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TUNNEL VENTILATION AND SAFETY, 10 CONFERENCES – THE STORY SO FAR

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1. BACKGROUND

Austria's topography presents a major challenge when attempting to establish an efficient transport network. For most of the past, routes traversing mountain ranges were time consuming and dangerous. Traffic and civil engineers thus started early on to focus on the possibility of tunnels. In the east of the country, in 1854, the first mountain railway with a standard gauge track, and gradients of up to 2.5%, was built to cross the Semmering Mountain range and to provide a rail link from Vienna to the Mediterranean region. A total of 14 tunnels and 16 viaducts had to be constructed in very difficult terrain. Looking to the west of Austria, the Arlberg massif is the main obstacle between the regions of Tirol and Vorarlberg. Here, an 11 km long rail tunnel was constructed as early as 1884. Between these two ends of Austria, a number of long railway tunnels pass through the Alps in a north-south direction. In the 1970s, the strong increase in road traffic and goods transport required the construction of various long road tunnels. The Tauern tunnel (length 6.5 km) and the Katschberg tunnel (5.9 km) were both opened in 1975, the 14 km long Arlberg road tunnel – running almost in parallel to the rail tunnel – was opened in 1978. These are only a few of the many long tunnels now in existence. Almost all of them originally operated using a counter-flow system. This poses a major challenge in terms of fresh air supply and the maintenance of in-tunnel air quality needed to allow for safe tunnel passage. Owing to the relatively high vehicle-specific CO emissions at the time, many of the tunnels were equipped with a transverse ventilation system. The first tunnel with a full transverse ventilation system in Austria was opened in 1958 (Dürnstein tunnel). In all of these tunnels the design chosen had to ensure a tenable environment for users.

Today, as a result of such a long history, Austrian engineers are well-known experts, not only in tunnel construction, but also in the design of the electro-mechanical systems needed in tunnel operation. Currently, more than 165 tunnels are in operation within the Austrian highway network and roughly the same number in the secondary road network. The technological standard is very high and often taken as a benchmark for projects in other countries. Safety standards are also second to none. Even though in the last 15 years the number of tunnel km driven has increased almost by a factor of 5, the number of fatalities due to tunnel incidents has fallen from 18 to 5 per year.

2. THE ROLE OF THE HOST INSTITUTE AT GRAZ UNIVERSITY OF TECHNOLOGY IN TUNNEL VENTILATION AND SAFETY

The design of tunnel ventilation systems requires extensive knowledge in aerodynamics, thermodynamics, and in the emission behaviour of vehicles propelled by internal combustion engines. As the Institute for Internal Combustion Engines and Thermodynamics (IVT)[1] at Graz University of Technology (TUG) has provided just such a combination of knowledge for several decades, it should come as no surprise that the institute has been at the centre of such

[1] Since January 1st 2022 Institute of Thermodynamics and Sustainable Propulsion Systems (ITnA)

research questions for already a considerable time. The tunnel-related research topics dealt with at ITnA can be split into the following areas of research:

- Investigation of fresh air requirement due to vehicle emissions
- Thermo- and aerodynamics
- Ventilation control strategy
- Environmental topics related to road and rail tunnels

2.1. Fresh air requirement due to vehicle emissions

Airborne pollutants from internal combustion engines have always been a major topic in engine development. For decades, emission measurements were only performed on a stationary test bed. However, it was well-known that this did not represent the emission behaviour of vehicles in road tunnels. Thus, from the late 1960s onwards, a major effort was made to measure carbon monoxide concentration and visibility in road tunnels, and to relate this to vehicle emissions [1][2]. The growing share of heavy goods vehicles in road tunnels over the years meant that the issue of particle/soot emissions, and of visibility, gained more and more in priority. Intense work was thus undertaken in order to investigate the correlation between particle concentration in tunnel air and light extinction [3][4]. Subsequent co-operation with Switzerland and Germany meant that the work could be extended in order to get a broader view of the impact of variations in vehicle fleet, and to gain a better understanding of the influence of altitude on vehicle emissions [6].

