

Model Identification for Advanced Tunnel Ventilation Control



ČESKÉ
VYSOKÉ
UČENÍ
TECHNICKÉ
V PRAZE

Ing. Jan Šulc

supervised by *doc. Ing. Lukáš Ferkl, Ph.D.*

Dissertation

Presented to the *Department of Control Engineering,*
Faculty of Electrical Engineering of
Czech Technical University in Prague
in Partial Fulfilment of the Requirements
for the Degree of

Doctor

in Ph.D. programme
Electrical Engineering and Information Technology
in the branch of study
Control Engineering and Robotics

Czech Technical University in Prague
October 2018

Acknowledgements

This doctoral thesis would never be completed without strong support of many people and several institutions.

First of all, I would like to thank my supervisor Lukáš Ferkl for his encouragement and continuous support during my Ph.D. studies. The same thanks belong to my head Jiří Cigler from Feramat Cybernetics, spol. s r.o., because my papers would never be finished without his final reading and corrections.

Besides, I would like to thank my colleagues from the Department of Control Engineering, especially David Charvát, Ondřej Nývlt, Zdeněk Váňa, Jan Salášek, Dan Martinec, Pavel Tomáško and Samuel Prívvara for unforgettable years spent at our department.

Many thanks also go to Sigurd Skogestad and Heinz Preisig from NTNU in Trondheim for their guidance and giving me a chance to spend unforgettable six months at the Department of Chemical Engineering during my student internship.

Great thanks belong to all people and institutions, who have collaborated with me on the amazing and long project ventilation control in the Blanka tunnel complex, namely ventilation designers Jan Pořízek and Jiří Záparka from the company Satra, spol. s r.o. and Adam Hamr and Petr Socha from Eltodo, a.s.

Last but not least, I would like to thank my students Vojtěch Talíř, Martin Procházka, Daniel Gola and Lenka Caletková to whom I have supervised diploma or bachelor thesis. I have learned a lot during the supervision.

This doctoral thesis was supported by internal grants of the Czech Technical University in Prague (CTU) No. SGS16/232/OHK3/3T/13, SGS13/209/OHK3/3T/13 and by the project of the Grant Agency of the Czech Republic (GACR) in the scope of grant No. GC13-12726J. It was further supported by the project of University Centre for Energy Efficient Buildings of CTU in Prague and by grant CZ.1.05/2.1.00/03.0091. The student internship in Trondheim was supported by Norway grants within the program CZ07.

Finally, I do not have to forget to thank my family for strong support during my Ph.D. studies.

Czech Technical University in Prague

Jan Šulc

October 2018

Declaration

This doctoral thesis is submitted in partial fulfilment of the requirements for the degree of doctor (Ph.D.). The work submitted in this dissertation is the result of my own investigation, except where otherwise stated. I declare that I worked out this thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic thesis. Moreover, I declare that it has not already been accepted for any degree and is also not being concurrently submitted for any other degree.

Czech Technical University in Prague
October 2018

Jan Šulc

Abstract

This doctoral thesis is focused on development, refinement and application of mathematical models of airflow dynamics in road tunnels having both a complex structure (long tunnels with entrance and exit ramps and many changes in tunnel geometry) and complex ventilation system. The mathematical models are simplified, one-dimensional and based on the first principle. These simplified models are suitable for control design.

The doctoral thesis introduces: i) a procedure to derive a simplified nonlinear dynamic model of airflow dynamics in road tunnels in the standard state-space form, ii) a new approach to design the airflow velocity control system for use during fire situations in road tunnels, iii) a new control structure for operational ventilation in road tunnels, and iv) how to adapt parameters of simplified ventilation models to fit real measured data in order to improve control performance.

The developed models were used for a design of ventilation control algorithms in the Blanka tunnel complex in Prague, Czech Republic, which is the largest city tunnel in Central Europe. The developed algorithms have been running in continuous operation on the tunnel complex for several years.

The first part of the thesis shows how to derive the dynamic model of airflow velocity and obtain its state space form. The mathematical model describes all important factors, which influence the airflow velocity in a tunnel, i.e. piston effect of vehicles, air friction, effect of ventilation, presence of fire, etc. The model is used for simulation of airflow velocity control during fire.

The second part of the thesis introduces a systematic approach to design and tune the airflow velocity control system for use during fire situations in road tunnels. The approach shows how to use the developed model from the first part of the thesis to tune the proportional-integral (PI) controllers of airflow velocity. The PI controllers are tuned based on the Skogestad Internal Model Control (SIMC) method.

The final part of the thesis presents a control structure design for operational ventilation in complex road tunnels. The control structure is based on the mathematical optimization which ensures the sufficient air quality inside and outside of a tunnel, while minimizing electricity costs for ventilation. From the control theory point of view, this control structure is feed-forward with an adaptive logic. This logic adapts parameters of the mathematical model of airflow velocity and compensates deviations between the mathematical model and the real airflow velocity, and thus provides a certain feedback for the control.

Keywords: airflow dynamics, fire ventilation, operational ventilation, road tunnels, Blanka tunnel complex, PI controller, optimization

Abstrakt

Dizertační práce je zaměřena na vývoj, zpřesňování a využití matematických modelů proudění vzduchu v silničních tunelech, které mají komplexní strukturu (dlouhé tunely s výjezdovými a příjezdovými rampami a mnoha změnami geometrie tunelu) i komplexní systém větrání. Matematické modely jsou zjednodušené, jednodimenzionální a založeny na základních fyzikálních principech. Zjednodušení těchto modelů umožňuje jejich použití pro návrh systémů regulace.

Dizertační práce představuje: i) postup pro odvození zjednodušeného nelineárního dynamického modelu rychlosti proudění vzduchu v silničních tunelech ve standardním stavovém popisu, ii) nový přístup návrhu regulátorů rychlosti proudění během požárního větrání v silničních tunelech, iii) nový přístup návrhu řídicí struktury pro provozní větrání silničních tunelů, iv) metodu pro adaptování parametrů matematického modelu tak, aby lépe odpovídal realitě, a tím zlepšil kvalitu regulace.

Vyvinuté matematické modely byly použity pro návrh regulace větrání v tunelovém komplexu Blanka v Praze, který je nejdelším městským tunelem ve střední Evropě. Vyvinuté algoritmy fungují na tunelovém komplexu v nepřetržitém provozu již několik let.

První část práce popisuje, jak odvodit dynamický matematický model proudění vzduchu a jak obdržet jeho stavový popis. Matematický model popisuje všechny důležité faktory, které ovlivňují rychlost proudění vzduchu v tunelu, t.j. píستový efekt vozidel, tření vzduchu, efekt ventilace, přítomnost požáru, atd. Matematický model je využit pro simulaci řízení rychlosti proudění vzduchu během požáru.

Druhá část práce představuje systematický přístup návrhu a ladění systému regulace rychlosti proudění vzduchu při požáru v silničních tunelech. Přístup ukazuje, jak využít vyvinutý model z první části práce pro návrh a ladění proporcionálně-integračních (PI) regulátorů rychlosti proudění vzduchu. PI regulátory jsou naladěny na základě metody SIMC – Skogestad Internal Model Control.

Poslední část práce se věnuje návrhu řídicí struktury pro provozní větrání v tunelových komplexech. Řídicí struktura je založena na matematické optimalizaci, která zajišťuje dostatečnou kvalitu vzduchu vnitřního i vnějšího prostředí tunelu a zároveň minimalizuje náklady na elektrickou energii nezbytnou pro provoz větrání. Z hlediska teorie řízení se jedná o přímovazební regulátor s adaptivní logikou. Tato logika adaptuje parametry matematického modelu proudění vzduchu a kompenzuje odchylky matematického modelu od reálné rychlosti proudění, a tedy poskytuje zpětnou vazbu pro regulaci.

Klíčová slova: dynamika proudění vzduchu, požární větrání, provozní větrání, silniční tunely, tunelový komplex Blanka, PI regulátor, optimalizace

Acronyms

PI	Proportional-integral controller
PID	Proportional-integral-derivative controller
MPC	Model predictive control
FLC	Fuzzy logic control
IAQ	Indoor air quality
IEQ	Indoor environmental quality
CFD	Computational fluid dynamics
FDS	Fire dynamics simulations
MIMO	Multiple-input multiple-output system
JF	Jet fans
VMR	Ventilation machine rooms
PLC	Programmable logic controller
CCTV	Circuit-closed television
PM	Particulate matter
SCADA	Supervisory control and data acquisition

Table of contents

Acknowledgements	i
Declaration	iii
Abstract	v
Acronyms	ix
1 Introduction	1
1.1 Motivation	1
1.2 Organization of the thesis	2
2 Goals of the doctoral thesis	3
3 State of the art	5
3.1 Types of tunnels	5
3.2 Fire ventilation control	8
3.3 Airflow velocity control during fire	9
3.4 Mathematical models of airflow dynamics	10
3.4.1 Navier-Stokes equations	10
3.4.2 Euler equations	11
3.4.3 Simplified one-dimensional models	11
3.5 Operational ventilation control	13
3.5.1 Rule-based control	13
3.5.2 Fuzzy-logic control	13
3.5.3 Optimization-based control	14
3.5.4 MPC control	14
	xi

Table of contents

4	Results of the thesis	17
4.1	Model-based airflow controller design for fire ventilation in road tunnels . . .	18
4.2	A Systematic Approach for Airflow Velocity Control Design in Road Tunnels	20
4.3	Optimization-based Control of Ventilation in a Road Tunnel Complex . . .	22
5	Fulfilment of the goals	25
6	Conclusions and future work	27
6.1	Summary	27
6.2	Future research	28
	Bibliography	34
	Publications of the author	35
	Curriculum vitae	39

