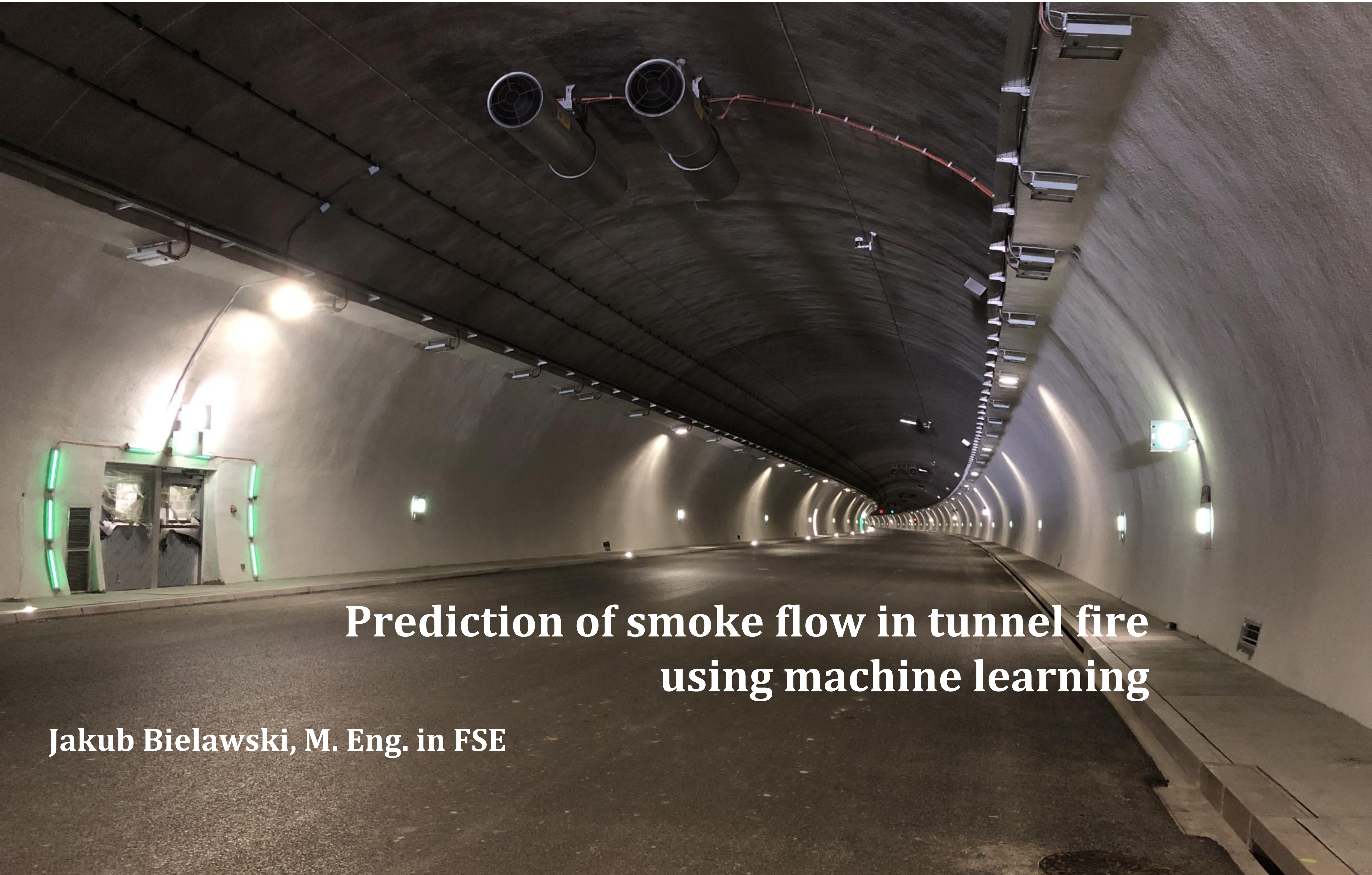
UNIVERSITY OF CHEMISTRY AND TECHNOLOGY PRAGUE

PhD Students' Seminar on Fire Safety Science 2022

Instytut Techniki Budowlanej



Prediction of smoke flow in tunnel fire using machine learning

Jakub Bielawski, M. Eng. in FSE

About me

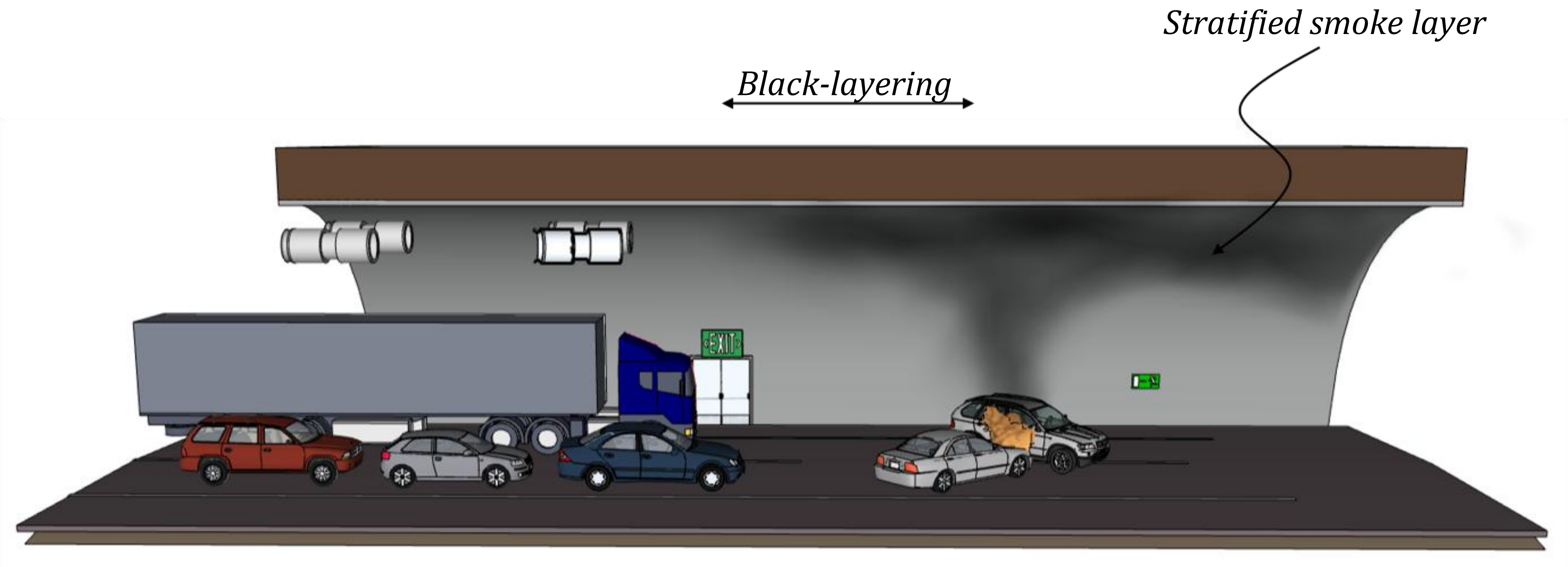
Fire safety engineer
CFD & evacuation analyses, in situ hot smoke tests, general fire safety expertise

Research
Tunnel fires, wind & fire engineering, façade fires, fire safety aspects in sustainablility

Experience
More then 80 hot smoke tests performed,
Engaged in 12 tunnel projects (road, railway, metro)

