The Critical Velocity for Smoke Control

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Bill Kennedy

- Bill Kennedy was a leading thinker in the area of critical velocity
- Application of critical velocity concept in SES
- Author of several seminal papers on critical velocity

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Motivation for Talk

- Some tunnel ventilation capacities have been significantly overdesigned
- Has the ‘critical velocity’ concept been misused?
- How much we really need to ventilate tunnels in a fire emergency?

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Agenda

1. Critical Velocity Concept
2. Design Requirements
3. Operational Procedures
4. Risks of Over-Ventilation
5. Fire Suppression
6. Conclusions

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1. Critical Velocity Concept

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Backlayering Video

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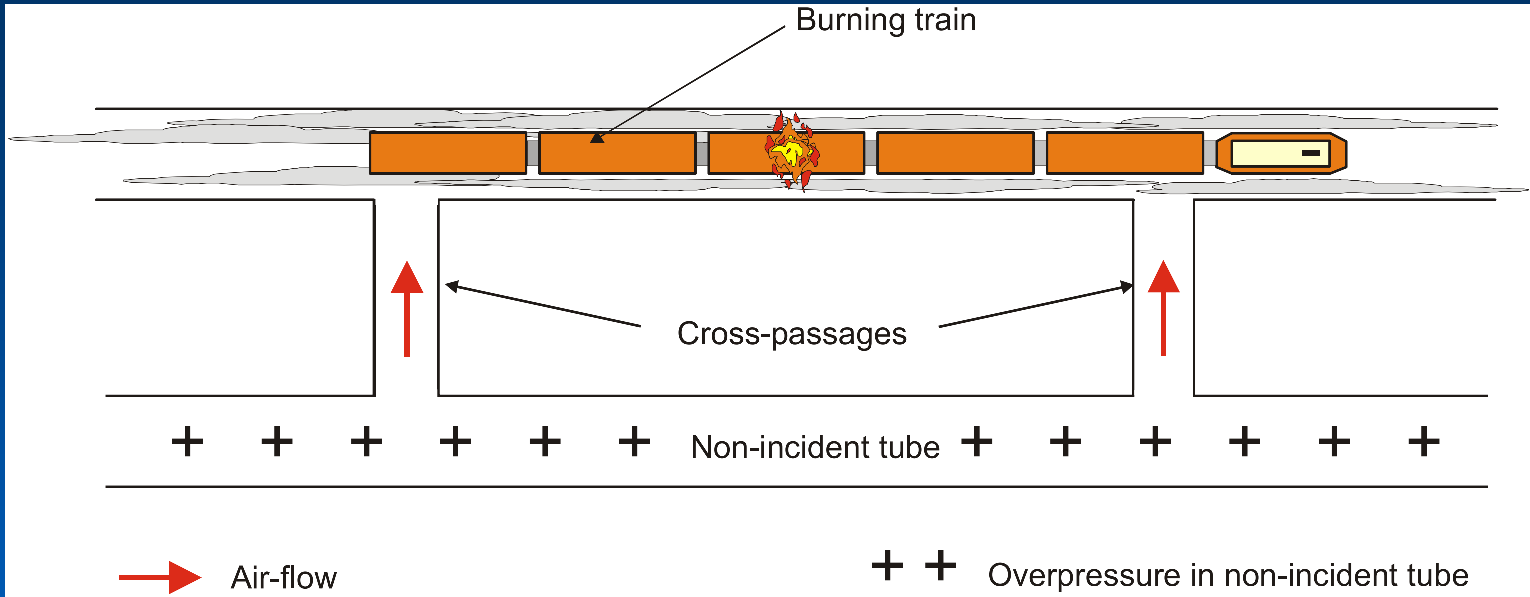
Critical Velocity Concept



➢ Generate a strong enough longitudinal flow to avoid back-layering

➢ Applies to main tunnel and also to cross-passages

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Basic Formulation

$$\mathrm{Fr_m} = \frac{gH(\rho - \rho_f)}{\rho U^2}$$

- Froude number = ratio between the buoyancy forces generated by the fire and the inertial forces due to the imposed ventilation air flow

Critical Velocity

$$V_c = \left(\frac{gH\dot{Q}_c}{\rho C_p A T_f Fr_c} \right)^{1/3}$$

$$T_f = \frac{\dot{Q}_c}{\rho C_p A V_c} + T$$

- Two coupled non-linear equations, to be solved simultaneously until convergence of the results

