Critical velocity and tunnel smoke control Part 2
Filling the NFPA 502 void

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This article should be read as continuation of our earlier ("Part 1") note to the ATS about Annex D of (NFPA 502, 2020). It proposes a value for critical velocity, filling the void to be left by the intended removal of Annex D from NFPA 502 in a practical way, and also offers internationally acknowledged fire response strategies, and air speeds that could be used in those strategies, for smoke control in tunnel fires. The tunnel ventilation system plays a key role in providing acceptable air quality for tunnel users during normal operation as well as in smoke control and providing tenable escape conditions during a fire. The realisation of the first task is often relatively clear, whereas the control of the tunnel ventilation system during a fire is subject to debate. A comprehensive overview of different ventilation control approaches during a fire is given in (Sturm, Beyer, & Rafiei, 2015), but will be more briefly summarised in this article.

A very common approach is the 'critical velocity philosophy', where an upstream propagation of a hot smoke layer is just prevented. This type of smoke control is usually applied in the US, as the national standard NFPA 502 historically proposes such an approach and, until mid-2021, provides for information a formula in its Annex D for calculating critical velocity. Control of hot smoke by preventing any smoke propagation upstream of the fire is also often specified by clients in Asia, Africa and the Middle East, as well as Australia, via NFPA 502. This smoke control philosophy typically requires high upstream air velocities and causes even higher downstream velocities due to the heat released by the fire and the subsequent expansion of the air/smoke mixture. The resulting smoke propagation velocities are much too high to maintain reasonable stratification. With smoke mixed down, it is much harder to escape from the toxic combustion gases downstream of the fire. Such an approach can only be used for tunnels with unidirectional traffic, where it can be assumed that traffic downstream of the fire can exit the tunnel (i.e., tunnels with low congestion and low risk of a second incident downstream of the fire). Beside the smoke mixing effect, a high upstream air velocity is also likely to cause faster fire growth, a higher peak heat release rate, and greater fire spread (Lönnermark, 2005). Interestingly, (NFPA 502, 2020) also points out the risks and concerns of high velocities during a tunnel fire and discusses the allowance of backlayering of smoke within an already untenable zone in the vicinity of a fire, but still promotes a 'critical velocity philosophy'.

NFPA 502, after mid-2021, will probably still adhere to preventing backlayering, but without providing a formula, which is in practice how the sufficiency of a proposed design has often been assessed. In 2023, NFPA 502 will likely change from preventing backlayering to *controlling* backlayering. So, taking the 'prevention' of backlayering as the first approach to smoke control (at least for a couple more years), there is only a need to fill the void left by the retraction of Annex D, and provide a value for critical velocity. This was started by (Stacey & Beyer, 2020b), who noted that a value for critical velocity of 2.7 m/s (with grade correction according to (NFPA 502, 2020) and (Kennedy, 1997)) or 3.0 m/s (for tunnel slopes up to 3.2%) fitted most of the reliable data quite well, across a range of tunnel sizes relevant to road tunnels. The original data must be respected. Theories and simplified trends as to why the critical velocity data are the way they are, have been used in place of real data on many occasions. Such trends may be interesting, but, there is not yet solid, accepted physics that allows a trend to be imposed onto data to deal with 'noise' in the data. To the extent that they seek to represent data within a modelling framework that is uncertain, or even unlikely, trends are less reliable than looking at the original data, with an understanding of experimental variability. As also stated in (Stacey & Beyer, 2020a), (Stacey & Beyer, 2020b), (PIARC (C5), 1999) and (Grant, Jagger, & Lea, 1998) caution should be taken in interpreting or using data from small scale tests.

Figure 1 below plots observed critical velocities from full-size fire tests and the same data adjusted to zero backlayering, and a best fit curve. It is seen from Figure 1 that 3.0 m/s is a reasonable value for critical velocity of large fires in down-grade tunnels up to 3.2% slope, but may be over-estimating critical velocity for very small fires, and lower velocities are appropriate if a tunnel has very restricted fire loads (such as a tunnel only for passenger cars).