PhD thesis
Transient evolution of smoke flow in tunnel fires

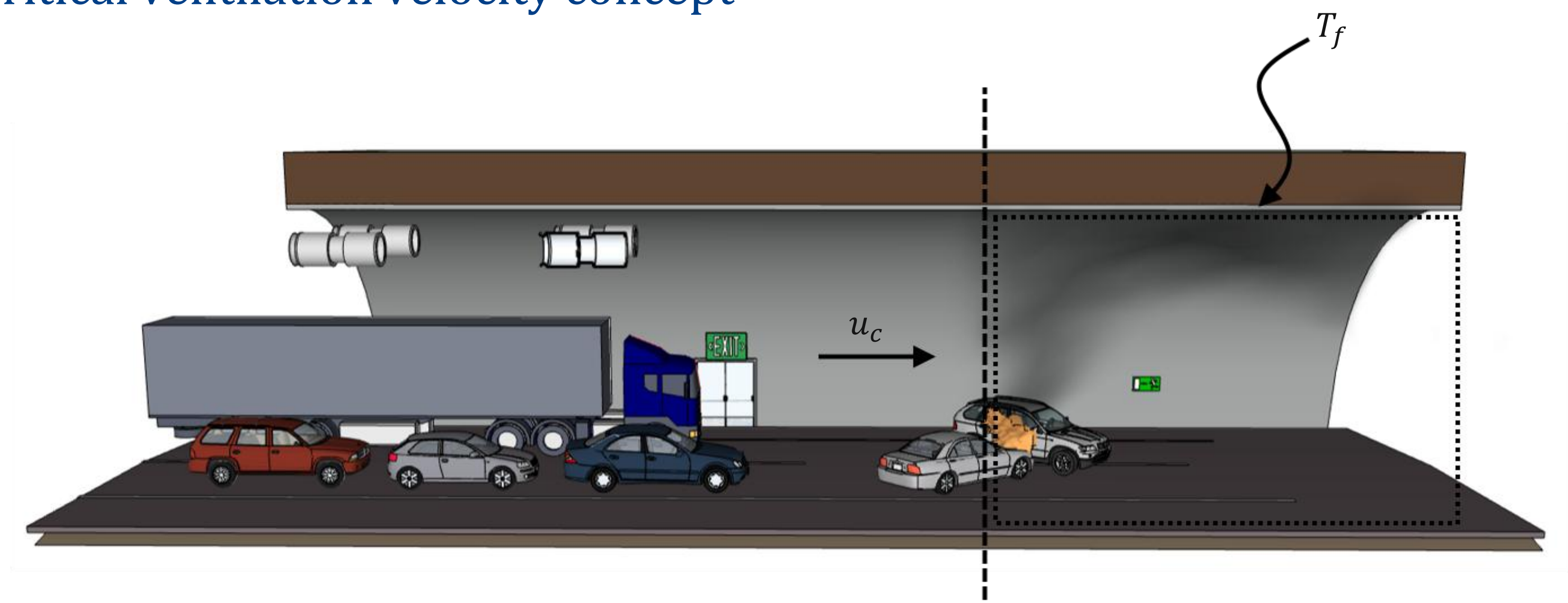
Brief intro in tunnel fires



$$L^* = \frac{L_b}{H} = 0,6\left(\frac{2gH}{\rho_0 T_0 C_p u_0^3 A} - 5\right)$$

Common design approach

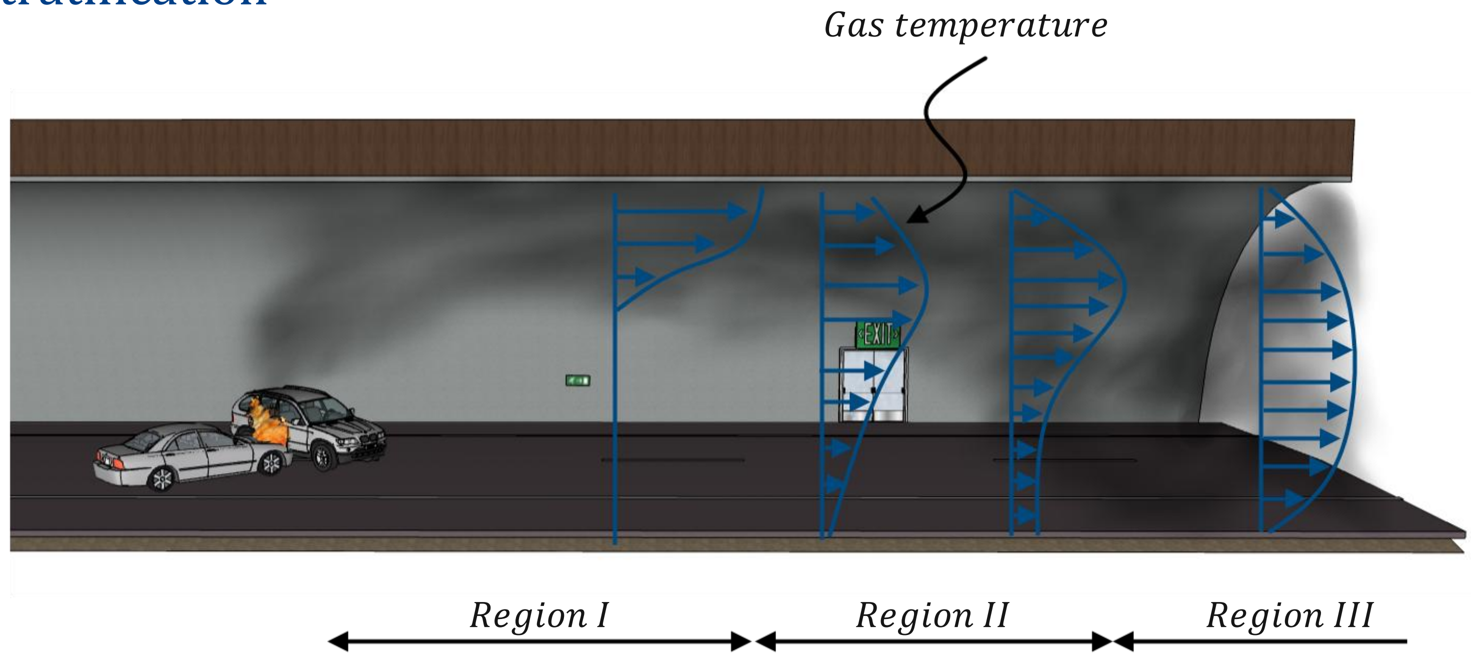
Critical ventilation velocity concept



$$u_c = \left(\frac{g \dot{Q}_c H}{\rho_0 C_p T_f A F r_c} \right)^{1/3} \qquad T_f = \frac{\dot{Q}_c}{\rho_0 C_p A u_c} + T_0$$

Common design approach

Smoke stratification



$$Fr = \frac{u_{avg}^2}{\sqrt{gh\Delta T_{cf}/T_{avg}}}$$

$$\Delta T_{cf} = 0{,}225\,\frac{gH\Delta T_{avg}^2}{T_{avg}\,u_{avg}^2}$$

$$\Delta T_{avg}(x,\tau) = \frac{2Q(\tau)}{3\dot{m}_o C_p}\cdot e^{\left(\frac{h_t W_p}{\dot{m}_0 C_p}\cdot x\right)}$$

$$u_{avg}(x) = \frac{u_0}{T_0}\,T_{avg}(x)$$

Common design approach

Pressure equilibrium

$$\Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} = \Delta p_{in} + \Delta p_{exit} + \Delta p_{fr} + \Delta p_{HGV} + \Delta p_{ob}$$

$$\Delta p_{jf} = \eta \frac{\mathrm{I_{fan}}}{A_t}$$

$$\Delta p_{in} = \xi_{in} \frac{1}{2} \rho_0 u_0^2 \qquad \Delta p_{exit} = \xi_{exit} \frac{T_e}{T_0} \frac{1}{2} \rho_0 u_0^2$$

$$\Delta p_{wind} = C_d \frac{1}{2} \rho_0 u_i^2$$

$$\Delta p_{fr} = \frac{f}{D} \left[L + L_{ds} \left(\frac{T_m}{T_0} - 1 \right) \right] \frac{1}{2} \rho_0 u_0^2$$

$$\Delta p_{stack} = \left(1 - \frac{T_e}{T_m} \right) \rho_0 g \Delta h$$

$$\Delta p_{ob,\,HGV} = \xi_{ob,\,HGV} \frac{T_g}{T_0} \frac{1}{2} \rho_0 u_0^2$$

$$\Delta h = \theta \cdot \frac{L_{ds}}{100}$$

$$\xi_{ob,HGV} = 1{,}15\, C_x \frac{\frac{A_{ob}}{A_p}}{\left(1 - \frac{\gamma A_{ob}}{A_p} \right)} \left(1 - \frac{2y}{D} \right)^{\frac{1}{3}}$$

