New Perspectives on the Critical Velocity for Smoke Control

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ABSTRACT

This paper presents new analytical solutions for the critical velocity for smoke control in tunnels and cross-passages. These analytical solutions for the critical velocity dispense with the need to solve for two coupled non-linear equations, and avoid the drawbacks associated with iterative approaches to solving for such equations. The paper also discusses the use of the critical velocity concept in road, rail and metro tunnels, both as a design objective and also as a target for emergency operations. It concludes that there are significant drawbacks in the generation of tunnel air velocities in excess of the critical velocity, due to the increased risks of fire growth and the destruction of any smoke stratification. The importance of tunnel ventilation control in emergency scenarios is therefore emphasised.

KEYWORDS: critical velocity, smoke, fire, tunnel

INTRODUCTION

Thomas [1] was the first to propose a simple relationship to determine the critical velocity needed to prevent the upstream movement of smoke from fire in a tunnel. He argued that the flow character depended, in essence, on the ratio of buoyancy to inertial forces over a cross-section of the tunnel, and that this ratio could be described by a parameter having the form of a Froude number, Fr_m:

$$Fr_m = gH\Delta\theta/(U^2 T) \tag{1}$$

where g is acceleration due to gravity, H is tunnel height, $\Delta\theta$ is the temperature rise above ambient, U is ventilation velocity and T is the hot layer temperature. Thomas assumed that the critical condition, when back-flow is just suppressed, occurs when Fr_m is of order unity, that is when the inertial and buoyancy forces are similar.

According to the experimental measurements of Lee et al [2], Froude numbers of less than 4.5 are required to preclude the movement of smoke against the imposed ventilation flow direction.

By relating the temperature rise of the hot gases from a fire ($\Delta\theta$) to the convective heat release rate from the fire $(\dot{Q}_c)$, Kennedy [3] proposed a formula for the critical velocity, such:

$$V_c = \left(\frac{gH\dot{Q}_c}{\rho C_p A T_f Fr_m} \right)^{1/3} \tag{2}$$

where the critical Froude number (Fr_m) is given by

$$Fr_m = 4.5(1 + 0.0374|\min(grade,0)|^{0.8})^{-3} \qquad (3)$$

and

grade = gradient of the tunnel in percent
A = cross-sectional area of tunnel (m^2)
ρ = density of upstream air (kg/m^3)

and the hot-gas temperature T_f is estimated from the enthalpy conservation equation:

$$T_f = \frac{\dot{Q}_c}{\rho C_p A V_c} + T \qquad (4)$$

Equations (2) and (4) form a coupled set that are solved within many well-used tunnel ventilation programmes including the Subway Environmental Simulation (SES) Computer Programme [4]. Nonetheless, Grant et al [5] have pointed out several methodological weaknesses in this model, including its failure to account for the complex near-fire flow field and the interaction between the fire source and the particular tunnel under consideration.

By analogy to the results for tunnels, Tarada [6] extended the model based on a critical Froude number approach to the calculation of the critical velocity within cross-passages. He proposed the simultaneous solution of the enthalpy equation for the junction between the tunnel and cross-passage:

$$(\dot{m}C_pT)_T + (\dot{m}C_pT)_d + \dot{Q}_c = (\dot{m}C_pT_f)_T \qquad (5)$$

(where the subscript 'T' refers to the main tunnel, 'd' refers to the cross-passage door and 'f' refers to the hot-gas conditions), with the equation for the critical Froude number at the cross-passage door, which is written as:

$$Fr_m = \frac{gH_d(\rho - \rho_f)}{\rho V_d^2} = 4.5(1 + 0.0374|\min(grade,0)|^{0.8})^{-3} \qquad (6)$$

One drawback of using the coupled non-linear equations (2&4) and (5&6) is that to date, no direct or analytical solutions were available. Rather, iterative approaches to solving the equations were employed. These have a number of drawbacks, including the need to provide a reasonable initial guess for the critical velocity, the complications relating to programming the iterative solution process, and residual errors due to incomplete convergence of the iterative solution. These issues will be resolved through the provision of analytical solutions to the critical velocities in tunnels and cross-passages in this paper.

