Inženjerska komora Crne Gore
Stručno predavanje SKMI 24. III 2023.

# VENTILACIJA I PROTIVPOŽARNA BEZBJEDNOST SAOBRAĆAJNIH TUNELA SA PREGLEDOM OBAVEZUJUĆIH STANDARDA I SMJERNICA

Doc.dr Milan Šekularac, dipl.maš.ing.

Mašinski fakultet

Univerzitet Crne Gore

# SADRŽAJ

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

## VRSTA SAOBRAĆAJA

- Drumski*
- Željeznički

## KONTEKST

- Gradski (urbani)
- Ruralni / Autoput*

## SMJER SAOBRAĆAJA

- Dvosmjerni saobraćaj*
- Jednosmjerni saobraćaj*

## TIP VENTILACIONOG SISTEMA

- Podužna (“longitudal”) ventilacija “jet” ventilatorima*
- Poprečna (“transversal”)
- Polupoprečna (“semitransvers.”) - kombinovana

*U FOKUSU PAŽNJE DANAŠNJEG PREDAVANJA

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

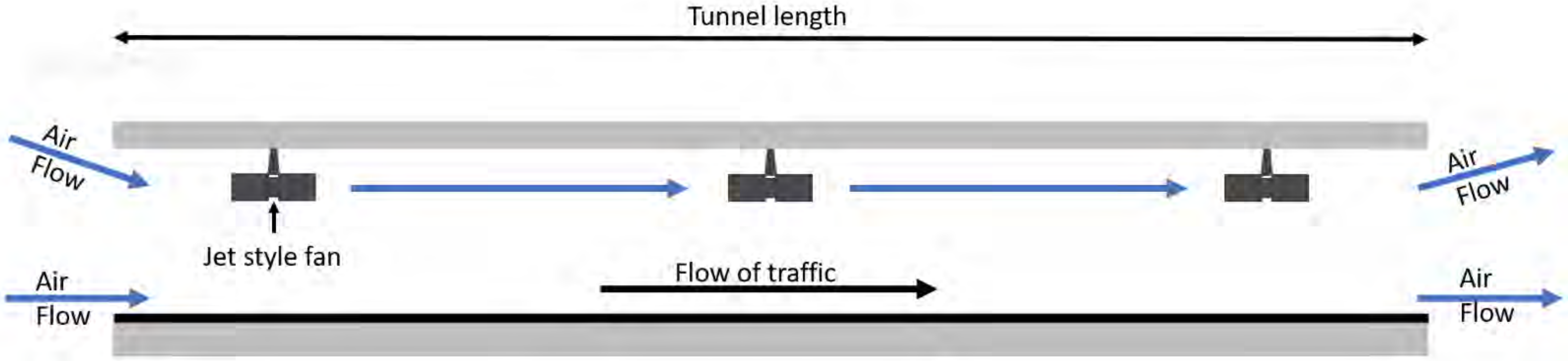
St Hellena tunnel, Pacific coast highway, SAD

Izvor: MoJet

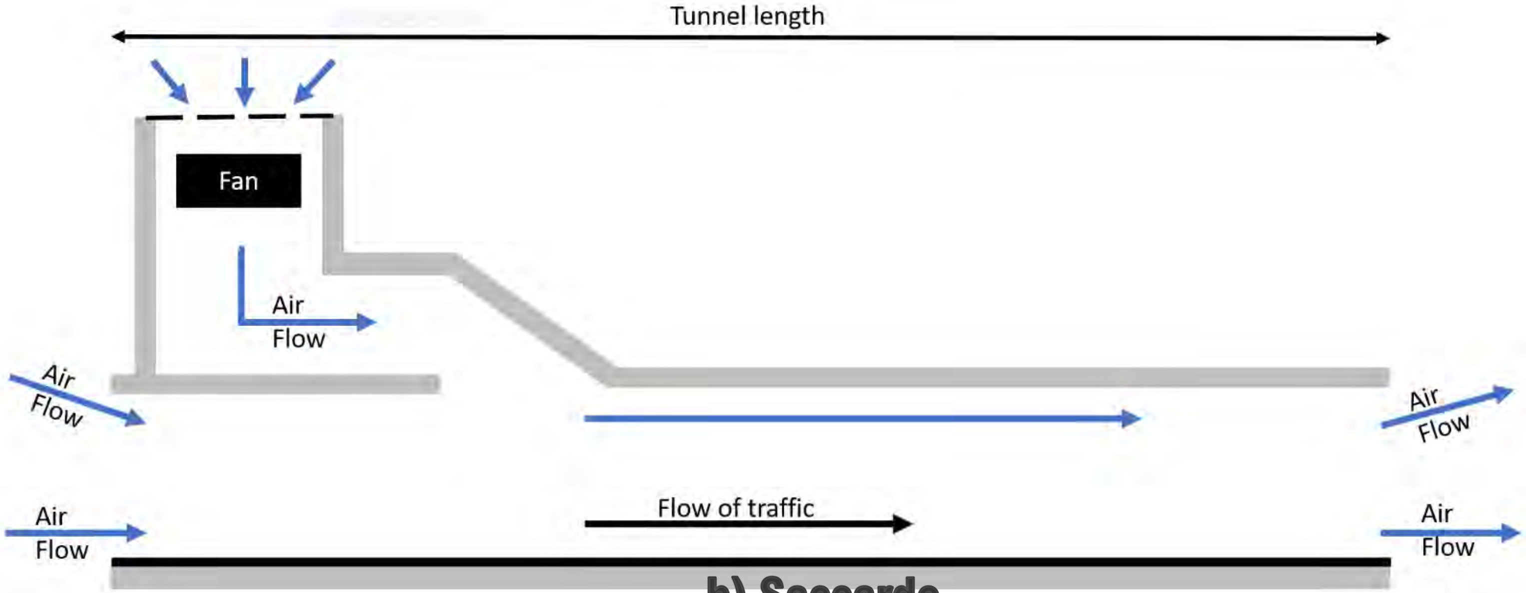
# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

# *1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU*

## Osnovne koncepcije u izvedbi ventilacionog Sistema – shema:



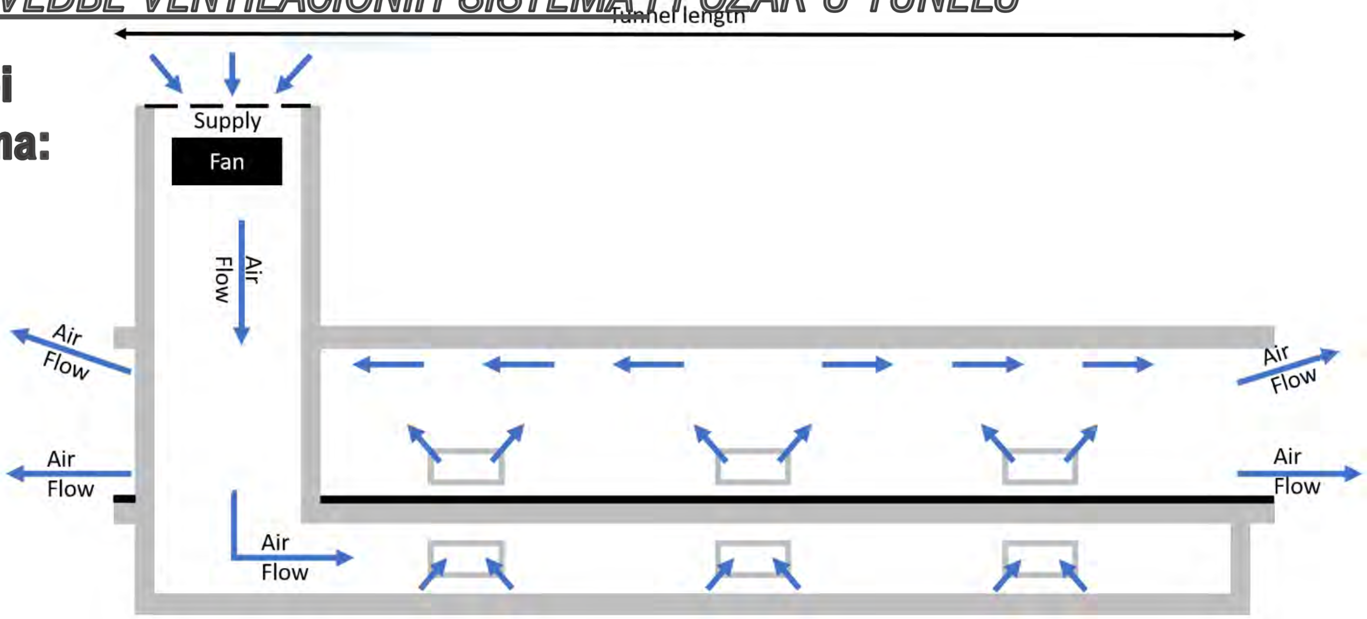
**a) podužna**



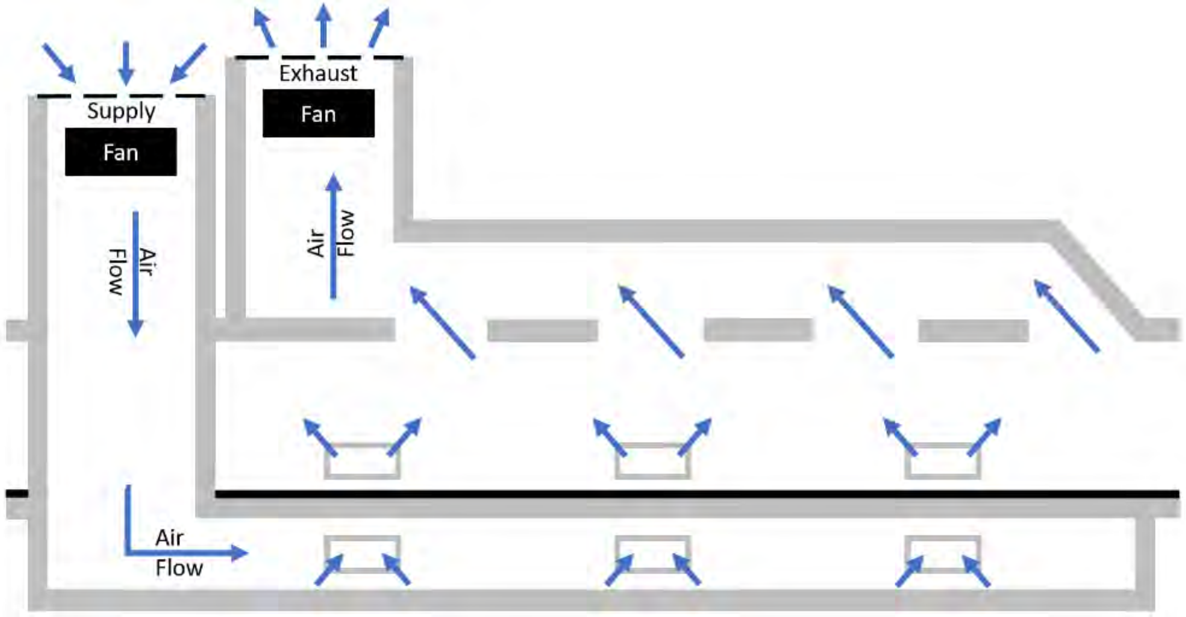
**b) Saccardo**

# 1. *TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU*

## Osnovne koncepcije u izvedbi ventilacionog sistema – shema:



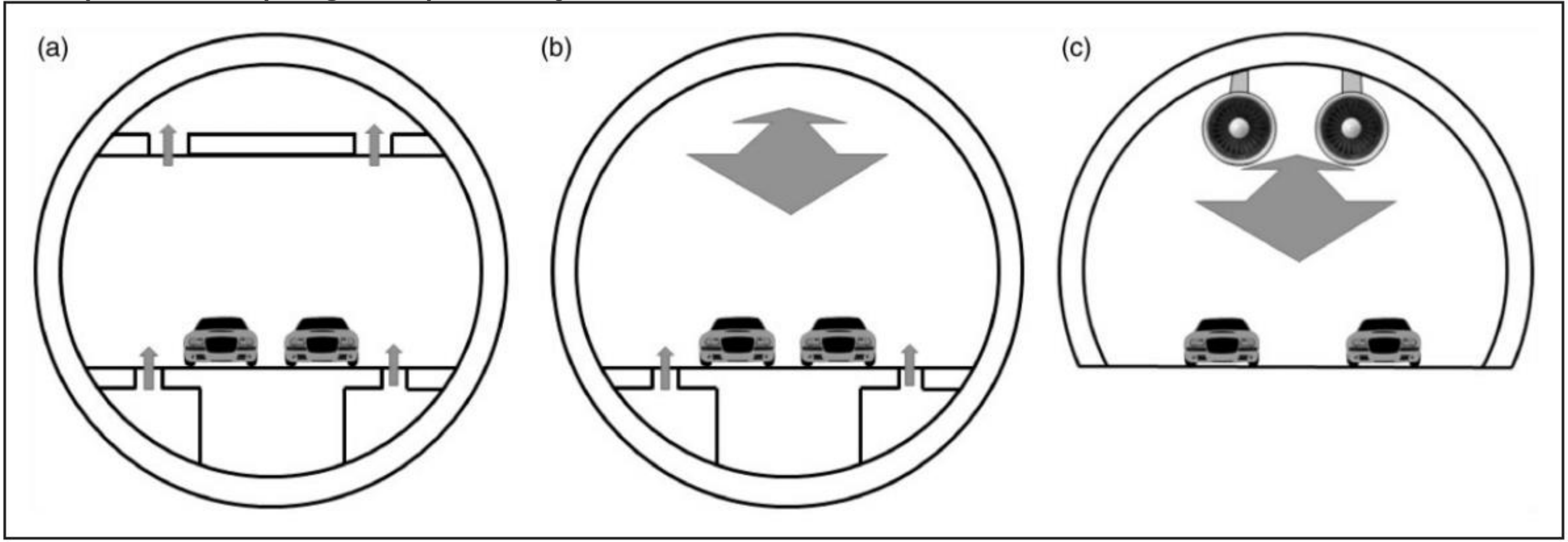
**c) polu-poprečna**



**d) poprečna**

## Osnovne koncepcije u izvedbi ventilacionog sistema* - presjek:

a) Poprečna (“transverse”);
b) Polu-poprečna (“semi-transverse”);
c) Podužna (“longitudal”) ventilacija;



**Application of Multi Objective Optimization Techniques to Improve the Aerodynamic Performance of a Tunnel Ventilation Jet Fan* Article in ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, January 2015 DOI: 10.1177/0954406214531566

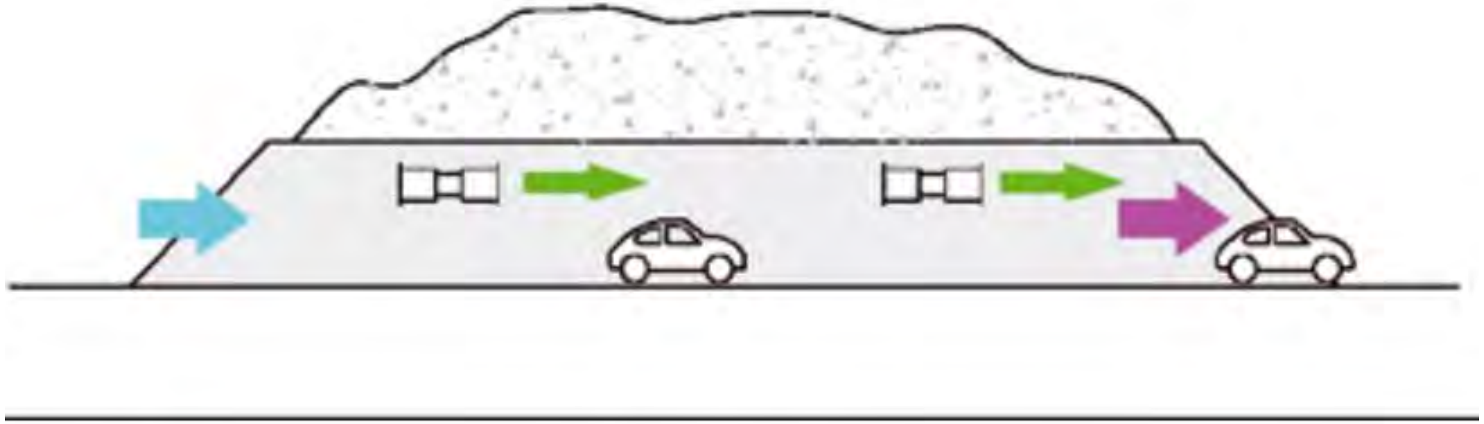


FIGURE 1 - LONGITUDINAL VENTILATION WITH JET FANS

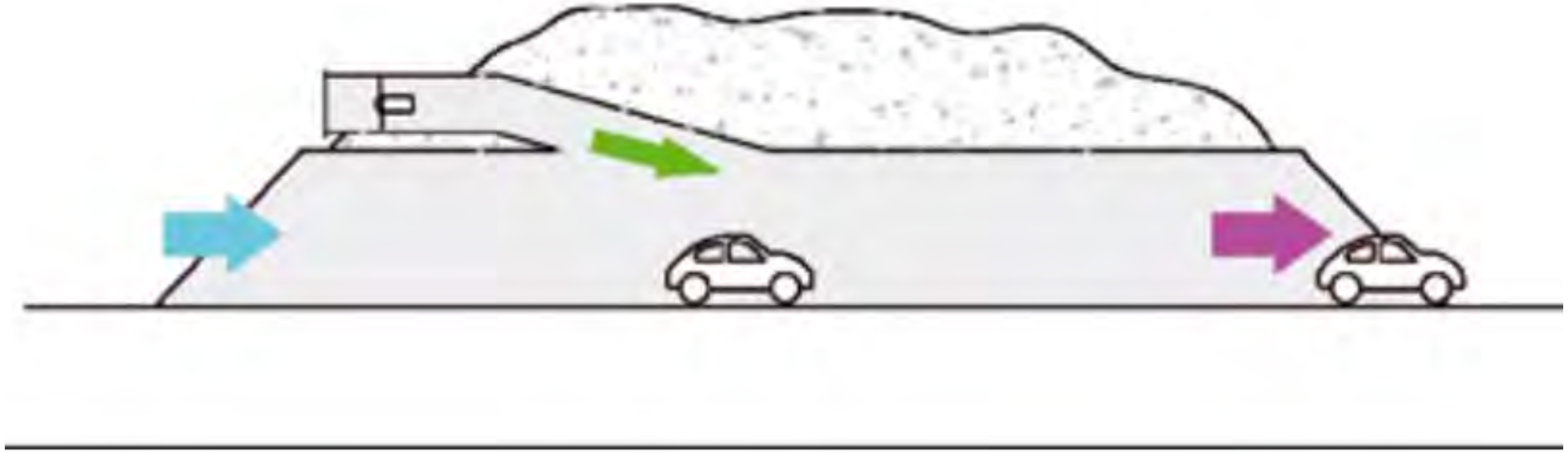


FIGURE 2 - LONGITUDINAL VENTILATION WITH SACCARDO NOZZLE

*Izvor: PIARC ,,Road Tunnels: Operational strategies for emergency ventilation"*

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

FIGURE 3 - SEMI-TRANSVERSE VENTILATION:
DURING NORMAL OPERATING CONDITIONS; FRESH AIR INJECTION

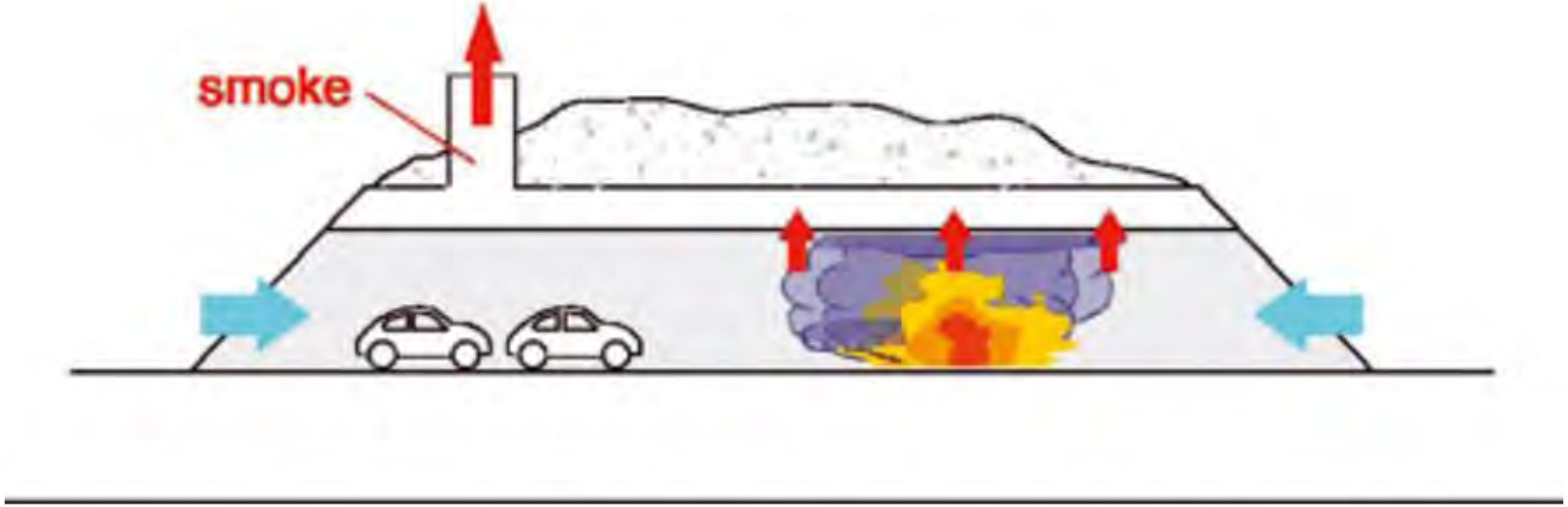


FIGURE 4. SEMI-TRANSVERSE VENTILATION WITH REMOTELY CONTROLLED DAMPERS.

[Note: In case of fire only the dampers near to the fire are opened. All others are closed.]

**Izvor: PIARC ,,Road Tunnels: Operational strategies for emergency ventilation”**

# *1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU*

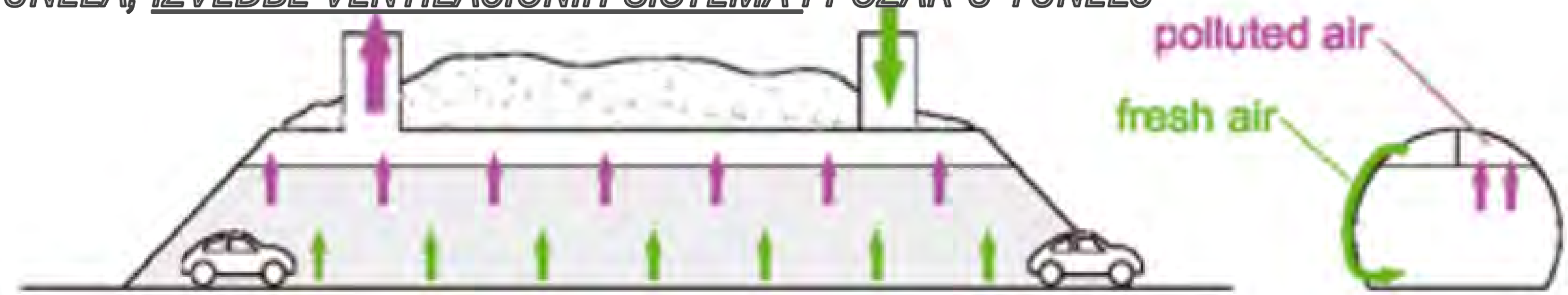


FIGURE 5 - TRANSVERSE VENTILATION SYSTEM
WITH UNIFORM SUPPLY AND EXTRACT OF AIR.

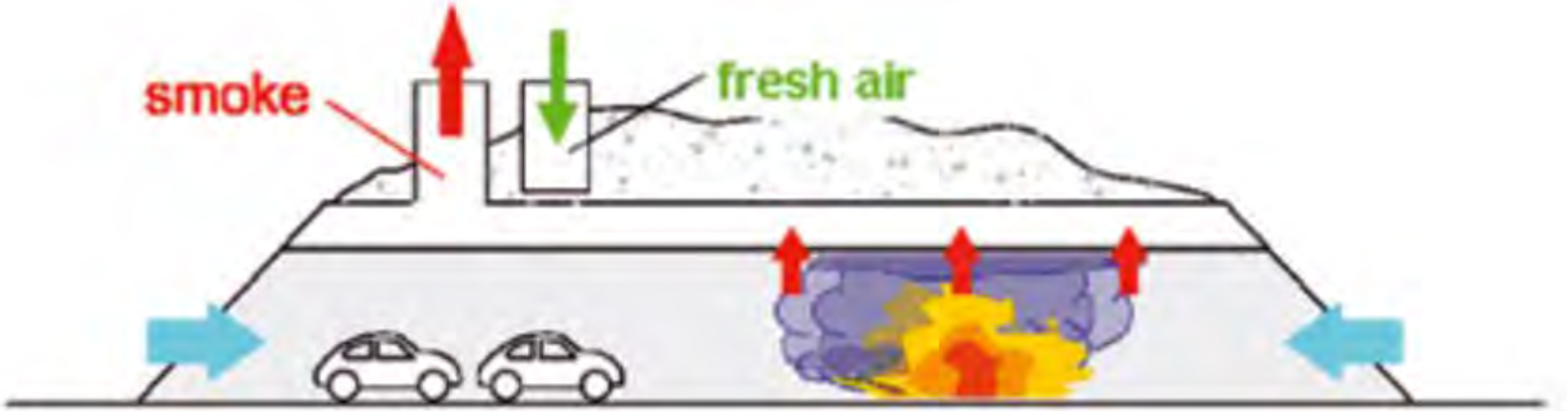


FIGURE 6 - TRANSVERSE VENTILATION WITH REMOTELY CONTROLLED DAMPERS.
[Note: In case of fire, only the dampers near to the fire are opened. All others are closed.]

***Izvor: PIARC ,,Road Tunnels: Operational strategies for emergency ventilation"***

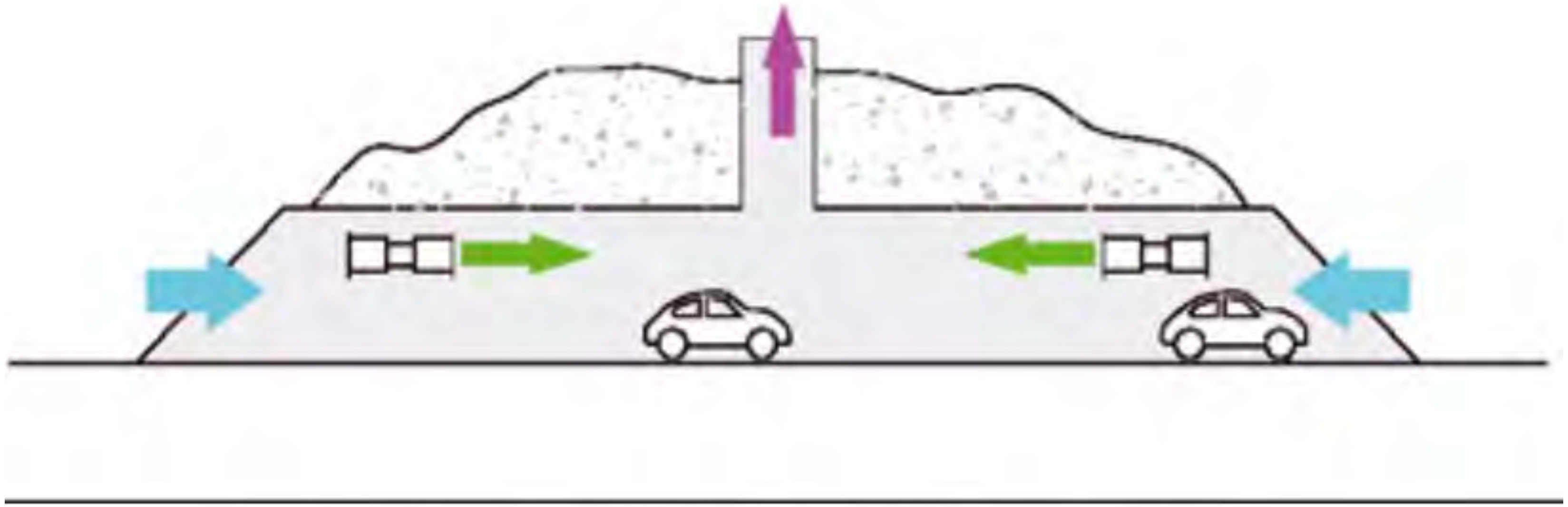
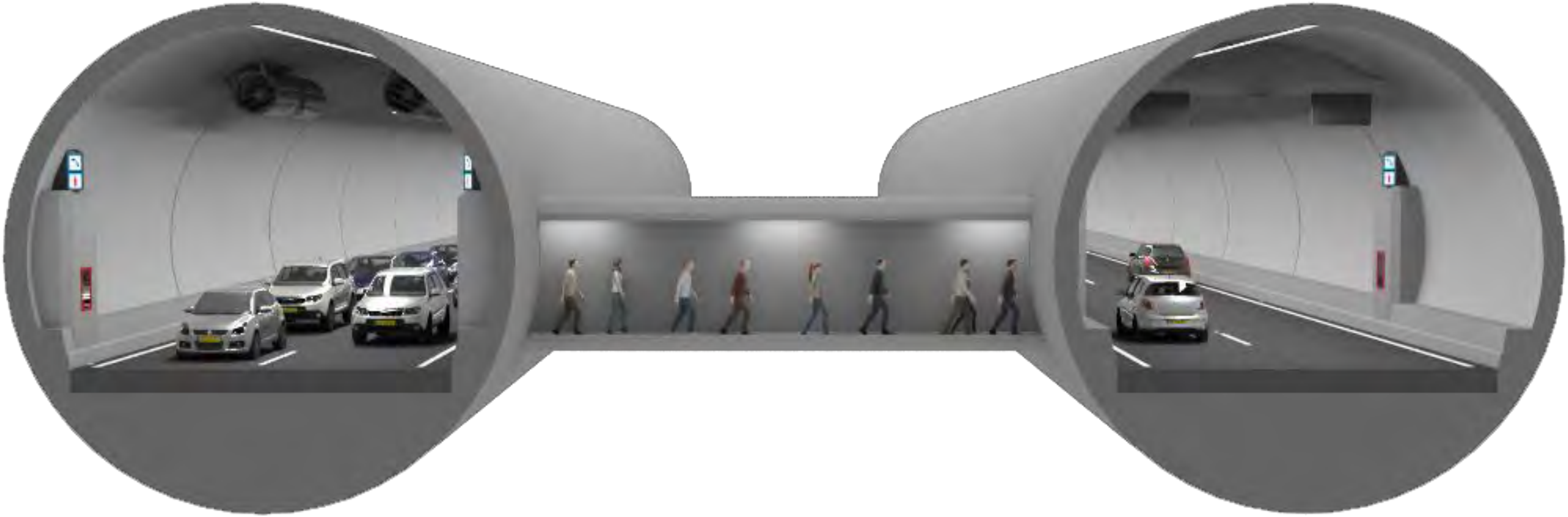


FIGURE 7 - MASSIVE POINT EXTRACTION SYSTEM

*Izvor: PIARC ,,Road Tunnels: Operational strategies for emergency ventilation"*

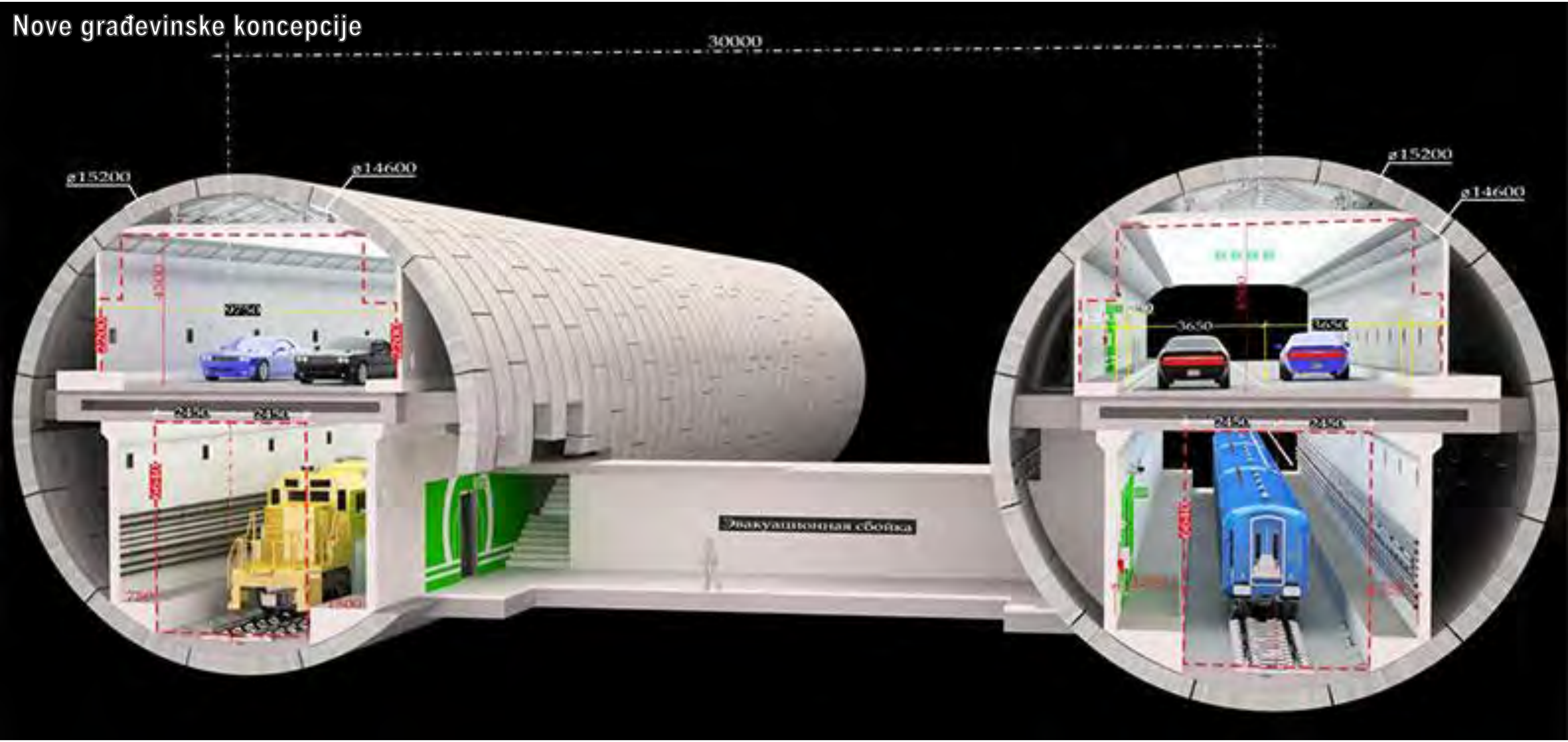
## Građevinske koncepcije i evakuacija



## Nove građevinske koncepcije

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

## Nove građevinske koncepcije



**Gothard tunel (SUI)**

https://en.wikipedia.org/wiki/Gotthard_Road_Tunnel

https://www.rts.ch/info/suisse/3540380-incendie-du-gothard-cetait-il-y-a-dix-ans.html

# 1. *TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I **POŽAR U TUNELU***

*https://www.youtube.com/watch?v=iCpeN4pUciw*

*Kamion koji je prenosio razređivač izaziva udes i požar u tunelu, koji zahvata 11 vozila*
*Povrijeđenih osoba 21. Mjesto Sangju tunel, Central Inland Expressway, grad Changwon (KOR)*

1. *TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I* ***POŽAR U TUNELU***


The 5th of May 2017 - five kilometres inside the Oslofjord tunnel.

**Kamion u plamenu, vozač izbjegao katastrofu**

https://www.youtube.com/watch?v=rpnCB2OwgVY

Kamion se samozapalio na autputu Lanhai jugoistočna kineska provincija Guizhou. Prisiljen da brzo rezonuje šta se može desiti ako požar eskalira unutar tunela i opasnosti po samog vozača i sve druge oko, vozač odlučuje da rizikuje svoj život i odveze kamion bezbjedno van tunela. Ubrzo nakon čega stižu i vatrogasci.

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I POŽAR U TUNELU

*Tunel "Mon Blan"*

**Tunel “Mon Blan” katastrofa**

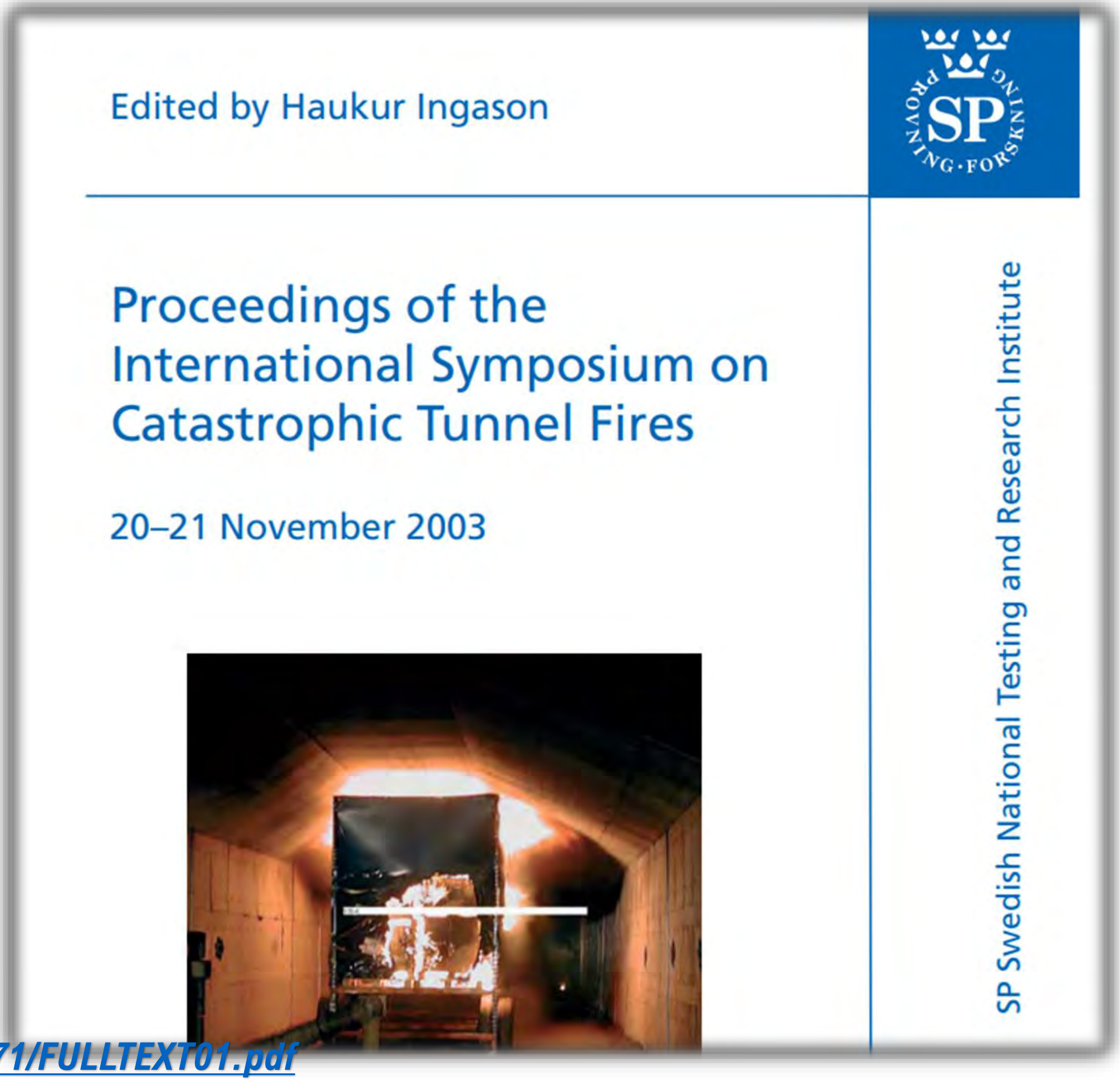
https://www.youtube.com/watch?v=7mggFQQPzJI

https://www.youtube.com/watch?v=tcLaogBvilA

https://www.youtube.com/watch?v=PfKpb1uoFoY

https://www.youtube.com/watch?v=EU55ranUPs8

# 1. TIPOLOGIJA TUNELA, IZVEDBE VENTILACIONIH SISTEMA I **POŽAR U TUNELU**



Edited by Haukur Ingason

Proceedings of the International Symposium on Catastrophic Tunnel Fires

20–21 November 2003

SP Swedish National Testing and Research Institute

***Zbornik radova sa skupa:***
***Proceedings of the International Symposium on Catastrophic Tunnel Fires***
***http://www.diva-portal.org/smash/get/diva2:962271/FULLTEXT01.pdf***

## LITERATURA:

1. PIARC
https://www.piarc.org/en/

2. TU Graz – institut & kongres:
https://www.tunnel-graz.at/

3. Priručnici

Tunnel fire dynamics
H. Ingason, Y.Li, A. Loennermark

A.Beard, R.Carvel
Handbook of tunnel fire safety

D.Drysdale
An introduction to fire dynamics

# 2. Relevantne smjernice i alati za proračun

## Smjernice

- ✓ Austrijski standard (RVS)
- ✓ Njemački standard (RABT)
- ✓ PIARC (World Road Association, 1909)
- ✓ Francuski, švajcarski, i dr.

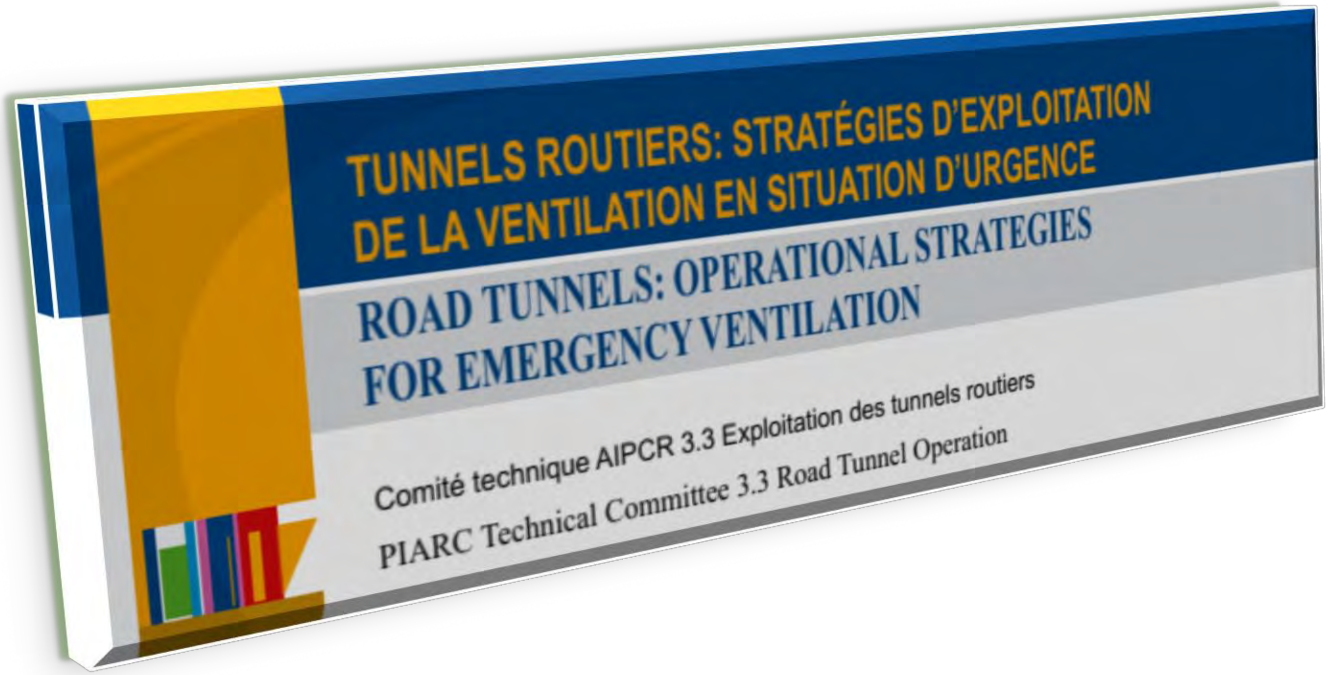
## Alati za proračun:

- ✓ Bazični projektni proračun – smjernice i opšta inž. literatura
- ✓ Napredni proračun - numerički proračun / simulacija rada sistema / požara

PIARC

## PIARC TECHNICAL REPORTS

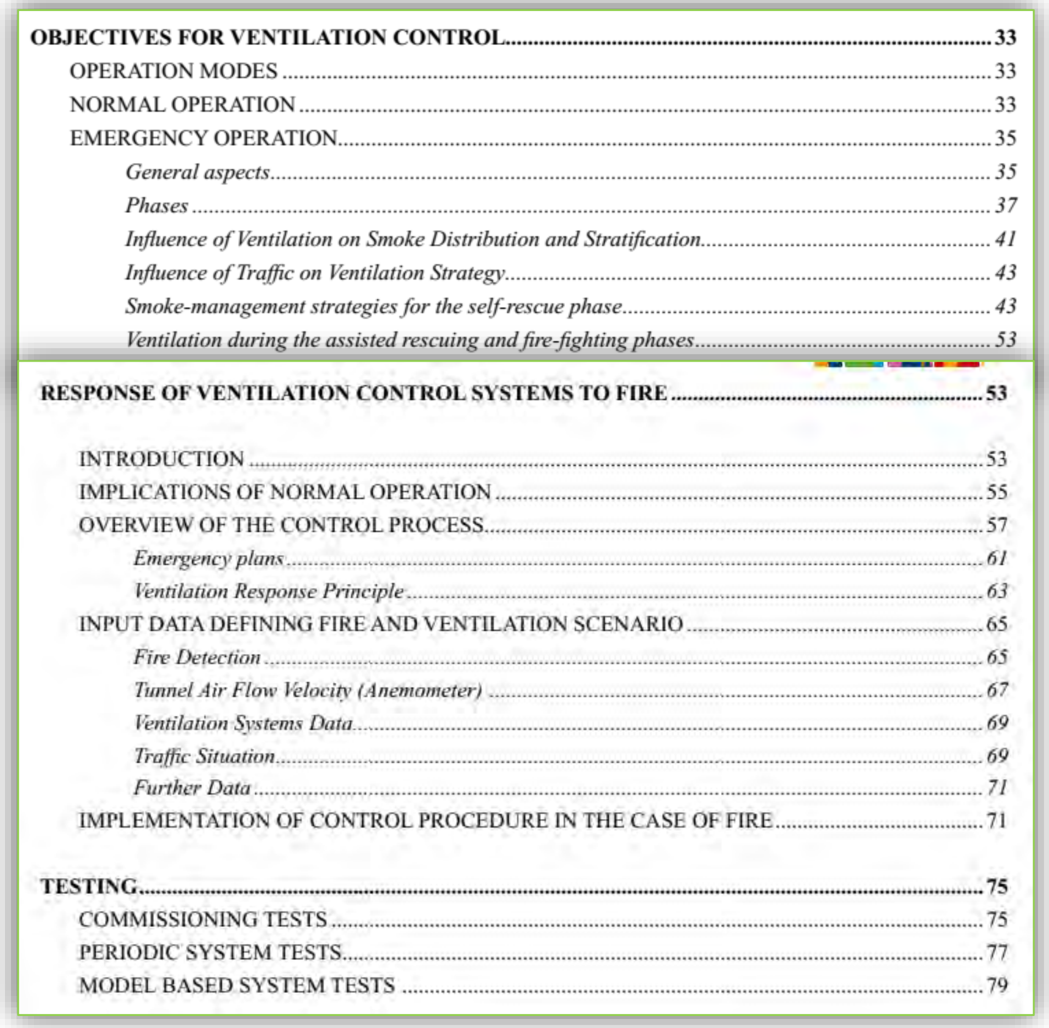
- *PIARC TECHNICAL REPORT 3.05.11.B – 2001 (Geometrija tunela, gustina i protok saobraćaja)*
- *PIARC Committee on Road Tunnels Operation (C3.3) – 2007: SYSTEMS AND EQUIPMENT FOR FIRE AND SMOKE CONTROL IN ROAD TUNNELS*
- ***PIARC Committee on Road Tunnels Operation (C3.3): OPERATIONAL STRATEGIES FOR EMERGENCY VENTILATION, 2011R02***