Common design approach

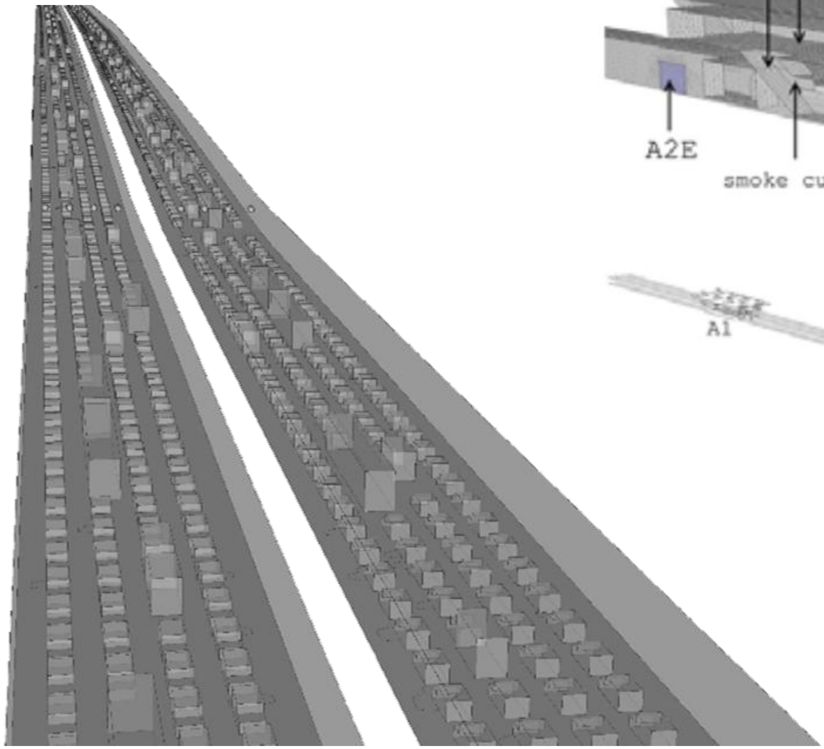
Average longitudinal velocity

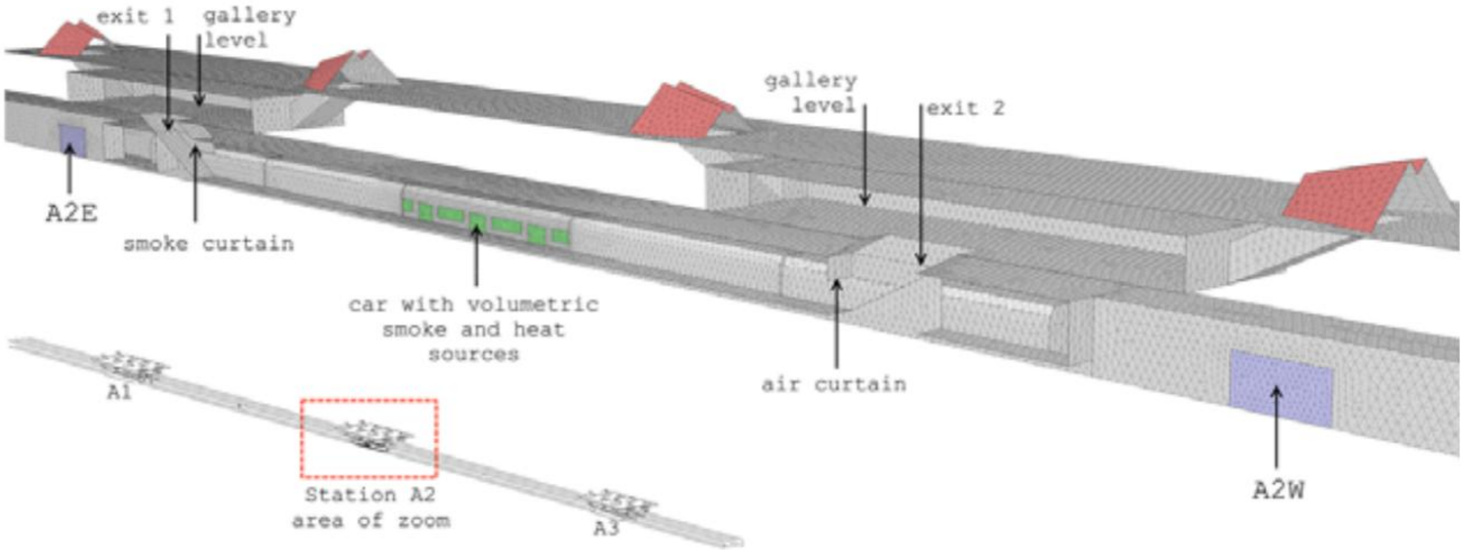
$$u_0 = \sqrt{\frac{2}{\rho_0}} \sqrt{\frac{\eta \frac{I_{fan}}{A_t} + \rho_0 g \Delta h \left(1 - \frac{T_e}{T_m}\right) + C_d \frac{1}{2} \rho_0 u_i^2}{\xi_{in} + \xi_{exit} + \frac{f}{D}\left[L + L_{ds}\left(\frac{T_m}{T_0} - 1\right)\right] + \xi_{HGV}\frac{T_g}{T_0} + \xi_{ob}\frac{T_g}{T_0}}}$$

