CRITICAL OF CRITICAL VELOCITY – AN INDUSTRY PRACTITIONER'S PERSPECTIVE

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ABSTRACT

Scale modellers have fuelled increased estimates of critical velocity, which have in turn found favour in client's requirements, and even the US standard NFPA 502. These increased values are causing problems on projects. Left unchallenged, they cause substantial increases in the required numbers of jet fans in road tunnels, and thereby increase capital cost, operational costs and system complexity. Importantly, during a tunnel fire, the resulting higher velocities potentially degrade any smoke stratification and cause a faster fire growth, possibly also fire spread between vehicles. With those incentives, the technical backing for the changes to the critical velocity values resulting from Annex D of NFPA 502 (2020) has been reviewed. The question is: Were the earlier critically velocity estimates flawed, or is there some systematic problem with the more recent approaches to their calculation? Clearly, as they are different by a factor of around 1.6 for a 50 MW road tunnel fire, the old and the new approaches cannot both be correct. The conclusion is that the important physical effects and flow characteristics for determining critical velocity in real tunnels are different to those in scale model tunnels, especially those used to support the 2020 NFPA 502 Annex D equation, and they do not scale to full size. The 2020 Annex D equation does not predict critical velocity in real tunnels.

Keywords: critical velocity, scaling, tunnel ventilation, 2020 NFPA 502

1. INTRODUCTION

For those new to the tunnel smoke control field, and those unfamiliar with practice based on US NFPA standards, in tunnel smoke control, "critical velocity" is that velocity of incoming air at which the upstream propagation of a hot smoke layer is just prevented (Danzinger & Kennedy, 1982), (Kennedy, 1997).

European approaches to keeping motorists safe from smoke do not rely upon critical velocity (RABT, 2016), (ASTRA 13001, 2008), (RVS 09.02.31, 2014). Especially for bidirectional traffic and tunnels with high congestion, the European Standards refer more to a 'low velocity' philosophy to preserve any smoke stratification and to allow tenable self-rescue conditions as far as possible. A good discussion about the different ventilation philosophies during a fire and the different applied velocity approaches are given in (Sturm, Beyer, & Rafiei, 2015).

Australian tunnel engineers struggle with the problem of having a document in the public domain that has dramatically increased the ventilation required for the design fire cases. By implication there might be something seriously wrong with ventilation systems designed to achieve the previous lower critical velocities.

Both authors of this paper were once fluid mechanics researchers, and are now focussed on engineering real tunnel ventilation and fire safety designs. In that capacity, designers would often like to ignore critical velocity, but it keeps coming up as a design requirement, generally via project documents invoking the US standard NFPA 502 (NFPA 502 is often specified by clients in Asia, Africa and the Middle East, as well as Australia). In the 2014 edition of NFPA 502, the equation for critical velocity appeared reasonable, in that there seemed to be a plausibility around the Annex D formula relative to known full-size tests. It was understood to be conservative for typical road tunnel design fires. It may have under-predicted critical velocity for small fires, but that had no relevance to road tunnel design. The velocities were not too high in terms of maintaining some smoke stratification and satisfying other concerns related to high velocities during a tunnel fire. For many tunnels, it did not push the design provisions above what was required to manage pollution from the prevailing fleet mix in heavy congestion. That is, it could be accommodated without a serious impact on sensible design for tunnel projects, so there was no incentive to examine it closely.

Less and less ventilation of pollution is required for a progressively cleaner vehicle fleet. The climate emergency should mean that at least the passenger car fleet, and maybe trucks, should be mostly non-polluting over the next 10% or 20% of a tunnel lifespan. At the same time, NFPA 502 is suggesting that up until 2017, we have got it badly wrong on ventilating for fire and in 2020, perhaps 1.6 times the air flow (for a 50 MW fire, Figure 1) is needed, which becomes something like 2.7 times the jet fans, and much bigger extraction flows if smoke is to be captured. This has a large cost impact with probably no improvement in fire safety, when the concerns related to high velocities are also considered. In terms of tunnel fire safety, it is probably better to have a project-specific solution in terms of smart jet fan activation and smoke management (as proposed in (Sturm, Beyer, & Rafiei, 2015)) rather than having high velocities to prevent any backlayering. However, it is understandable that the fulfilment of one equation as a design requirement, independent of the specific tunnel characteristics (traffic situation, fire risk, egress distance, ventilation system etc.) is appealing. It is easier to apply and to check/verify, and is more suited to prescriptive standards and regulations.

2. A VERY SHORT HISTORY OF CRITICAL VELOCITY IN NFPA 502

The earliest critical velocity paper (Thomas, 1958) that Agnew and Tuckwell (2017) discussed looked at smoke layering in mines, cautioning that the answer will vary with the position and size of fire in the passage. Thomas' approach was based on Froude number but also stated that the fire size and geometry would be important. Various other authors like (Oka & Atkinson, 1995) and (Kennedy, 1997) also discussed the influence of fire dimensions, both in isolation, and in relation to the tunnel geometry. As elaborated below, the current formula does not reference the fire dimensions or any of the effects of them, which is a problem when using scaled results. So, over the last 62 years, the main difference is that we have chosen wrongly to neglect a key parameter. A more extended discussion about this can be found in (Agnew & Tuckwell, 2017). Development of the old NFPA 502 formula did not reference fire geometry or intensity either, but it acknowledged full-size test data and so inherently reflected some realism in fire intensity.

The buoyancy (density deficit) of a smoke plume creates a driving pressure for the smoke to spread in all directions under the ceiling. The dynamic pressure of the flow arriving from upstream resists the upstream spread of the smoke. A Froude number, which looks at the gravity-related buoyancy against the flow dynamic pressure, seems like it might be a reasonable place to start, as indeed Thomas did in 1958. A Froude number has been central since then.

(Kennedy, 1997) looked at the past, present and future of critical velocity and gave the background to the NFPA 502 formula current up to and including 2014 issue. Kennedy proposed to use the total heat release rate (HRR) rather than the convective HRR to first be conservative and second, to match the Memorial Tunnel test results. That formula was changed in NFPA 502 in 2017, when NFPA added conservatism to the approach based largely on the work of (Li, Lei, & Ingason, 2010). In the 2020 version of NFPA 502, the newly adopted formula was taken more directly from their work (Li, Lei, & Ingason, 2010) and (Li & Ingason, 2017).

A different version of the recent NFPA 502 developments is given in (Bowman, 2019).

Figure 1 shows a plot of critical velocity against total heat release rate for typical (3-lane) road tunnel dimensions at zero slope. The obvious question is: Were the earlier critically velocity estimates so badly misguided, or is there some systematic problem with the recent approaches? Note that the equations in NFPA 502 2014 and 2017 are based on the convective heat release rate, while the approach in NFPA 502 2020 reverts to the total heat release rate.