1 Introduction

1.1 Motivation

Nowadays, road tunnels have a significant importance in the transport infrastructure. They are usually constructed where the surface is economically (such as in cities), socially (in historical areas) or environmentally valuable areas [PIARC (2008)]. Especially in urban areas, they reduce impact on the surrounding area in terms of air and noise pollution. On the other hand, they require a comprehensive design of a tunnel technology, such as ventilation, lighting, traffic signs and also the control system. First, a well-designed tunnel ventilation system can significantly improve conditions for evacuation and rescue and fire-fighting operations. Second, during the normal operation of a tunnel, the efficient system of ventilation can significantly improve quality of indoor environment and reduce the impact on the ambient environment. Finally, ventilation in road tunnels forms a large part of electricity consumption, depending on ventilation requirements and a type of the tunnel. According to [Frey et al. (2016)], it is 8% in average for tunnels with unidirectional traffic and longitudinal ventilation system, and much more in the case of tunnels with ventilation machine rooms (VMR) for air exhaust and supply and for tunnels having high requirements on indoor environmental quality (IEQ) and ambient air quality (up to 30% in the case of Blanka tunnel complex in Prague ¹). For this reason, it is highly demanded to optimize ventilation system including control algorithms in order to decrease electricity consumption.

The series of tragic events at the turn of the century, such as Mont Blanc tunnel (39 fatalities), Tauern road tunnel (12 fatalities), St. Gotthard tunnel (11 fatalities), Gleinalm tunnel (5 fatalities) and Seljestads-tunnel (6 injured), triggered writing the recommendations and directives which aim to support and address fire safety in road tunnels. All these directives emphasize the importance of **ventilation control**. For example, recommendation by PIARC (Fire and Smoke Control in Road Tunnels [PIARC (1999)]) states:

„The recent developments of such fire tests show that the efficiency of the ventilation is both linked to its quantitative capacity and the way it is operated. As this second point is never treated by recommendations or regulations, specific developments are necessary to determine optimal reactions adapted to the fire.“

Later, these recommendations also emphasize the importance of air quality inside the tunnel. For example, recommendation by PIARC (Road Tunnels: A Guide to Optimising the Air Quality Impact upon the Environment [PIARC (2008)]) says:

¹According to evaluation of operational ventilation in the Blanka tunnel complex in cooperation with the company Satra, spol. s r. o.

„Emissions from internal combustion engines are harmful to human health and because tunnels redistribute these emissions, special care must be taken to ensure that these emissions are managed responsibly from a human health perspective.“

Moreover, the most recent recommendations, such as recommendation by PIARC (Road Tunnels: Operational Strategies for Emergency Ventilation [PIARC (2011)]) aim to minimize impact on the environment at tunnel portals. They also emphasize that the control of ventilation during the normal operation should be achieved with minimal operational costs.

In summary, the following objectives of the ventilation control system in a tunnel should be achieved:

1. Provide suitable conditions for evacuation and emergency operations during fire.
2. Ensure the desired IEQ, i.e. to keep concentrations of exhaust gases (mainly NO_x , CO and opacity) below defined limit values.
3. Reduce the impact of pollution on the ambient environment (especially in the case of city tunnels).
4. Minimize electricity costs for the running ventilation.

1.2 Organization of the thesis

The thesis is organized as follows. Chapter 2 states the goals which should the thesis achieve. Chapter 3 gives an introduction to the state of the art in the topic of modelling and control of ventilation in road tunnels. The results of the thesis are shown in chapter 4. This chapter contains three main published papers of the author with a short commentary and a brief description of their interconnection with the topic of the thesis. Chapter 5 demonstrates the fulfilment of thesis goals. The thesis is concluded by chapter 6, which summarizes the results and suggests possible future research and topics to be explored.

2 Goals of the doctoral thesis

The goal of the thesis is to investigate and provide new methods for ventilation modelling and advanced control in complex road tunnels, i.e. road tunnels with complex topology (branched tunnels including ramps) and complex ventilation system (longitudinal ventilation with transverse air exhaust and supply, respectively). All proposed methods should be validated in simulations and in the real operation.

The main goals of the thesis can be briefly described as follows:

1. **Propose a procedure for obtaining the airflow dynamics model for complex road tunnels in the standard state-space form.**
2. **Propose a systematic procedure for airflow velocity control design for use during fire situations in road tunnels. Verify this approach on the real tunnel data.**
3. **Propose a control structure for ventilation during the normal operation of road tunnels. This control structure will use the model of airflow dynamics from point 1. Furthermore, this structure must fulfil the following requirements:**
 - ensure desired IEQ and ambient environment quality,
 - ability to control MIMO systems,
 - robustness against control input failures,
 - minimize electricity costs.

Verify this control structure in the real operation of a complex road tunnel.

4. **Propose an algorithm for compensation of the airflow dynamics model obtained in point 1. This algorithm must be implemented as an on-line compensation method leading to a refined model against the real data. Provide an experimental validation of the proposed algorithm.**

3 State of the art

This chapter presents a literature overview on topics modelling, identification and ventilation control in road tunnels. In general, ventilation in road tunnels can be divided into the operational ventilation and the fire ventilation. The operational ventilation ensures the desired IEQ during the normal operation of a tunnel. Especially in the case of urban tunnels, there are often requirements on the quality of ambient environment, meaning that the impact of a tunnel on the ambient environment, in terms of a pollution, should be minimized. The main aim of fire ventilation is to provide suitable conditions for evacuation, fire-fighting and rescue operations.

The first part of this chapter classifies tunnels according to several criteria and explains basic ventilation concepts. The second part deals with the overview of models used for the description of airflow dynamics in road tunnels. It involves the most popular models: Navier-Stokes equations, Euler equations and simplified one-dimensional models based on the continuity and Bernoulli equations. The third part provides an overview of used controllers for fire ventilation. It also discusses fire ventilation guidelines and directives valid in different countries. The last part is focused on the operational ventilation control and summarizes requirements and possibilities of ventilation control in road tunnels.

3.1 Types of tunnels

This section should introduce types of tunnels and their ventilation systems to the reader. The exact classification of road tunnels according to the specific criteria cannot be done, as there are many types of tunnels and several types of ventilation systems including their combinations. In general, road tunnels can be classified by several factors:

- Length
- Topology (simple tunnels, branched tunnels including ramps, crossroads or roundabouts)
- Type of traffic (uni-directional, bi-directional)
- Type of ventilation (longitudinal, transverse, semi-transverse, etc.)

According to the criteria mentioned above, there exist many types of tunnels, long tunnels that are not branched, e.g. *Laerdal tunnel* (12.5 km) in Norway or shorter tunnels with exit and entrance ramps, e.g. *Mrázovka tunnel* (1.1 km) in Prague, Czech Republic.

Short tunnels, say up to 400 m of total length, with uni-directional traffic, do not need any ventilation devices, because the tunnel is ventilated naturally thanks to the piston effect of vehicles [Ferkel (2007)]. Moreover, in the case of fire in short tunnels, the distance

between fans and fire location is too small for an effective control [Sturm et al. (2015)], and thus it could have undesirable effect. In many cases, this critical length is not so strict. For instance, [Sturm et al. (2015)] states this critical length as 600-800 m depending on the slope of the road in a tunnel. This critical length can also differ according to national directives and guidelines. For example, according to „Nařízení vlády č. 264/2009 Sb., o bezpečnostních požadavcích na tunely pozemních komunikací delší než 500 metrů“ [Government of the Czech Republic (2009)], tunnels in the Czech Republic with the traffic intensity higher than 2000 veh/day/lane and longer than 1000 m must be equipped with mechanical ventilation system.

The most used ventilation system in tunnels is called the longitudinal ventilation system. Its principal scheme is shown in Figure 3.1. The longitudinal system consists of axial jet fans located under the ceiling of the tunnel, which support or brake the airflow velocity in the tunnel. The smoke is extracted from the tunnel in the direction of traffic through tunnel portals. The longitudinal ventilation system is usually operated in shorter highway tunnels with uni-directional traffic where there is a smaller risk of congestion. All highway tunnels in the Czech Republic are ventilated longitudinally, e.g. *Panenská* (2.2 km) [Zápařka (2009)]. The main advantage of the longitudinal ventilation system is low constructional costs.

For tunnels with bi-directional traffic or tunnels with complex topology including ramps, it is suitable to use transverse ventilation system. The use of transverse or semi-transverse ventilation system is a subject of national standards. For example, according to the EU directive 2004/54/EC [Council of European Union (2004)], the use of transverse ventilation system is mandatory only for tunnels with bi-directional traffic longer than 3000 m. However, the recommendation „METODICKÝ POKYN – větrání silničních tunelů. Volba systému, navrhování, provoz a zabezpečení jakosti větracích systémů silničních tunelů“ [Pospisil (2013)] valid in the Czech Republic states that every tunnel with bi-directional traffic must be equipped with transverse ventilation system. The transverse ventilation system is much more efficient but more expensive than the longitudinal one. Tunnels with the transverse ventilation system are equipped with axial fans in ventilation machine rooms. Typically, two systems of smoke extraction can be used; distributed smoke extraction and massive point extraction.