ANALYTICAL SOLUTIONS

Critical Air Velocities for Tunnels

It is possible to recast equations (2) and (4) into the following single equation:

$$\left(Fr_m \cdot A \cdot C_p \cdot T \cdot \rho\right) \cdot V_c^3 + \left(Fr_m \cdot Q_c\right) \cdot V_c^2 - g \cdot H \cdot Q_c = 0 \qquad (7)$$

This represents a cubic equation for the critical velocity V_c, with up to three distinct solutions (roots). For a general cubic equation in the form

$$Ax^3 + Bx^2 + Cx + D = 0 \tag{8}$$

the nature of the three roots will depend on the value of the discriminant Δ [7]:

$$\Delta = 18ABCD - 4B^3D + B^2C^2 - 4AC^3 - 27A^2D^2 \tag{9}$$

The following cases need to be considered:

- If $\Delta > 0$, then the equation has three distinct real roots.
- If $\Delta = 0$, then the equation has a multiple root and all its roots are real.
- If $\Delta < 0$, then the equation has one real root and two nonreal complex conjugate roots.

From equation (7), the linear coefficient $C=0$, hence the discriminant $\Delta < 0$, as long as

$$Q_c < \frac{\rho A C_p T}{2} \sqrt{\frac{27gH}{Fr_m}} \tag{10}$$

For a road tunnel with the following parameters:

A=80 m^2, T=300 K, C_p=1040 J/(kgK), ρ=1.1 kg/m^3, H=6m, grade=0%

it can be seen that equation (10) implies that the discriminant $\Delta<0$ as long as $Q_c<258$ MW. Thus, for all practical purposes, equation (7) has only one real root. The term on the right-hand side of equation (10) may be considered an upper limit on the fire convective heat release rate for the Froude number analogy to have any physical meaning.

By reference to the analytical solutions for a cubic equation for the case of $\Delta<0$ given in [8], the critical velocity for smoke control in a tunnel is given by

$$V_c = \hat{S} + \hat{T} - \frac{a}{3} \tag{11}$$

where

$$\begin{aligned} a &= \frac{Q_c}{\rho C_p A T} \\[2mm] c &= -\frac{gHQ_c}{Fr_m \rho C_p A T} \\[2mm] \hat{Q} &= -\frac{a^2}{9} \\[2mm] \hat{R} &= \frac{-27c - 2a^3}{54} \\[2mm] \hat{S} &= \left(\hat{R} + \sqrt{\hat{Q}^3 + \hat{R}^2} \right)^{1/3} \\[2mm] \hat{T} &= \left(\hat{R} - \sqrt{\hat{Q}^3 + \hat{R}^2} \right)^{1/3} \end{aligned} \tag{12}$$

Equation (11) is the analytical solution for the critical velocity for smoke control in a tunnel. In order to check the feasibility of the solutions, comparisons were undertaken between the values provided by equation (11) and those generated through the coupled solutions of equations (2) and (4). Using the road tunnel example provided above with $Q_c=30\times10^6$ W, we arrive at $V_c=2.112$ m/s using equation (11), and the same result within three decimal places using four iterations of equations (2) and (4).

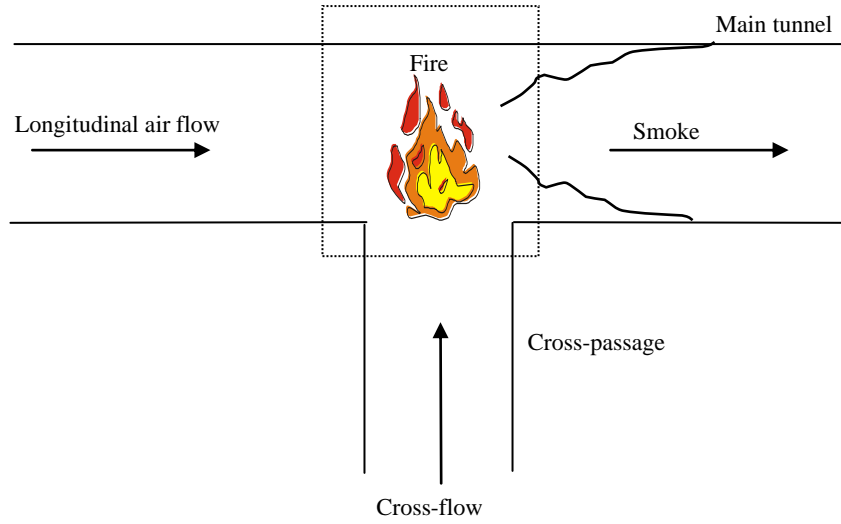**Critical Air Velocities for Cross-Passages**