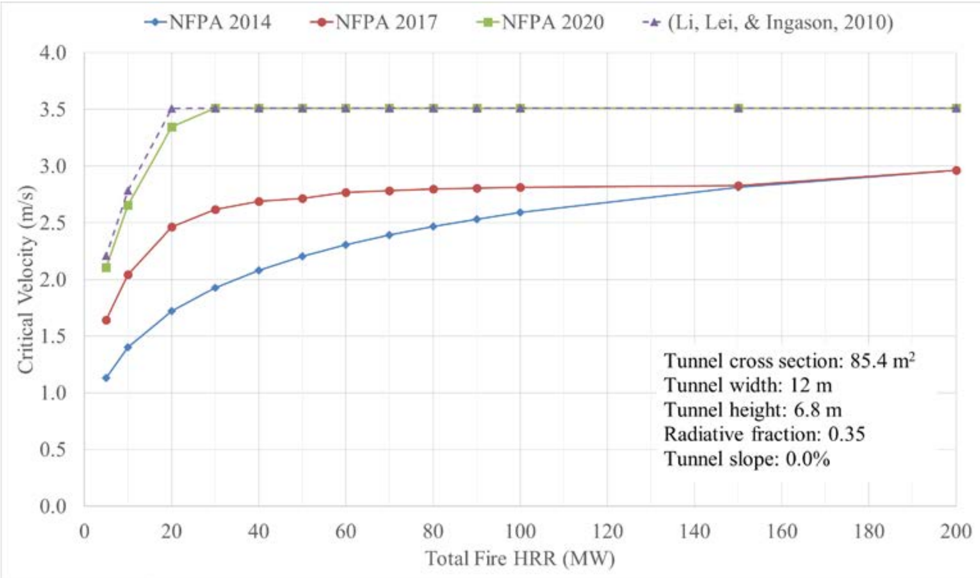

Figure 1: Progressive increase of NFPA 502 critical velocity for a typical road tunnel.

3. THE CURRENT SUPPORTING DATA

Figure 4, from (Li & Ingason, 2014) based on (Li, Lei, & Ingason, 2010) shows the data they referenced in their approach, which is the base of the new 2020 NFPA 502 Annex D equation. Three things are apparent to practitioners. Firstly, the figure is a log-log plot, which can make poor correlations look meaningful, and so indicates a need for caution from the reader. Secondly, the fitted curve has a discontinuity in gradient at [non-dimensional] fire size of 0.15. No insights are offered as to the physics going on there. Thirdly, the trend line (Equation (4) or Equation (3)) is based on data only from two different scale model tunnels (Li, Lei, & Ingason, 2010), not on full-size data. Referring to (Bowman, 2019), the trend line was mostly compared with other scale model data or computational data calibrated against scale models. The model data from (Li, Lei, & Ingason, 2010) and (Wu & Bakar, 2000) show big differences in critical velocity (see Figure 5) as noted by Agnew & Tuckwell (2017). However, it is interesting to see that, while being very different from each other, both (Li, Lei, & Ingason, 2010) and (Wu & Bakar, 2000) claim a good agreement between their respective model-based approaches and the full scale fire test results. So, how can we say which scale model equation is right? Or are they all wrong, following groupthink about the dimensional analysis, and differing mainly because some important effects have been treated differently in their scale models? Also, Kennedy achieved, with his proposed equation giving lower velocities, sufficient agreement with full scale fire tests conducted in the Memorial Tunnel (Kennedy, 1997). Was he right?

In addition to the results of scale model tests and CFD simulation, the test results from (Li, Lei, & Ingason, 2010) were also compared to full scale fire test results. We first look at the Runehamar and EUREKA tests, where the main focus was not on the analysis of backlayering and critical velocity. The Runehamar tests in 2003 in Norway included one pool fire test (T0) and four HGV mock-up tests (T1 to T4) with wooden and plastic pallets, furniture and fixtures, tyres, polyester tarpaulin and paper cartons (Lönnermark, 2005), (Ingason, Lönnermark, & Li, 2011). The fire load for all these tests was placed in a 7.1 m wide, 5 m height and 75 m long fire protection lining. (Lönnermark, 2005) discussed critical velocity for T1 to T4 in his dissertation, and extracted the heat release rate and velocity for a point in time when the backlayering reached 15 m upstream of the centre of the fire for each of those tests. Detailed information about the fire centre line and fire length for T1 to T4 can be found in (Ingason, Lönnermark, & Li, 2011). Based on this information, the backlayering length can be assumed to be between 2.8 m and 9.8 m when the backlayering reached 15 m upstream of the fire centre. The heat release rates of those extracted data points were below 40 MW. As noted in (Li, Lei, & Ingason, 2010), the critical velocities from the Runehamar tests were corrected, in their work, to zero backlayering by assuming an average backlayering length of 15 m, which is more than was noted in the test reports. However, (Lönnermark, 2005) states that the Runehamar test results cannot be taken as validation for critical velocity approaches since there are only few data points, the velocity was not systematically varied (as it was done during the Memorial Tunnel tests) and the HRR during the tests were transient (no real steady state conditions were reached). Additionally, the Promat protective lining formed a re-entrant step in ceiling level not far upstream of the backlayering detection station (Figure 2). That could not have left a normal velocity profile, and confirms that the tests were not designed for investigating critical velocity. The correct treatment of these data in (Li, Lei, & Ingason, 2010) and (Li & Ingason, 2014) was not examined further. It is simply noted that Lönnermark reported velocities in the range 2.62 to 2.82 m/s for HRR from 10 to 39 MW, with minor backlayering.

The single EUREKA test plotted below was also in a narrow tunnel, with something approaching 50% blockage by the burning truck. Also, the reported test data (EUREKA 499 Report, 1995), (Ingason, 1994), (Sorlie & Mathisen, 1994) and (Steinert, 1994) leave 'room for interpretation' as shown in Figure 5. Only one test with a high HRR can be found in (EUREKA 499 Report, 1995) with a detailed description of backlayering behaviour and critical velocity. However, the reported velocity during these observations (when backlayering went back to the fire source) was between 2.0 and 3.8 m/s and the HRR between 90 and 140 MW. Also, the tunnel height at the fire site varied between 4.8 and 5.5 m.

So, for large fires (>25 MW) as we worry about in road tunnels, that leaves us with only the well recorded and documented Memorial Tunnel fire tests (Memorial Tunnel Fire Test, 1995) as being carefully designed, relevant to road tunnels, and from a full-size experiment. And those data, when treated properly, seem to be well below the trendline according to (Li, Lei, & Ingason, 2010) that was adopted by 2020 NFPA 502.