The distributed smoke extraction system is shown in Figure 3.2. The smoke is extracted through openings at the ceiling of the tunnel, further through remote controlled dampers in fire extraction duct and finally through axial fans in ventilation machine rooms to the ambient environment. The fire extraction duct is located usually upon or under the ceiling of the tunnel. The distributed smoke extraction system is used in *Strahov tunnel* (1.9 km) and in most sections of the *Blanka tunnel complex* (5.5 km) in Prague, Czech Republic [Zápařka (2012)]. Much more about the ventilation system in the Blanka tunnel complex is provided in sections 4.1 and 4.3.

If it is not possible to construct the fire extraction duct (construction price, routes of water networks, etc.), then the smoke is extracted directly at the location of ventilation machine room. This way of smoke extraction is called massive point extraction, see Figure 3.3. Massive point extraction can be also used for operational ventilation, as it provides extraction of polluted air and supply of fresh air, respectively.

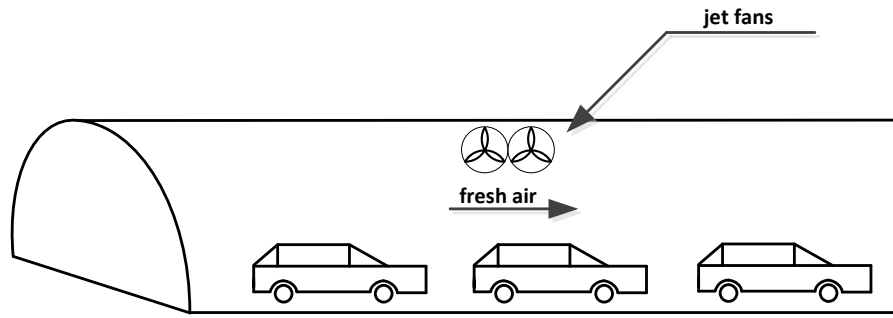


Figure 3.1 – Longitudinal system of ventilation in road tunnels.

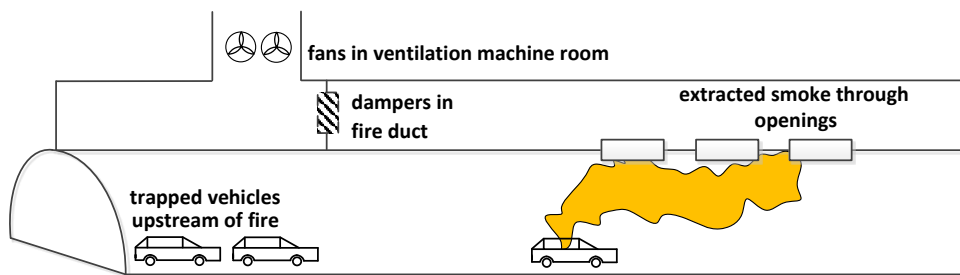


Figure 3.2 – Transverse ventilation system in road tunnels, distributed smoke extraction.

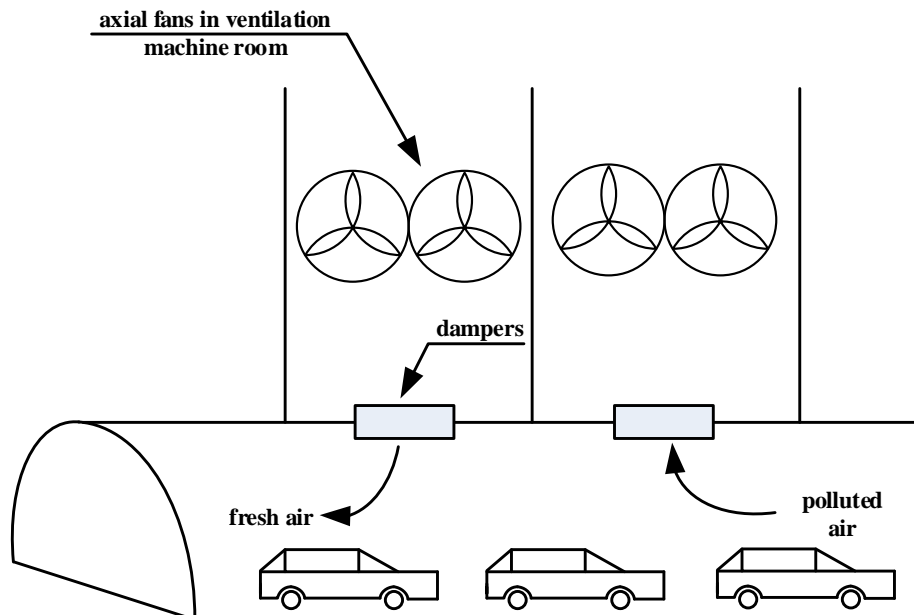


Figure 3.3 – Transverse ventilation system in road tunnels, massive point extraction.

3.2 Fire ventilation control

In this section, the main principles of fire ventilation control in road tunnels are summarized. The overview article [Sturm et al. (2015)] introduces possible ways of fire ventilation control. The paper summarizes all important facts and results in recommendations written by PIARC [PIARC; PIARC; PIARC (1999; 2007; 2011)] and CETU [CETU (2003)]. Fire and smoke control in road tunnels is important to:

- provide suitable conditions for evacuation
- support rescue and fire-fighting operations
- reduce risk of explosions
- reduce damage to tunnel installations

During fire in a road tunnel, there can be blocked vehicles upstream of the fire and there exist different ways regarding fire ventilation control. Some of them prefer to avoid backlayering effect; the movement of smoke upstream of fire, meaning against the blocked vehicles. Other ones are focused on maintaining low airflow velocities to reduce smoke propagation and support evacuation, at least during the self-evacuation phase. This is usually important in the case of urban road tunnels where there can be blocked vehicles both, upstream and downstream of fire due to the possible congestion.

The first way preventing the backlayering requires relatively high airflow velocities upstream of the fire. The minimum airflow velocity upstream of fire preventing the backlayering is called the *critical velocity*. The critical velocity depends on many factors, such as heat release rate of fire, cross-section area of the tunnel, slope of the road, etc., and the exact value can be determined based on detailed Computational fluid dynamics (CFD) simulations. More about critical velocities and CFD simulations is stated in section 3.4.1. According to [Sturm et al. (2015)], the typical value of critical velocity is 2.5-3 m/s.

The other way focused on reduction of smoke propagation requires low airflow velocity, typically about 0.5 m/s. This is somehow controversial, and in practice, a trade-off is often made, either by applying a low velocity (1.0-1.5 m/s) upstream of fire or by dividing the ventilation control into two phases; evacuation phase and fire-fighting phase.

The European directive 2004/54/EC [Council of European Union (2004)] defines minimum safety requirements for road tunnels within the Trans European Road Network (TERN). Although the directive covers requirements for ventilation and equipment, it does not cover issues regarding the emergency operations and ventilation control during fire.

The aforementioned recommendations are not binding and can be customized according to national guidelines [PIARC (2011)], such as RVS in Austria [RVS 09.02.31 (2014)], RABT in Germany [RABT (2006)], ASTRA in Switzerland [ASTRA (2008)], FHWA in United States [FHWA (2004)] or guidelines [Japan Road Association (2001)] in Japan and [RTA (2007)] in Australia.

In the Czech Republic, there are several valid standards for fire ventilation equipment, „ČSN 73 7507 – Projektování tunelů pozemních komunikací“ [CTN PRAGOPROJEKT (2014)] or „TP98 – Technologické vybavení tunelů pozemních komunikací“ [ELTODO, a.s. (2004)] and [Pospisil (2013)] for fire ventilation control in road tunnels.

3.3 Airflow velocity control during fire

In this section, the current state of the art control algorithms for airflow velocity during fire in road tunnels are provided. As stated in section 3.2, airflow velocity control during fire is important and there can be different requirements on airflow velocity upstream of fire.

Many tunnels around the world still use simple approaches (rule-based or heuristic approach) to control the airflow velocity. Even though Ferkl [Ferkl (2007)] proposed a complex control approach in 2007, there has been a rather slow progress in the development of control algorithms for airflow velocity.

These approaches are developed based on the experience from past and work well on simple tunnels that are not branched. Some of them are feedback and some of them are feed-forward due to the unreliable measurement of airflow velocity. As stated by Pospisil [Pospisil, P. and Brandt, R. (2005)], control of airflow velocity using wrong values may lead to catastrophic scenarios in a real fire incident, as was confirmed during the full-scale fire test in the *Plabutsch tunnel* [Waltl, A. (2004)].

There have been few presented results of airflow velocity control achieved by PID controllers. Mizuno [Mizuno, A. (1991)] simulated the PID control of airflow velocity with disturbance estimation during emergency situations. This method is suitable especially for long tunnels, as he simulated on two Japanese tunnels; *Kan-etsu tunnel* (11 km) and *Ena-san tunnel* (8.6 km). Although the simulation results are satisfactory, it is not clear, whether this control method has ever been applied in practice.

Schmölzer [Schmölzer et al. (2016)] presented a simple, generally applicable procedure for PI controllers tuning in tunnel ventilation systems. The design procedure is based on the system identification using step response. Although the transfer function of the system can be relatively easily found, especially via the time percentage value method, this method is, however, restricted to the following; the tunnel must be absolutely free of any traffic, a steady state condition of airflow velocity in the tunnel must be ensured before the start and termination of the recording and jet fans have to be activated as fast as possible.