The plot, and the underlying data, also does not provide for the wide range of gradients in real road tunnels. We are not aware of a reliable data set that fills in that missing information, which is the reason why the plotted data in Figure 1 are not grade-corrected. Our recommended approach for tunnels with high gradients (especially >3.2%) and other aberrant tunnel characteristics right now (in the absence of a useful model) would be to carry out CFD of the subject tunnel, having previously calibrated the CFD technique (including software, inputs and preferably analyst) against a relevant known real case. CFD methodology recommendations for analysing smoke propagation in tunnel are given in (PIARC (C5), 1999), (Karki, Patankar, Rosenbluth, & Levy, 2000) and (Kashef, Benichou, & Lougheed, 2003).

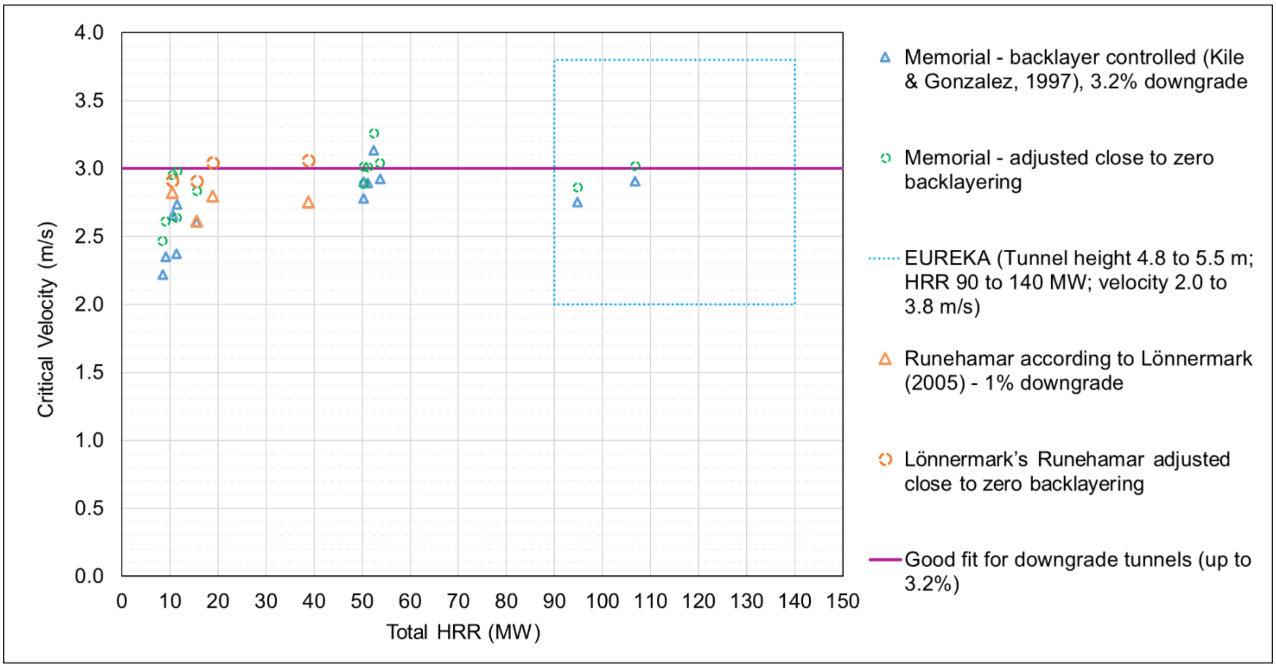

Figure 1. Critical velocity values from full scale fire tests with an applied best fit curve. Memorial Tunnel test data are taken from (Kile & Gonzalez, 1997), Runehamar test data from (Lönnermark, 2005) and EUREKA test results are from (EUREKA 499 Report, 1995), (Ingason, 1994), (Sorlie & Mathisen, 1994) and (Steinert, 1994). Note: Unlike the Memorial Tunnel Tests, the velocity in the Runehamar tests was not varied to pinpoint the conditions where the upstream backlayering of smoke was balanced or just prevented. As also stated in (Lönnermark, 2005), the HRR in the Runehamar test were transient and no real steady state conditions were reached. Caution should also be taken in interpreting the 'adjusted' Memorial and Runehamar data as the minor backlayering correction was also done by the method of (Li, Lei, & Ingason, 2010)*, problems with which resulted in the Annex D equations*

being urgently withdrawn from NFPA 502 2020. However, the corrections are minor, so in this case, the errors will be second order.