Figure 2: Fire protection of the Runehamar test tunnel shown from the east (upstream) side and the HGV trailer mock-up (Ingason, Lönnermark, & Li, 2011).

3.1. Treatment of Memorial Tunnel test data

Comparison of Figure 3 against Figure 4 was a prompt to analyse the treatment ('correction') of the Memorial Tunnel test data in more detail.

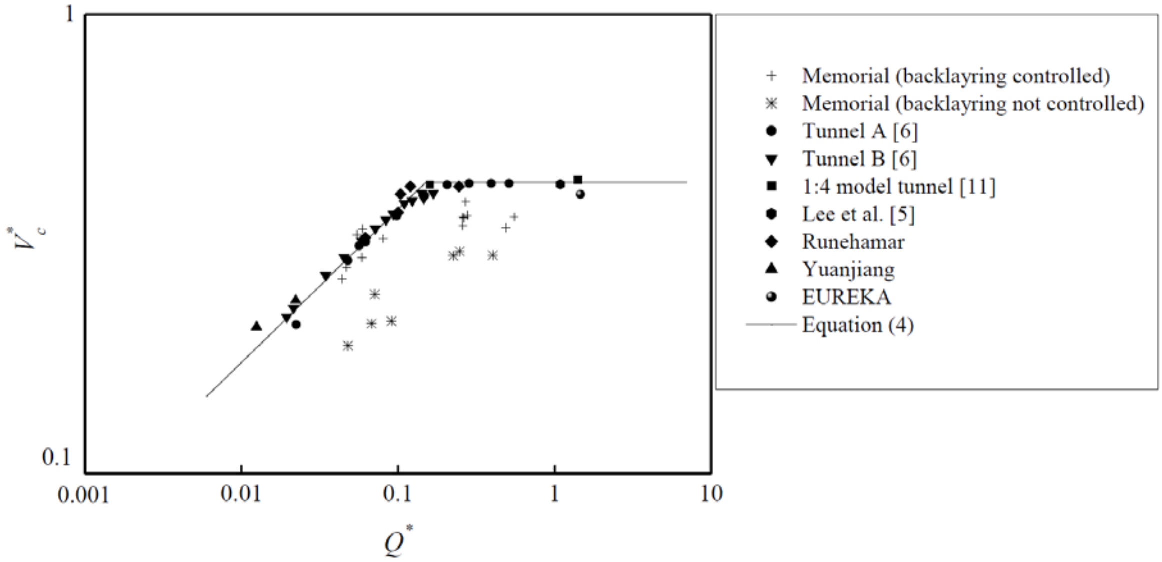

Figure 3: Model scale test data and full-scale test data in log-log plot (before 'correction') (Li & Ingason, 2014)

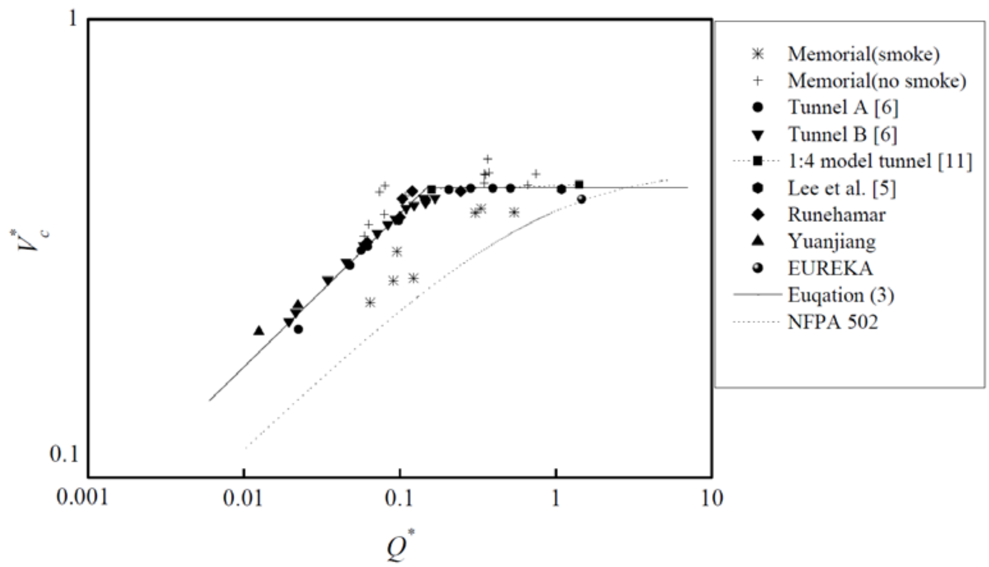

Figure 4: Model scale test data and full-scale test data in log-log plot (after 'correction') (Li & Ingason, 2014). The difference from Figure 3 prompted investigation of the treatment of the backlayering controlled data.

Data from (Memorial Tunnel Fire Test, 1995) include tests where backlayering and critical velocity were recorded quite well. The records in (Kile & Gonzalez, 1997) list both tests where significant backlayering occurred, and tests where it was 'controlled'. The backlayering length for backlayering controlled tests was recorded as less than about 12 m (about 40ft), with some possibly having 'negative' backlayering ($V > V_C$). A detailed analysis of the comprehensive test report (Memorial Tunnel Fire Test, 1995) showed that the velocity profile, temperature profile etc. was measured and recorded about 40ft upstream the centre line of the fire pan array, which means that it was possible to determine an occurrence of back layering at this position very accurately. All the Memorial Tunnel test records are available in form of spreadsheets of all parameters as a function of time, and can be analysed anytime (Memorial Tunnel Fire Ventilation Test Program, 1996). They include records of the pan positions used for each test.

In (Ingason, Li, & Lönnermark, 2015) and earlier papers, all Memorial Tunnel test data (with backlayering controlled and not controlled) were 'corrected' to zero backlayering. In (Li, Lei, & Ingason, 2010) as well as (Ingason, Li, & Lönnermark, 2015), it is noted that an "*average value of 35.5 m*" was used for the assumed backlayering lengths of all tests, to assign a critical velocity by using their own equation for backlayering length prediction (see also (NFPA 502, 2020)). With such correction, Figure 3 transforms to Figure 4. That the same correction (assuming 35.5 m backlayering) was applied to all tests, including those where (Kile & Gonzalez, 1997) noted that backlayering was generally less than 12 m (measured from fire array centre-line), was confirmed recently by (Ingason, 2020).