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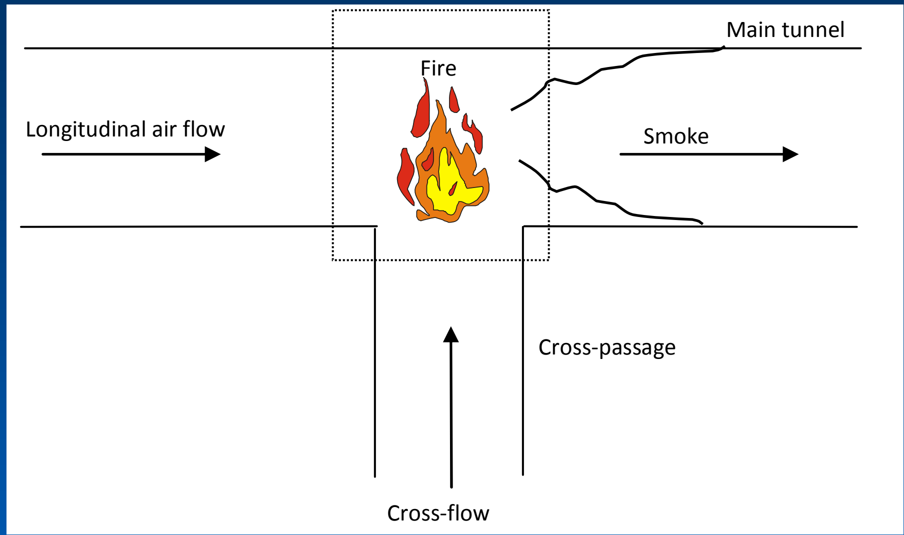
Cross-Passage Critical Velocity



- It is possible to calculate a critical velocity for smoke control in a cross-passage, in the same way as that for the main tunnel

Basic Assumptions

- Smoke is fully mixed with tunnel airflow *(not valid for high aspect ratio tunnels)*
- Ratio between the buoyancy forces generated by the fire and the inertial forces due to the imposed ventilation air flow is similar *(evidence from full-sized tunnels? high heat release rates?)*
- No heat transfer to surrounding walls *(conservative assumption – but cold smoke may sink)*

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Drawbacks of Current Approach

- Iterative approach – needs to be programmed (e.g. into Excel)
- Reasonable first guesses need to be supplied
- Convergence criterion needs to be applied
- No guarantee of convergence
- Can be a slow process

➢ *An analytical solution would be beneficial*

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Analytical Solutions

- Combine Froude number definition and enthalpy equation into a single equation
- This single equation is a cubic function of the critical velocity
- Establish the determinant of the cubic equation
- Find the roots of the cubic function
- Identify the real root

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Final Formulation

$$V_c = \hat{S} + \hat{T} - \frac{a}{3}$$

- Critical velocity can be calculated directly
- Identical results to iterative approach
- Very similar solutions available for cross-passage critical velocity

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Limitation

$$Q_c < \frac{\rho A C_p T}{2}\sqrt{\frac{27gH}{Fr_m}}$$

- Fire heat release rate limited to above value for the cubic determinant to remain below zero
- For typical road tunnel, the limiting rate is about 258 MW (hence no practical limitation)
- Is Froude number analogy applicable for higher heat release rates in any case?

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2. Design Requirements

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Tunnel Ventilation Concept Design

1. Define design fire
2. Define operational scenarios
3. Establish the required air velocities for smoke control
4. Calculate ‘hot case’ conditions
5. Calculate ‘cold case’ conditions

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'Hot' & 'Cold' Cases

- 'Hot' case: with fire, adverse wind, open cross-passage doors and with no fan redundancy → *check if critical velocity is achieved*
- 'Cold' case: without fire, favourable wind, closed cross-passage doors and with full fan redundancy → *check if air velocities exceed 11 m/s*

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Fan Redundancy

- Assumed destruction of fans due to fire
- Redundancy requirements in case of maintenance

Fire Size (MW)	Distance Upstream of Fire (m)	Distance Downstream of Fire (m)
5	-	-
20	10	40
50	20	80
100	30	120

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Design Consequences

- Due to analysis for the ‘worst case’ scenarios, tunnel ventilation systems are overdesigned for more typical fire scenarios
- Tunnel air velocities can be much greater than critical values
- Feedback control is a good option to consider