Schmölzer et al. tested several tuning rules for PI controllers on the real ventilation system; „second“ setting rule by Ziegler and Nichols [Ziegler et al. (1942)], four setting options by Chien, Hrones and Reswick [Smith and Corripio (1985)] and rules that are specifically derived for the time percentage value method [Zacher and Reuter (2011)]. The settings by Chien, Hrones and Reswick resulted in best disturbance response with limited overshoot. They applied the design procedure to two Austrian tunnels; *Neumarkt tunnel* (2 km, longitudinal ventilation system with jet fans equipped with variable speed drives), *Götschka tunnel* (4.5 km long, semi-transverse ventilation system and jet fans with soft-starters). The achieved results are satisfactory enough and their approach could be used for the design of airflow velocity control system in future tunnels.

Altenburger [Altenburger et al. (2015)] analysed and compared two controllers through simulations; PI/PID and Model predictive control (MPC), to show their advantages and disadvantages. The PI/PID controller was tuned via the Ziegler-Nichols method and the

MPC controller was tuned for the simplified linearised second and third order dynamic system, respectively. Although the MPC controller is, according to simulations, faster than the PI/PID controller, the authors still recommend to use the PI/PID controller for longitudinal airflow velocity control in the case of fire, due to its simple structure, the small number of parameters and good control performance.

The most recent work [Euler-Rolle et al. (2017)] presents a dynamic feed-forward control strategy of jet fans using feedback linearization. Euler-Rolle et al. demonstrated this control strategy on the Austrian highway tunnel. This strategy is novel but it is limited to highway tunnels that are not branched.

3.4 Mathematical models of airflow dynamics

The mathematical model of airflow dynamics in a road tunnel is the most important part for the airflow controller design for both fire and normal operation. Basically, there exist three ways how to model airflow in road tunnels; Navier-Stokes equations, Euler equations and simplified one-dimensional models (dynamic and quasi-dynamic).

3.4.1 Navier-Stokes equations

Navier-Stokes equations provide the most general description of airflow dynamics in road tunnels. They are very accurate, the airflow dynamics can be modelled in three dimensions.

Navier-Stokes equations have many forms that can be found in literature, such as [Douglas et al. (2011)]. One way to express the Navier-Stokes equation is to use the Cauchy momentum equation in tensor form:

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla(\rho \mathbf{v} \mathbf{v}^T) = -\nabla \cdot p \mathbf{I} + \nabla \cdot \tau + \rho \mathbf{g} \quad (3.1)$$

where ρ is the flow density, \mathbf{v} is the vector of flow velocity, p is the pressure, \mathbf{I} is the identity matrix, τ is the Cauchy stress tensor and \mathbf{g} represents body accelerations and external forces acting on the mass of flow.

Equation (3.1) is valid for compressible flows where the flow density ρ is supposed to be time variable. The assumption of incompressibility holds in road tunnels because the Mach number for airflow is considerably lower than 0.3 [Drikakis and Rider (2005)]. For incompressible flows ($\rho = \text{constant}$), the Navier-Stokes equation can be expressed in the following way:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \nabla) \mathbf{v} - \nu \nabla^2 \mathbf{v} = -\nabla \left(\frac{p}{\rho_0} \right) + \rho \mathbf{g} \quad (3.2)$$

where ν represents the kinematic viscosity and ρ_0 is the uniform density.

The branch of fluid mechanics, which simulates real fluids using Navier-Stokes equations, is called Computational Fluid Dynamics (CFD). In tunnel field, fire dynamics simulators (FDS), such as [McGrattan et al. (2017)] are widely used for simulation and design of fire ventilation.

In recent years, many papers dealing with CFD simulations have been published. For example, Wang [Wang and Wang (2016)] developed a numerical model of tunnel fire and investigated the influence of cross-sectional fire location on the smoke movement in a tunnel. Chow, et al. [Chow et al. (2015)] carried out numerical simulations of fire with CFD for tilted tunnel with longitudinal ventilation. The result of the paper is a corrected empirical formula for critical velocity in a tilted tunnel based on experimental and simulation results. After that they published paper [Wang and Wang (2016)], in which they presented results from tunnel fire simulation under natural ventilation. Results of the paper are empirical expressions of smoke temperature and velocity decay in the longitudinal direction. Similar topic, tunnel fire in a sloping tunnel, was investigated by Miao-cheng, et al. [Miao-cheng et al. (2016)]. They provided 250 simulations on nine typical tunnels using FDS. The contribution of this paper are prediction models for critical velocity on different slopes. The benefit of this paper is also a comparison of these models with the existing ones.

3.4.2 Euler equations

Euler equations can be derived from Navier-Stokes equations by removing terms describing viscous actions. Euler equations can be expressed in several forms. Incompressible Euler equations in convective form can be written as follows [Rieutord (2015)]:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho_0} \nabla p + \mathbf{g} \quad (3.3)$$

$$\nabla \cdot \mathbf{v} = 0 \quad (3.4)$$

Equation (3.3) is the momentum-balance equation and equation (3.4) is the momentum conservation equation also called continuity equation. Euler equations have been used for analysis of specific problems in tunnels, such as oscillations and airflow transient response. For example, Lotsberg [Lotsberg, G. (1997)] calculated and verified pressure oscillations caused by heavy trucks in *Fodnes tunnel* in Norway (6.5 km). The transient time of the airflow velocity in a tunnel was calculated and measured by Lotsberg about 5 minutes for significant airflow changes and about 1 minute for minor airflow changes.

3.4.3 Simplified one-dimensional models

Euler equations are also being used for derivation of simplified 1D airflow velocity models described by Bernoulli equations and continuity equations.

The simplified models of airflow dynamics in road tunnels assume incompressible flow, meaning that the density of air ρ is constant along the whole length of the tunnel and does not depend on time. Furthermore, they consider 1D model with lumped parameters, i.e. that the airflow velocity vector \mathbf{v} does not depend on the y- and z-coordinate. These assumptions imply that the airflow velocity v is constant along each section of the tunnel.

These simplified models allow to design airflow velocity controllers, such as PID or MPC and simulate IEQ in a tunnel under different traffic conditions.

The current literature overview involves models for longitudinally ventilated tunnels that are not branched (usually highway tunnels) but there is lack of models for complex road tunnels (transversely or semi-transversely ventilated tunnels with ramps). The dynamic and quasi-dynamic models are briefly described in the following sections and details on both models are provided in chapter 4.

Dynamic model

The simplified 1D dynamic model of airflow velocity in tunnels with no branches (ramps) is based on the first principle equation:

$$m \frac{dv}{dt} = F_{tot} \quad (3.5)$$

where m is the mass of air in the tunnel, v is the airflow velocity, time dependent but constant along the whole length of the tunnel, F_{tot} represents all forces, which act on the mass of air in the tunnel (piston effect, air friction, effect of jet fans, etc.)

These dynamic models have been used for simulation and design of airflow velocity control in previous years. Ohashi [Ohashi, H. et al. (1982)] developed the numerical program to optimize the ventilation system in *Kan-etsu tunnel* in Japan (10.9 km). This numerical program uses the simplified 1D model to control the pollutant concentrations in the tunnel. Altenburger [Altenburger et al. (2015)] analyzed and compared PID controller and Model predictive control (MPC) on the 1D model of airflow dynamics to show their advantages and disadvantages, as already mentioned in section 3.3. The most recent work published by Euler-Rolle [Euler-Rolle et al. (2017)] uses the model of airflow dynamics to design the control system for fire ventilation based on feedback linearization.

The dynamic models are suitable for simulation and control design in cases where the changes in control input are more frequent compared to the transient time of the system. Typically, in the case of fire ventilation control, the dynamics of airflow cannot be neglected as the controller period is several seconds.

Quasi-dynamic model

Quasi-dynamic models are suitable in cases where the dynamics of the system is very fast compared to the changes in control input. As mentioned in section 3.4.3, the transient time of airflow velocity in a tunnel is about 5 minutes for significant changes caused by traffic or jet fans and when the simulation period is larger than 5 minutes, the dynamics of airflow can be neglected ($\frac{\partial v}{\partial t} = 0$). Equation (3.5) describing the dynamic model is therefore simplified to:

$$F_{tot} = 0 \quad (3.6)$$

In fact, Equation (3.6) describes the steady-state of the system, which depends on input variables, such as number and type of vehicles passing the tunnel, number of running jet fans in the tunnel, wind velocity acting on tunnel portals, etc.

In recent years, quasi-dynamic models have been used for simulation and control design of ventilation in road tunnels. The literature overview is involved in section 3.5.

3.5 Operational ventilation control

The aim of ventilation control during the normal operation is to maintain the IEQ, i.e. to keep pollutant concentrations, such as carbon monoxide CO, nitrogen oxides (NO, NO₂) and opacity under predefined limit values. Although ventilation in road tunnels is mainly designed for fire ventilation, especially in urban tunnels, there are still high demands on IEQ. Nowadays, the operational ventilation is primarily focused on nitrogen oxides NO_x and opacity due to the improved combustion and catalyst technology in cars [Longley, I. (2014)].

In recent years, there have been several papers presenting different control approaches for normal operation of a road tunnel. They can be divided into several groups:

- Rule-based approaches
- Fuzzy-logic control
- Optimization-based control
- MPC control

3.5.1 Rule-based control

The rule-based control usually works well for short tunnels with no branches and low requirements on IEQ. Rule-based control techniques are simple for programmable-logic controller (PLC) implementation and they do not require any additional computational server, such as for example MPC requires. The rule-based control involves ventilation control based on the specific time schedule (for example a different ventilation program for working days and weekdays, respectively for traffic peak hours and night hours) or hysteresis type of control. Typically, the rule-based control in most tunnels combines both techniques; time schedule based ventilation and hysteresis type of control. For example, a tunnel is ventilated naturally during night hours and a small number of jet fans is running during the peak traffic hours. When the concentration of exhaust fumes reaches 80% of a limit value, more jet fans are started and they are running until the concentration does not drops below 60% of a limit value.