Such work, for the most part driven by our institute, was subject to a continual process of updating concerning new developments in vehicle technology and measurements of real-world emissions. This work resulted in the well-known emission factor database for calculation for road tunnel air demand, published by PIARC [9][10][12][13][14].

2.2. Thermo- and aerodynamics

Ventilation design is based on the application of aerodynamics, combined with empirically-gained knowledge. The possibility of a tunnel fire obviously requires the inclusion of various matters related to thermodynamics. From very early on, a tunnel fire was perceived as presenting a major source of risk for tunnel users, and appropriate tests were performed as early as the 1960s [15]. In Austria, a relatively large fire experiment was performed in 1974/75 in the Zwenbergtunnel, an abandoned railway tunnel which was upgraded to a road tunnel test facility with a full transverse ventilation system. For a long time, such tests served as a benchmark in investigations of tunnel smoke propagation and the impact of the different ventilation strategies [7][8]. In 1978, the report 'Conception of Ventilation Systems for Road Tunnels', was published. This report was the starting point for the development of Austrian guidelines for tunnel ventilation. With respect to research on full-scale fires, the EUREKA 499 FIRETUN project, from 1990 to 1995, represented a further milestone. Multiple fire experiments were performed in the Repafjord in Norway [16][17]. Here, ITnA provided measurement technique. While fire tests in tunnels continued to remain a core area of research, the focus slowly shifted more towards smoke propagation and smoke management. In 2017 full-scale fire tests with heat release rates up to 21 MW were performed in the Koralm rail tunnel. This was done in order to investigate smoke propagation in the region of cross passages, and to assess the most efficient measures needed to keep egress ways smoke-free [18]. Current research now focuses on the combustion behaviour of battery electric vehicles in tunnels.

2.3. Ventilation design and ventilation control strategy

Ventilation design and operation is strongly related to the associated control strategy. While the ventilation strategy is clear under conditions of normal operation, i.e. the need to maintain in-tunnel air quality through sufficient ventilation – a different strategy is required in cases of fire. For example, achieving critical velocity in order to avoid backlayering represents one possible strategy, and maintaining a controlled velocity (at lower speeds) to support self-rescue, represents another. These strategies are mainly relevant for longitudinally ventilated tunnels. In transverse ventilation systems smoke is extracted via the return air duct. However, the big fires in the Mt. Blanc and the Tauerntunnel in the late 1990s totally changed the prevailing ventilation philosophy for transverse ventilated tunnels. Instead of extracting smoke over a series of small openings in the false ceiling between traffic room and return air duct, massive point extraction systems with remotely controlled dampers and large cross sections were introduced [19]. This also made it necessary to introduce closed loop control systems into ventilation control. One of the first fully automatic closed loop ventilation systems was developed in 2003 by IVT for the 10 km long, fully transverse ventilated Plabutsch tunnel in Graz, Austria [20]. These systems subsequently became state of the art in tunnel ventilation control. Despite such advances, the associated increase in complexity with respect to sensor technique and control mechanisms requires intense research in optimizing methods for system tests, especially in the case of complex road tunnels. As a result of such new developments, IVT now focuses strongly on ventilation control and system tests [21] [22] [27].