$$u_0 > u_c$$

Common design approach

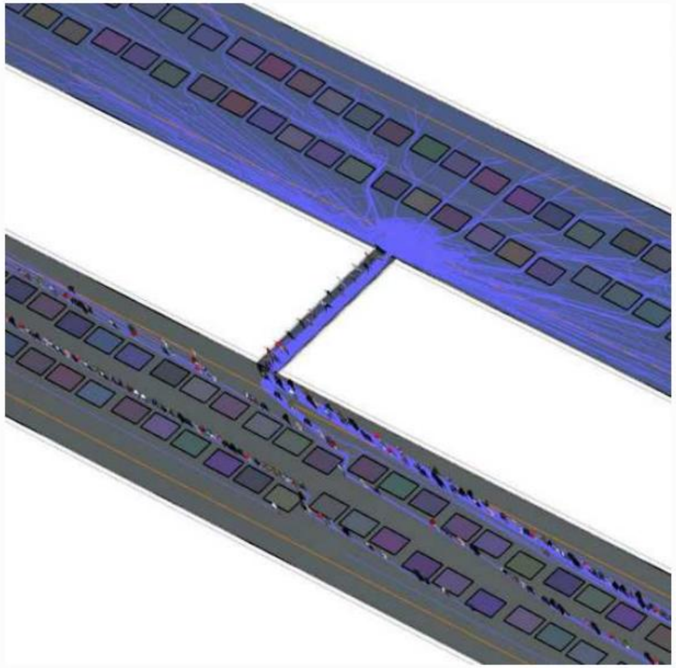
CFD analyses

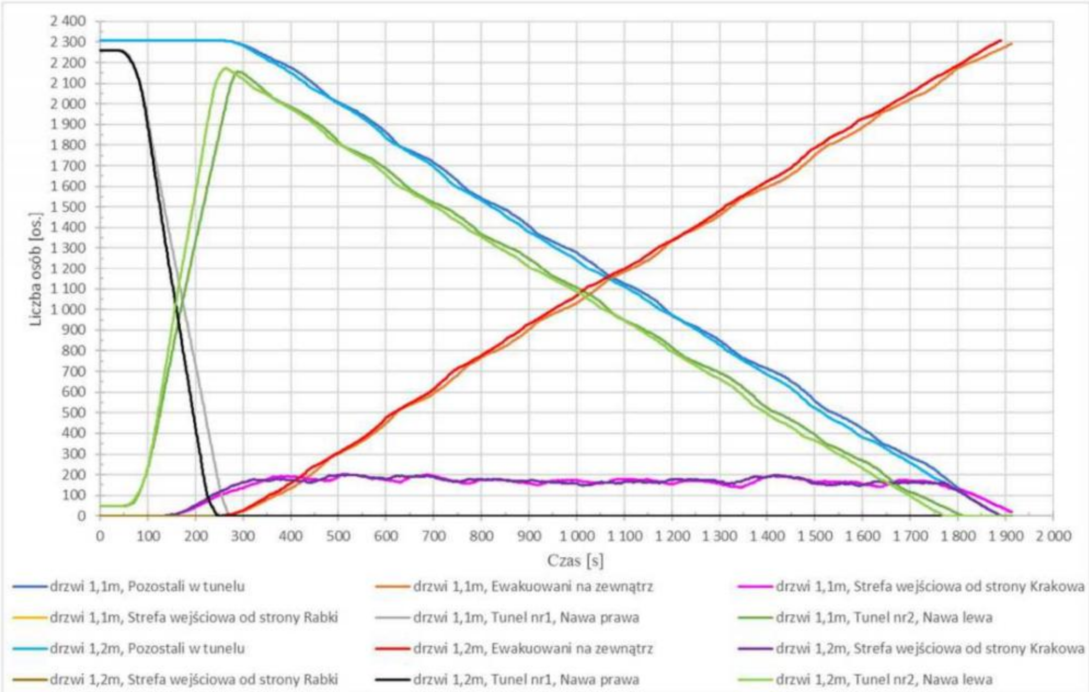




Common design approach

Evacuation modelling





Fire in an actual tunnel

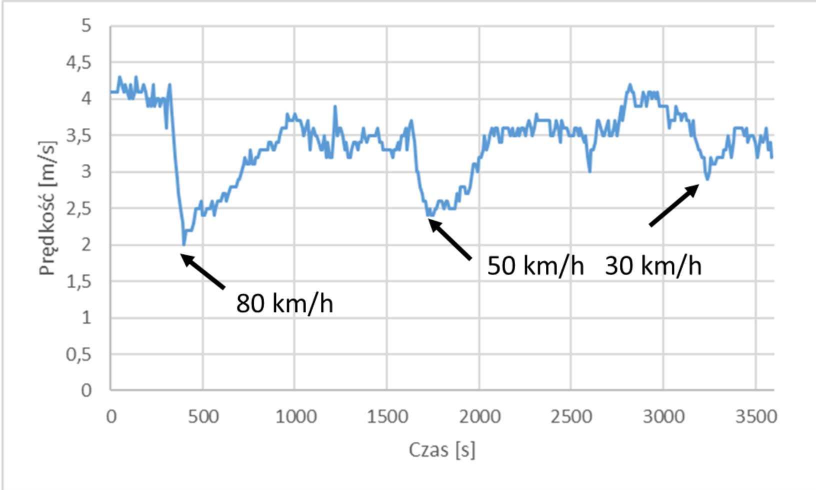
traffic direction

Expressway S7 Tunnel, Poland

Proposed solution

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$



$$\Delta p_{veh} = \frac{1}{2} n A_v c_X \rho (u_v - u_0)^2 \Delta t$$

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

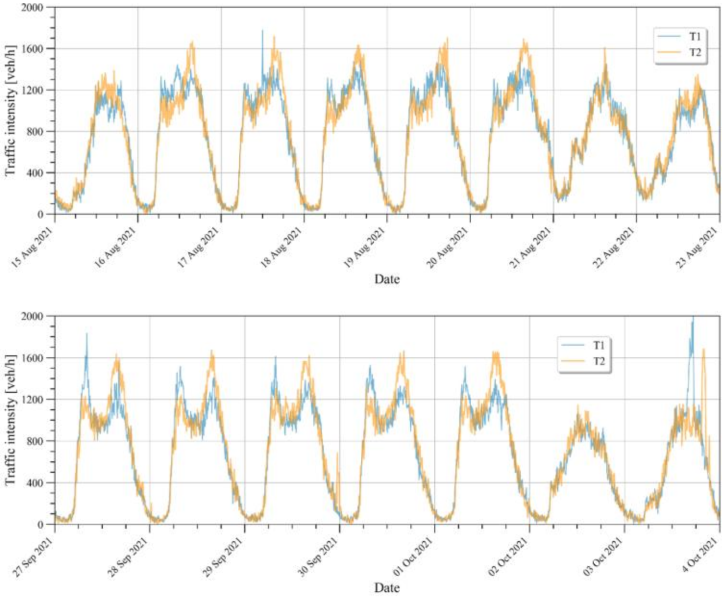
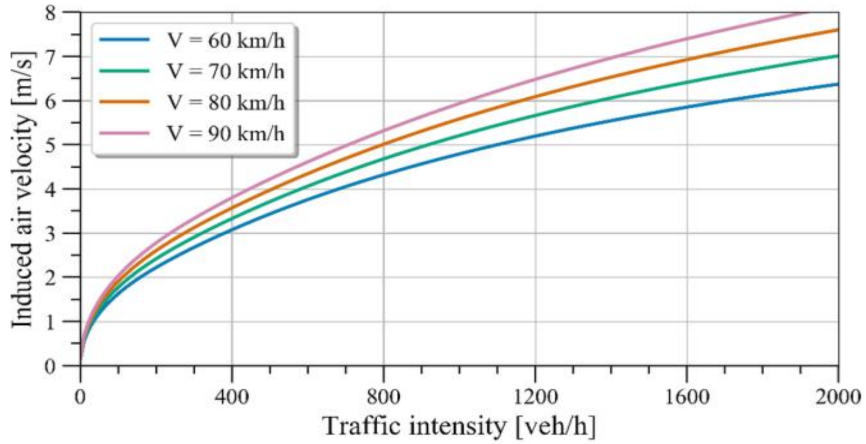


Fig. 13. Traffic intensity for both periods.

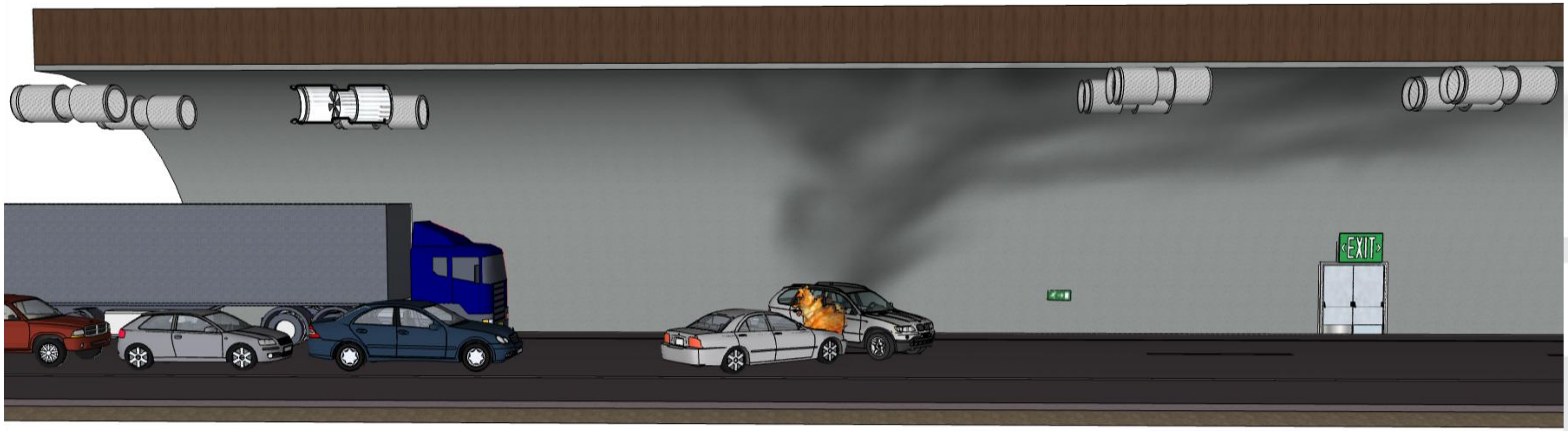


a)

Król A., Król. M., Węgrzyński W., 2022. A study on airflows induced by vehicle movement in road tunnels by the analysis of bulk data from tunnel sensors. (in review)

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{jf} = \eta \frac{I_{fan}}{A_t} \qquad I_{fan} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \rho Q_J \cdot (u_j - u_0)$$



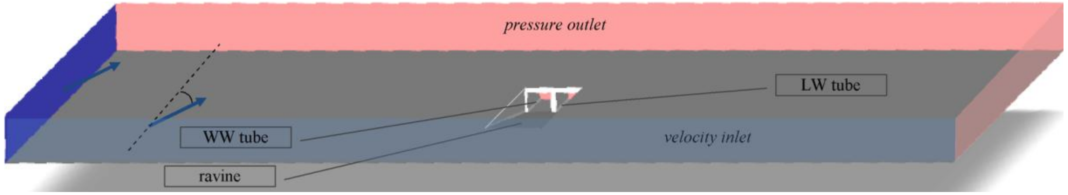
$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

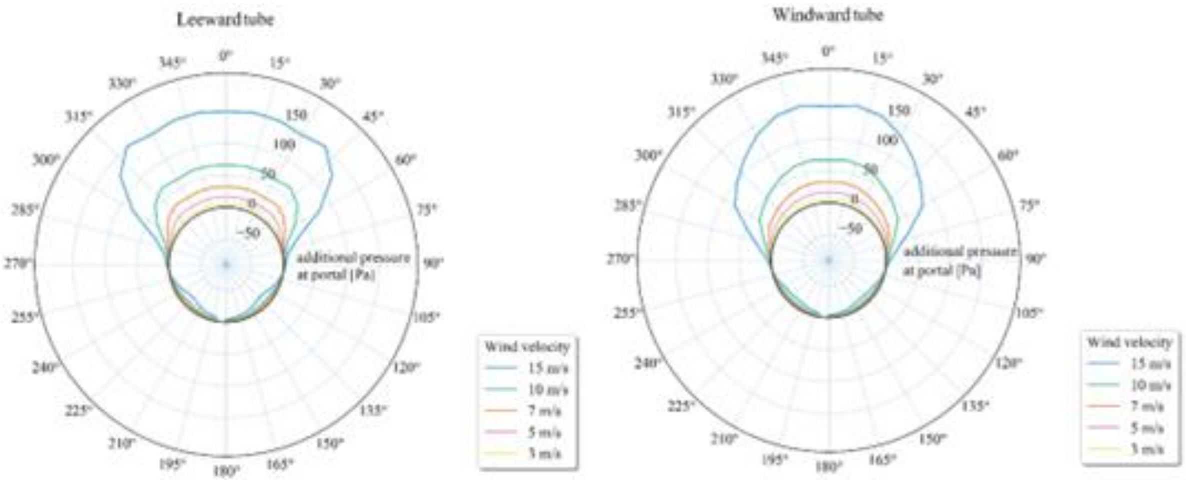
$$\Delta p_{jf} = \eta \frac{I_{fan}}{A_t}$$

$$I_{fan} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \rho Q_J \cdot (u_j - u_0)$$

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{wind} = C_d \frac{1}{2} \rho_0 u_i^2$$