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3. Operational Procedures

Operational Procedures

- Actual performance of the tunnel ventilation system is dependent on operational procedures
- Influenced by uni- or bi-directional traffic flow, traffic control measures, application of fire suppression
- Feedback control of ventilation has a significant effect

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World Road Association Guidelines

CASE	TRAFFIC PRIOR TO INCIDENT	PRINCIPLE FOR LONGITUDINAL VENTILATION
A	Unidirectional traffic **without** traffic congestion	Flow velocities in the direction of traffic to prevent or at least minimize backlayering of smoke
B	Unidirectional traffic **with** traffic congestion	Relatively low flow velocities (e.g. 1.2 ± 0.2 m/s) in the direction of traffic in order to minimize flow spread upstream, allow smoke stratification, support dilution of toxic gases and enable people to escape.
C	Bidirectional traffic	Relatively low flow velocities should be maintained, to avoid flow reversal unless circumstances dictate otherwise (for example fires near portals), allow smoke stratification and enable people to escape in both directions.
Note: reference should also be made to National Guidelines, the EU Directive or similar for further advice on the design aspects relating to tunnel length, ventilation objectives and design etc.		

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Differing Country Approaches

- Ventilation control system is considered standard in a number of European countries including Switzerland and Austria, but not in the United Kingdom
- Austria: air velocity in unidirectional traffic between 1.5 m/s to 2 m/s, and for bidirectional traffic between 1 m/s and 1.5 m/s.
- For unidirectional traffic without congestion, German RABT guidelines require a minimum velocity of the air flow exceeding the critical velocity for smoke control.

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4. Risks of Over-Ventilation

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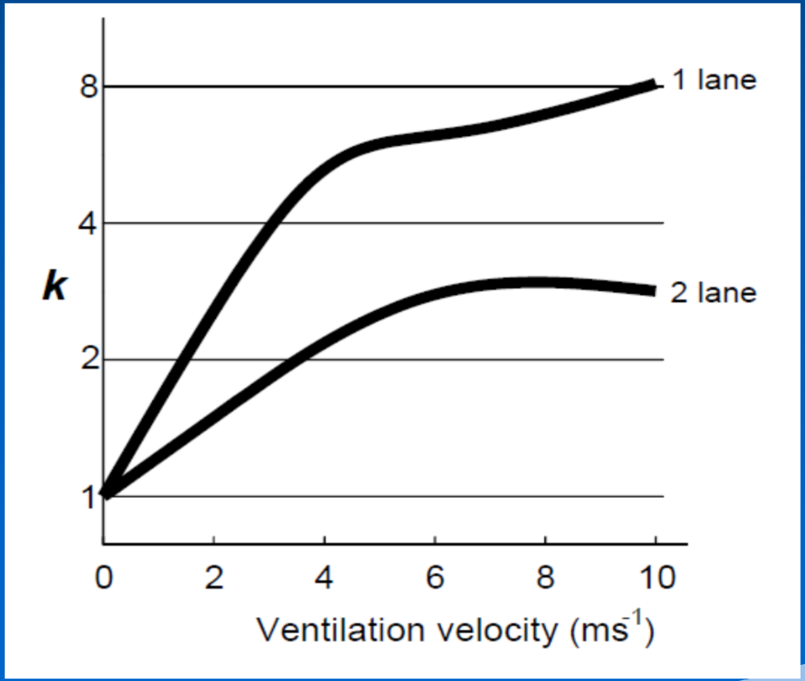
Risks of Over-Ventilation

- Destruction of any smoke stratification
- Enhancement of fire heat release rate