Other approaches presented in literature, such as [Bellasio (1997)] or [Bring et al. (1997)] are based on the calculation of a minimum required airflow for the worst-case situation (congestion, stop-and-go situation, etc.).

3.5.2 Fuzzy-logic control

Other approaches have applied fuzzy logic control (FLC). Funabashi [Funabashi et al. (1991)] presented a predictive fuzzy control scheme for operational ventilation. They used the simplified dynamic model of airflow, pollution concentration and vehicles to set rules for the fuzzy control scheme. Moreover, they implemented an adaptation logic to refine

parameters of the a-priori model based on actual observations. The control scheme was applied to tunnels on *Kyushu Highway* in Japan. Although this paper was breakthrough, the control system is slightly complicated and does not guarantee the faultless operation under all possible conditions. The control system was applied only on a one-tube tunnel and possible extension to a tunnel complex that are branched is not discussed at all. The proposed fuzzy control system was patented by Inoue in 1991 [Funabashi et al. (1991)].

Chen [Chen et al. (1998)] developed the FLC with defined membership functions. They applied inference and defuzzification to design the ventilation control. This FLC has been validated only through computer simulations and experimental validation is not provided in this work.

Karakas and Kühlünk [Karakas, E. and Külünk, H.; Karakas (1998; 2003)] proposed another adaptive FLC for ventilation control as well, which is designed for highway tunnels with simple topology. They experimentally validated the developed FLC in *the Bolu tunnel* in Turkey and compared it with the PID controller. The results are not convincing and it is not clear from the paper whether the FLC really works in the real operation.

3.5.3 Optimization-based control

Optimization-based control of ventilation aims to keep pollutant concentrations under acceptable limits while minimizing electricity costs, but it can not be considered as MPC control because it does not use prediction of process variables.

Ohashi [Ohashi, H. et al. (1982)] developed the simulation model of airflow and pollutant concentrations for *Kan-etsu tunnel* in Japan (10.9 km). This simulation model is based on dynamic models and further used for the optimum setting of ventilating units. Optimum setting of ventilating units and optimum adjustment of the ventilation rate are achieved in terms of the normal traffic flow using the non-linear programming method. The paper lacks any experimental validation of the proposed algorithm.

Ferkl [Ferkl et al.; Kurka et al. (2006; 2005)] developed a simulation program of airflow, traffic and pollutant concentrations for tunnels within the City Ring in Prague. The airflow model is quasi-dynamic and based on the Bernoulli and continuity equations. This simulation program was validated on the *Mrázovka tunnel* in Prague, which involves one entrance and one exit ramp. The program was further used for the design and simulation of the ventilation control system in other tunnels within the Prague City Ring. This was published by Ferkl and Meinsma [Ferkl and Meinsma (2007)]. They developed the linear and quadratic program that keeps the pollutant concentrations under pre-defined limit values with minimum operational costs.

3.5.4 MPC control

Although MPC has many important advantages, such as constraint handling, possibility to control MIMO systems or variable prediction, application of the MPC control strategy in road tunnels is still limited due to several factors. First, the typical MPC algorithm requires knowledge of the process dynamics. The dynamic model in the explicit form can

be found for tunnels without ramps (usually highway tunnels), but obtaining the dynamic model for complex road tunnels with connected ramps is difficult. Second, typical MPC algorithms assume simplified linear models, which are unsatisfactory for models of airflow dynamics in road tunnels. Moreover, a lot of variables, such as NO_x or opacity have to be estimated due to the lack of sensors in the tunnel.

Simulation analysis of MPC control in highway tunnels without ramps are performed in [Hrbček, J. and Šimák, V. (2011)] or [Tan et al. (2012)]. In these cases, MPC uses the linearized dynamic model of airflow and pollutant concentrations. The aim of MPC control is to keep CO concentrations and opacity below acceptable limits while minimizing electricity costs. Unfortunately, the papers lack any experimental validation of the proposed MPC algorithms.

4 Results of the thesis

This chapter presents results of the author's research related to the topic of this thesis in the form of three main author's papers relevant to the topic in combination with the integrating text¹. Each paper has a short commentary, a summary of the paper, co-authorship of individual authors according to V3S² and its contribution to the thesis goals. The order of the papers presented here follows the development of author's ideas. Each of these papers is presented in the original formatting in this chapter.

¹This format of the thesis is approved at the Faculty of Electrical Engineering of the Czech Technical University in Prague by the directive of dean from 13 December 2017.

²<https://v3s.cvut.cz/login?lang=en>

4.1 Model-based airflow controller design for fire ventilation in road tunnels

Full citation:

Šulc, J., Ferkl, L., Cigler, J. and Zápafka, J. (2016). Model-based airflow controller design for fire ventilation in road tunnels. In: *Tunnelling and Underground Space Technology*, 60. Supplement C. pp. 121-134. ISSN: 0886-7798. DOI: <https://doi.org/10.1016/j.tust.2016.08.006> URL: <http://www.sciencedirect.com/science/article/pii/S0886779815303369>

Co-authorship (according to V3S):

Šulc: 70 % (main author), Ferkl: 10 %, Cigler: 10 %, Zápafka: 10 %

Journal: Tunnelling and Underground Space Technology

Citations (September 2018):

- Web of Science: 4 (out of which 2 are self-citations)
- Google Scholar: 4 (out of which 2 are self-citations)

Journal statistics according to the Journal Citation Report[®] (2017)

Total Cites:	4963
Impact Factor:	2.418
5-Year Impact Factor:	2.822
Immediacy Index:	0.620
Citable Items:	200
Cited Half-life:	6.3
Citing Half-life:	8.9

Quartile in categories

JCR [®] category	Rank in category	Quartile in category
Construction & Building Technology	16 of 62	Q2
Engineering, Civil	27 of 128	Q1

Annotation:

This paper brings several important insights for modeling and control of ventilation in road tunnels in the case of fire. First, the paper provides a way to derive the mathematical model of airflow dynamics for complex road tunnels. It is a dynamic model and can be expressed in the standard state-space form. The model is based on continuity and extended Bernoulli equations. The model is extended to the simplified model of fire introduced by Opstad and Aune [Opstad et al. (1997)]. Second, it summarizes principles and goals of fire ventilation in complex road tunnels including ramps and ventilation machine rooms. Further, control of ventilation in the case of fire is ensured by PI/PID controllers and verified through simulations. Finally, results of the paper are demonstrated by the case study; the Blanka tunnel complex in Prague, Czech Republic, which is the largest city tunnel in Central Europe.

4.1. Model-based airflow controller design for fire ventilation in road tunnels

Contribution to the thesis:

This paper contributes to the first goal of the thesis. The contribution to the first point is the procedure to obtain the nonlinear model of airflow dynamics in road tunnels in the standard state-space form. Although this paper partially contributes to the second goal of the thesis, as it provides some simulations of airflow velocity control using PI controllers, it does not describe any systematic procedure to design the controllers. This is covered in the next author's paper presented in Section 4.2.

This paper is available at <https://doi.org/10.1016/j.tust.2016.08.006>

4.2 A Systematic Approach for Airflow Velocity Control Design in Road Tunnels

Full citation:

Šulc, J. and Skogestad, S. (2017). A systematic approach for airflow velocity control design in road tunnels. In: *Control Engineering Practice*, 69. Supplement C. pp. 61-72. ISSN: 0967-0661. DOI: <https://doi.org/10.1016/j.conengprac.2017.09.005> URL: <http://www.sciencedirect.com/science/article/pii/S0967066117302022>

Co-authorship (according to V3S): Šulc: 70 % (main author) , Skogestad: 30 %

Journal: *Control Engineering Practice*

Citations (September 2018):

- Web of Science: 2 (out of which 1 is self-citation)
- Google Scholar: 2 (out of which 1 is self-citation)

Journal statistics according to the Journal Citation Report[®] (2017)

Total Cites:	6917
Impact Factor:	2.616
5-Year Impact Factor:	2.962
Immediacy Index:	0.786
Citable Items:	187
Cited Half-life:	8.1
Citing Half-life:	8.2

Quartile in categories

JCR [®] category	Rank in category	Quartile in category
Automation & Control Systems	22 of 61	Q2
Engineering, Electrical & Electronic	89 of 260	Q2

Annotation:

This paper continues with the topic mentioned in the previous work [Dis-A1], see section 4.1. The paper introduces a systematic approach to design PI controllers for airflow velocity in complex road tunnels for use during fire situations. The design is based on the SIMC tuning method proposed by Skogestad [Skogestad (2003)] which uses the linearized model of process dynamics. This model can be obtained from linearization of the nonlinear model from section 4.1 at a certain operating point. The systematic procedure was validated through simulations on the model of the Blanka tunnel complex.

Contribution to the thesis:

This paper contributes mainly to the second point of the thesis goals, as it describes a systematic procedure for the design of PI controllers of airflow velocity for use during fire situations in road tunnels. Moreover, this approach was validated on the real tunnel data and simulation model described in section 4.1.