The following section looks at smoke control approaches that do not start with the premise that backlayering must be prevented absolutely.

A ‘low-velocity philosophy’ as proposed by (PIARC (C3.3), 2011) is implemented in several national regulations, such as in Germany ((RABT, 2016), Switzerland (ASTRA 13001, 2008), and Austria (RVS 09.02.31, 2014)). It is especially applicable for tunnels with bidirectional traffic, or unidirectional traffic with a risk of congestion (traffic downstream the fire cannot exit the tunnel). In this approach, the upstream (approaching ‘cold’ air) velocity is aimed to be between 1.0 and 1.5 m/s. This velocity range is known as the best compromise between allowing some backlayering of smoke and low smoke/air velocities downstream of the fire. The reduced inertia forces and low turbulence together with high buoyancy forces facilitate the smoke stratification and allow people to still escape downstream as well as upstream of the fire, underneath the smoke layer. In addition, the target velocity is below the walking speed of people in good visibility conditions (see (PIARC (C5), 1999) and (PIARC (C3.3), 2011)) which also improves the evacuation situation downstream.

While there is an agreement between the noted standards and regulations about the ventilation strategy for tunnel with unidirectional traffic with a risk of traffic congestion and bidirectional traffic, the ventilation philosophy for unidirectional traffic with low risk of traffic congestion in the tunnel is more controversial. The PIARC and the Austrian (RVS 09.02.31, 2014) regulation proposes a set point air velocity between 1.5 and 2.0 m/s. The Swiss regulation (ASTRA 13001, 2008), on the other hand recommends capability for a velocity of 3.0 m/s, which fits the critical velocity values in Figure 1 very well, but is not prescriptive about what velocity control for smoke should be applied operationally. The German regulation (RABT, 2016) prescribes a longitudinal velocity which corresponds to the critical velocity according to (Kennedy, 1997). The proposed critical velocity values are between 2.3 and 3.6 m/s, and are provided in tabulated form in the (RABT, 2016) for HRR between 30 and 100 MW, tunnel slope between 0 and 6% and typical two-lane tunnel profiles. These figures also correspond reasonably closely with the values already discussed and illustrated in Figure 1 when considering the tunnel slope variation.

Since the traffic situation during a fire (congestion, or clear tunnel downstream of the fire) may not be clear or cannot be assured, an operational ventilation strategy with a target velocity upstream of the fire of between 1.0 and 1.5 m/s is found appropriate in many cases, and is recommended as a base operational case until more information is known (Sturm, Beyer, & Rafiei, 2015), (PIARC (C3.3), 2011).

It is one thing to have a strategy as to how to control air speed, but it is another thing to be able to do it. In our experience, the effective control of the tunnel air velocity requires sensors at several positions along the tunnel. In Austrian tunnels, this is achieved by ensuring that all velocity sensors are subject to automated continuous plausibility checks, and by including three individual velocity sensors at the same location in the tunnel (see (RVS 09.02.31, 2014)). In addition, an adequate and well parametrised controller has been found essential to accurately maintain the upstream air velocity at the desired value, given the changing variables like buoyancy force, and external wind gusts acting on the tunnel portal during a fire. In long tunnels, traffic still moving through the tube is another disturbing influence on the control. More information about the implementation and requirements of such controllers can be found in (Ridley, Agnew, & Stacey, 2011), (Schmölzer, Sturm, Zettl, Koppensteiner, & Wierer, 2016) and (Euler-Rolle, Bammer, Reinwald, & Jakubek, 2016).

A quick detection of the incident and determination of fire location in combination with the right jet fan activation is also crucial in maintaining smoke stratification. Any jet fan activation or operation in the vicinity of the fire zone should be avoided as they introduce a high turbulence and would destroy any existing smoke layer. Jet fans already running in this area should be immediately switched off. The quick detection and determination of the fire location is important in this. The Swiss approach is to switch all jet fans off after the fire detection until the stationary fire location is determined. The need for rapid fire location information is then to allow the correct fans to be turned on.