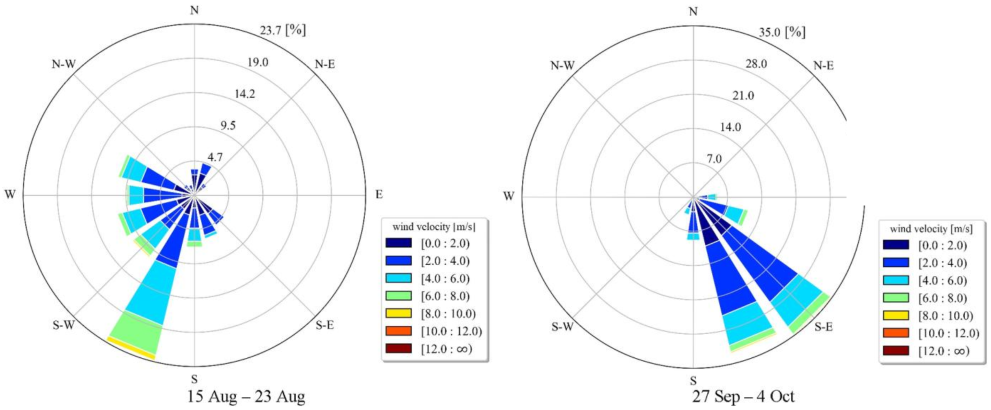


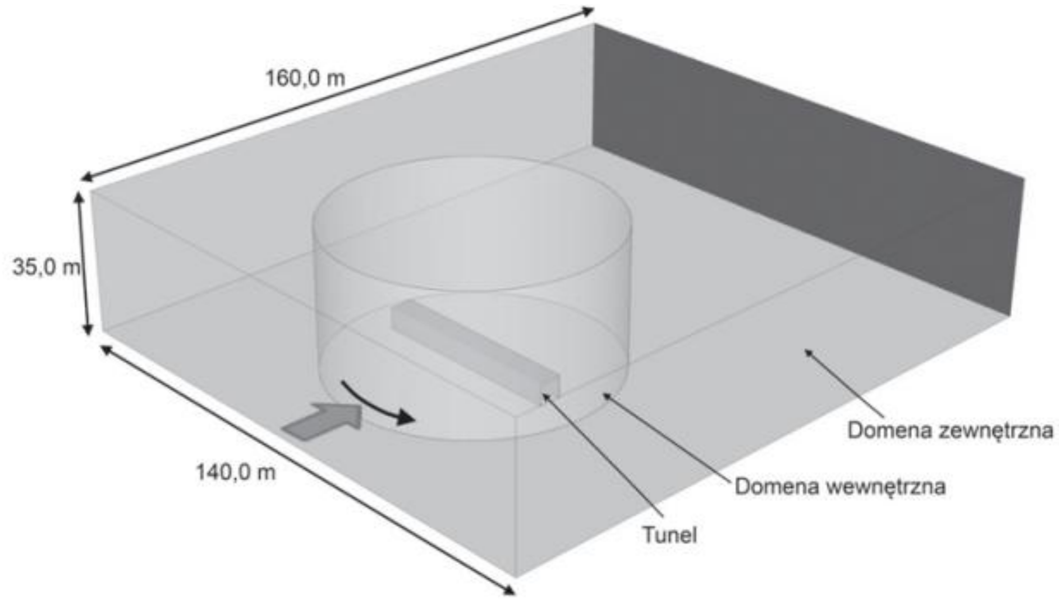
Król A., Król. M., Węgrzyński W., 2022. A study on airflows induced by vehicle movement in road tunnels by the analysis of bulk data from tunnel sensors. (in review)

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{wind} = C_d \frac{1}{2} \rho_0 u_i^2$$

$$p(\alpha, u_{ref,local})$$





$$\bar{U}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \qquad k = \frac{u_*^2}{\sqrt{C_\mu}}$$

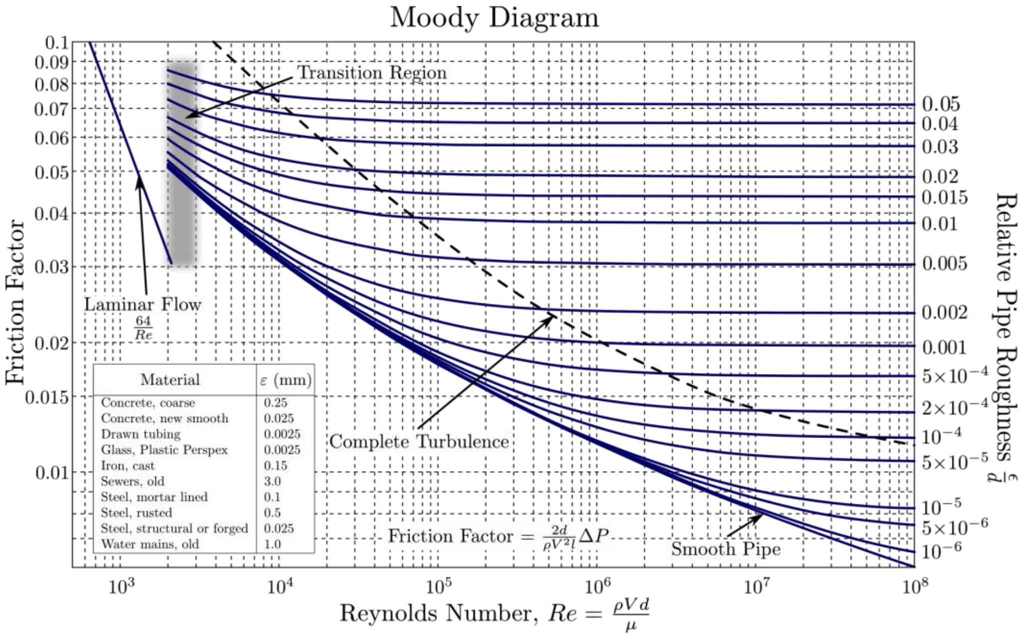
$$\varepsilon(z) = \frac{u_*^3}{\kappa(z + z_0)} \qquad u_* = \frac{u_{ref}\kappa}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{in} = \xi_{in} \frac{1}{2} \rho_0 u_0^2 \qquad \Delta p_{exit} = \xi_{exit} \frac{T_e}{T_0} \frac{1}{2} \rho_0 u_0^2$$

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{fr} = \frac{f}{D}\left[L + L_{ds}\left(\frac{T_m}{T_0} - 1\right)\right]\frac{1}{2}\,\rho_0 u_0^2$$



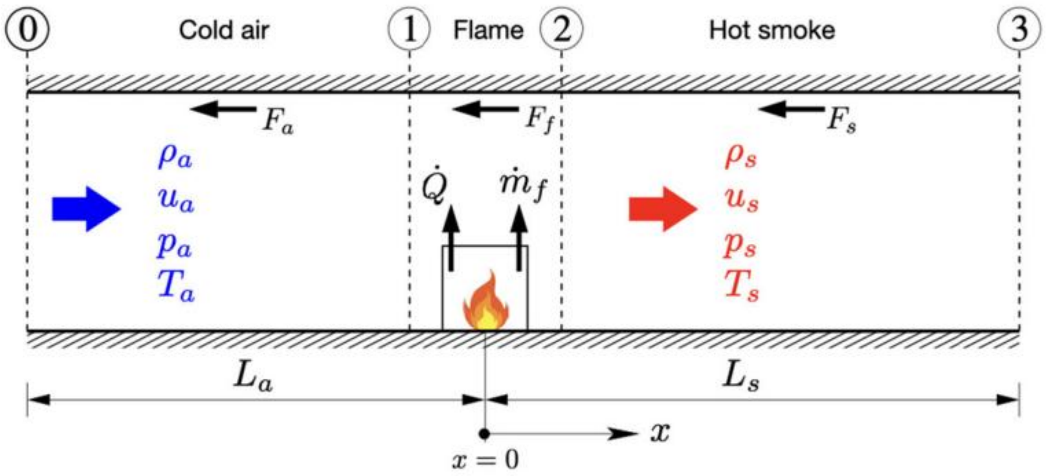
$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

$$\Delta p_{throt} = \frac{Q_c}{D_h^2\, u_0} \cdot C_1$$

$$\Delta p_{throt} = \frac{Q^{0,8}\, u_0^{1,5}}{D_h^{1,5}} \cdot C_1$$

$$\Delta p_{throt} = \frac{Q_c\, u_0}{C_p A_t T_0}$$

$$\Delta p_{throt} = \frac{1}{2}\frac{Q_c\, u_0}{C_p A_t T_0} + \frac{1}{2}\zeta_{fire}\rho u_0^2$$



Ang C. D., Piero J., Reiss I., Rein G. (2022) *Analysis of fire throttling in longitudinally ventilated tunnels with a one-dimensional model,* Fire Technology 58