To analyse this a bit further, the correction was reconstructed, based on the reported test data from (Kile & Gonzalez, 1997) and according to the description and records in (Memorial Tunnel Fire Test, 1995) as well as the data provided by (Li, 2020). The calculation method was obtained from (Li, Lei, & Ingason, 2010) and (NFPA 502, 2020). Recorded velocities from the Memorial Tunnel test were corrected by the gradient factor according to (Kennedy, 1997) and (NFPA 502, 2020), for the reported downgrade of 3.2%. For the velocity conversion to nondimensional values, the total tunnel height of 7.864 m has been used which complies with (NFPA 502, 2020) and (Li, Lei, & Ingason, 2010). A copy of the spreadsheet is available by contacting the authors of this paper. Table 1 lists the results of this reconstruction. Despite the backlayering length for backlayering controlled tests being recorded as generally less than about 12 m (measured from fire array centre-line), when following the published method diligently, to get the 'controlled' backlayering data as plotted by (Li, Lei, & Ingason, 2010) and (Li & Ingason, 2014) backlayering lengths up to 61 m (instead of 0 to 12 m) have to be assumed. Such correction erroneously represents V_C from the Memorial Tunnel tests, making the velocities much too high.

In recent correspondence (Ingason, 2020) advised that they used the height from the pans to the ceiling for the velocity transformation to nondimensional values and the backlayering correction, and that they used the gradient correction according to (Wu, Stoddard, James, & Atkinson, 1997) which, taken together, leads to 35.5 m assumed backlayering instead of up to 61 m. The consequences of this deserves more explanation. HRR (Q) and critical velocity (V_C) are nondimensionalised according to following equations (Li, Lei, & Ingason, 2010):

$$Q^* = \frac{Q}{\rho_o c_p T_o g^{1/2} H^{5/2}}, \quad V_c^* = \frac{V_c}{\sqrt{gH}}$$

H tunnel height (m)

Assuming that the gravity g, and the ambient air conditions (ρ_0, c_p and T_0) were similar during the model test and the Memorial Tunnel tests, the transformation of the Memorial Test data depends on the tunnel height only. Using a different tunnel height than proposed during the derivation of the scaling equations leads to an adulterated illustration of the real situation. Besides, for the transformation of the HRR, the tunnel height rather than the height from the pans to the ceiling was used, which is not consistent. The equation used for the gradient correction is also not consistent with the gradient correction given in 2020 NFPA 502. Use of the alternative gradient correction also leads to a slight increase of the Memorial Tunnel velocities compared to the gradient correction given in 2020 NFPA 502.

To sum up, as the tunnel height in 2020 NFPA 502 Annex D equation is applied to road tunnels, the critical velocity differences between that equation and the Memorial Tunnel test results are much higher than represented in (Li, Lei, & Ingason, 2010). Using the height from the pans to the ceiling increases the V* plotted, but still does not make the Memorial Tunnel data align with the Figure 3 trend line, unless a backlayering ‘correction’ of 35.5 m instead of something like 12 m is also applied (Figure 4). The real backlayering ‘correction’ required for data alignment under the NFPA equation is more like 61 m.

Table 1: Backlayering length correction, reconstructed based on test data from (Kile & Gonzalez, 1997) and (Memorial Tunnel Fire Test, 1995) as well as (Li, Lei, & Ingason, 2010), (NFPA 502, 2020) and the data provided by (Li, 2020) and (Ingason, 2020).

Data from (Kile & Gonzalez, 1997)				Dimension-less local velocity	‘Corrected’ Memorial Tunnel dimension-less velocity (Li, Lei, & Ingason, 2010)	Backlayering length required to obtain “corrected” data in (Li, Lei, & Ingason, 2010) (m)
Backlayer controlled	Total HRR (MW)	Local velocity (m/s)	Backlayer length (m) (*Note 1*)			
yes	8.5	2.22	~12 or less	0.2308	0.3371	55.08
yes	9.1	2.35	~12 or less	0.2446	0.3571	55.08
no	9.3	1.52	?	0.1585	0.2411	61.02
yes	10.6	2.66	~12 or less	0.2763	0.4202	61.02
yes	11.4	2.37	~12 or less	0.2467	0.3752	61.02
yes	11.5	2.74	~12 or less	0.2847	0.4331	61.02
no	13.1	1.70	?	0.1770	0.2692	61.02
no	13.8	1.97	?	0.2050	0.3118	61.02
yes	15.6	2.61	~12 or less	0.2710	0.4122	61.02
no	17.6	1.72	?	0.1791	0.2724	61.02
no	43.7	2.39	?	0.2488	0.3784	61.02
no	47.9	2.44	?	0.2541	0.3865	61.02
yes	50.3	2.78	~12 or less	0.2890	0.4395	61.02
yes	50.3	2.90	~12 or less	0.3016	0.4588	61.02
yes	51.2	2.90	~12 or less	0.3011	0.4580	61.02
yes	52.4	3.13	~12 or less	0.3259	0.4958	61.02
yes	53.7	2.93	~12 or less	0.3043	0.4628	61.02
no	78	2.40	?	0.2493	0.3793	61.02
yes	94.8	2.75	~12 or less	0.2863	0.4355	61.02
yes	106.8	2.91	~12 or less	0.3022	0.4596	61.02

Note 1: Noted in the source as: “*Generally when backlayering was prevented, smoke was contained within 40 feet (12 m) upgrade of the fire.*”

Now, to have a clearer understanding of what the non-dimensional plots mean in a practical sense, Figure 5 shows all the test data again, plotted in real dimensions. Such a plot is more readily interpreted by practicing engineers, as a difference in velocity in m/s can be understood as a difficulty with jet fan numbers.

In Figure 5, those Memorial Tunnel data with backlayering controlled have also been ‘re-corrected’ by assuming a backlayering length between about 6 m and 15 m (depending on the position of the fire pan(s) used, relative to the measurement loop 305. Loop 305 was about 12 m upstream of the centre of the array of available fire pans as recorded in (Memorial Tunnel Fire Test, 1995). The data were then re-plotted on linear axes. The model data for Tunnels A and B from (Li, Lei, & Ingason, 2010) and the trend line from (Oka & Atkinson, 1995) were scaled up to Memorial Tunnel size using the methods of (Li, Lei, & Ingason, 2010) and the total height of the Memorial Tunnel (7.864 m). For the trend line from (Wu & Bakar, 2000), the tunnel hydraulic diameter (7.75 m) (as proposed by them) was used instead.

