Physical reasoning behind the critical velocity equation development

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ABSTRACT: This paper provides additional background on the development of the Beyer Stacey Brenn equation for estimating critical velocity in tunnel fires. Building on the need for a more physically consistent model, it focuses on how the critical velocity problem was approached and explains and illustrates the underlying principles that formed the revised critical velocity model. The role of CFD validation and full-scale test data in shaping the model is highlighted, along with key design considerations that may clarify the intent behind the simplified model adopted in NFPA 502 (2026 edition).

1 BACKGROUND

Critical velocity, the air speed needed to stop smoke spreading upstream in a tunnel fire, is a familiar design parameter in our industry, especially in the US, Australia, Asia, Africa and the Middle East. For many practitioners, it's seen as settled science, supported by decades of testing, modelling, and international standards. It has not been that simple. The go-to reference for road tunnel critical velocity calculation has long been an annex to the US standard NFPA 502. The 2014 edition (NFPA 502, 2014) and prior editions referenced an equation proposed by (Danzinger & Kennedy, 1982) and (Kennedy, 1996). That equation followed a 1/3 power of the heat release rate, which is now known to be over-simplified, but it gave reasonable results compared to the Memorial Tunnel tests (MTFVTP, 1995a), (MTFVTP, 1995b) at around 50 MW or so, and consequently it had reasonable utility for road tunnel design.

The equations were adjusted in the 2017 edition of the NFPA 502 (NFPA 502, 2017) to better represent small-scale test results published by (Li, et al., 2010), (Li & Ingason, 2018) and were fully replaced in the 2020 edition (NFPA 502, 2020) by Li et al.'s proposed formula (Li, et al., 2010), (Li & Ingason, 2017), (Li & Ingason, 2019). These changes moved progressively further from values that were known and accepted. The adjustments in the 2017 edition increased ventilation requirements considerably for typical tunnels. In the 2020 edition, which was public late in 2019, the critical velocity values went up again, by around 40% over the 2014 values at 50 MW HRR (by using the Memorial Tunnel as example).

Based on the investigation by (Stacey & Beyer, 2020a), (Stacey & Beyer, 2020b) for the Graz conference in 2020, it has been made clear that the work by (Li, et al., 2010), (Li & Ingason, 2017), (Li & Ingason, 2019) and (Li & Ingason, 2018) overpredicts the critical velocity. That was because it used the critical velocity values recorded during the Memorial Tunnel data but 'corrected' them for backlayering which was neither there nor recorded in the test notes, and adjusted them using a tunnel height different from the one required by the formula the authors were supposedly using, as demonstrated in (Stacey & Beyer, 2020a), (Stacey & Beyer, 2020b), (Beyer, et al., 2021), (Li, et al., 2024). That fully explains why Kennedy (Kennedy, 1996) and Li et al. (Li, et al., 2010) could both claim support from Memorial Tunnel data for very different critical velocity values. The representation of the Memorial Tunnel data by (Kennedy, 1996) was correct. Based on these findings, Annex D of the 2020 version of the standard NFPA 502 was retracted in 2021 (NFPA 502, 2020).

The subsequent revision of Annex D in the 2023 edition of NFPA 502 (NFPA 502, 2023) re-instated equations from the 2014 and 2017 editions of NFPA 502 (except that the definitions of the tunnel height and tunnel area parameter had been changed). Having two equations with one of them (2017 edition) still connected to the 2020 edition did not achieve the required clarity. The investigations by (Shi, et al., 2022) and (Shi, et al., 2023) further revealed the connections to the 2020 edition and the 'limitations' of the equations in the 2017 edition. That led to work on a new Annex D for the 2026 edition (NFPA 502, 2026) and eventually to the adoption of the Beyer Stacey Brenn equation (Beyer, et al., 2024).

The paper explains how the critical velocity problem was approached and how mathematical modeling helped to understand and confirm observations from full-scale tests, which finally led to the physical model proposed by Beyer, Stacey & Brenn (Beyer, et al., 2024).

2 HOW TO APPROACH THE PROBLEM

The fundamentals about smoke movement in tunnels had already been established by Thomas in 1958 (Thomas, 1958), (Thomas, 1968), who concluded that the upstream spread of hot smoke in tunnel fires can be described by the ratio between the inertial and the buoyancy forces. The buoyancy force is of course related generally to the fire heat release rate (HRR), but more specifically to the density deficit. So, it appeared to be crucial to describe the density deficit in a way that is more relevant for the upstream smoke propagation (than just using HRR). To obtain equilibrium between the inertial and the buoyancy force in relation to upstream smoke propagation, the inertial force (velocity head) needs to be increased once the buoyancy force (density deficit) increases. Equipped with that understanding, further observations were made.

