

# Tunnel Ventilation

## The Actual State of the Art



## Design

- What has to be installed ? → Equipment and its layout
- Calculations  
To a achieve a desired state under defined design conditions
- *Subject to Guidelines and Standards*

## Operation

- How does it have to work ?
- Procedures  
To a achieve a desired state, if possible, under any conditions  
within an adequate time
- *For road tunnel ventilation, often neglected / not clearly defined*

# Normal operation

Provide adequate air quality in the tunnel and in the environment

Ample sight distance prevents accidents

For majority of tunnels,  
natural ventilation is sufficient

- Not to be taken into account for design
- Always has to be considered for operation !

Forced ventilation is required:

- For long tunnels with bidirectional traffic and heavy traffic load
- For city tunnels with stringent environmental restrictions



## Normal operation

Special case:

Fogging of windshields of vehicles entering a tunnel with bidirectional traffic (under specific meteorological conditions) causing collisions !

Can be prevented by appropriate ventilation



## Normal operation

Ventilation systems require the highest installed power of all tunnel equipment, but mostly lead only to minor energy consumption

Different funding for investment – for operational costs

Operation of forced ventilation costs energy

- Tunnel operators have to save costs
- Tunnel users complain about bad air quality...



# Fire ventilation

Smoke kills people

Heat destroys equipment



## 1. Phase: Self rescue

- Support escape of tunnel users
- Prevent smoke from moving where persons are situated

## 2. Phase: Assisted rescue, fire fighting

- create smoke free zone on one side for access
  - blow smoke to opposite direction
- may endanger people that are left there !**

## Fire ventilation

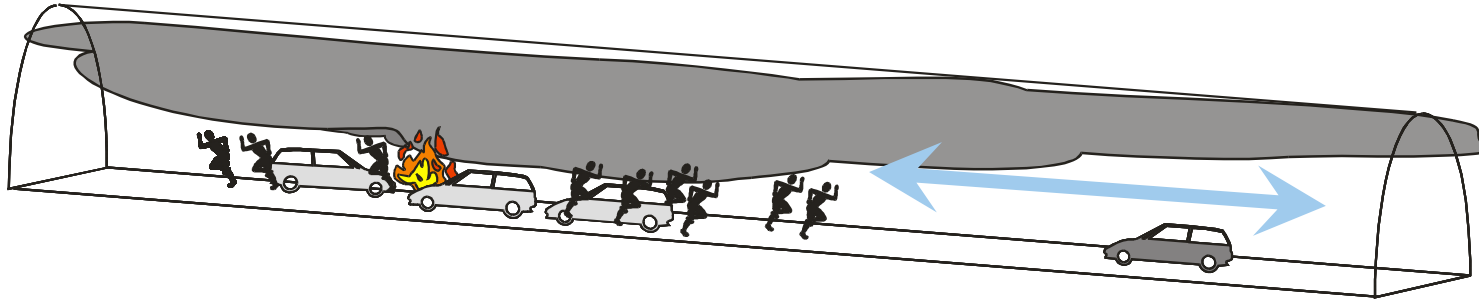


Fire fighters prefer stable conditions

Fire fighters equipped with breathing apparatus and IR vision devices, are able to operate in the smoke (for a limited time)

→ *Recommendation not to change the ventilation regime for the 2. phase !*

## Fire ventilation = Smoke Control



one-dimensional system

→ fast linear spread

Smoke control  
= handling the longitudinal flow in the tunnel

## Tunnel categories

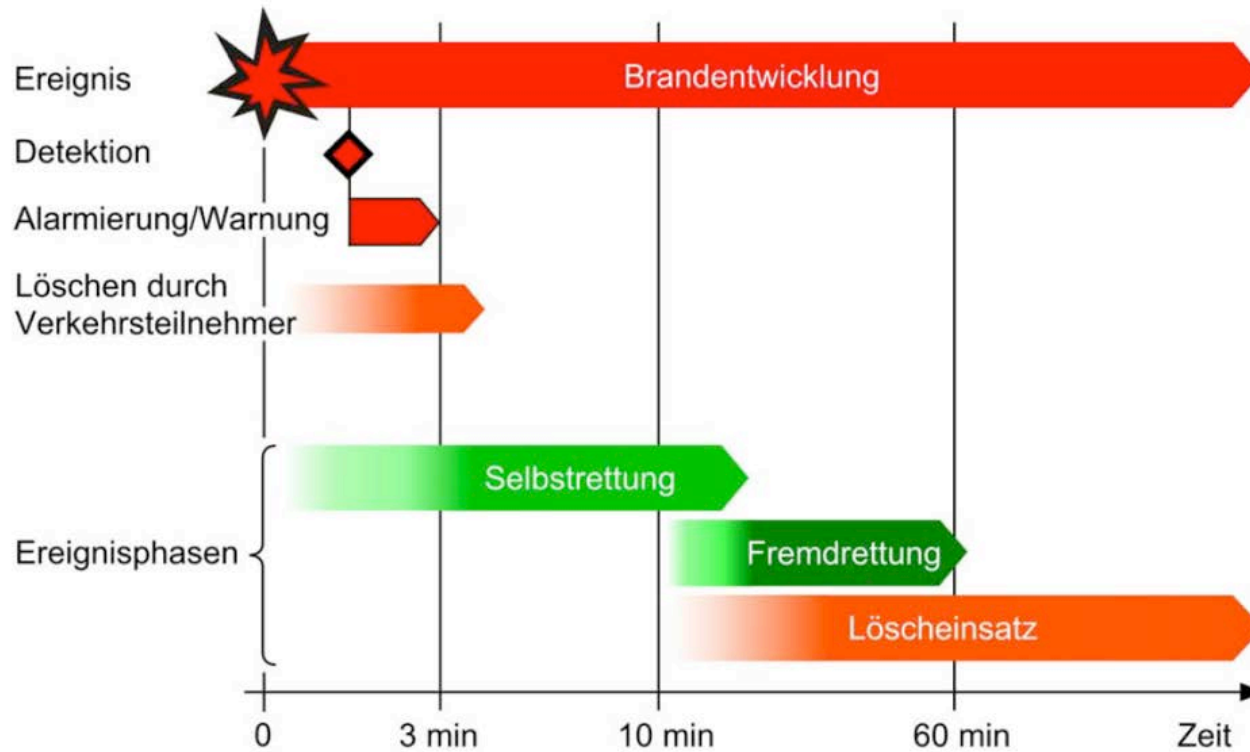
Where are persons situated ?