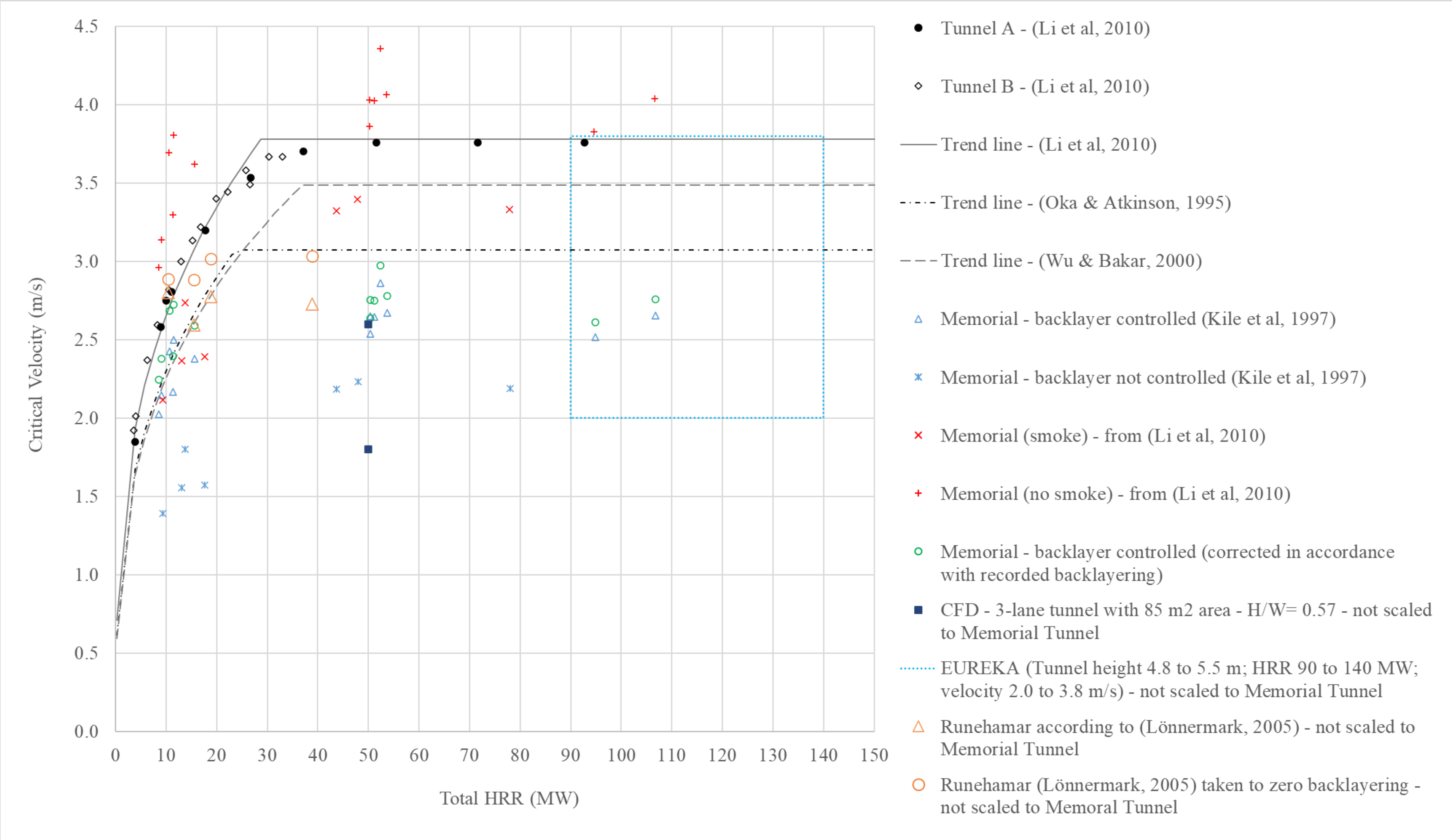

Figure 5: Model scale test data referred to full size, using relations from (Li, Lei, & Ingason, 2010), and full-size test data, both plotted in real dimensions.

Figure 5 shows the critical velocity 'corrected' by (Li, Lei, & Ingason, 2010) from Memorial Tunnel experiments with backlayering (Memorial – smoke) now exceeding by a large margin the velocity at which backlayering was known to be controlled (Memorial –- backlayer controlled – corrected in accordance with recorded test procedure). Obviously the two data sets are for the same tunnel and test setup. At higher HRR, the overlap is 0.4 m/s to 0.7 m/s. When the backlayering data correction is constrained so as not to exceed the V_C of the backlayering-controlled data (backlayering length of between about 6 m and 15 m), then for the numerous and credible Memorial Tunnel data, which are the most relevant to road tunnels, the critical velocity falls well below the trend line according to (Li, Lei, & Ingason, 2010). Besides the size of the correction made, the method of the backlayering 'correction' applied to the Memorial Tunnel test data is also questionable, as the validity of the applied equation (Li, Lei, & Ingason, 2010) and (NFPA 502, 2020) is not proven for real road tunnels.

Figure 5 is very informative. The data from the scale models no longer look like they have any relevance at all to the full-size Memorial Tunnel data. Putting aside the Memorial Tunnel test data where the backlayering was not controlled, Figure 5 clearly shows that critical velocity for fires > 15 MW is significantly lower than predicted by the scaled-up model tests. In Figure 5, the rectangle for the EUREKA data represents all possibilities for the single data point, given the differing values for heat release rate and airspeed in the EUREKA report and associated papers (EUREKA 499 Report, 1995), (Ingason, 1994), (Sorlie & Mathisen, 1994) and (Steinert, 1994). In addition, Figure 5 depicts the data points extracted from the Runehamar tests according to (Lönnermark, 2005). To be consistent, those data were also 'corrected' to zero backlayering by assuming a backlayering length between 2.8 m and 9.8 m (according to the description in (Lönnermark, 2005) and (Ingason, Lönnermark, & Li, 2011)). The EUREKA and the Runehamar data points were not scaled to the Memorial Tunnel height, due to the unproven nature of the scaling method.

3.2. Discussion about the physical restrictions when applying scaling methods

Scaling methods and dimensionless parameters are a useful approach when analysing flow fields and resistance coefficients in a wind tunnel. However, in complex physical processes, it is generally impossible to scale all the dimensionless parameters that are necessary to get the same flow regimes. For Reynolds number, if the flow stays highly turbulent, it may be necessary only to check that the flow is fully turbulent ($Re>10^6$), leaving a scaling window several orders of magnitude wide. Froude number is obviously critical. But heat transfer to the tunnel ceiling seems important, and is it also possible to get the Reynolds, Grashof and Nusselt numbers right as well as the relevant parameters describing thermal radiation and combustion? And what if it is not?