This paper is available at <https://doi.org/10.1016/j.conengprac.2017.09.005>

4.3 Optimization-based Control of Ventilation in a Road Tunnel Complex

Full citation:

Šulc, J., Ferkl L., Cigler J. and Pořízek J. (2017). Optimization-based control of ventilation in a road tunnel complex. In: *Control Engineering Practice*, 69. Supplement C. pp. 141-155. ISSN: 0967-0661. DOI: <https://doi.org/10.1016/j.conengprac.2017.09.011> URL: <https://www.sciencedirect.com/science/article/pii/S0967066117302149>

Co-authorship (according to V3S):

Šulc: 75 % (main author) , Ferkl: 10 % , Cigler: 10 % , Pořízek: 5 %

Citations (September 2018):

- Web of Science: 1 (out of which 0 is self-citation)
- Google Scholar: 3 (out of which 0 is self-citation)

Journal statistics according to the Journal Citation Report[®] (2017)

Total Cites:	6917
Impact Factor:	2.616
5-Year Impact Factor:	2.962
Immediacy Index:	0.786
Citable Items:	187
Cited Half-life:	8.1
Citing Half-life:	8.2

Quartile in categories

JCR [®] category	Rank in category	Quartile in category
Automation & Control Systems	22 of 61	Q2
Engineering, Electrical & Electronic	89 of 260	Q2

Annotation:

During standard operation of a road tunnel, it is required the ventilation must keep the pollutant concentrations under limit values. Furthermore, in the case of city tunnels, there can be also requirements on the quality of ambient environment. The paper is focused on the development and application of a control structure for the ventilation during the standard operation in a road tunnel complex. The control structure is basically feed-forward with an adaptive logic which provides a feedback. The feed-forward part involves an optimization algorithm that calculates the optimum setting of ventilation devices (jet fans, ventilation machine rooms) in order to ensure desired indoor, respectively ambient air quality and minimize the operational costs at the same time. The adaptive logic is represented by the recursive least squares algorithm with the exponential forgetting.

4.3. Optimization-based Control of Ventilation in a Road Tunnel Complex

Contribution to the thesis:

The paper contributes to the third goal of the thesis. The control structure is described in detail in the paper and verified through more than two-year operation in the Blanka tunnel complex. The control structure uses the simplified mathematical model of airflow described in sections 4.1 and 4.2. The fourth goal of the thesis is also accomplished within the paper, as the paper describes the adaptive logic which compensates the mathematical model of airflow against the real measured data. The experimental validation of the proposed algorithm is also included in the paper.

This paper is available at <https://doi.org/10.1016/j.conengprac.2017.09.011>

5 Fulfilment of the goals

This chapter presents a short summary of the fulfilment of the thesis objectives which are described in section 2:

1. The paper [Dis-A1] presents the simplified 1D model of airflow dynamics for a road tunnel complex based on Bernoulli and continuity equations. It shows how to calculate all important factors influencing the airflow velocity in a tunnel, such as piston effect, friction, effect of jet fans, etc. Further, it shows how to derive the model of airflow dynamics for a road tunnel complex in the standard state-space form.

Requirements on airflow velocity control during fire in a tunnel are presented in the second part of the paper and it is shown how to use the PI/PID controller to achieve and keep the desired airflow velocity upstream of fire. The mathematical model is validated through the comparison against real measured data from fire scenarios within the tunnel testing in the Blanka tunnel complex.

The first goal of the thesis is fulfilled mainly within the paper [Dis-A1] and further within papers [Dis-A2] and [Dis-B1].

2. The paper [Dis-A2] details a systematic approach for airflow velocity control design during fire in road tunnels. The control structure includes the PI controller as the most used industrial controller. The tuning method is the SIMC method which uses the simplified nonlinear model of airflow dynamics. The tuning of the PI controller is presented on the case study, the Blanka tunnel complex in Prague and results of the paper are simulations of the PI controller for different sections and validation of the proposed method on the real tunnel data.

The second goal of the thesis is therefore fulfilled in the paper [Dis-A2].

3. The third goal of the paper is fulfilled mainly within the paper [Dis-A3] and further within the paper [Dis-B1]. The paper [Dis-B1] introduces briefly the ventilation control system of the Blanka tunnel complex which is optimization-based and ensures desired IEQ and ambient air quality of the tunnel with minimum operational costs. Whereas the paper [Dis-B1] presents rather simulations of the ventilation control system, the paper [Dis-A3] provides a detailed insight into the optimization-based controller of ventilation in the Blanka tunnel complex. This paper also includes the experimental validation of the proposed control structure. This control structure can be reused for ventilation control in future tunnels.
4. The fourth goal of the thesis is fulfilled within the papers [Dis-A3] and [Dis-B2]. Whereas the paper [Dis-B1] describes a procedure for refinement of the simplified 1D model of airflow based on the real measured data in highway tunnels, the paper

[Dis-A3] provides an extension to tunnel complexes including ramps and ventilation machine rooms. The proposed algorithm is validated through simulations and real operation in the Blanka tunnel complex.

In summary, the results of the third and fourth goal of the thesis were successfully implemented in the real operation of the Blanka tunnel complex. The optimization-based control of ventilation has been smoothly operated with continuous improvements since September 2015.

6 Conclusions and future work

6.1 Summary

In recent years, the growth of digital technologies causes that road tunnels are much better equipped with technologies for measurement and control, such as sensors for measuring physical quantities and data collection and Supervisory Control and Data Acquisition (SCADA) systems. Unfortunately, data from tunnel operation are often not used as they could be, even though they show a huge potential for improvement of the control performance. Better equipment of road tunnels allows to fulfil complex requirements on both fire and operational ventilation.

The doctoral thesis uses data from real operation of the Blanka tunnel complex mainly for model validation, design of control structure for operational ventilation and its evaluation. The doctoral thesis introduces how to create the nonlinear model of airflow dynamics that can be used for both the design of airflow velocity control system during fire situations and the design of control system structure for operational ventilation in complex road tunnels.

The first part of the thesis deals with the mathematical modeling of airflow dynamics in road tunnels having a complex structure, i.e. entrance and exit ramps and ventilation machine rooms for airflow supply and extraction, respectively. This part introduces a derivation of the nonlinear dynamics model of airflow dynamics in the standard state-space form based on the Bernoulli and continuity equations. It also provides formulas for the calculation of pressure losses included in the Bernoulli equations, such as friction, piston effect of vehicles or influence of jet fans and also how to choose parameters of this models including reference to literature. This part also introduces the use of this model for the design of the PI/PID controller for the control of airflow during fire in road tunnels. The use of this model is demonstrated by the case study, the Blanka tunnel complex in Prague, Czech Republic. This part, however, does not introduce any systematic procedure for the design of PI/PID controllers.

The second part of the thesis provides the systematic procedure of PI controller design for airflow velocity control during fire in road tunnels. This procedure is based on the SIMC method which uses the nonlinear model from the first part of the thesis that is linearized at an operating point. The advantage of this method is that it has only one tuning parameter and has a good response for set-point changes and good disturbance response. The SIMC method is verified for two different fire scenarios of the Blanka tunnel complex and results show that the SIMC method is suitable for PI controllers design in future tunnels.

The third part of the thesis introduces a novel approach for operational ventilation cont-

rol in complex road tunnels in terms of a practical deployment in the real operation. The control structure is basically feed-forward with an adaptive logic providing feed-back. The feed-forward part involves the mathematical model from the first part and mathematical optimization, which ensures the quality of indoor and ambient environment while minimizing the electricity costs. The adaptive logic is based on the recursive least squares with exponential forgetting compensating deviation between the mathematical model and real measured data. The main results of this part is validation of the control structure through the long-term evaluation of the real operation.

The doctoral thesis has shown that the mathematical modeling of airflow dynamics in road tunnels has a huge potential for improving the ventilation control of complex road tunnels that are branched and including ventilation machine rooms. First, the model can be used for PI controller design in the case of fire situations, and thus significantly increase safety in road tunnels. Second, the model can be used for optimizing the ventilation control during standard operation for a purpose of IEQ maintenance and reducing the impact on the ambient environment of tunnels.

6.2 Future research

There are still a few research topics which are to be addressed in order to improve performance of ventilation in future tunnels. Based on the ongoing requirements on operational ventilation three topics should be investigated to improve control performance and reduce electricity costs:

- Control the 15 minutes reserve of electricity
- Find the global solution of optimization task
- Involve a pollutant concentration model into the mathematical optimization

In many European countries a large electricity customer must contract to the maximum average power consumed within each 15 minutes period (15 minutes reserve of electricity). There can be thousands of Euro penalties when exceeding this reserve. Unfortunately, in many cases the 15 minutes reserve of electricity is not controlled at all. This leads to developing some procedures to control the 15 minutes reserve of electricity based essentially on switching off manually the ventilation technology. A more efficient solution would be to include this reserve directly into the optimization task as a constraint in order to prevent this exceedance automatically. This measure would save the costs of the 15 minutes reserve exceedance that can achieve thousands of Euro per year.

Second, the optimization task in section 4.3 is non-convex and therefore its optimum solution can not be guaranteed. The local optimization methods, such as IPOPT or SQP converge only to a local optimum, which can be far from the global one. Some methods for finding the global solution of optimization task are suggested in section 4.3 in the paper [Dis-A3]. According to latest simulations, the branch and bounds algorithm based on [McCormick (1976)] is suitable for finding the global solution with respect to calculation time.