How is the supposed smoke movement ?

- A:** Vehicles and persons are supposed to be only on one side of fire location
- B:** Persons may be situated on both sides of fire location,  
short tunnels and long tunnels with escape ways in short distances
- C:** Persons may be situated on both sides of fire location,  
long tunnels without escape ways

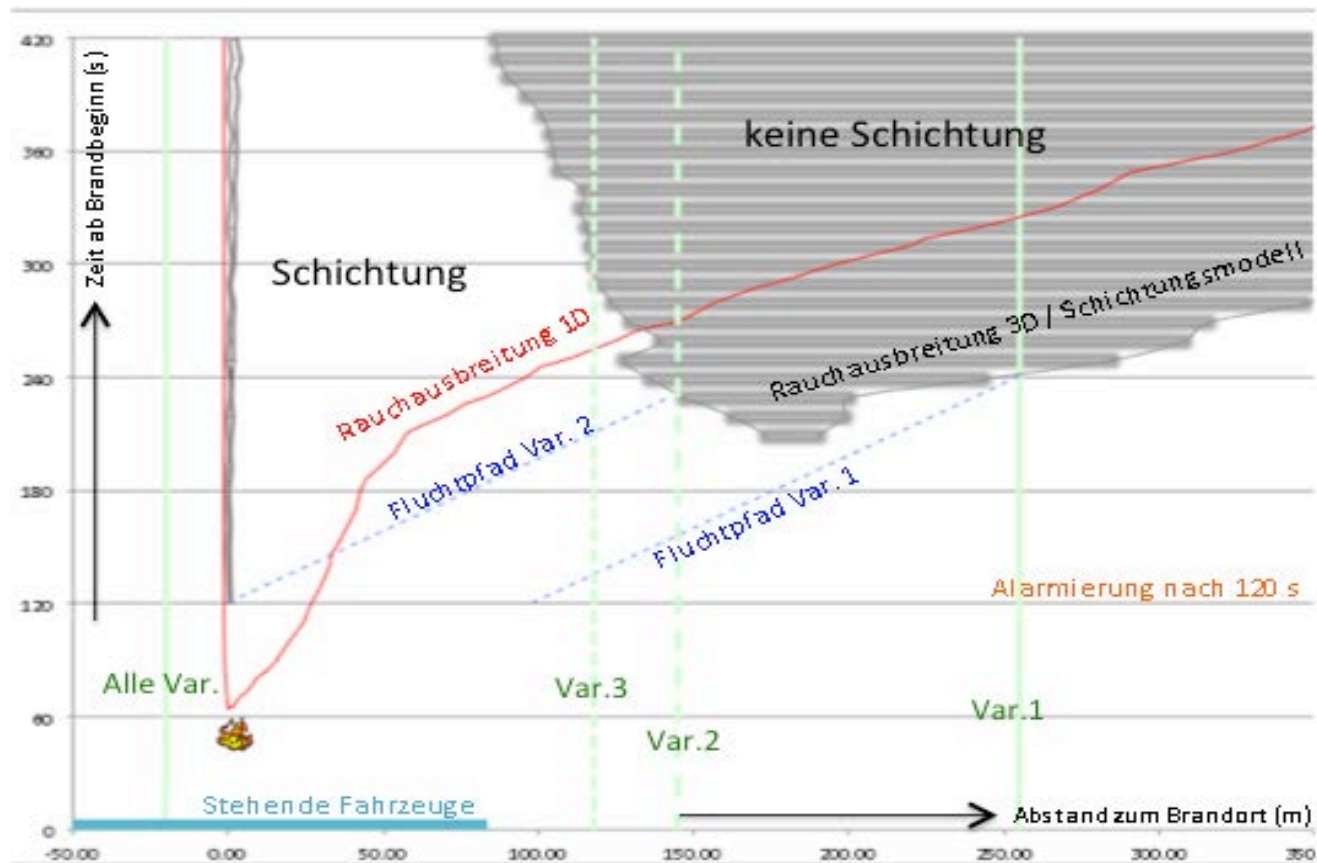
# Time scales

Self-rescue is essential !



