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ON SMOKE STRATIFICATION IN A 1-D TUNNEL VENTILATION MODEL

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ABSTRACT

Tunnel ventilation design and risk analysis rely on modelling smoke propagation. I often read that 3-D numerical models are required, commonly Fire Dynamic Simulator in combination with the egress model EVAC. But these simulations are costly. Design decisions are made following one simulation scenario with the design fire in a single location and with steady-state boundary conditions.

1-D models cannot represent the nature of the flow? This is where I disagree. The paper includes references to analytical and empirical models, as the underlying equations have been published elsewhere. Here, we concentrate on a simple model to represent smoke stratification as a function of the local flow velocity and smoke temperature. As a result, we have a 1-D numerical model that gives a plausible representation of tunnel aerodynamics, thermodynamics of the fire, moving and stopping vehicles, smoke propagation, stratification, and egress.

Such a model must be validated against data from tunnel fires, fire tests and/or 3-D CFD simulations. Once validated, the computation of a fire scenario only takes a few seconds. This allows us to run multiple scenarios with a variation of boundary conditions for better system understanding and consequently for better design decisions.

Keywords: tunnel ventilation, simulation, fire, smoke, back-layering, stratification.

1. INTRODUCTION

About 20 years ago, there was a significant change in tunnel ventilation design. The focus shifted from normal operation to smoke control. And a new ventilation concept was born: smoke control by means of local smoke extraction with remote controlled dampers and feedback controlled longitudinal airflow in the tunnel. Tunnel ventilation concepts became more complex and more dynamic.

Two further developments had an impact on tunnel ventilation design as we know it today: the advance of CFD models with increasing computational power available to the designer and the development of risk analysis tools that provide black-box answers to any design variation. It appears that any design decision can be made based on CFD simulation and risk analysis.

However, this neglects the dynamic processes in a real fire scenario. CFD simulations usually start with the initial condition of standing traffic. Ventilation operation is pre-defined, thereby neglecting the dynamics of the ventilation control system. To understand the dynamics of a fire scenario, 1-D models still have their place.

There are two weaknesses in 1-D tunnel ventilation models: Effects that are caused by 3-D flow phenomena must be included by sub-models – including smoke stratification and smoke back-layering. And every physical effect that is relevant for the flow regime must be included explicitly, for example the throttling effect or the inertia of ventilation control.

2. PREVIOUS WORK

The complete description of the flow model goes beyond the scope of this paper. The underlying equations have been published before. The equations for the longitudinal airflow in the tunnel are the core of the model: Friction, pressure force of moving and standing vehicles against the longitudinal airflow, local losses at the portals, stack effect due to longitudinal gradient and the temperature distribution. These equations are given in [1] for longitudinal ventilation and in [2] for combined ventilation systems. Later, the model has been extended to include a transport equation for smoke concentration and a deterministic egress model [3].

A few years ago, the model SpitFire was re-written, simplified and extended. Heat radiation is no longer modelled explicitly but included in the heat transfer coefficient. The model for the in-tunnel temperature now follows the model described in Austrian design guideline RVS 09.02.32. The heat capacity of the tunnel wall was removed, as this caused problems with long simulation times. Long simulation times (>20 min) may be required for egress simulations in tunnels with a long distance between egress doors. For short simulation times, there are no significant differences between the previous temperature model and the simplified one.

The most notable inclusion in this model is the propagation of hot smoke under the tunnel ceiling. The model can predict back-layering of smoke with the density driven smoke propagation superimposed to the 1-D analysis [1]. Smoke propagation is driven by density differences between the hot smoke and the cooler tunnel air.

The relation between the smoke temperature and the smoke front velocity has been derived from buoyancy driven flow problems, such as the lock-exchange experiment, see Figure 1 [4]. The light fluid intrusion front into the heavy fluid represents a model for the smoke front in a tunnel fire.