As an example, when analysing the Reynolds number a bit further, it can be seen that for the model Tunnel A of (Li, Lei, & Ingason, 2010), it has a value of about 10^4, whereas the value in a real tunnel like the Memorial tunnel is about 10^6. If Reynolds number based on hydraulic duct diameter falls below 10^6, the gradient near the wall becomes a function of the Reynolds number. Assuming, that the backlayering thickness is about 10% of the total tunnel height, the approaching velocity in this region is about 8 to 30% lower, which means that the dynamic head opposing the backlayer is greatly reduced in the upper part of the tunnel (see Figure 6). Besides the velocity profile, there are other Reynolds number influences like friction losses, wall heat transfer etc. Such effects are not addressed in the scaling relations used by (Li, Lei, & Ingason, 2010).

There are several different flow regimes underway in a tunnel fire, at least: the interaction of the air with the fuel geometry and combustion; the shape, rise and mixing of the plume to give the plume density and velocity; the 'impact' and spread of the high velocity plume on the ceiling due to momentum gained while rising, and; the slower flow of the established smoke layer under buoyancy. There is no evidence that the applied scaling methods are valid. It would be extraordinary if simple scaling could come anywhere near unifying results from tests that differ in scale by a factor of 20, so it is not surprising to see from Figure 5 that it does not.

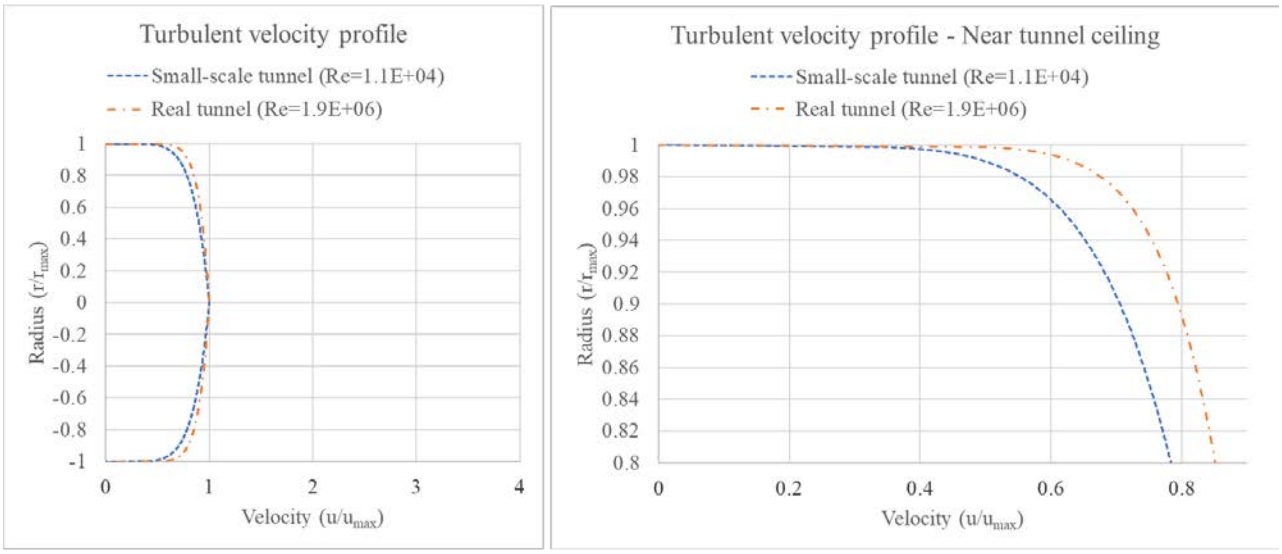

Figure 6: Turbulent velocity profile in Tunnel A and in a real tunnel. Tunnel profile (left) and the near ceiling region (right).

Making all corrections to the model scale techniques, so that the important physical effects and flow characteristics are included in the scaling methods, would be more cumbersome and less certain than full-size tests extrapolated using CFD verified with real full-size tests.

Small scale models might be great for helping to understand mechanisms and trends, but for predicting absolute values like critical velocity, they are barely credible, especially if there are also full-size experimental data available.

4. LOOKING AT THE FIRE AND PLUME DYNAMICS

The idea that the critical velocity for real road tunnels can be evaluated using the total heat release rate and leaning on results from scaling model tests needs to be explored further.

Consider a 5 MW fire in an area of 2 m (~truck width) wide, and 2 m long. Then consider a series of 10 such fires positioned in a row along the tunnel. Taken together, the 10 fires form a fire with a total heat release rate of 50 MW, and a total length of 20 m (~truck length).

The question then is whether the plume from the most downstream of the 5 MW sub-fires contributes the same to the forces that seek to drive backlayering. Backlayering of course is measured from the front of the first 5 MW component. With 18 m of extra shear on the smoke layer down to the last 5 MW component, it does not seem real that it would be contributing so strongly as the first few 5 MW fire components.

This thought experiment can be taken to extremes, looking at a petrol soaked mooring rope, burning at say 20 kW/m for 2500 m down the tunnel to give 50 MW total. Very clearly, the critical velocity for that "50 MW" fire would be very low indeed. The point is that the geometry of the fire clearly matters very much to the tendency to backlayer. Thomas was right in 1958. It seems that it has been forgotten.

The assumption that the backlayering is measured from the front of the fire source (i.e. first 5 m) would also explain why the critical velocities obtained from the Memorial tests are almost independent of the HRR (change from about 2.5 m/s to 3.0 m/s for HRR changing from about 10 MW to 100 MW). The HRR was increased by adding additional pans (with fuel oil) in the longitudinal direction. That means that the fire intensity at the front of the fire was always very similar.

To explore this further, CFD simulations of the 20 m long 50 MW fire mentioned above, and a 50 MW fire occupying only 5 m of tunnel length were carried out by varying the inflow airspeed to establish critical velocity. A radiative fraction of 0.35 was assumed. The modelling techniques were adopted from those used to calibrate CFD to real road tunnel fires (Karki, Patankar, Rosenbluth, & Levy, 2000), (Kashef, Benichou, & Lougheed, 2003). Heat transfer to the wall and wall heating were also considered. Tunnel wall properties were obtained from (Sturm, Bacher, Beyer, Höpperger, & Croll, 2011). Simulations are based on a 3-lane tunnel with a cross section area of about 85 m^2 and a tunnel down-slope of 4% (a sensible limit for motorway tunnels). While critical velocity seems to have been adequately modelled, the interest here is not so much on the absolute value of critical velocity but on the trend with fire length.

Figure 7 shows the results after 20 minutes simulated time. The short (5 m) fire has a much higher critical velocity (2.6 m/s) than the truck-sized fire (1.8 m/s). Yet the NFPA 502 formula makes no distinction between the two. The two results from Figure 7 are plotted as black squares in Figure 5, showing the large variation in V_C that can be attributed to fire geometry alone. The CFD replicates full-size fires acceptably, but more importantly, it shows the huge variation in V_C with fire geometry and intensity.

