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Calibration of a fuzzy model estimating fire response time in a tunnel

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ABSTRACT

Safety is one of the most important aspects when designing a road tunnel system. Apart from the general design of a road tunnel, different technological safety systems can contribute to increased safety. There is, however, no agreed methodology on how to evaluate such systems prior to their design and installation. In this paper, it is recommended that the time required to detect a fire and warn people about it in the tunnel be used as a quality criterion since it has a direct effect on the probability of saving lives. In their previous paper, the authors proposed a fuzzy system called SAFECALC for effectively evaluating fire sensors and warning systems in tunnels, even in the early design phase.

The biggest challenge in designing a fuzzy system is the original identification and calibration of such a system. For that reason, this paper focuses on the identification stage and, using the example of a linear fire sensor, it suggests a new methodology for performing such early level calibration. This methodology consists of several steps and, after the original design of the system, it uses inputs provided by experts in the field (via surveys and brainstorming) for fine tuning of the system. A physical model is used to simulate the propagation of a fire in a tunnel. The results of such the process are then evaluated on a real world case study from Lochkov tunnel near the city of Prague.

1. Introduction

Over recent years, the number of road tunnels has significantly increased. Their purpose is not only to avoid natural obstacles; tunnels currently form complex underground structures (Falconnat, 2013). Tunnel systems have lately even been adding new functionality to urban areas, including tunnel intersections, parking possibilities or even services for pedestrians. Therefore, because of the increased usability of tunnels, the prevention of fire and the safety evacuation of people lies on the critical path of the sustainable development of these important infrastructural elements. Particularly, the fire has proved to be especially dangerous since it can cause massive injuries or death of people trapped in the tunnel.

To minimize the negative impact of a fire, different technical safety systems have been installed to tunnels (Hrbček et al., 2014). The primary role of those systems is to quickly detect such fire and efficiently warn the people in danger. It has been repeatedly reported that the first six to eight minutes are decisive in rescuing the trapped people.

The design of escape routes, requirements for lighting systems and some other measures related to the construction of a tunnel are typically sufficiently described in existing standards. On the other hand, a large group of technological devices, such as fire sensors or warning systems, could not be entirely prescribed by standards. It is caused mainly by rapid innovations and new possibilities in this field, where the standardization effort would limit this natural progress. Moreover, every tunnel is unique and there is not universal guide for design of all facilities. Since the number, combination and placement of different fire sensors and warning devices vary at different installations and depend significantly on the construction and geometry of the tunnel, a decision which configuration is sufficient and in which case a redesign has to be recommended is not trivial. Typically, the design of safety devices depends on the designer and usually it is discussed and finally approved by the project owner. Because of the considerably individual approach, it is important to have an evaluation system available that can provide the decision-making support whether the technological safety system provides sufficient safety for people in the tunnel. Such the assessment has to be provided before the actual installation of the technology (in order to minimize the future investment).

This article provides a solution for the assessment of reaction time of fire sensors during the design stage, even though the same procedure can be used for the evaluation of the detection time of smoke sensors or the warning system as well. It focuses on quantitative evaluation, while a more common approach lies in assessment conducted on a qualitative scale, as presented, for example, in Manca and Brambilla (2011).

The authors present a model using the principles of artificial intelligence to address this problem. In this paper however, the focus is on

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the calibration of such models without the necessity for real-world fire tests, i.e. burning a vehicle or a truck in a selected tunnel. Such tests are expensive, and at the same time, the results are highly dependent on the actual tunnel geometry and current conditions. For these reasons, physical models of heat and smoke propagation under predefined boundary conditions are used to estimate the time response of fire sensors placed in the tunnel. The real-world tests are used only to validate the physical model (Holborn et al., 2004; Xiaoping and Qihui, 2013). This can be done once and the resulting model can be used for all different settings. This article presents the methods and results with respect to one particular group of temperature sensors - Linear Fire Sensors (LFS). Results of a case study – the fire of a lorry in the Lochkov Tunnel in the Czech Republic – are provided to validate the proposed solution.