The institute is a sought-after partner when it comes to solving complex tasks in the area of tunnel ventilation design. This is especially true when aging tunnel systems are to be upgraded to the latest safety standards. Requirements that were once state of the art, are no longer acceptable today. In particular, today's higher traffic volume now means that much higher fire loads have to be taken into account. The extraction of any fire gases that may occur requires a completely different approach. However, this also requires a change in the mechanical equipment that is now required to control the tunnel airflows. As part of the renovation of transverse-ventilated tunnel systems, a system was developed with targeted fresh air injection using air momentum. This was first used in the Katschberg tunnel in 2010 and is now often used in all long tunnels with full transverse ventilation systems [23]. Refurbishment of the ventilation system in the Arlberg tunnel was particularly challenging. In addition to the necessary ventilation requirements, the supply air duct also had to be used as an escape route. This project required the combined use of fresh air impulse dampers and jet fans in order to meet the most advanced requirements with regard to ventilation and smoke evacuation [24]. In order to better understand the efficiency losses of jet fans, and to improve related installation factors [25], intense work was performed based on full-scale experiments, and supplemented with detailed CFD simulations. This work showed that the widely used installation factors based on the work of Kempf [26] clearly underestimated jet fan efficiency loss.

2.4. Environmental topics related to road and rail tunnels

The interface between emissions from transport and their effects on the environment has always been a key focus of research at IVT. What applies to the environment, naturally applies also to tunnels. Two aspects require particular consideration. One is the tunnel air itself, and the other, the effects resulting from polluted tunnel air.

When considering in-tunnel air quality, the main pollutants are carbon monoxide, nitrogen oxides and soot. Treatment of tunnel air may be one means of improving in-tunnel air quality and/or minimizing the negative effects of tunnel air upon the environment. In 1990 the IVT started field tests in various tunnels in Austria in order to investigate filtration of dust/aerosols and airborne pollutants. These tests lasted over a decade and are still ongoing, albeit on a smaller scale. Electrostatic dust filters as well as catalytic and biogenic treatment of airborne gases were investigated. Although some positive results were found, in general tunnel air treatment proved not feasible except for special applications (mainly PM filters) [28][29][30][31].

The dispersion of tunnel-generated pollution is a further area of research. This has mainly to be considered for city tunnels or for portal or stack locations in close proximity to built-up areas. In the 1980s, IVT started to investigate this topic in detail. As simple dispersion models failed to correctly model the dispersion of the tunnel jet wind, model tests were performed to simulate the interaction between portal air and built-up areas [32]. Such wind tunnel tests supplemented by full-scale experiments at tunnel portals were then used to validate first generation CFD models for applications in ambient air [33][34][35]. Based on all these experimental data, and supported by other international research, a numerical code, called GRAL, was eventually developed. This was designed to model pollution dispersion from low level sources like road traffic, tunnel portals and stacks [36][37]. This software code has since become state of the art in dispersion modelling of airborne pollution in complex terrain [38].

3. THE CONFERENCES

Graz University of Technology, together with the Mining University in Leoben, has always been a focal point for knowledge exchange in tunnel construction. That it has also become a focal point with respect to research on tunnel equipment, operation and safety, is thus no surprise. Based on IVT's long history of experience in tunnel ventilation and tunnel safety, a decision was made in 2002 - following upon the almost revolutionary changes in tunnel safety arising from the fires of the late 1990s - to organize a small venue for information exchange within the Alpine countries. The resulting conference was hosted on the campus of the university and attracted almost 150 persons, mainly from Europe, but also with a noticeable overseas contingent. As a result of the positive feedback from this initial event, a second meeting was organized two years later. This latter event even included a small trade fair. By 2004, the event already had so many participants that it had outgrown campus facilities. A decision was therefore made to organise the conference biannually and to move to a more suitable off-campus venue. The next event was held in the Graz Congress Centre but once again, due to the growing demand for space, had to be moved to the Messecongress Graz. While the initial conferences were strongly related to road tunnels, the later ones had already begun to shift their focus more towards the requirements and safety issues concerning long trans-Alpine and sub-sea rail tunnels.

The following section is intended to point out several highlights from past conferences, covering, amongst other things, both the successful and the less successful innovations in tunnel safety. All conference papers can be downloaded from www.tunnel-graz.at/archive.