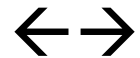
# Time scales

Self-rescue often takes place before ventilation is effective



## Time scales

Self-rescue completed within approx. 10 Min. after start of incident



Requirements in ventilation guidelines:

RABT (D), ASTRA (CH),... - no requirements (only stationary design)

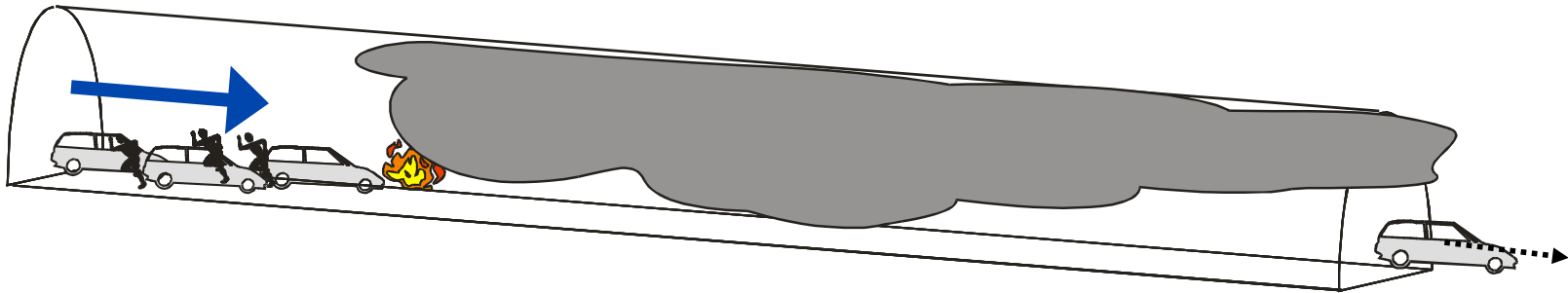
RVS09.02.31 (A): Target condition to be achieved within 5 Min.  
(2014) / within 10 Min. for transversal ventilation systems (!)

TP12/2011 (SK): Target condition to be achieved within 2 Min.

METODICKÝ POKYN Větrání silničních tunelů (CZ, 2013):

Target condition (stable within a bandwidth of +/- 0.3 m/s)  
to be achieved within 1 Min. from a deviation of +/- 1 m/s

## Free flowing unidirectional traffic



No persons downstream (?) → direct smoke to one side

= *concept for all tunnel systems for fire at portals  
and for 2. phase (smoke removal) → demanding case for layout*

Most important:

Traffic control to ensure that vehicles downstream can really leave the tunnel !

## 'Traditional' Philosophy – Fast longitudinal ventilation with fixed setting $v > v_{crit}$

(design value in most guidelines, e.g. NFPA 502, RABT, ASTRA etc.)

+ No backlayering

+ simple, cheap control

+ flow situation in most cases is the same as before outbreak of fire

- Real velocity depends on random boundary conditions:

for short tunnels, in first order wind pressures

for long tunnels, in first order traffic\*

(\*for long Alpine tunnels, also barometric pressure and buoyancy)

Fire dynamics !

→ In reality, target condition may be either excessively exceeded, or not be achieved

## 'Traditional' Philosophy – Fast longitudinal ventilation

- High flow velocity may increase heat release rate and smoke production
- People trapped downstream are deliberately exposed to the smoke !

Most victims in tunnel fires have died in first order due to the inapt application of this philosophy !

E.g.

Metro Baku 1995 (> **300 fatalities**)

Mont Blanc road tunnel 1999 (**39 fatalities**)

Gotthard road tunnel 2001 (**11 fatalities**)



# 'Modern' Philosophy: Limiting flow velocity by controlled longitudinal ventilation

$V_{\text{Target}} \approx 1.5 - 2 \text{ m/s}$  with closed-loop control (e.g. Austrian RVS for tunnels Kat. A)

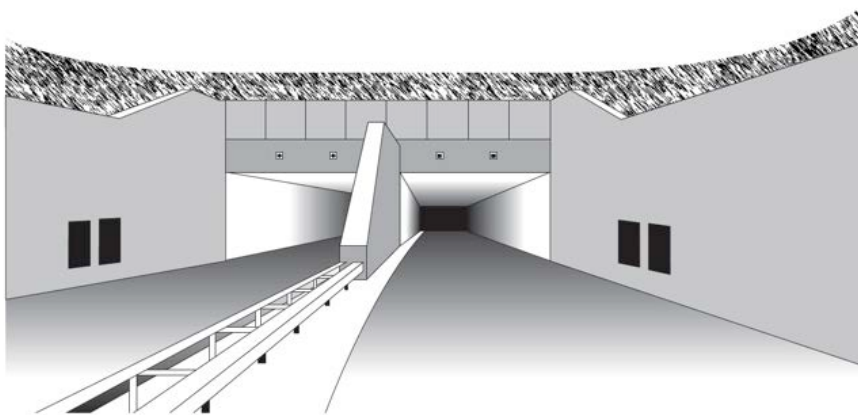
- + Smoke stratification can be maintained
- + People trapped downstream in tenable conditions
- Backlayering may occur
- Complex control and instrumentation



Limiting the flow velocity is especially important when applying Fixed Fire Fighting Systems (Sprinklers, Water mist)



Most important: Prevent smoke propagation to adjacent non-incident tube by portals, open cross passages, ramps etc.