An observation was that all the analysed small-scale test data showed similar characteristics where the critical velocity increases with the HRR and then stays constant above a specific HRR (Oka & Atkinson, 1995), (Wu & Bakar, 2000) and (Li, et al., 2010). The Memorial Tunnel data in contrast showed that the critical velocity stays pretty much the same over a wide range of HRR (from a nominal HRR of 10 MW to 100 MW) (MTFVTP, 1995a) and (MTFVTP, 1995b). A further observation was that all the analysed small-scale tests used propane burners with a fixed diameter/area and increased the HRR by increasing the fuel flow (Oka & Atkinson, 1995), (Wu & Bakar, 2000) and (Li, et al., 2010) while the Memorial Tunnel tests had fuel pans (constantly re-filled with fuel-oil) where the HRR was increased by increasing the pool area (by adding fuel pans in longitudinal direction) (MTFVTP, 1995a) and (MTFVTP, 1995b). If the geometric tunnel parameters and ambient conditions stay the same for individual tests sequences, the only parameter that distinctly influences critical velocity is the density deficit relevant for the upstream smoke spread. For tunnel fires, a measure for the local density deficit (local temperature) is the heat release rate per unit area (HRRPUA or fire intensity). By putting the fundamentals and the observations together, it became clear that increasing the HRR by increasing the pool area in the longitudinal direction does not change the heat release rate per unit area (density deficit or fire intensity) and therefore does not change the critical velocity. In contrast, increasing the HRR (by increasing an LPG fuel flow) and keeping the burner area the same increases the heat release rate per unit area (density deficit or fire intensity) and so the critical velocity changes with HRR.

There is also a physical limit on the HRRPUA. If too much gaseous fuel gets injected (or evaporated) into a small area, some of it gets advected and burned downstream as also observed and confirmed by (Wu & Bakar, 2000). That extends the effective area of combustion downstream, keeping the fire intensity at the front of the fire nearly constant. This is believed to be the reason for the kink in the critical velocity plots, and the velocity becoming independent of further rise in the total HRR in the trend lines derived from small-scale tests. It appears that the characteristics of the trend lines are a result of the burner types used in the very confined space of small-scale tunnels, and therefore are not seen to be so relevant for real tunnel fires. However, they have contributed by confirming the relevance of fire intensity.

Based on the observations, it became evident that the fire intensity is probably the most important parameter for estimating critical velocity once the fire is large, but there was then a task to find out how much of the fire extent contributes to the plume dynamics and the density deficit relevant for building a smoke backlayer. There was that thought experiment regarding a petrol soaked mooring rope that may burn at 20 kW/m for 2500 m down the tunnel to give 50 MW total (Stacey & Beyer, 2020a). The last bit of the mooring rope 2.5 km away clearly does not contribute to the most upstream part of the fire or any backlayering. Especially for fires considerably extended in the longitudinal direction, the most upstream part of the fire will have the most influence on backlayering, with subsequent parts being progressively less influential.

The extent of the fire is of course directly connected to the HRR and fire intensity. The fire intensity depends on the fuel type (heat of combustion) and the burning rate (fuel to mix and burn before being advected downstream). For a given fuel type and burning rate, the HRR is proportional to the fire extent. With a fixed or maximum fire width, to increase HRR, the fire needs to extend in the longitudinal direction, and so critical velocity becomes more and more independent of the HRR.

A further parameter that was believed to be relevant for the local density deficit (local temperature) was the amount of air that gets mixed with the plume. Much of the air arriving along the tunnel may bypass the plume front, especially if the fire is narrow (relative to the tunnel width) or the ratio of tunnel width to tunnel height is high.

All these observations and considerations needed to be implemented in a physical model with the aim of estimating critical velocity from both small-scale tests and full-scale tests, with a priority on the full-scale tests as being the most relevant. This approach ensured that the geometrical dependencies were adequately taken into account.

To confirm certain dependencies (e.g. grade factor, width of the fire) there was also a need for a validated CFD model. Despite earlier gravity-related research, grade was not so readily adjustable in the Memorial Tunnel. So, one of the first tasks was to build a CFD model and establish a methodology that was able to appropriately reproduce the Memorial Tunnel full-scale test data over a wide range of HRR (10 MW to 100 MW). More details about the validation of the CFD model can be found in (Beyer, et al., 2024) and (Beyer & Stacey, 2022).

As demonstrated in the noted references, the CFD model methodology used could represent the smoke propagation and temperature distribution of the Memorial Tunnel tests with sufficient accuracy for the three different fire sizes. With that confidence in the model methodology, the relative change of critical velocity between a sloped tunnel and a flat tunnel based on the Memorial Tunnel geometry and fire characteristics was analysed for different tunnel slopes. This was done for a nominal fire size of 50 MW, as, based on tunnel design practice, it is perhaps the most relevant fire scenario for road tunnels. As noted in (Beyer, et al., 2024), it was concluded that for most design purposes, the grade factor can be ignored for the critical velocity problem (when there is no smoke propagation upstream of the fire front).

However, as discussed in a different study by (Beyer & Stacey, 2024), the tunnel slope affects the backlayer dynamics if upstream smoke propagation is controlled to a certain maximum smoke backlayer distance ('confinement velocity'). It is shown that in some circumstances, the backlayer distance is lower for downgrade tunnels at the same airspeed.