TUNNELS ROUTIERS: STRATÉGIES D'EXPLOITATION DE LA VENTILATION EN SITUATION D'URGENCE

ROAD TUNNELS: OPERATIONAL STRATEGIES FOR EMERGENCY VENTILATION

Comité technique AIPCR 3.3 Exploitation des tunnels routiers

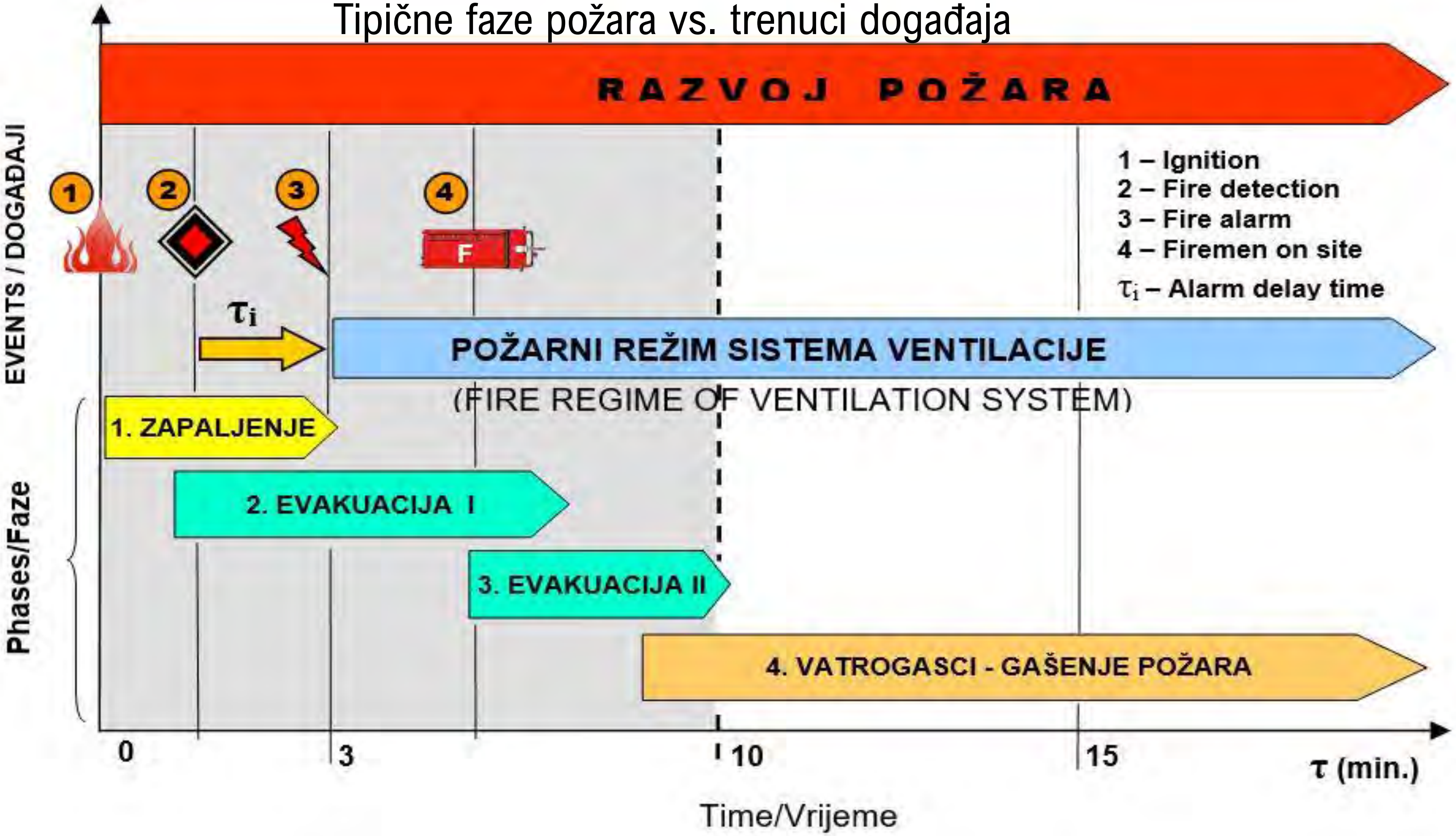
PIARC Technical Committee 3.3 Road Tunnel Operation



**PIARC**

*izvod iz smjernice PIARC*

# Tipične faze požara vs. trenuci događaja



$t_0$ – startni trenutak vatre

$t_1$ – detekcija vatre – događaj “b” (CCTV video det; sensor toplote; vizuelna detekcija operatera; i dr)

$t_2$ – potvrda požara – događaj “c” (može se poklapati sa $t_1$ ako postoje sistemi aut.det. Uključuje se požarni alarm i započinju protokoli vanrednog stanja

$t_3$ – radni parametri ventilacije postignuti (kašnjenje zbog vremena zaleta sistema)

$t_4$ – dolazak ekipa za spašavanje – događaj “d”

$t_5$ – spašavanje uz podršku je započelo

$t_6$ – početak vatrogasne aktivnosti od ekipe za spašavanje

$t_7$ – kraj evakuacije

$t_8$ – kraj vanrednih procedura

Izvor TU Graz

**Izvod iz predmetne smjernice PIARC:**

*,,Uticaj ventilacije na distribuciju dima i stratifikaciju*

*Vreli dim požara u tunelu se diže usled sila prirodnog uzgona. Ako se vazduh ne kreće, ili se kreće vrlo sporo, dim će se širiti ispod plafona na obije strane u odnosu na mjesto požara. Ako je tunel sa nagibom, sile uzgona (efekta dimnjaka) mogu biti dovoljne da pokreću vazduh odn. dim u smjeru uspona. Ispod ovih slojeva dima, sveži vazduh biva uvučen, stvarajući hladnu struju vazduha koja se kreće ka požaru, tj. u suprotnom smjeru u odnosu na dim koji se širi ispod plafona. Ovo raslojavanje između vrućeg gornjeg sloja i hladnijeg donjeg sloja se zove strafifikacija.*

*Usled složenog procesa razmjene toplote i mase, dim se postepeno hladi i miješa sa vazduhom, te nakon određenog vremena obije (uzvodna i nizvodna) sekcija tunela mogu biti potpuno ispunjene dimom. Dakle, strafikacija je privremeni fenomen, a iskustvo kaže da ne traje duže od 15min, osim ako se ne održava pogodnim sistemom ventilacije, uključujući i ekstrakciju dima sa plafona i kontrolom podužnog strujanja vazduha. Ovaj period vremena je ključan za korisnike tunela da se samoevakuišu. Dakle, ako je stratifikacija dio strategije za vanrednu situaciju u tunelu, tada pouzdana i robusna kontrola podužnog kretanja vazduha je ključna. Ako je podužna brzina mala, a turbulencija nije izražena, tada se stratifikacija može održati i duže vremena, naročito kada je system ventilacije opremljen sistemom za ekstrakciju dima u plafonu."*

**PIARC**

*PIARC TECHNICAL COMMITTEE C4 ROAD TUNNEL OPERATIONS TECHNICAL REPORT:*

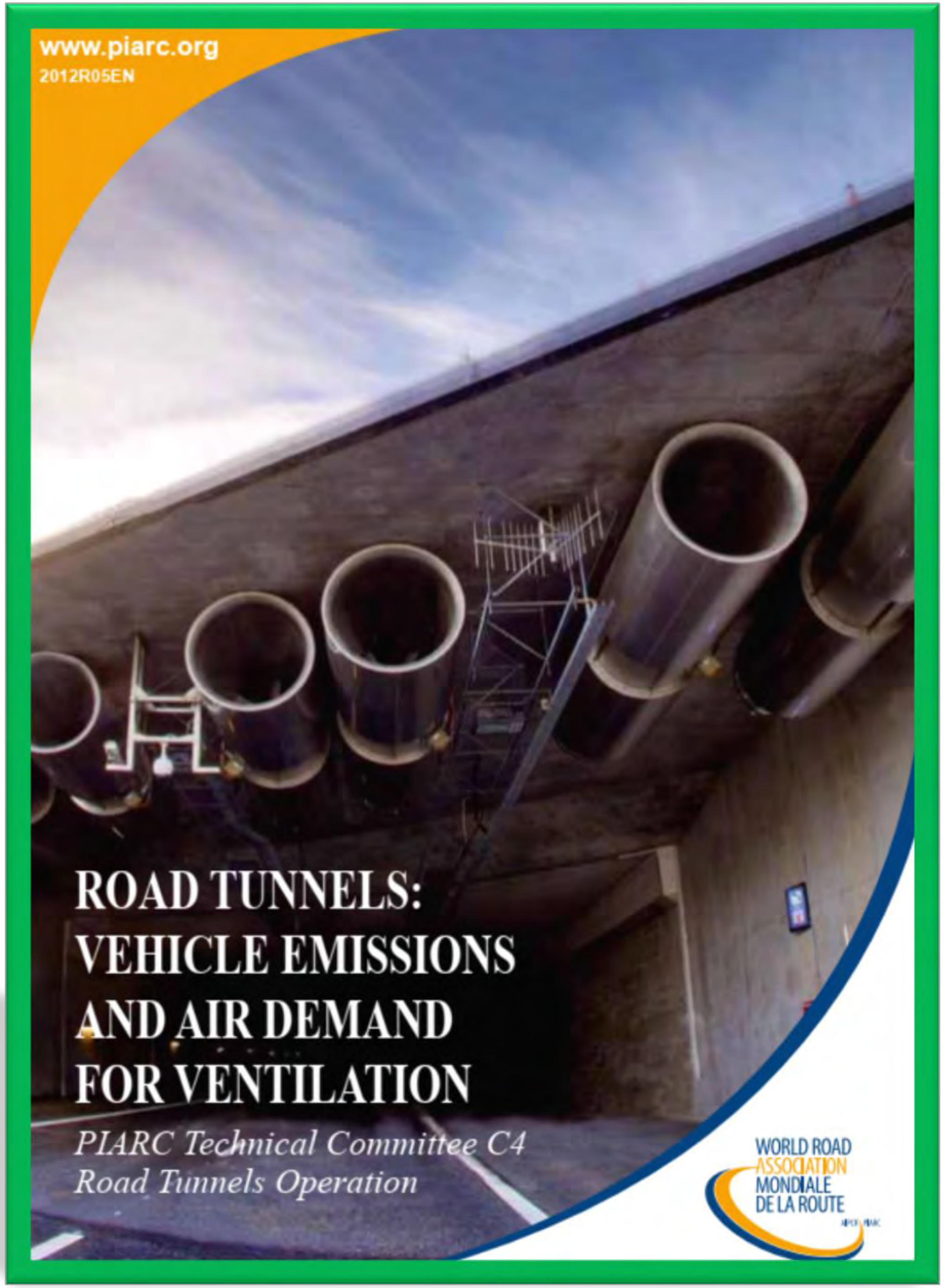
## *ROAD TUNNELS: VEHICLE EMISSIONS AND AIR DEMAND FOR VENTILATION*

*The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport. The study that is the subject of this report was defined in the PIARC Strategic Plan 2008 – 2011 approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.*

*Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.*

*This report is available from the internet site of the World Road Association (PIARC) http://www.piarc.org*

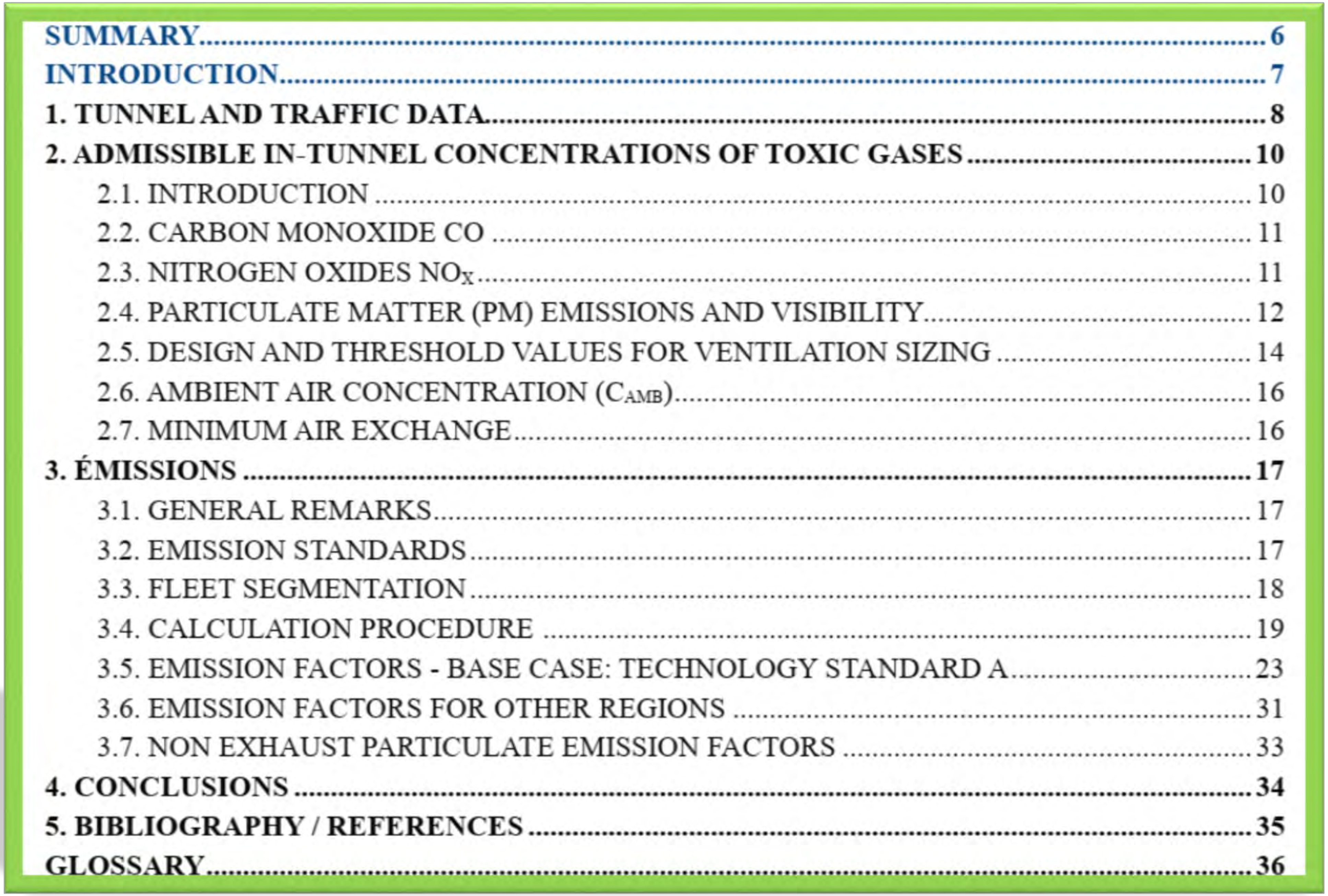
*World Road Association (PIARC) La Grande Arche, Paroi nord, Niveau 2 92055 La Défense cedex, FRANCe International Standard Book Number 2-84060-269-5*

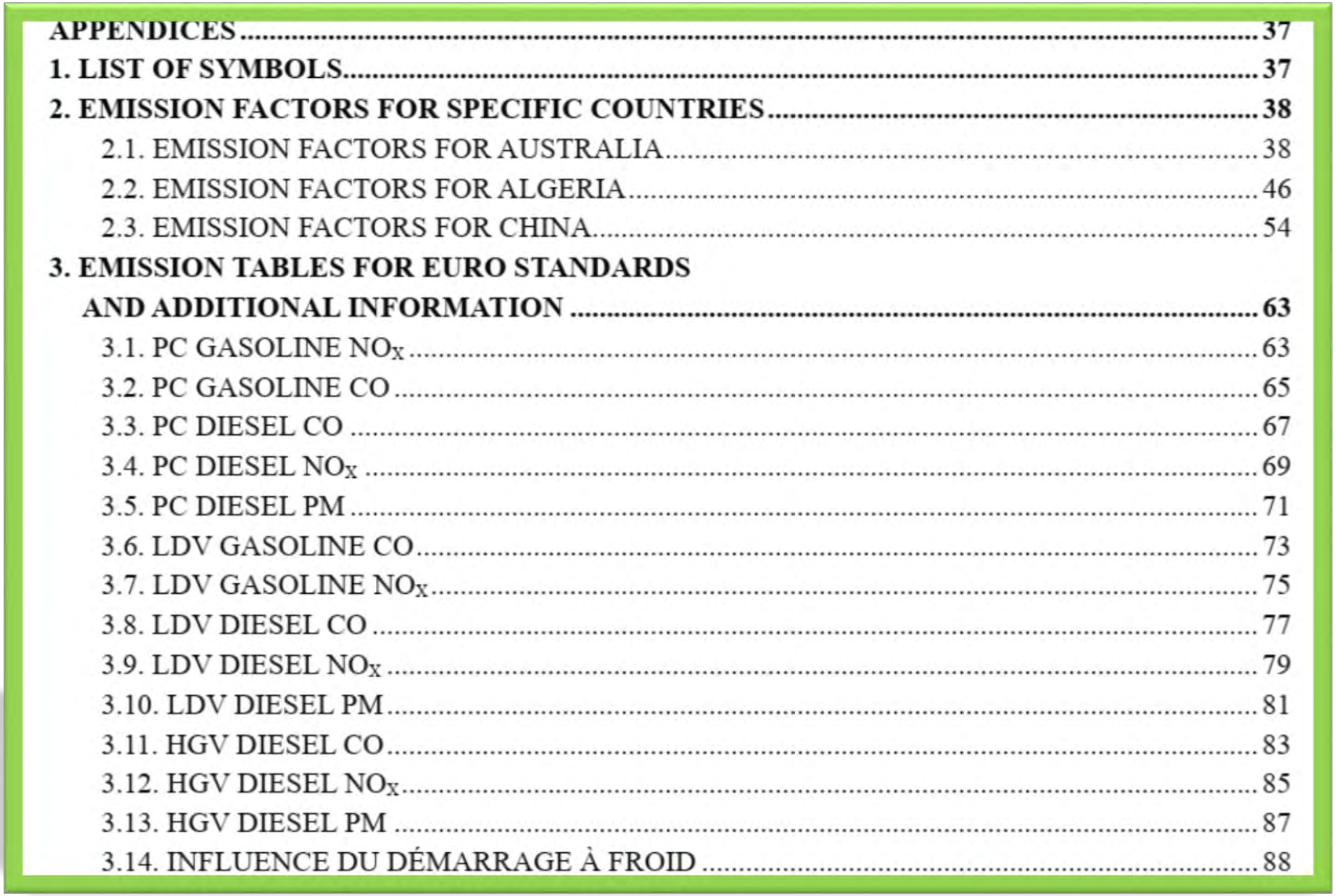

www.piarc.org
2012R05EN

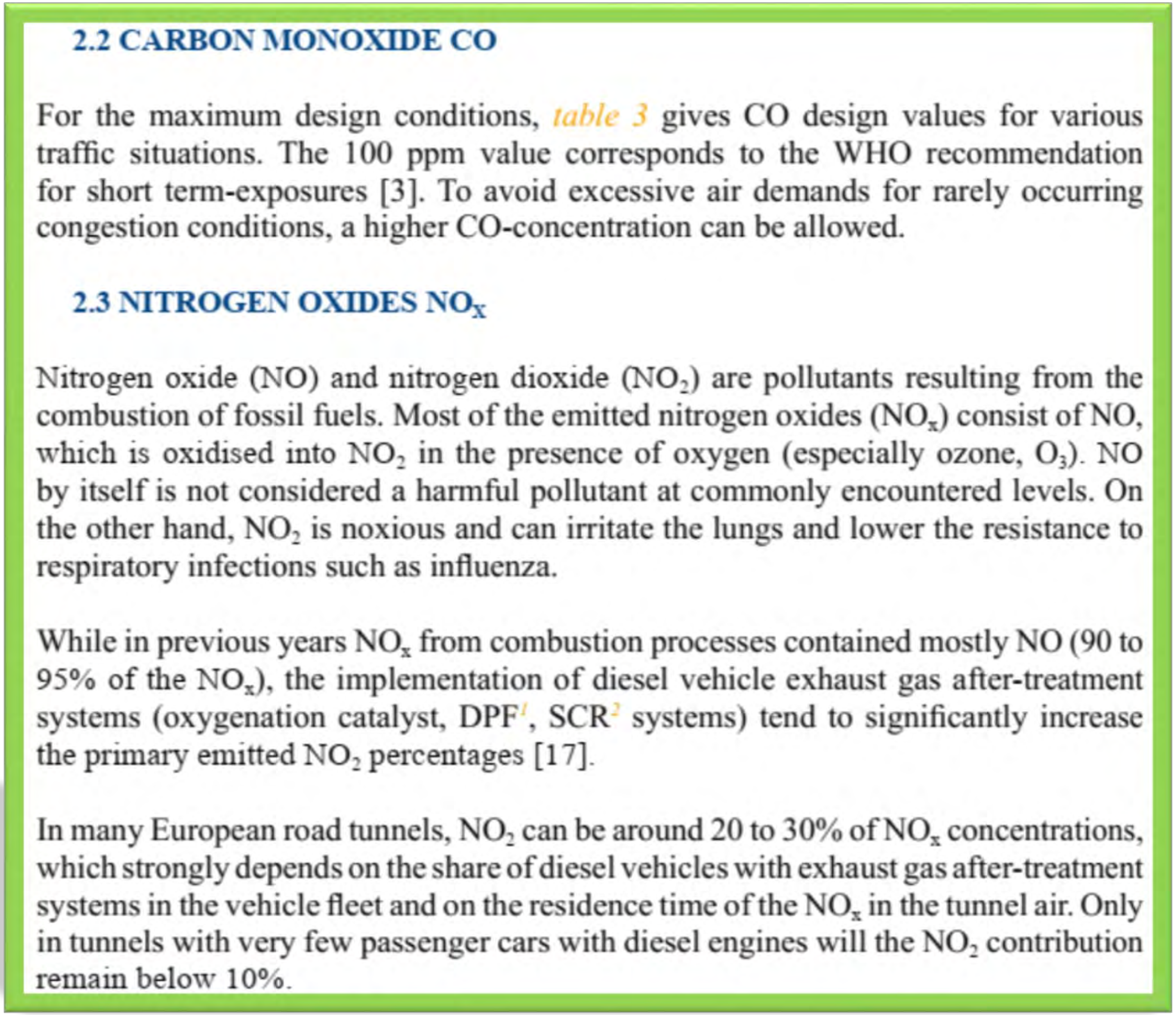
ROAD TUNNELS:
VEHICLE EMISSIONS
AND AIR DEMAND
FOR VENTILATION

*PIARC Technical Committee C4*
*Road Tunnels Operation*

WORLD ROAD
ASSOCIATION
MONDIALE
DE LA ROUTE







## 2.2 CARBON MONOXIDE CO

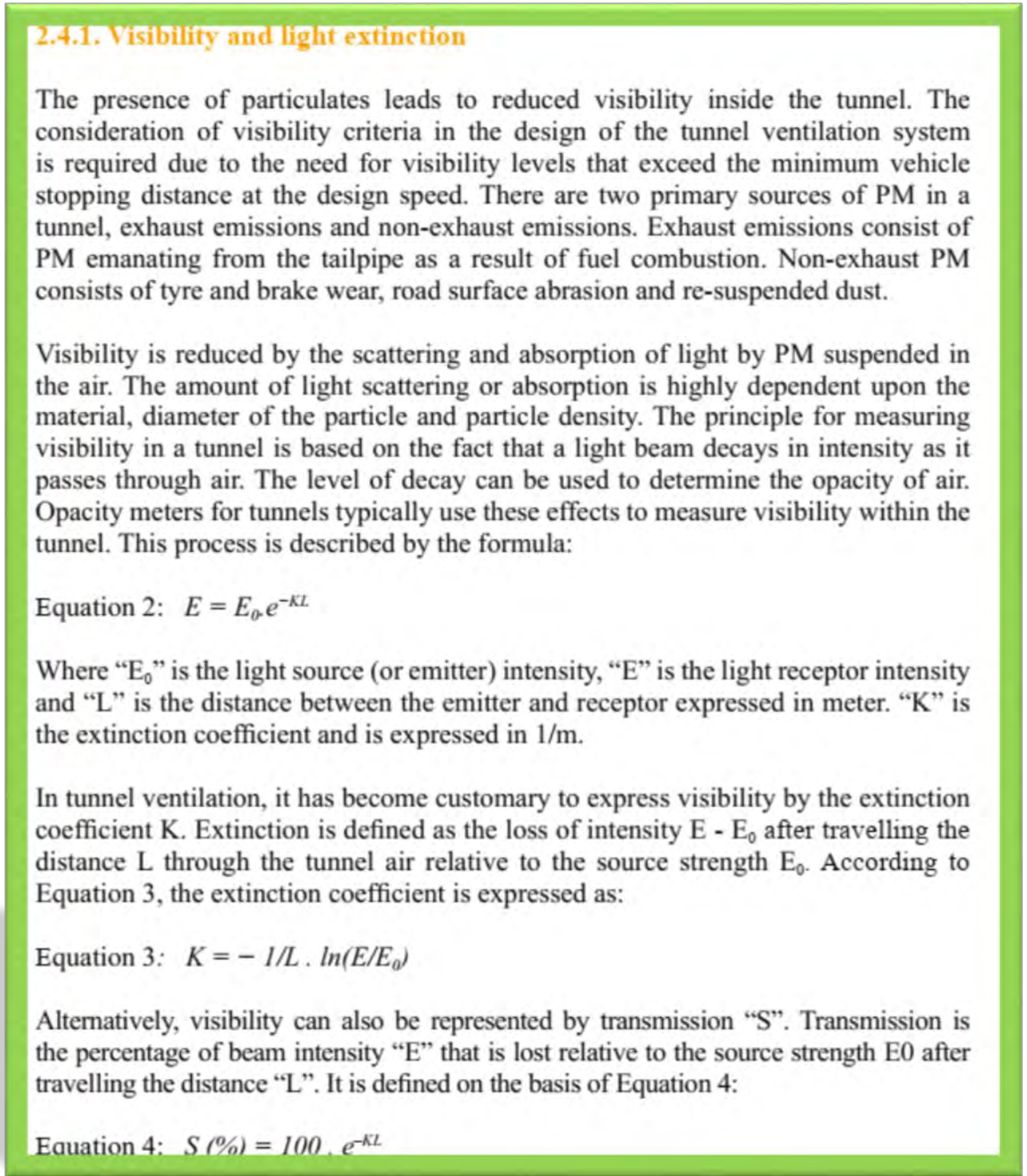
For the maximum design conditions, *table 3* gives CO design values for various traffic situations. The 100 ppm value corresponds to the WHO recommendation for short term-exposures [3]. To avoid excessive air demands for rarely occurring congestion conditions, a higher CO-concentration can be allowed.

## 2.3 NITROGEN OXIDES $NO_X$

Nitrogen oxide (NO) and nitrogen dioxide ($NO_2$) are pollutants resulting from the combustion of fossil fuels. Most of the emitted nitrogen oxides ($NO_x$) consist of NO, which is oxidised into $NO_2$ in the presence of oxygen (especially ozone, $O_3$). NO by itself is not considered a harmful pollutant at commonly encountered levels. On the other hand, $NO_2$ is noxious and can irritate the lungs and lower the resistance to respiratory infections such as influenza.

While in previous years $NO_x$ from combustion processes contained mostly NO (90 to 95% of the $NO_x$), the implementation of diesel vehicle exhaust gas after-treatment systems (oxygenation catalyst, DPF[1], SCR[2] systems) tend to significantly increase the primary emitted $NO_2$ percentages [17].

In many European road tunnels, $NO_2$ can be around 20 to 30% of $NO_x$ concentrations, which strongly depends on the share of diesel vehicles with exhaust gas after-treatment systems in the vehicle fleet and on the residence time of the $NO_x$ in the tunnel air. Only in tunnels with very few passenger cars with diesel engines will the $NO_2$ contribution remain below 10%.



### 2.4.1. Visibility and light extinction

The presence of particulates leads to reduced visibility inside the tunnel. The consideration of visibility criteria in the design of the tunnel ventilation system is required due to the need for visibility levels that exceed the minimum vehicle stopping distance at the design speed. There are two primary sources of PM in a tunnel, exhaust emissions and non-exhaust emissions. Exhaust emissions consist of PM emanating from the tailpipe as a result of fuel combustion. Non-exhaust PM consists of tyre and brake wear, road surface abrasion and re-suspended dust.

Visibility is reduced by the scattering and absorption of light by PM suspended in the air. The amount of light scattering or absorption is highly dependent upon the material, diameter of the particle and particle density. The principle for measuring visibility in a tunnel is based on the fact that a light beam decays in intensity as it passes through air. The level of decay can be used to determine the opacity of air. Opacity meters for tunnels typically use these effects to measure visibility within the tunnel. This process is described by the formula:

Equation 2: $E = E_0 . e^{-KL}$

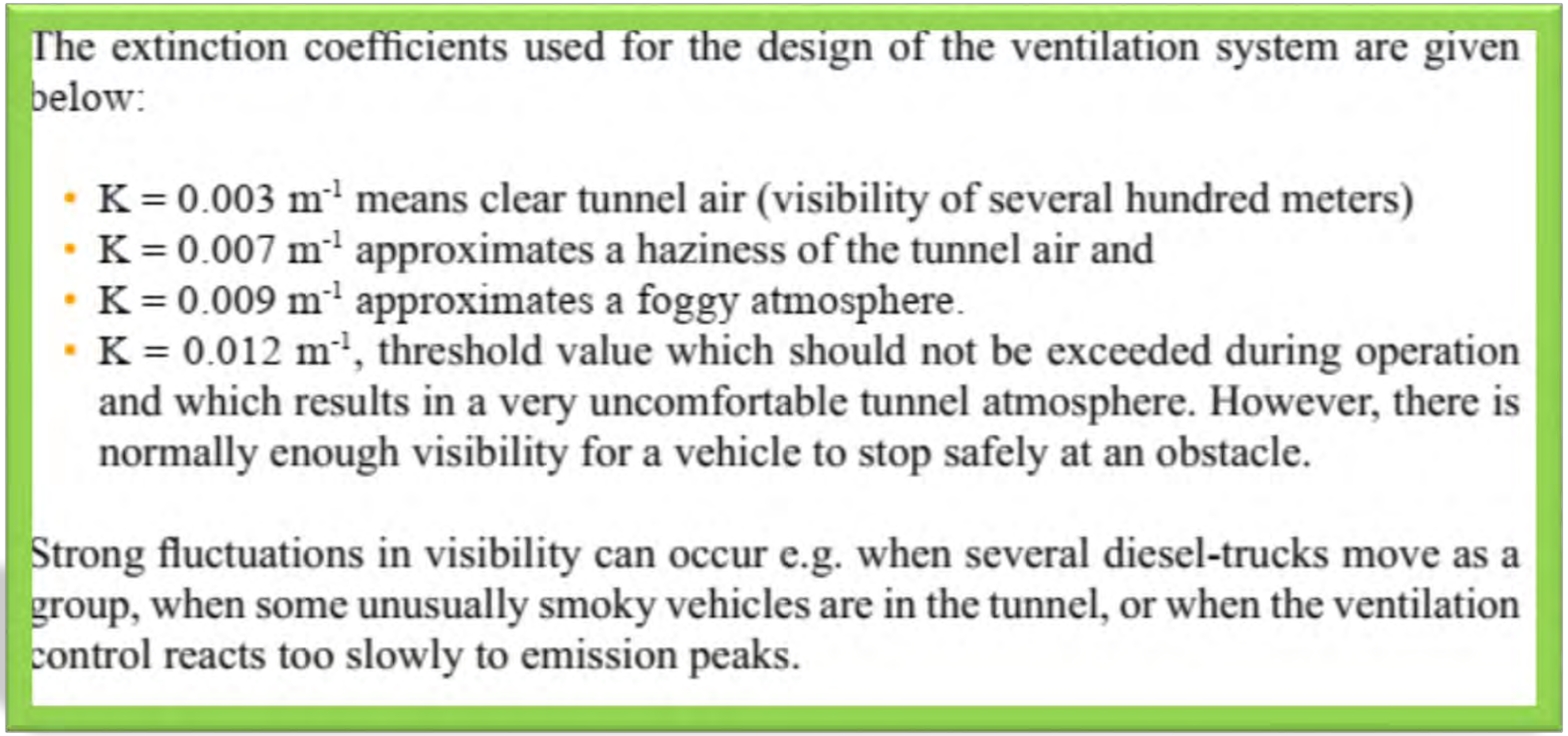
Where "$E_0$" is the light source (or emitter) intensity, "E" is the light receptor intensity and "L" is the distance between the emitter and receptor expressed in meter. "K" is the extinction coefficient and is expressed in 1/m.

In tunnel ventilation, it has become customary to express visibility by the extinction coefficient K. Extinction is defined as the loss of intensity $E - E_0$ after travelling the distance L through the tunnel air relative to the source strength $E_0$. According to Equation 3, the extinction coefficient is expressed as:

Equation 3: $K = -1/L . ln(E/E_0)$

Alternatively, visibility can also be represented by transmission "S". Transmission is the percentage of beam intensity "E" that is lost relative to the source strength E0 after travelling the distance "L". It is defined on the basis of Equation 4:

Equation 4: $S(\%) = 100 . e^{-KL}$



The extinction coefficients used for the design of the ventilation system are given below:

- K = 0.003 $m^{-1}$ means clear tunnel air (visibility of several hundred meters)
- K = 0.007 $m^{-1}$ approximates a haziness of the tunnel air and
- K = 0.009 $m^{-1}$ approximates a foggy atmosphere.
- K = 0.012 $m^{-1}$, threshold value which should not be exceeded during operation and which results in a very uncomfortable tunnel atmosphere. However, there is normally enough visibility for a vehicle to stop safely at an obstacle.

Strong fluctuations in visibility can occur e.g. when several diesel-trucks move as a group, when some unusually smoky vehicles are in the tunnel, or when the ventilation control reacts too slowly to emission peaks.

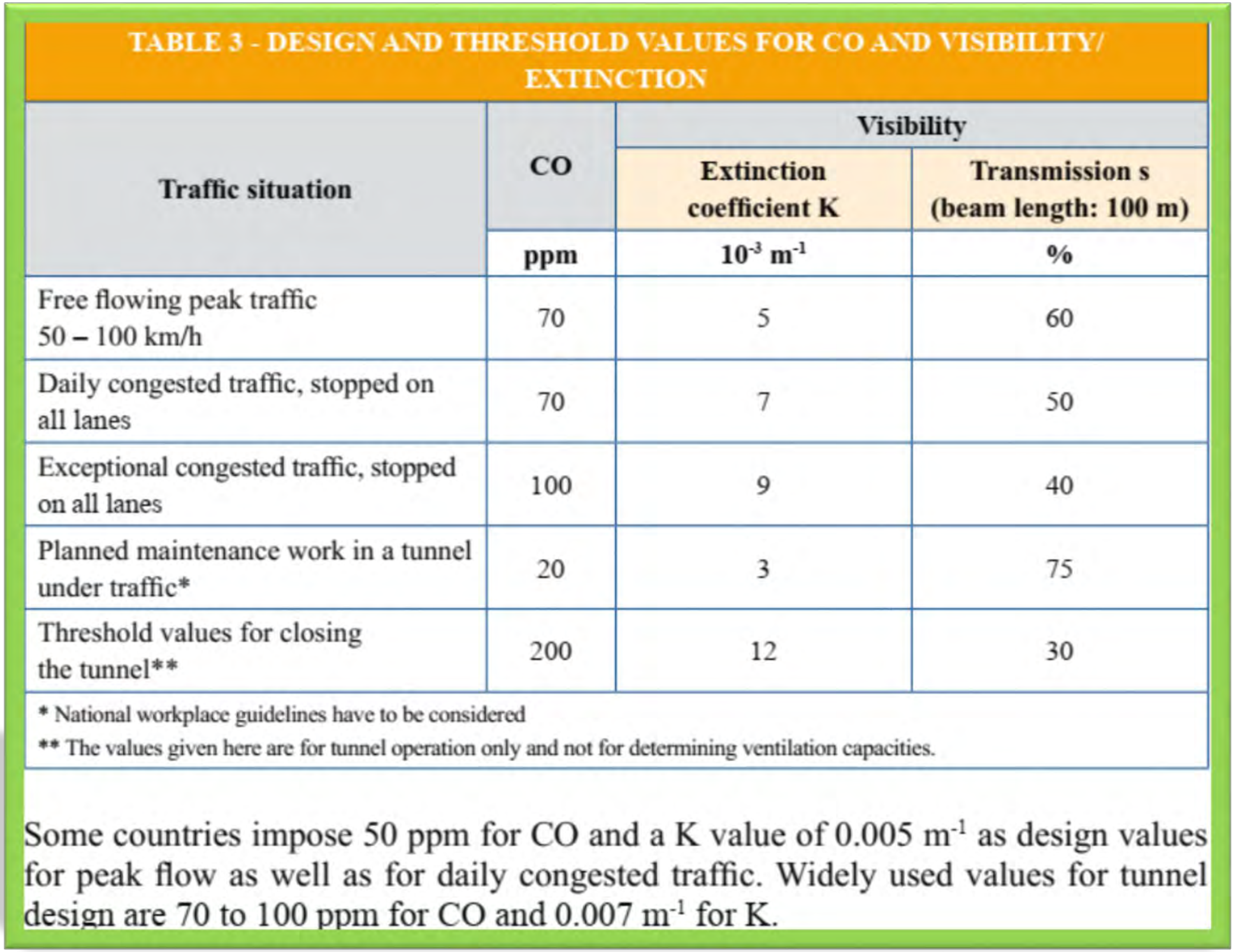


**TABLE 3 - DESIGN AND THRESHOLD VALUES FOR CO AND VISIBILITY/ EXTINCTION**

| Traffic situation | CO | Visibility | |
|---|---|---|---|
| | | **Extinction coefficient K** | **Transmission s (beam length: 100 m)** |
| | **ppm** | **$10^{-3}$ m$^{-1}$** | **%** |
| Free flowing peak traffic<br>50 – 100 km/h | 70 | 5 | 60 |
| Daily congested traffic, stopped on all lanes | 70 | 7 | 50 |
| Exceptional congested traffic, stopped on all lanes | 100 | 9 | 40 |
| Planned maintenance work in a tunnel under traffic* | 20 | 3 | 75 |
| Threshold values for closing the tunnel** | 200 | 12 | 30 |

* National workplace guidelines have to be considered

** The values given here are for tunnel operation only and not for determining ventilation capacities.

Some countries impose 50 ppm for CO and a K value of 0.005 m$^{-1}$ as design values for peak flow as well as for daily congested traffic. Widely used values for tunnel design are 70 to 100 ppm for CO and 0.007 m$^{-1}$ for K.

## 2.7. MINIMUM AIR EXCHANGE

In tunnels with mechanical ventilation, the minimum air exchange rate is determined using design values. Where traffic volumes are low, the minimum fresh air requirement might be quite small. However, the ventilation system should be able to accommodate sudden demands such as for high emitting HGVs.

For such cases, an air-exchange rate of at least 4 times per hour should be considered. Where longitudinal ventilation systems are provided, a minimum longitudinal air velocity of 1.0 to 1.5 m/s is recommended to be used as a design criterion.

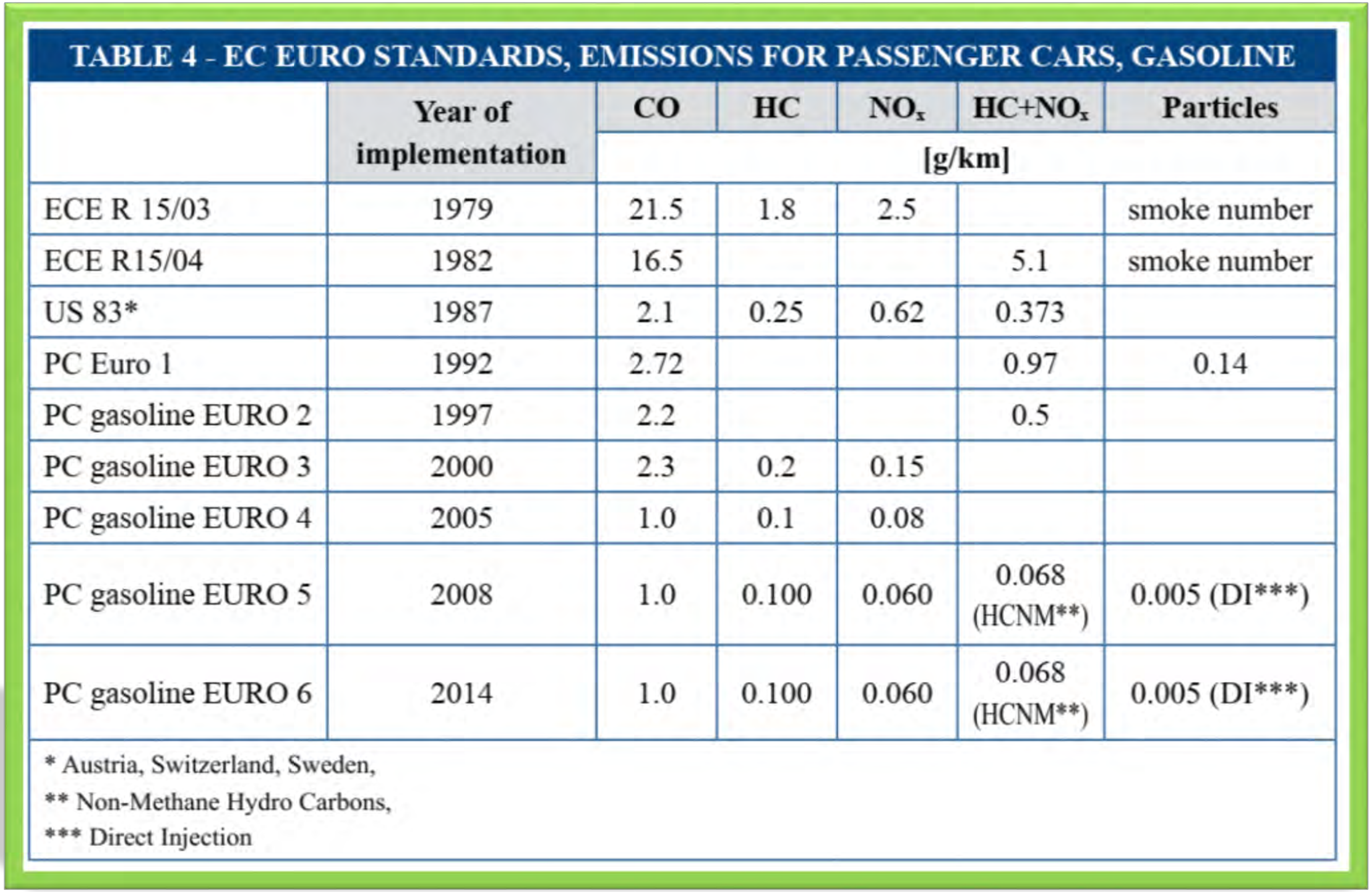
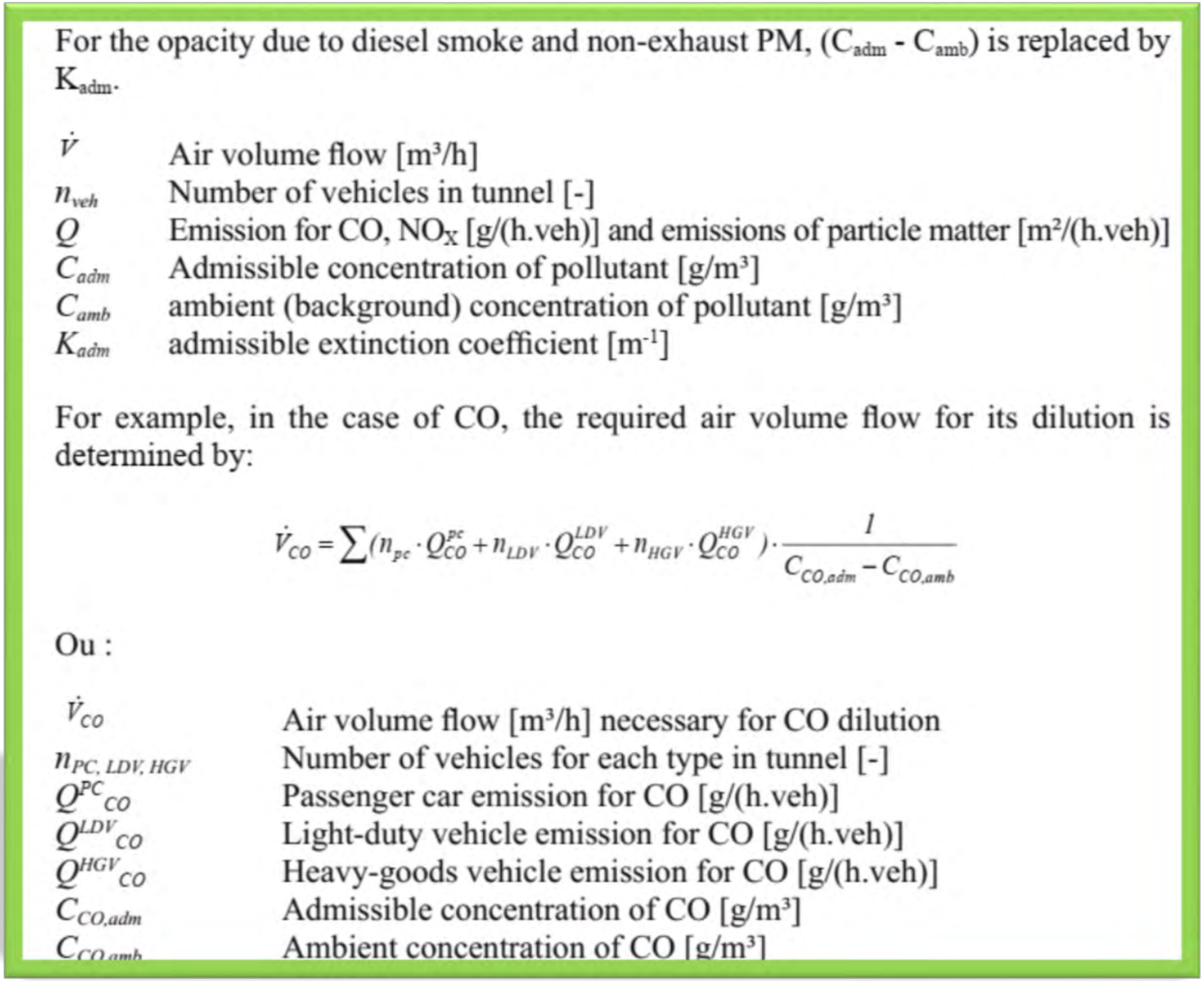


**TABLE 4 - EC EURO STANDARDS, EMISSIONS FOR PASSENGER CARS, GASOLINE**

| | Year of implementation | CO | HC | $NO_x$ | $HC+NO_x$ | Particles |
|---|---|---|---|---|---|---|
| | | [g/km] | | | | |
| ECE R 15/03 | 1979 | 21.5 | 1.8 | 2.5 | | smoke number |
| ECE R15/04 | 1982 | 16.5 | | | 5.1 | smoke number |
| US 83* | 1987 | 2.1 | 0.25 | 0.62 | 0.373 | |
| PC Euro 1 | 1992 | 2.72 | | | 0.97 | 0.14 |
| PC gasoline EURO 2 | 1997 | 2.2 | | | 0.5 | |
| PC gasoline EURO 3 | 2000 | 2.3 | 0.2 | 0.15 | | |
| PC gasoline EURO 4 | 2005 | 1.0 | 0.1 | 0.08 | | |
| PC gasoline EURO 5 | 2008 | 1.0 | 0.100 | 0.060 | 0.068<br>(HCNM**) | 0.005 (DI***) |
| PC gasoline EURO 6 | 2014 | 1.0 | 0.100 | 0.060 | 0.068<br>(HCNM**) | 0.005 (DI***) |

* Austria, Switzerland, Sweden,
** Non-Methane Hydro Carbons,
*** Direct Injection



For the opacity due to diesel smoke and non-exhaust PM, $(C_{adm} - C_{amb})$ is replaced by $K_{adm}$.

| | |
|---|---|
| $\dot{V}$ | Air volume flow [m³/h] |
| $n_{veh}$ | Number of vehicles in tunnel [-] |
| $Q$ | Emission for CO, $NO_X$ [g/(h.veh)] and emissions of particle matter [m²/(h.veh)] |
| $C_{adm}$ | Admissible concentration of pollutant [g/m³] |
| $C_{amb}$ | ambient (background) concentration of pollutant [g/m³] |
| $K_{adm}$ | admissible extinction coefficient [$m^{-1}$] |