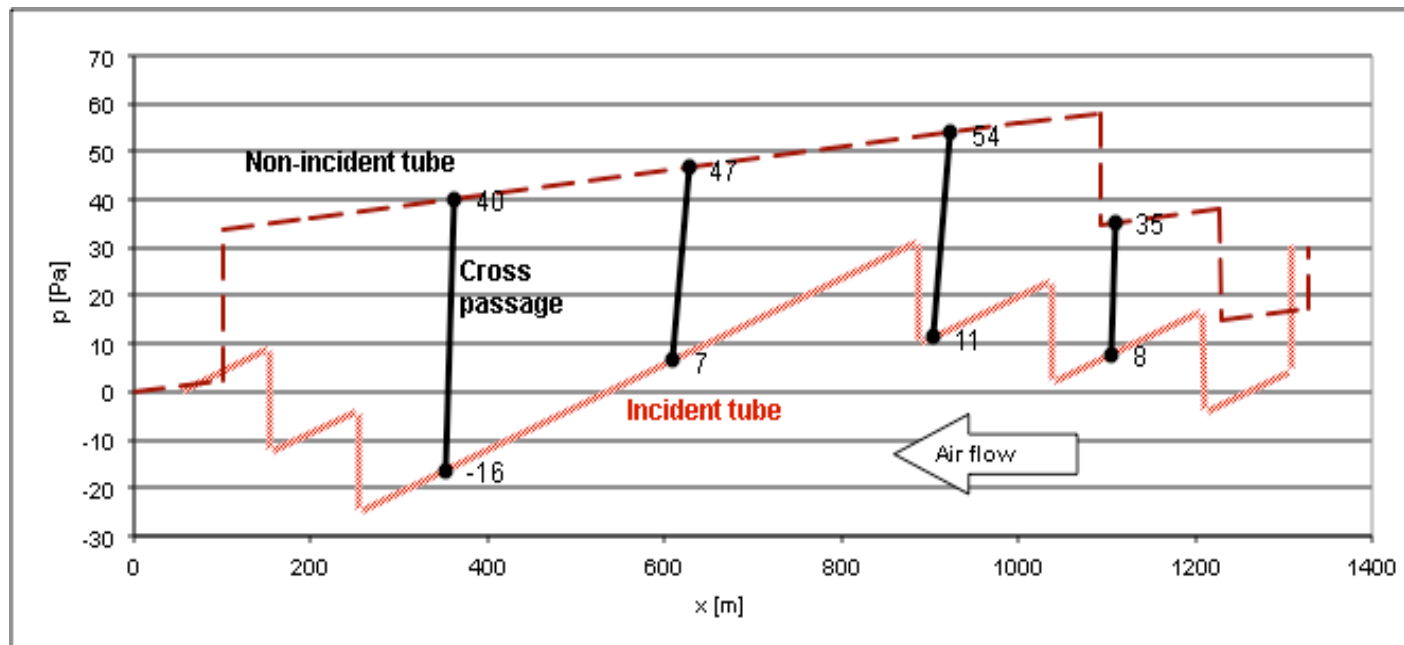
- Theory:  
Anti-recirculation wall  
(e.g. BD 78/99, Fig. 5.5)

Practice:  
Constructional measures don't work !



Most important: Prevent smoke propagation to adjacent non-incident tube by portals, open cross passages, ramps etc.

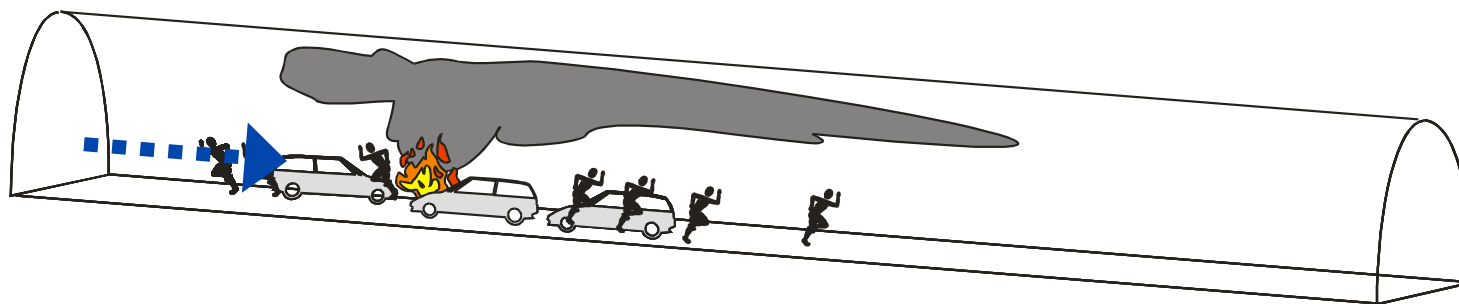
Fast flow reversal, build up overpressure,  $v_{\text{Target}} \approx -0.5$  m/s (with closed-loop control)



Most important: Prevent smoke propagation to adjacent non-incident tube by portals, open cross passages, ramps etc.



## Congested unidirectional traffic / Bi-directional traffic



tunnel users on both sides of fire location

- prevent flow inversion
- smoke movement < escape velocity (ca. 0.5 - 1.5 m/s)
- maintain possible smoke layer in ceiling

→ **Longitudinal ventilation**  
with closed-loop control of longitudinal airflow