Fig. 1: Control Volume for the Enthalpy Balance in a Tunnel Cross-Passage

A similar analytical solution can be inferred for the critical velocity in cross-passages. The enthalpy balance from equation (5) can be rewritten as

$$\rho A_T V_T C_p T + \rho A_d V_d C_p T + Q_c = (\rho A_T V_T + \rho A_d V_d) C_p T_f \tag{13}$$

Substituting equation (6) into equation (13), the following cubic equation can be derived for the critical velocity through a cross-passage door (V_d):

$$\{Fr_m \rho C_p A_d T\} V_d^3 + \{Fr_m [Q_c + \rho A_T V_T C_p T]\} \ V_d^2 - gH_d Q_c = 0 \tag{14}$$

By reference to the analytical solutions for a cubic equation with $\Delta<0$ given in [8], the critical velocity for smoke control through a cross-passage is given by

$$V_d = \hat{S} + \hat{T} - \frac{a}{3} \tag{15}$$

where

$$a = \frac{Q_c + \rho A_T V_T C_p T}{\rho C_p A_d T} \tag{16}$$

$$c = -\frac{g H_d Q_c}{Fr_m \rho C_p A_d T}$$

$$\hat{Q} = -\frac{a^2}{9}$$

$$\hat{R} = \frac{-27c - 2a^3}{54}$$

$$\hat{S} = \left(\hat{R} + \sqrt{\hat{Q}^3 + \hat{R}^2} \right)^{1/3}$$

$$\hat{T} = \left(\hat{R} - \sqrt{\hat{Q}^3 + \hat{R}^2} \right)^{1/3}$$

Equation (15) is the analytical solution for the critical velocity for smoke control through a cross-passage. In order to check the feasibility of the solutions, comparisons were undertaken between the values provided by equation (15) and those generated through the coupled solutions of equations (6) and (13). Using the road tunnel example provided above with $A_d=4.4$m^2, $H_d=2.2$m *and* $V_T=2$m/s, we arrive at $V_d=1.287$ m/s using equation (16), and the same result within three decimal places using two iterations of equations (6) and (13).

APPLICATION TO TUNNEL VENTILATION DESIGN

The estimation of the critical velocity for smoke control is only a small component in the process of tunnel ventilation design. The main steps in defining the required ventilation capacity for smoke control in a tunnel

1. Define design fire, including incident vehicle type(s) and heat release rates
2. Define operational scenarios, including vehicular traffic and wind conditions
3. Establish the required air velocities for smoke control
4. Calculate 'hot case' conditions (with fire, adverse wind, open cross-passage doors and with no fan redundancy)
5. Calculate 'cold case' conditions (without fire, favourable wind, closed cross-passage doors and with full fan redundancy)

While the purpose of step (4) is to ensure that sufficient ventilation capacity has been designed to control smoke movement, step (5) is required to ensure that the tunnel air velocity does not exceed 11m/s during its envisaged operation (as per NFPA 130 [9] and NFPA 502 [10], for example). This is particularly critical for tunnel ventilation systems that are installed without any feedback systems to control the tunnel air velocity during an incident.

THE CASE FOR TUNNEL VENTILATION CONTROL

Most tunnel ventilation systems designed to recent standards have significant levels of redundancy, and are capable of controlling smoke movement even during very adverse circumstances (adverse wind, open cross-passage doors, fans damaged due to proximity to fire). As an example of the level of jetfan redundancy required, the UK's Design Manual for Roads and Bridges BD78/99 recommends that the greater of two jetfans or 10% of the jetfans (to the next whole fan number) should be considered to be out of service, and a number of jetfans should be considered destroyed due to the fire, in accordance with Table 1. However, it is possible that during the initial stages of a fire, all the jetfans may actually be available, leading to a significant oversupply of fan capacity.