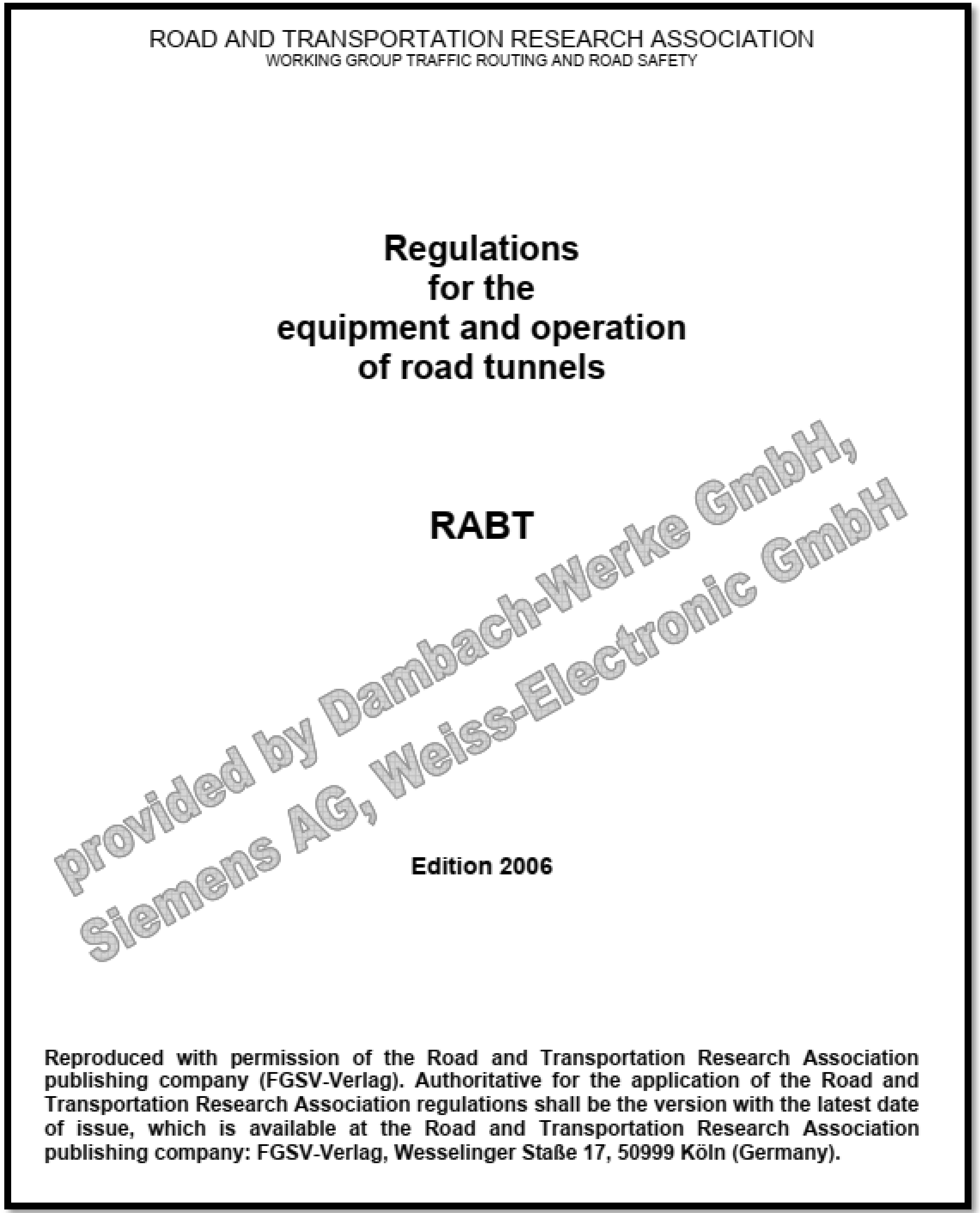
For example, in the case of CO, the required air volume flow for its dilution is determined by:

$$\dot{V}_{CO} = \sum (n_{pc} \cdot Q_{CO}^{pc} + n_{LDV} \cdot Q_{CO}^{LDV} + n_{HGV} \cdot Q_{CO}^{HGV}) \cdot \frac{1}{C_{CO,adm} - C_{CO,amb}}$$

Ou :

| | |
|---|---|
| $\dot{V}_{CO}$ | Air volume flow [m³/h] necessary for CO dilution |
| $n_{PC,\ LDV,\ HGV}$ | Number of vehicles for each type in tunnel [-] |
| $Q^{PC}{}_{CO}$ | Passenger car emission for CO [g/(h.veh)] |
| $Q^{LDV}{}_{CO}$ | Light-duty vehicle emission for CO [g/(h.veh)] |
| $Q^{HGV}{}_{CO}$ | Heavy-goods vehicle emission for CO [g/(h.veh)] |
| $C_{CO,adm}$ | Admissible concentration of CO [g/m³] |
| $C_{CO,amb}$ | Ambient concentration of CO [g/m³] |

# Njemački standard RABT (2006)



ROAD AND TRANSPORTATION RESEARCH ASSOCIATION
WORKING GROUP TRAFFIC ROUTING AND ROAD SAFETY

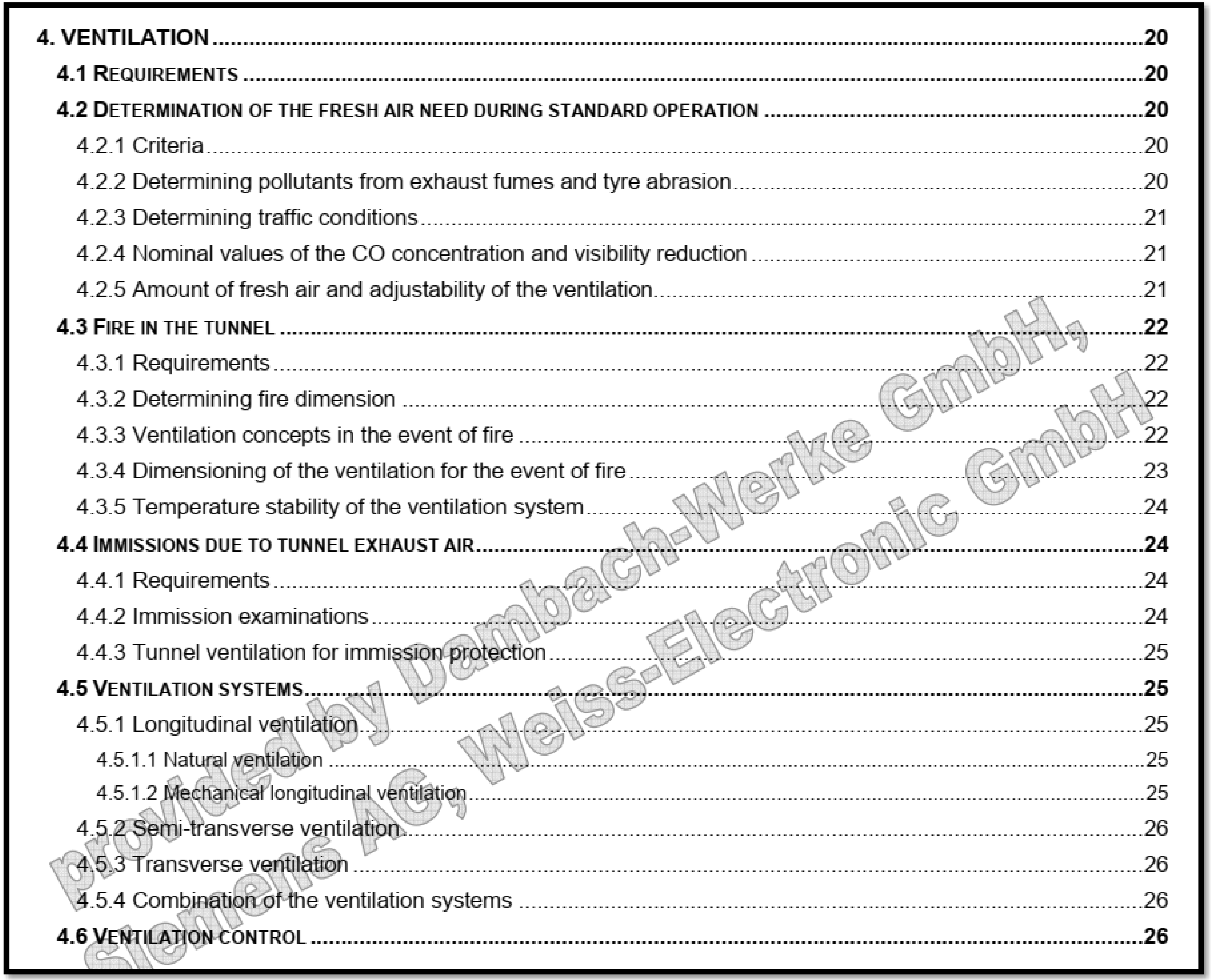
## Regulations for the equipment and operation of road tunnels

## RABT

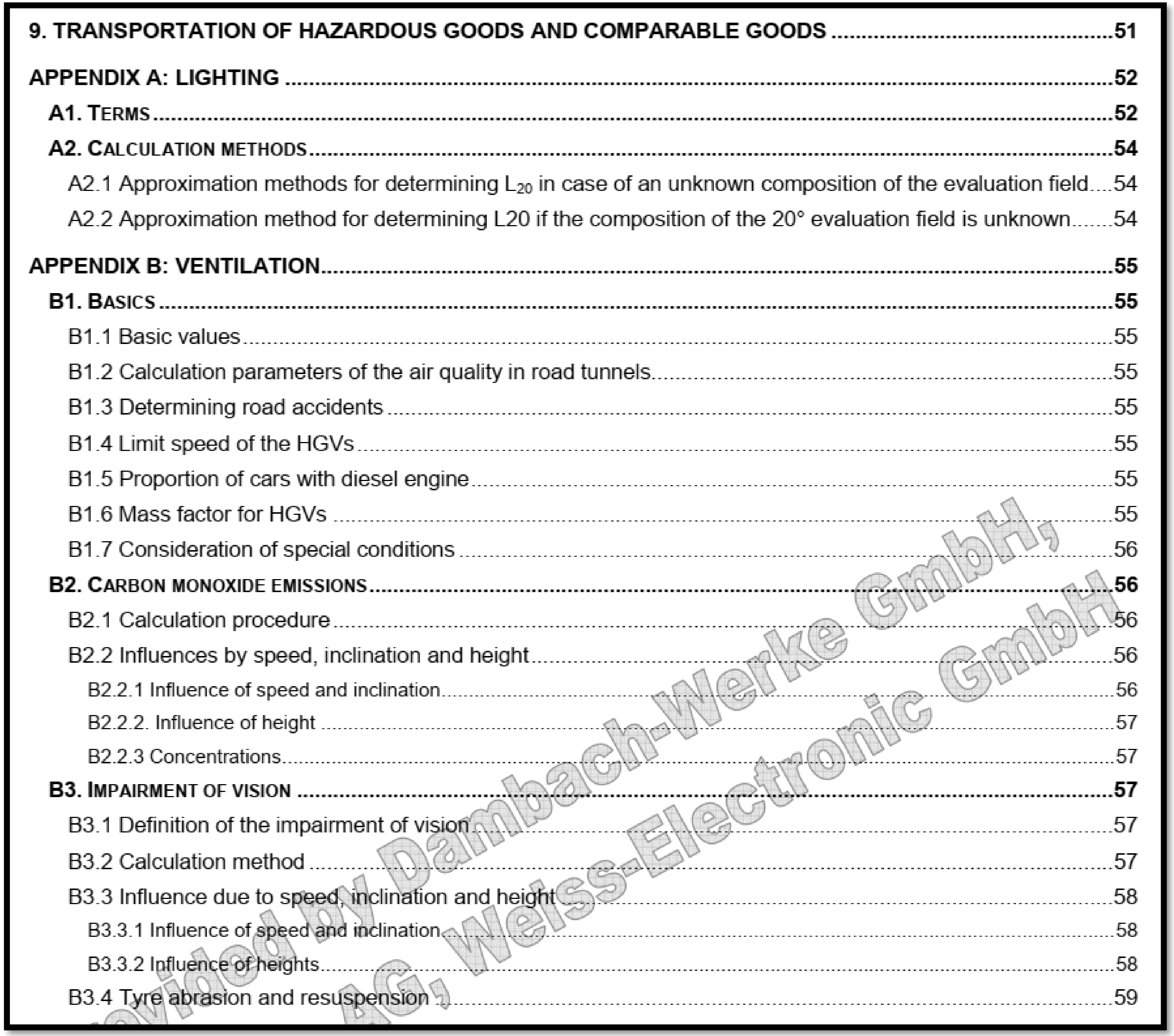
**Edition 2006**

**Reproduced with permission of the Road and Transportation Research Association publishing company (FGSV-Verlag). Authoritative for the application of the Road and Transportation Research Association regulations shall be the version with the latest date of issue, which is available at the Road and Transportation Research Association publishing company: FGSV-Verlag, Wesselinger Staße 17, 50999 Köln (Germany).**

RABT (2006)



# RABT (2006)



# RABT (2006)

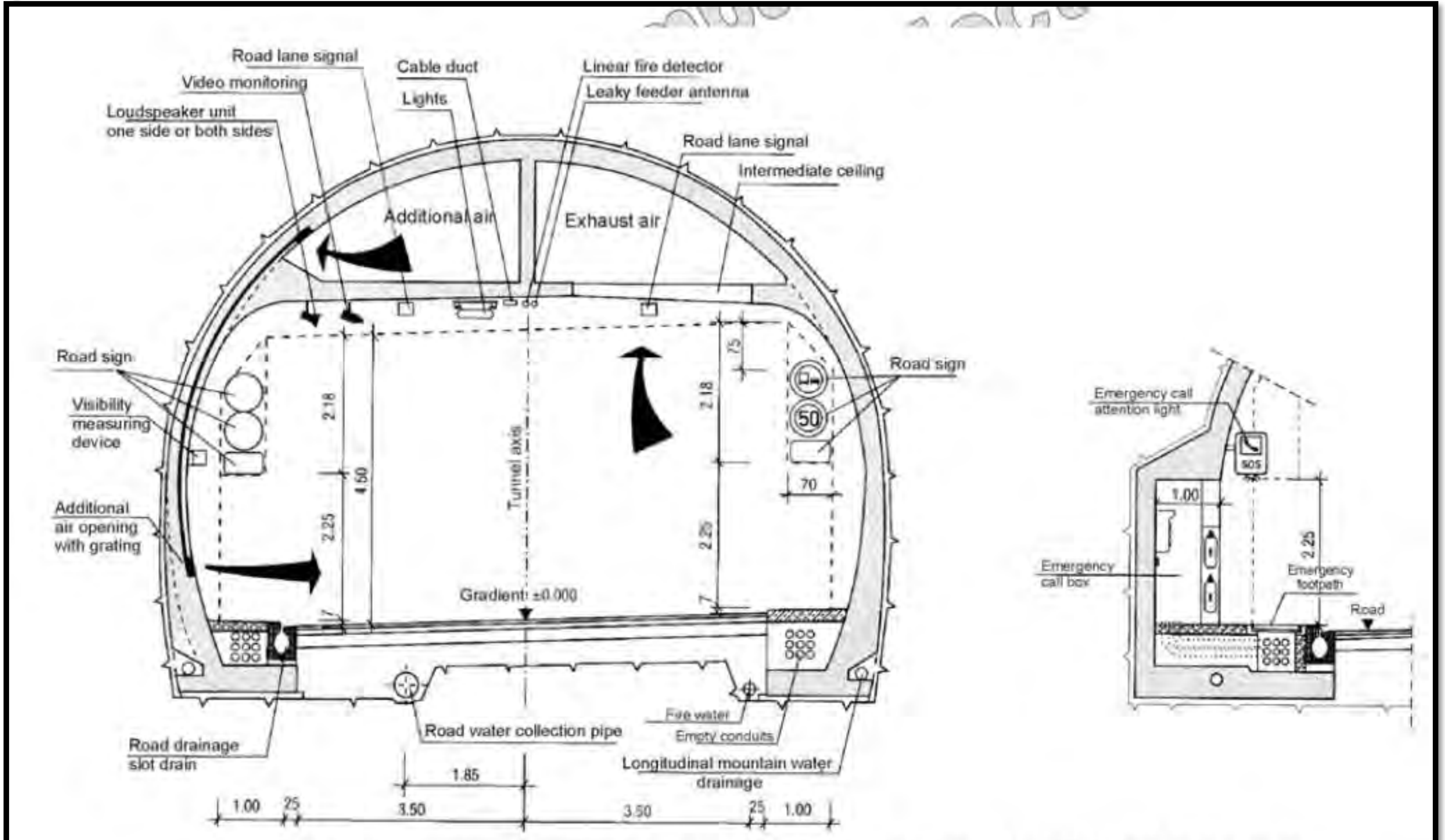


Figure 4: Equipment example vault cross section – depiction of the technical possibilities

# RABT (2006)

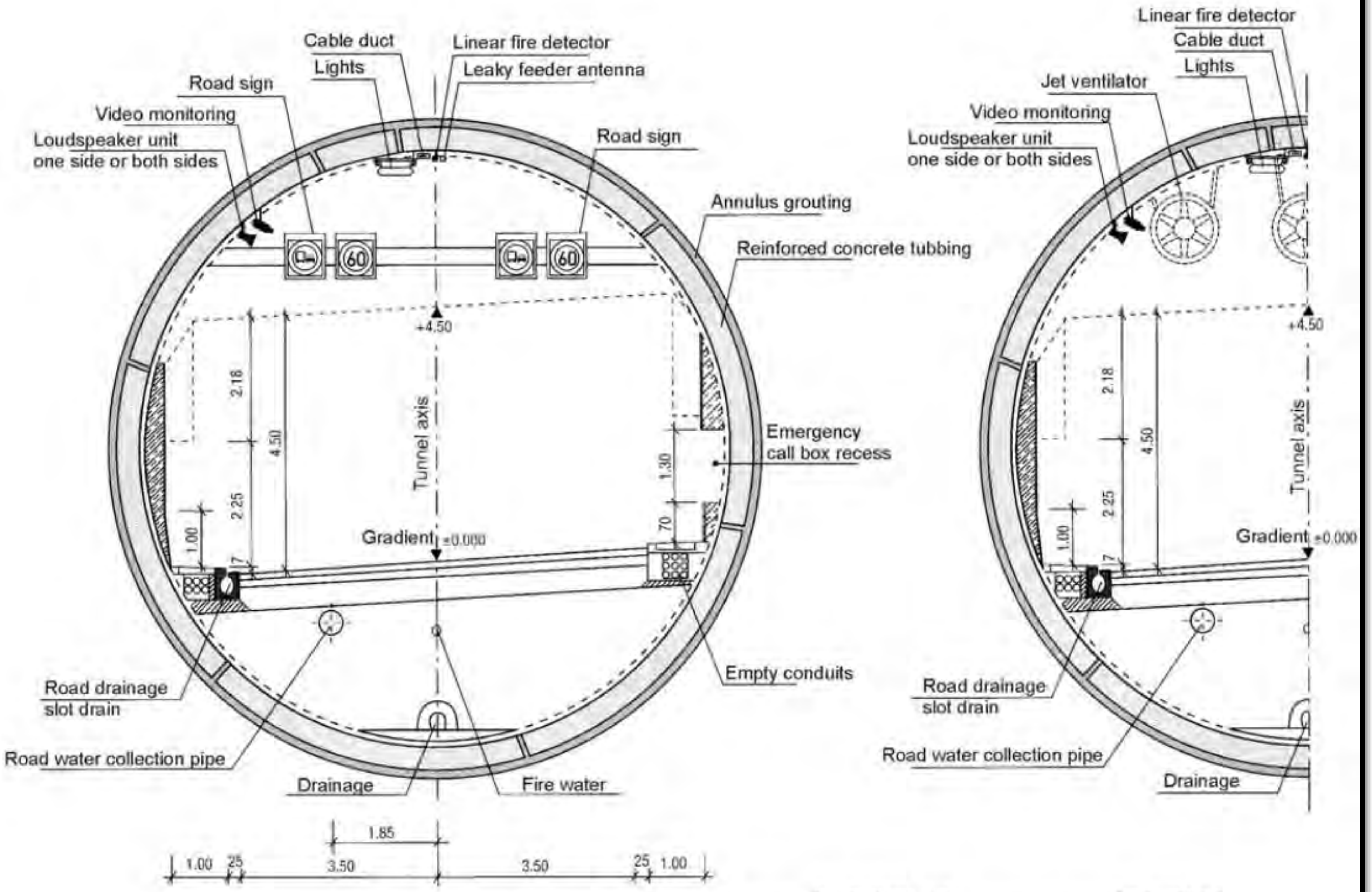


Figure 5: Equipment example circular cross section – tubbing – depiction of the technical possibilities

# RABT (2006)

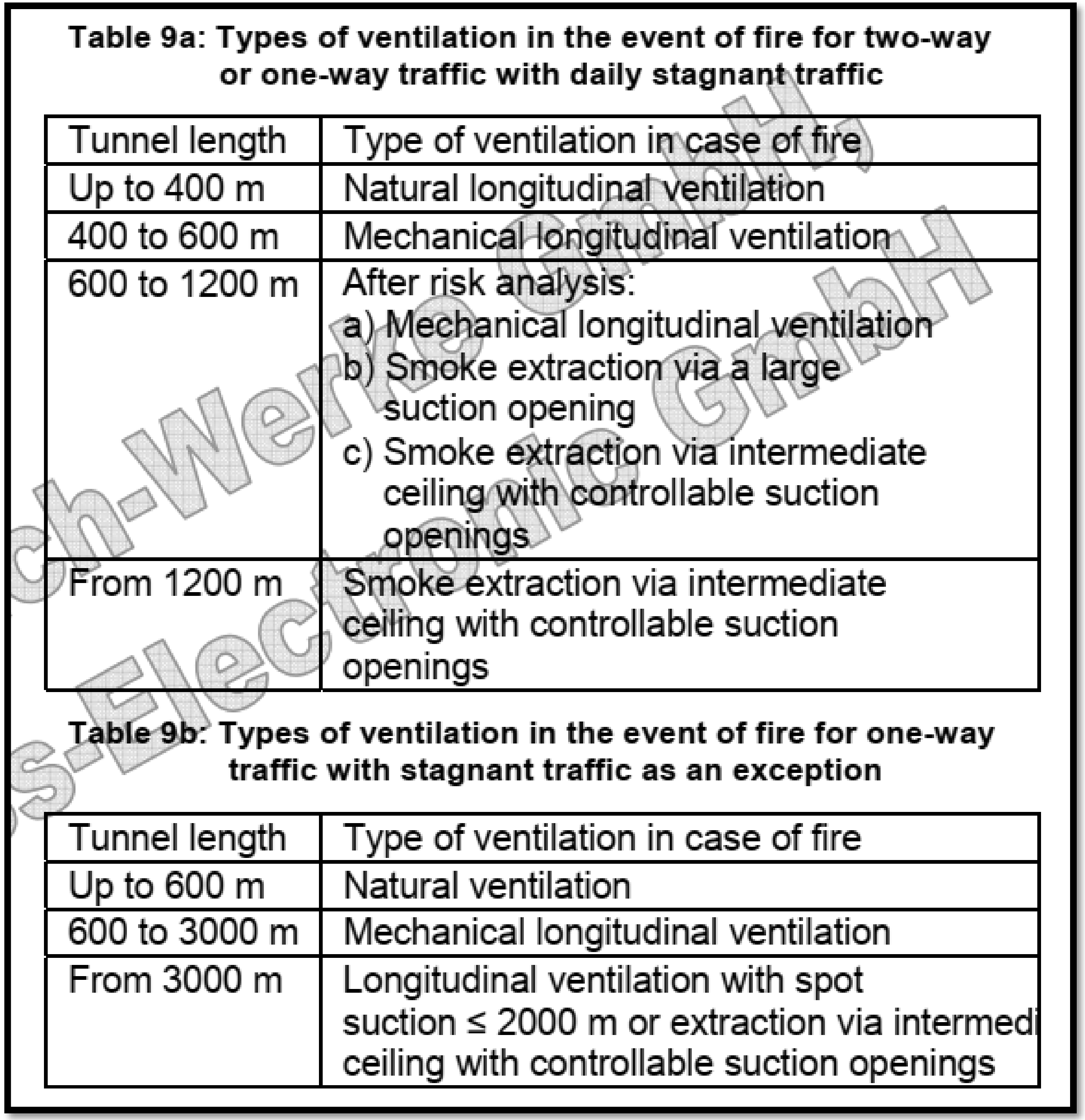


**Table 9a: Types of ventilation in the event of fire for two-way or one-way traffic with daily stagnant traffic**

| Tunnel length | Type of ventilation in case of fire |
|---|---|
| Up to 400 m | Natural longitudinal ventilation |
| 400 to 600 m | Mechanical longitudinal ventilation |
| 600 to 1200 m | After risk analysis:<br>a) Mechanical longitudinal ventilation<br>b) Smoke extraction via a large suction opening<br>c) Smoke extraction via intermediate ceiling with controllable suction openings |
| From 1200 m | Smoke extraction via intermediate ceiling with controllable suction openings |

**Table 9b: Types of ventilation in the event of fire for one-way traffic with stagnant traffic as an exception**

| Tunnel length | Type of ventilation in case of fire |
|---|---|
| Up to 600 m | Natural ventilation |
| 600 to 3000 m | Mechanical longitudinal ventilation |
| From 3000 m | Longitudinal ventilation with spot suction ≤ 2000 m or extraction via intermedi ceiling with controllable suction openings |

# RABT (2006)

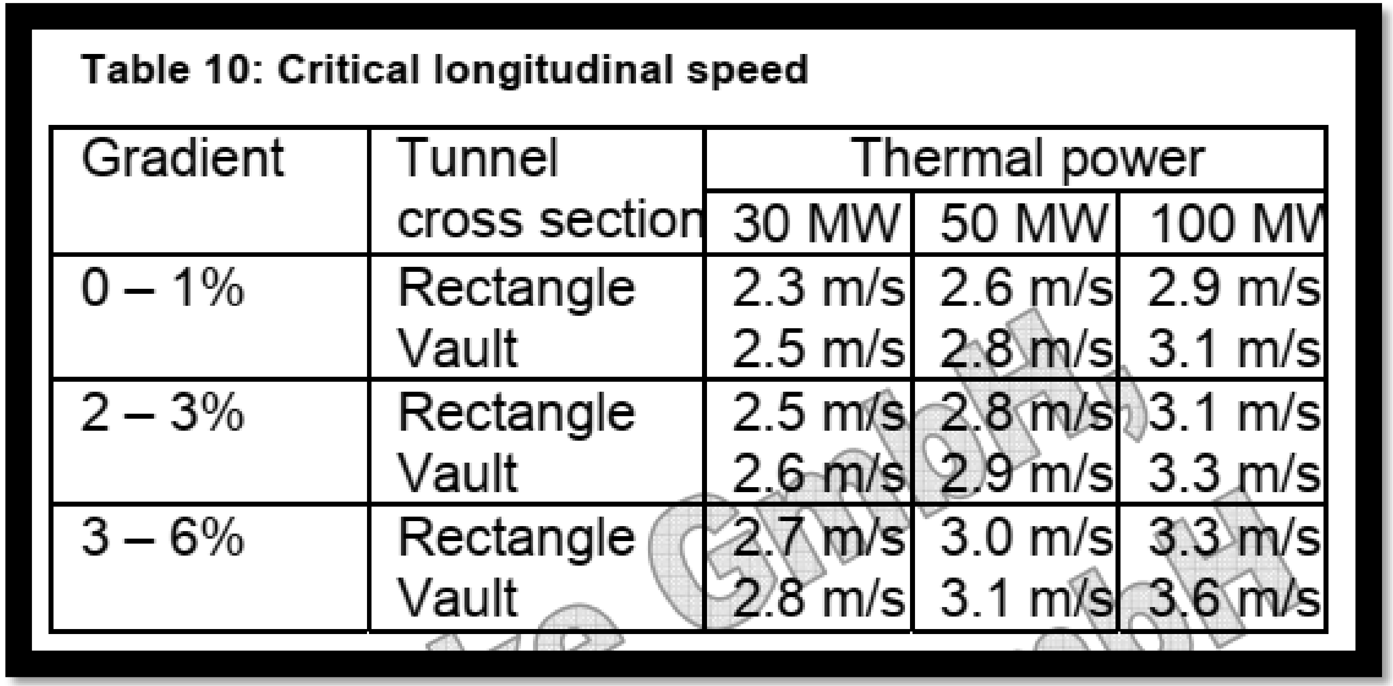
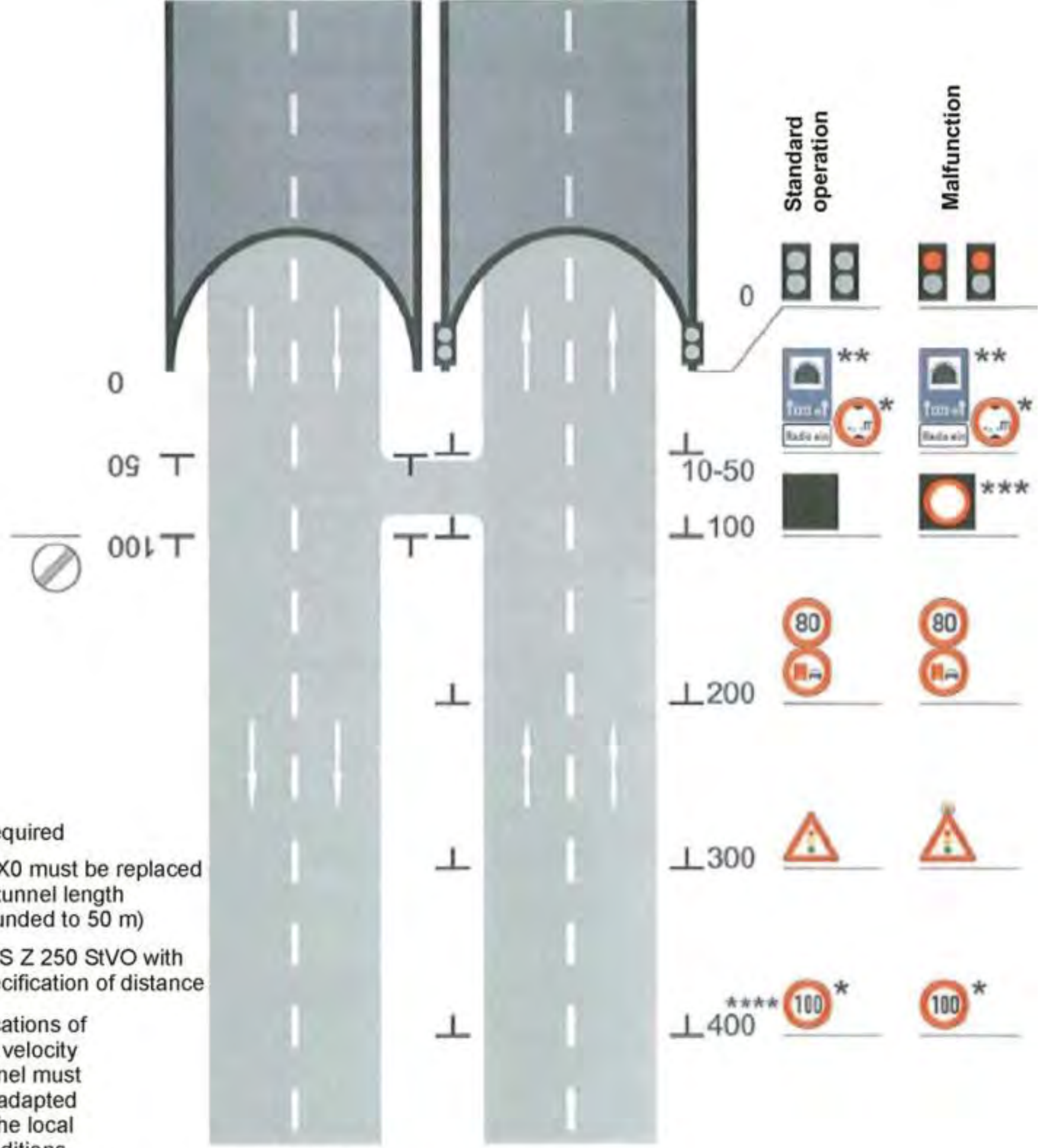


**Table 10: Critical longitudinal speed**

| Gradient | Tunnel cross section | Thermal power | | |
|---|---|---|---|---|
| | | 30 MW | 50 MW | 100 MW |
| 0 – 1% | Rectangle | 2.3 m/s | 2.6 m/s | 2.9 m/s |
| | Vault | 2.5 m/s | 2.8 m/s | 3.1 m/s |
| 2 – 3% | Rectangle | 2.5 m/s | 2.8 m/s | 3.1 m/s |
| | Vault | 2.6 m/s | 2.9 m/s | 3.3 m/s |
| 3 – 6% | Rectangle | 2.7 m/s | 3.0 m/s | 3.3 m/s |
| | Vault | 2.8 m/s | 3.1 m/s | 3.6 m/s |

# RABT (2006)



* if required

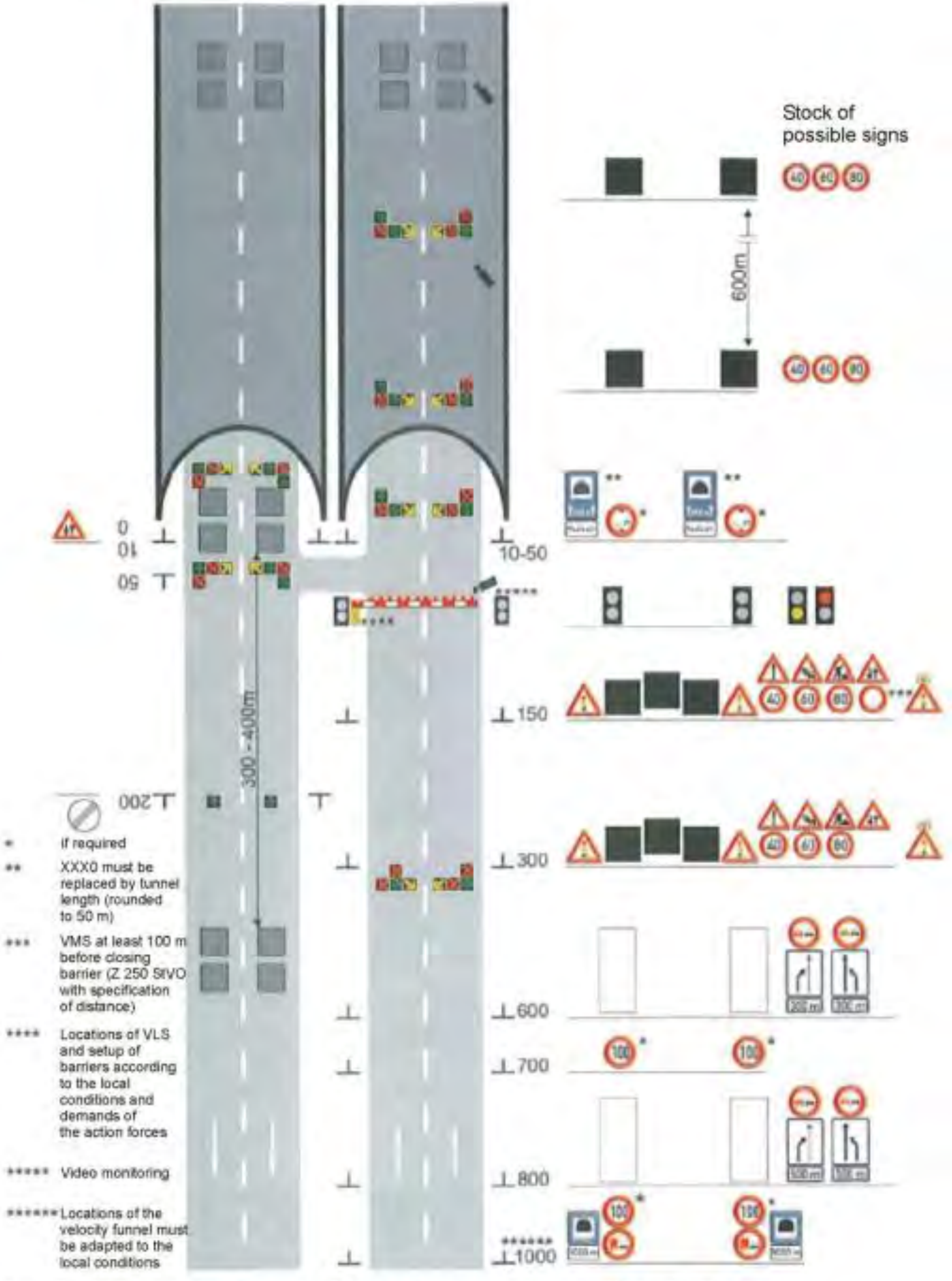
** XXX0 must be replaced by tunnel length (rounded to 50 m)

*** VMS Z 250 StVO with specification of distance

**** Locations of the velocity funnel must be adapted to the local conditions

Figure 13: Minimum equipment with signal lights – system draft for one-way traffic (can be transferred to two-way traffic correspondingly)

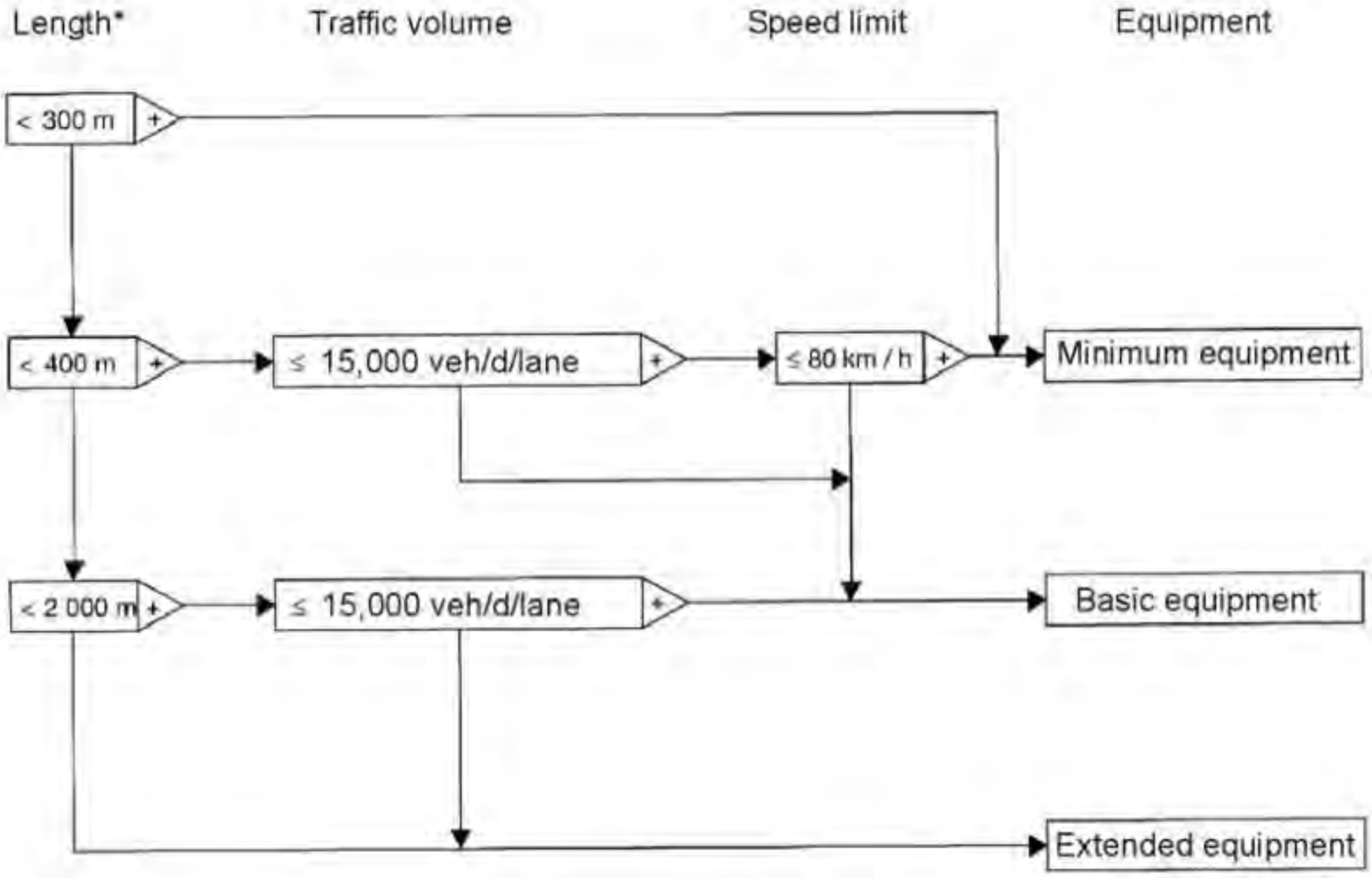
# RABT (2006)



|  |  |
|---|---|
| * | If required |
| ** | XXX0 must be replaced by tunnel length (rounded to 50 m) |
| *** | VMS at least 100 m before closing barrier (Z 250 StVO with specification of distance) |
| **** | Locations of VLS and setup of barriers according to the local conditions and demands of the action forces |
| ***** | Video monitoring |
| ****** | Locations of the velocity funnel must be adapted to the local conditions |

Figure 15: Extended equipment – System draft for one-way traffic (can be transferred to two-way traffic analogously)

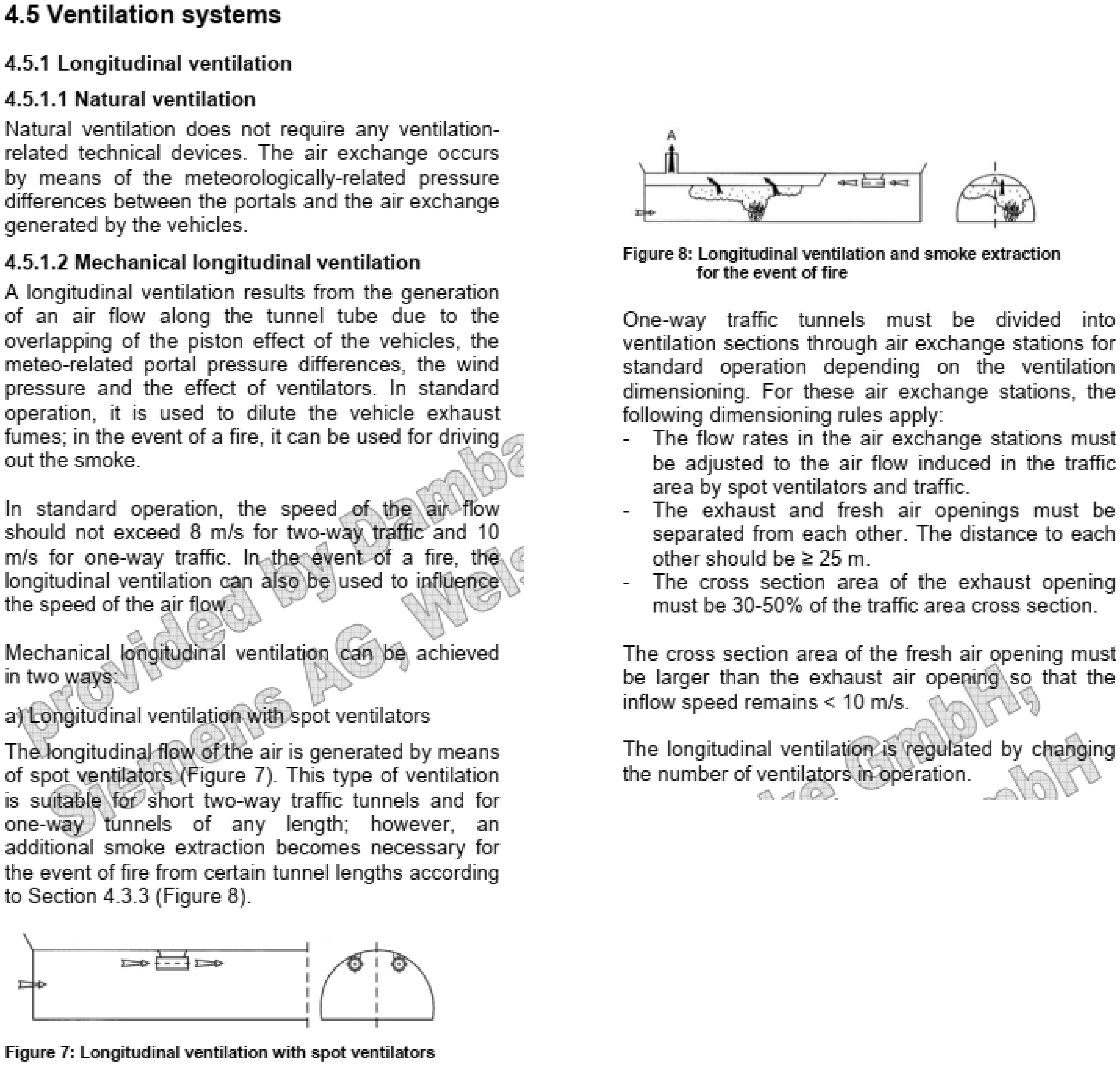
# RABT (2006)



* Tunnel length, if applicable, also length of a chain of tunnels

**Figure 12: Determination of the traffic-related tunnel equipment**

# RABT (2006)



## 4.5 Ventilation systems

### 4.5.1 Longitudinal ventilation

### 4.5.1.1 Natural ventilation

Natural ventilation does not require any ventilation-related technical devices. The air exchange occurs by means of the meteorologically-related pressure differences between the portals and the air exchange generated by the vehicles.

### 4.5.1.2 Mechanical longitudinal ventilation

A longitudinal ventilation results from the generation of an air flow along the tunnel tube due to the overlapping of the piston effect of the vehicles, the meteo-related portal pressure differences, the wind pressure and the effect of ventilators. In standard operation, it is used to dilute the vehicle exhaust fumes; in the event of a fire, it can be used for driving out the smoke.

In standard operation, the speed of the air flow should not exceed 8 m/s for two-way traffic and 10 m/s for one-way traffic. In the event of a fire, the longitudinal ventilation can also be used to influence the speed of the air flow.

Mechanical longitudinal ventilation can be achieved in two ways:

a) Longitudinal ventilation with spot ventilators

The longitudinal flow of the air is generated by means of spot ventilators (Figure 7). This type of ventilation is suitable for short two-way traffic tunnels and for one-way tunnels of any length; however, an additional smoke extraction becomes necessary for the event of fire from certain tunnel lengths according to Section 4.3.3 (Figure 8).

Figure 7: Longitudinal ventilation with spot ventilators

Figure 8: Longitudinal ventilation and smoke extraction for the event of fire

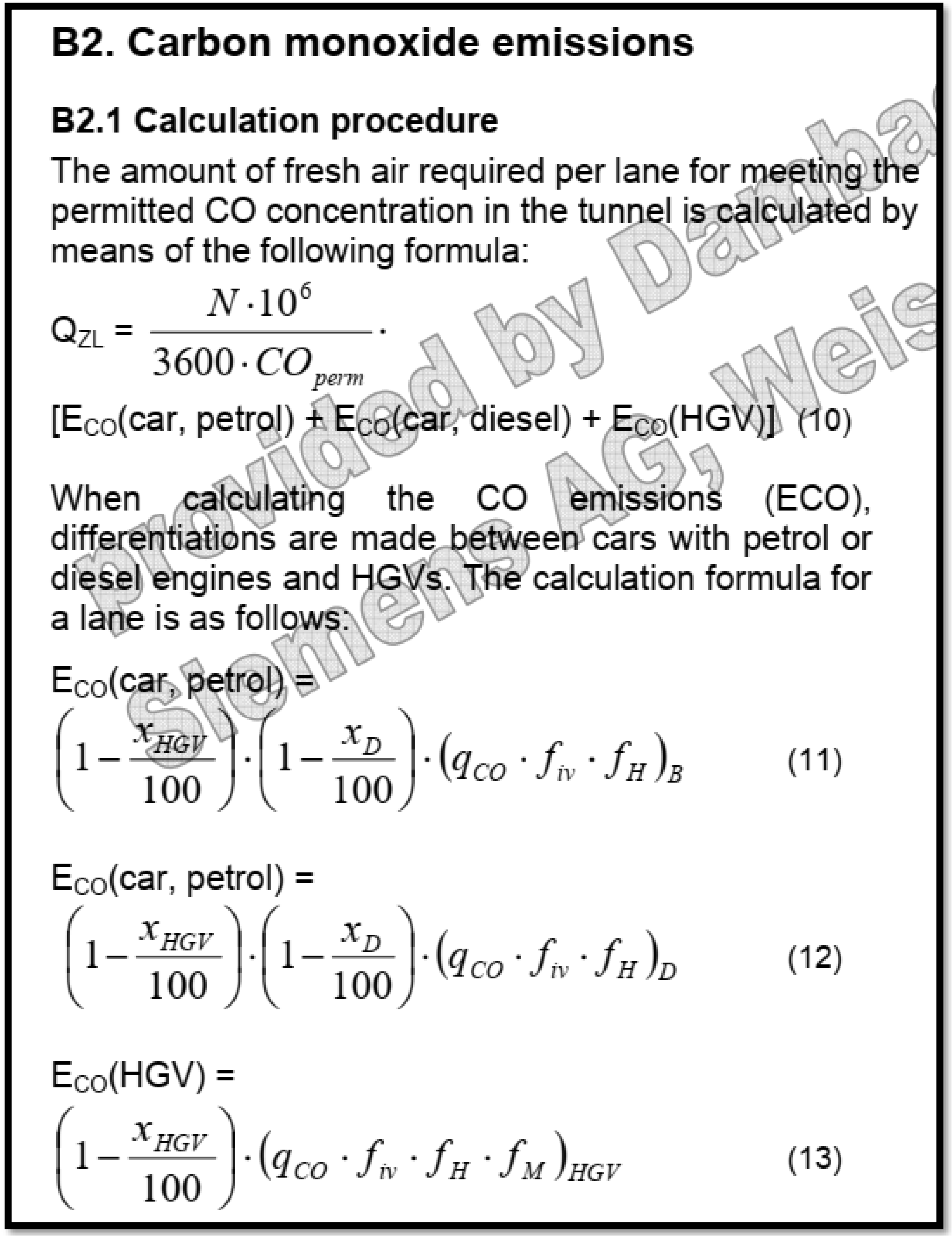
One-way traffic tunnels must be divided into ventilation sections through air exchange stations for standard operation depending on the ventilation dimensioning. For these air exchange stations, the following dimensioning rules apply:

- The flow rates in the air exchange stations must be adjusted to the air flow induced in the traffic area by spot ventilators and traffic.
- The exhaust and fresh air openings must be separated from each other. The distance to each other should be ≥ 25 m.
- The cross section area of the exhaust opening must be 30-50% of the traffic area cross section.

The cross section area of the fresh air opening must be larger than the exhaust air opening so that the inflow speed remains < 10 m/s.

The longitudinal ventilation is regulated by changing the number of ventilators in operation.