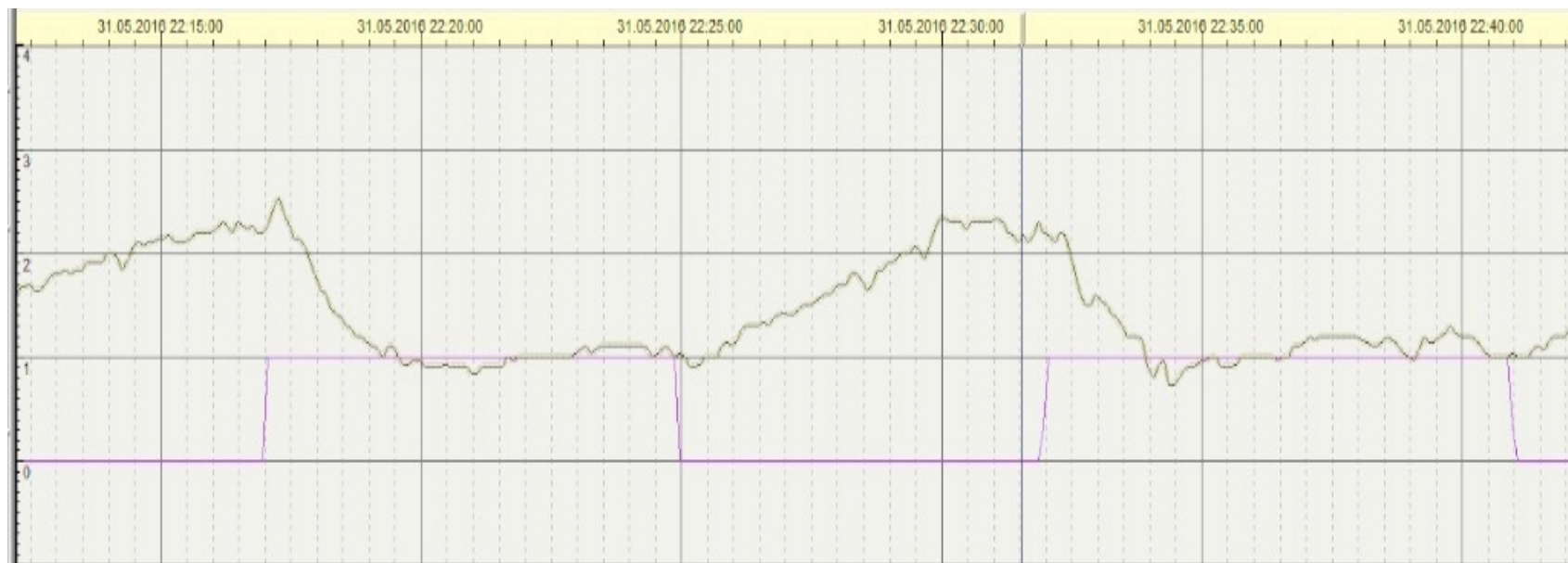
# Longitudinal ventilation

with closed-loop control of longitudinal airflow

Velocity target value:

- Smoke spreads faster than airflow
- Measuring uncertainty
- Fluctuations within bandwidth achievable by controller

→  $v_{\text{Target}} \approx 1 \text{ m/s}$  for tunnels Kat. B



# Longitudinal ventilation

with closed-loop control of longitudinal airflow

Precise and reliable measurement of flow velocity is essential !

- 3 independent measurements for plausibility check
- Calibration of instruments in the tunnel with grid measurement (according to ISO5802) is necessary

- Without flow measurement, fixed setting as a back-up (i.e. switch off !)

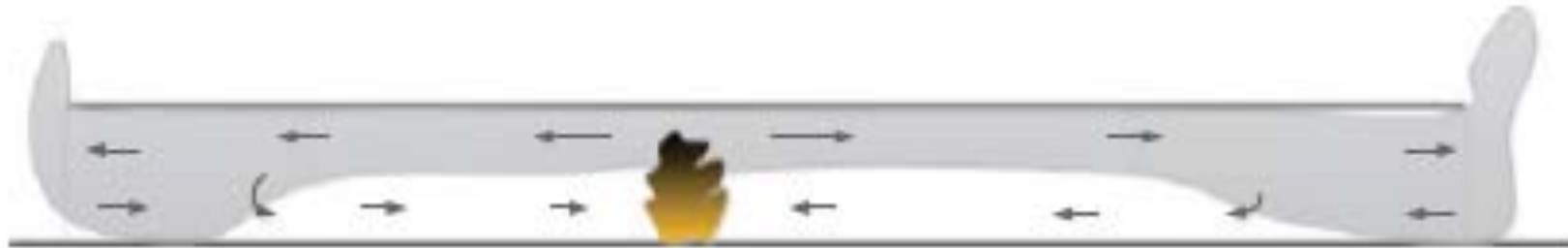


# Longitudinal ventilation

with closed-loop control of longitudinal airflow

Disadvantages:

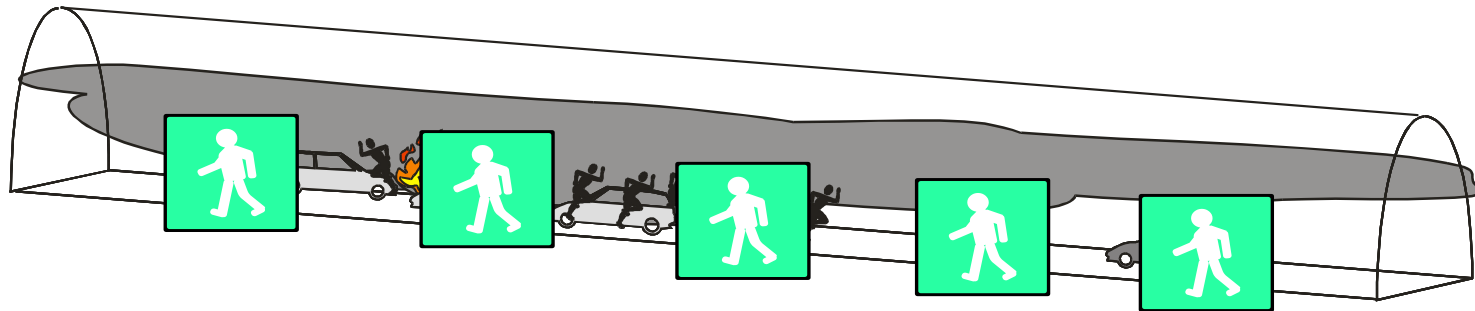
- Smoke stratification only over a limited length even under ideal conditions
- under traffic conditions, smoke stratification is less likely
- Sooner or later tunnel will completely be filled with smoke up to one portal
- People must react quickly, trapped persons are endangered