3.1. Conference 2002

The fires in the Mt. Blanc and Tauern tunnel, together with their consequences, had a major impact on the conference in 2002. The subsequent rise in public awareness concerning tunnel fires has also had a significant impact on activities in the field of tunnel safety. It is worth mentioning, however, that this problem was not at all new to safety experts. Various contributions in the 2002 conference proceedings refer to the 1999 PIARC report, Fire and Smoke Control in Road Tunnels [11], which was, and still is, a crucial reference point for many activities in this area. At the time, there was a definite change of opinion among several decision-makers regarding potential problems and solutions.

There were also far-reaching consequences with respect to tunnel safety equipment. This is illustrated in the presentations concerning the new directives in Austria and Switzerland. In particular, the new design of the ventilation systems helped to achieve a breakthrough in terms of the acceptability of massive smoke extraction in long tunnels, and as a result, remote-controlled smoke extraction dampers have since become state of the art in tunnels with a transverse ventilation system.

Various presentations on theoretical and numerical work (smoke behaviour, escape behaviour) as well as practical work (tests, component development) provided a new basis for the design of the requisite installations. For example, the article by Rudolf Hörhan, emphasized the need to allow for interaction between the different safety systems. Several articles underlined the necessity of tests, pointing to existing uncertainties in the theoretical considerations, as well as the need for maintenance and servicing of the more complex systems.

One presentation even dealt with qualitative risk assessments, using the new ventilation design for the Tauern Tunnel as an example. Arnold Dix emphasized legal aspects, and the importance of clear documentation in the implementation of new systems. He foresaw the impact of increasingly complex systems and pointed to the acute problems that can arise at the interface between design and operations, when, for example, an innovative engineer and a high-performing maintenance worker must work together. The problem of quantifying the effectiveness of safety measures was pinpointed and a warning was voiced concerning the possibility of confusing low probability/high consequence events with successful risk reduction.

3.2. Conference 2004

The catastrophic tunnel fires that had occurred in the late 1990s continued to exert an influence on the second conference in 2004. Hence, a majority of the papers presented dealt with issues concerning optimized ventilation and smoke control strategies, new generations of incident detection systems, and methods for assessing tunnel safety.

A highlight of the conference was the presentation of the first closed loop ventilation control system. This system was installed in the 10 km long twin-tube Plabutsch tunnel (Almbauer, Waltl). The tunnel was equipped with a full transverse ventilation system and the ventilation control system was designed to manage up to 12 axial fans per tube in parallel. Fire tests confirmed that the system worked but also revealed that problems may arise when important sensors react too slowly or malfunction.

In one presentation, John Day addressed the discrepancy that often exists concerning the effort made to reduce the effects of tunnel fires and the unpredictable behaviour of tunnel users. He highlighted the growing gap between the costs of training tunnel users and the costs of improving safety installations. He concluded that the most cost-efficient option would be improving the behaviour of tunnel users and the weakest one is to invest in additional safety systems.

3.3. Conference 2006

The 3rd conference in 2006 was strongly influenced by topics such as video detection and incident management, with particular focus on the early detection of incidents and on establishing a well designed management system. A further focus was on the usage of fixed fire fighting systems (FFFS). While papers from Australia (A. Irvin) dealt with deluge systems, high water mist systems were also presented for use in road tunnel applications (S. Kratzmeir, G. Reichsthaler), and implementations of fixed water shield systems in Japan (R. Amano) were also discussed. The PIARC position with respect to FFFS was presented by A. Haack. The safety issues in operation were complemented by presentations concerning a broad range of topics dealing with issues such as sudden wind shield fogging, safe cabling systems, and as a novelty, data security in the ethernet network.

3.4. Conference 2008

In 2008 the focus was placed on differentiating between theoretical simplifications and the reality of tunnel operating requirements. Of particular interest were papers exploring the difference between actual human behaviour and model simplification, as well as those covering the challenges pertaining to refurbishments and emerging technologies in incident detection.