For longitudinally ventilated tunnels with bi-directional traffic, fans upstream of the fire (beginning from the upstream portal towards the fire location) should be activated first, followed, only if required, by activation of fans downstream of the fire (also beginning from the downstream portal towards the fire location). In tunnels with unidirectional traffic and low risk of traffic congestion, a prioritised activation of downstream jet fans is preferable. First, this reduces the turbulence upstream of the fire (where tunnel users are more likely come to a stop) and smoke stratification may still be important. Second, by using downstream fans, the pressure upstream of the fire is more likely to be lower than the non-incident tube or egress tunnel pressure. Thus, the likelihood of smoke propagation into the non-incident tube or any egress path is greatly reduced. Reversal of air flow should certainly be avoided, to avoid surprising evacuees and de-stratifying the smoke.

When controlling the air velocity in the tunnel during a fire, the ventilation system reacts to the current situation and ensures similar flow conditions for different fire sizes, different wind conditions, traffic situations etc. Usually, a ventilation system is designed for the most onerous case of each parameter (HRR, adverse wind pressure, vehicle queue lengths inside the tunnel etc.). For most of the spectrum of fire cases, a lower number of jet fans is usually sufficient. In this way, active control allows the rational minimisation of jet fans in use, which also is beneficial in maintaining smoke stratification.

Besides maintaining smoke stratification and facilitating low propagation of smoke in the tunnel, passive safety measures like short escape routes or fixed firefighting systems are similarly important. The usual cross passage distance of 120 m in Australian road tunnels and a deluge system installed in almost every road tunnel represents a high safety standard. The short escape distances allow the tunnel user to escape hazards within a relatively short time. With the deluge system, the HRR of the design fire will be reduced, and so there is less need to design Australian tunnels for high critical velocities. Fire and Emergency Services are also able to approach via the non-incident tunnel and the cross passages.

The options suggested above leave the choice for specifiers and/or designers quite open.

Thankfully, engineers are well placed to deal with these types of uncertainties. Indeed, it is our professional duty to do so. Under most legal systems we are obliged to understand the limitations of existing practices, standards, and contractual obligations but to nonetheless formulate our designs by applying understanding and expertise. We are now aware of the limitations of previously published models for predicting critical velocity and must therefore turn our professional expertise to how best to size and control tunnel ventilation in fires, despite the shortcomings in the published approaches. To do so is nothing more than discharging our professional obligations as engineers.

Lastly, an update on the NFPA processes from the first article. Processes within the NFPA 502 are administratively very slow. Although the Chair of NFPA 502, as well as the working group on critical velocity, has already confirmed the immediate need to retract the formula for critical velocity in Annex D of (NFPA 502, 2020), the tentative interim amendment (TIA) to

NFPA 502 will not be issued before August 2021, and Committee Members must still be balloted on the TIA. However, there is no need to wait for the standard to be changed (the TIA to issue) as the technical issues are proven and our practices should change to reflect our knowledge on the current state of the art. Such action is required of us as professional engineers because we must exercise our professional skills - not just follow a standard or practice we know to be wrong.

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References

ASTRA 13001. (2008). *Lüftung der Strassentunnel - Systemwahl, Dimensionierung und Ausstattung (2008 V2.03).* Bern, CH: Richtlinie, Bundesamt für Strassen ASTRA.

Euler-Rolle, N., Bammer, C., Reinwald, M., & Jakubek, S. (2016). Model Based Dynamic Feedforward Control of Longitudinal Tunnel Ventilation. *8th International Conference 'Tunnel Safety and Ventilation'*, (pp. 212-219). Graz, AT.

EUREKA 499 Report. (1995). *EUREKA-Project EU 499: FIRETUN, Fires in Transport Tunnels, Report on Full-Scale Tests.* Düsseldorf: Studiengesellschaft Stahlanwendungen e.V.

Grant, G., Jagger, S., & Lea, C. (1998). Fires in tunnels. *Philosophical Transaction on Royal Society of London 356*, 2873-2906.

Ingason, H. (1994). Heat Release Rate Measurements in Tunnel Fires. *Proceedings of the International Conference on Fires in Tunnels* (pp. 86-103). Boras, Sweden: Swedish National Testing and Research Institute, Fire Technology, SP Report 1994:54.