The derived equations indicated that there might be a dependency of critical velocity on the width of the fire. The Memorial Tunnel tests had the same fire width throughout all tests and the small-scale results (Oka & Atkinson, 1995), (Wu & Bakar, 2000) and (Li, et al., 2010) were not sufficient to fully understand the trend between fire width and critical velocity (e.g. change in fire intensity, insufficient datapoints, use of water spray, lack of systematic parameter change). The most economical way to find an answer was to use the validated CFD model based on the Memorial Tunnel geometry and change the fire width systematically, keeping everything else the same (e.g. length of the fire pan, fire intensity, tunnel profile etc.). The CFD results showed that the critical velocity decreases if the fire width increases. The observed behaviour can be explained by considering that the frontal area of the rising plume represents an obstacle for the flow past the fire. If the fire is wide and spans almost across the tunnel width, there is not much space for the oncoming air to go around the plume. Therefore, the plume becomes more deflected by the upstream flow, and more mixing into the plume occurs, so that the upstream velocity required to prevent backlayering goes down. This finding on fire width was not new, as Oka & Atkinson made similar observations in small scale tests (Oka & Atkinson, 1995). An appropriate correlation that describes the behavior was found and implemented via the function K_F (see (Beyer, et al., 2024)).

For the full development and for the holistic set of the Beyer Stacey Brenn equation, limitations and parameter description, please refer to the original source (Beyer, et al., 2024), https://doi.org/10.1007/s10694-024-01607-8.

2.1 *Validation and checking behaviour of equations*

If the relevant physical factors that influence critical velocity are captured, then the equations should be able to reproduce results from full-scale as well as small-scale tests. The empirical constants in the equations were adjusted to match both full-scale and small-scale test results, keeping the empirical constants the same throughout the comparison with different test results (trying to capture the variety of the different tests such as tunnel geometry, fire geometry, fire intensity, HRR etc. with one set of empirical constants). That process was assisted by the validated CFD model, where different parameters were systematically varied (e.g. fire intensity, fire length, fire width, tunnel profile) to increase the variety of the data and confirm that the derived empirical constants were appropriately calibrated. The CFD allowed trends for individual parameters to be explored, before seeking an overall 'best fit' with all test datasets considered. The derived empirical factors and constants can be found in (Beyer, et al., 2024).

3 CONSIDERATIONS FOR DESIGN

The full set of equations, providing adjustment for all sorts of scenario parameters, are good for comparison against specific tests. However, for practical design, many of those parameters cannot be known or assumed, as a design fire is usually defined by a HRR and not a particular fire scenario. A tunnel design needs to address reasonably foreseeable fires (so far as is reasonably practicable) that can lead to the design fire HRR (e.g. most onerous possible fire scenario such as pool fire). Designers will not know the width or length or intensity of a 'design' fire, or the height of the fire seat. Appropriate values need to be assumed, taking a conservative view within reasonable bounds. A set of such assumptions led to a simplified equation (as presented in Section 6.3 in Beyer, Stacey & Brenn (Beyer, et al., 2024)) that is sufficient for most design purposes. The assumptions are summarised below but for the set of simplified equations and their limitations please refer to (Beyer, et al., 2024).

The greatest critical velocity from a fire relates to the fire seat being on the roadway with a high heat release rate per unit area, such as a pool fire. It is reasonable that some fuel load may spill down to the roadway as a result of collision or the fire, so the fire plume height will be taken as the tunnel height (from floor to highest point at the ceiling). With the fire width dependence discussed in Section 0 and using the Memorial Tunnel parameters as an example, it turns out that for road tunnels with similar geometrical characteristics, critical velocity is about at a maximum for fire seats about 2.5 m wide. As this is the same as the width of a truck and is a potential spill width (Beyer, et al., 2024), it was a realistic but conservative figure to adopt for design. With tunnels typically much wider than 2.5 m ($A > H(2.5\ [m] + 0.35 \cdot H)$), that makes the minimum function noted in the denominator of ΔT_p in Equation (36) of (Beyer, et al., 2024) redundant. Most tunnel designs need to address fires much larger than 10 MW (for tunnel height $H < 9\ m$), so the minimum function noted in the numerator of ΔT_p in Equation (36) of (Beyer, et al., 2024) can also be discarded. Hydrocarbon pool fires are about as intense as fires come, so the fire intensity can reasonably be taken from a pool fire value (on the roadway).

The Beyer Stacey Brenn equation presented in (Beyer, et al., 2024) are not derived or validated for fires with considerable blockage. The blockage would have additional effects on the plume and would require an appropriate implementation in the equations. However, as a tunnel design can't rely on a considerable blockage once a fire occurs, such a scenario was not seen to be important for the study.

The several years in which the design guidance from NFPA 502 (NFPA 502, 2017), (NFPA 502, 2020), and (NFPA 502, 2023) lost its way has been the driver for improving the science of critical velocity estimation, with the improved critical velocity model now serving that purpose, including within NFPA 502 2026 edition (NFPA 502, 2026).

After establishing a sensible critical velocity value for a proposed tunnel, the ventilation power and equipment to achieve that can be determined and designed. Whether critical velocity is the appropriate operational target for any particular fire scenario is a different matter, for another discussion.

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