RABT (2006)



## B2. Carbon monoxide emissions

### B2.1 Calculation procedure

The amount of fresh air required per lane for meeting the permitted CO concentration in the tunnel is calculated by means of the following formula:

$$Q_{ZL} = \frac{N \cdot 10^6}{3600 \cdot CO_{perm}} \cdot [E_{CO}(\text{car, petrol}) + E_{CO}(\text{car, diesel}) + E_{CO}(\text{HGV})] \quad (10)$$

When calculating the CO emissions (ECO), differentiations are made between cars with petrol or diesel engines and HGVs. The calculation formula for a lane is as follows:

$E_{CO}$(car, petrol) =

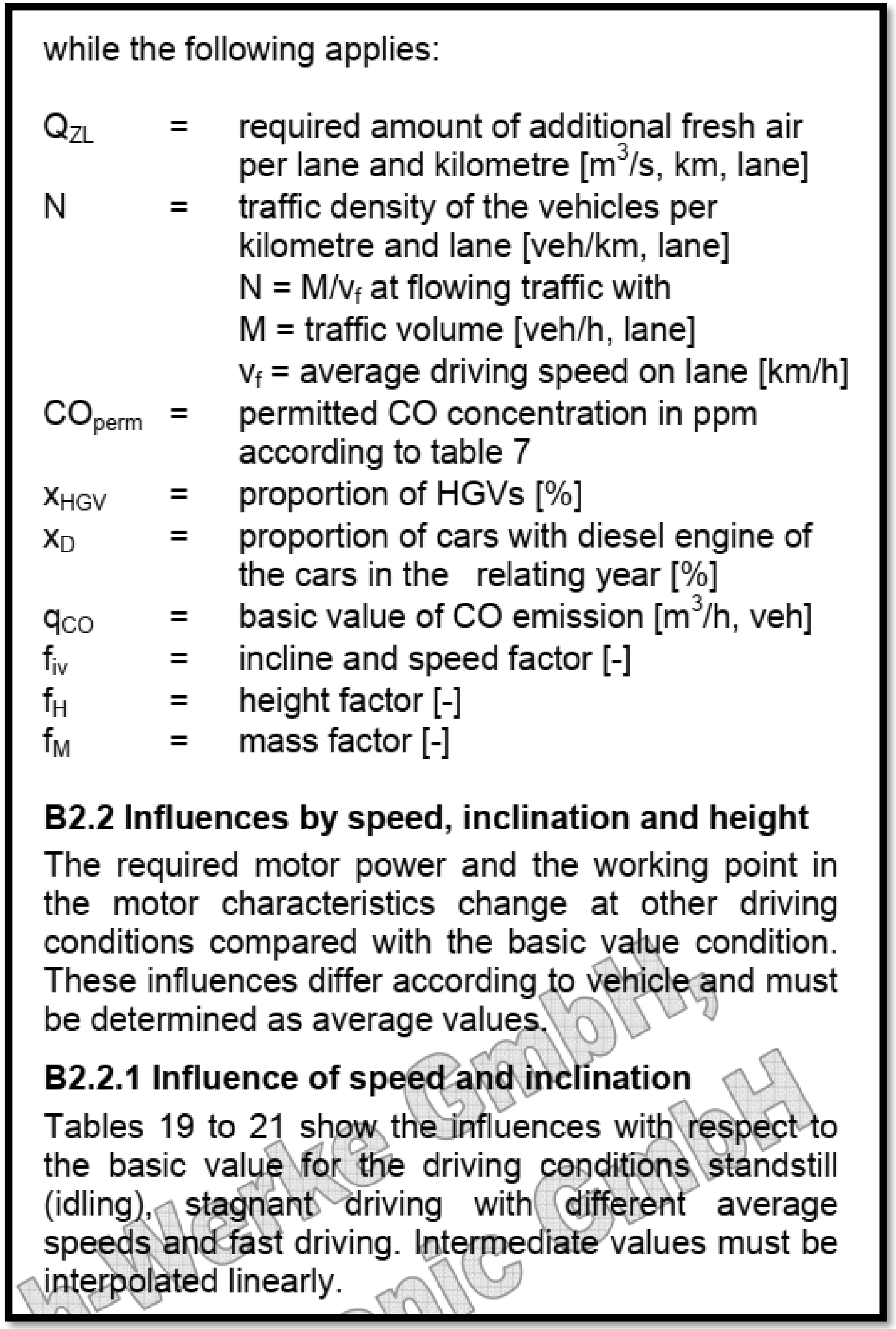
$$\left(1 - \frac{x_{HGV}}{100}\right) \cdot \left(1 - \frac{x_D}{100}\right) \cdot (q_{CO} \cdot f_{iv} \cdot f_H)_B \qquad (11)$$

$E_{CO}$(car, petrol) =

$$\left(1 - \frac{x_{HGV}}{100}\right) \cdot \left(1 - \frac{x_D}{100}\right) \cdot (q_{CO} \cdot f_{iv} \cdot f_H)_D \qquad (12)$$

$E_{CO}$(HGV) =

$$\left(1 - \frac{x_{HGV}}{100}\right) \cdot (q_{CO} \cdot f_{iv} \cdot f_H \cdot f_M)_{HGV} \qquad (13)$$



while the following applies:

$Q_{ZL}$ = required amount of additional fresh air per lane and kilometre [$m^3$/s, km, lane]
N = traffic density of the vehicles per kilometre and lane [veh/km, lane]
N = M/$v_f$ at flowing traffic with
M = traffic volume [veh/h, lane]
$v_f$ = average driving speed on lane [km/h]
$CO_{perm}$ = permitted CO concentration in ppm according to table 7
$x_{HGV}$ = proportion of HGVs [%]
$x_D$ = proportion of cars with diesel engine of the cars in the relating year [%]
$q_{CO}$ = basic value of CO emission [$m^3$/h, veh]
$f_{iv}$ = incline and speed factor [-]
$f_H$ = height factor [-]
$f_M$ = mass factor [-]

### B2.2 Influences by speed, inclination and height

The required motor power and the working point in the motor characteristics change at other driving conditions compared with the basic value condition. These influences differ according to vehicle and must be determined as average values.

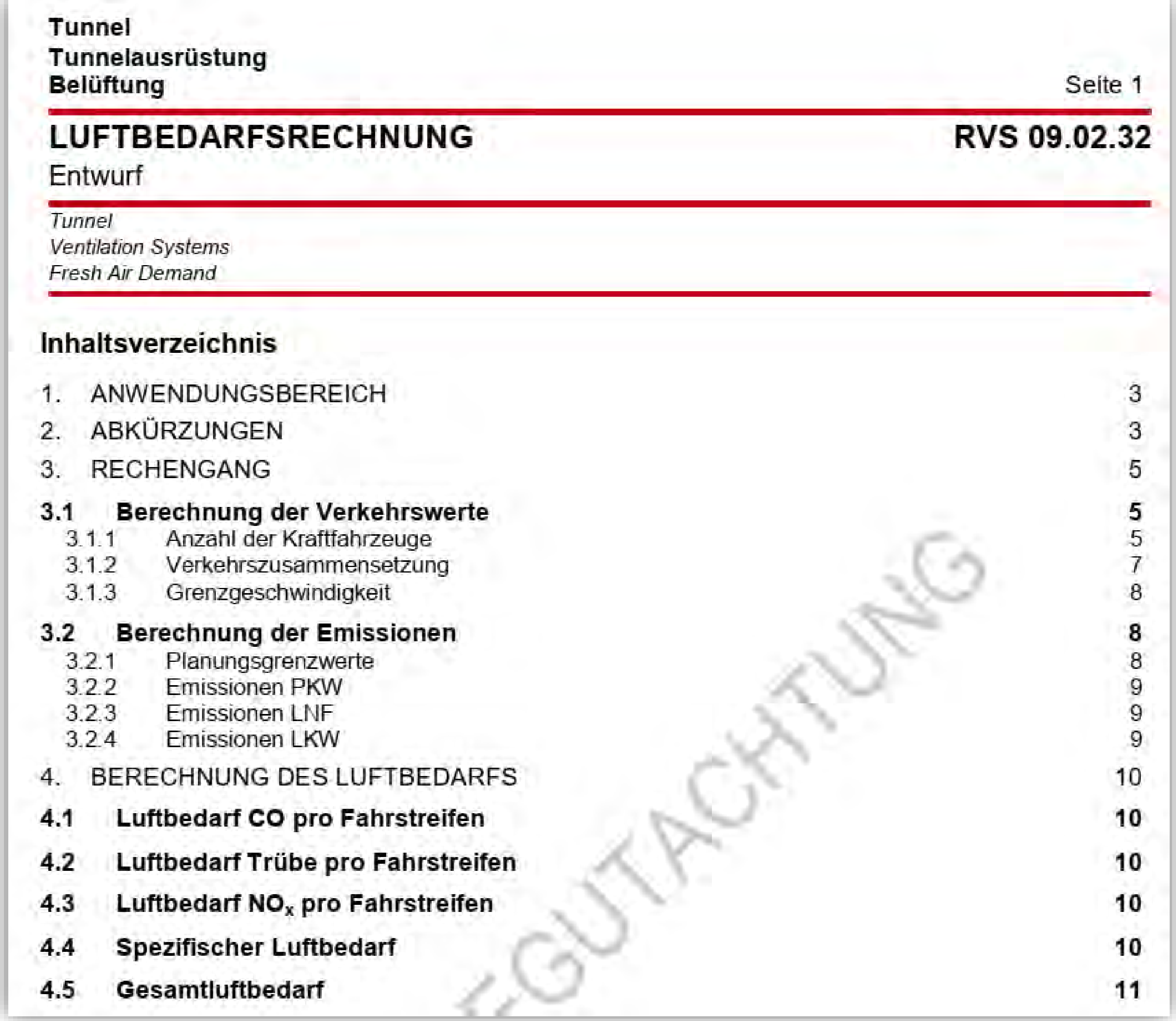
### B2.2.1 Influence of speed and inclination

Tables 19 to 21 show the influences with respect to the basic value for the driving conditions standstill (idling), stagnant driving with different average speeds and fast driving. Intermediate values must be interpolated linearly.

# RVS - Austrija

1. RVS 09.262 (1997): Uređaji za provjetravanje. Proračun potrebne količine vazduha
2. RVS 09.261 (2001): Smjernice za projektovanje, uređaji za provjetravanje (regularni režim rada tunela)
3. RVS 09.281 (2002): Smjernice za radne i sigurnosne uređaje; Građevinski dio.
4. RVS 09.282 (2005): Oprema za tunele
5. **RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi**
6. RVS 09.02.31 (2009): Izgradnja i projektovanje tunela, građevinski aspekti
7. **RVS 09.02.32 (2019): Tunel, ventilacioni sistem, protok svježeg vazduha**
8. **RVS 09.02.22 (2014): Tunel, tunelska oprema, rad i bezbjednost**

# RVS 09.02.32 (2019): Tunel, ventilacioni sistem, protok svježeg vazduha



**Tunnel**
**Tunnelausrüstung**
**Belüftung**

## LUFTBEDARFSRECHNUNG

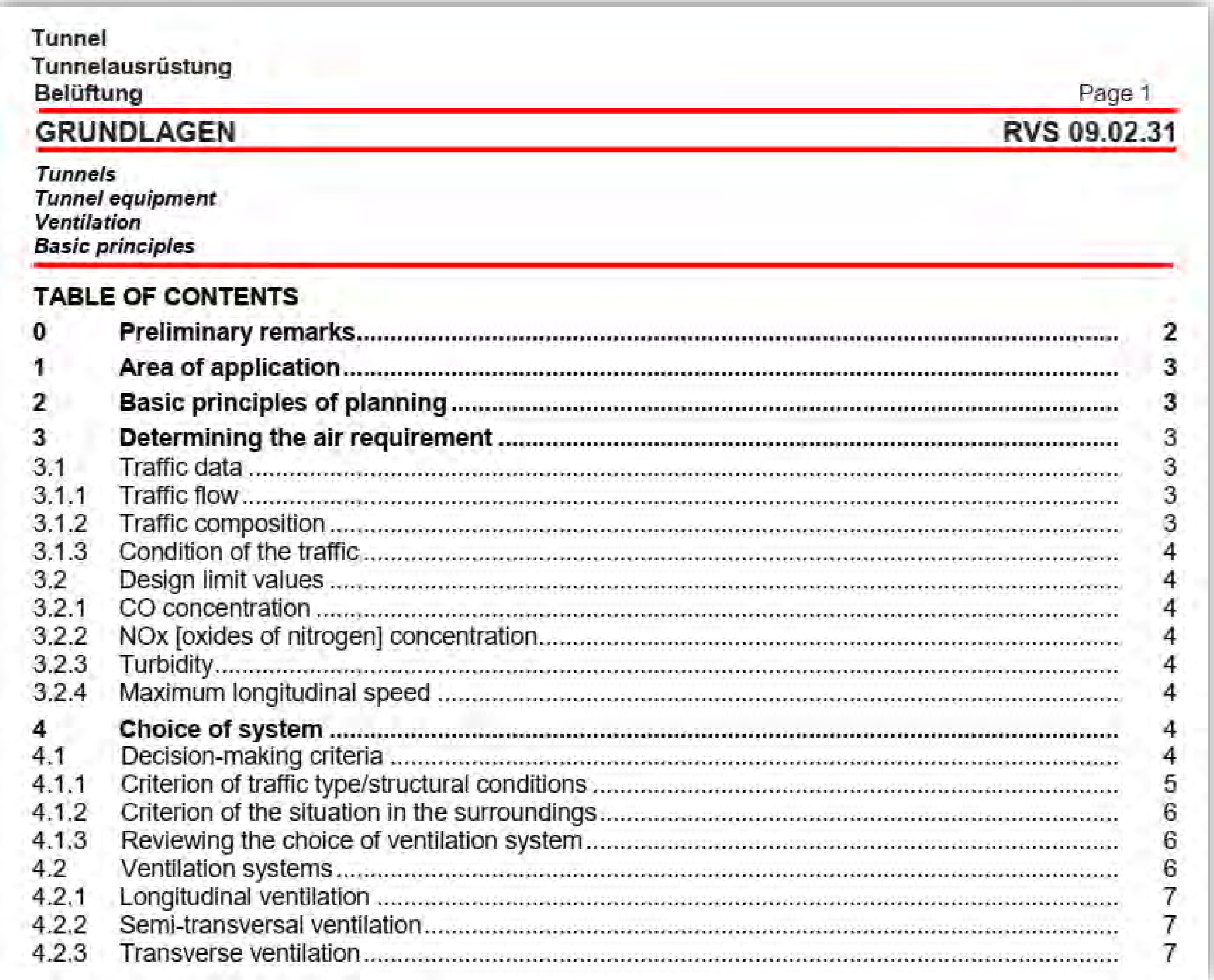
**RVS 09.02.32**

Entwurf

*Tunnel*
*Ventilation Systems*
*Fresh Air Demand*

### Inhaltsverzeichnis

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



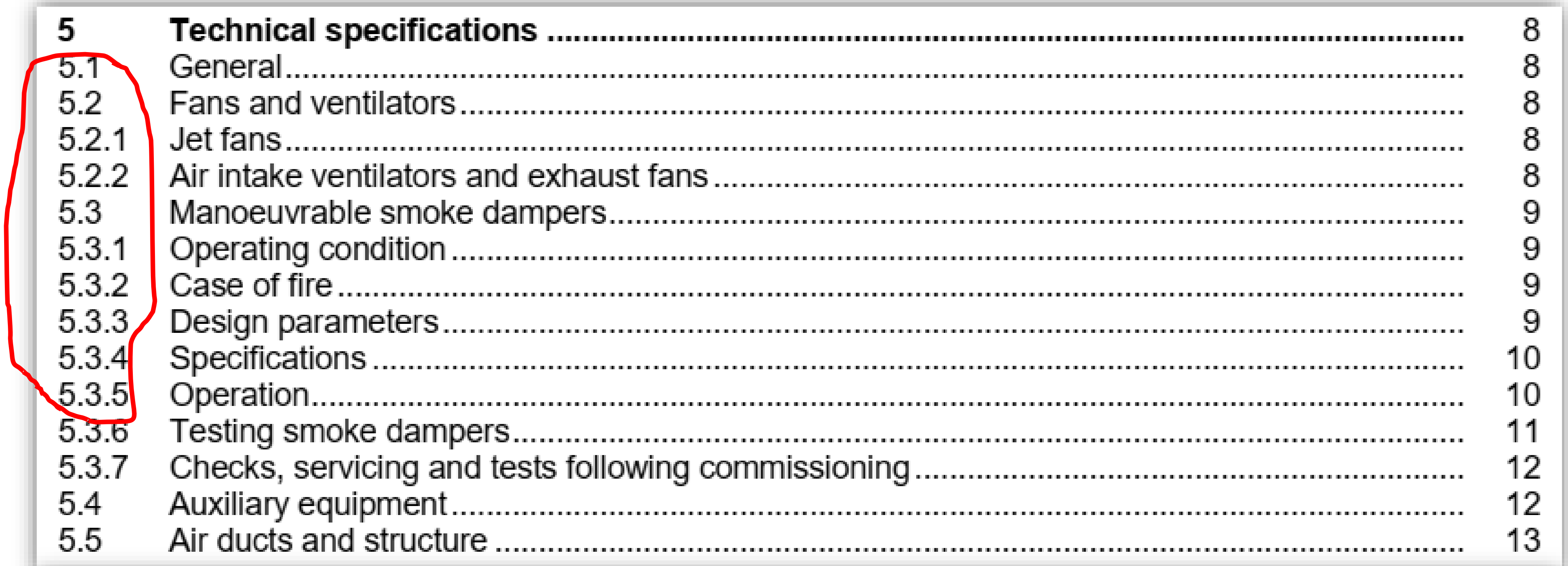
Tunnel
Tunnelausrüstung
Belüftung

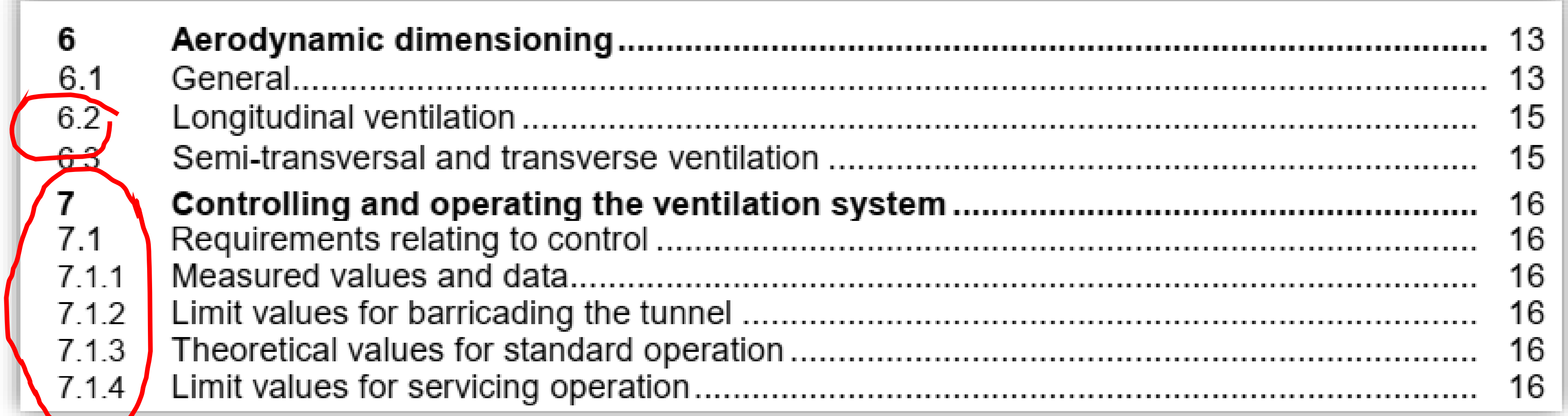
## GRUNDLAGEN RVS 09.02.31

*Tunnels*
*Tunnel equipment*
*Ventilation*
*Basic principles*

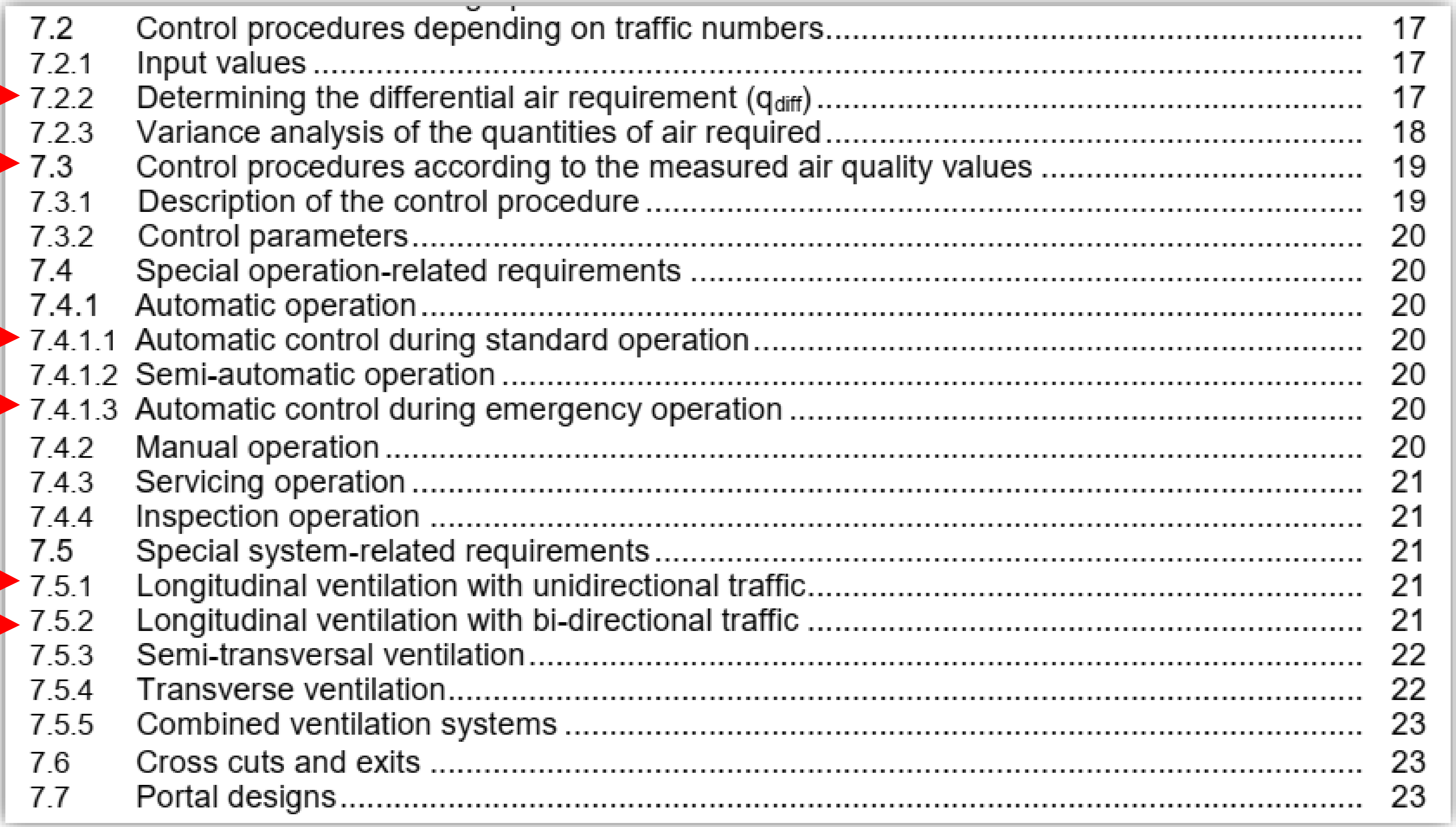
### TABLE OF CONTENTS

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi

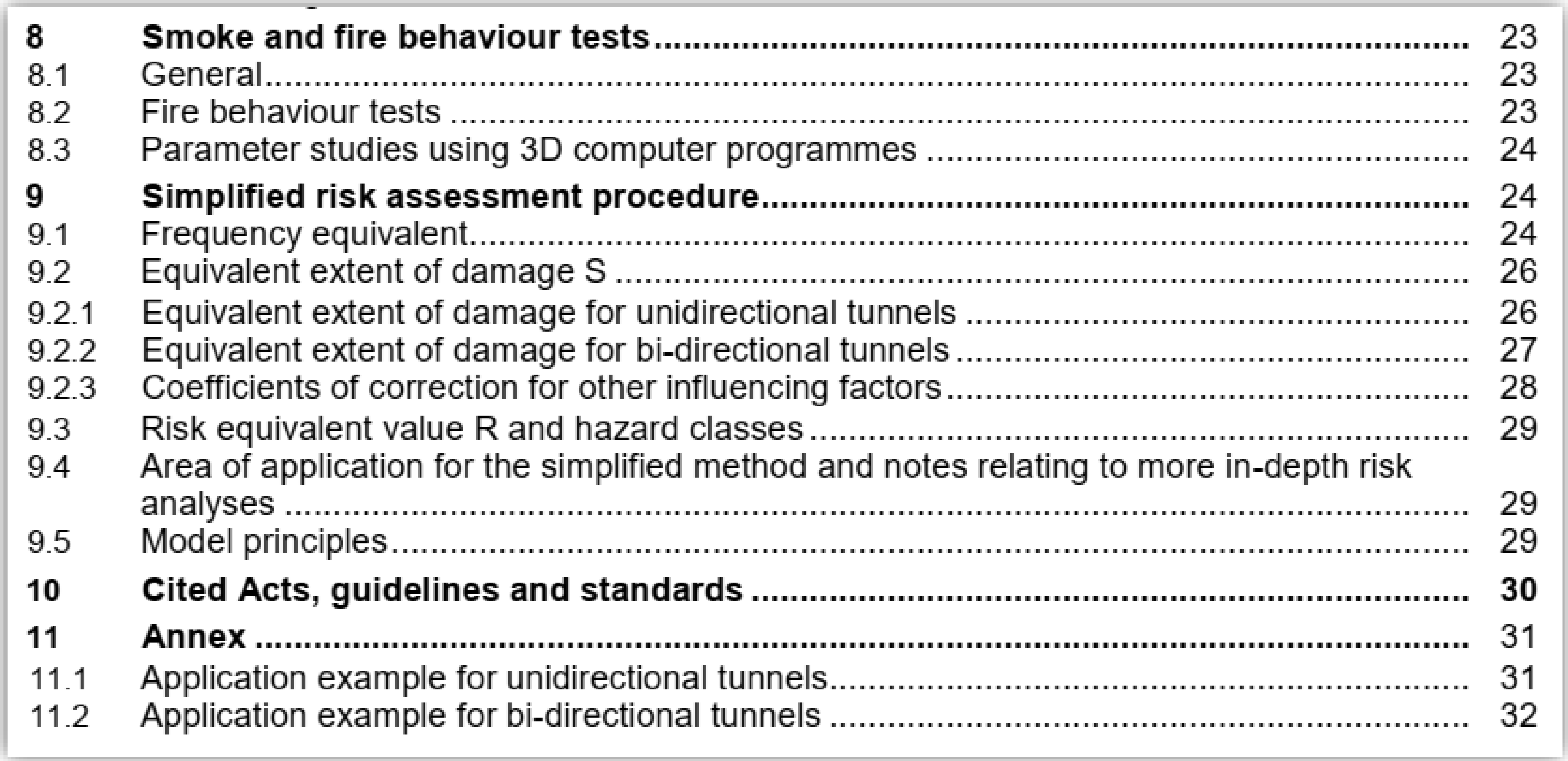




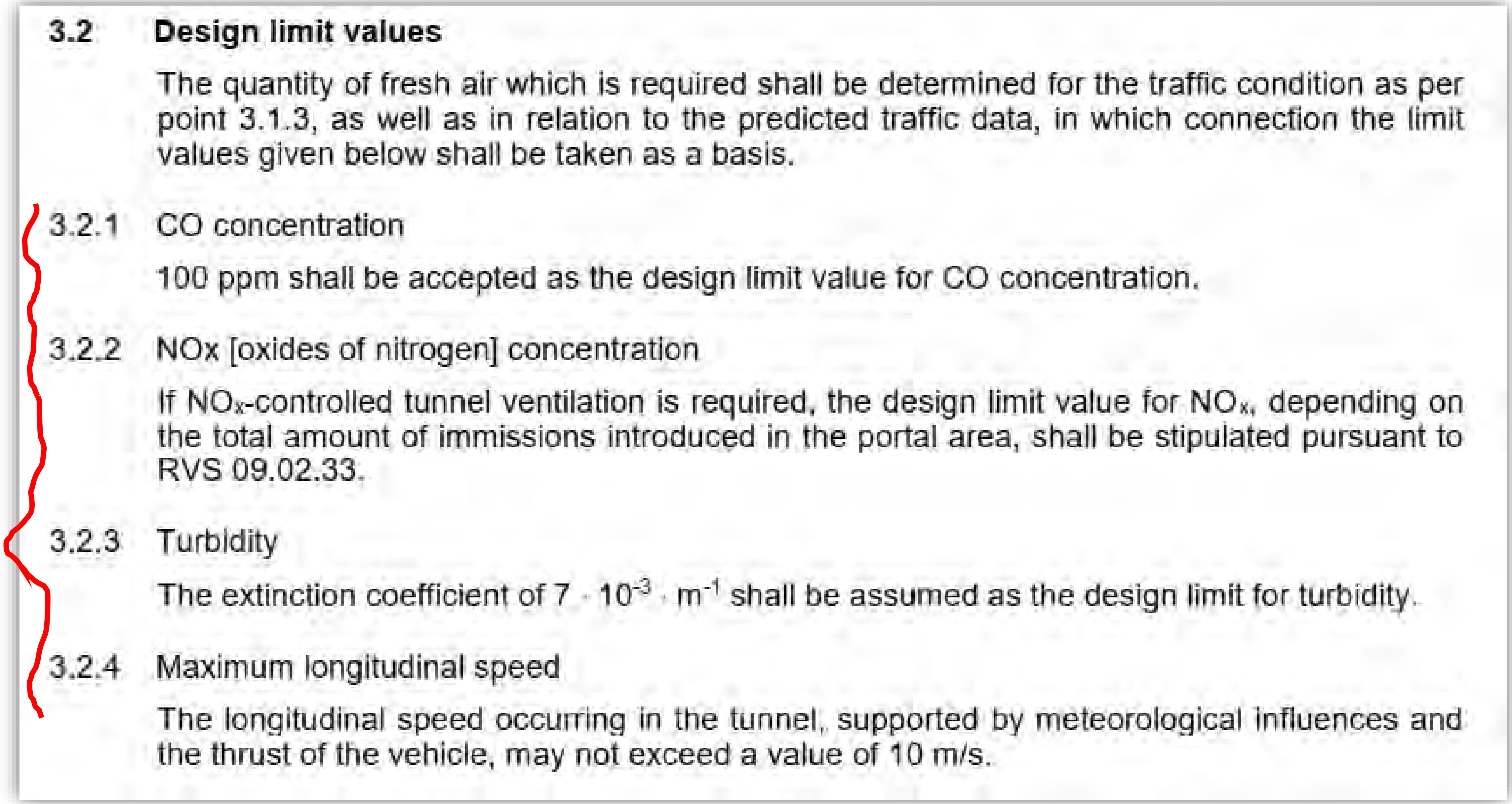
# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



### 3.2 Design limit values

The quantity of fresh air which is required shall be determined for the traffic condition as per point 3.1.3, as well as in relation to the predicted traffic data, in which connection the limit values given below shall be taken as a basis.

#### 3.2.1 CO concentration

100 ppm shall be accepted as the design limit value for CO concentration.

#### 3.2.2 NOx [oxides of nitrogen] concentration

If $NO_x$-controlled tunnel ventilation is required, the design limit value for $NO_x$, depending on the total amount of immissions introduced in the portal area, shall be stipulated pursuant to RVS 09.02.33.

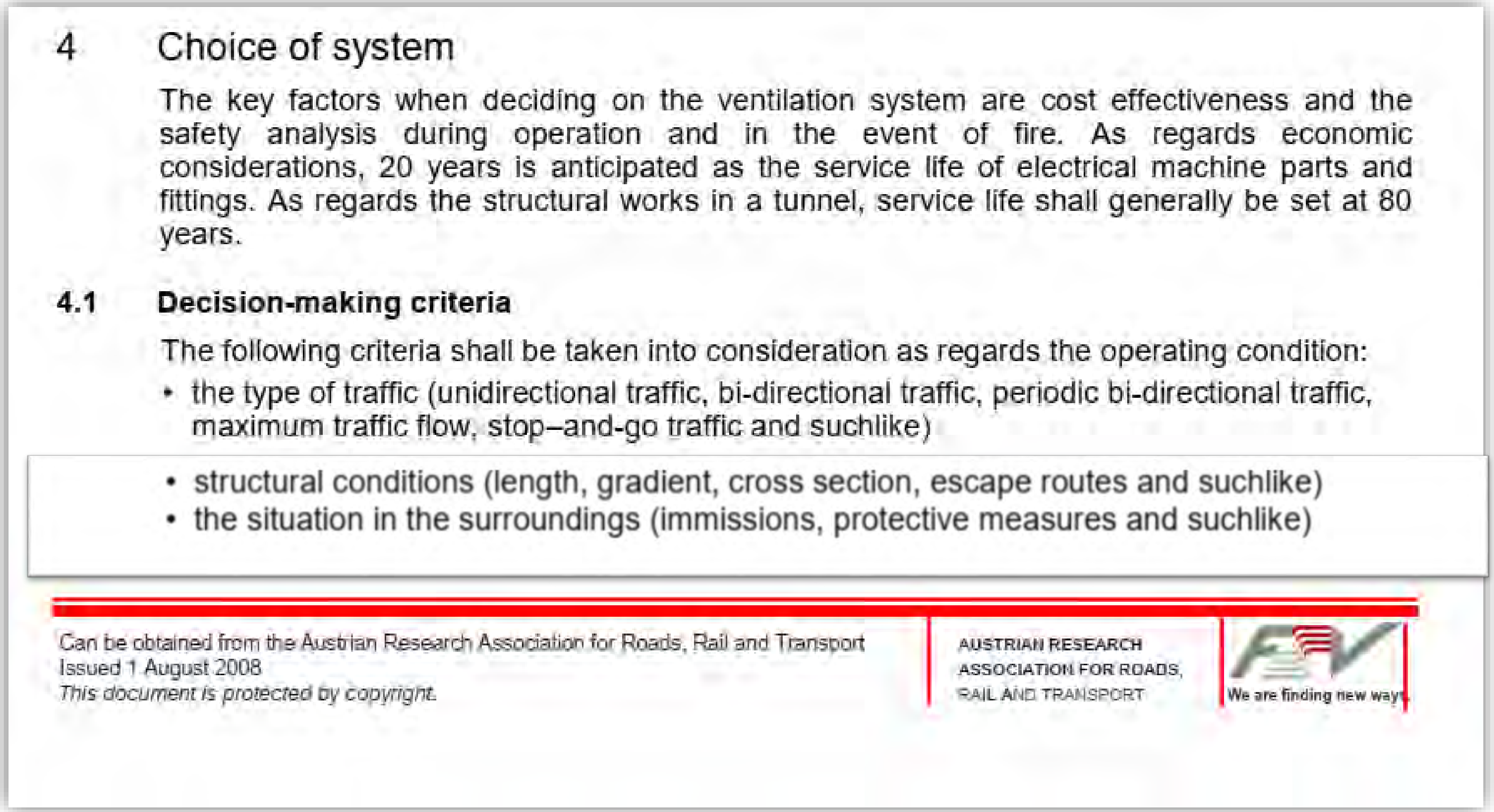
#### 3.2.3 Turbidity

The extinction coefficient of $7 \cdot 10^{-3} \cdot m^{-1}$ shall be assumed as the design limit for turbidity.

#### 3.2.4 Maximum longitudinal speed

The longitudinal speed occurring in the tunnel, supported by meteorological influences and the thrust of the vehicle, may not exceed a value of 10 m/s.

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



## 4 Choice of system

The key factors when deciding on the ventilation system are cost effectiveness and the safety analysis during operation and in the event of fire. As regards economic considerations, 20 years is anticipated as the service life of electrical machine parts and fittings. As regards the structural works in a tunnel, service life shall generally be set at 80 years.

### 4.1 Decision-making criteria

The following criteria shall be taken into consideration as regards the operating condition:

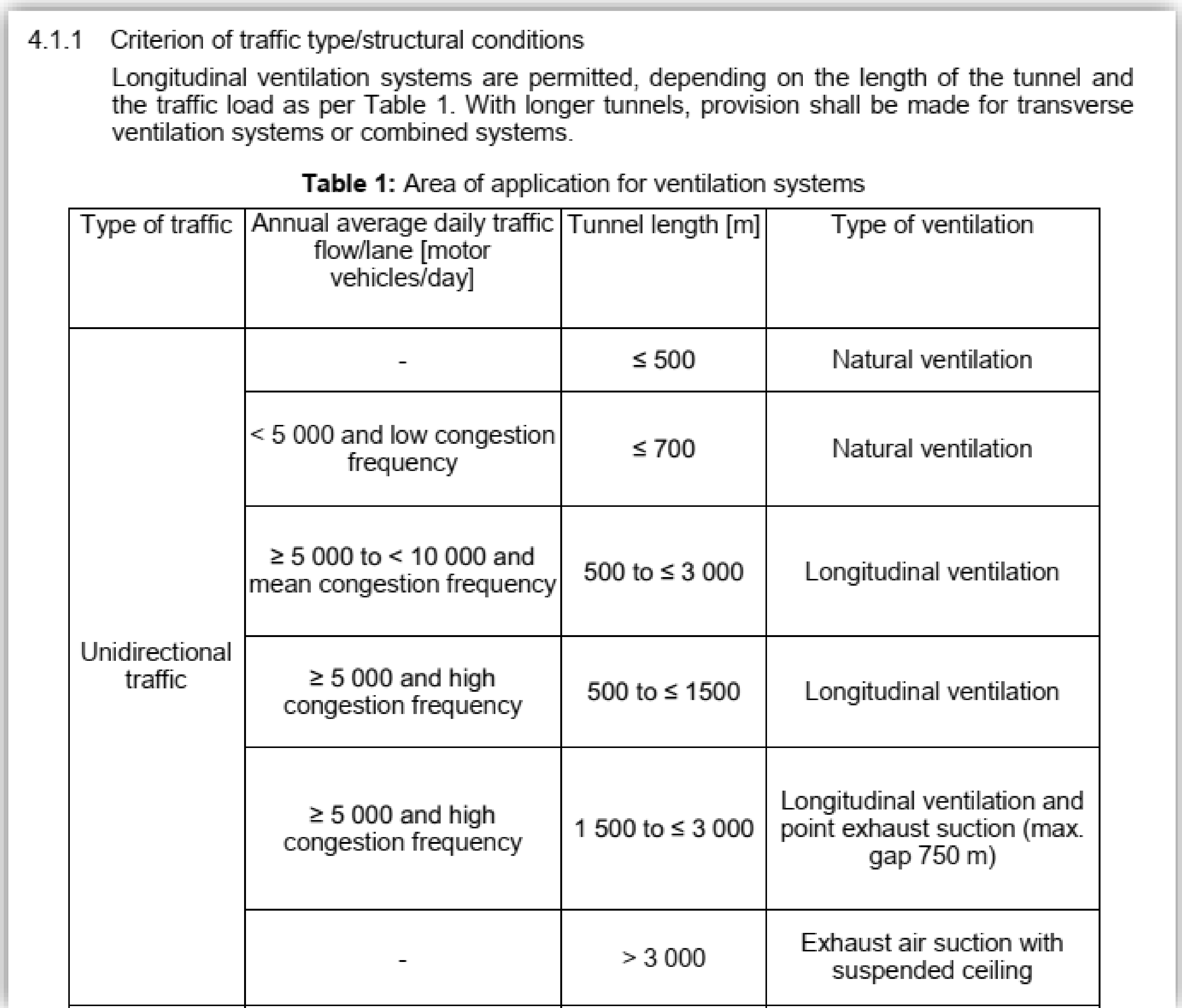
- the type of traffic (unidirectional traffic, bi-directional traffic, periodic bi-directional traffic, maximum traffic flow, stop–and-go traffic and suchlike)
- structural conditions (length, gradient, cross section, escape routes and suchlike)
- the situation in the surroundings (immissions, protective measures and suchlike)

Can be obtained from the Austrian Research Association for Roads, Rail and Transport
Issued 1 August 2008
*This document is protected by copyright.*

AUSTRIAN RESEARCH
ASSOCIATION FOR ROADS,
RAIL AND TRANSPORT

We are finding new ways

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



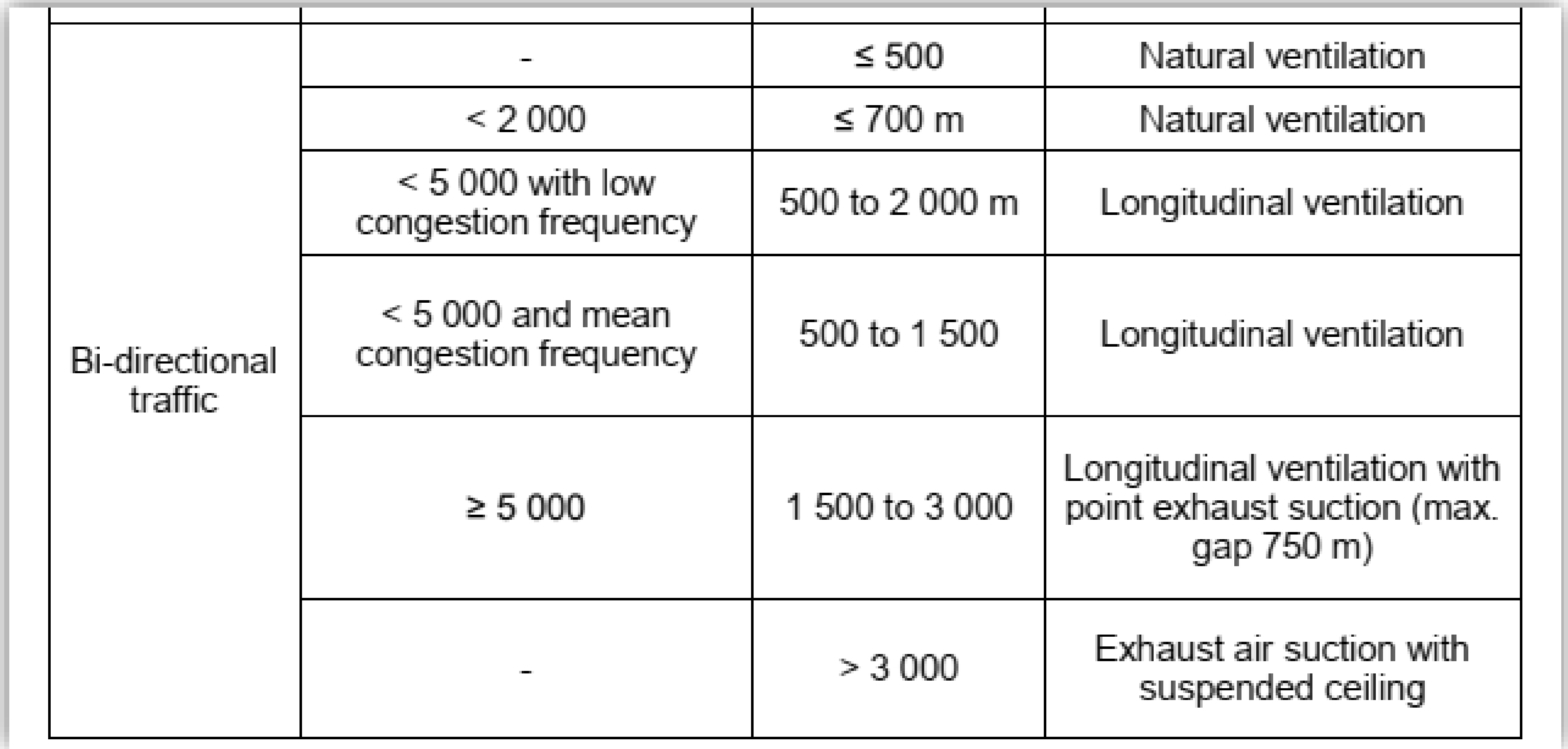
### 4.1.1 Criterion of traffic type/structural conditions

Longitudinal ventilation systems are permitted, depending on the length of the tunnel and the traffic load as per Table 1. With longer tunnels, provision shall be made for transverse ventilation systems or combined systems.

**Table 1:** Area of application for ventilation systems

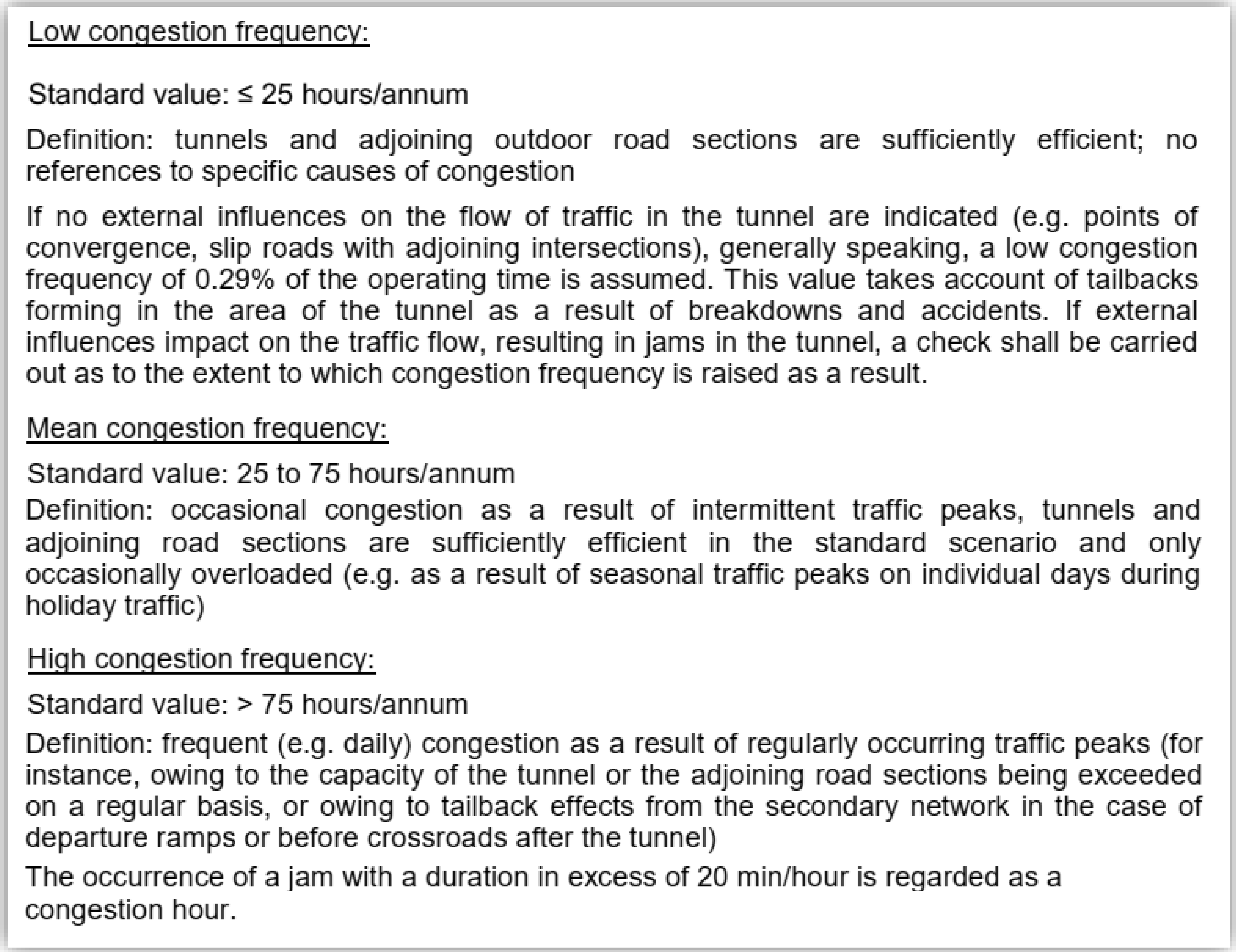
| Type of traffic | Annual average daily traffic flow/lane [motor vehicles/day] | Tunnel length [m] | Type of ventilation |
|---|---|---|---|
| Unidirectional traffic | - | ≤ 500 | Natural ventilation |
| | < 5 000 and low congestion frequency | ≤ 700 | Natural ventilation |
| | ≥ 5 000 to < 10 000 and mean congestion frequency | 500 to ≤ 3 000 | Longitudinal ventilation |
| | ≥ 5 000 and high congestion frequency | 500 to ≤ 1500 | Longitudinal ventilation |
| | ≥ 5 000 and high congestion frequency | 1 500 to ≤ 3 000 | Longitudinal ventilation and point exhaust suction (max. gap 750 m) |
| | - | > 3 000 | Exhaust air suction with suspended ceiling |

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



| | | | |
|---|---|---|---|
| Bi-directional traffic | - | ≤ 500 | Natural ventilation |
| | < 2 000 | ≤ 700 m | Natural ventilation |
| | < 5 000 with low congestion frequency | 500 to 2 000 m | Longitudinal ventilation |
| | < 5 000 and mean congestion frequency | 500 to 1 500 | Longitudinal ventilation |
| | ≥ 5 000 | 1 500 to 3 000 | Longitudinal ventilation with point exhaust suction (max. gap 750 m) |
| | - | > 3 000 | Exhaust air suction with suspended ceiling |

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



Low congestion frequency:

Standard value: ≤ 25 hours/annum

Definition: tunnels and adjoining outdoor road sections are sufficiently efficient; no references to specific causes of congestion

If no external influences on the flow of traffic in the tunnel are indicated (e.g. points of convergence, slip roads with adjoining intersections), generally speaking, a low congestion frequency of 0.29% of the operating time is assumed. This value takes account of tailbacks forming in the area of the tunnel as a result of breakdowns and accidents. If external influences impact on the traffic flow, resulting in jams in the tunnel, a check shall be carried out as to the extent to which congestion frequency is raised as a result.

