24	PLOVDIV	Martvitsa-4 RT on Road II-86 Asenovgrad-Bachkovo	33+426	165	Asenovgrad	6.5	8.67	14.67
25	GABROVO	III-5004 " Detour of Gabrovo, Stage Five, Tunnel № 1, size 12/13.5 from km. 22+720	22+720	160	Kazanlak	n. a.		
26	BLAGOEV-GRAD	RT at Ilinden Border Checkpoint on Road II-19 Bulgaria - Greece	106+259	149	Gotse Delchev	20	26.67	32.67
27	VELIKO TARNOVO	RT №2 on Road I-5 Ruse-Veliko Tarnovo, Detour of Valiko Tarnovo	103+814	141	Veliko Tarnovo	3.5	4.67	10.67
28	PLOVDIV	RT on Road III-866 Mihalkovo – Krichim	97+793	132	Stamboliyski	22	29.33	35.33
29	GABROVO	Dyado Nikola RT on Road I-5/E-85 in Gabrovo	150+814	112	Gabrovo	5	6.67	12.67
30	GABROVO	Dryanovski Monastery RT on Road I-5/E-85 between Dryanovo and Gabrovo	133+387	112	Dryanovo	7	9.33	15.33

The temperature development of the Cellulosic fire curve (ISO-834) is described by the following equation:

$$T = 20 + 345 \times \log (8 \times t + 1) \quad (3)$$

Hydrocarbon curve - Although the standard curve has been in use for many years, it soon became apparent that the burning rates for certain materials e.g. petrol gas, chemicals etc., were well in excess of the rate at which timber would burn (SOLIT Safety of Life in Tunnels, 2012). As such, there was a need for an alternative exposure for the purpose of carrying out tests on structures and materials used within the petrochemical industry, and thus, the hydrocarbon curve was developed.

The hydrocarbon curve is applicable where small petroleum fires might occur, i.e. car fuel tanks, petrol or oil tankers, certain chemical tankers etc.

The temperature development of the Hydrocarbon (HC) fire curve is described by the following equation:

$$T = 20 + 1080 \times (1-0{,}325 \times e^{-0{,}167xt} - 0{,}675 \times e^{-2{,}5x\,t}) \quad (4)$$

Hydrocarbon Modified curve - Derived from the above-mentioned Hydrocarbon curve, the French regulation asks for an increased version of that Hydrocarbon curve, the so-called HydroCarbon **Modified** curve (HCM).

The maximum temperature of the HCM curve is 1300°C instead of the 1100°C, standard HC curve.

However, the temperature gradient in the first few minutes of the HCM fire is as severe as all Hydrocarbon based fires (RWS, HCM, HC), possibly causing a temperature shock to the surrounding concrete structure and concrete spalling as a result of it.

The temperature development of the Hydrocarbon Modified (HCM) fire curve is described by the following equation:

$$T = 20 + 1280 \times (1 - 0{,}325 \times e^{-0{,}167\,x\,t} -0{,}675 \times e^{-2{,}5\,x\,t}) \quad (5)$$

RABT ZTV curve (https://www.promat-tunnel.com) - The RABT curve was developed in Germany as a result of a series of test programmes such as the Eureka project. In the RABT curve, the temperature rise is very rapid up to 1200°C within 5 minutes. The duration of the 1200°C exposure is shorter than other curves with the temperature drop off starting to occur at 30 minutes for car fires.

RWS (Rijkswaterstaat) curve - The RWS curve was developed by the Rijkswaterstaat, Ministry of Transport in the Netherlands. This curve is based on the assumption that in a worst-case scenario, a 50 m³ fuel, oil or petrol tanker fire with a fire load of 300 MW could occur, lasting up to 120 minutes. The RWS curve was based on the results of testing carried out by TNO in the Netherlands in 1979.

Figure 2 presents comparison of the Standard time/temperature curve ISO 834 and various curves defining tunnel fire development.

The comparison between the response time of Fire & Rescue Services (Table 4) and the fire curves (Figure 2) characterising ire dynamics leads to the conclusion that firefighting in the tunnels under review may only commence after fires have reached maximum heat release rate, i.e. firefighting would proceed at reduced effectiveness and efficacy.

In support of those arguments, results of foreign studies may be pointed out as detailed on Figure 2.