Of particular note was the paper by Porizek, Zaparka and Ferkl. Their paper “Ventilation Control of the Blanka Tunnel: A mathematical programming approach” described the use of model-based predictive controllers that adapt to changes in operational conditions in real time, and thereby optimise system performance in terms of both safety and energy consumption. The level of complexity revealed in their case study on the Blanka Tunnel was sufficient to demonstrate that their proposed methodology was well-suited to real world application. The pragmatic evidence they presented clearly demonstrated that such emerging techniques can be quite useful in practice, and need not be confined to the realm of theory.

Their proposed technique now forms part of the intellectual framework that is being developed for the optimisation of tunnel systems using artificial intelligence. Their 2008 contribution may thus quite legitimately be regarded as an especially significant paper.

3.5. Conference 2010

The 5th Conference took place in 2010. The conference topics continued to be heavily influenced by ventilation and detection problems. Ventilation as a safety feature has been featured in several papers reflecting the changes brought about by the major fire events of the past decade. Franz Zumsteg pointed out that many of the most drastic changes in tunnel ventilation that have been proposed in recent years have already become more or less a matter of course. However, since many new ideas are based on predictions, and since predictions are fraught with uncertainty, it is important to remain critical lest we fall under the illusion that most incidents are relatively easy to deal with.

Many of the systems presented at this conference have now become state of the art, e.g. sensor technology in relation to incident detection, recognition of hazmat in tunnels, and detection of thermal problems in heavy goods vehicles before entering a tunnel. A very interesting paper about the usage of incident information and safety systems by tunnel users was presented by Günter Rattei from the Austrian highway operator ASFINAG. He showed quite clearly that automatic detection systems, e.g. linear heat detectors, video systems etc. are really quite efficient, while, in contrast, all the possibilities available to tunnel users, such as emergency phones, emergency call buttons etc. failed to have the desired effect.

A further cornerstone of the conference was the topic of fixed fire fighting systems, such as deluge, or high-pressure water mist systems. While some papers covered different installations and system acceptance tests, the paper of Arnold Dix concerning, from a legal point of view, the review of the Burnley fire accident (AUS), also demonstrated the positive effect of such a system.

The closing paper by John Day brought the participants of the conference back to reality. He clearly pointed out that ‘equipping a tunnel with each and every safety measure does not mean that the tunnel is safe’. He further demanded that ‘a minimum level of operating safety measures should be determined for each tunnel and the tunnel should be closed when that level is not achieved’. This requirement is now generally accepted, even though it causes severe problems for tunnel operators as they need to keep the tunnel under operation as long as possible.

3.6. Conference 2012

In 2012 risk assessment was a hot topic. Papers looked at the topic from a number of different perspectives, and the application of risk assessment tools was subjected to considerable critical analysis. The paper by Berhard Kohl demonstrated that a risk analysis can provide a solid basis for safety-relevant decisions in tunnel design and operation. However, risk analysis is only one of a variety of aspects which have to be included in a decision-making process. Discussion in this area was completed by looking at applications of QAR for complex tunnel systems (R. Brandt) and galleries (G. Mayer).

A further key aspect in this conference concerned rail tunnels. Here, several complementary contributions were made, concerning, for example, the ventilation system of the new Semmering Base Tunnel in Austria (G. Gobiet), selected topics from Russia (S. Gendler), and the safety concept for the Crossrail in London (Y. Ting). Finally, Franz Zumsteg pointed out that, particularly where short, steep road tunnels are concerned, improvements in escape possibilities are much more important than any additional technical safety installation.

3.7. Conference 2014

The 2014 symposium covered a broad range of high-quality papers. Ever stricter regulatory requirements for ventilation control in normal and incident tunnel operating mode, call for complex control mechanisms. As soon as these requirements have to be applied in complex tunnel systems with multiple on/off ramps and connections to other tunnels, control system complexity increases non-linearly. This then requires significant and time-consuming on-site testing in order to adjust the control systems. L. Elertson demonstrated how such systems can be successfully applied and tested, taking the Norra Länken in Stockholm as an example. T. Aralt gave an overview of the future needs of automated response systems, based on the requirements for the Bergen Control Center in Norway, which is responsible for monitoring more than 250 tunnels.