Mean congestion frequency:

Standard value: 25 to 75 hours/annum

Definition: occasional congestion as a result of intermittent traffic peaks, tunnels and adjoining road sections are sufficiently efficient in the standard scenario and only occasionally overloaded (e.g. as a result of seasonal traffic peaks on individual days during holiday traffic)

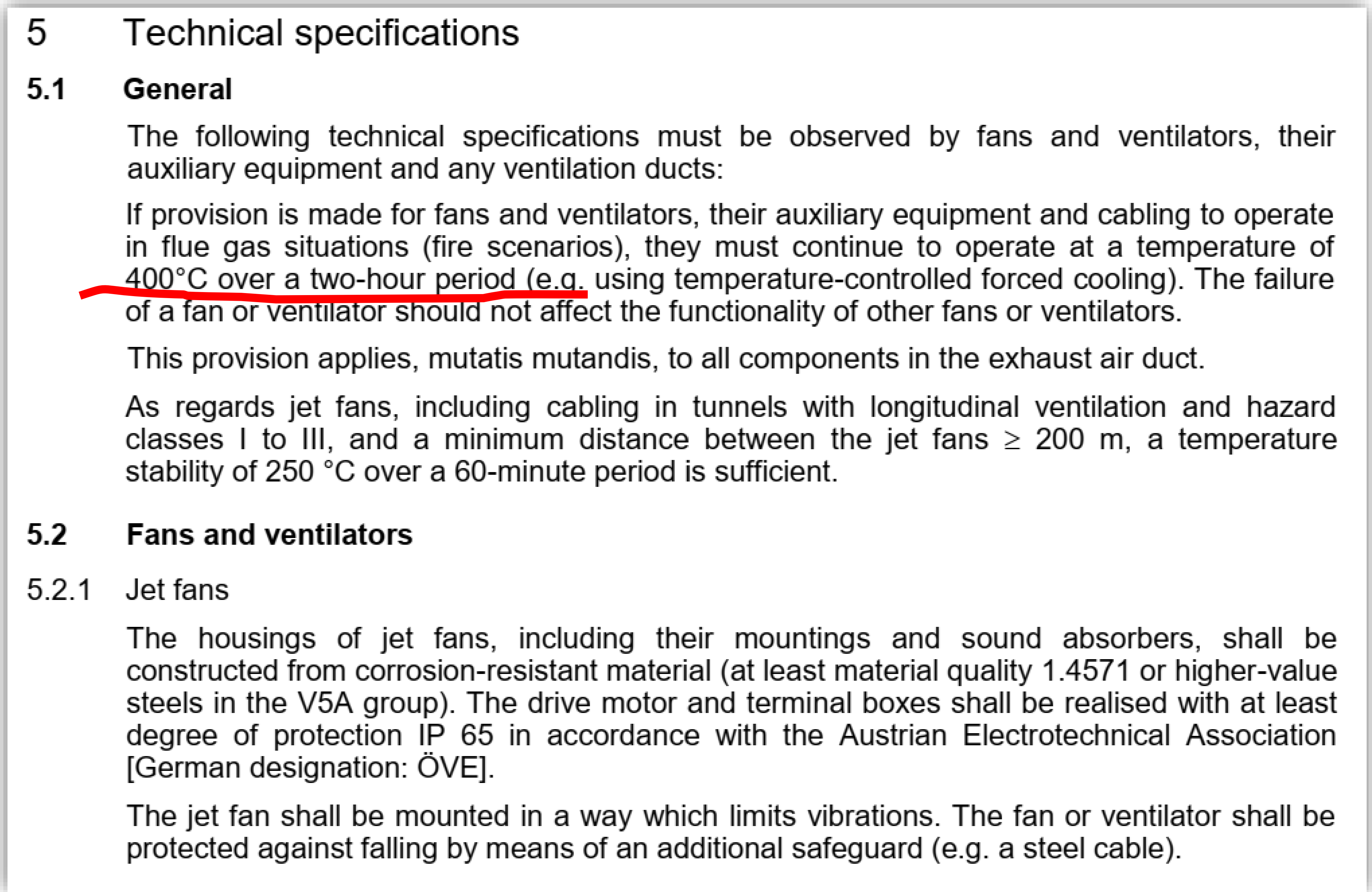
High congestion frequency:

Standard value: > 75 hours/annum

Definition: frequent (e.g. daily) congestion as a result of regularly occurring traffic peaks (for instance, owing to the capacity of the tunnel or the adjoining road sections being exceeded on a regular basis, or owing to tailback effects from the secondary network in the case of departure ramps or before crossroads after the tunnel)

The occurrence of a jam with a duration in excess of 20 min/hour is regarded as a congestion hour.

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



## 5 Technical specifications

### 5.1 General

The following technical specifications must be observed by fans and ventilators, their auxiliary equipment and any ventilation ducts:

If provision is made for fans and ventilators, their auxiliary equipment and cabling to operate in flue gas situations (fire scenarios), they must continue to operate at a temperature of 400°C over a two-hour period (e.g. using temperature-controlled forced cooling). The failure of a fan or ventilator should not affect the functionality of other fans or ventilators.

This provision applies, mutatis mutandis, to all components in the exhaust air duct.

As regards jet fans, including cabling in tunnels with longitudinal ventilation and hazard classes I to III, and a minimum distance between the jet fans $\geq$ 200 m, a temperature stability of 250 °C over a 60-minute period is sufficient.

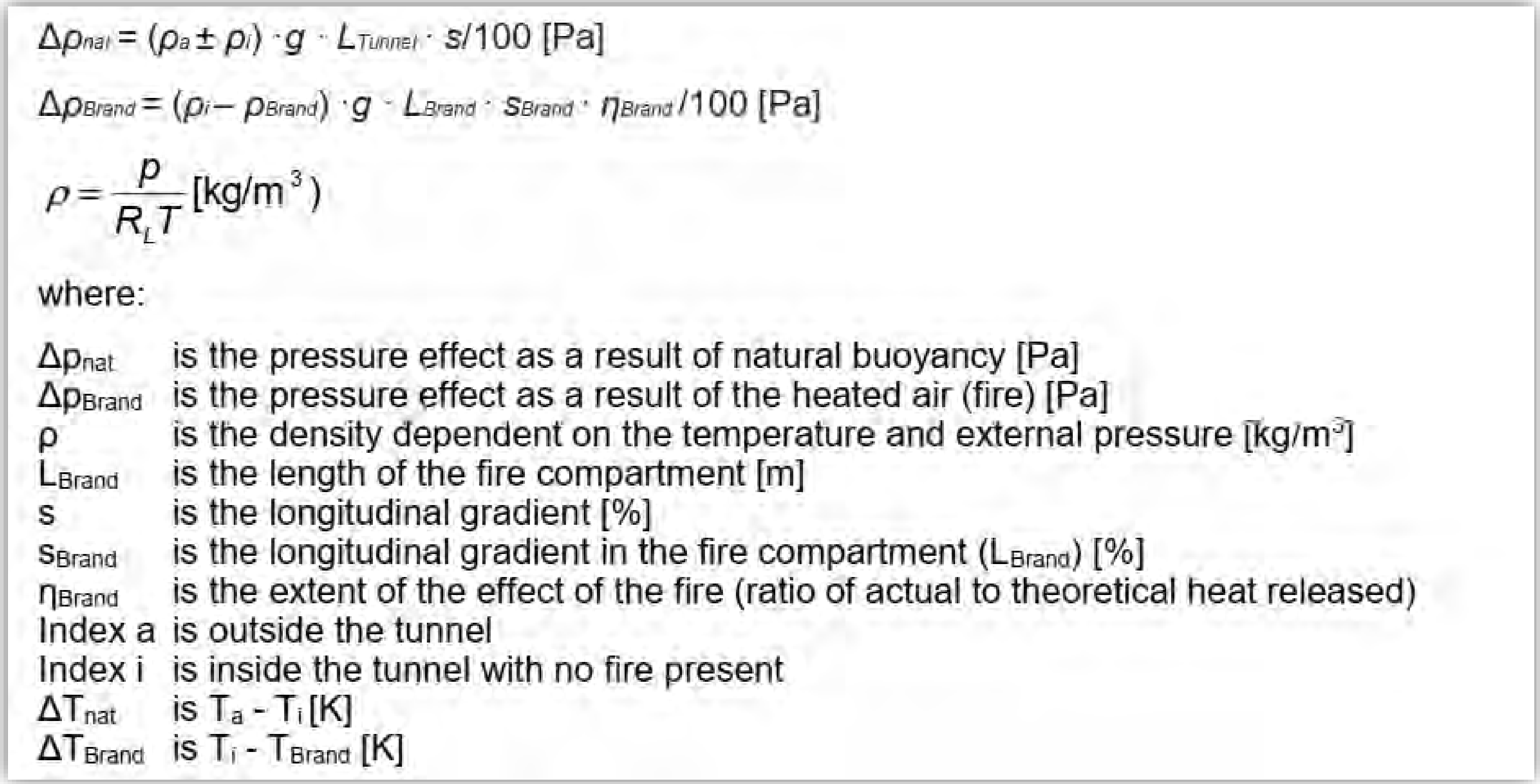
### 5.2 Fans and ventilators

#### 5.2.1 Jet fans

The housings of jet fans, including their mountings and sound absorbers, shall be constructed from corrosion-resistant material (at least material quality 1.4571 or higher-value steels in the V5A group). The drive motor and terminal boxes shall be realised with at least degree of protection IP 65 in accordance with the Austrian Electrotechnical Association [German designation: ÖVE].

The jet fan shall be mounted in a way which limits vibrations. The fan or ventilator shall be protected against falling by means of an additional safeguard (e.g. a steel cable).

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



$$\Delta p_{nat} = (\rho_a \pm \rho_i) \cdot g \cdot L_{Tunnel} \cdot s/100 \text{ [Pa]}$$

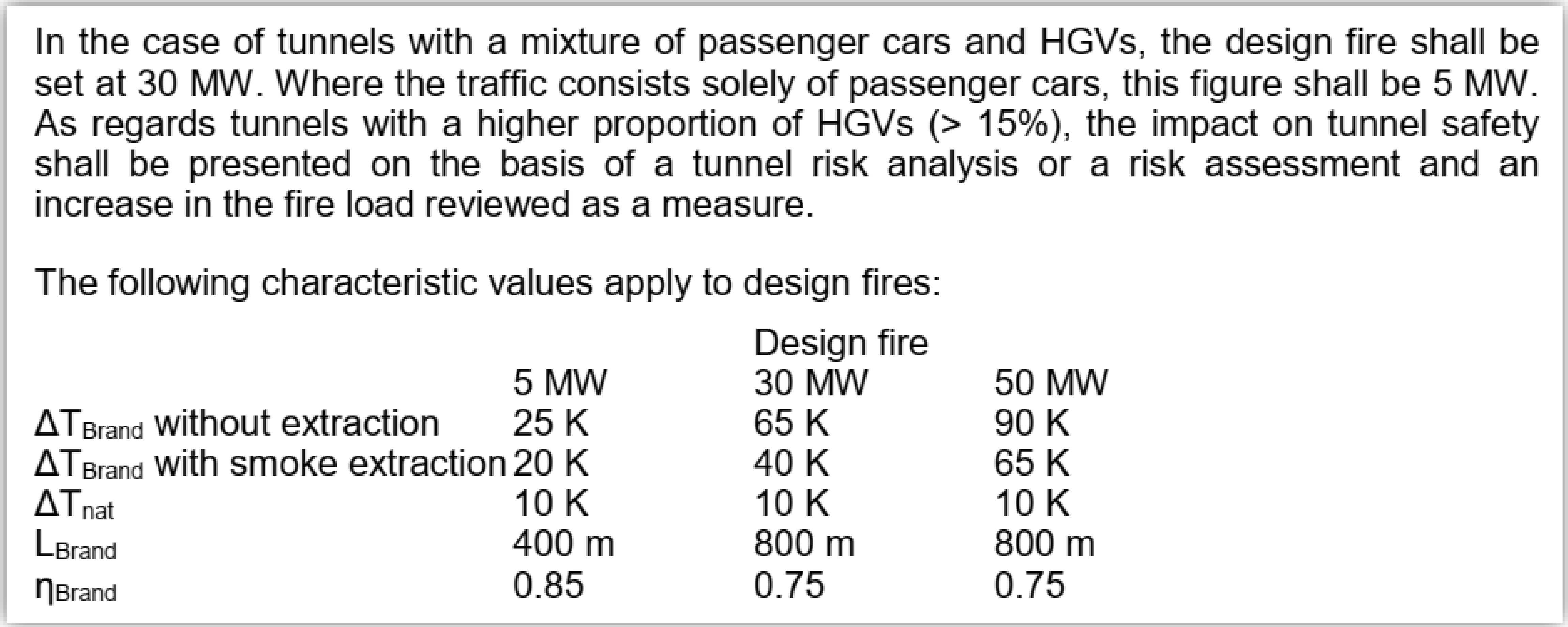
$$\Delta p_{Brand} = (\rho_i - \rho_{Brand}) \cdot g \cdot L_{Brand} \cdot s_{Brand} \cdot \eta_{Brand}/100 \text{ [Pa]}$$

$$\rho = \frac{p}{R_L T} \text{ [kg/m}^3\text{)}$$

where:

| | |
|---|---|
| $\Delta p_{nat}$ | is the pressure effect as a result of natural buoyancy [Pa] |
| $\Delta p_{Brand}$ | is the pressure effect as a result of the heated air (fire) [Pa] |
| $\rho$ | is the density dependent on the temperature and external pressure [kg/m³] |
| $L_{Brand}$ | is the length of the fire compartment [m] |
| s | is the longitudinal gradient [%] |
| $s_{Brand}$ | is the longitudinal gradient in the fire compartment ($L_{Brand}$) [%] |
| $\eta_{Brand}$ | is the extent of the effect of the fire (ratio of actual to theoretical heat released) |
| Index a | is outside the tunnel |
| Index i | is inside the tunnel with no fire present |
| $\Delta T_{nat}$ | is $T_a$ - $T_i$ [K] |
| $\Delta T_{Brand}$ | is $T_i$ - $T_{Brand}$ [K] |

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi

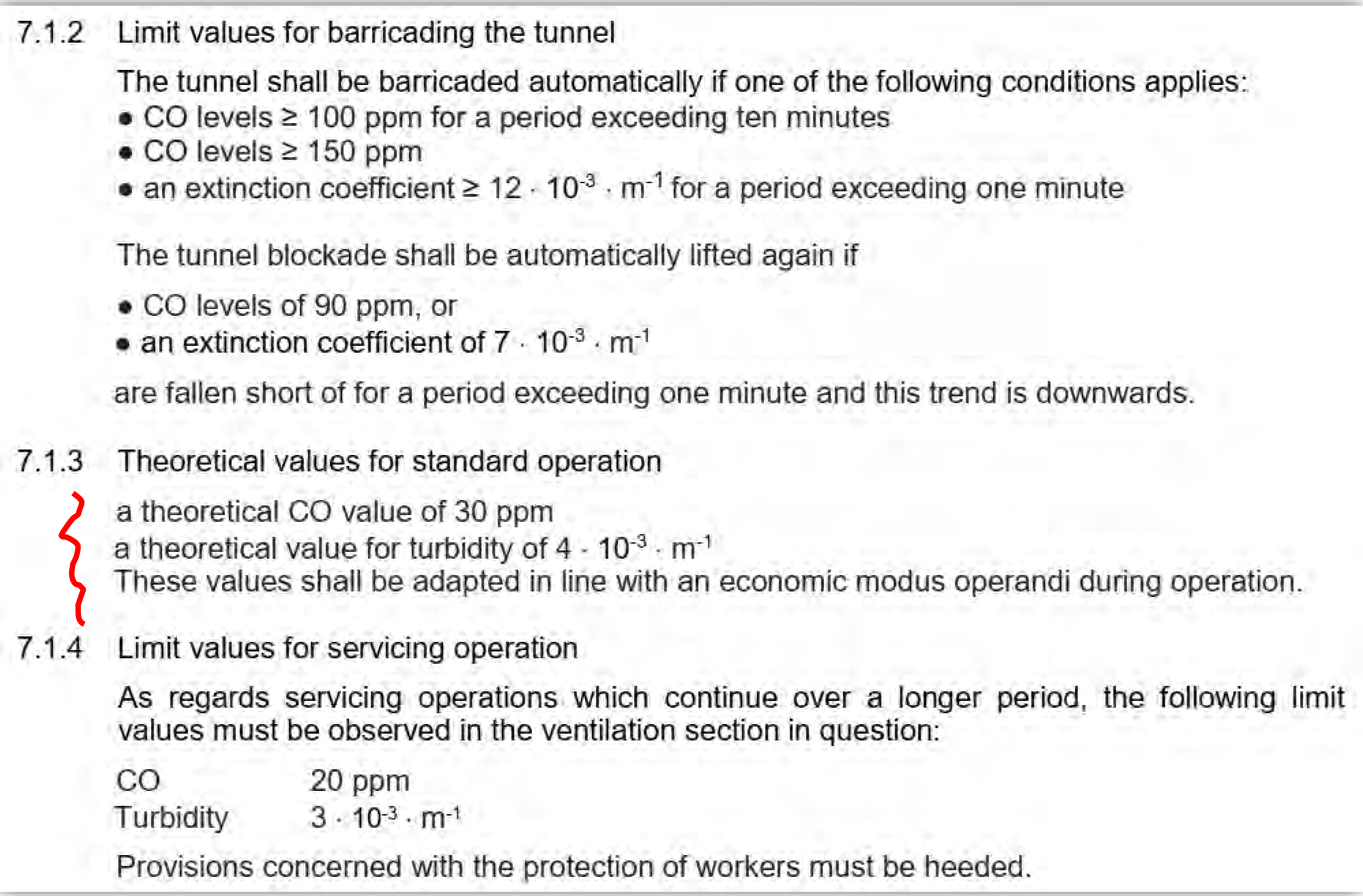


In the case of tunnels with a mixture of passenger cars and HGVs, the design fire shall be set at 30 MW. Where the traffic consists solely of passenger cars, this figure shall be 5 MW. As regards tunnels with a higher proportion of HGVs (> 15%), the impact on tunnel safety shall be presented on the basis of a tunnel risk analysis or a risk assessment and an increase in the fire load reviewed as a measure.

The following characteristic values apply to design fires:

| | | Design fire | |
|---|---|---|---|
| | 5 MW | 30 MW | 50 MW |
| $\Delta T_{Brand}$ without extraction | 25 K | 65 K | 90 K |
| $\Delta T_{Brand}$ with smoke extraction | 20 K | 40 K | 65 K |
| $\Delta T_{nat}$ | 10 K | 10 K | 10 K |
| $L_{Brand}$ | 400 m | 800 m | 800 m |
| $\eta_{Brand}$ | 0.85 | 0.75 | 0.75 |

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



### 7.1.2 Limit values for barricading the tunnel

The tunnel shall be barricaded automatically if one of the following conditions applies:

- CO levels $\geq$ 100 ppm for a period exceeding ten minutes
- CO levels $\geq$ 150 ppm
- an extinction coefficient $\geq 12 \cdot 10^{-3} \cdot m^{-1}$ for a period exceeding one minute

The tunnel blockade shall be automatically lifted again if

- CO levels of 90 ppm, or
- an extinction coefficient of $7 \cdot 10^{-3} \cdot m^{-1}$

are fallen short of for a period exceeding one minute and this trend is downwards.

### 7.1.3 Theoretical values for standard operation

a theoretical CO value of 30 ppm
a theoretical value for turbidity of $4 \cdot 10^{-3} \cdot m^{-1}$
These values shall be adapted in line with an economic modus operandi during operation.

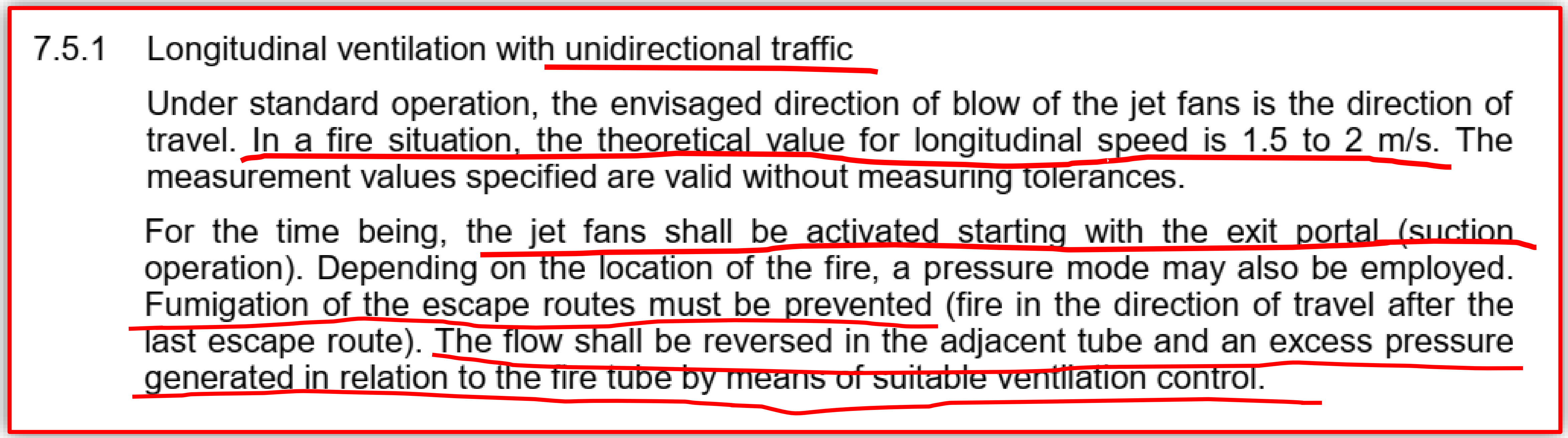
### 7.1.4 Limit values for servicing operation

As regards servicing operations which continue over a longer period, the following limit values must be observed in the ventilation section in question:

| | |
|---|---|
| CO | 20 ppm |
| Turbidity | $3 \cdot 10^{-3} \cdot m^{-1}$ |

Provisions concerned with the protection of workers must be heeded.

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi

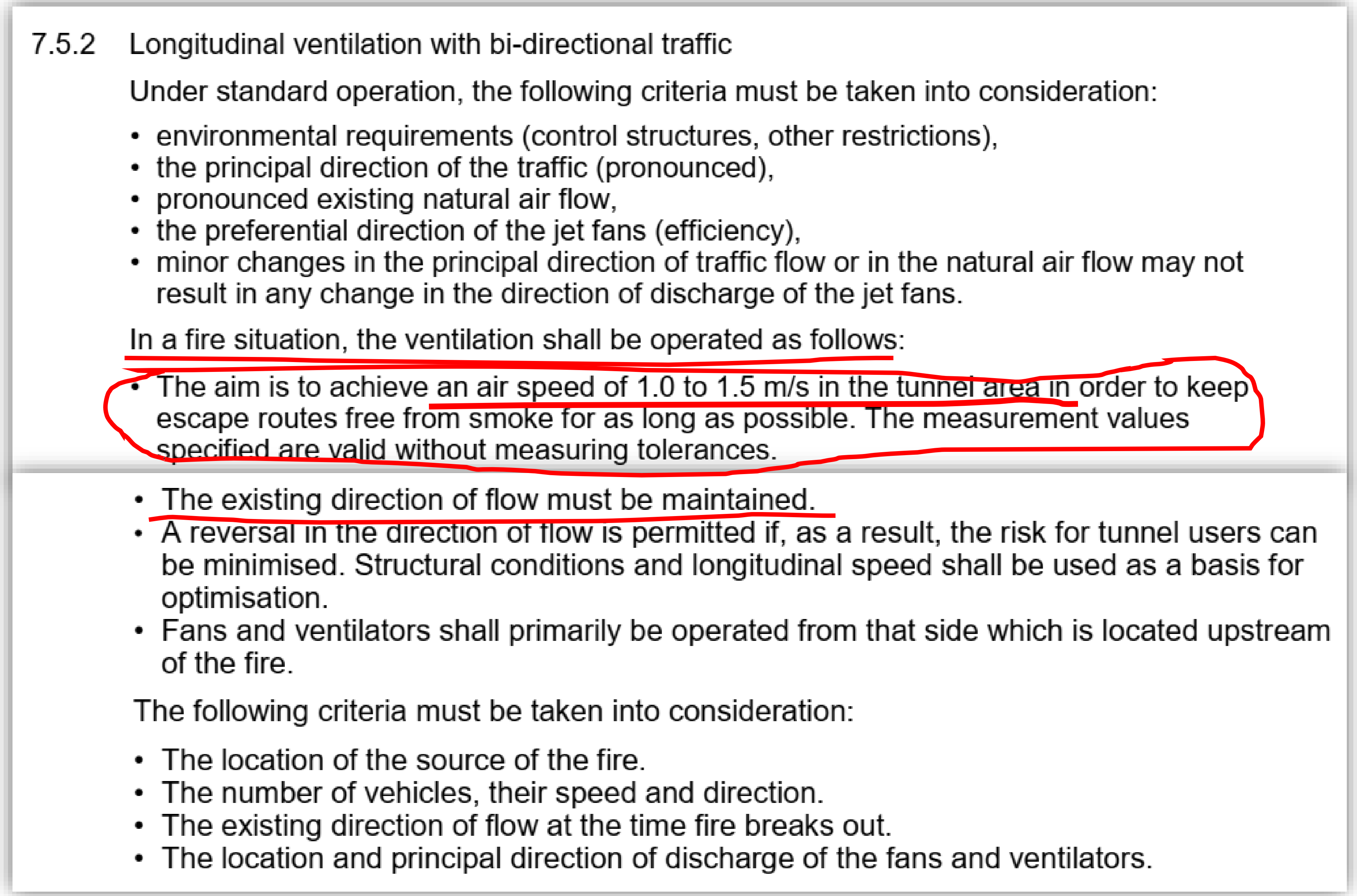


7.5.1 Longitudinal ventilation with unidirectional traffic

Under standard operation, the envisaged direction of blow of the jet fans is the direction of travel. In a fire situation, the theoretical value for longitudinal speed is 1.5 to 2 m/s. The measurement values specified are valid without measuring tolerances.

For the time being, the jet fans shall be activated starting with the exit portal (suction operation). Depending on the location of the fire, a pressure mode may also be employed. Fumigation of the escape routes must be prevented (fire in the direction of travel after the last escape route). The flow shall be reversed in the adjacent tube and an excess pressure generated in relation to the fire tube by means of suitable ventilation control.

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



### 7.5.2 Longitudinal ventilation with bi-directional traffic

Under standard operation, the following criteria must be taken into consideration:

- environmental requirements (control structures, other restrictions),
- the principal direction of the traffic (pronounced),
- pronounced existing natural air flow,
- the preferential direction of the jet fans (efficiency),
- minor changes in the principal direction of traffic flow or in the natural air flow may not result in any change in the direction of discharge of the jet fans.

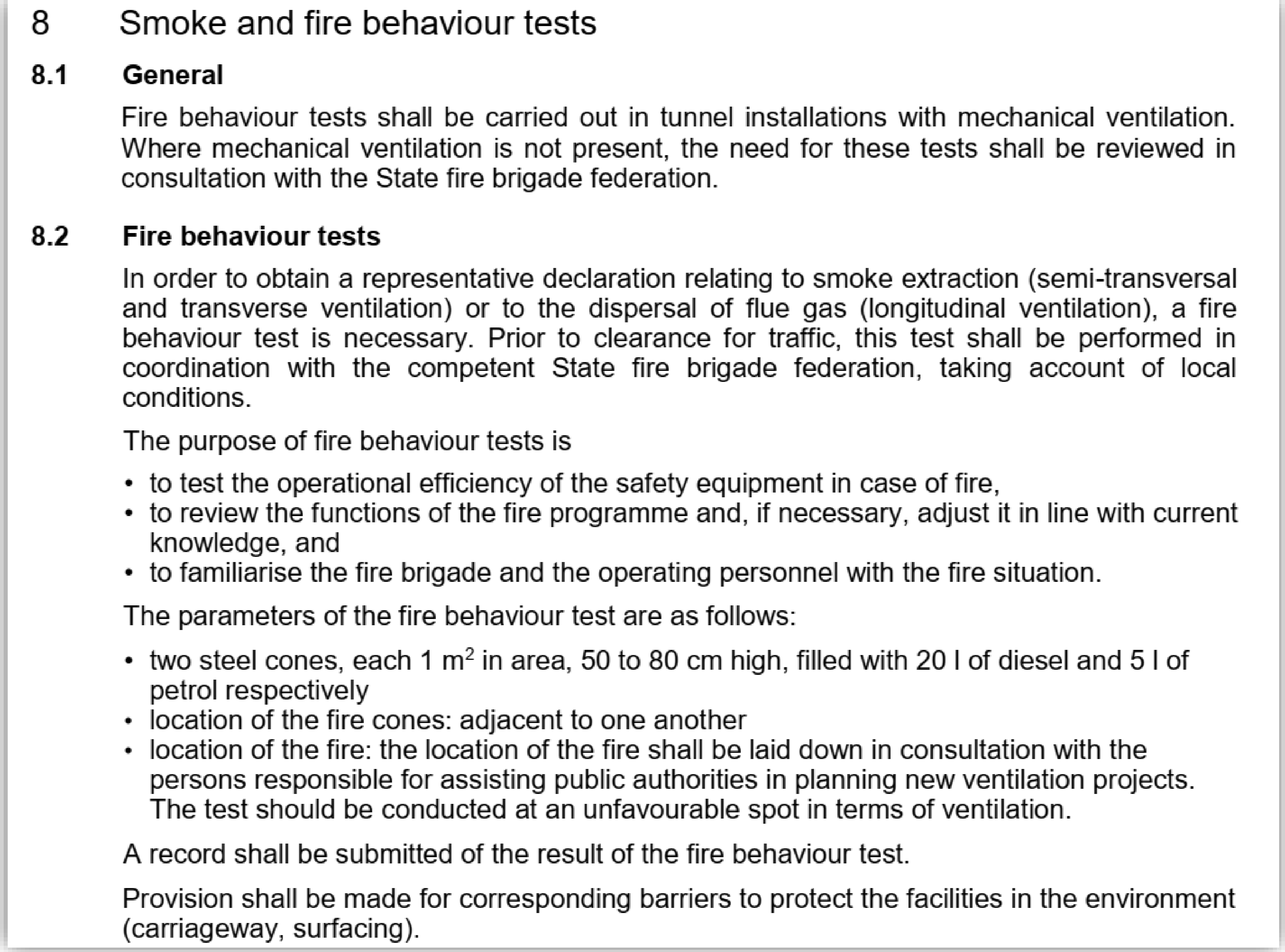
In a fire situation, the ventilation shall be operated as follows:

- The aim is to achieve an air speed of 1.0 to 1.5 m/s in the tunnel area in order to keep escape routes free from smoke for as long as possible. The measurement values specified are valid without measuring tolerances.
- The existing direction of flow must be maintained.
- A reversal in the direction of flow is permitted if, as a result, the risk for tunnel users can be minimised. Structural conditions and longitudinal speed shall be used as a basis for optimisation.
- Fans and ventilators shall primarily be operated from that side which is located upstream of the fire.

The following criteria must be taken into consideration:

- The location of the source of the fire.
- The number of vehicles, their speed and direction.
- The existing direction of flow at the time fire breaks out.
- The location and principal direction of discharge of the fans and ventilators.

# RVS 09.02.31 (2008; 2014): Tuneli, oprema, ventilacija, osnovni principi



## 8 Smoke and fire behaviour tests

### 8.1 General

Fire behaviour tests shall be carried out in tunnel installations with mechanical ventilation. Where mechanical ventilation is not present, the need for these tests shall be reviewed in consultation with the State fire brigade federation.

### 8.2 Fire behaviour tests

In order to obtain a representative declaration relating to smoke extraction (semi-transversal and transverse ventilation) or to the dispersal of flue gas (longitudinal ventilation), a fire behaviour test is necessary. Prior to clearance for traffic, this test shall be performed in coordination with the competent State fire brigade federation, taking account of local conditions.

The purpose of fire behaviour tests is

- to test the operational efficiency of the safety equipment in case of fire,
- to review the functions of the fire programme and, if necessary, adjust it in line with current knowledge, and
- to familiarise the fire brigade and the operating personnel with the fire situation.

The parameters of the fire behaviour test are as follows:

- two steel cones, each 1 $m^2$ in area, 50 to 80 cm high, filled with 20 l of diesel and 5 l of petrol respectively
- location of the fire cones: adjacent to one another
- location of the fire: the location of the fire shall be laid down in consultation with the persons responsible for assisting public authorities in planning new ventilation projects. The test should be conducted at an unfavourable spot in terms of ventilation.

A record shall be submitted of the result of the fire behaviour test.

Provision shall be made for corresponding barriers to protect the facilities in the environment (carriageway, surfacing).

Literatura:

1. Austrijske smjernice:
http://www.fsv.at/shop/produktlisteEN.aspx?ID=3197C858-15DE-4517-9EF2-F3B7E22175A4

2. Njemačke smjernice:
https://www.fgsv-verlag.de/

3. PIARC smjernice
https://www.piarc.org/en/activities/PIARC-Directory-Technical-Reports

4. CETU – Francuska:
https://www.cetu.developpement-durable.gouv.fr/textes-de-reference-a1584.html

# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE

## PRORAČUN PADA PRITISKA U TUNELU

Pad pritiska u tunelskoj cijevi predstavlja zbrir internog gubitka pritiska ($\Delta p_i$) uzrokovanog trenjem i lokalnim gubicima, pada pritiska usled klipnog efekta / otpora vozila odn. saobraćaja ($\Delta p_v$) i eksternog gubitka pritiska ($\Delta p_e$) usled aerodinamičke interakcije s okolinom.

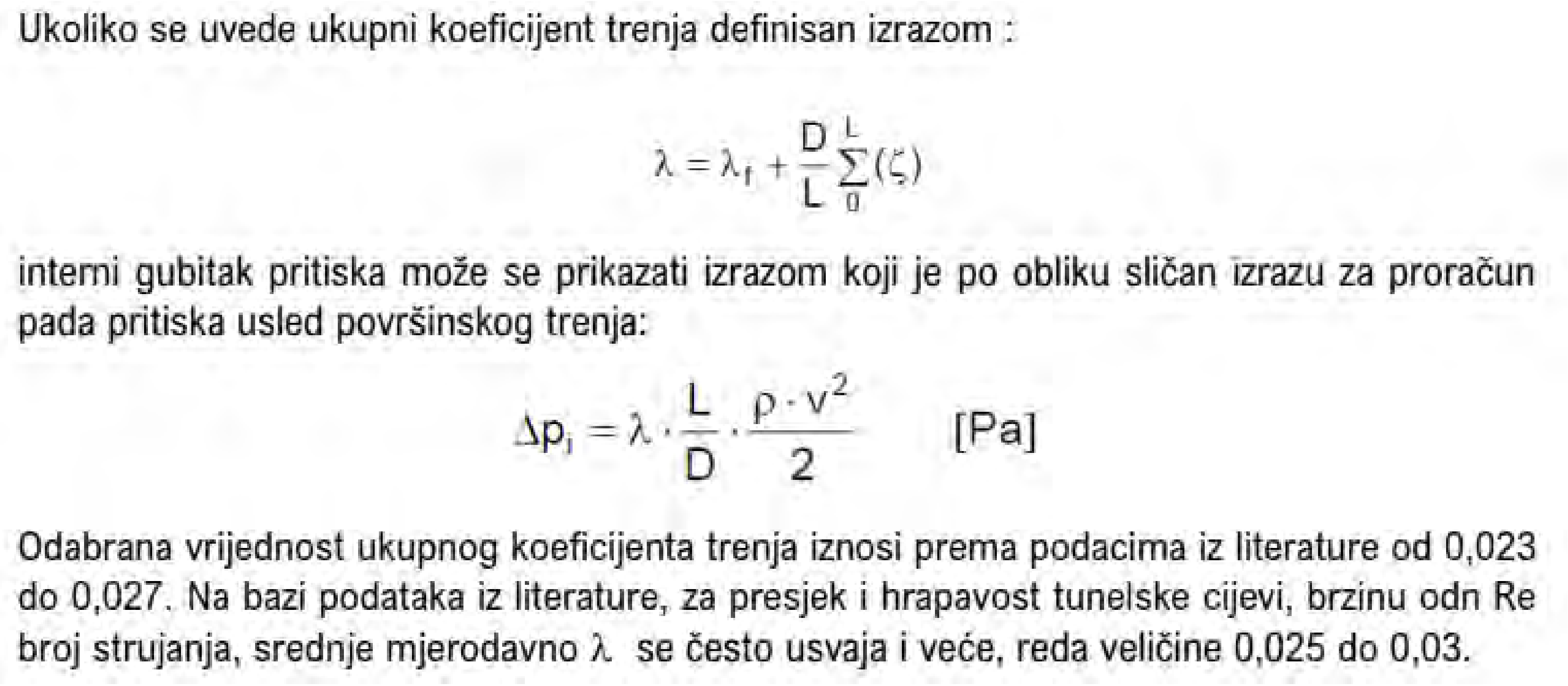
### Interni gubitak pritiska

Strujanje vazduha kroz tunelsku cijev može se opisati kao nestišljivo, jedno-dimenziono, kvazistacionarno strujanje. Stoga se interni gubitak pritiska ($\Delta p_i$) određuje na bazi poznatog izraza za pad pritiska u cijevima:

$$\Delta p_i = \underbrace{\left(\lambda_f \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2}\right)}_{\text{TRENJE}} + \underbrace{\sum_{0}^{L} (\zeta) \cdot \frac{\rho \cdot v^2}{2}}_{\text{LOKALNI GUBICI}} \qquad [\mathrm{Pa}]$$

gdje su :

$\lambda_f$ - Darcy-jev koeficijent površinskog trenja [-],
L - dužina tunela [m],
D - hidraulički prečnik tunelske cijevi [m],
$\rho$ - gustina vazduha [kg/m$^3$],
v - srednja uzdužna brzina vazduha [m/s],
$\zeta$ - koeficijent lokalnog otpora
(proširenja/suženja, rasvjeta, signalizacija, ventilatori i sl.) [-].



Ukoliko se uvede ukupni koeficijent trenja definisan izrazom :

$$\lambda = \lambda_f + \frac{D}{L}\sum_{0}^{L}(\zeta)$$

interni gubitak pritiska može se prikazati izrazom koji je po obliku sličan izrazu za proračun pada pritiska usled površinskog trenja:

$$\Delta p_i = \lambda \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2} \qquad [Pa]$$

Odabrana vrijednost ukupnog koeficijenta trenja iznosi prema podacima iz literature od 0,023 do 0,027. Na bazi podataka iz literature, za presjek i hrapavost tunelske cijevi, brzinu odn Re broj strujanja, srednje mjerodavno $\lambda$ se često usvaja i veće, reda veličine 0,025 do 0,03.

### Pad pritiska uslijed saobraćaja

Kretanje vozila u tunelskoj cijevi izaziva složene aerodinamične efekte koji imaju neposredan uticaj na iznos i distribuciju pritiska u tunelskoj cijevi.

Najznačajnija pojava je tzv. ***"efekat klipa"*** koji predstavlja indukciju kretanja vazduha u tunelu izazvanu prolazom vozila pri povećanoj brzini vožnje. Pojava spomenutog efekta, koji ustvari predstavlja sumu svih aksijalnih sila koja vozila prilikom vožnje prenose na okolni vazduh, se u uslovima dvosmjernog saobraćaja, približno istog protoka vozila, praktično (približno) poništava odn anulira, dok u tunelu jednosmjernog saobraćaja efekat klipa u regularnom radu može biti dovoljan za provjetravanje tunela odn. obezbijediti brzinu višestruko veću od potrebne za provjetravanje. U režimu požara, zbog zaustavljanja vozila uzvodno od mjesta požara a napuštanja tunela onih vozila koja su to mjesto prošla, efekat klipa odumire od trenutka zastoja do konačnog anuliranja.

U uslovima požarnog incidenta pretpostavlja se da su sva vozila zaustavljena - vozila predstavljaju čisti nepokretni aerodinamični otpor usled smanjenja slobodnog poprečnog presjeka tunela, a određuje se prema izrazu:

$$\Delta p_V = n \cdot \frac{(c_w \cdot A)_{veh}}{A_T} \cdot \frac{1}{2} \cdot \rho \cdot v^2 \qquad \text{[Pa]}$$

gdje su :

**Eksterni pad pritiska**

Eksterni gubitak pritiska predstavlja kombinaciju djelovanja različitih efekata izvan tunelske cijevi kao što su :

a) portalni gubici pritiska, tj. pad pritiska ulaza i izlaza vazduha iz tunelske cijevi,
b) gubici pritiska uslijed konverzije statičkog pritiska u dinamički i obrnuto, neposredno uz portale tunela,
c) efekat dimnjaka,
d) otpor samog požara,
e) uticaj lokalnih vjetrova,
f) uticaj meteoroloških parametara (barometarske razlike).

### a) Portalni gubici pritiska

Definišu se kao lokalni gubici, prema izrazu za lokalni gubitak pritiska na ulazu:

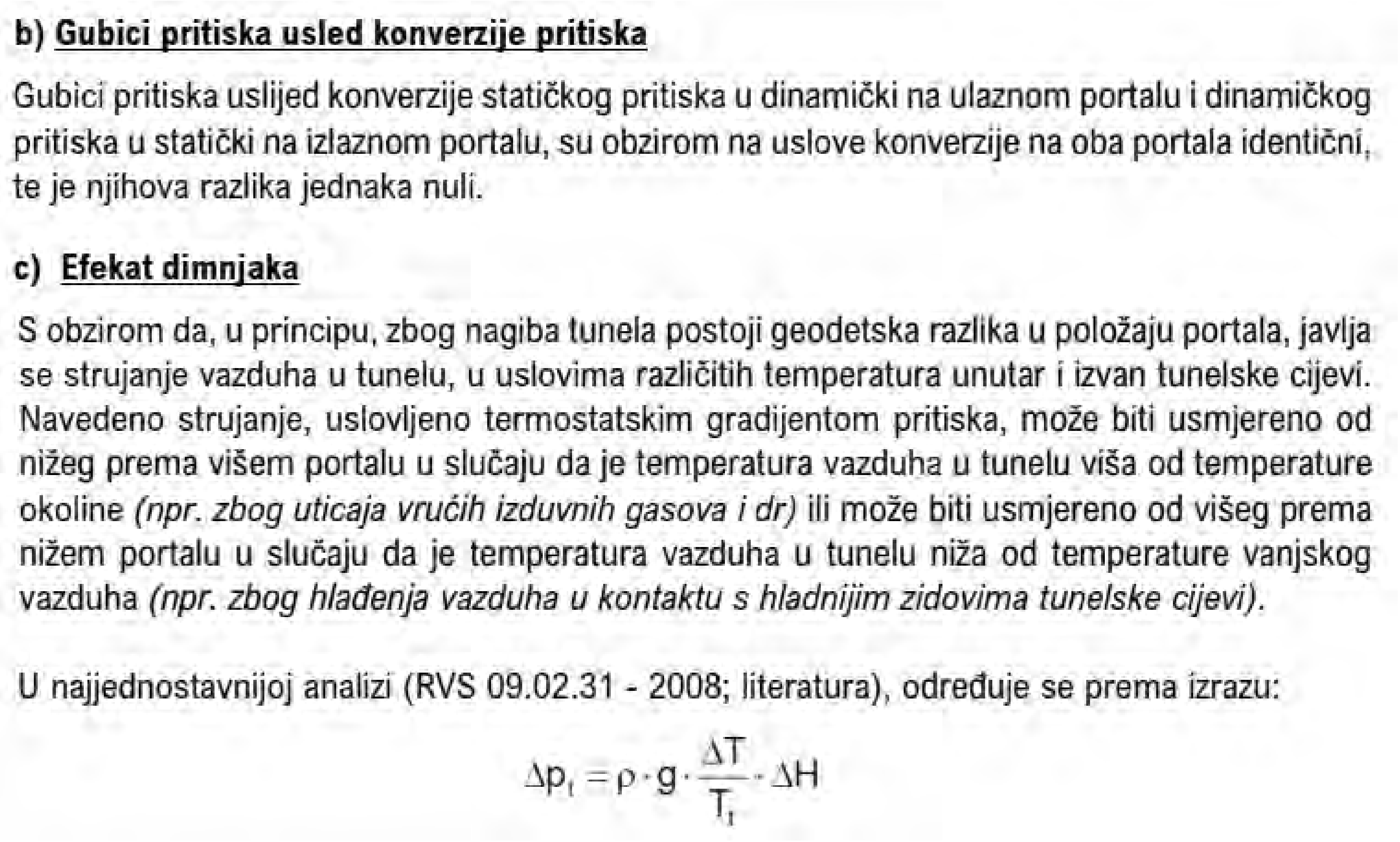
$$\Delta p_{UL} = \zeta_{UL} \cdot \frac{\rho \cdot v^2}{2} \quad [Pa]$$

odnosno, kao lokalni gubitak pritiska na izlazu:

$$\Delta p_{IZL} = \zeta_{IZL} \cdot \frac{\rho \cdot v^2}{2} \quad [Pa]$$

gdje su koeficijenti lokalnih gubitka:

$$\zeta_{UL} = 0,5\ ; \quad \zeta_{IZL} = 1,0$$



**b) Gubici pritiska usled konverzije pritiska**

Gubici pritiska uslijed konverzije statičkog pritiska u dinamički na ulaznom portalu i dinamičkog pritiska u statički na izlaznom portalu, su obzirom na uslove konverzije na oba portala identični, te je njihova razlika jednaka nuli.

**c) Efekat dimnjaka**

S obzirom da, u principu, zbog nagiba tunela postoji geodetska razlika u položaju portala, javlja se strujanje vazduha u tunelu, u uslovima različitih temperatura unutar i izvan tunelske cijevi. Navedeno strujanje, uslovljeno termostatskim gradijentom pritiska, može biti usmjereno od nižeg prema višem portalu u slučaju da je temperatura vazduha u tunelu viša od temperature okoline *(npr. zbog uticaja vrućih izduvnih gasova i dr)* ili može biti usmjereno od višeg prema nižem portalu u slučaju da je temperatura vazduha u tunelu niža od temperature vanjskog vazduha *(npr. zbog hlađenja vazduha u kontaktu s hladnijim zidovima tunelske cijevi)*.

U najjednostavnijoj analizi (RVS 09.02.31 - 2008; literatura), određuje se prema izrazu:

$$\Delta p_t = \rho \cdot g \cdot \frac{\Delta T}{T_t} \cdot \Delta H$$

gdje su :

$\rho$ - gustina vazduha na nižem portalu tunela [kg/m$^3$],
$g$ - gravitaciono ubrzanje 9.81 [m/s$^2$],
$\Delta T$ - razlika srednje ekvivalentne temperature u tunelu i temperature spolj. vazduha na nižem portalu tunela [K],
$T_t$ - srednja temperatura vazduha u tunelu [K],
$\Delta H$ - razlika u geodetskoj visini portala [m].

Egzaktno određivanje termostatskog gradijenta pritiska zahtjeva statistički obrađene meteorološke podatke o vremenskoj distribuciji temperatura u tunelskoj cijevi i na oba portala. U nedostatku ovih podataka, uobičajeno se za proračun pretpostavlja da je maksimalna temperaturna razlika $\Delta T$ = 5-10 K u slučaju redovnog pogona tunela, što je po pravilu, zanemarivo za rezultate proračuna.

S druge strane u uslovima požarnog incidenta dolazi do strujanja vrućih dimnih gasova prema višim dijelovima tunela, što u određenim uslovima može biti nepovoljan smjer. Zato je potrebno dimenzionisati ventilacioni sistem tako da je u mogućnost da savlada i nadpritisak izazvan efektom dimnjaka usled odn. da pokrene dimne gasove smjeru suprotstavljenom efektu dimnjaka.