Karki, K., Patankar, S., Rosenbluth, E., & Levy, S. (2000). CFD Modeler for Jet Fan Ventilation Systems. *BHR Group 10th ISAVVT.* Boston, USA.

Kashef, A., Benichou, N., & Lougheed, G. (2003). *Numerical Modelling of Movement and Behaviour of Smoke Produced from Fires in the Ville-Marie and L.-H.-La Fontaine Tunnels: Literature Review, National Research Council Canada.* NRC Puplications Archive.

Kennedy, W. (1997). *Critical velocity: Past, Present and Future (Revised 6 June 1997).* New York City: Parsons Brinckerhoff.

Kile, G. W., & Gonzalez, J. (1997). The Memorial Tunnel Fire Ventilation Test Program: The Longitudinal and Natural Tests. *ASHRAE Transactions 103, ProQuest Science Journals*, 701.

Lönnermark, A. (2005). *On the characteristics of fires in tunnels.* Lund University, Lund, Sweden: Dissertation, Department of Fire Safety Engineering.

NFPA 502. (2020). *Standard for Road Tunnels, Bridges, and Other Limited Access Highways.* NFPA 502.

PIARC (C3.3). (2011). *Operational Strategies for Emergancy Ventilation.* (P. C. (C3.3), Ed.) World Road Association (PIARC).

PIARC (C5). (1999). *Fire and Smoke Control in Road Tunnels.* (P. C. (C5), Ed.) World Road Association (PIARC).

RABT. (2016). *Richtlinie für die Ausstattung und den Betrieb von Straßentunnel (RABT).* Germany: Richtlinie, Forschungsgesellschaft für Straßen- und Verkehrswesen , Arbeitsgruppe Verkehrsführung und Verkehrssicherheit.

Ridley, P., Agnew, N., & Stacey, C. (2011). Automatic control of ventilation in short bi-directional road tunnels. *ISAVT14* (pp. 405-418). Dundee: BHR Group.

RVS 09.02.31. (2014). *Tunnel / Tunnel Equipment / Ventilation Systems - Basic Principles.* Wien, AT: Richtlinie, Österreichische Forschungsgesellschaft Straße - Schiene - Verkehr.

Schmölzer, G., Sturm, P., Zettl, D., Koppensteiner, W., & Wierer, A. (2016). Ventilation Control in the Case of FireÖ A Practical Approach to the Implementation of PI Controllers. *8th International Conference 'Tunnel Safety and Ventilation'*, (pp. 220-229). Graz, AT.

Sorlie, R., & Mathisen, M. (1994). EUREKA-EU 499 Firetun-project: Fire Protection in Traffic Tunnels - Measurements and Calculations of the Heat Release Rate in Tunnel Fires. Fire test "Heavy Goods Vehicle". *Proceedings of the International Conference on Fires in Tunnels* (pp. 104-116). Boras, Sweden: Swedish National Testing and Research Institute, Fire Technology, SP Report 1994:54.

Stacey, C., & Beyer, M. (2020a). Critical of critical velocity - An industry practioner's perspective. *10th International Conference 'Tunnel Safety and Ventilation'*, (pp. 220-235). Graz. Retrieved from https://www.tunnel-graz.at/assets/files/tagungsbaende/2020/13_Stacey_Beyer_Tunnel2020.pdf

Stacey, C., & Beyer, M. (2020b). Presentation on Critical of critical velocity - An industry practioner's perspective. *10th International Conference 'Tunnel Safety and Ventilation'.* Graz. Retrieved from https://www.youtube.com/watch?v=-5rTvTnCm1M&trk=organization-update-content_share-embed-video_share-article_title

Steinert, C. (1994). Smoke and Heat Production in Tunnel Fires. *Proceedings of the International Conference on Fires in Tunnels* (pp. 123-137). Boras, Sweden: Swedish National Testing and Research Institute, Fire Technology, SP Report 1994:54.

Sturm, P., Beyer, M., & Rafiei, M. (2015). On the problem of ventilation control in case of a tunnel fire event. *Case Studies in Fire safety, CSFS 22, Elsevier publishing, doi: 10.1016/j.csfs.2015.11.001.*