# Longitudinal ventilation

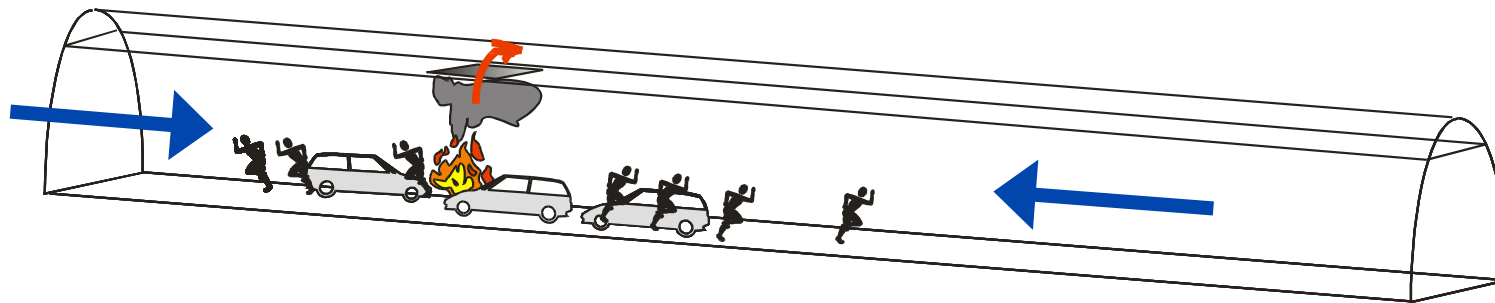
with closed-loop control of longitudinal airflow

→ For tunnels with high risk (high traffic volume, congestions or bidirectional traffic), longitudinal ventilation is allowed only in combination with escape ways in short distances



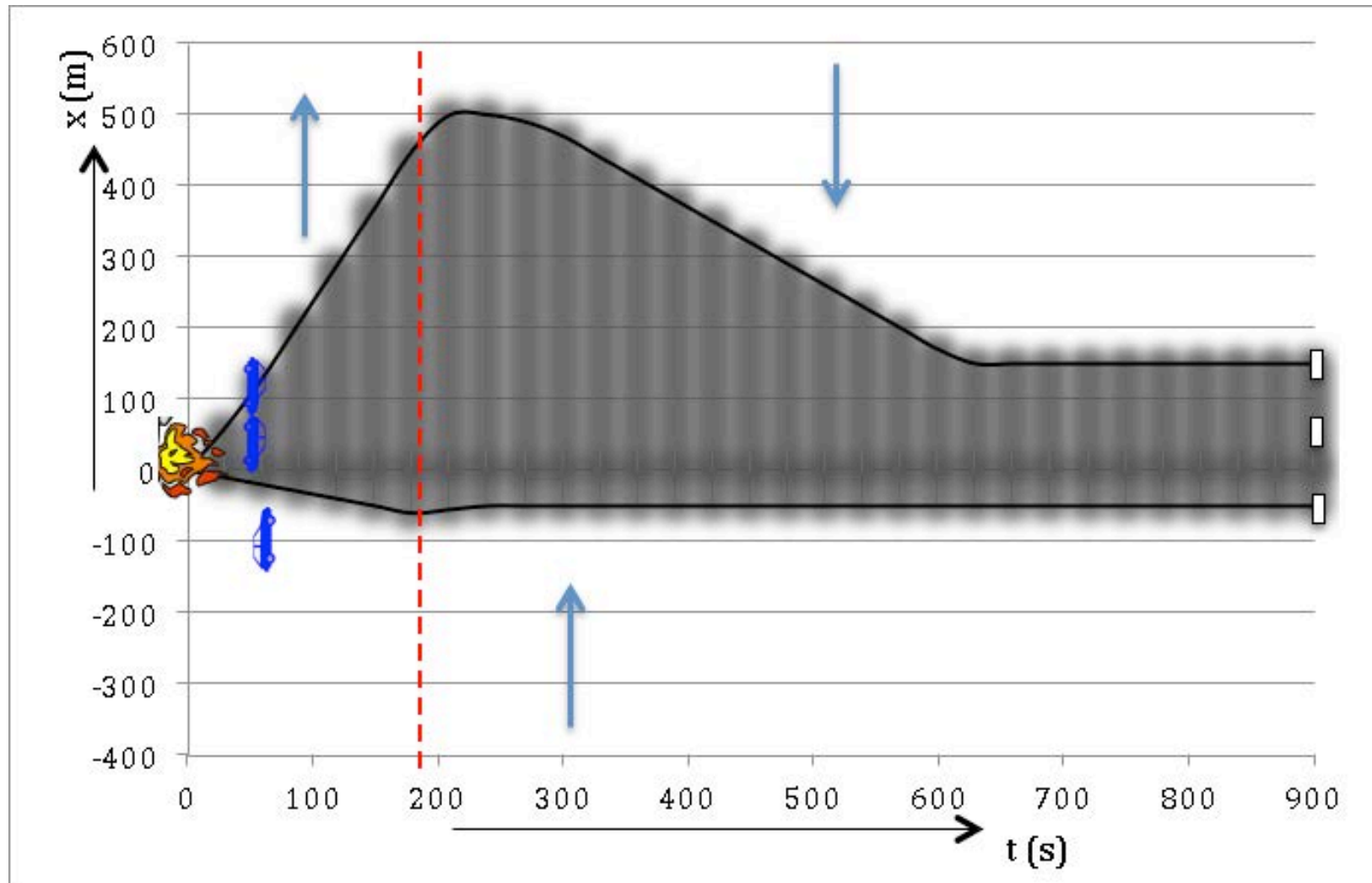
→ or concentrated smoke extraction...