Nadpritisak izazvan efektom dimnjaka određuje se prema izrazu (vidi RVS 2008):

$$\Delta p_t = \rho \cdot g \cdot \frac{\Delta T}{T_t} \cdot \eta \cdot \Delta H$$

gdje su :

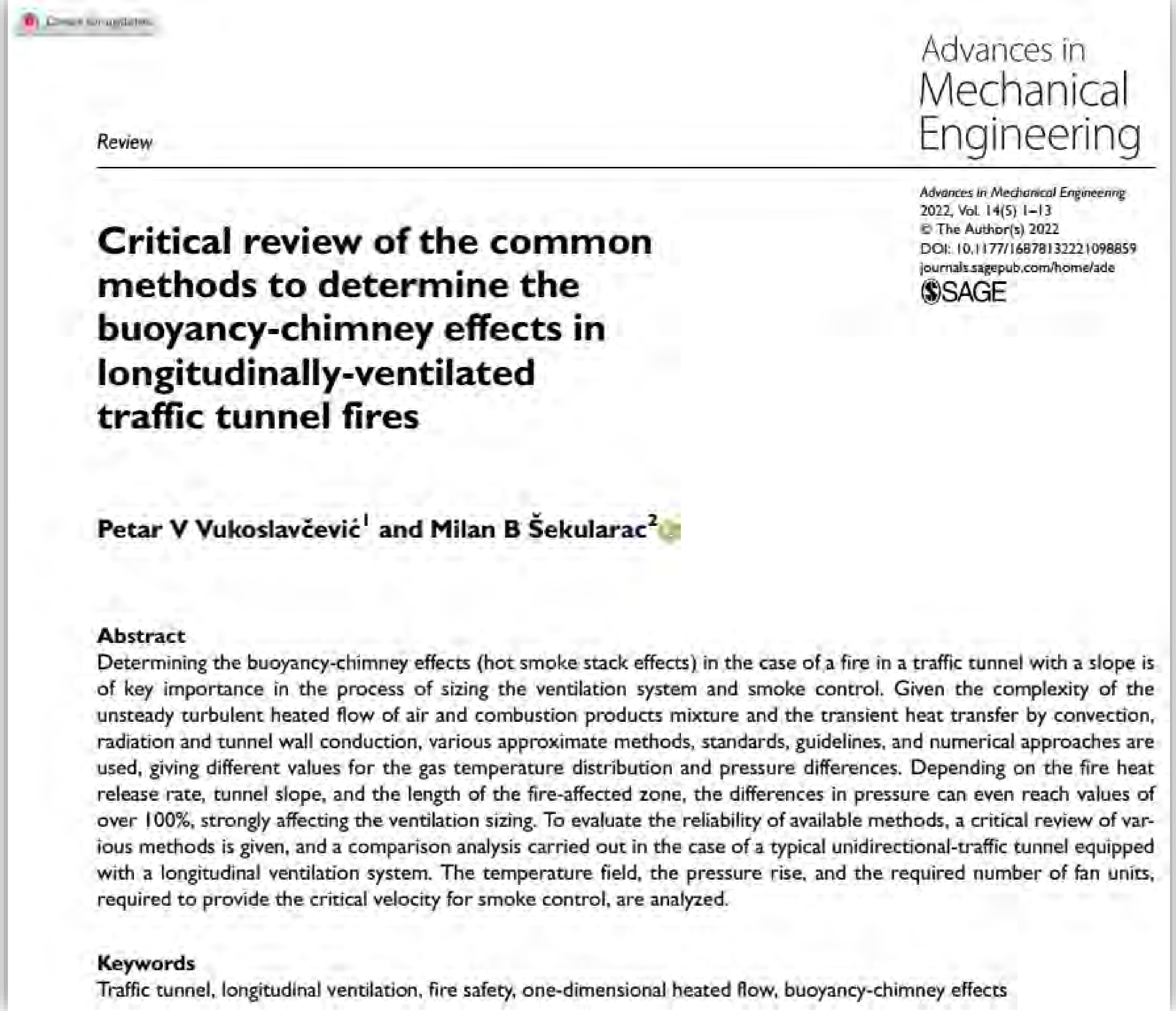
$\rho$ - gustina vazduha na nižem portalu tunela [kg/m$^3$],
g - gravitaciono ubrzanje [m/s$^2$],
$\Delta T$- povećanje srednje temperature u tunelu usled požara [K],
$T_t$ - srednja temperatura vazduha u tunelu [K],
$\Delta H$ - razlika u geodetskoj visini relevantna za efekat dimnjaka [m],
$\eta$ - efekat požara (odnos između stvarnog i teoretskog efekta dimnjaka), iznosi 0,75

Prema istraživanjima obavljenim za potrebe austrijskih smjernica RVS 09.02.31 (2008) na TU Grac (*Technical University of Graz*) za požar od 50 MW povećanje srednje temperature u tunelu na ograničenoj sekciji do max. 800 m iznosi $\Delta T$ = 90 K (Tabela 4) a koeficijent $\eta$=0.75.

**Tabela 4.** Izvod iz RVS 09.02.31: Projektna snaga požara i prosječne temperature dima (tzv $\Delta T_{Brand}$) u tunelskoj cijevi u zavisnosti od mjerodavne dužine tunela (tzv $L_{Brand}$)

| | 5 MW | 30 MW | 50 MW |
|---|---|---|---|
| $\Delta T_{Brand}$ without smoke extraction | 25 K | 65 K | 90 K |
| $\Delta T_{Brand}$ with smoke extraction | 20 K | 40 K | 65 K |
| $\Delta T_{nat}$ | 10 K | 10 K | 10 K |
| $L_{Brand}$ | 400 m | 800 m | 800 m |
| $\eta_{Brand}$ | 0,85 | 0,75 | 0,75 |

# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE



*Review*

Advances in
Mechanical
Engineering

*Advances in Mechanical Engineering*
2022, Vol. 14(5) 1–13
© The Author(s) 2022
DOI: 10.1177/16878132221098859
journals.sagepub.com/home/ade
SAGE

## Critical review of the common methods to determine the buoyancy-chimney effects in longitudinally-ventilated traffic tunnel fires

**Petar V Vukoslavčević[1] and Milan B Šekularac[2]**

**Abstract**
Determining the buoyancy-chimney effects (hot smoke stack effects) in the case of a fire in a traffic tunnel with a slope is of key importance in the process of sizing the ventilation system and smoke control. Given the complexity of the unsteady turbulent heated flow of air and combustion products mixture and the transient heat transfer by convection, radiation and tunnel wall conduction, various approximate methods, standards, guidelines, and numerical approaches are used, giving different values for the gas temperature distribution and pressure differences. Depending on the fire heat release rate, tunnel slope, and the length of the fire-affected zone, the differences in pressure can even reach values of over 100%, strongly affecting the ventilation sizing. To evaluate the reliability of available methods, a critical review of various methods is given, and a comparison analysis carried out in the case of a typical unidirectional-traffic tunnel equipped with a longitudinal ventilation system. The temperature field, the pressure rise, and the required number of fan units, required to provide the critical velocity for smoke control, are analyzed.

**Keywords**
Traffic tunnel, longitudinal ventilation, fire safety, one-dimensional heated flow, buoyancy-chimney effects

Analiza problema određivanja raspodjele srednje temperature gasa i efekta dimnjaka može se naći u preglednom radu u prilogu:
https://doi.org/10.1177/1687813222109885
https://journals.sagepub.com/doi/full/10.1177/16878132221098859

Prezentirani prilaz odn. raspodjelu $T_{avg}(x)$ treba iskoristiti i pri određivanju koeficijenta $\eta_T$

# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE

$$-\dot{m}c_p \frac{1}{P}\frac{dT_{avg}}{dx} = \phi_c + \phi_r,$$

$$\phi_c = h_c\left(T_{avg} - T_w\right)\left(\mathrm{W/m^2}\right),$$

$$\phi_r = \epsilon F\sigma\left(T_{avg}^4 - T_w^4\right)\left(\mathrm{W/m^2}\right),$$

$$\Phi_r = h_r(T_{avg} - T_w),$$

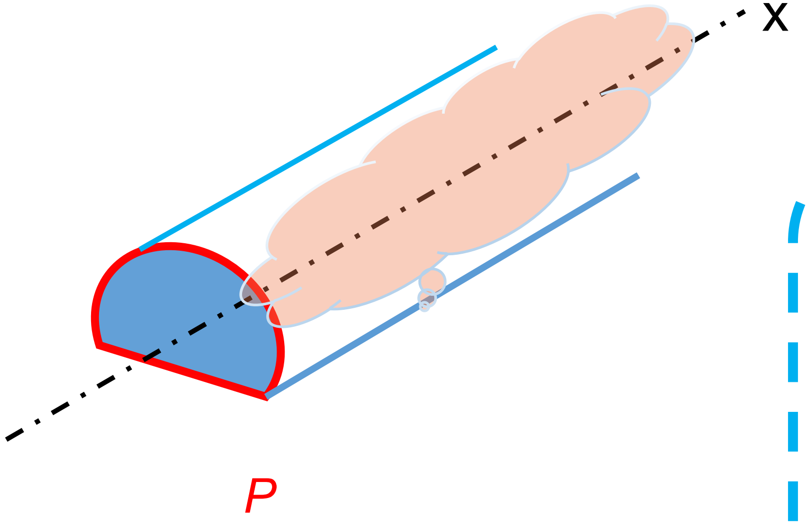
$$h_r = \varepsilon\sigma(T_{avg} + T_w)(T_{avg}^2 + T_w^2).$$

$$h_{cr} = h_c + h_r,$$

$$h_{crc} = \frac{\phi_c + \phi_r}{T_{avg} - T_\infty},$$

$$-\dot{m}c_p \frac{1}{P}\frac{dT_{avg}}{dx} = h_{cr}\left(T_{avg} - T_w\right)$$

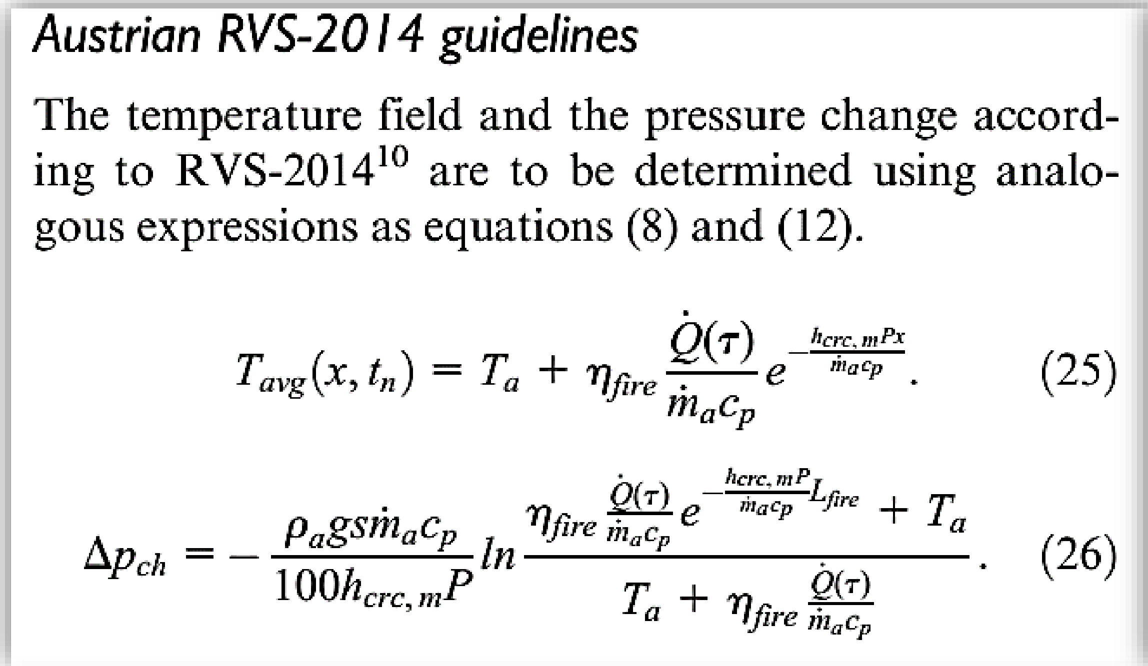
$$\Delta p_{ch} = \int_0^L (\rho_a - \rho)g\frac{s}{100}dx = \int_0^L \rho_a\left(1 - \frac{T_a}{T_{avg}(x)}\right)g\frac{s}{100}dx,$$



$$T_{avg}(x,t) = T_\infty + [T_{max} - T_\infty]e^{-\frac{h_{crc,m}Px}{\dot{m}_a c_p}},$$

$$T_{max} = T_a + \frac{2}{3}\frac{\dot{Q}_{(\tau)}}{\dot{m}_a c_p},$$

$$\Delta p_{ch} = -\frac{\rho_a g s \dot{m}_a c_p}{100 h_{crc,m} P} ln \frac{\frac{2}{3}\frac{\dot{Q}(\tau)}{\dot{m}_a c_p}e^{-\frac{h_{crc,m}P}{\dot{m}_a c_p}L} + T_a}{T_a + \frac{2}{3}\frac{\dot{Q}(\tau)}{\dot{m}_a c_p}}.$$

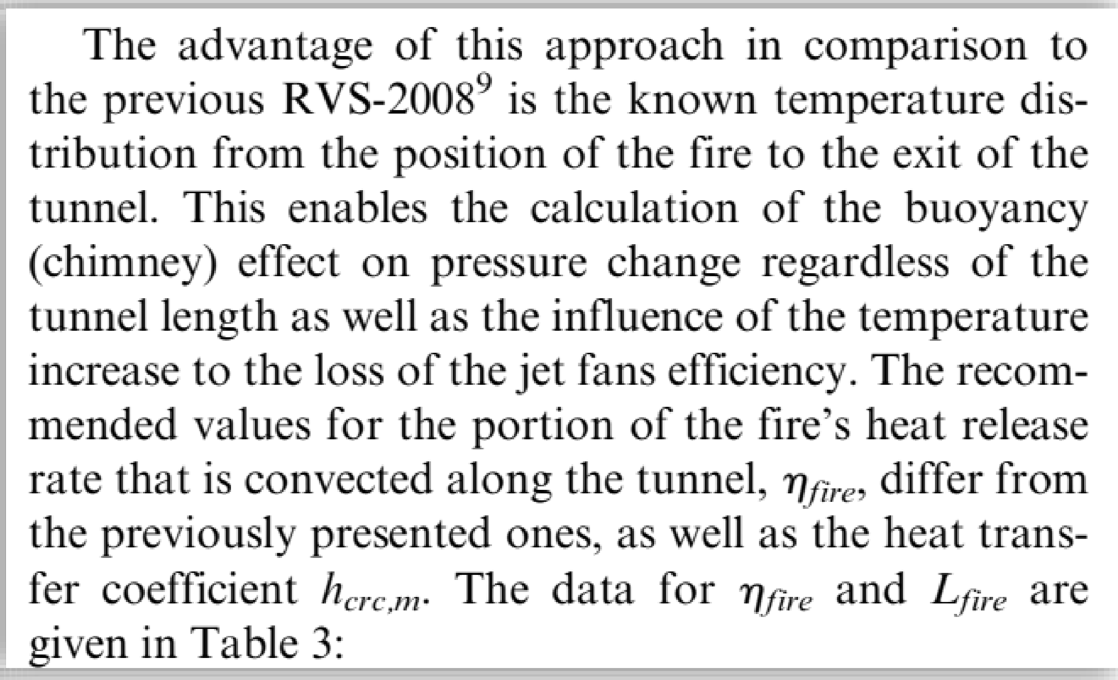


## Austrian RVS-2014 guidelines

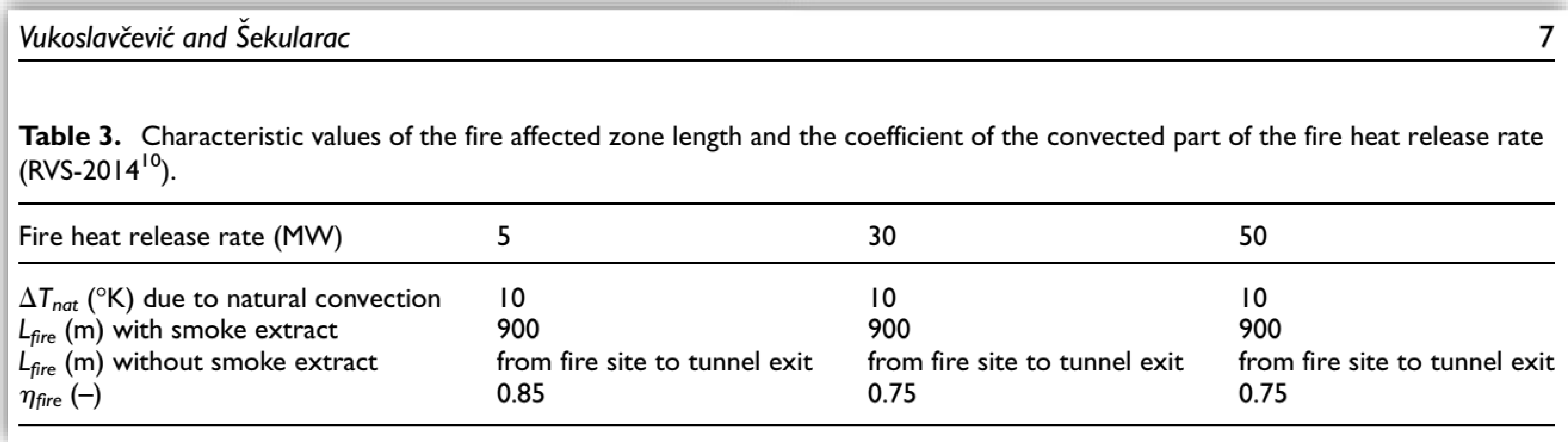
The temperature field and the pressure change according to RVS-2014[10] are to be determined using analogous expressions as equations (8) and (12).

$$T_{avg}(x,t_n) = T_a + \eta_{fire}\frac{\dot{Q}(\tau)}{\dot{m}_a c_p}e^{-\frac{h_{crc,m}Px}{\dot{m}_a c_p}}. \qquad (25)$$

$$\Delta p_{ch} = -\frac{\rho_a g s \dot{m}_a c_p}{100 h_{crc,m}P}\,ln\,\frac{\eta_{fire}\frac{\dot{Q}(\tau)}{\dot{m}_a c_p}e^{-\frac{h_{crc,m}P}{\dot{m}_a c_p}L_{fire}} + T_a}{T_a + \eta_{fire}\frac{\dot{Q}(\tau)}{\dot{m}_a c_p}}. \qquad (26)$$



The advantage of this approach in comparison to the previous RVS-2008[9] is the known temperature distribution from the position of the fire to the exit of the tunnel. This enables the calculation of the buoyancy (chimney) effect on pressure change regardless of the tunnel length as well as the influence of the temperature increase to the loss of the jet fans efficiency. The recommended values for the portion of the fire's heat release rate that is convected along the tunnel, $\eta_{fire}$, differ from the previously presented ones, as well as the heat transfer coefficient $h_{crc,m}$. The data for $\eta_{fire}$ and $L_{fire}$ are given in Table 3:



Vukoslavčević and Šekularac 7

**Table 3.** Characteristic values of the fire affected zone length and the coefficient of the convected part of the fire heat release rate (RVS-2014[10]).

| Fire heat release rate (MW) | 5 | 30 | 50 |
|---|---|---|---|
| $\Delta T_{nat}$ (°K) due to natural convection | 10 | 10 | 10 |
| $L_{fire}$ (m) with smoke extract | 900 | 900 | 900 |
| $L_{fire}$ (m) without smoke extract | from fire site to tunnel exit | from fire site to tunnel exit | from fire site to tunnel exit |
| $\eta_{fire}$ (–) | 0.85 | 0.75 | 0.75 |

## HRR(t) (Q, “heat release rate” – toplotni kapacitet požara u MW)

Tehnike određivanja: “Oxygen consumption calorimetry method”; Mjerenje gubitka mase materijala koji gori poznatog hemijskog sastava. Tretirano brojnim radovima. Može se naći u priručnicima, radovima i smjernicama. U prilogu je CETU kriva HRR(t):

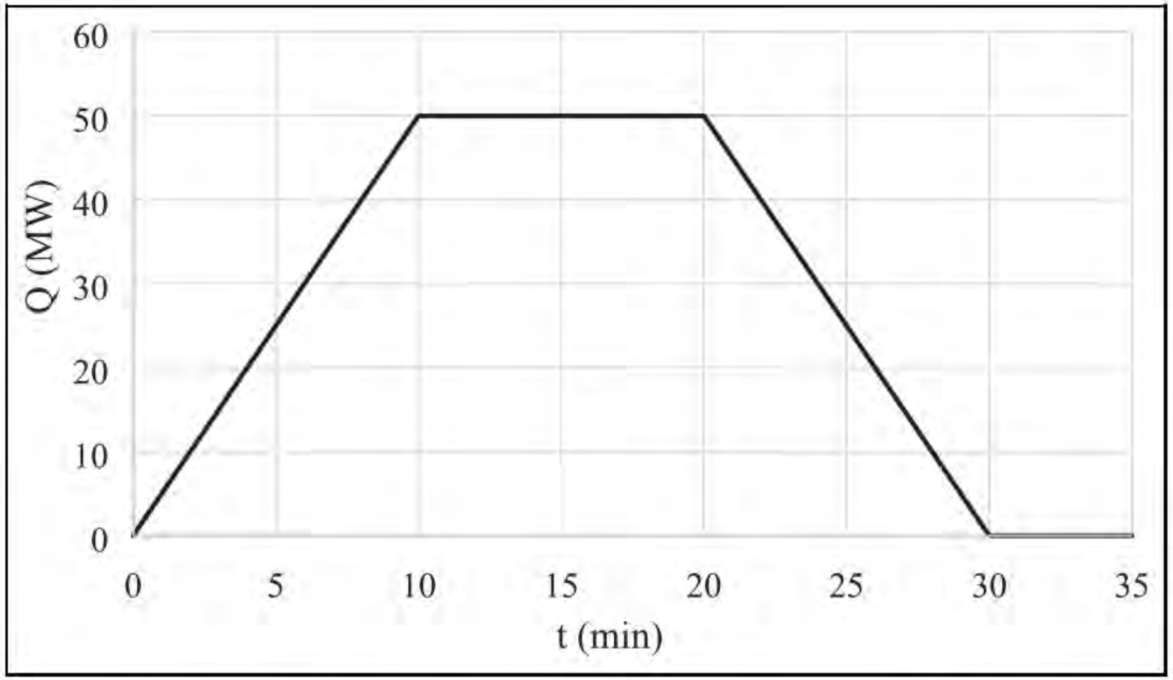


**Figure 1.** The fire heat release rate with respect to time (CETU’s Guide to road tunnel safety documentation,[36] 2003).

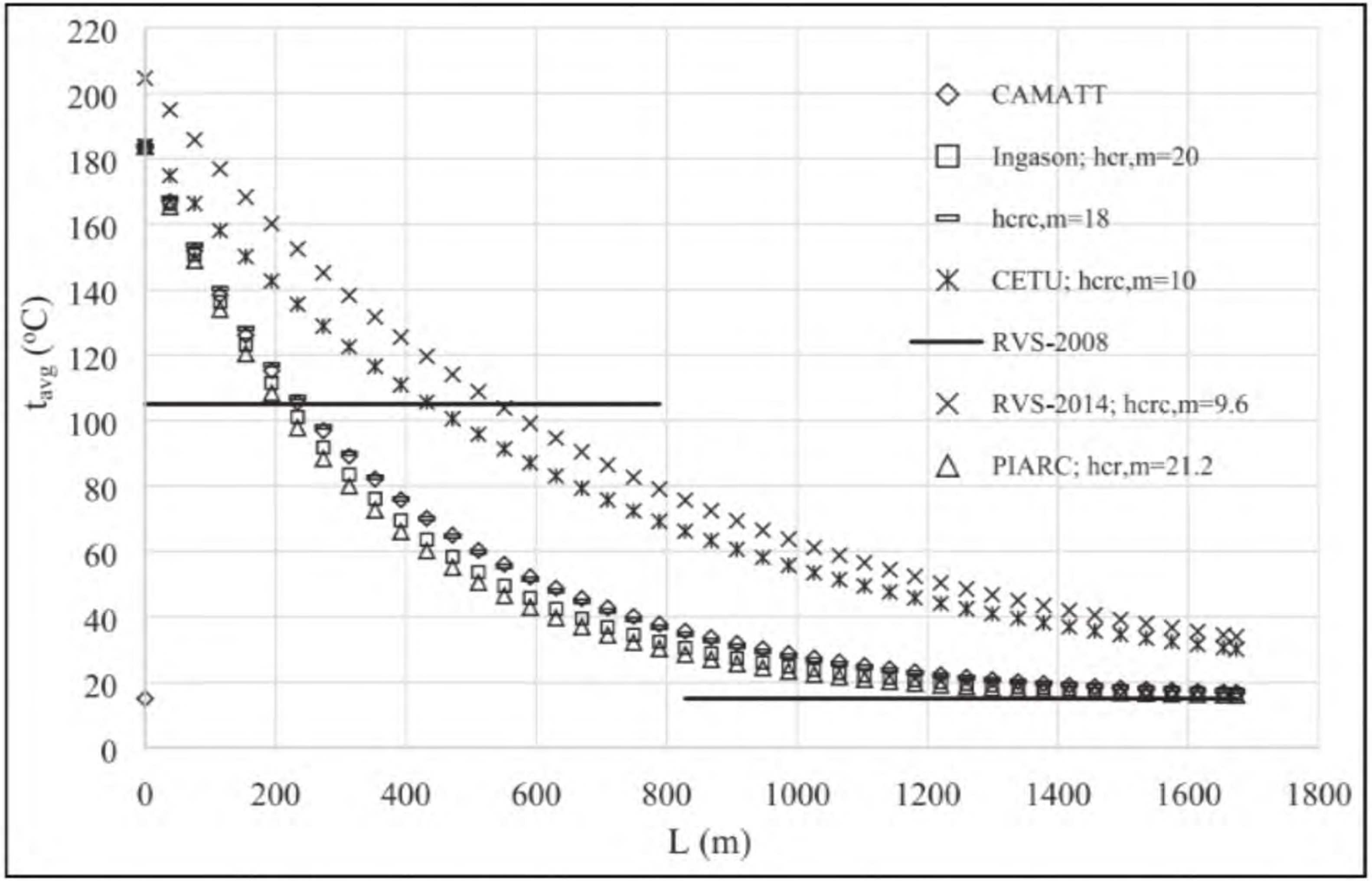
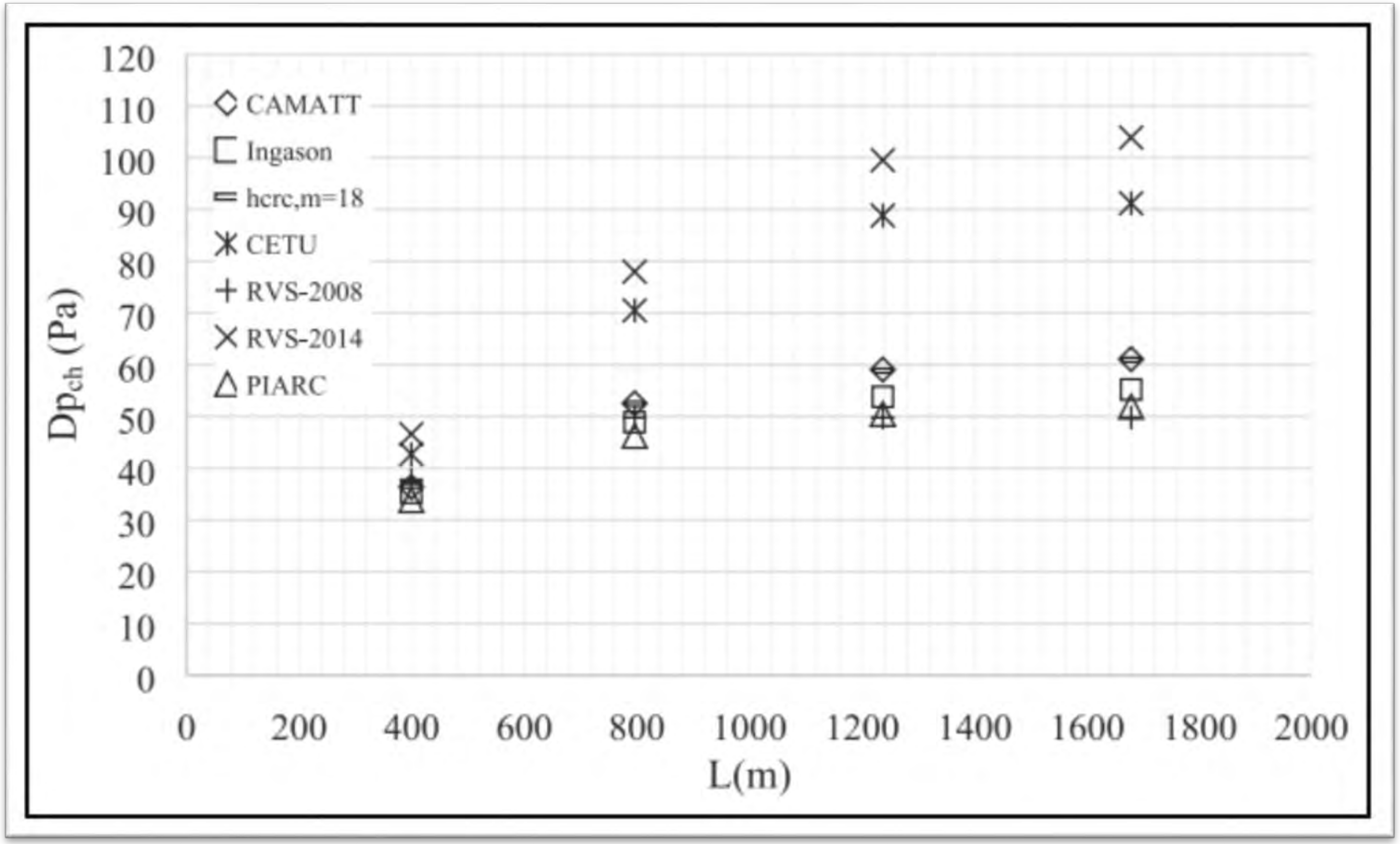


**Figure 2.** Distribution of $T_{avg}$ along the tunnel axis in the case of a fire site 1700 m ahead of tunnel exit in the example tunnel problem.

# *3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE*



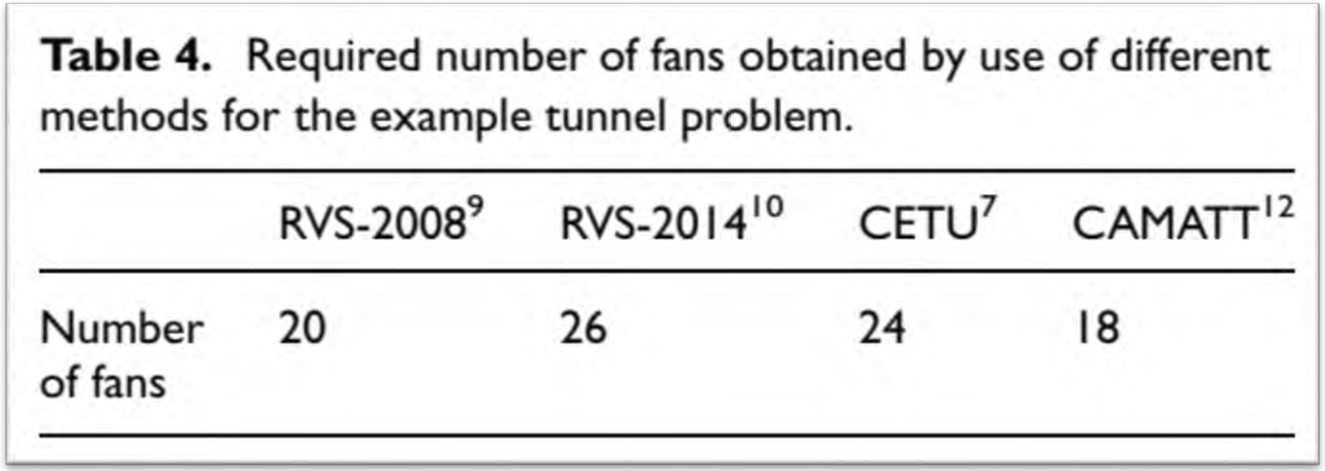


**Table 4.** Required number of fans obtained by use of different methods for the example tunnel problem.

| | RVS-2008[9] | RVS-2014[10] | CETU[7] | CAMATT[12] |
|---|---|---|---|---|
| Number of fans | 20 | 26 | 24 | 18 |

### d) Otpor mjesta požara

Ventilacioni sistem treba, osim brojnih aerodinamičkih otpora da savlada i otpor prolaska vazduha kroz plameno-dimni stub. Radi se o efektu blokiranja, od strane mjesta požara, pri čemu požar svojim djelovanje prigušuje vazdušnu struju.

Postoje brojni numerički izrazi i rezultati simulacija koji potvrđuju da otpor požara iznosi od 0 do 35 Pa za široki raspon požarnih snaga do 100 MW. Može se koristiti izraz prema Dutrieue i Jacques (2006. god.) koji glasi:

$$\Delta p_{fire} = \frac{Q^{0.8} \cdot v^{1.5}}{D_H^{\;1.5}} \cdot C \qquad \text{[Pa]}$$

gdje je:

Q – snaga požara, tzv. HRR [W],

v – brzina vazduha [m/s],

$D_H$ – hidraulički prečnik [m], iznosi $D_H = \frac{4A}{O}$, pri čemu je A površina poprečnog presjeka tunelske cijevi, a O predstavlja obime presjeka tunelske cijevi,

C – empirijska konstanta 41,5 x $10^{-6}$

Za slučaj tunela tipičnih ulaznih podataka koji slijede:

Q – 50 x $10^6$ W (50 MW)
$D_H$ – 7.5 m
C – 41,5 x $10^{-6}$
O = 28 m

otpor požara iznosi:

$$\Delta p_{fire} = 14{,}4 Pa \text{ ,} \quad \text{za brzinu v = 3,0 m/s}$$

### e) Uticaj lokalnih vjetrova

Vjetar može imati uticaj na uslove provjetravanja tunela, bilo da pospješuje ili umanjuje efikasnost mehaničke ventilacije. Po pravilu, sistem mehaničke ventilacije treba da se prilagodi rezultantnom strujanju vazduha uspostavljenom u tunelu i na koji svakako ima pozitivan uticaj djelovanje vjetra na portalima tunela. Ovo je naročito evidentno u tunelu dvosmjernog saobraćaja, gdje se klipni efekti od kretanja vozila u suprotnim trakama približno poništavaju.

Međutim, u slučaju požarnog incidenta (ograničena mogućnost pristupa vatrogasnih i spasilačkih ekipa!), sistem ventilacije određuje smjer strujanja prema kriterijumu trenutnih potreba odimljavanja i u tom slučaju dinamički pritisak vjetra može se pojaviti kao dodatni kontrapritisak kojeg mora savladati sistem ventilacije (prema publikaciji PIARC-a “Fire and Smoke Control in Road Tunnels”, 1999. god., str. 167. i dr izvori). Potrebno je napomenuti da se uticaj vjetrova ne uzima u obzir s ekstremnim pojavnim vrijednostima, već se za sve vrste vjetrova *uzmaju 95%-tne polusatne srednje vrijednosti brzina, mjerene na 4m iznad tla (prema RVS 09.02.31, Poglavlje 6, Aerodinamičko projektovanje).* Egzaktni meteorološki podaci o vjetrovima često nisu dostupni.

Uvidom u literaturu, meteo podatke i projektnu dokumentaciju za 1. fazu autoputa, u dosadašnjoj praksi je uzimano da na portalu tunela duva vjetar brzine 30 km/h (8,3 m/s), paralelno osi tunela ($\varphi_W = 0°$), a koeficijent oblika portala iznosi $c_W = 0,7$. U tom slučaju, na portalu tunela se javlja nadpritisak vjetra ($\Delta p_W$), opisan sledećim izrazom:

$$\Delta p_W = c_W \cdot \frac{\rho \cdot w^2}{2} \cdot \cos\phi_W \qquad \text{Pa}$$

Za gore opisane uslove iznosi: $\approx 30\text{Pa}$

### f) Uticaj meteo razlike pritisaka (barometarski nadpritisak)

Gradijent pritiska koji se može pojaviti zbog razlike barometarskih pritisaka na portalima svedenih na istu visinu, može uticati na formiranje strujanja u tunelu.

Spomenuta razlika pritisaka na portalima pojavljuje se samo kod dužih tunela, koji se nalaze na granici različitih klimatskih zona.

Određivanje ove razlike pritisaka je složeno. Postoje formule dobijene empirijski za alpske uslove. Iskustvo komandnog centra tunela Sozina pokazuje da je prirodna promaja u tunelu nekada (isključena ventilacija, tunel dvosmjernog saobraćaja) reda veličine 1-2m/s ili veća - što govori o značajnim barometarskim razlikama pritisaka između portala!

Ako se tunel nalazi na razmeđu klimatskih zona moguće se razlike pritisaka od reda veličine 100-200Pa i više, što dramatično utiče na dimenzionisanje ventilacije.

Zanemarivanje ovog uticaja može imati dramatične negativne posljedice na bezbjednost tunela u slučaju požara.

Jedini ispravan prilaz su adekvatna meteorološka mjerenja barometarskih pritisaka na pozicijama portala planiranih tunela, prije faze projektovanja ventilacije. Mjerenja se moraju uraditi u trajanju od barem godinu dana, odn. minimalno sezonski (ljeto vs zima) zbog mogućih značajnih razlika.

## Određivanje potrebnog broja ventilatora

Određivanje potrebnog broja aksijalnih ventilatora koji svojim impulsnim djelovanjem indukuju kretanje struje vazduha u tunelu vrši se po formuli:

$$n = \frac{N_{UK}}{N_E}$$

gdje su :

$N_{UK}$ - ukupna sila potiska [N],

$N_E$ - efektivna sila potiska jednog ventilatora [N]

Ukupno potrebna sila potiska NUK (engl. "thrust"), koju treba da ostvari sistem ventilacije, određuje se na bazi izraza:

$$N_{UK} = \Delta p_{UK} \cdot A \quad [N]$$

gdje su :

$\Delta p_{UK}$ -ukupni pritisak koji ventilacioni sistem mora svladati [Pa],

A -poprečni presjek tunelske cijevi [m2].

Potisna sila tipičnog tunelskog ventilatora je obično reda veličine 900-1000 N

Efektivna (iskoristiva) sila potiska pojedinačnog ventilatora u realnim uslovima (regularnog rada) u tunelu, prenesena na struju vazduha po presjeku tunela, je uvijek manja od nominalno deklarisane statičke sile potiska a određuje se izrazom :

$$N_E = N_S \cdot (1 - \frac{u_t}{u_j}) \cdot C_1 \cdot C_2 \cdot C_3 = Ns \cdot k \cdot \eta_i \qquad [N]$$

gdje su:

$N_S$ - statička sila potiska ventilatora prema podacima iz kataloga proizvođača [N],

$k = 1 - u_t / u_j$ – faktor diktiran brzinama (~0.9)

$\eta_i$ - efikasnost prenosa impulsa ($=C_1C_2C_3$ = ~0.70-0.85)

$u_t$ - uzdužna brzina vazduha u tunelu [m/s], određeno izrazom : Q/A

$u_j$ - izlazna (impulsna) brzina mlaza vazduha iz ventilatora [m/s],

$C_1$ - instalacioni faktor, kao funkcija položaja ventilatora unutar ventilatorske baterije, u principu 1,00.

$C_2$ - instalacioni faktor, kao funkcija udaljenosti ventilatora od svoda tunela, red veličine ~ 0,75

$C_3$ - instalacioni faktor, kao funkcija međusobne udaljenosti ventilatora. U principu je ~1 kada je međusobna udaljenost baterija duž tunela, u skladu s preporukom tj. $\geq 100 \times D_V$ (po pravilu ~100m ili više).

Budući da je za dimenzionisanje ventilacije mjerodavan režim požara, ukupnu silu potiska $N_E$ treba pomnožiti i sa koeficijentom iskorišćenja (umanjenja sile potiska) $\eta_T$ po osnovu povišene temperature gasa u tunelu (niže gustine odn masenog protoka gasa kroz ventilatore), koji se sračunava po formuli (PIARC):

$$\eta_T = \frac{\left(\frac{T_0}{T} u_j - u_0\right)}{u_j - u_0} \qquad (*)$$

tj. $$N_E = Ns \cdot k \cdot \eta_i \cdot \eta_T \, ,$$

gdje su:

- $u_j$ brzina mlaza na izlazu iz ventilatora (≈const)
- $u_0$ brzina vazduha u tunelu (kritična brzina za kontrolu dima, u hladnom dijelu tunela, tj. $u_0 = u_{kr} = \sim 2.8 - 3.5$ m/s = const)
- $T$ lokalna srednja temperatura gasa po poprečnom presjeku tunela, tj $T=T(x)$.

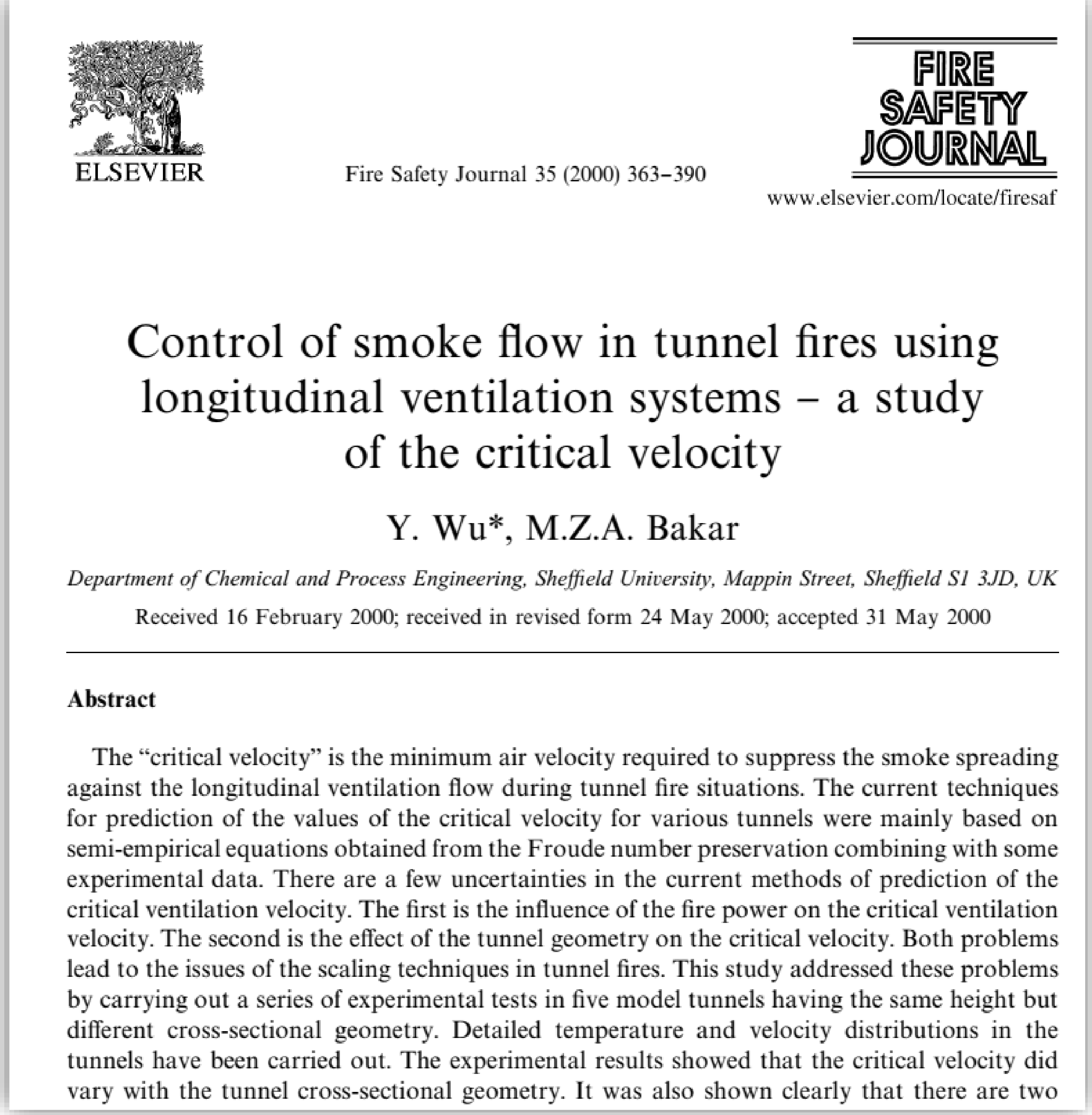
U francuskoj smjernici („Dossier – Pilote“ CETU) može se naći sledeći izraz za $\eta_T$:

$$N_E = \eta_i \cdot Ns \cdot \frac{T_0}{T}\left(1 - \frac{u_0}{u_j}\frac{T}{T_0}\right) \qquad (**)$$

Može se pokazati da je (*) ekvivalentan izrazu (**).

Kritična brzina za kontrolu dima **$u_{cr}$ = f(Q)**

Control of smoke flow in tunnel fires using longitudinal ventilation systems—A study of the critical velocity. November 2000.
Fire Safety Journal 35(4):363-390.
DOI: 10.1016/S0379-7112(00)00031-X



ELSEVIER
Fire Safety Journal 35 (2000) 363–390
FIRE SAFETY JOURNAL
www.elsevier.com/locate/firesaf

# Control of smoke flow in tunnel fires using longitudinal ventilation systems – a study of the critical velocity

Y. Wu*, M.Z.A. Bakar

*Department of Chemical and Process Engineering, Sheffield University, Mappin Street, Sheffield S1 3JD, UK*

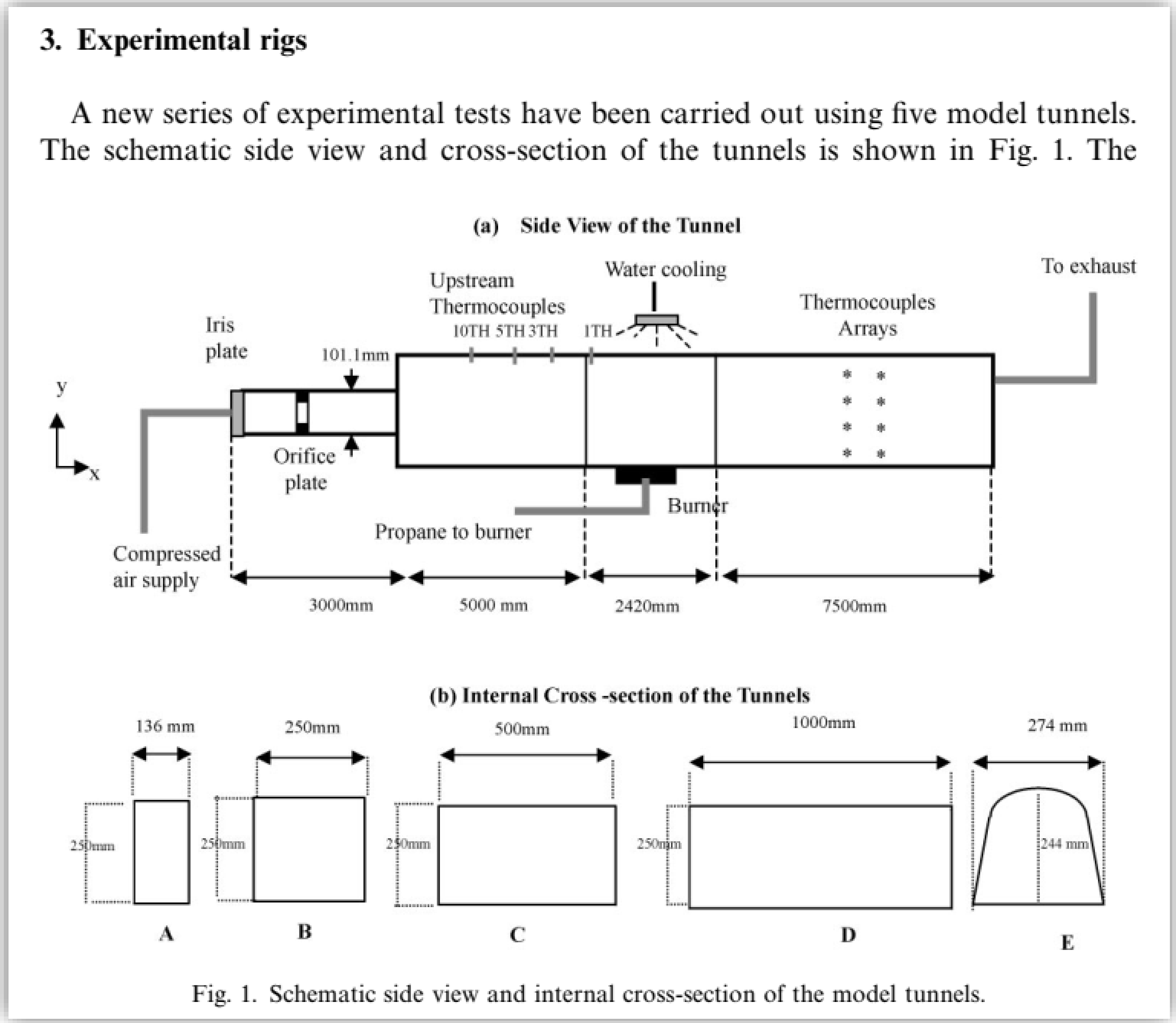
Received 16 February 2000; received in revised form 24 May 2000; accepted 31 May 2000

---

**Abstract**

The "critical velocity" is the minimum air velocity required to suppress the smoke spreading against the longitudinal ventilation flow during tunnel fire situations. The current techniques for prediction of the values of the critical velocity for various tunnels were mainly based on semi-empirical equations obtained from the Froude number preservation combining with some experimental data. There are a few uncertainties in the current methods of prediction of the critical ventilation velocity. The first is the influence of the fire power on the critical ventilation velocity. The second is the effect of the tunnel geometry on the critical velocity. Both problems lead to the issues of the scaling techniques in tunnel fires. This study addressed these problems by carrying out a series of experimental tests in five model tunnels having the same height but different cross-sectional geometry. Detailed temperature and velocity distributions in the tunnels have been carried out. The experimental results showed that the critical velocity did vary with the tunnel cross-sectional geometry. It was also shown clearly that there are two

# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE



## 3. Experimental rigs

A new series of experimental tests have been carried out using five model tunnels. The schematic side view and cross-section of the tunnels is shown in Fig. 1. The

Fig. 1. Schematic side view and internal cross-section of the model tunnels.

# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE

$$Q'' = \frac{Q}{\rho_0 T_0 C_p g^{1/2} \bar{H}^{5/2}}, \quad V'' = \frac{V}{\sqrt{g\bar{H}}}.$$

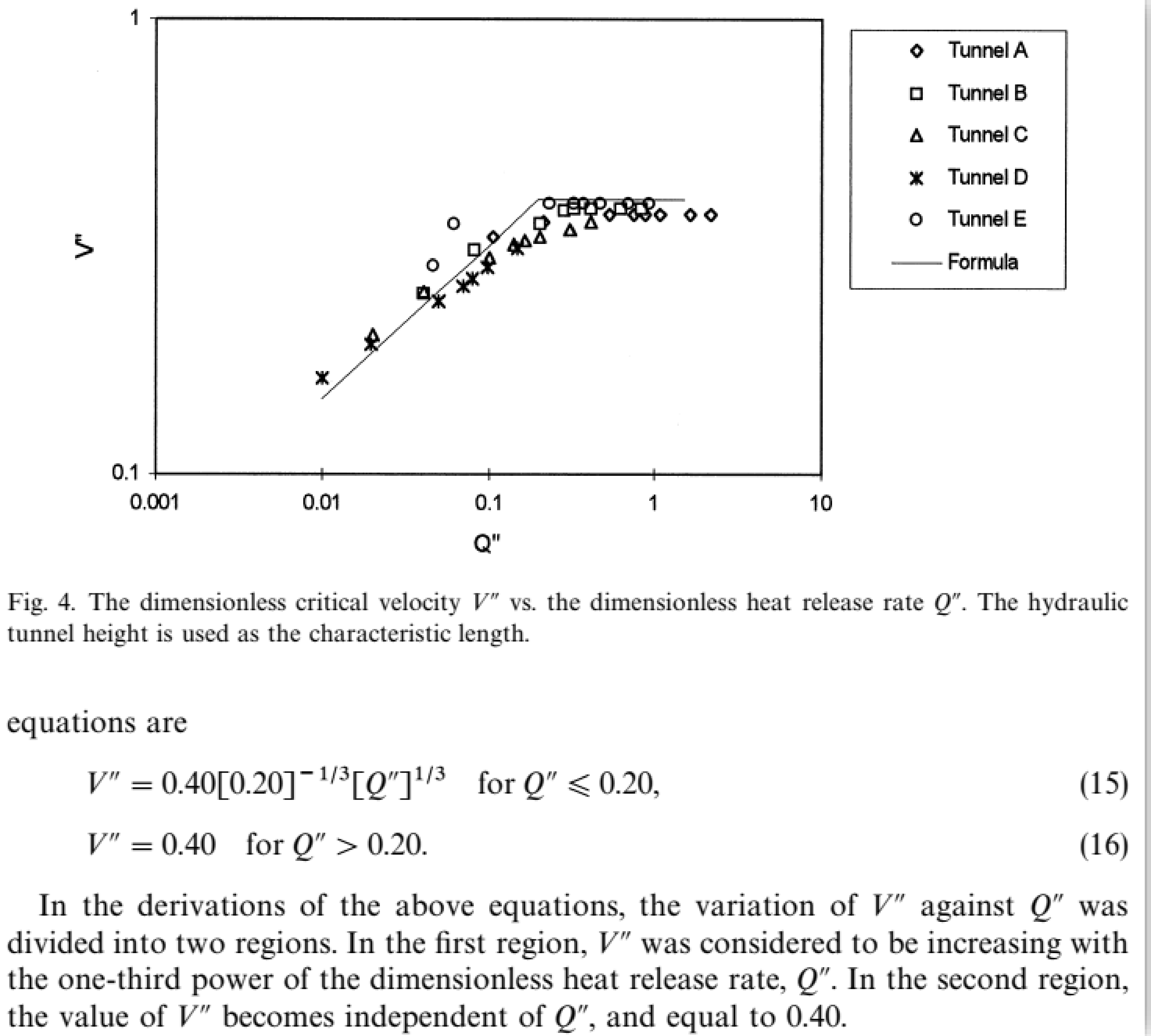


Fig. 4. The dimensionless critical velocity $V''$ vs. the dimensionless heat release rate $Q''$. The hydraulic tunnel height is used as the characteristic length.

equations are

$$V'' = 0.40[0.20]^{-1/3}[Q'']^{1/3} \quad \text{for } Q'' \leqslant 0.20, \tag{15}$$

$$V'' = 0.40 \quad \text{for } Q'' > 0.20. \tag{16}$$

In the derivations of the above equations, the variation of $V''$ against $Q''$ was divided into two regions. In the first region, $V''$ was considered to be increasing with the one-third power of the dimensionless heat release rate, $Q''$. In the second region, the value of $V''$ becomes independent of $Q''$, and equal to 0.40.

# ANALIZA

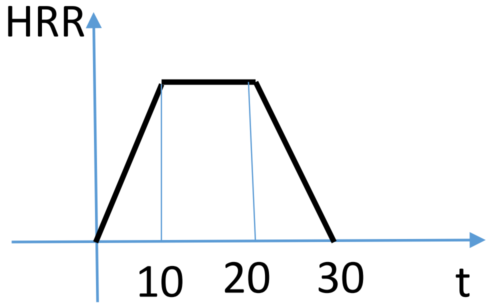
## Numerički primjer

- Ulazni podaci odgovaraju *opštem slučaju tunela jednosmjernog saobraćaja – autoput (CG)*

| Tunnel cross section area $A_t$ [$m^2$] | Considered tunnel length $L_t$ [m] | $D_h$ Tunnel hydraulic diameter[m] | Inflow air velocity: $u_{cr}$ [m/s] | $HRR_{max}$ [MW] | Effective Darcy friction factor $f_D$ | Tunnel wall thermal properties |
|---|---|---|---|---|---|---|
| *55.1* | *800* | *7.7* | *3* | *50* | *0.0275* | $k=1.65$ W/mK<br>$\rho=2400$ kg/m$^3$<br>$c = 920$ J/kgK |

- Prilaz u rješavanju: 1D CFD – CAMATT software $(CETU)^*$

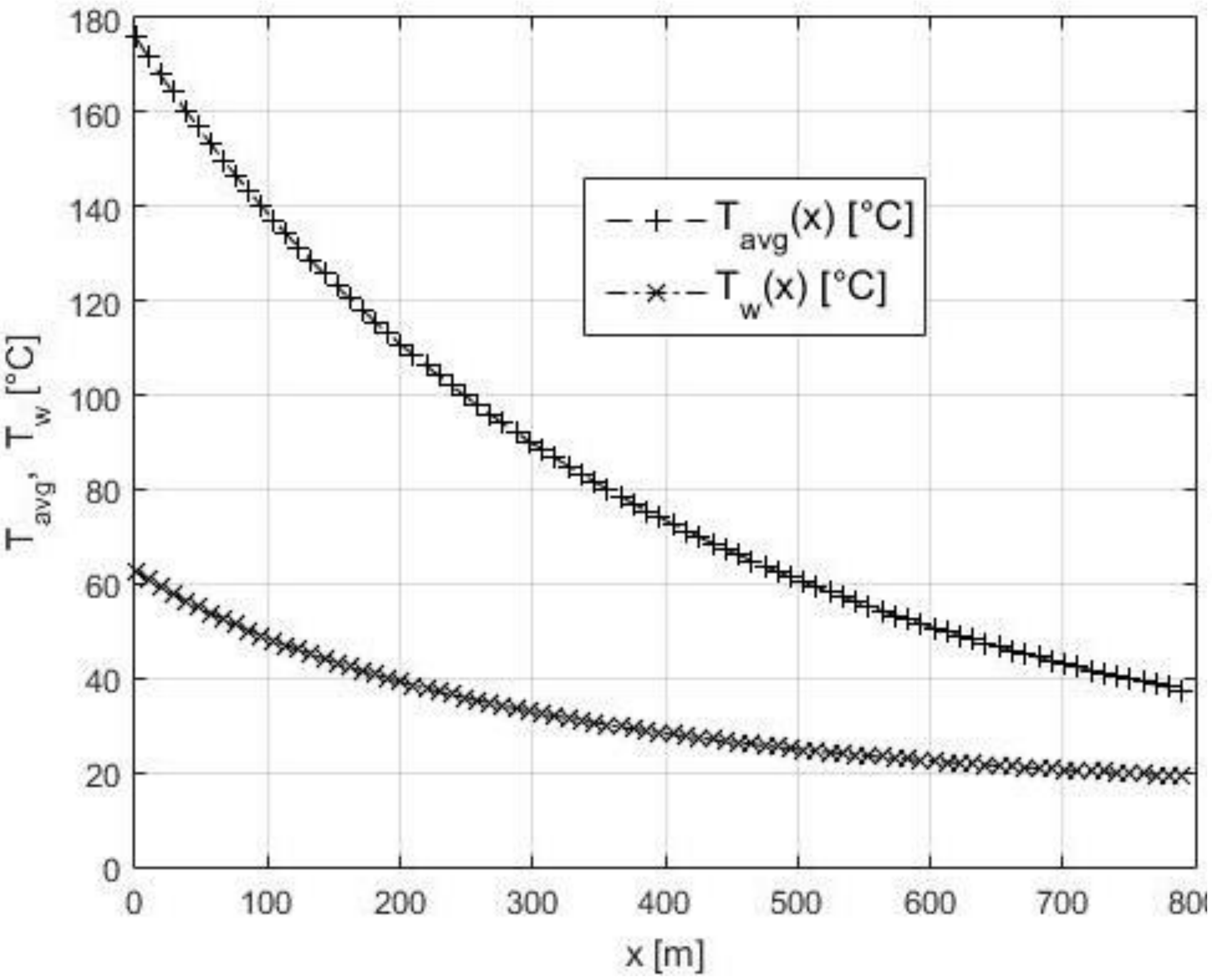
- Rješenje izvezeno za vremenski trenutak: $t=15min$: $T_{avg}(x)$, $T_w(x)$

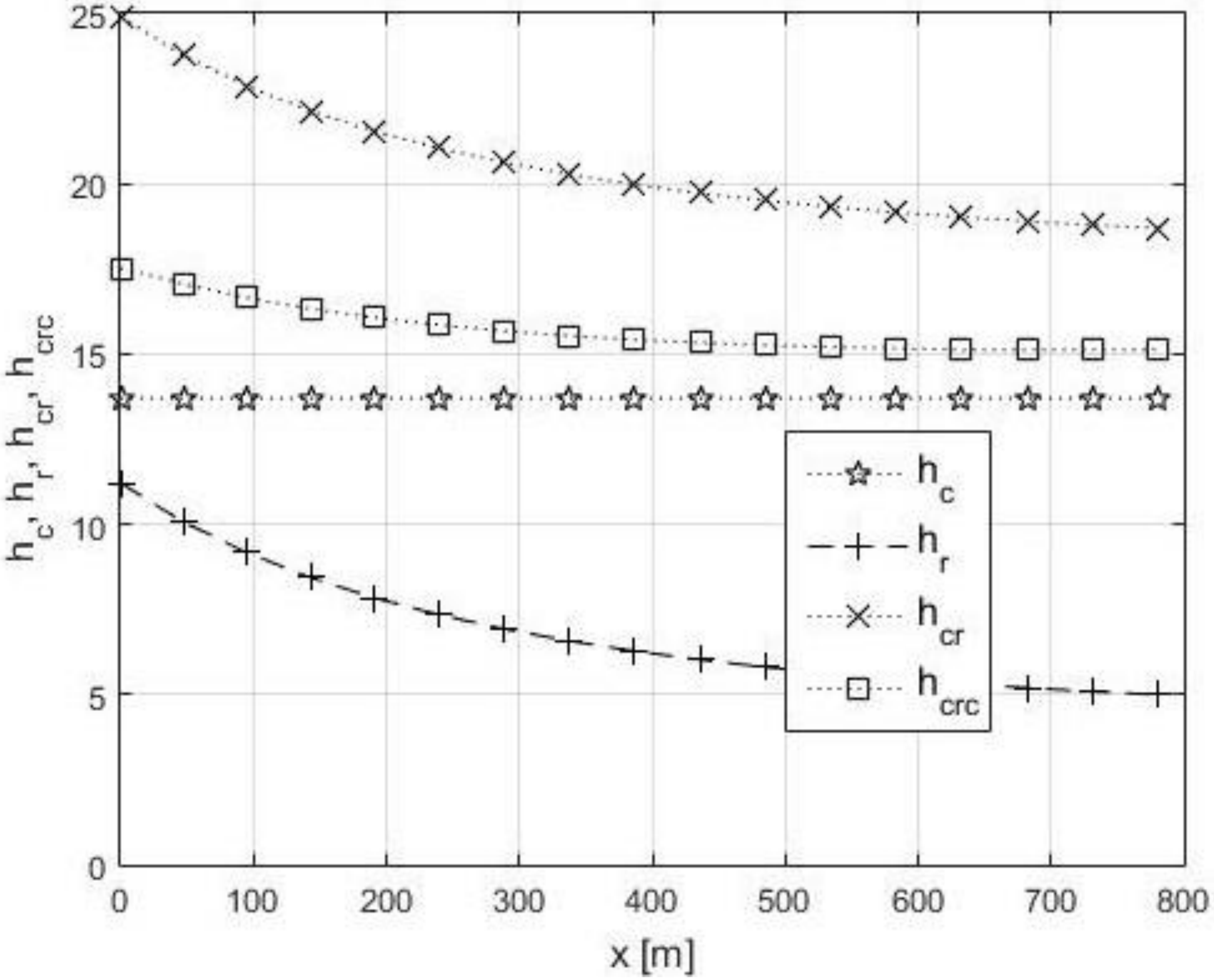


---

*CAMATT 2.20, 2011. Centre d'Etudes des Tunnels, France.

# Numerički rezultat





# SREDNJE VRIJEDNOSTI KOEFICIJENATA PRENOSA TOPLOTE

$$h_{*,m} = \frac{\int_0^L h_*(T_{avg}(x) - T_w(x))P\,dx}{\int_0^L (T_{avg}(x) - T_w(x))P\,dx}, \quad h_* \text{ is: } h_c(\mathrm{x}),\ h_r(\mathrm{x}), \text{ or } h_{cr}(x)$$

$$h_{crc,m} = \frac{\int_0^L h_{crc}(T_{avg}(x) - T_0)P\,dx}{\int_0^L (T_{avg}(x) - T_0)P\,dx}$$

## SRAČUNATE SREDNJE VRIJEDNOSTI ZA $h_c$, $h_r$, $h_{cr}$, $h_{crc}$

| HRR | $h_{c,m}$ | $h_{r,m}$ | $h_{cr,m}$ | $h_{crc,m}$ |
|---|---|---|---|---|
| 50 MW | 13.7 | 7.53 | 21.33 | 16.1 |

## KOEFICIJENT TRENJA I KOEF. KONVEKCIJE – LITERATURNE VRIJEDNOSTI

ULAZNI PODACI ZA NUMERIČKI SLUČAJ (OPŠTI TUNEL):

$Pr=0.7$
$T_0=288K$
$\nu=2.2986\cdot10^{-5}\ \mathrm{m^2/s}$
$k = 0.0316\ W/mK$
$T_m=70°C$
$u_m = 3.57\ m/s$
$Re = 1.33\cdot10^6$
*Absolutna hrapavost: ~ 3-9mm*

⇒ Darcy koeficijent trenja : $f_D = 0.011 \mid 0.016 \mid 0.020$

- Efektivna $f_D$ vrijednost* u tunelima (hrapavi zid) : ***0.023 – 0.026, ili više***

- Usvojeno za numerički primjer tunela - opšteg-slučaja: ***$f_D$ = 0.0275***

*Jang HM and Chen F. On the determination of the aerodynamic coefficients of highway tunnels. *Journal of Wind Engineering and Industrial Aerodynamics* 2002; 90: 869–896.

** Levoni P, Angeli D, Stalio E, et al. Fluid dynamics characterization of the Mont Blanc tunnel by multi-point airflow measurements. *Tunneling and underground space technology* 2015; 48: 110-122.

## VRIJEDNOST KOEF. KONVEKCIJE ZA "GLATKU" TUNELSKU CIJEV *$f_D$=0.011*

General formula: $h_{c,s} = 0.0265 \cdot Re_m^{0.8} \cdot Pr^{0.333} \cdot k_m/D_h = \ldots\ldots\ldots\ldots = 7.58$ W/m$^2$K

Sieder-Tate formula: $h_{c,s} = 0.027 \cdot Re_m^{0.8} \cdot Pr^{0.3} \cdot k_m/D_h \cdot (v_m/v)^{0.14} \ldots\ldots\ldots = 8.11$ W/m$^2$K

Newman formula: $h_{c,s} = 0.026 \cdot Re_m^{-0.2} \cdot (1 + (D_h/1500)^{0.7}) \cdot 1.2 \cdot 1010 \cdot u_m = 7.48$ W/m$^2$K

Petukhov: $h_{c,s} = \dfrac{\frac{f_D}{8} c_p \rho u}{1.07+12.7\left(Pr^{\frac{2}{3}}-1\right)\sqrt{\frac{f_D}{8}}} = \ldots\ldots\ldots\ldots\ldots\ldots = 5.03$ W/m$^2$K

## "HRAPAVA" CIJEV TUNELA – VRIJEDNOST KOEF. KONVEKCIJE:

- **Petukhov** *($f_D$ = 0.0275 ):*.......................................................................................***$h_{c,ro}$***=*13.7 W/m2K*
- **Norris formula*:**

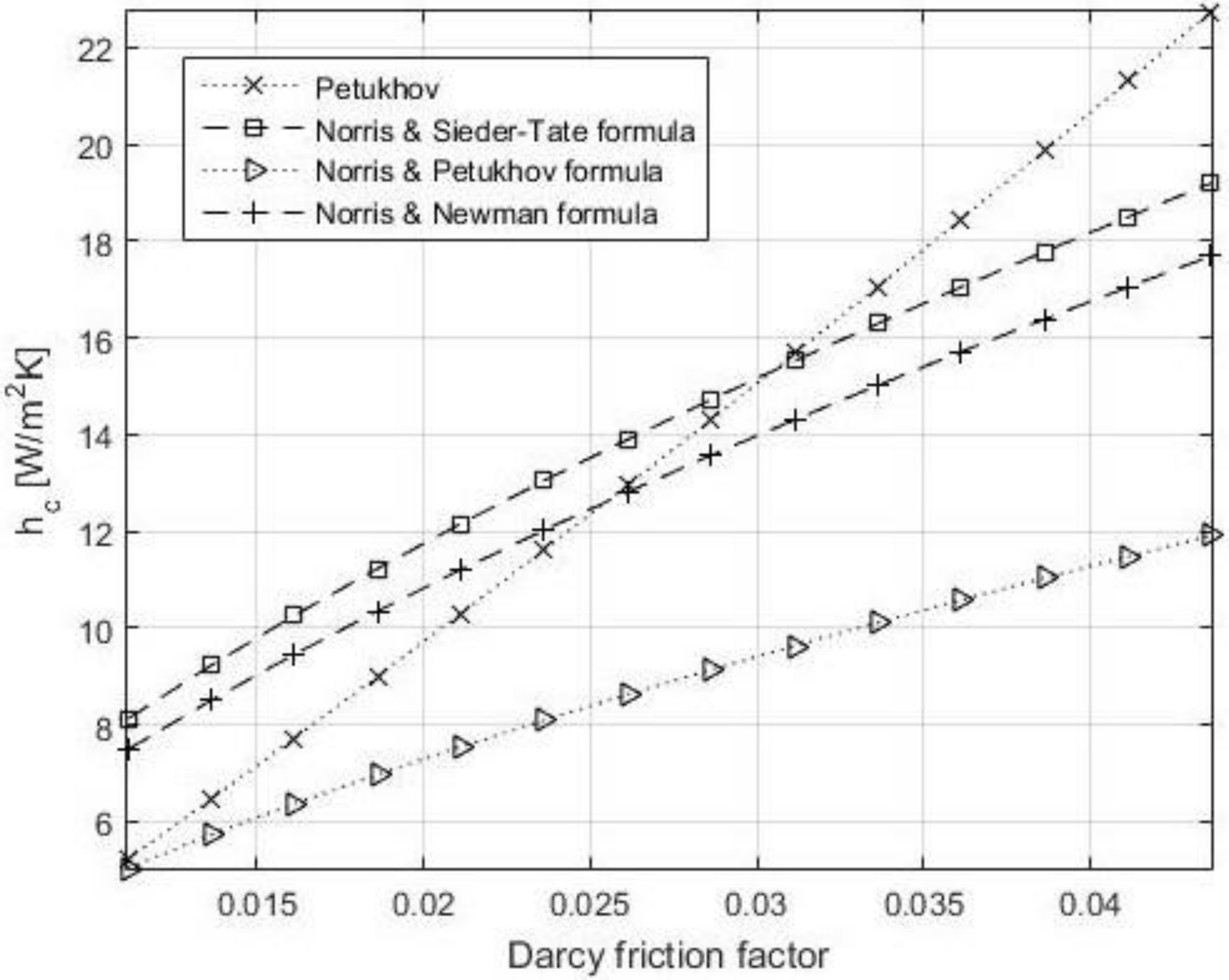
$$h_{c,ro} = h_{c,sm}\left(\frac{f_{D,ro}}{f_{D,sm}}\right)^{n}, n = 0.68 \cdot Pr^{0.215}$$

$h_{c,ro}$ = 14.45 | 8.97 | 13.32 W/m$^2$K ..........................................................

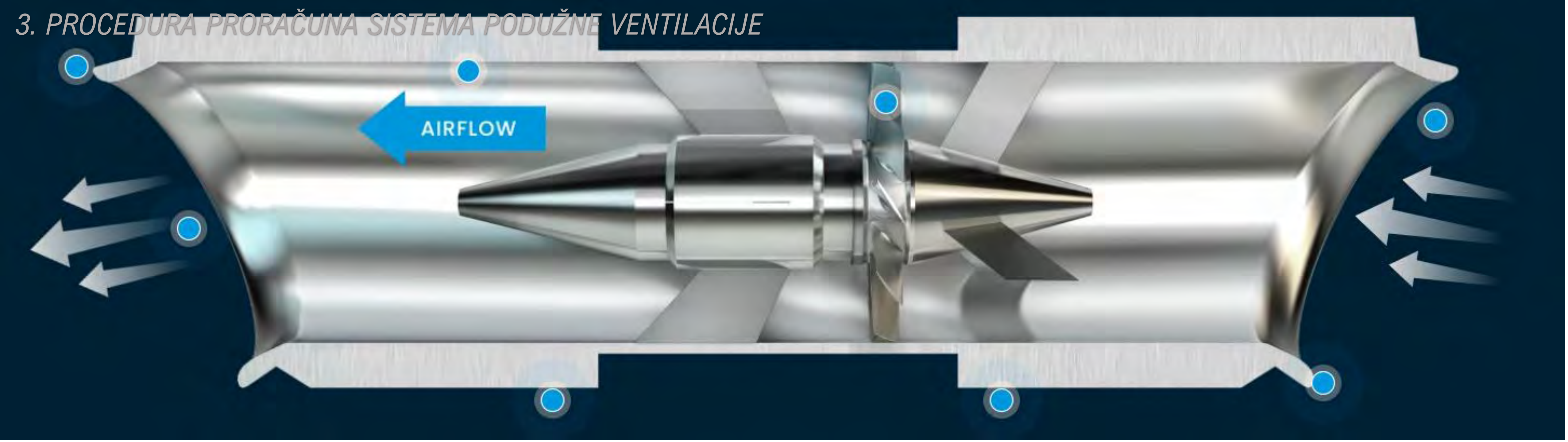
*Shodno relativnoj hrapavosti odgovarajući opseg $f_D$ : $f_D$ = ($f_{D,smooth}$ – 4 $f_{D,smooth}$)*

**Kays WM, and Crawford ME. Convective heat and mass transfer. McGraw – Hill, Inc. 1980. McGraw Hill series in mechanical engineering. ISBN 0-07-033457-9.*

# UTICAJ EFEKTIVNOG DARCY KOEF. TRENJA $f_D$ NA KOEF. KONVEKCIJE $h_c$



## 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE



**1 Reducing the Coanda effect**
*The discharged jet is turned away from the tunnel surfaces, which significantly reduces the proportion of thrust lost due to aerodynamic friction. The MoJet® achieves this by using an inclined trailing edge, and a bellmouth design which improves the flow conditions at the inlet side, while acting as a deflector on the outlet side.*

**2 Static pressure recovery**
*downstream of the fan (due to an increase in silencer cross-sectional area). This means that more thrust is generated using the static pressure at the outlet (which is a reversible, efficient process) rather than the discharge velocity (an irreversible, inefficient process).*

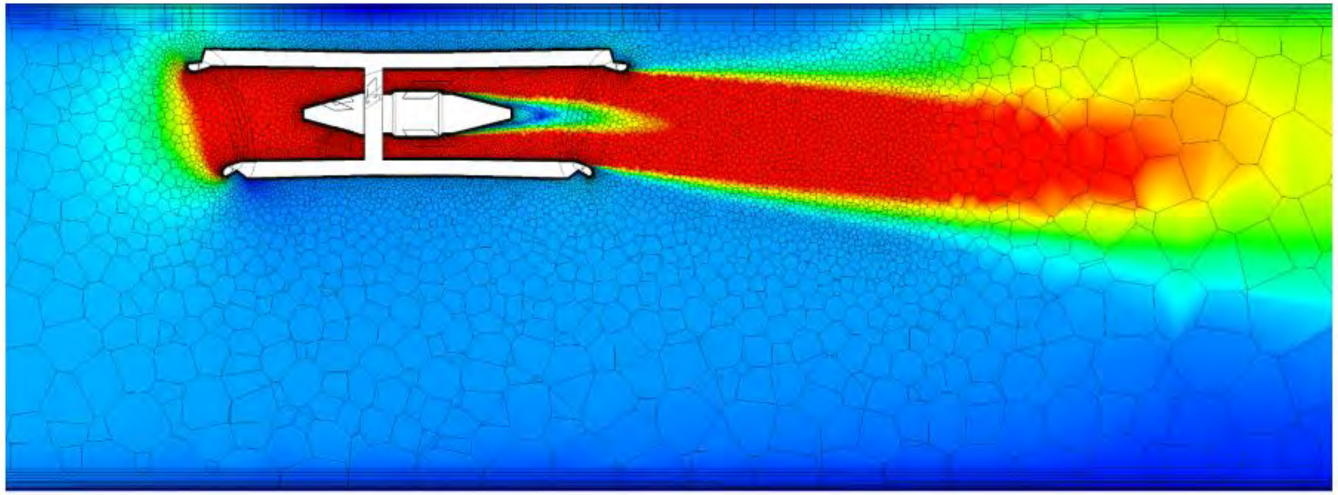
**3 Increased mass flowrate**
*through the fan (due to reduced inlet and outlet pressure drops). The pressure drops at the inlet and outlet are reduced due to the larger cross-sectional areas compared to conventional jetfans.*

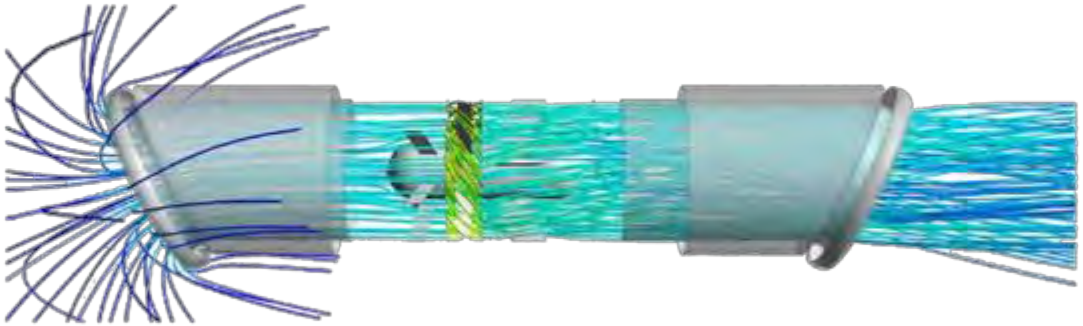
**4 Confining effects of the tunnel soffit on the silencer inlet are reduced**
*because the silencer inlet area is directed away from the tunnel soffit.*

**5 Reduced discharge velocity**
*leading to lower shear stress at the tunnel soffit immediately downstream of the MoJet®.*

**Izvor: MoJet (Fathi Tarada): https://mojet.global/**

## 3D CFD Calculations





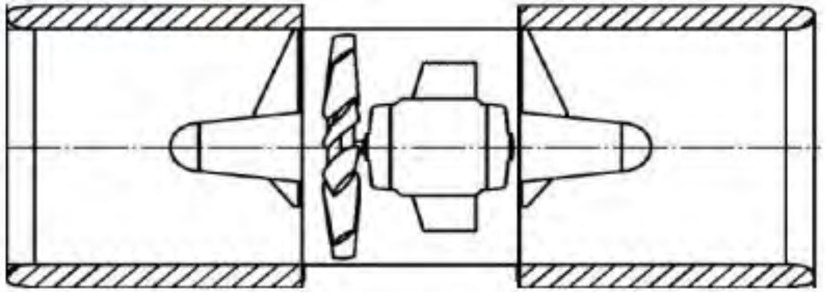
Confirmation of the additional thrust, on the basis of ANSYS Fluent modelling.

**Izvor: https://mojet.global/**

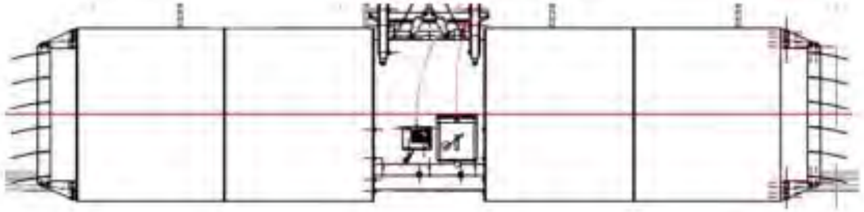
***Izvor:***
[***https://mojet.global/***](https://mojet.global/)

[redacted]

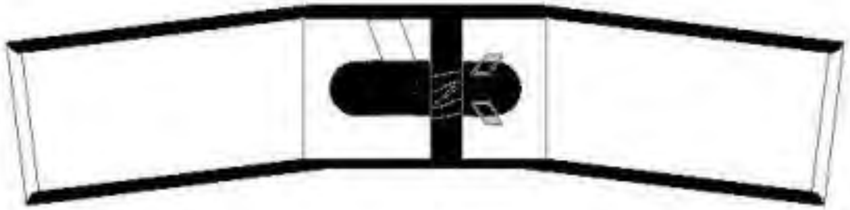
# Jet Fan Technologies



Conventional jet fan



Jet fan with deflectors



Slanted silencers

Shaped nozzles

Oldest

Most recent

Izvor skice: Road tunnel fire safety and risk: a review
Gehandler Fire Science Reviews (2015) 4:2
DOI 10.1186/s40038-015-0006-6

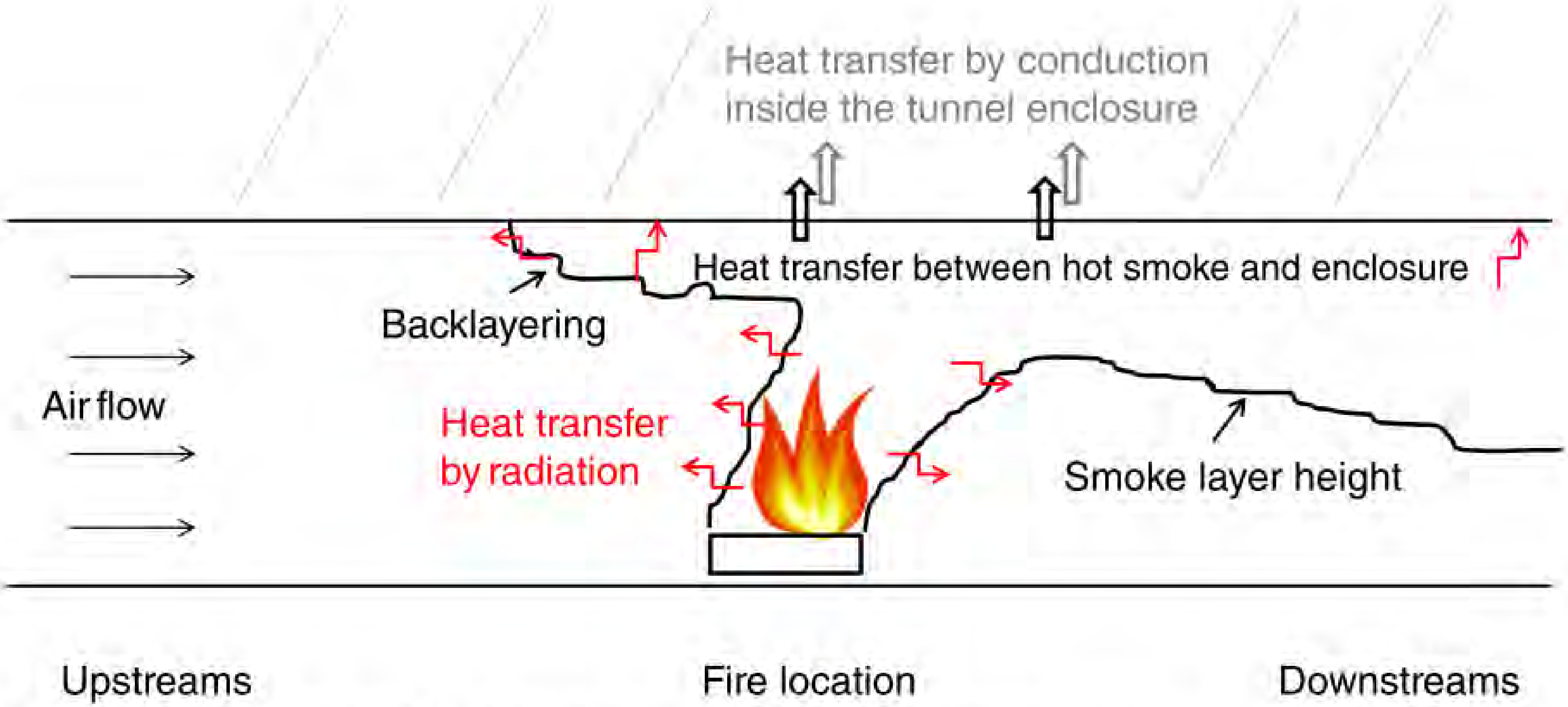
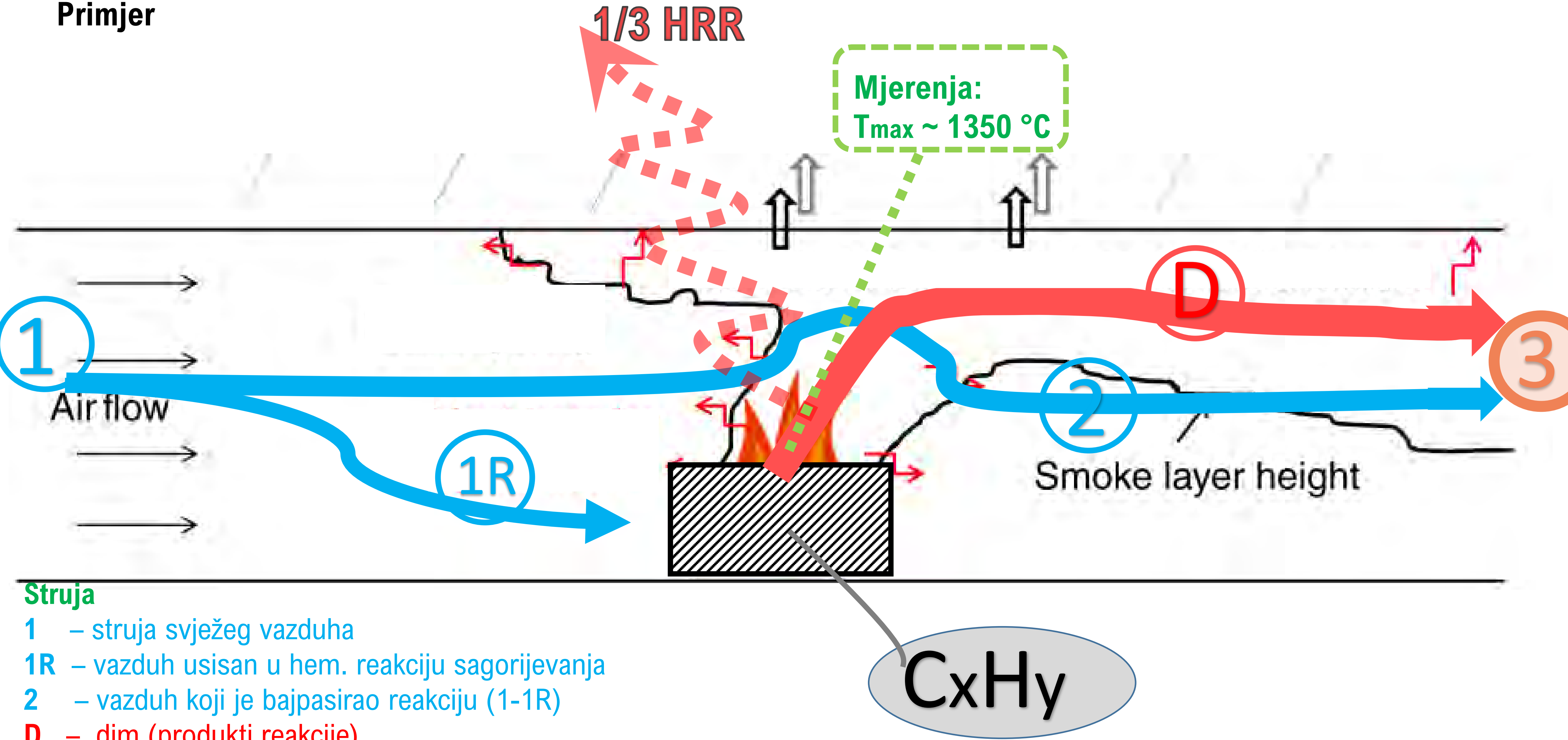


**Figure 1** A schematic diagram over a tunnel fire introducing several important terms.

**Primjer**



**Struja**

**1** – struja svježeg vazduha

**1R** – vazduh usisan u hem. reakciju sagorijevanja

**2** – vazduh koji je bajpasirao reakciju (1-1R)

**D** – dim (produkti reakcije)

**3** – konačna smješa po uništenju stratifikacije

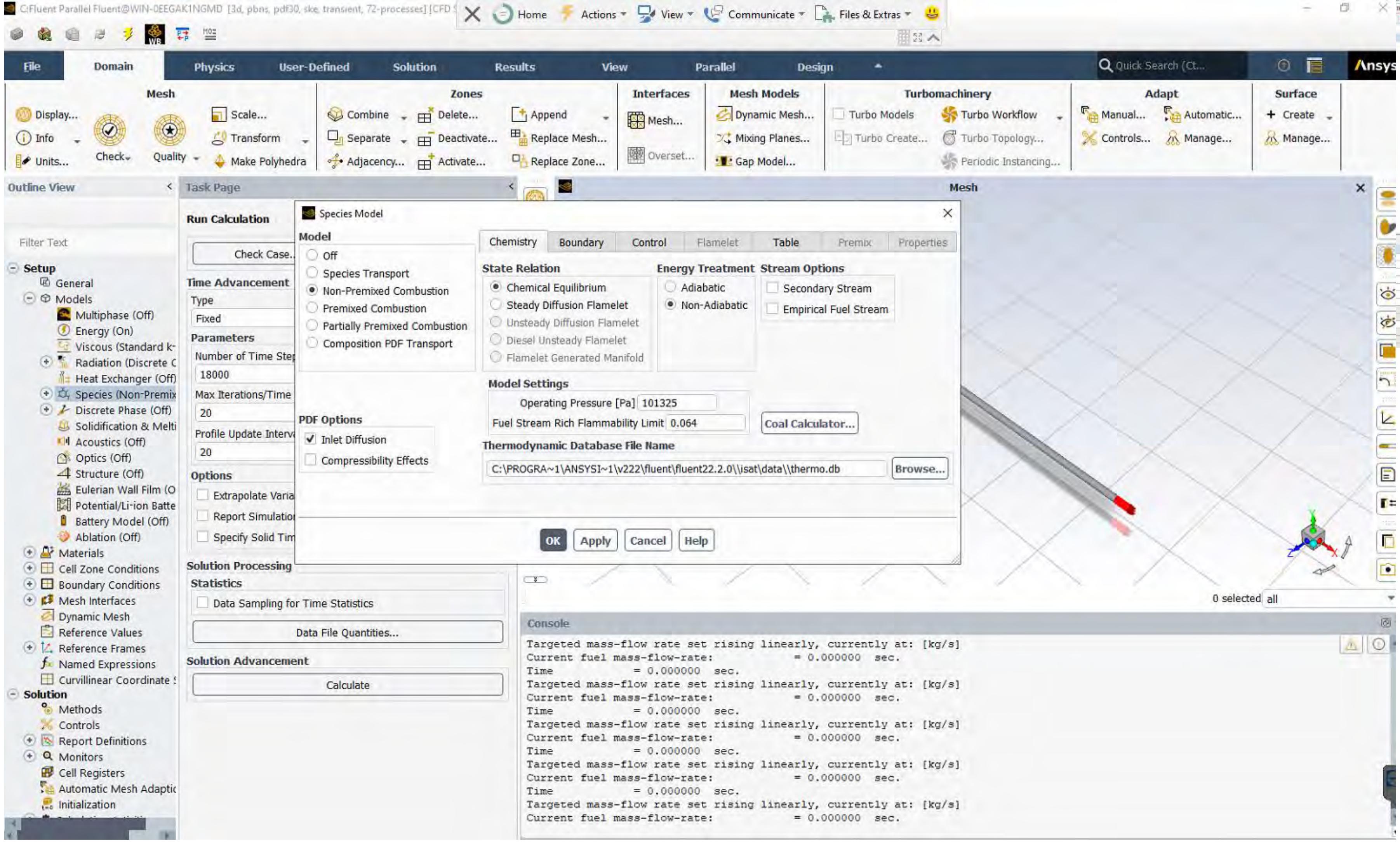
# 3. PROCEDURA PRORAČUNA SISTEMA PODUŽNE VENTILACIJE

Postavke: u=3m/s, $T_0$=15°C, $A_t$=55m$^2$; Gori materija $C_xH_y$ - TNG (65-35% propan-butan, Mgor = 48.9 kg/kmol), $HRR_{max}$ = 50MW; Gubitak toplote zračenjem Qr = -1/3 HRR , odn. 1/3 entalpije reakcije & $T_{max,D}$ = 1350°C (empirija i literatura);
Rješenje:⇔ iter. proračunom se iz I zakona za otv.sistem sa hem. reakcijom dobija: koef. viška vazduha (reakcija 1R+Gorivo TNG): λ = 1.115 & sledeći sastav / koordinate stanja i protoci struja: (1), (1R), (2), (D), (3):

| | 1 | 1R | 2 | D | 3 | Gorivo |
|---|---|---|---|---|---|---|
| $\dot{n}\ [kmol/s]$ | 6.973 | 0.6572 | 6.316 | 0.706 | 7.022 | 0.0224 |
| $\dot{m}\ [kmol/s]$ | 202.22 | 19.06 | 183.16 | 20.05 | 203.2 | 1.096 |
| $r_{C_3H_8}$ [/]<br>$r_{C_4H_{10}}$ [/]<br>$r_{O_2}$ [/]<br>$r_{N_2}$ [/]<br>$r_{H_2O}$ [/]<br>$r_{CO_2}$ [/] | -<br>-<br>0.21<br>0.79<br>-<br>- | -<br>-<br>0.21<br>0.79<br>-<br>- | -<br>-<br>0.21<br>0.79<br>-<br>- | -<br>-<br>0.0202<br>0.7354<br>0.1381<br>0.1063 | -<br>-<br>0.1909<br>0.7845<br>0.01388<br>0.01069 | 0.65<br>0.35<br>-<br>-<br>-<br>- |
| $\rho\ [kg/m^3]$ | 1.225 | 1.225 | 1.225 | 0.213 | 0.832 | tečno |
| T [K] | 288 | 288 | 288 | 1623.15 | 421.55 | 300 |
| $R$ | 287 | 287 | 287 | 292.73 | 288.7 | - |
| $\dot{V}\,[m^3/s]$ | 165 | 15.55 | 149.45 | 94.04 | 243.49 | - |

## CFD PRILAZI

- Fluid je samo vazduh (približno, zbog spec.toplota i zanemaruje se zračenje)
- "Species transport" (polje koncentracija komponenti nereagujuće smješe)
- Species transport +Chemical eqilibrium (mixture fraction): reakcija tretirana statistički - pdf
- Flamelet + CHEMKIN (uključena hemija reakcije)



Run Calculation
Check Case...

Time Advancement
Type: Fixed

Parameters
Number of Time Step: 18000
Max Iterations/Time: 20
Profile Update Interv: 20

Options
☐ Extrapolate Varia
☐ Report Simulatio
☐ Specify Solid Tim

Solution Processing
Statistics
☐ Data Sampling for Time Statistics
Data File Quantities...

Solution Advancement
Calculate

Species Model

Model
○ Off
○ Species Transport
● Non-Premixed Combustion
○ Premixed Combustion
○ Partially Premixed Combustion
○ Composition PDF Transport

Chemistry Boundary Control Flamelet Table Premix Properties

State Relation
● Chemical Equilibrium
○ Steady Diffusion Flamelet
○ Unsteady Diffusion Flamelet
○ Diesel Unsteady Flamelet
○ Flamelet Generated Manifold

Energy Treatment
○ Adiabatic
● Non-Adiabatic

Stream Options
☐ Secondary Stream
☐ Empirical Fuel Stream

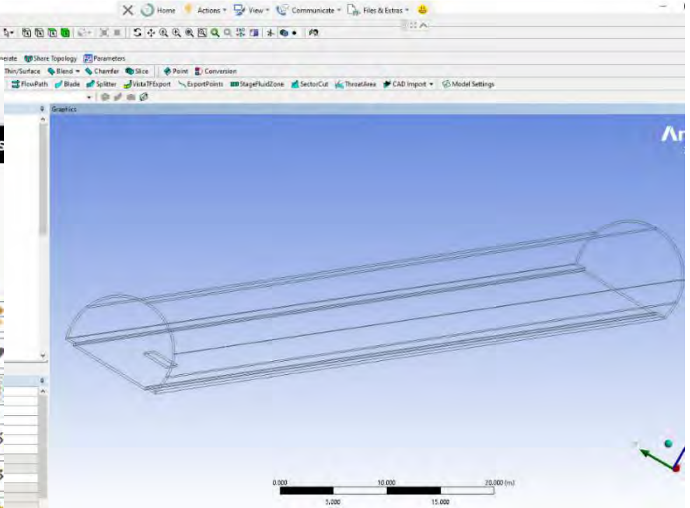
PDF Options
☑ Inlet Diffusion
☐ Compressibility Effects

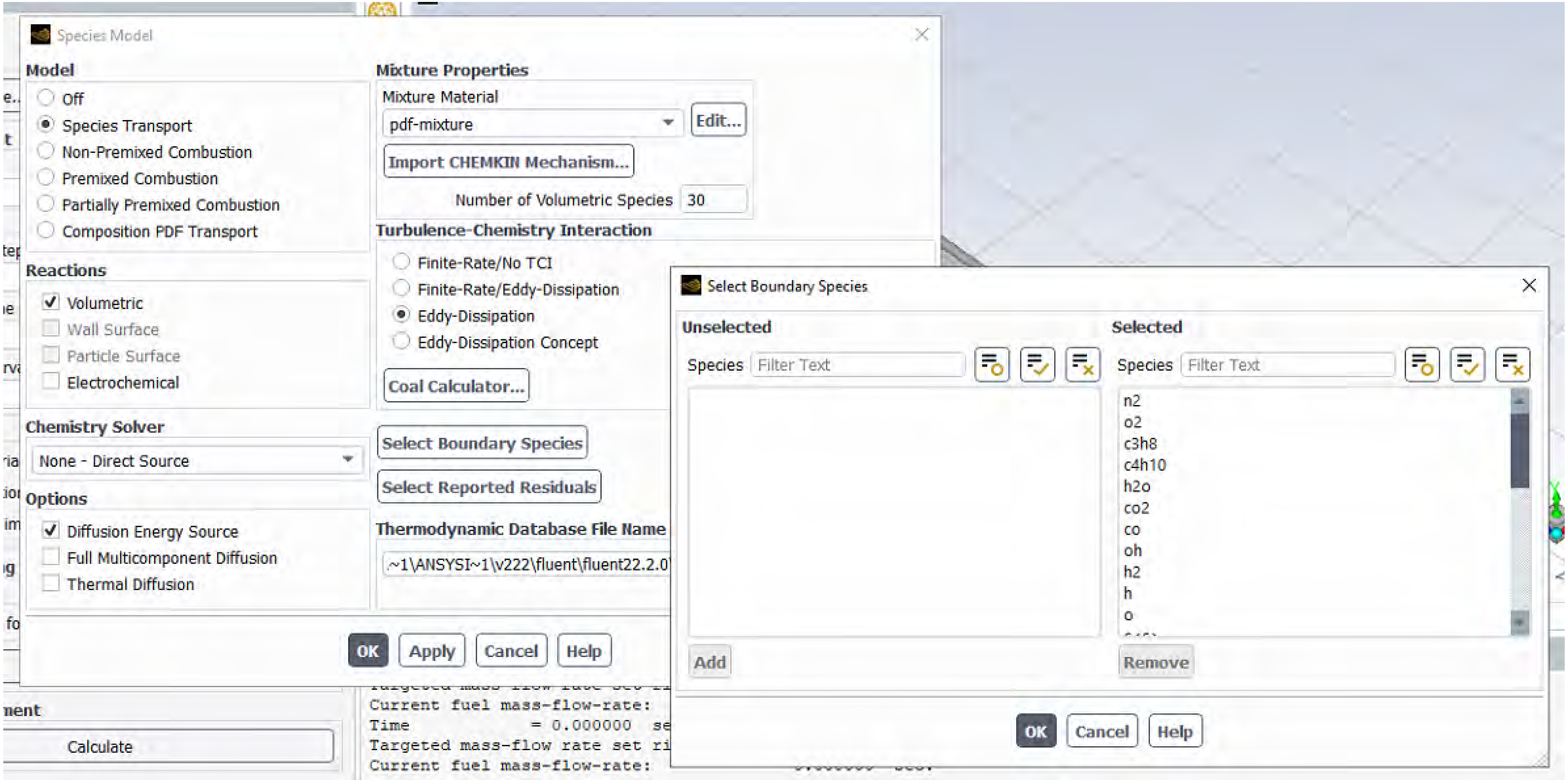
Model Settings
Operating Pressure [Pa] 101325
Fuel Stream Rich Flammability Limit 0.064
Coal Calculator...