Last but not least, the topic that can improve IEQ in road tunnels is inclusion of a

pollutant concentration model into the optimization task. Although there exist models for estimating the pollutant concentrations inside the tunnel, such as [Bellasio (1997)], [PIARC (2012)] or [Smit et al. (2010)], there are still several obstacles that need to be resolved for successful implementation of a pollutant concentration model into the optimization task. The main obstacles are insufficient traffic information (information on the position of cars and division into vehicle categories), uncertainties in emission factors of vehicles passing through the tunnel and ambient pollutant concentration, which is usually not measured and must be estimated.

References

- Altenburger, P., Riess, I., and Brandt, R. (2015). On effective close-loop control of longitudinal ventilation in road tunnels in case of fire. In *Proceedings of the 16th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels*, 661–675.
- ASTRA (2008). Lüftung der Strassentunnel, Systemwahl, Dimensionierung und Ausstattung, Ausgabe 2008 V2.01. Technical report, Bundesamt für Strassen, Abteilung Strassennetze.
- Bellasio, R. (1997). Modeling traffic air pollution in road tunnels. *Atmospheric Environment*, 31, 1529 – 1551.
- Bring, A., Malmström, T., and Boman, C.A. (1997). Simulation and measurement of road tunnel ventilation. *Tunnelling and Underground Space Technology*, 12(3), 417–424.
- CETU (2003). Dossier pilote des tunnels equipements, section 4.1, Ventilation. Technical report.
- Chen, P.I., Lai, J.H., and Lin, C.T. (1998). Application of fuzzy control to a road tunnel ventilation system. *Fuzzy Sets and Systems*, 100, 9–28.
- Chow, W., Gao, Y., Zhao, J., Dang, J., Chow, C., and Miao, L. (2015). Smoke movement in tilted tunnel fires with longitudinal ventilation. *Fire Safety Journal*, 75(Supplement C), 14 – 22.
- Council of European Union (2004). Directive 2004/54/EC of the European parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.
- CTN PRAGOPROJEKT (2014). ČSN 73 7507 – Projektování tunelů pozemních komunikací.
- Douglas, J., Gasiorek, J., and Swaffield, J. (2011). *Fluid Mechanics*. Prentice Hall.
- Drikakis, D. and Rider, W. (2005). *High-Resolution Methods for Incompressible and Low-Speed Flows*. Springer.
- ELTODO, a.s. (2004). *TP 98 – Technologické vybavení tunelů pozemních komunikací*.
- Euler-Rolle, N., Fuhrmann, M., Reinwald, M., and Jakubek, S. (2017). Longitudinal tunnel ventilation control. part 1: Modelling and dynamic feedforward control. *Control Engineering Practice*, 63, 91–103.
- Ferkl, L. (2007). *Simulation and Control of Ventilation in Tunnels*. Ph.D. thesis, Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Control Engineering.

References

- Ferkl, L. and Meinsma, G. (2007). Finding optimal ventilation control for highway tunnels. *Tunnelling and Underground Space Technology*, 22, 222–229.
- Ferkl, L., Sládek, O., and Pořízek, J. (2006). Tunnel ventilation simulation of the city ring in prague. *Tunnelling and Underground Space Technology*, 21, 443–443.
- FHWA (2004). FHWA-If-05-023, Road Tunnel Design Guidelines. Technical report, Federal Highway Administration.
- Frey, S., Riess, I., and Welte, U. (2016). Improving the energy efficiency of road tunnels. Technical report, Amstein + Walthert Progress AG.
- Funabashi, M., Aoki, I., Yahiro, M., and Inoue, H. (1991). A fuzzy model based control scheme and its application to a road tunnel ventilation system. In *Industrial Electronics, Control and Instrumentation, 1991. Proceedings. IECON '91., 1991 International Conference on*, 1596–1601 vol.2.
- Government of the Czech Republic (2009). Nařízení vlády č. 264/2009 Sb., o bezpečnostních požadavcích na tunely pozemních komunikací delší než 500 metrů.
- Hrbček, J. and Šimák, V. (2011). Implementation of Multi-dimensional Model Predictive Control for Critical Process with Stochastic Behavior. In *Advanced Model Predictive Control*, 109–124.
- Japan Road Association (2001). National Safety Standard of Emergency Facilities on Road Tunnel. Technical report.
- Karakas, E. (2003). The control of highway tunnel ventilation using fuzzy logic. 16, 717–721.
- Karakas, E. and Külünk, H. (1998). Adaptive control of bolu highway tunnel ventilation system using fuzzy logic. In *Proceedings of the 1998 ACM Symposium on Applied Computing*, SAC '98, 282–286. ACM, New York, NY, USA.
- Kurka, L., Ferkl, L., Sládek, O., and Pořízek, J. (2005). Simulation of traffic, ventilation and exhaust in a complex road tunnel. volume 38, 60 – 65. 16th IFAC World Congress.
- Longley, I. (2014). TP11: Criteria for In-Tunnel and Ambient Air Quality. Technical Report July, NSW Government.
- Lotsberg, G. (1997). Measurement of the wall friction factor and the installation efficiency of jet fans. In *Proceedings of the 9th International Conference on Aerodynamics and Ventilation of Vehicle Tunnels*. Aosta (Italy).
- McCormick, G.P. (1976). Computability of global solutions to factorable nonconvex programs: Part i — convex underestimating problems. *Mathematical Programming*, 10(1), 147–175.
- McGrattan, K.B., McDermott, R., Floyd, J.E., Hostikka, S., Weinschenk, C., and Overholt, K. (2017). *Fire Dynamics Simulator, User's Guide*. National Institute of Standards and Technology, 6 edition.

- Miao-cheng, W., Xin-ling, L., L., F., and Cheng-xian, D. (2016). Study on the critical velocity in a sloping tunnel fire under longitudinal ventilation. *Applied Thermal Engineering*, 94(Supplement C), 422 – 434.
- Mizuno, A. (1991). An Optimal Control With Disturbance Estimation For the Emergency Ventilation of a Longitudinally Ventilated Road Tunnel. In *Flucom '91: Proceedings of the 3rd Triennial International Symposium on Fluid Control, Measurement, and Visualization*, 393 – 399. American Society of Mechanical Engineers.
- Ohashi, H. et al. (1982). A new ventilation method for the kanetsu road tunnel. In *Proc. 4th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels (York, U.K. March 23-25, 1982)*, pp. 31–47. Cranfield, U.K., BHRA Fluid Engineering Centre.
- Opstad, K., Aune, P., and Henning, J.E. (1997). Fire emergency ventilation capacity for road tunnels with considerable slope. In *Proceedings of the 9th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels*, 535–543. Aosta.
- PIARC (1999). Fire and Smoke Control In Road Tunnels. Technical report.
- PIARC (2007). Systems and equipment for fire and smoke control. Technical report.
- PIARC (2008). Road Tunnels: A Guide to Optimising the Air Quality Impact upon the Environment. Technical report.
- PIARC (2011). Road tunnels: Operational strategies for emergency ventilation. Technical report.
- PIARC (2012). Road tunnels: Vehicle emissions and air demand for ventilation. Technical Report December.
- Pospisil, P. (2013). METODICKÝ POKYN – větrání silničních tunelů. Volba systému, navrhování, provoz a zabezpečení jakosti větracích systémů silničních tunelů. Technical report.
- Pospisil, P. and Brandt, R. (2005). Smoke control in road tunnels. In *Proceedings of the Conference Significance of Tunnels in Transport*, 1–6. Podbanské (Slovakia).
- RABT (2006). Richtlinien für die Ausstattung und den Betrieb von Straßentunneln. Technical report, Forschungsgesellschaft für Straßen- und Verkehrswesen, Arbeitsgruppe Verkehrsführung und Verkehrssicherheit.
- Rieutord, M. (2015). *Fluid Dynamics: An Introduction*. Springer.
- RTA (2007). Road Tunnel Design Guideline, Fire Safety Design, Part 1 – 3. Technical report, Roads and Traffic Authority (RTA).
- RVS 09.02.31 (2014). Tunnel, tunnel equipment, ventilation, basic principles. Technical report, Forschungsgemeinschaft Straße, Schiene, Verkehr.
- Schmölzer, G., Sturm, P., Zettl, D., Koppensteiner, W., and Wierer, A. (2016). Ventilation control in the case of a fire: A practical approach to the implementation of pi controllers. In H. Eichlseder (ed.), *IVT Reports*, volume 100, 200. Verlag der Technischen Universität Graz.

- Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13, 291–309.
- Smit, R., Ntziachristos, L., and Boulter, P. (2010). Validation of road vehicle and traffic emission models - a review and meta-analysis. *Atmospheric Environment*, 44(25), 2943–2953.
- Smith, C.A. and Corripio, A.B. (1985). *Principles and practice of automatic process control[M]*. Wiley, New York.
- Sturm, P., Beyer, M., and Rafiei, M. (2015). On the problem of ventilation control in case of a tunnel fire event. *Case Studies in Fire Safety*.
- Tan, Z., Huang, Z.Y., Wu, K., and Xu, L.T. (2012). Simulation analysis of longitudinal ventilation system with jet fan speed control for MPC strategy in a road tunnel. In *15th International IEEE Conference on Intelligent Transportation Systems*, 1471–1476. Anchorage, Alaska.
- Waltl, A. (2004). Safety Measures for Road Tunnels – Newest Developments for the Plabutschunnel. In *Proceedings of the Conference 2nd Symposium of Tunnel Safety and Ventilation*. Graz (Austria).
- Wang, F. and Wang, M. (2016). A computational study on effects of fire location on smoke movement in a road tunnel. *Tunnelling and Underground Space Technology*, 51(Supplement C), 405 – 413.
- Zacher, S. and Reuter, M. (2011). *Regelungstechnik für Ingenieure*. Vieweg + Teubner Verlag/ Springer Fachmedien Wiesbaden GmbH.
- Zápařka, J. (2009). Bezpečnost při požáru v tunelu. *Stavebnictví*, 5. Available on http://www.casopisstavebnictvi.cz/bezpecnost-pri-pozaru-v-tunelu_N2345.
- Zápařka, J. (2012). Větrací systém tunelu Blanka. *Stavebnictví*, 4. Available on <http://www.satra.cz/data/publikovani/stavebnictvi201204-vetraci-system-tunelu-blanka.pdf>.
- Ziegler, J.G., Nichols, N.B., and Rochester, N.Y. (1942). Optimum settings for automatic controllers. *Transactions of the A.S.M.E.*, 759–765.