As an outcome of this investigation, apart from other parameters, it is important to implement representative fire/heat source dimensions and a real fire intensity (MW/m^2 and MW/m^3) to get the plume dynamics right for a specific fire scenario (car fire, train fire, etc). Even the Memorial Tunnel fire tests represent a conservative fire intensity (fuel oil pool fire with high calorific value) compared to a car, bus or train fire. They are probably more appropriate for dangerous goods fires in a road tunnel.

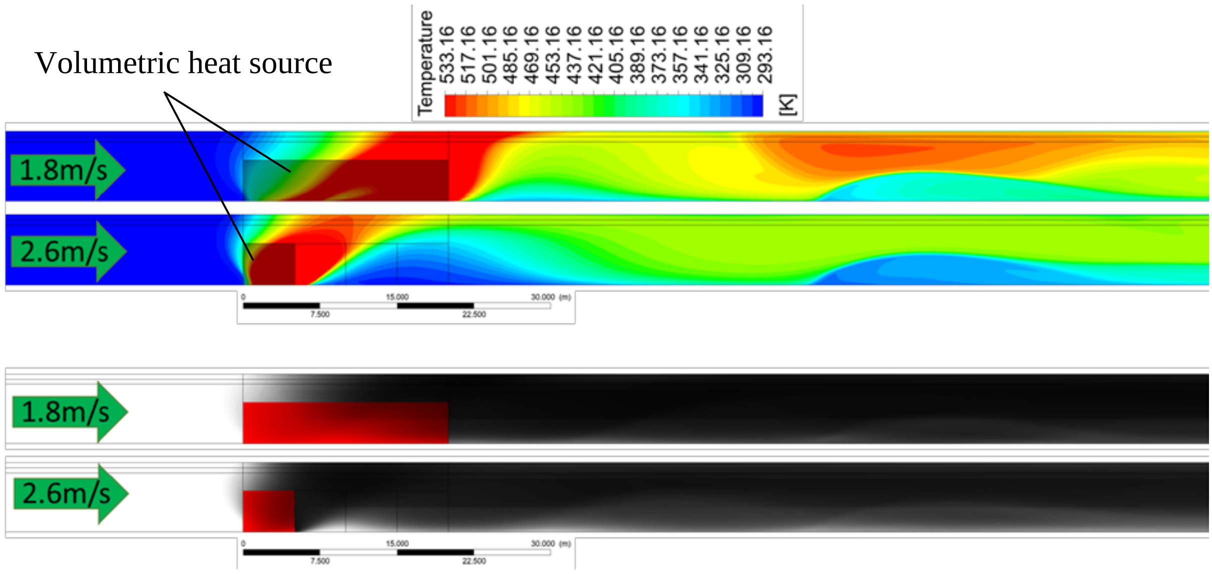

Figure 7: CFD results of a 50 MW fire (radiative fraction of 0.35) with a 20 m long (above) and a 5 m long (below) volumetric heat source. The pictures at the top show the temperature distribution at the tunnel symmetry and the pictures at the bottom the smoke distribution. Critical velocity is 2.6 m/s for the 5 m long fire and 1.8 m/s for the 20 m fire. The NFPA 502 (2020) value for both cases, regardless of fire geometry, is 3.91 m/s.

The essence of mathematical modelling of complex physical phenomena is to boil the physical effects down to the core drivers, such that the model captures the fundamental drivers of what you are studying. Excluding the transport of bulk acetylene etc, big fires do not come from tiny footprints, they occupy some length along the tunnel. The NFPA 502 (2020) equation does not qualify the heat release rate in terms of its distribution along the tunnel.

In this context, some of the scale model experiments supporting the equation development have been analysed in more detail. Figure 8 below is taken from (Li, Lei, & Ingason, 2010), showing the footprint of a test fire in a scale model rig.

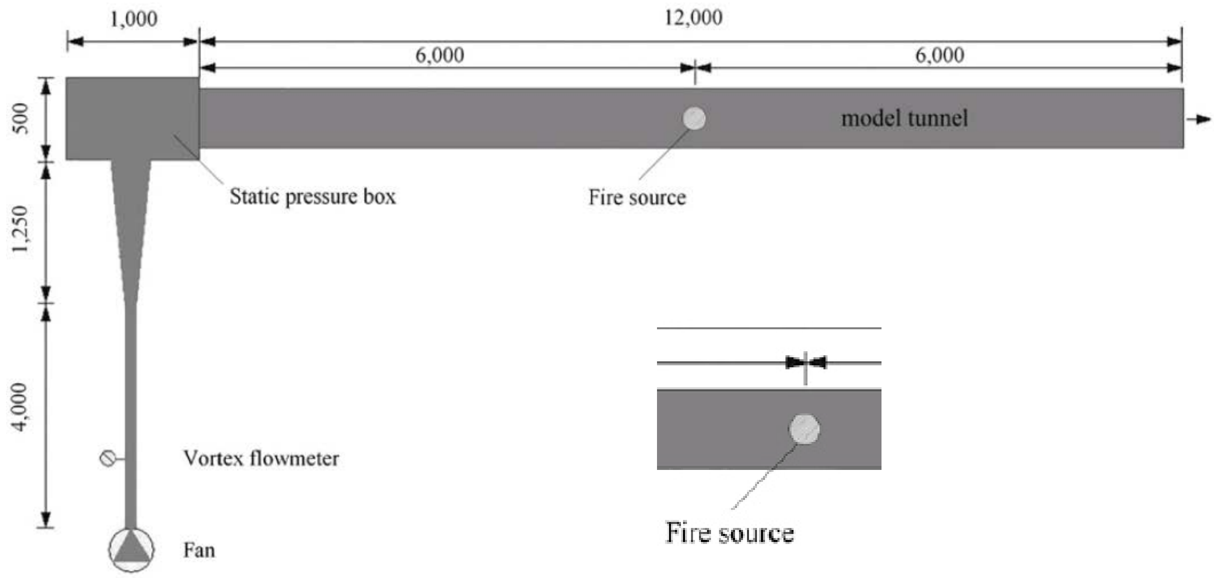

Figure 8: Diagram of the test rig taken from (Li, Lei, & Ingason, 2010). Insert shows the fire source at a larger scale.

In Figure 8, the fire is represented by a circle of diameter 100 mm in Tunnel A and 150 mm in Tunnel B. Using the scaling of (Li, Lei, & Ingason, 2010), this corresponds to a full-size diameter of 3.0 m for Tunnel A and 3.3 m for Tunnel B. That is dimensionally a very small fire. To use these data for calculating the critical velocity for a fire >15 MW in a 6 m high tunnel would be problematic, even if the other scaling would have been valid. It could clearly give a much more forceful plume than a fire with realistic physical dimensions, and hence a much higher critical velocity. Figure 9 compares the fire intensity during the Memorial Tunnel tests to that of the model tunnel tests by (Li, Lei, & Ingason, 2010), scaled by their formulae. The scaled-up model fire intensity for HRR's greater than 20 MW are unrealistically high, and hence are not applicable to a real tunnel. The scaling of the fire size applied to support the (NFPA 502, 2020) Annex D equation depends on this. It is a function of the tunnel height (and only the height). With reference to Figure 9, why should the same model fire appear to have a different intensity when scaled up to two tunnels of different height?