Thermodynamic Database File Name
C:\PROGRA~1\ANSYSI~1\v222\fluent\fluent22.2.0\\isat\data\\thermo.db
Browse...

OK Apply Cancel Help

```
Targeted mass-flow rate set rising linearly, currently at: [kg/s]
Current fuel mass-flow-rate:            = 0.000000  sec.
Time            = 0.000000  sec.
Targeted mass-flow rate set rising linearly, currently at: [kg/s]
Current fuel mass-flow-rate:            = 0.000000  sec.
Time            = 0.000000  sec.
Targeted mass-flow rate set rising linearly, currently at: [kg/s]
Current fuel mass-flow-rate:            = 0.000000  sec.
Time            = 0.000000  sec.
Targeted mass-flow rate set rising linearly, currently at: [kg/s]
Current fuel mass-flow-rate:            = 0.000000  sec.
Time            = 0.000000  sec.
Targeted mass-flow rate set rising linearly, currently at: [kg/s]
Current fuel mass-flow-rate:            = 0.000000  sec.
```





Species Model

**Model**

○ Off
● Species Transport
○ Non-Premixed Combustion
○ Premixed Combustion
○ Partially Premixed Combustion
○ Composition PDF Transport

**Reactions**

☑ Volumetric
☐ Wall Surface
☐ Particle Surface
☐ Electrochemical

**Chemistry Solver**

None - Direct Source

**Options**

☑ Diffusion Energy Source
☐ Full Multicomponent Diffusion
☐ Thermal Diffusion

**Mixture Properties**

Mixture Material: pdf-mixture

Number of Volumetric Species: 30

**Turbulence-Chemistry Interaction**

○ Finite-Rate/No TCI
○ Finite-Rate/Eddy-Dissipation
● Eddy-Dissipation
○ Eddy-Dissipation Concept

**Thermodynamic Database File Name**

~1\ANSYSI~1\v222\fluent\fluent22.2.0

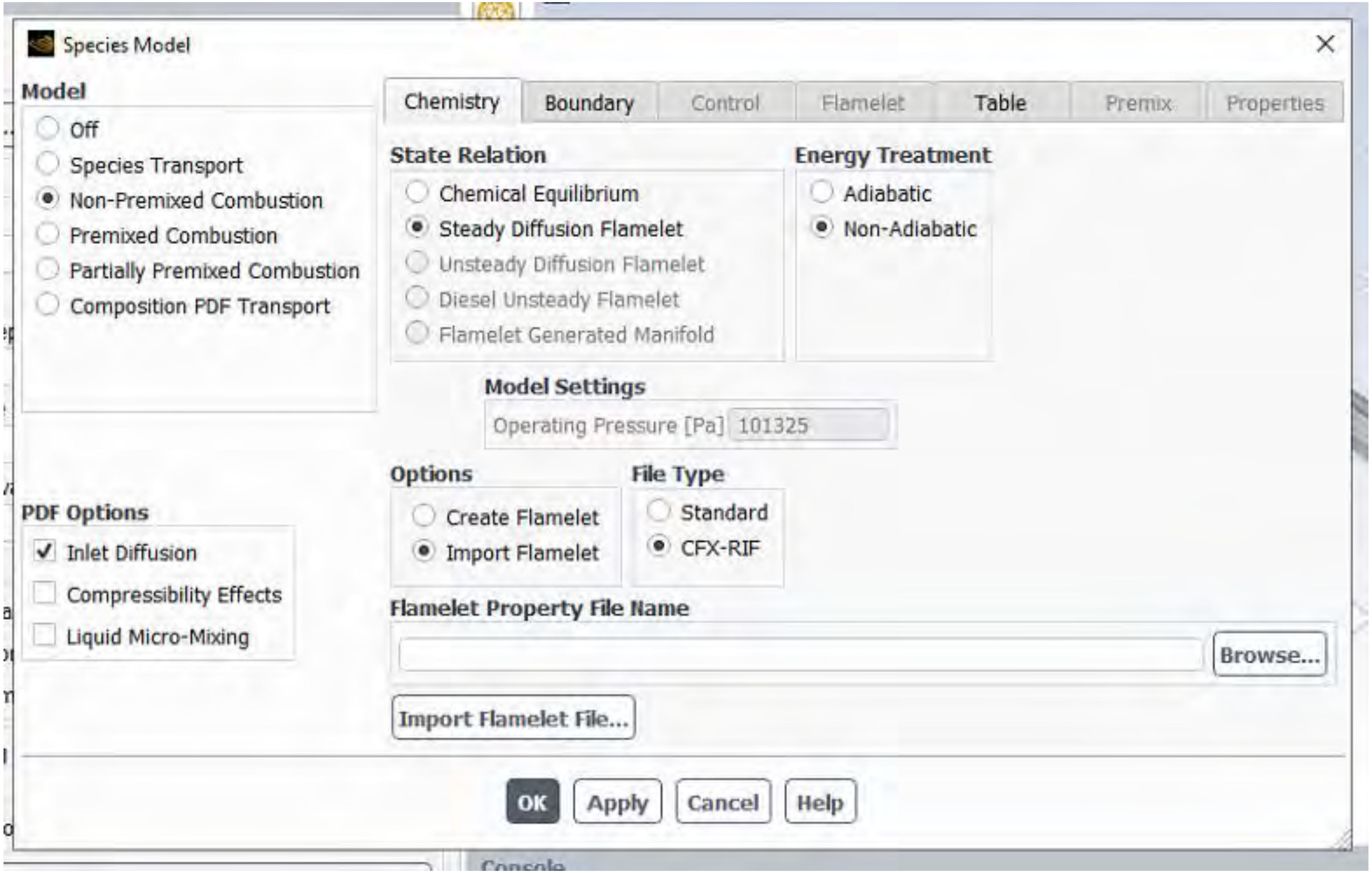
Select Boundary Species

**Unselected**

**Selected**

n2
o2
c3h8
c4h10
h2o
co2
co
oh
h2
h
o

```
Current fuel mass-flow-rate:
Time            = 0.000000   se
Targeted mass-flow rate set ri
Current fuel mass-flow-rate:
```



**Model**
- ○ Off
- ○ Species Transport
- ● Non-Premixed Combustion
- ○ Premixed Combustion
- ○ Partially Premixed Combustion
- ○ Composition PDF Transport

**PDF Options**
- ☑ Inlet Diffusion
- ☐ Compressibility Effects
- ☐ Liquid Micro-Mixing

**State Relation**
- ○ Chemical Equilibrium
- ● Steady Diffusion Flamelet
- ○ Unsteady Diffusion Flamelet
- ○ Diesel Unsteady Flamelet
- ○ Flamelet Generated Manifold

**Energy Treatment**
- ○ Adiabatic
- ● Non-Adiabatic

**Model Settings**

Operating Pressure [Pa] 101325

**Options**
- ○ Create Flamelet
- ● Import Flamelet

**File Type**
- ○ Standard
- ● CFX-RIF

**Flamelet Property File Name**

## LITERATURA:

1. PIARC Technical report o dimenzionisanju ventilacije
2. Dossier Pilote – CETU, smjernica o dimenzionisanju ventilacije
3. Priručnici (vidi poglavlje 1)
4. Primijenjena termodinamika: Nenad Kažić, skripta
5. Bilješke sa vježbi iz primijenjene termodinamike, Milan Šekularac
6. Kenneth Wark, Donald Richards: Thermodynamics
7. Schaum's outline series: Heat transfer
8. T. Poinsot, D.Veynante: Theoretical and Numerical Combustion & online predavanja
9. Norbert Peters: Turbulent combustion & predavanja i slajdovi
10. Michael Modest: Radiative heat transfer
11. M.Modest, D. Haworth: Radiative heat transfer in turbulent combustion systems – theory and applications
12. CETU Cammat softver - userguide
13. CFD - ANSYS Fluent Theory Guide
14. CFD - ANSYS Fluent User Guide + tutorijali
15. CFD - Open Foam tutorijali

# 4. ISTRAŽIVANJA U CRNOJ GORI. NEKA AKTUELNA PITANJA U VENTILACIJI TUNELA

Na Mašinskom fakultetu u Podgorici problematika ventilisanja saobraćajnih tunela bila je predmet istraživanja kroz dva nacionalna naučno-istraživačka projekta i jednog bilateralnog sa Mašinskim fakultetom u Beogradu, tokom poslednjih 13 g. Iz ovog istraživanja na MF Podgorica publikovani su sledeći radovi:

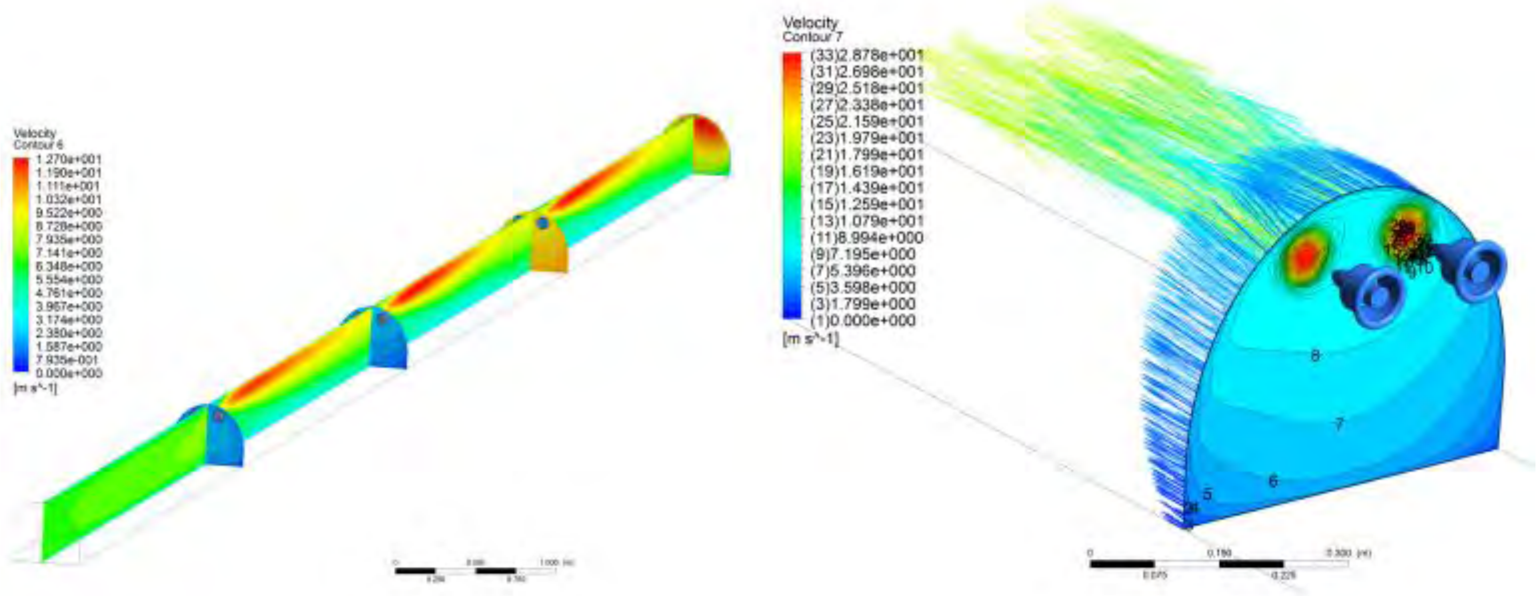
1. Vukoslavčević, P., Šekularac, M. (2022) Critical review of the common methods to determine the buoyancy-chimney effects in lonfitudinally-ventilated traffic tunnel fires. Advances in Mechanical Engineering, Vol 14(5) 1-13.
2. Šekularac, M. On heat transfer coefficients and temperature distribution in longitudinally ventilated tunnel fires. 11th International Conference 'Tunnel Safety and Ventilation' 2022, Graz
3. Šekularac, M., Jankovic, N., Vukoslavcevic, P. (2016) Ventilation Performance and Pollutant Flow in a UnidirectionalTraffic Road Tunnel. Thermal Science Journal, DOI: 10.2298/TSCI160321117S. Year 2017, Vol. 21, Suppl. 3, pp. S783-S794
4. Šekularac, M. (2016) Experimental Determination of Tunnel Ventilation Axial Ducted Fan Performance. Thermal Science Journal, DOI.10.2298/TSCI 140624108S ; Year 2016, Vol. 20, No. 1, pp. 209-221
5. Šekularac, M., Janković N. Experimental and numerical analysis of flow field and ventilation performance in a traffic tunnel ventilated by axial fans, Theoretical and applied mechanics, DOI: https://doi.org/10.2298/TAM171201010S (2018)
6. Šekularac, M. Analiza složenih strujnih polja sistema ventilacije saobraćajnih tunela. Doktorska disertacija, Univerzitet Crne Gore, Mašinski fakultet Podgorica, 2015.
7. Šekularac, M., Vukoslavčević, P. One Approach to Experimental and Numerical Investigation of Longitudinally Ventilated Road Tunnels. (2012) ICTTE International Conference on Traffic and Transport Engineering, Belgrade. Nov.2012. Volume 1; pp. 499-507.; ISBN 978-86-916153-0-7; COBISS.SR-ID 195032076;
8. Šekularac, M, Radulović, P. Energy Efficiency of Ventilation Systems of Longitudinally Ventilated Traffic Tunnels. (2011) International conference on Alternative energy sources and energy efficiency, CANU – Montenegrin Academy of Sciences and Arts. Oct.2011. Scientific meetings Vol.112, Section of Natural Sciences Vol.15, pp.131-147. ISBN 978-86-7215-292-0

a)

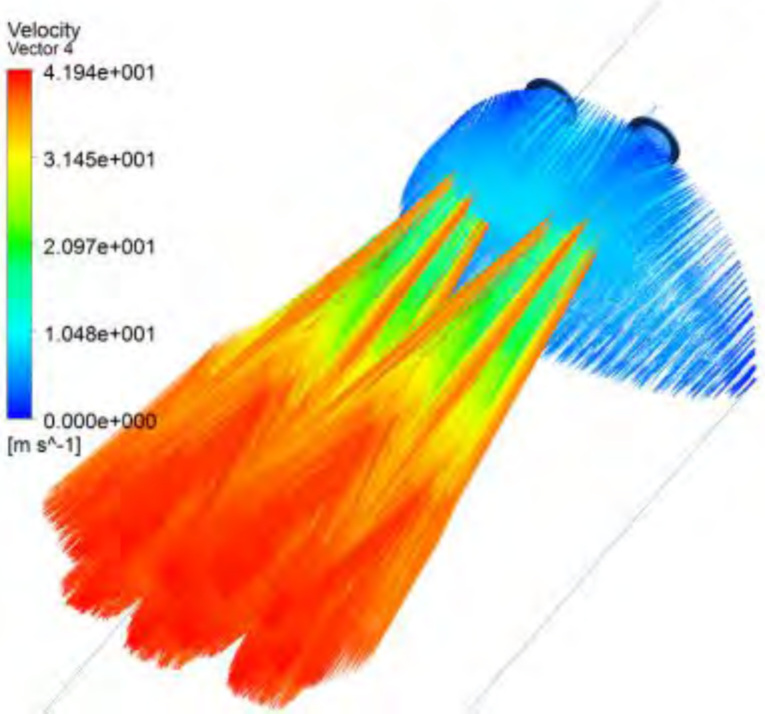
b)

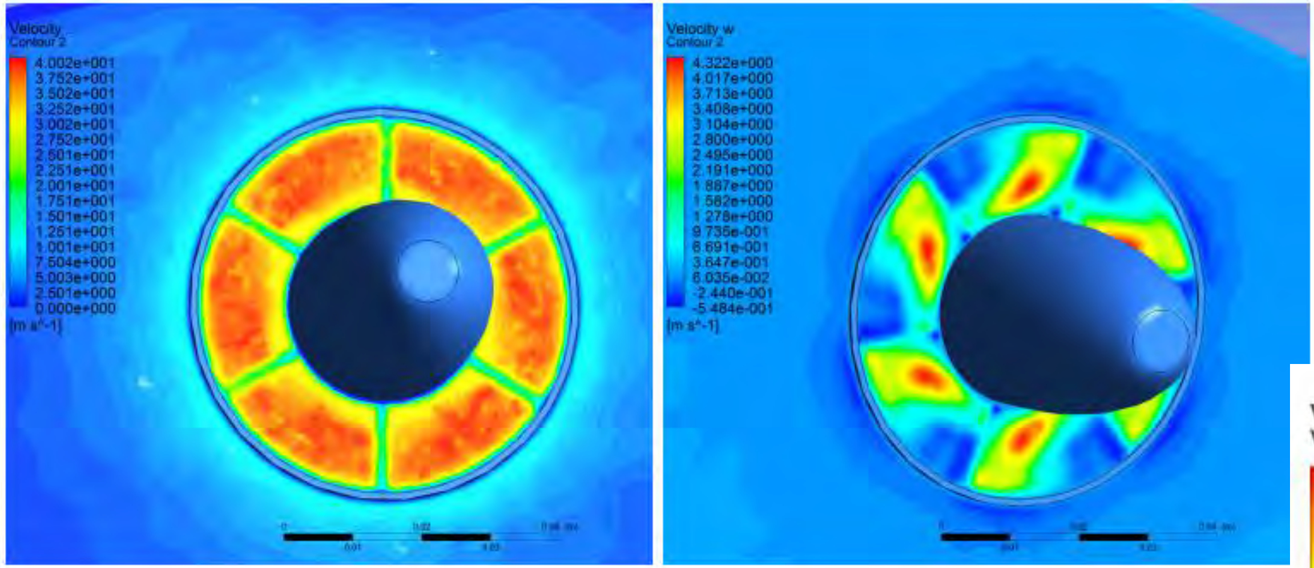
c)

d)


Velocity
Contour 6
1.270e+001
1.190e+001
1.111e+001
1.032e+001
9.522e+000
8.728e+000
7.935e+000
7.141e+000
6.348e+000
5.554e+000
4.761e+000
3.967e+000
3.174e+000
2.380e+000
1.587e+000
7.935e-001
0.000e+000
[m s^-1]
Velocity
Contour 7
(33)2.878e+001
(31)2.698e+001
(29)2.518e+001
(27)2.338e+001
(25)2.159e+001
(23)1.979e+001
(21)1.799e+001
(19)1.619e+001
(17)1.439e+001
(15)1.259e+001
(13)1.079e+001
(11)8.994e+000
(9)7.195e+000
(7)5.396e+000
(5)3.598e+000
(3)1.799e+000
(1)0.000e+000
[m s^-1]
8
7
6
5
0
0.150
0.300 (m)
0.075
0.225

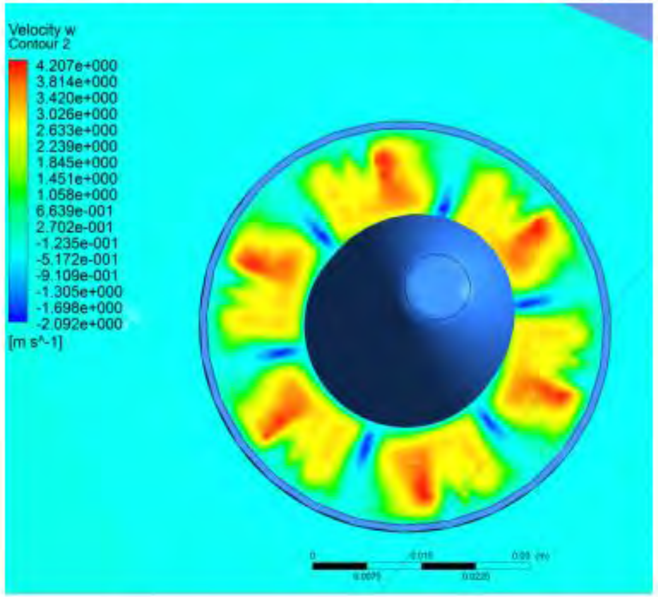
a) b)


Velocity
Vector 4
4.194e+001
3.145e+001
2.097e+001
1.048e+001
0.000e+000
[m s^-1]

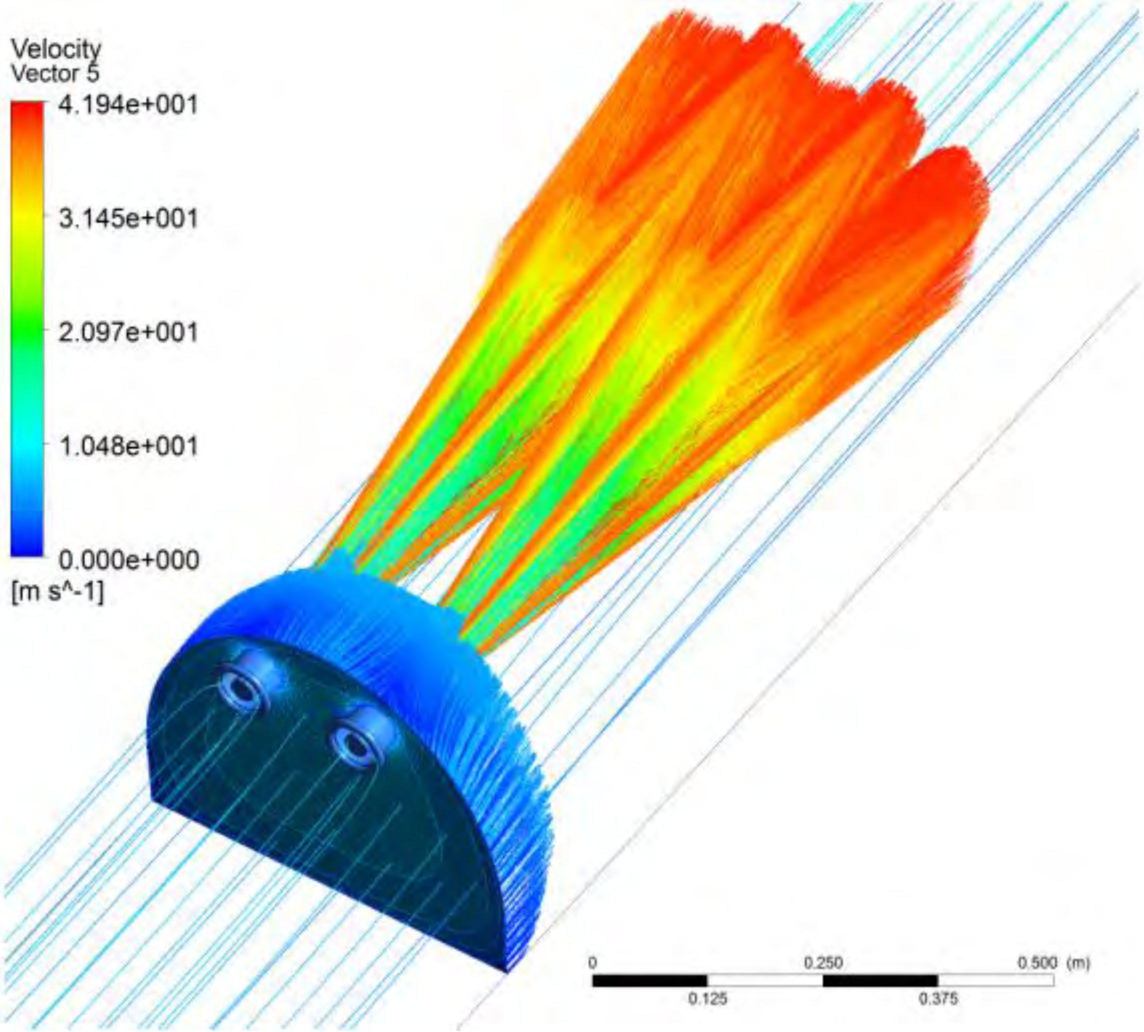


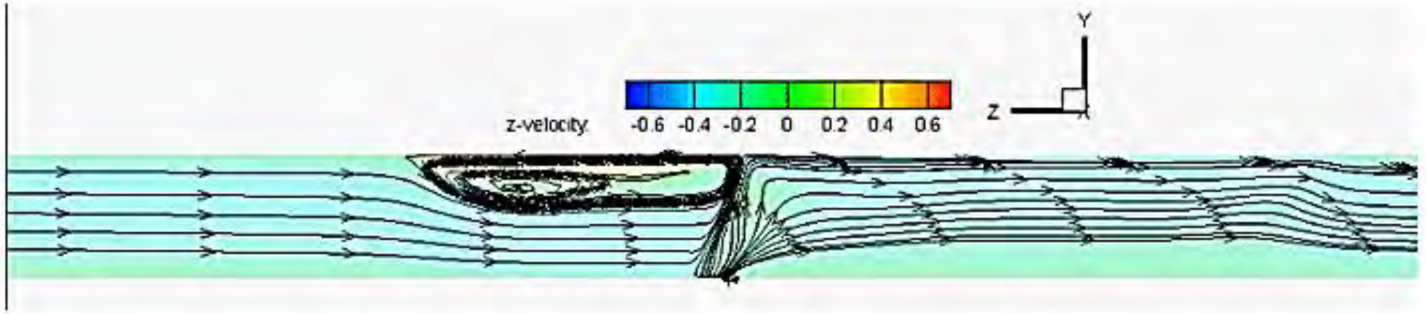
a) Intenzitet brzine

b) Radijalna komponenta $\bar{v}_r$

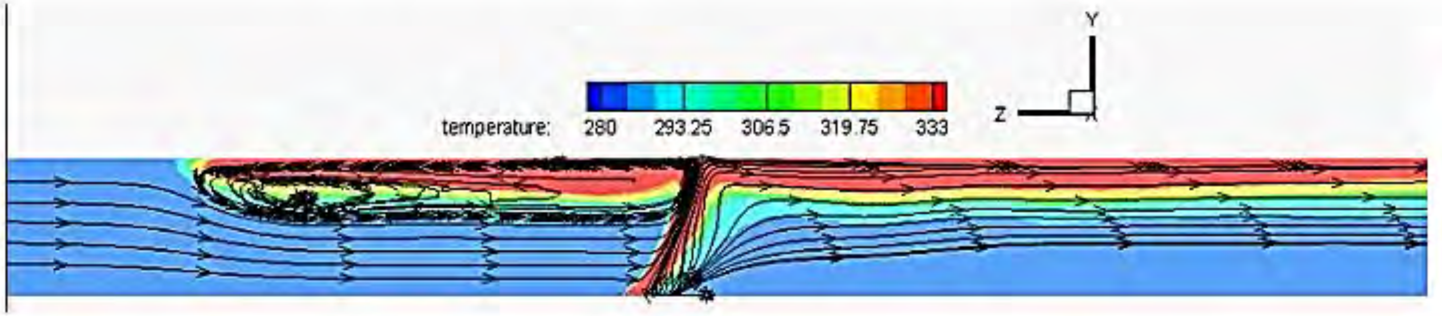


c) Tangentna komponenta brzine $\bar{v}_t$

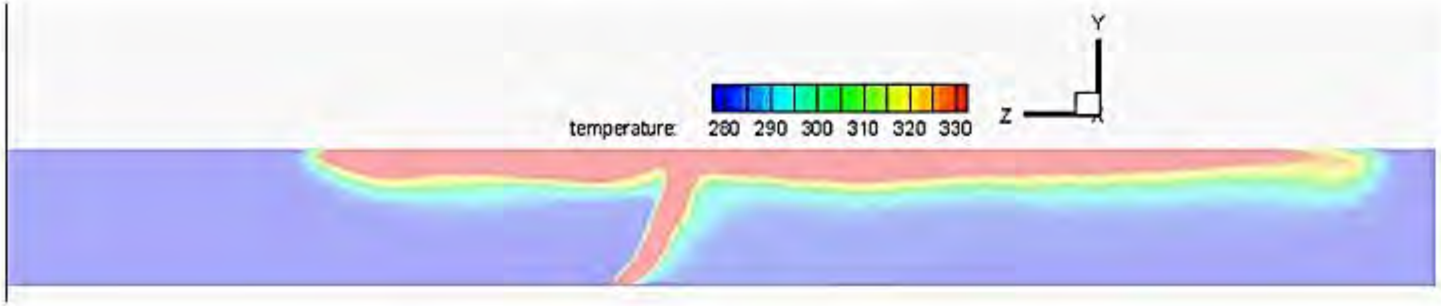




Polje aksijalne komponente brzine u vremenu & strujnice



Polje temperature u zoni požara



Polje temperature u zoni požara: opseg +0 - +60°C

# NEKA AKTUELNA PITANJA IZ VENTILACIJE TUNELA

- Alternativni sistemi propulzije vozila: Električna vozila, CNG (komprimovani prirodni gas), Vozila na vodonik

- Problematika gašenja i ekspolozija

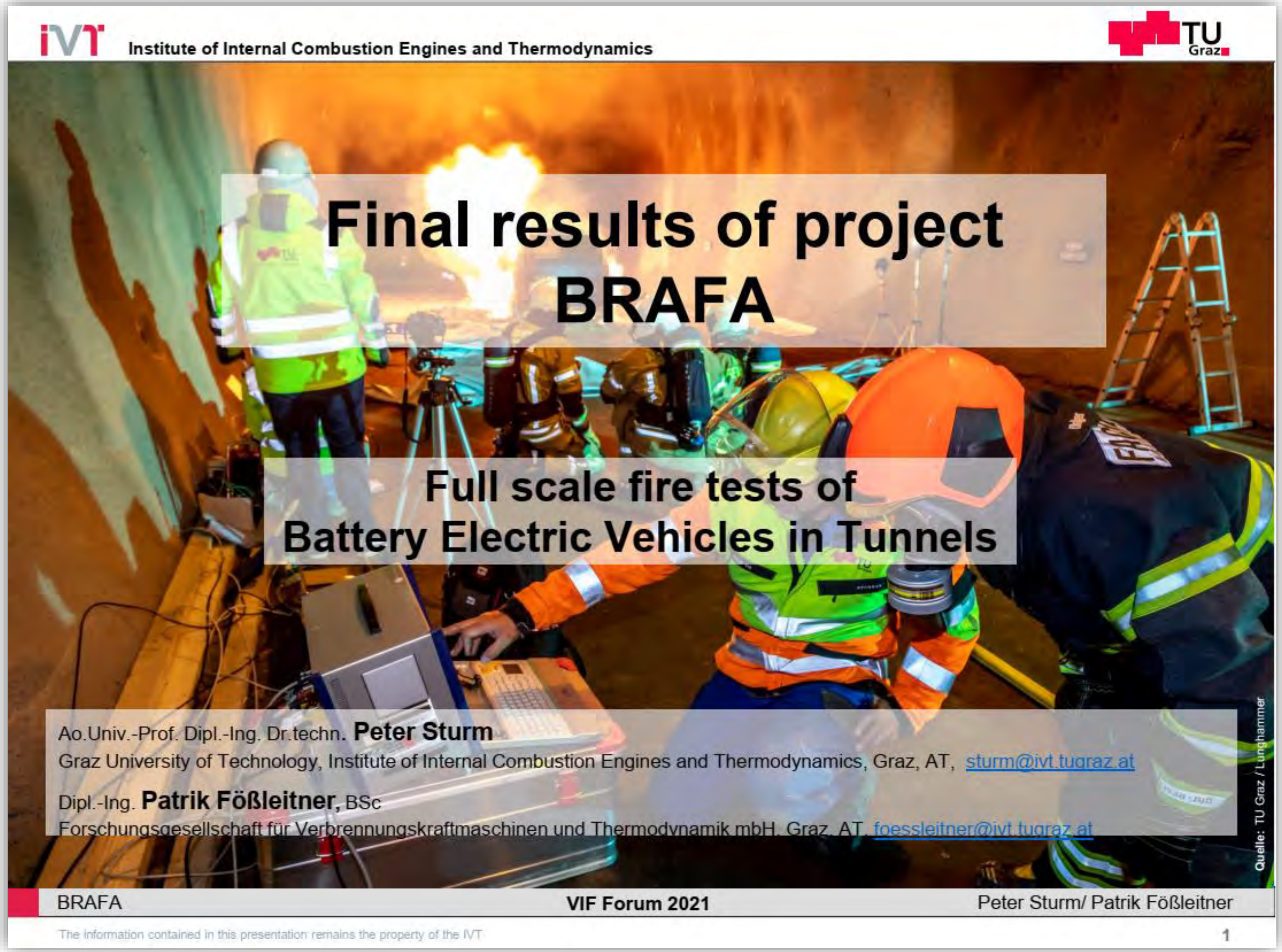
- Problematika HRR(t)

- Problematika toksičnih polutanata

VIDEO:
Hanover, Njemačka
Jan 2023.
Zapaljenje električnog autobusa

Izvor: TU Graz, Peter Sturm
Projekat ispitivanje sastava polutanata, HRR
i tehnika gašenja požara električnih vozila u tunelu

Izvor: TU Graz, Peter Sturm
Projekat ispitivanje sastava polutanata, HRR
i tehnika gašenja požara električnih vozila u tunelu



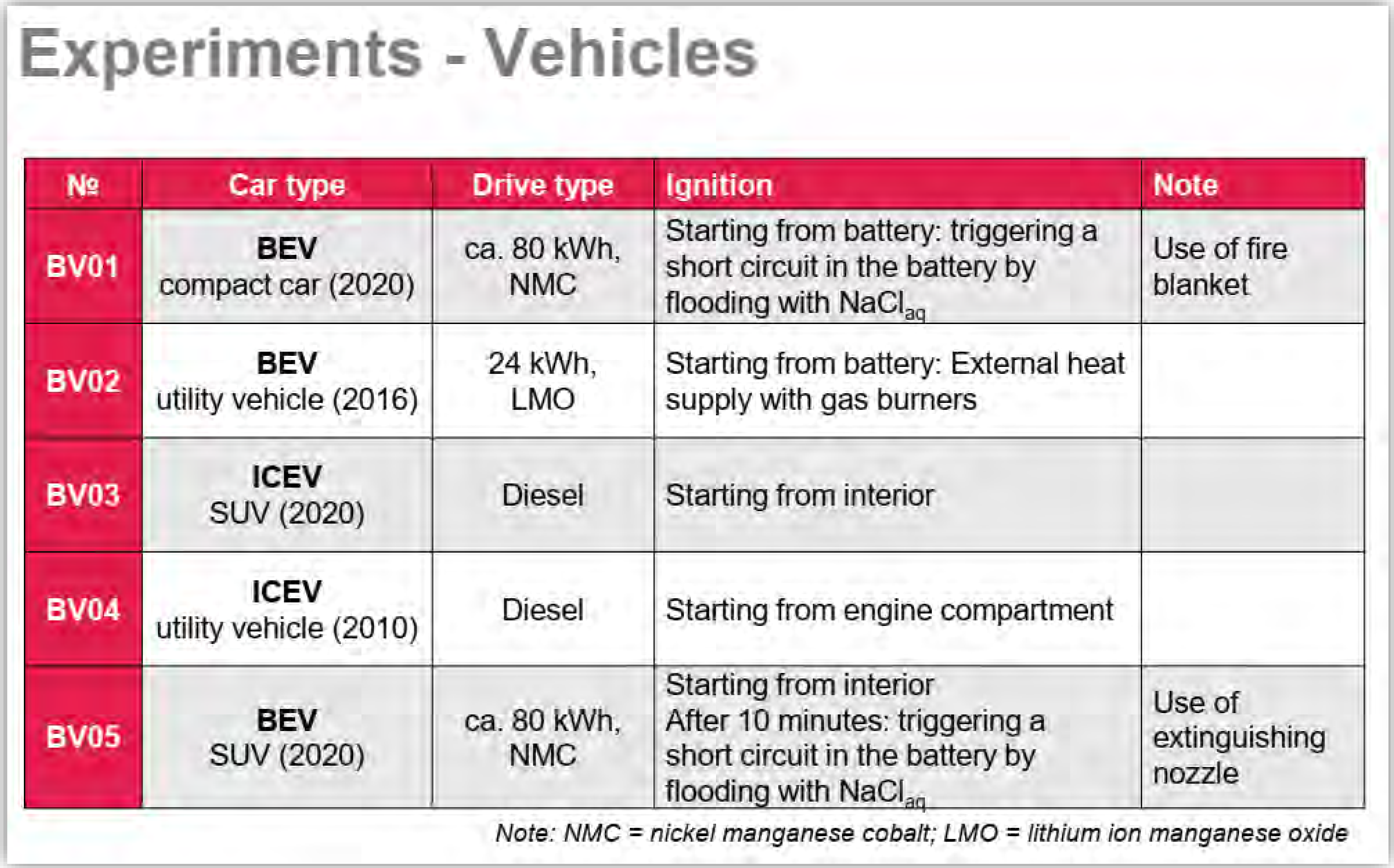
# Final results of project BRAFA

## Full scale fire tests of Battery Electric Vehicles in Tunnels

Ao.Univ.-Prof. Dipl.-Ing. Dr.techn. **Peter Sturm**
Graz University of Technology, Institute of Internal Combustion Engines and Thermodynamics, Graz, AT, sturm@ivt.tugraz.at

Dipl.-Ing. **Patrik Fößleitner**, BSc
Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik mbH, Graz, AT, foessleitner@ivt.tugraz.at

Quelle: TU Graz / Lunghammer

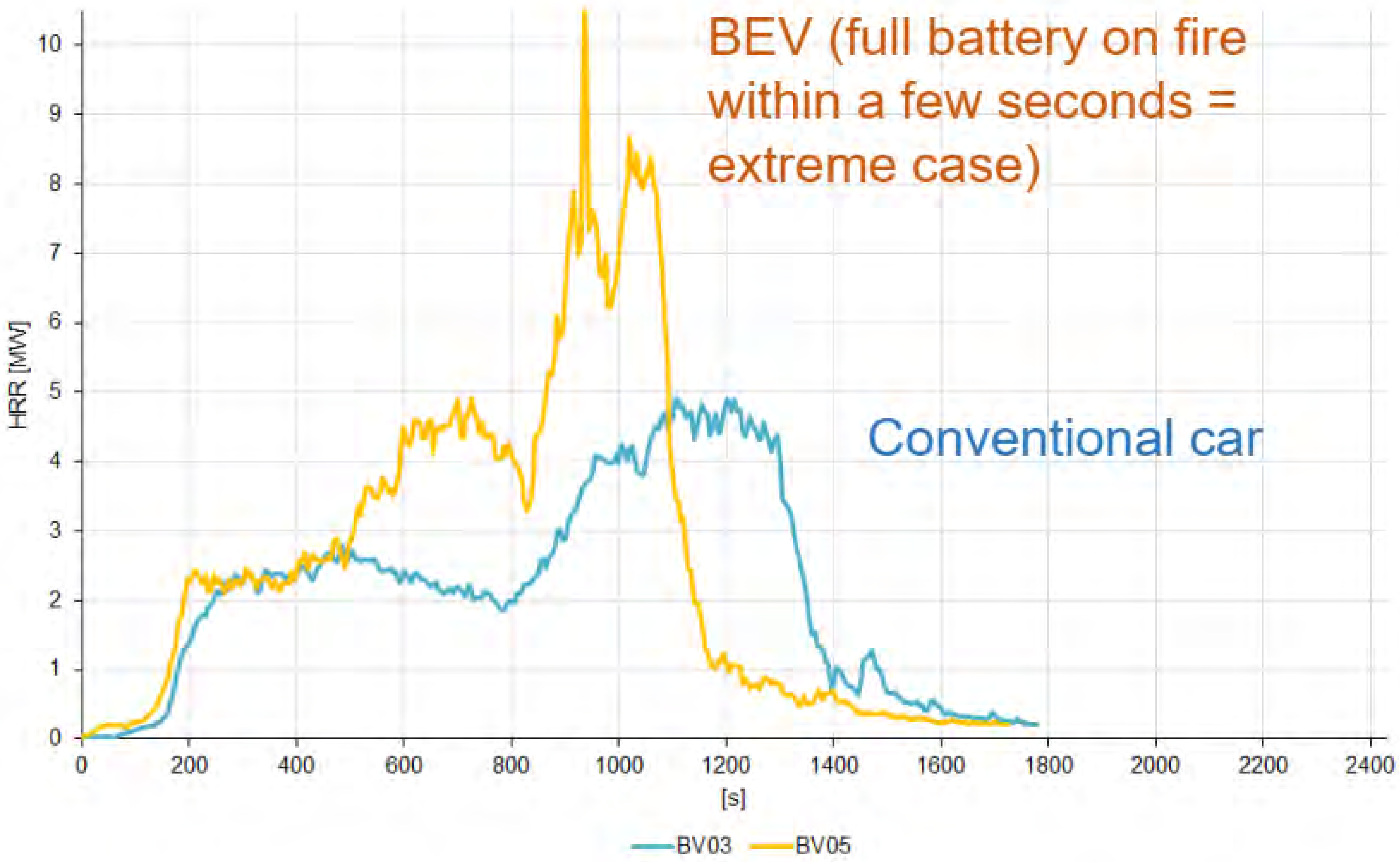


# Experiments - Vehicles

| № | Car type | Drive type | Ignition | Note |
|---|---|---|---|---|
| **BV01** | **BEV**<br>compact car (2020) | ca. 80 kWh,<br>NMC | Starting from battery: triggering a short circuit in the battery by flooding with $NaCl_{aq}$ | Use of fire blanket |
| **BV02** | **BEV**<br>utility vehicle (2016) | 24 kWh,<br>LMO | Starting from battery: External heat supply with gas burners | |
| **BV03** | **ICEV**<br>SUV (2020) | Diesel | Starting from interior | |
| **BV04** | **ICEV**<br>utility vehicle (2010) | Diesel | Starting from engine compartment | |
| **BV05** | **BEV**<br>SUV (2020) | ca. 80 kWh,<br>NMC | Starting from interior<br>After 10 minutes: triggering a short circuit in the battery by flooding with $NaCl_{aq}$ | Use of extinguishing nozzle |

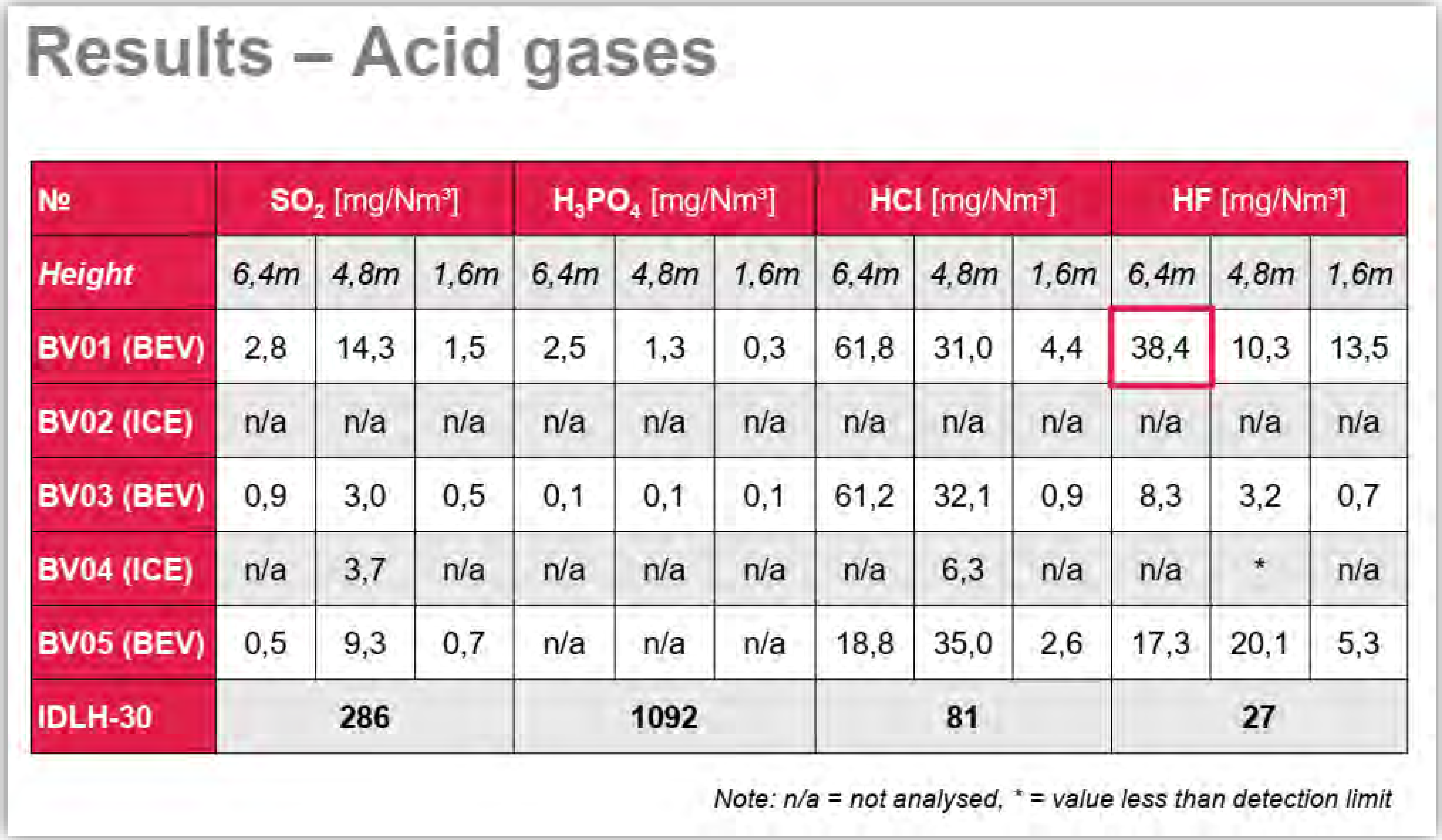
*Note: NMC = nickel manganese cobalt; LMO = lithium ion manganese oxide*

# Results - Heat Release Rate



BEV (full battery on fire within a few seconds = extreme case)

Conventional car



# Results – Acid gases

| № | $SO_2$ [mg/Nm³] | | | $H_3PO_4$ [mg/Nm³] | | | HCl [mg/Nm³] | | | HF [mg/Nm³] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Height*** | *6,4m* | *4,8m* | *1,6m* | *6,4m* | *4,8m* | *1,6m* | *6,4m* | *4,8m* | *1,6m* | *6,4m* | *4,8m* | *1,6m* |
| **BV01 (BEV)** | 2,8 | 14,3 | 1,5 | 2,5 | 1,3 | 0,3 | 61,8 | 31,0 | 4,4 | 38,4 | 10,3 | 13,5 |
| **BV02 (ICE)** | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| **BV03 (BEV)** | 0,9 | 3,0 | 0,5 | 0,1 | 0,1 | 0,1 | 61,2 | 32,1 | 0,9 | 8,3 | 3,2 | 0,7 |
| **BV04 (ICE)** | n/a | 3,7 | n/a | n/a | n/a | n/a | n/a | 6,3 | n/a | n/a | * | n/a |
| **BV05 (BEV)** | 0,5 | 9,3 | 0,7 | n/a | n/a | n/a | 18,8 | 35,0 | 2,6 | 17,3 | 20,1 | 5,3 |
| **IDLH-30** | **286** | | | **1092** | | | **81** | | | **27** | | |

*Note: n/a = not analysed, * = value less than detection limit*

# Conclusions

- Tests performed for
  - Battery cells, modules, packs
  - Vehicles (3 BEV, 2 ICEV)
- Comparison of BEV:
  - **HRR:** average HRR as ICEV, peak HRR higher
  - **Acid gases**: HF increased values
    HCl similar to ICEV
- Extinguishing techniques:
  - **Fire blanket:** no successful application
  - **Extinguishing lance:** effective, but difficult to use
  - **Water (standard approach):** currently still the standard
    recommended method for fire fighting

## LITERATURA:

Zbornici sa aktuelnih konferencija:

1. PIARC skupovi (2022): https://www.piarc-tunnels-spain2022.org/
2. TU Graz (2022) – P.Sturm: https://www.tunnel-graz.at/
3. ISTSS 2023 https://www.ri.se/en/istss
4. Časopisi: Fire safety journal, Fire technology, Tunnelling and underground space technology, Advances in Mechanical Engineering, Case studies in thermal engineering, Applied thermal engineering, i dr.
5. Researchgate

# *Hvala na pažnji*

Kontakt
*Doc dr Milan Šekularac, dipl.maš.ing*
*Kontakt:*
*milans@ucg.ac.me*
*milan.sekularac.mne@gmail.com*
*Tel: +382 69 204 946*
*Mašinski fakultet Podgorica*
*Univerzitet Crne Gore*
*Cetinjski put bb, 81000 Podgorica*