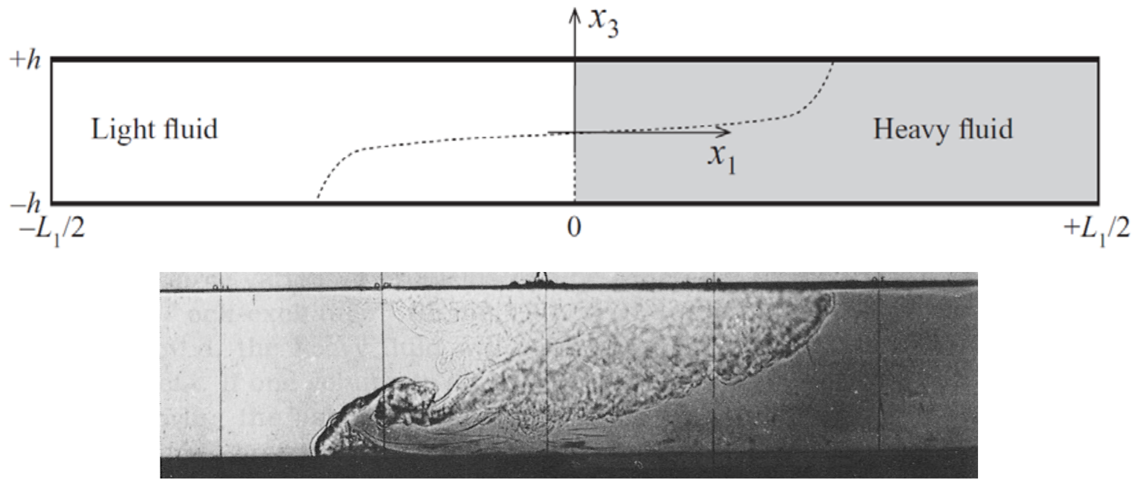

Figure 1: Definition and shadowgraph image of the lock-exchange experiment [4]

The velocity of the hot smoke front intruding into the colder tunnel air can be expressed as

$$u_{smoke} = k \cdot \sqrt{g\, H \frac{T_{smoke} - T_0}{2\, T_{smoke}}}$$

with the velocity of the smoke front u_{smoke}, the gravitational acceleration g, the height of the tunnel profile H, the tunnel air temperature T_0 and the smoke temperature T_{smoke} (the average smoke temperature between the fire and the smoke front). This is a simple model for the gravity driven flow. It does not include the height of the smoke layer. An empirical parameter $k = 0.62$ is defined to match the smoke front velocity to experimental data for the back-layering length and to predict critical velocity. k is expected to depend on the shape of the cross-section [4]. It applies to the geometry corresponding to the experiments. The calculation of the smoke front velocity must be combined with a transport equation for heat propagating with the smoke (and heat conduction to the tunnel wall as described above). The model assumes stable temperature stratification. Any drastic disturbance, such as jet fan operation in the smoke, will limit the extent of gravity driven smoke propagation. Temperature stratification may still be present in scenarios where smoke stratification is no longer visible [5].

SPITFIRE includes a variation of air density as a function of temperature. This feature captures the increased flow velocity downstream of a large fire and the reduced thrust of jet fans operating in hot smoke. The model is still incompressible, as pressure variations do not affect air density. Jet fan operation in a fire scenario may be pre-defined or automatically controlled using a PI-controller. The parameters of the PI-controller are defined automatically using the procedure described in the ASFINAG design guideline [6]. The parameters can then be optimized by the user.

The airflow resistance of the tunnel fire in longitudinal ventilation is captured using the equation proposed in [7]. The more conservative approach described in [8] and [9] has not yet been adopted, as the validation of these findings is still work in progress.

3. STRATIFICATION MODEL

The application of the combined model for 1-D smoke propagation and egress may lead to non-plausible results when stratification is not included. People that are in the smoke affected part of the tunnel would be exposed to the average concentration in the cross-section. Applying such a model to a longitudinal ventilation system leads to the conclusion that the best ventilation strategy is to run the system at maximum capacity to reduce exposure by dilution of smoke. As we know, the recommended approach is to maintain flow direction and to limit the airflow velocity between 1 to 1.5 m/s to maintain smoke stratification. For a more plausible egress evaluation, stratification is included in SPITFIRE.