# Very long tunnels with congested traffic / with bi-directional traffic → Concentrated smoke extraction



- limit smoke spread  
→ create smoke free zones on both sides of fire side
- remove smoke from tunnel, ideally near fire site
- defined airflow in tunnel towards extraction point  
→ Requirement of closed-loop control of longitudinal airflow

# Concentrated smoke extraction



## Concentrated smoke extraction

The time to drive the smoke back is in the same scale like the assumed escape time of people in the first phase

### Benefits:

- For people who are trapped in their cars
- For fire fighting  
(benefit for structure, not for tunnel users)
- Ventilation for normal operation



## Concentrated smoke extraction



### Disadvantages:

- Within extraction zone, tunnel is filled with smoke (where most persons are supposed to be !)
- Massive increase of costs for
  - Constructional measures (ducts, fan buildings, chimneys,...)
  - Fans, dampers, auxiliary equipment
  - Power supply

## Concentrated smoke extraction

Basic consideration whether a concentrated smoke extraction is useful in urban tunnels with unidirectional traffic:

**Can the vehicles ahead of the fire leave the tunnel with sufficient speed (faster than smoke propagation) ?**

Limit value:

approx. 2.5 m/s (controlled by ventilation) = 9 km/h vehicle speed

- Exit from tunnel must be enabled under any circumstances
- Depending on reliable traffic management on adjacent road network

**If not – are there emergency exits in short distances ?**

## Concentrated smoke extraction

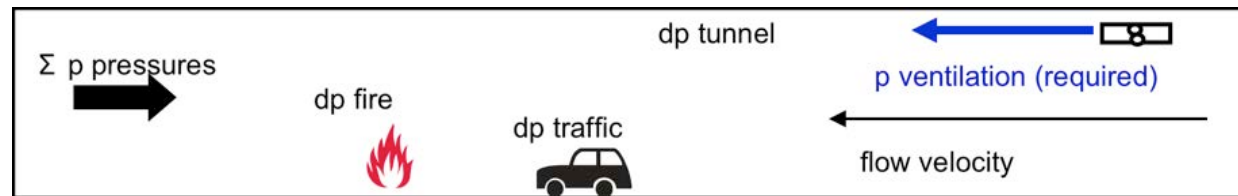
→ From the point of view of safety / costs per life saved,  
the high costs of a concentrated extraction cannot be justified !

Concentrated extraction is economically feasible  
for long tunnels with bidirectional traffic for normal operation  
(limiting soot / noxious substances in the tunnel)  
e.g. Alpine tunnels

# Closed-loop control of longitudinal airflow

Consequences for design:

Stationary design (target velocity, boundary conditions)  
as required by actual guidelines, is only of secondary importance



→ Dynamic design has to take into account:

- Inertia of moving air
- Wind fluctuations (short tunnels)
- Moving traffic behaviour (long tunnels)
- Assumptions on fire dynamics

## Closed-loop control of longitudinal airflow

Before 2000: Fixed settings – no reliable flow measurement  
– achievable flow in reality according to random boundary conditions

~ 2005: Stage switching

Flow velocity → number of JF to be switched on / off

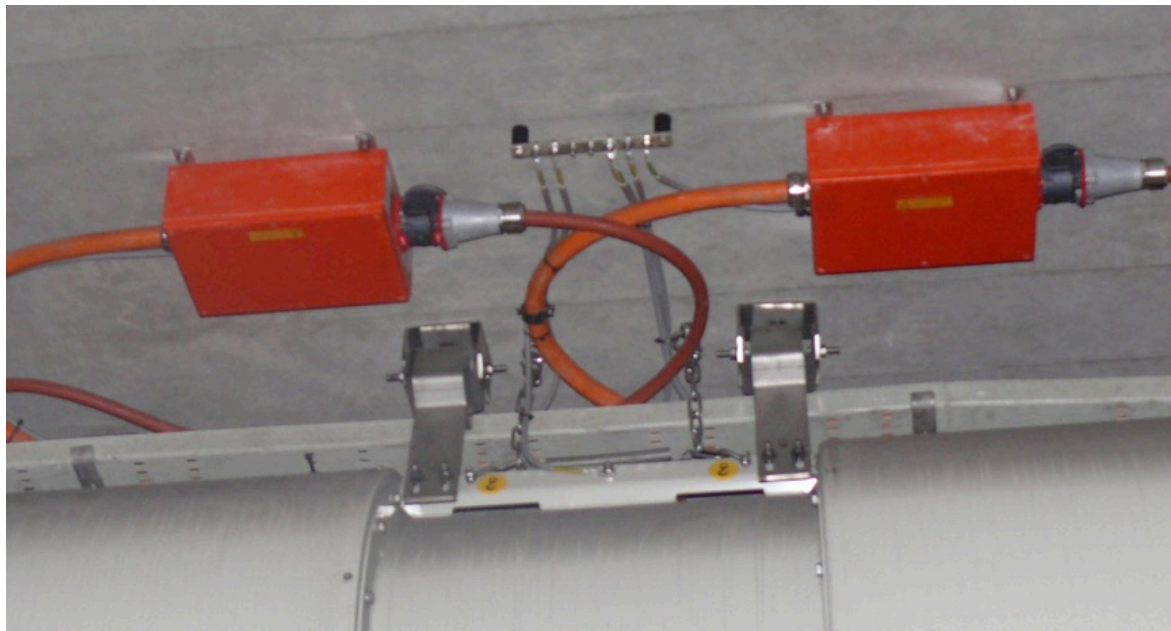
(switching tables based on tunnel model calculations, later use of PI-Controller)

- without VSD, target condition cannot be achieved fast enough, and often only very roughly
- Overheating of fan motors may lead to failure

$$F_{\text{sofl}} = \left( \begin{array}{l} F_{\text{istW}} + F_{\text{istO}} + (C_E + C_{\text{RF}} \cdot x_W) \cdot (C_{\text{TA}}^2 \cdot Q_A^2 - u_W^2) - (C_E + C_{\text{RF}} \cdot x_O) \cdot (C_{\text{TA}}^2 \cdot Q_A^2 - u_O^2) + (u_W^2 - u_O^2) + \dots \\ \dots + C_D \cdot \frac{C_{\text{TL}}}{\Delta t} \cdot (C_{\text{TA}} - 2 \cdot u_W(t) + u_W(t - \Delta t)) \end{array} \right)$$