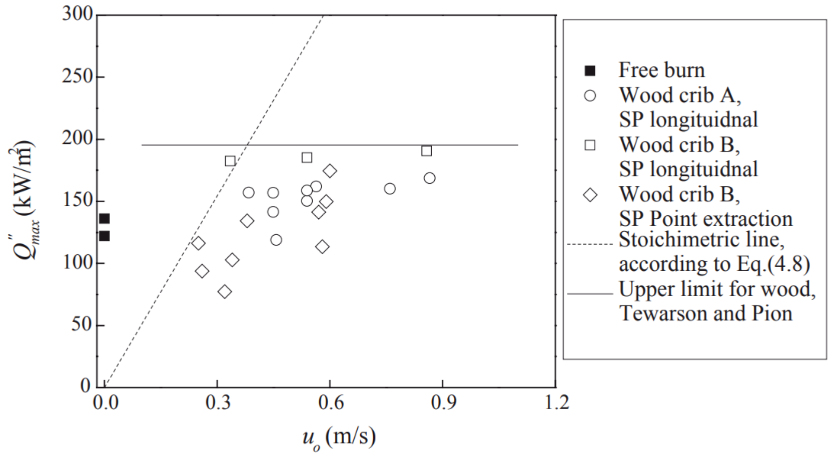
Reiss I. (2020). *Aerodynamics resistance of Fires in Tunnels,, Project Applied Research*

$$\Delta p_{piston} + \Delta p_{jf} \pm \Delta p_{wind} \pm \Delta p_{stack} - \Delta p_{in} - \Delta p_{out} - \Delta p_{fr} - \Delta p_{HGV} - \Delta p_{throt} = p_{dyn}$$

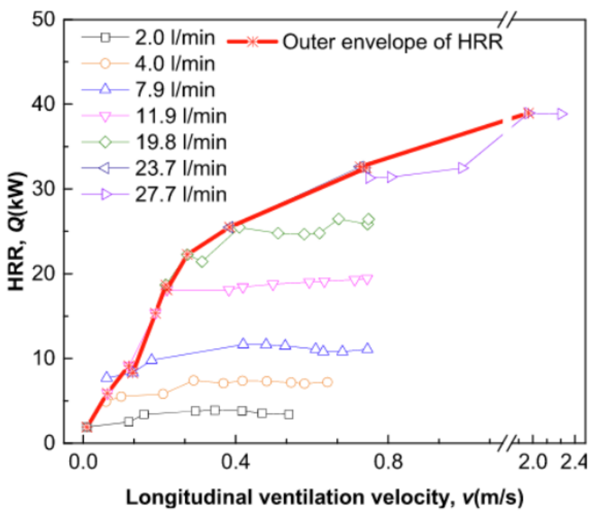
$$\Delta p_{dyn} = \frac{1}{2}\rho_0 (x,t) u_0^2 (x,t)$$

HRR dependencies

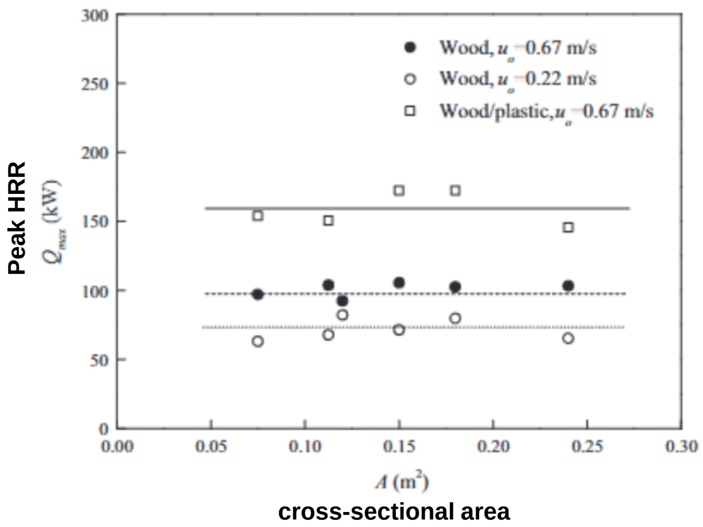
$$Q_{stoi} = \frac{\dot{Q}}{A_s} = 3600\frac{A}{A_s}u_0$$



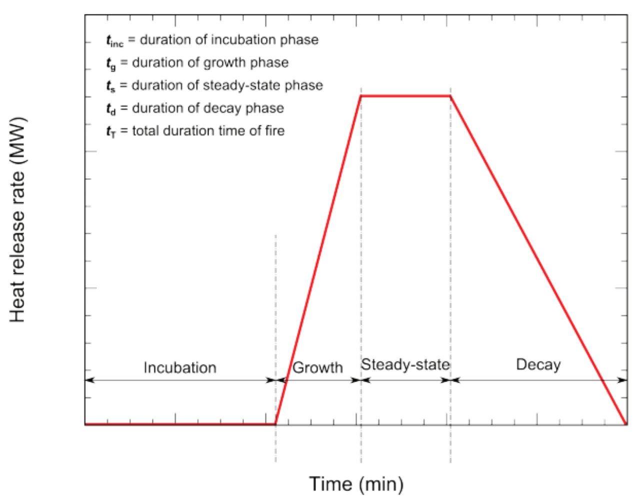
Ingason H., Li YZ. (2011). *Model scale tunnel fires tests with point extraction ventilation*, Journal of Fire Protection Engineering 21



Chen X., Jiang Z., Qiu H., Gao D., Lin P. (2021). Study on the impact of ventilation on HRR of propane fires in tunnels, Tunneling and Underground Space Tech. 118



Li Y. Z., Fan C. G., Ingason H., Lonnermark A., Ji. J.(2016). Effect of cross section and ventilation on HRR in tunnel fires, Tunneling and Underground Space Tech. 118



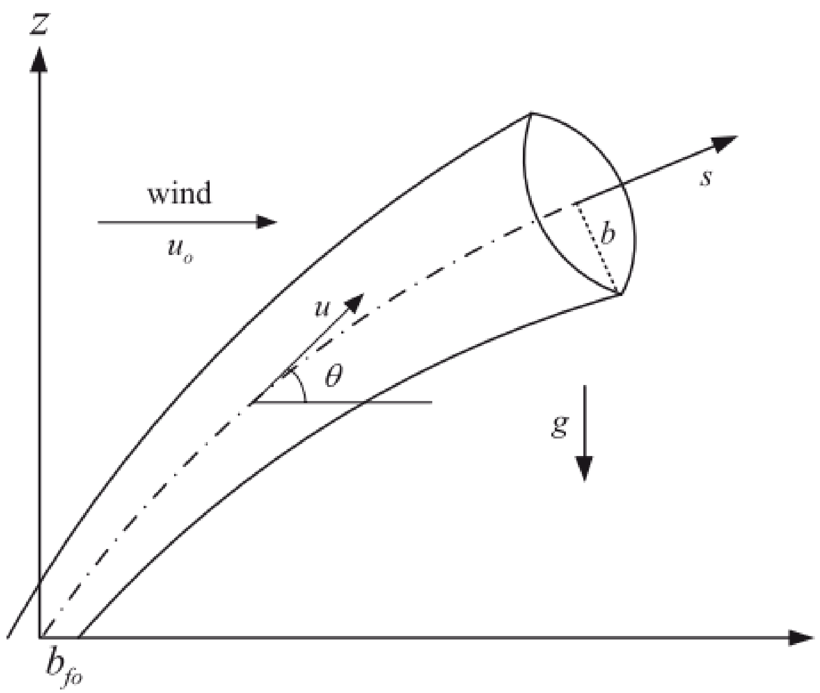
Design fire characteristics for road tunnels (2017), World Road Association (PIARC)