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5. Fire Suppression

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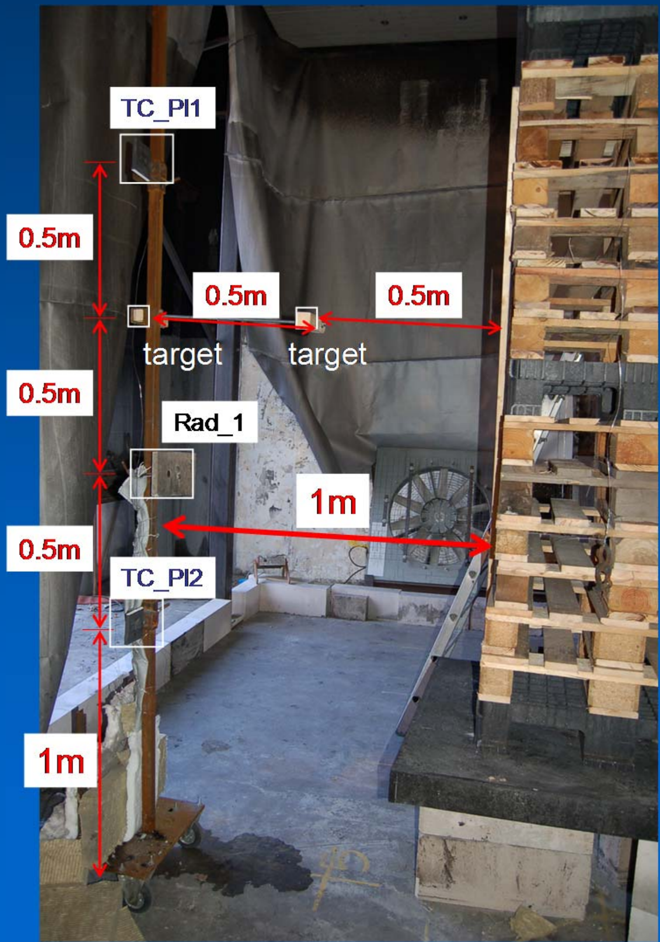
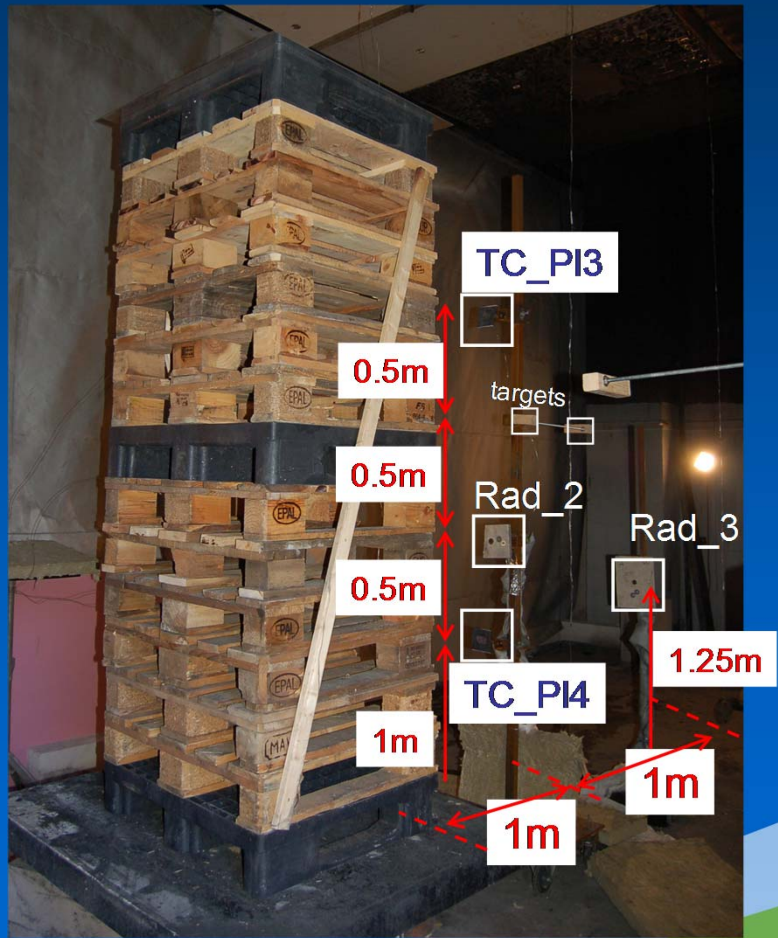
Fire Suppression - Lab Tests





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Energy Budget in Suppressed Fires

- Oxygen calorimetry: measures full heat release rate
- Measurements using stacks of wooden (80%) and plastic (20%) pallets
- Low-pressure deluge fire suppression
- 30-50% of the released energy is absorbed by evaporation of water
- 25-50% is absorbed by convective heat transfer to the gas phase

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Implications for Critical Velocity

- Reduced heat release rate can be assumed, e.g.

  140 MW HGV fire ⇨ 30 MW (suppressed)

  ⇨ 15 MW (convective, for critical velocity)

- Buoyancy of hot smoke reduced by water droplets (small droplets more effective)

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6. Conclusions

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Conclusions

- The critical velocity for smoke control is a useful concept, but should be used with care
- The actual velocity achieved in a tunnel may be very different from the design value
- Analytical solutions are available
- There are significant risks in over-ventilation
- Fire suppression can have multiple benefits

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