Another focus was on the refurbishment of tunnels and tunnel infrastructure. Upgrading of relatively old tunnels means that, in most cases, project-specific solutions are needed in order to meet modern tunnel requirements. M. Bacher demonstrated the cornerstones entailed in the upgrading of the 14 km long Arlberg Tunnel (A), where the fresh air duct of the transverse ventilation system has to be used as an egress way, and a combination of Saccardo nozzles and jet fans are employed to overcome the large pressure differences acting between the portals. Discussion of refurbishment work in Spain (F. Portugues) as well as of the usage of water-based FFFS as passive protection systems (R. Rothe, M. Lakkonen, A. Wierer) complemented the topic.

A very critical paper by C. Stacey, concerning the controversial topics of fire, risk and project governance, as well as a presentation by R. Brandt on ‘the four elements of tunnel safety’ served to round off the conference.

3.8. Conference 2016

The 2016 meeting provided the usual collection of content-rich papers. This conference saw studies on the consequences of false alarms, intended as an incentive for stimulating advancements in sensors (Sakaguchi et al), and leading to an LHD signal processing paper in 2018. Traxler et al explained how AI might be applied in order to reduce the occurrence of false alarms.

For anyone involved in even slightly complicated tunnel projects, there were six interesting papers on control design, testing, and simulation of tunnel ventilation, which together, still form quite a valuable resource.

In addition, there was some great information on motorist responses to emergencies, from Japan, Germany and Austria.

And there was also good design information on jet fan performance, lighting efficiency, and the use of the PIARC emission data.

3.9. Conference 2018

The 9th conference focused on the big rail tunnel projects currently under construction in Austria. The Koralm Tunnel (KAT, 33 km), and the Semmering Base Tunnel (SBT, 28 km), are the core parts of the new Baltic – Adriatic Rail Corridor. The tunnels are to go into operation in 2026 and 2027, respectively. In the KAT, large-scale fire tests were carried out up to a maximum heat release rate of 21 MW in order to examine the spread of smoke in the tunnel. With cross-passage equipment reduced to a minimum, it was possible to prove that the over-pressure ventilation of the safe tunnel tube is sufficient to prevent smoke from entering the cross passage. Further investigations looked at the thermal management necessary for maintaining acceptable temperatures inside the utility rooms, so as to support operation and communication purposes. Such utility rooms are located at every 500 m inside the tunnel. They require a lot of electrical energy and produce remarkable amounts of waste heat. As the rock temperature can go up to 36°C, a cost-efficient cooling system is essential. Furthermore, it was demonstrated that the effects of climate change also need to be considered as increasing ambient temperatures strongly reduce the scope of using ventilation for cooling.

One further challenging presentation concerned the usage of a sound-based incident detection system in road tunnels. The so-called AKUT system was introduced some 8 years ago into Austrian tunnels (after 8 years of research and development) and has now become almost standard in road tunnels. The period of its permanent operation has revealed that the system provides the fastest identification of a tunnel incident, and that it exhibits a very low failure rate.

3.10. Conference 2020

A celebration was planned for the 10th Tunnel Safety and Ventilation Conference in April of 2020. Then COVID-19 happened and all of the event preparation was lost. The conference venue and social events had been booked but had to be cancelled and ultimately the 2020 conference became a virtual event.

In spite of the challenges faced in 2020, the conference was a strong technical success. Published papers and presentations included advances in the state-of-the art in alternative fueled vehicles, critical velocity and safety of rail transport of dangerous goods through tunnels. Specifically, battery and fuel cell vehicles were demonstrated to be as safe as gasoline and diesel driven vehicles and an intense discussion on critical velocity has led to a detailed re-examination of the topic.

While we all missed the networking opportunities and the trade exhibition in 2020, the conference was a great success, both interesting and informative.

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