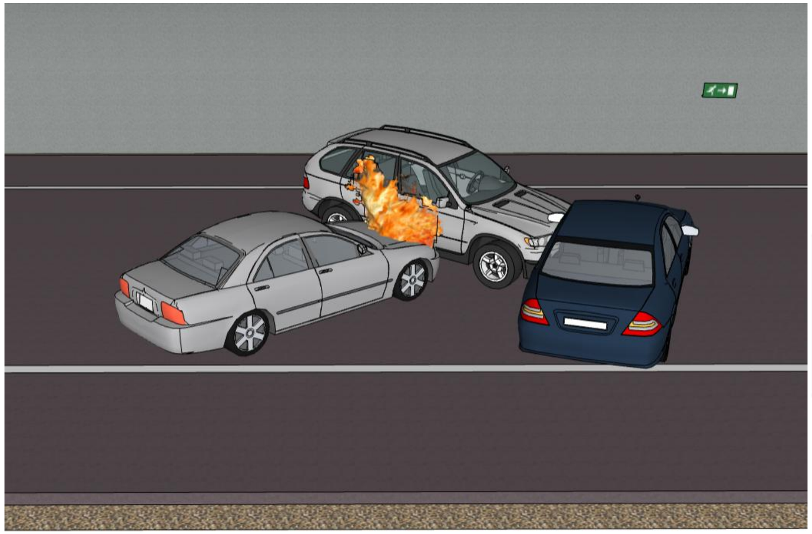
Flame angle

$$V' = \frac{u_0}{w^*}$$

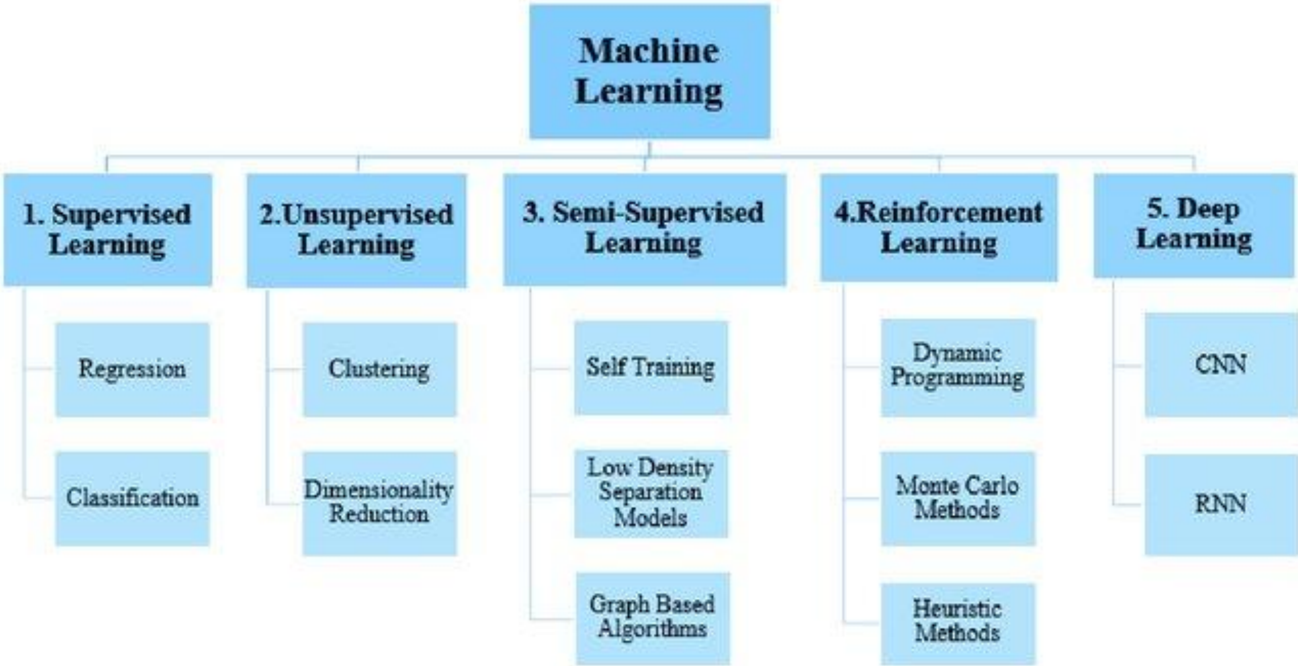
$$w^* = \left(\frac{g\dot{Q}_c}{b_{fo}\rho_0 C_p T_0}\right)^{\frac{1}{3}}$$

$$sin\theta = \begin{cases} 1, & V' \leq 0{,}19 \\ (5{,}26V')^{-1/2}, & V' > 0{,}19 \end{cases}$$



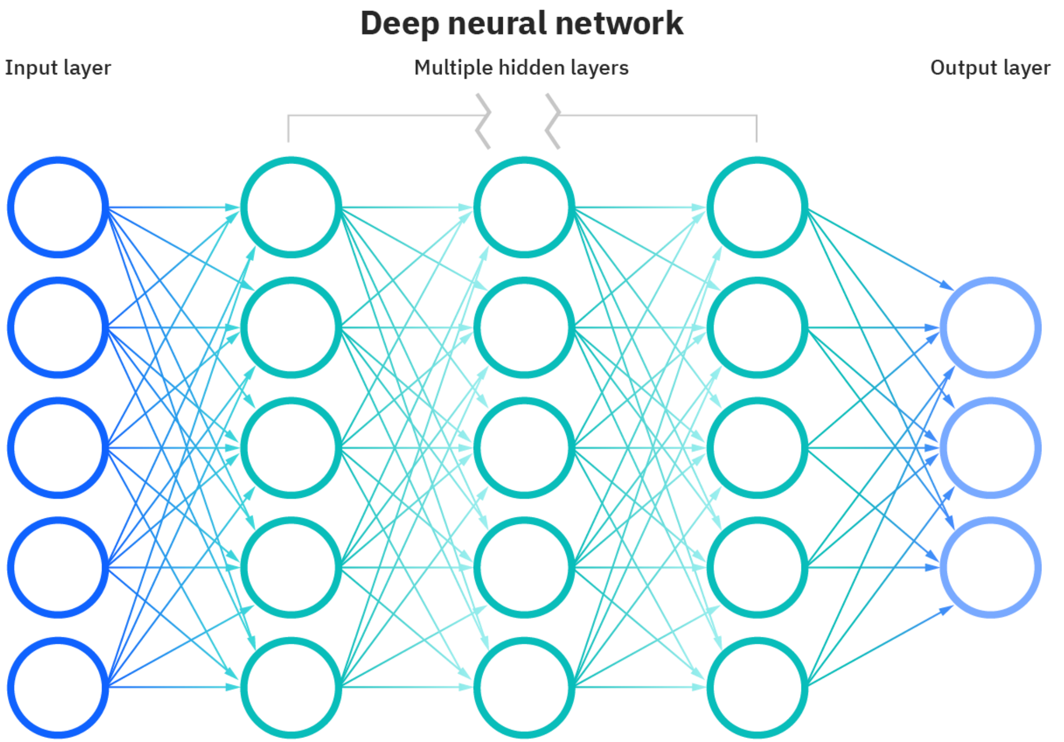


Machine learning



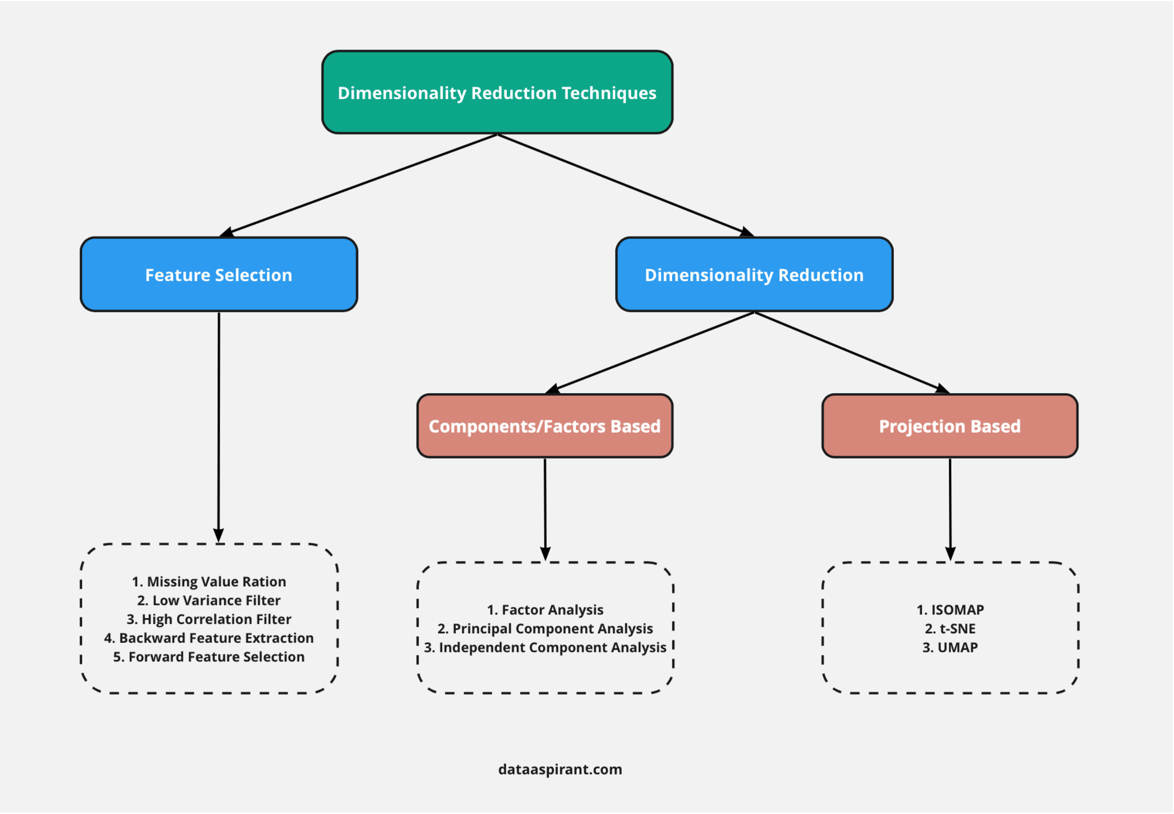
Why machine learning?