A simple model for the stability of smoke stratification is given by Newman [10]. A measure for smoke layer stability can be defined by the local Froude number. The Froude number is a dimensionless parameter defined by the ratio of flow inertia to buoyancy forces. Increased flow inertia causes flow disturbances and de-stratification. Increased buoyancy leads to more stable temperature stratification. Here, the Froude number is defined by

$$Fr(x) = \frac{u_x}{\sqrt{g\,H\,\Delta T / T_{ave}}}$$

with the local Froude number $Fr(x)$, the flow velocity u_x (average in the cross-section), the gravitational acceleration g, the tunnel height H, the temperature difference between smoke and cold air ΔT and the average temperature in the cross-section T_{ave}. In [10], three regions are defined: $Fr \leq 0.9$ as a region for stable temperature stratification, $0.9 < Fr \leq 10$ described as region of increased mixing and $Fr > 10$, a region without significant temperature stratification. For an assessment of smoke stratification, it is sufficient to include the limit of $Fr = 0.9$. The smoke layer may be disturbed even when temperature stratification is still present.

The 1-D stratification model is based on the following assumptions:

- The propagation of a smoke layer against the mean airflow (back-layering) is only possible if stratification is present.
- The stability of stratification downstream of the fire can be estimated by evaluation of the local Froude number. Stratification is destroyed for $Fr > 0.9$.
- When smoke is de-stratified close to the fire, stratification in further distance of the fire is very unlikely due to smaller temperature differences.

Figure 2 (right) shows smoke propagation, airflow, and egress for a fire scenario with a fast-developing 30MW fire. The x-axis shows the location in the tunnel, the y-axis shows the time. The fire is at x=1050m. The scenario assumes uni-directional traffic from left to right. Egress doors are marked in green, people movement in red lines. Smoke is shown in grey with the stratified smoke being indicated by a lighter shade. The ventilation schematic is shown above. In Figure 2 (left), the longitudinal airflow is shown left (red) and right (green) of the extraction section over the vertical time axis.

Initially, the smoke is de-stratified due to high mean flow velocity in the tunnel. The ventilation response is defined by smoke extraction beginning at t=3min. Full capacity is reached one minute later. At the same time, jet fans close to the entry portal are used to control the longitudinal airflow to 2m/s resp. -2m/s.