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

Table 1: Distances over which Jet Fans may be considered as destroyed during Fire [12]

It is certainly possible that a tunnel ventilation system may 'blow too hard' and actually increase the fire heat release rate from a burning vehicle. Fig. 2 depicts the possible enhancement factors 'k' of peak fire heat release rates from burning heavy goods vehicles (HGVs), as a function of tunnel ventilation velocity. Values of 'k' above unity indicate an enhancement in the fire heat release rate. The two curves shown are for single-lane and dual-lane tunnels The exact physical processes involved in the fire heat release rate enhancement are not well understood, but could involve providing additional oxygen to partially shielded fires within a burning HGV. Apart from enhancing the peak fire heat release rate, there is also the possibility of a higher fire growth rate within the burning vehicle, and of fire spread to other vehicles within the tunnel.
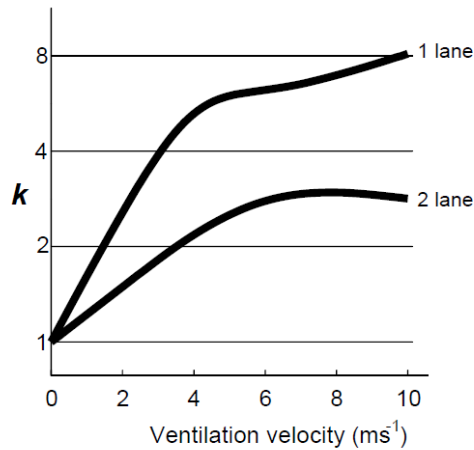

Fig. 2: Fire Heat Release Rate Enhancement Factors (after Carvel et al [11])

In order to avoid the drawbacks of excessive air velocities and possible fire enhancement, a control system may be required to monitor the tunnel air velocities and feed these air velocities back to an automatic control system. Such a ventilation control system is considered standard in a number of European countries including Switzerland and Austria, but not in the United Kingdom, for example. The Austrian design standard RVS 09.02.31 [13] specifies that the longitudinal ventilation system should reduce the air velocity in unidirectional traffic to between 1.5 m/s to 2 m/s, and for bidirectional traffic to a value between 1 m/s and 1.5 m/s. The Austrian design standard does not however mention any requirement to meet the critical air velocity for smoke control.

For unidirectional traffic without congestion, the German RABT guidelines [14] require a minimum velocity of the air flow exceeding the critical velocity for smoke control.

The World Road Association's report on "Operational Strategies for Emergency Ventilation" [15] provides three different cases for operational control of the tunnel air velocity in case of an incident, as summarised in Table 2. Although the text of the report does refer to the critical air velocity for smoke control, it does counsel that while high flowrates may have the advantage of reducing temperature and decreasing toxicity, they may lead to higher fire heat release rates and will completely destroy any smoke stratification.

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.		

Table 2: Strategies for Smoke Control with Longitudinal Ventilation Systems [15]

Any tunnel ventilation control system is critically dependent on the quality of the real-time air velocity measurements provided during an incident. Key issues to consider in any ventilation control system design include: the redundancy of air velocity sensors and their locations; the effect of hot smoke movement through the air velocity sensors, and the control algorithm to interpret significant differences in the measurements provided by the sensors, including elimination of false readings. None of these issues is insurmountable, however – perfectly feasible control system designs are available that address these challenges.

As our understanding of the risks of fire enhancement and smoke destratification due to excessive ventilation increases, it is likely that feedback ventilation control systems will become specified in tunnels as a matter of course. This is particularly true in the case of road tunnels, where the number of independent parameters that may affect the air velocity are generally greater than in rail or metro tunnels.

CONCLUSIONS

The concept of a critical velocity to control the upstream movement of smoke in tunnels has been available for many decades. This paper represents an effort towards quantifying the critical velocity, by providing analytical solutions for its value in tunnels and cross-passages. However, the paper also proposes caution in how the concept of a critical velocity is interpreted and applied in tunnel ventilation designs, since there are a number of drawbacks in the generation of high air velocities in tunnels during a fire emergency. These drawbacks include a possible enhancement of vehicle fires, and loss of smoke stratification. Careful engineering design, backed up by references to national and international guidelines, is therefore called for in the interpretation and application of the critical air velocity concept.

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