## Closed-loop control of longitudinal airflow

- ~ 2010: Continuous control by Variable Speed Drive (VSD) and PI-Controller
- + Fast achievement of target condition
- EMC issues / Problems with long shielded cables between VSD and Fans
- Reliability of VSD
- Error proneness of centralised SCADA system

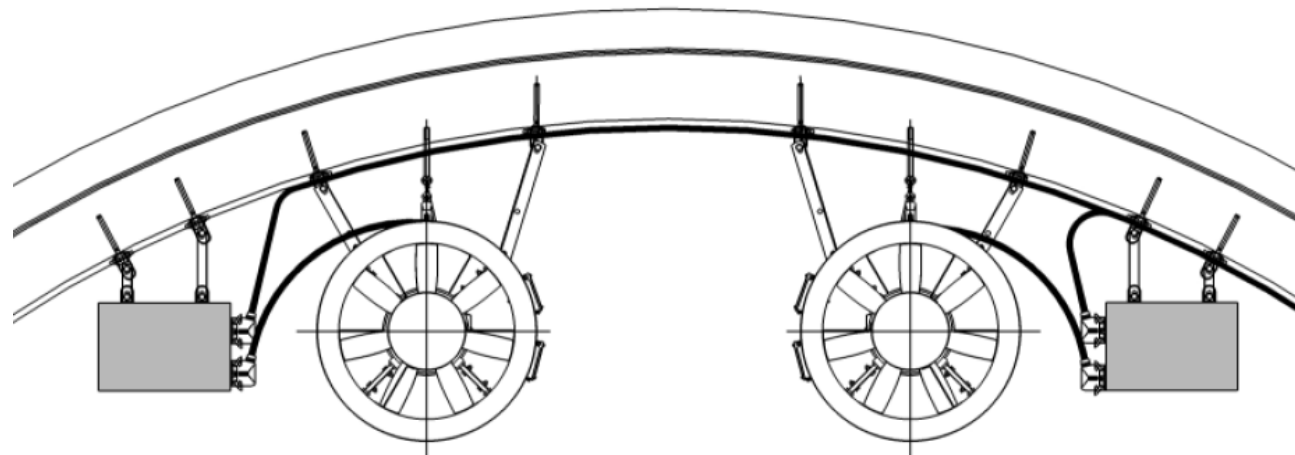


# Closed-loop control of longitudinal airflow

The State of the art:  
**Integrated Turn-Key System**

Jet Fans with Control Box, including:

- VSD
- Controller
- Flow measurement processing
- Communication interface (Ethernet)
- Switchgear / Bypass (→ additional redundancy)



# Closed-loop control of longitudinal airflow

The State of the art:  
**Integrated Turn-Key System**

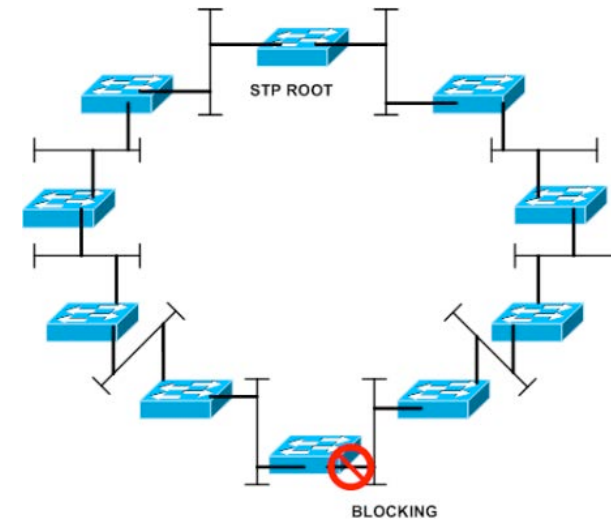
Control Box installed on

- tunnel ceiling
  - tunnel walls
  - niches
  - ...
- 
- + Suitable for corrosive tunnel environment / IP65
  - + Short cable length between Fan and VSD, EMC compliance
  - + High temperature resistance in bypass mode (up to 400°C)
  - + Standardized product → high reliability, low costs
  - + Easy to replace in case of failure, damage, or aging

# Closed-loop control of longitudinal airflow

The State of the art:  
**Integrated Turn-Key System**

- Modern Ethernet based Ring Communication between all control boxes and anemometers (according to clients requirements)
- Enabling a Decentralized Control of the Airflow as Turn-Key Entity  
→ clear assignment of responsibility
- Operating independently from / parallel to existing SCADA system



# Closed-loop control of longitudinal airflow

The State of the art:

## **Integrated Turn-Key System**

- + Increased redundancy and system reliability
- + Preassembled and tested before installation in the tunnel
- + Control previously optimized by 'Hardware in the Loop' Tunnel Simulator
- + Reduced time for implementation
- + Possibility of refurbishment of existing ventilation systems  
(VSD can be applied on 'old' motors by use of appropriate filters)



# Questions ?

**Lüftung von Strassentunneln**

**Kompendium und praktischer Leitfaden *(Deutsch)***

**Road Tunnel Ventilation**

**Compendium and practical guideline *(English)***

**Вентиляция автодорожных туннелей**

**Краткий курс и практические рекомендации  
*(по-русски)***

**→ [www.p-i.ch/books](http://www.p-i.ch/books)**