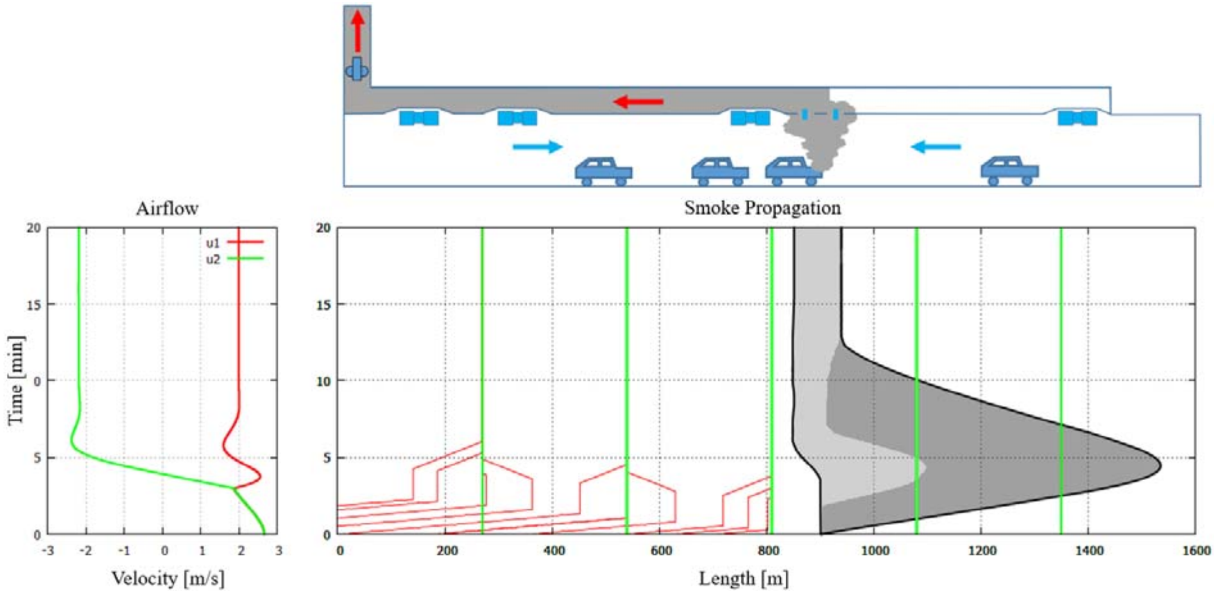

Figure 2: Smoke control – PI-control of longitudinal airflow

The graph shows that due to the initial flow velocity, smoke stratification downstream of the fire is unlikely. When the fire develops more heat and when the airflow is controlled, a section of stratified smoke is developed close to the fire. In this scenario, stratification does not influence egress, as smoke back-layering to the left is mostly avoided and tunnel users can evacuate to the nearest egress door.

4. VALIDATION

Model validation has been performed over the years with every available dataset from fire tests or CFD simulations. Most test cases have been derived from site acceptance fire tests. These are tests required for project approval of Austrian highway tunnels. Usually, validation is limited to parts of the model, depending on the dataset. Test heat release rates are small; and there is no moving traffic present.

4.1. Smoke stratification

The model for smoke stratification has not yet been validated due to lack of reliable data. The model has been adopted from literature without further empirical coefficients. And the results are plausible.

4.2. Control dynamics

Control dynamics are unrelated to smoke propagation and stratification. But these models must include system properties explicitly. In this case the inertia of system reaction. Figure 3 shows a comparison of test data and a SPITFIRE simulation. The graph depicts the system response (flow velocity) to a fire alarm and start of the emergency ventilation.

The fuel pan fire was started at about 22:30:00. Only a few seconds after ignition the fire alarm was set manually to avoid damage to the tunnel structure. The controlled airflow conditions limit the maximum temperature. The test was then run continuously until the fuel was burnt completely, see Figure 4.

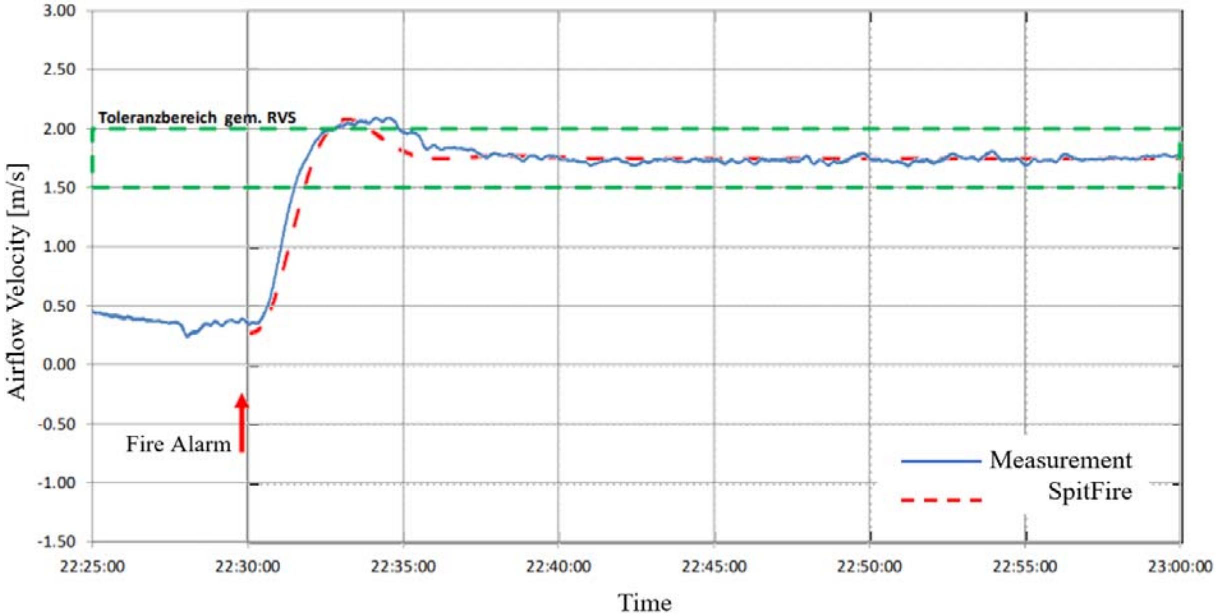

Figure 3: Flow velocity – fire test and SPITFIRE model

Figure 4: Smoke back-layering and downstream stratification in the first minutes of the test