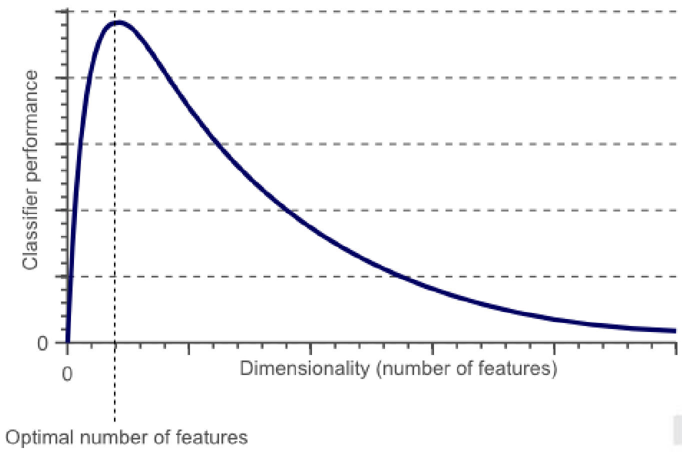
Artifical neural network (ANN)



Why machine learning?

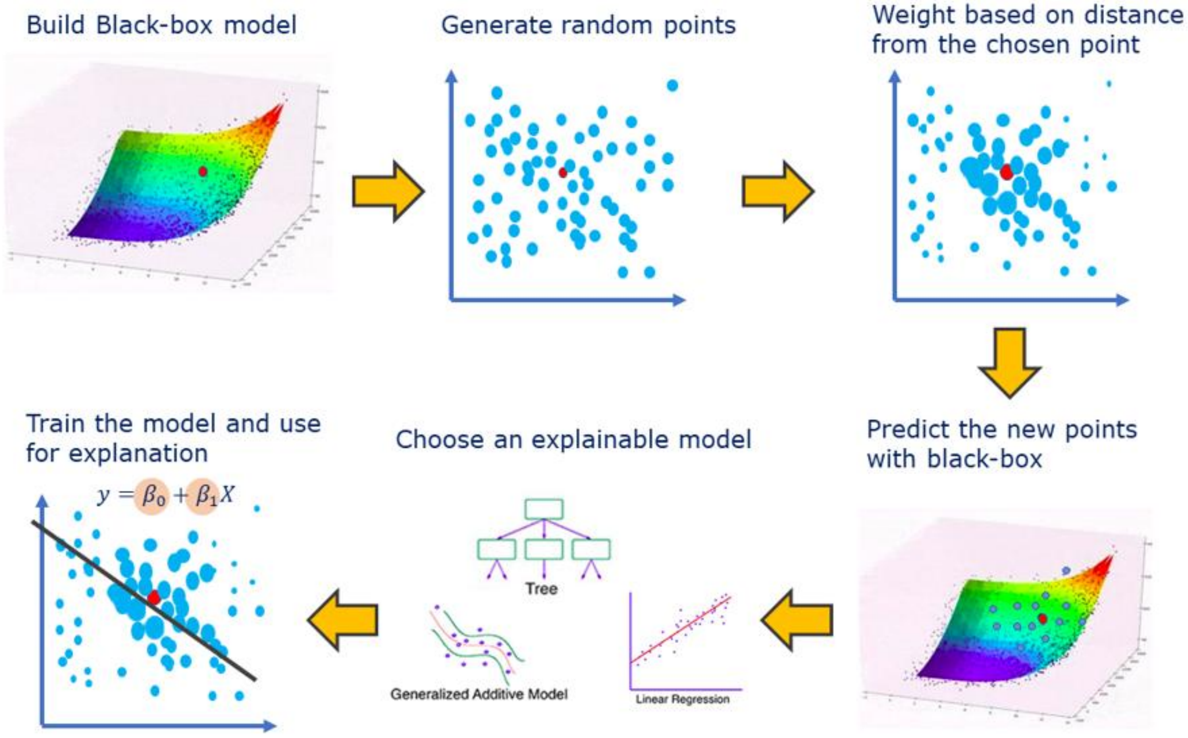
Dimensionality reduction





Why machine learning?

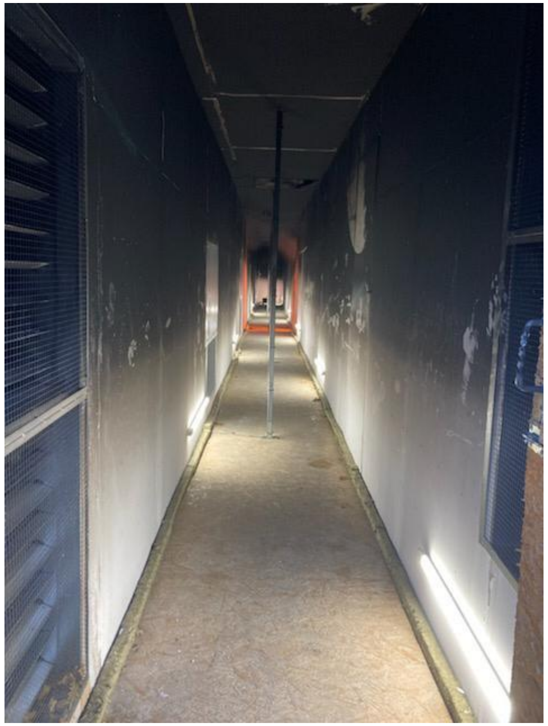
Prediction



Data collection

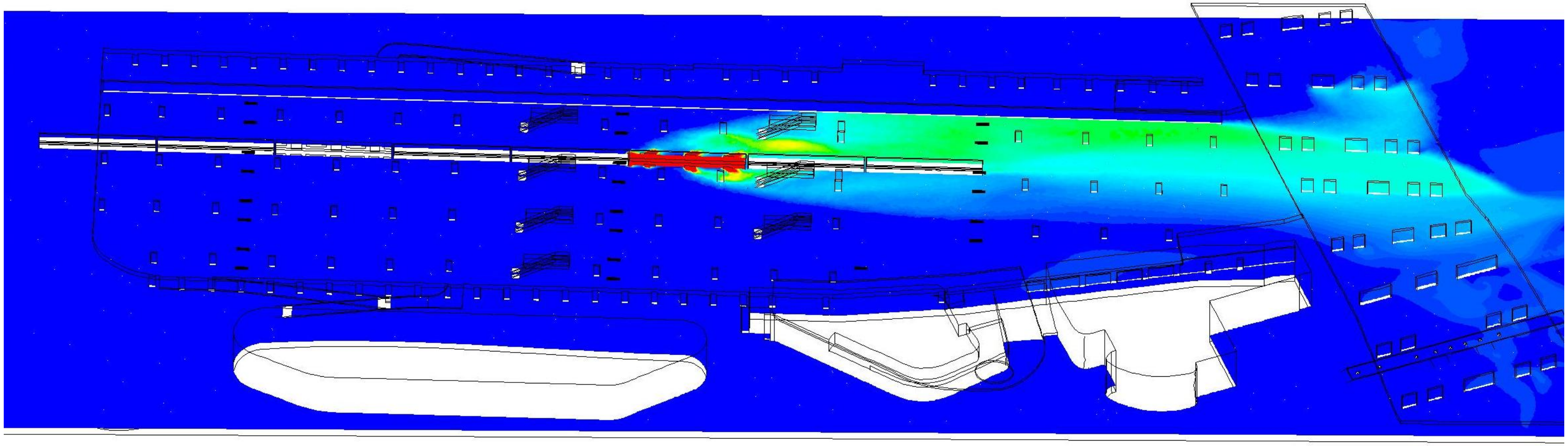
Small scale tests

Data collection



Medium scale tests

Data collection



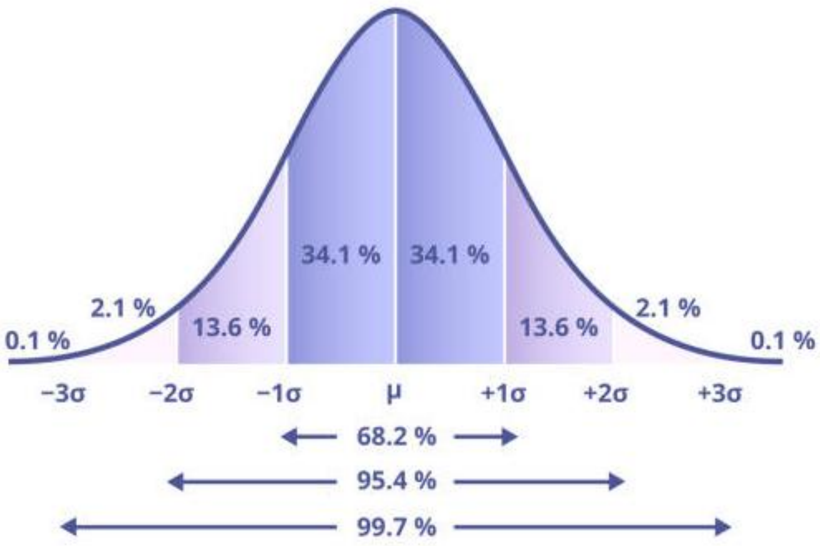
CFD analyses

Final outcome

Trained ML algorithm

Optimisation at the design stage

Dynamic changing smoke control system



Thank you for your attention!

Jakub Bielawski, M. Eng. in FSE

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