Publications of the author

Publications related to the thesis

Publications in journals with impact factor

- [Dis-A1] Šulc, J., Ferkl, L., Cigler, J. and Záparka, J. (2016). Model-based airflow controller design for fire ventilation in road tunnels. In: *Tunnelling and Underground Space Technology*, 60. Supplement C. pp. 121-134. ISSN: 0886-7798. DOI: <https://doi.org/10.1016/j.tust.2016.08.006>. Co-authorship: 70%.
- [Dis-A2] Šulc, J. and Skogestad, S. (2017). A systematic approach for airflow velocity control design in road tunnels. In: *Control Engineering Practice*, 69. Supplement C. pp. 61-72. ISSN: 0967-0661. DOI: <https://doi.org/10.1016/j.conengprac.2017.09.005>. Co-authorship: 70%.
- [Dis-A3] Šulc, J., Ferkl L., Cigler J. and Pořízek J. (2017). Optimization-based control of ventilation in a road tunnel complex. In: *Control Engineering Practice*, 69. Supplement C. pp. 141-155. ISSN: 0967-0661. DOI: <https://doi.org/10.1016/j.conengprac.2017.09.011>. Co-authorship: 75%.

Publications in reviewed journals

- [Dis-B1] Šulc, J., Pořízek, J., Ferkl, L. and Cigler, J. (2016). Soustava provozního větrání tunelového komplexu Blanka. In: *Automa – časopis pro automatizační techniku*, 22. 11. pp. 32–35. ISSN: 1210-9592. Co-authorship: 25%.
- [Dis-B2] Šulc, J., Ferkl, L., Cigler, J. and Záparka, J. (2016). Návrh, simulace a vyhodnocení regulace podélného proudění vzduchu během požárního větrání v tunelovém komplexu Blanka. In: *VVI – Vytápění, větrání, instalace*, 25. 5. pp. 256-263. ISSN: 1210-1389. Co-authorship: 60%.
- [Dis-B3] Šulc, J. and Ferkl, L. (2015). Návrh, algoritmů provozního větrání tunelu Blanka. In: *VVI – Vytápění, větrání, instalace*, 24. 4. pp. 178-183. ISSN: 1210-1389. Co-authorship: 90%.

Conference publications

- [Dis-C1] Šulc, J., Nývlt, O. and Ferkl, L. (2014). Design and Implementation of the Control System of the Operational Ventilation in the Blanka Tunnel. In: *Tunnels for a better life – Proceedings of the World Tunnel Congress 2014*. ISBN: 978-85-67950-00-6. Co-authorship: 20%.

- [Dis-C2] Šulc, J., Ferkl, L. and Lebl, A. (2015). Refinement Algorithm for Mathematical Model of Airflow Velocity in Highway Tunnels. In: *Symposium Energeticky efektivní budovy*. Společnost pro techniku prostředí, pp. 295–300. ISBN: 978-80-02-02615-0. Co-authorship: 34%.
- [Dis-C3] Šulc, J. and Ferkl, L. (2014). Design of fire ventilation control in the Blanka Tunnel. In: *Zagreb Underground – Symposium on Underground Solutions in Cities in South-East Europe*. HUBITG, pp. 200–212. ISBN: 978-953-55728-8-6. Co-authorship: 90%.
- [Dis-C4] Šulc, J., Ferkl, L. and Cigler, J. (2016). Preliminary Results of Operational Ventilation of the Blanka Tunnel Complex During Trial Operation. In: *Proceedings of 13th International Conference Underground Construction Prague 2016*. Česká tunelářská asociace ITA-AITES. ISBN: 978-80-906452-0-2. Co-authorship: 33%
- [Dis-C5] Pořízek, J. and Šulc, J. (2016). Forced Ventilation in the Blanka Tunnel: Benefits in Respect of the Need to Reduce the Air Pollution Loads Around the Exit Portals. In: *Proceedings of 13th International Conference Underground Construction Prague 2016*. Česká tunelářská asociace ITA-AITES. ISBN: 978-80-906452-0-2. Co-authorship: 50%.
- [Dis-C6] Šulc, J., Zápařka, J., Cigler, J. and Pořízek, J. (2016). Control of Longitudinal Airflow Velocity during Fire Situations in the Tunnel Complex Blanka. In: *Conference Proceedings of the 8th International conference "Tunnel safety and Ventilation"*. Verlag der Technischen Universität Graz, pp. 230–237. ISBN: 978-3-85125-464-8. Co-authorship: 25%.
- [Dis-C7] Zápařka, J., Šajtar, L., Pořízek, J. and Šulc, J. (2016). Tunnel Complex Blanka in Prague — Testing of The Operational Safety and Fire Ventilation System. In: *Conference Proceedings of the 8th International conference "Tunnel safety and Ventilation"*. Verlag der Technischen Universität Graz, pp. 77–82. ISBN: 978-3-85125-464-8. Co-authorship: 25%.
- [Dis-C8] Nývlt, O., Ferkl, L. and Šulc, J. (2013). Reliability of tunnel ventilation control: A conceptual design. In: *Proceedings 19th ISSAT International Conference on Reliability and Quality in Design*. International Society of Science and Applied Technologies, pp. 24–28. ISBN: 978-0-9763486-9-6. Co-authorship: 40%.

Publications not related to the thesis

Conference publications

- [NonDis-A1] Cigler, J., Váňa, Z., Mužík, T., Šulc, J. and Ferkl, L. (2016). Usage of spot market prices prediction for demand side management. In: *2016 European Control Conference (ECC)*. pp. 1165–1170. ISBN: 978-1-5090-2591-6. DOI: 10.1109/ECC.2016.7810447. Co-authorship: 20%.
- [NonDis-A2] Včelák, J., Wolf, P., Šulc, J., Procházka, M., Maška, M. and Kohout, J. (2016). Využití předpovědi osvitu pro řízení hybridních fotovoltaických systémů. In: *37. ročník konference Nekonenční zdroje elektrické energie*. Česká

elektrotechnická společnost, pp. 118–121. ISBN: 978-80-02-02653-2.
Co-authorship: 17%.

[NonDis-A3] Šulc, J., Maška, M. and Včelák, J. (2016). Návrh algoritmů pro získání předpovědi dopadajícího slunečního záření. In: *Sborník konference Alternativní zdroje energie*. Společnost pro techniku prostředí, pp. 185–192. ISBN: 978-80-02-02666-2. Co-authorship: 25%.

[NonDis-A4] Boháč, J., Bašta, J. and Šulc, J. (2017). Modelování provozního chování otopných těles. In: *Konference vytápění Třeboň*. Společnost pro techniku prostředí, pp. 175–181. ISBN: 978-80-02-02712-6. Co-authorship: 33%.

Curriculum vitae

Jan Šulc was born in Náchod, Czech Republic, in 1987. He finished his bachelor degree in 2010 at the Faculty of Electrical Engineering (FEE) of the Czech Technical University in Prague (CTU) in the study program *Cybernetics and measurement*. In 2012 he received his master degree at FEE CTU in the study program *Cybernetics and robotics*. He started his Ph.D. studies in February 2013 at the Department of Control Engineering (DCE) FEE CTU in the study program *Control engineering and robotics*.

Jan Šulc has been involved in several research and development projects:

- Research grant of the Grant Agency of the Czech Republic (GACR) within the scope of no. GC13-12726J – Unified framework for multi-criteria identification, control and fault detection,
- Internal grants of CTU – SGS13/209/OHK3/3T/13 and SGS16/232/OHK3/3T/13,
- Grant of the University Centre for Energy Efficient Buildings (UCEEB) of CTU CZ.1.05/2.1.00/03.0091.
- MPC-GT. – Model Predictive Control and Innovative System Integration of GEOTABS;-) in Hybrid Low Grade Thermal Energy Systems – Hybrid MPC GEOTABS

During his Ph.D. studies, he spent six months at Norwegian University of Science and Technology (NTNU) in Trondheim in the group of professor Sigurd Skogestad.

Jan Šulc taught two courses at his department during his Ph.D. studies: Automatic control (bachelor course) and Theory of dynamic systems (master course). He also supervised several bachelor and diploma theses.

He presented his scientific work at several important international conferences e.g. at *World Tunnel Congress (WTC)* in 2014 or at *Symposium of Tunnel Safety and Ventilation* in 2016. He published three papers in international reviewed journals, which have been indexed in the database of Web of Science. He also published three papers in Czech reviewed journals. The paper *Návrh algoritmů řízení provozního větrání tunelu Blanka* in the journal *Vytápění, větrání, instalace (VVI)* was awarded by Professor's Pulkrábek Award as the best paper among young authors for the year 2015.