The simulation uses the tunnel geometry data. The heat release rate is estimated from the area of the fuel pan. Deviations between measurement and numerical model may be attributed to the detailed control parameter settings. The ventilation control system was optimized in preparation of the site acceptance test. The simulation includes the calculated default parameter settings. Other potential sources of deviations may be the ramp settings in the jet fans' variable speed drives. The detailed settings were not documented in the test report.

In the fire test, back-layering is mostly controlled due to the small heat release rate. This is confirmed in the test report, stating that back-layering extended to a maximum of 15m. It was quickly driven back to the fire. The simulation shows a maximum back-layering of 2m.

4.3. Critical velocity

The critical velocity is defined as the upstream airflow towards a fire that prevents the propagation of smoke back-layering beyond the source of the fire. In the past couple of years, several methods to calculate critical velocity have been published. The current consensus for practical applications appears to be the relation published in NFPA502:2017 [11].

SPITFIRE has been tested against this standard. The geometry has been assumed for the tunnel shown in Figure 4 without longitudinal gradient. Ventilation control is set up to achieve the critical velocity as calculated from NFPA. The back-layering for the quasi-steady state case is evaluated. For heat release rates increasing from 20MW to 90MW, the model shows back-layering increasing from 1.3m up to 8.6m. This is only slightly more than the hydraulic tunnel diameter or the length of a single grid cell, which is deemed acceptable. The model has been developed for the assessment of dynamic fire scenarios and not for steady-state design.

4.4. Smoke back-layering

Most of the published research on smoke propagation in tunnels appears to concentrate on the critical velocity. At the 2020 conference in Graz, a paper [12] has been presented, comparing smoke back-layering in seven full size fire tests with corresponding FDS simulations and two analytical models. This paper provides an ideal collection of experimental, numerical, and analytical data to allow a validation/verification of the smoke propagation in SPITFIRE.

While the paper does not list the detailed tunnel geometry of the fire tests, the missing information can be derived from the back-layering lengths calculated using the models by Li/Ingason and Thomas. The data used in the SPITFIRE simulation is shown in Table 1. The analytical models show good agreement for all cases except Test 7, where my calculation using the model by Thomas gives a back-layering length of 338m instead of 256m as shown in Table 2 [12]. For this case, the model by Li/Ingason gives a back-layering length of 112m instead of 103m.

Table 1: Tunnel geometry

Parameter	Symbol	Value
Tunnel cross-section	A	36.0 m^2
Tunnel height	H	6.15 m
Air density	ρ_0	1.251 kg/m^3
Initial Temperature	T_0	283.15 K

Table 2 describes qualitatively the deviations of the back-layering length, taking observations from fire tests as reference. A graphical representation of Table 2 is shown in Figure 5. Please note that the column for Test 7 and the model by Thomas is cut at 200m to allow an easier comparison for the cases with shorter back-layering.

Although SPITFIRE includes a very simple model for the smoke front velocity, it provides a surprisingly good agreement with backlayering observed in fire tests and in FDS simulations. The most notable deviation is visible in Test 6, where SPITFIRE underpredicts back-layering similar to the analytical models by Li/Ingason and Thomas. In the other test cases, SPITFIRE appears to underpredict smoke back-layering by 10 to 20%.

Table 2: Back-layering lengths – comparison experiment/FDS/literature [12] and SpitFire

# Test	Experiment			FDS simulation		Thomas		Li/Ingason		SPITFIRE	
	Peak HRR Q	airflow v_0	back-layering length	back-layering length	% from experiment	back-layering length	% from experiment	back-layering length	% from experiment	back-layering length	% from experiment
	[MW]	[m/s]	[m]	[m]	[%]	[m]	[%]	[m]	[%]	[m]	[%]
3	4.0	1.10	90	130	145	85	71	77	86	78	86
4	7.7	1.30	90	140	156	103	114	83	92	99	109
5	11.5	1.61	120	100	84	79	66	74	94	85	71
6	14.3	2.00	110	100	90	43	39	57	52	50	45
7	19.5	1.25	160	150	94	256	160	103	64	142	89
8	6.7	1.32	100	140	140	82	82	76	76	78	78
13	21.0	1.72	140	135	97	124	89	75	54	127	91