The burner size was kept the same during the model tests (for the individual tunnel), which means that the fire intensity (MW/m^2) increased with the HRR. Expecting that the critical velocity increases with the fire intensity as already discussed (see Figure 7), it becomes logical that, in the model tunnels, the critical velocity should climb steeply with increasing HRR. The kink in the trend lines (see Figure 5) may be related to a thermal restriction based on the fire dimensions in relation to the confined model tunnel.

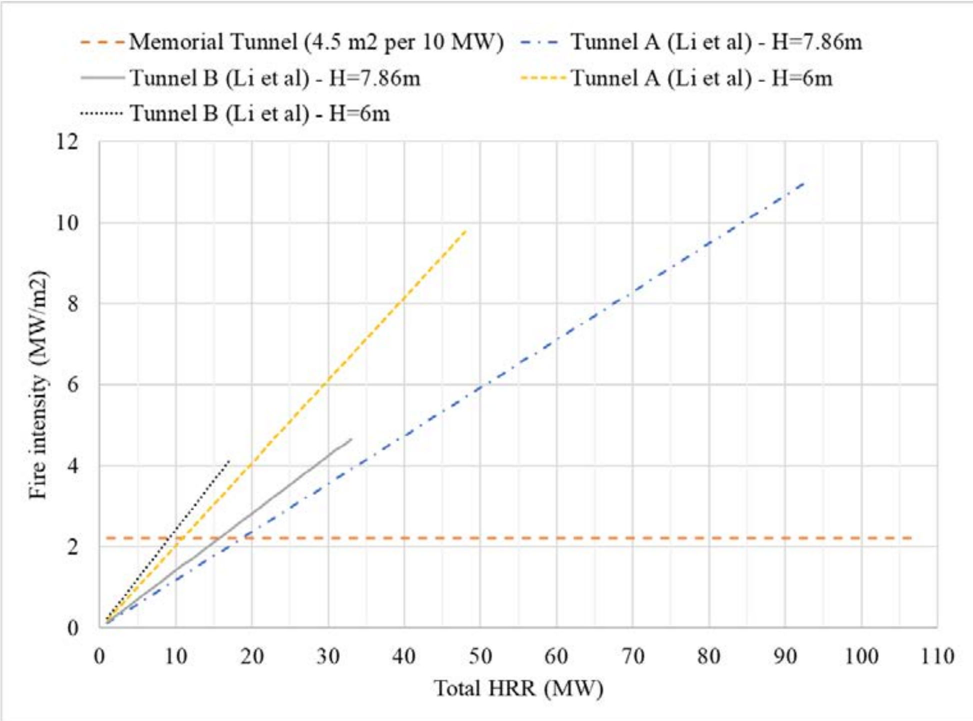

Figure 9: Fire intensity in the model tunnels compared to that of the Memorial Tunnel tests.

(Oka & Atkinson, 1995) discussed the influence of the fire geometry and analysed different burner dimensions in a scaled tunnel model. The burner dimensions were also small, and varied between 1.2 and 3.1 m along the full-size tunnel axis and between 3.1 and 7.3 m across the tunnel width, with heat release rates between approximately 2 MW and 150 MW (corresponding to a full-sized tunnel). However, even in the model tunnel, the burner with a bigger area resulted in lower critical velocities for similar HRRs (Oka & Atkinson, 1995).

Many of the small-scale tests used similar fire dimensions in relation to the tunnel geometry, which potentially explains why results and trend lines are similar. If the scaling fails to represent the full-size physics, as suggested above, it will be similarly misleading for all small-scale tests when referred to full size.

Kennedy discussed the influence of the fire intensity on critical velocity (in terms of temperature at the fire site), and the interaction of the approaching tunnel air with the fire during combustion (Kennedy, 1997). Kennedy’s critical velocity equation also does not include such influences, but was proposed after comparison to full-scale data and so probably doesn’t need adjustment for fire intensity.

It appears that there are major deficiencies in the investigations and resulting equations for critical velocity in the 2020 version of NFPA 502. No scaling of the fire seat dimensions is included in the (NFPA 502, 2020) equation. Given that the physics seem to be all about the ‘energy density’ of the plume (actually the density deficit) it would be expected to see the heat release rate normalised in some way by a length of the fire along the tunnel. Considering the full-scale data for high HRR as noted above, the equation according to (Kennedy, 1997) probably remains the best approach to estimating critical velocity for road tunnel design at the moment (excluding tailored CFD). It perhaps requires an adaptation in the calculation of the temperature at the fire site by considering the fire dimensions and intensity, combustion characteristic and behaviour, air/fire interaction etc. in relation to the tunnel geometry.

5. CONCLUSIONS

Scaling of road tunnel fires may be an interesting academic exercise and mathematically attractive, but responsible design of major infrastructure must be mindful of the construction, operational and safety implications of the results. The results must be demonstrably valid. The model scaling by (Li, Lei, & Ingason, 2010) and (Li & Ingason, 2017) has not yet sufficiently captured the physics and geometry of road tunnel fires to drive tunnel design. There is even less basis to drive the reform of internationally adopted standards such as NFPA 502.

(Li, Lei, & Ingason, 2010), (Ingason, Li, & Lönnermark, 2015) and (Li & Ingason, 2017) did not treat the Memorial Tunnel test data in accordance with the reported test procedure and test records (Memorial Tunnel Fire Ventilation Test Program, 1996) and (Kile & Gonzalez, 1997), particularly with respect to the reported backlayering. The treatment was also not in accordance with their own suggested approach as given in NFPA 502 (2020), with respect to the height reference and grade correction. With their backlayering ‘correction’ applied, it appears that the Memorial Tunnel data are close to their trend line. As demonstrated in this paper, the Memorial Tunnel data are far below their trend line.

Given the resource implications of the higher than necessary values and the risk that older systems may be wrongly criticised for being inadequate, NFPA should quickly retract Annex D of NFPA 502. We (via NFPA 502 2020) are now grossly over-conservative at calculating critical velocity for typical road tunnels, which does not really improve tunnel fire safety.

Project designers must look for themselves how to keep the smoke away from people, mindful also of the safety benefits of keeping velocities low around a fire.

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