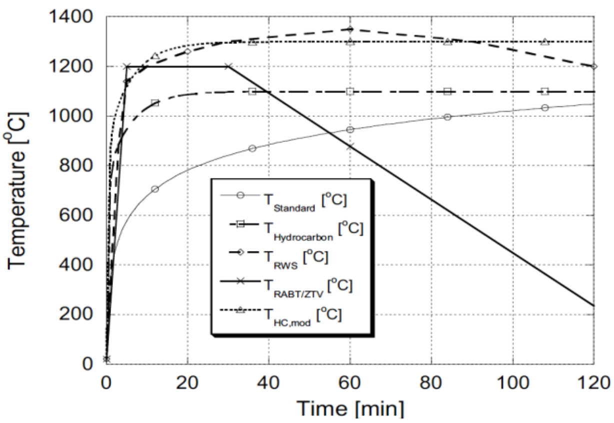

Fig. 2. Fire curves describing fire dynamics

$T_{Standard}$ – standard time/temperature (cellulosic) curve;
$T_{Hydrocarbon}$ – hydrocarbon curve in North European countries;
T_{RWS} – time/temperature curve used in Dutch regulations;
$T_{RABT/ZTV}$ – curve according to the German Directive on tunnel equipment and operation;

The issue under review is further aggravated by the fact that, in the event of fire, the tunnel ventilation will be increased to ensure safe evacuation of those present in the tunnel thus increasing fire severity.

Figure 3 provides graphic illustration of the data presented in Table 4 demonstrating that, in 29% of tunnels in Bulgaria, Fire & Rescue teams would start firefighting up to the 15th minute after receipt of fire notification. In the remaining 71% tunnels located in the country, firefighting would start after the 15th minute from receipt of fire notification when fires would have reached maximum severity.

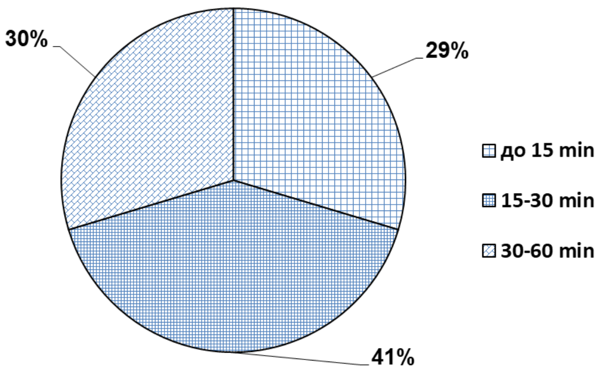

Fig. 3. Response time of Fire & Rescue Services in the event of tunnel fire

The aforementioned circumstances call for tunnel protection by a water-based fixed firefighting system or other suitable means for creating a favourable environment for safe evacuation and access to emergency help. Such need is supported by the short time of fire growth (Fig. 2), after which suppression becomes more difficult because it is impossible for firefighting personnel to sufficiently approach the burning area. The situation is further aggravated by the increase of ventilation flowrate to enable safe escape of tunnel users. This impacts fire rate m" in (1) and fire severity.

Response and travel times of fire vehicles (Table 4), for almost all tunnels, is much greater than the growth time for most tunnel fires (Fig. 2).

The main hazard is for the fire to spread to adjacent vehicles (Liu et al., 2007). The fixed firefighting system, in the worst-case scenario, will keep the fire at very low energy level (HRR on Fig. 1) and will facilitate evacuation and suppression.

After consideration of all impacting factors, at this stage installation of such systems may be recommended in:

- longer tunnels with heavy traffic and long escape routes;
- tunnels with two-directional traffic equipped with longitudinal ventilation systems and long escape routes;
- tunnels associated with too long response time of Fire & Rescue Services.

With reference to the specifics of road tunnel fire occurrence and growth, regular training and upgrade of firefighting skills is necessary for fire and rescue teams operating in underground facilities.

Training should be organised and held in two major directions: theoretical training and practical training.

Theoretical training should include specifics of fire suppression in road tunnels, core principles and methods of training and practical application thereof.

Practical training should aim at acquiring knowledge and skills that are necessary for proper assessment of fire situation, selection of the most appropriate firefighting agents and skilful management of firefighting personnel and means.

Training should employ all possible organisational methods and forms of tactical approach to firefighting.

Response time to beginning of active fire suppression by Fire & Rescue Services should have higher weight in risk assessment.

Emergency ventilation includes two functional and modal stages:

⇒ Stage 1 – includes the first 15 min after fire occurrence. During this initial period "self-rescue" and evacuation of tunnel users is of the utmost importance. Evacuees must be protected, by means of ventilation manoeuvres, from smoke exposure – toxic gases, reduced visibility and high temperature. In such cases, ventilation system operation may be controlled automatically to ensure fast response;

⇒ Stage 2 – ventilation assists fire suppression via effective suction of smoke from fire area or via unilateral smoke exhaustion from the fire area. At stage 2, ventilation control should be coordinated with rescue personnel involved in fire suppression.

Conclusion

Given the fire dynamics in road tunnels and response time of Fire & Rescue Services in the Republic of Bulgaria, installation may be recommended of fixed firefighting systems in tunnels to keep low energy level of the fire and facilitate evacuation and fire suppression.

After consideration of all impacting factors, at this stage **installation of such systems** may be recommended in:

⇒ unidirectional road tunnels of length exceeding 900 meters;

⇒ tunnels with two-directional traffic and length exceeding 600 meters, and

⇒ tunnels with lengthy escape routes due to the absence of connection workings therein.

Fixed firefighting systems can control fires, preserve tunnel structure and prevent linear spread of tunnel fire.

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