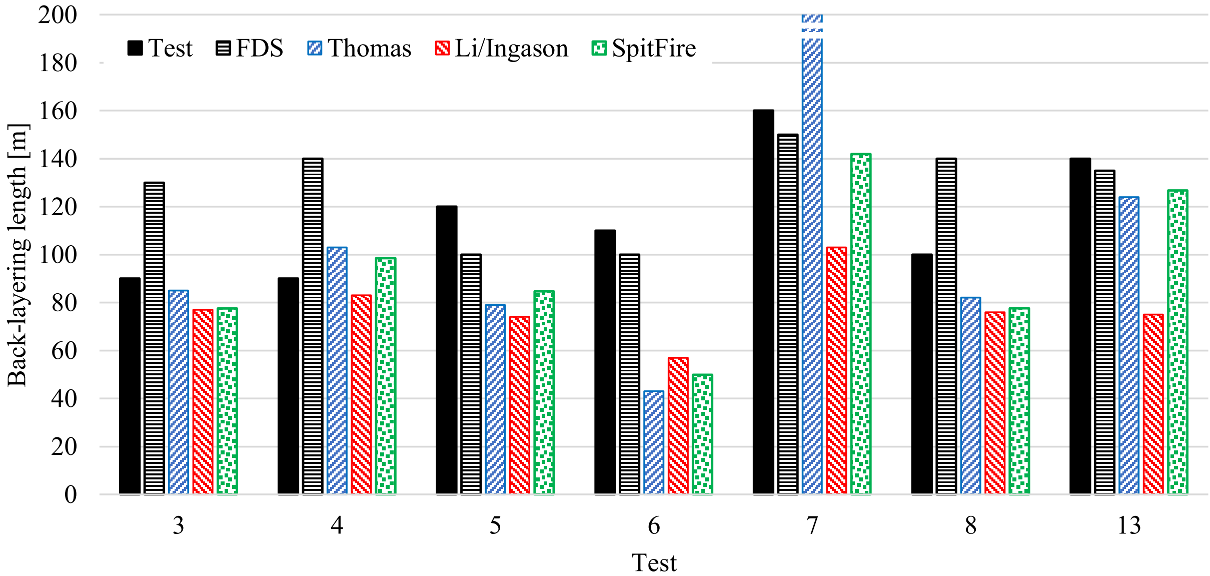

Figure 5: Back-layering lengths – comparison experiment/FDS/literature [12] and SPITFIRE

5. SUMMARY AND CONCLUSION

1-D models can represent airflow, smoke propagation and ventilation operation in road tunnels. In this paper – together with previously published work – a simple 1-D numerical model is described that gives a plausible representation of tunnel aerodynamics, thermodynamics of the fire, moving and stopping vehicles, automated ventilation control, smoke propagation, stratification, and egress.

The model has been validated against test cases showing specific aspects of the model, namely the dynamic system reaction in a fire scenario, smoke control towards critical velocity and smoke back-layering in scenarios with reduced longitudinal flow. The model performed reasonably well in all test cases.

The main advantage of a 1-D model against 3-D CFD lies in the short computation time. For a typical tunnel, SPITFIRE computes a fire scenario in 5 to 10 seconds. This allows a wide variation of boundary conditions in short time and a better understanding of the dynamic behaviour of the tunnel ventilation system in a fire scenario. This may lead to better design decisions.

The main disadvantage of a 1-D model lies in the simplifications. If the model does not include a sub-model for smoke stratification, there is no stratification. If the model does not include a sub-model for the pressure loss of a fire in longitudinal flow, there is no pressure loss. We are required to observe the limitations of the model – always. And we must test the model against available data – always.

Only by regular and frequent validation, the special cases are identified where the model is not applicable in its current form. And when these cases are identified, the model can be developed for a wider range of applications – but only after further validation.

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