2. Evacuation process in road tunnels

In order to evaluate technological systems in a road tunnel, the behavior of people trapped in a tunnel fire have to be analyzed. According to Persson (2002), the evacuation process can be divided into three phases, each taking certain amount of time:

1. Awareness phase (t_a - awareness time)
2. Reaction phase (t_r - reaction time)
3. Movement phase (t_m - movement time)

More details about the particular steps and how they are affected by the technological systems were provided in Přibyl and Přibyl (2014). Here, only a short overview is provided. An interesting overview focusing on the situation awareness problem field is provided in Fenza et al. (2010). The *awareness time*, t_a, is defined as the time needed by an individual to become aware of the danger (Fraser-Mitchell and Charters, 2005; Boer, 2003). The *reaction time*, t_r, is the time for an individual to realize that there is a potential danger. There can be substantial difference between the time when the individual is informed about a danger and the time when s/he decides about her/his action. The *movement time*, t_m, is then determined by the individual's physical and health condition, the configuration of the tunnel escape exits, the distance to the nearest safe exit and additional factors, such as the number of people in the tunnel heading to the same exit.

When we were discussing the different criteria to evaluate a tunnel technological system, we concluded that its major objective shall be saving lives. And lives are mostly dependent on the above mentioned three phases (i.e. time) of the evacuation process. We can conclude that, with regard to the ability to save human lives, time is the decisive value.

Nowadays, a lot of effort has been dedicated to the last – movement phase. There are simulation models able to answer all different questions with this regards (Caliendo et al., 2012; Ronchi et al., 2012). On the other hand, no generally accepted model to estimate the time of fire detection and warning people prior to actual implementation has been developed.

The authors presented a solution in a form of a set of fuzzy models, system called SAFECALC (formerly named CAPITA) (Přibyl and Přibyl, 2014). The particular fuzzy models address the different technological sensors, the time to detect a fire and to disseminate the information to the people trapped in a tunnel. Usage of fuzzy systems is generally recommended for many applications (Swain, 2006). Fuzzy logic provides means for a formal handling of verbal statements of experts which is not possible by using traditional mathematics; fuzzy systems are robust and suitable for non-linear systems with high level of uncertainty. This is true even for applications related to road tunnels. Fuzzy logic algorithm taking in account weather conditions, traffic density and other entirely different conditions provides predictive ventilation control in Bogdan et al. (2008). In the case of a long tunnel, fuzzy logic has been used for ventilation control since it is able to generalize the results of field experiments (Borchiellini and Verda, 2009). Another application of fuzzy systems in ventilation control is provided in Karkas (2003). All of the above mentioned examples use fuzzy systems for some kind of control. In the article (Mechevske and Wang, 2001), fuzzy systems are used for the justification of a maintenance strategy based on multiple criteria. This paper describes the possibility how to apply a fuzzy method to quantitative assessment of a complex system. Fuzzy logic was also used for the evaluation of parameters needed for the choice between a road tunnel and a surface road (Panou and Sofianos, 2002). The reason is that some parameters that could be interesting to decision makers are either absent or existing in a purely quantitative form that does not lend itself for comparison between alternative solutions.

The biggest challenge limiting the usage of fuzzy systems is the calibration step (Babuska, 2005). In this paper, we focus on one particular model from the SAFECALC system – fire identification – and present a general methodology for its calibration.

3. Fuzzy system for evaluation of effectiveness of a tunnel safety system - SAFECALC

The fire identification system uses in general fire, smoke and pollution sensors, or their combination. The system SAFECALC evaluates their time of response to a fire and the quality of warning facilities related to the time which is sufficient to inform the majority of trapped people about the danger. In this way, SAFECALC covers completely the two first phases of the evacuation process – awareness and reaction time. The general structure of the model as adopted from Přibyl and Přibyl (2014) is depicted in Fig. 1.

A fire is in general characterized by the heat transmission, smoke propagation and pollution production. A set of two fuzzy models (denoted FM1 and FM2 in the figure) estimates the time response to those three characteristics. The output of these fire identification systems is the reaction time t_{ID} representing the shortest time of the fire identification by temperature, smoke or pollution sensors. The time t_{IF} denotes the time needed to disseminate warning information to the majority of the people trapped in the tunnel. t_{PN} is the delay time depending on the operational rules for the particular control system (in our case the SCADA control system as well as optional confirmation by an operator).

The total time from fire identification to warning most people about the need to launch immediate evacuation t_{TS} is defined as a sum of the three time components described above

$$t_{TS} = t_{ID} + t_{IF} + t_{PN}. \tag{1}$$

Since t_{PN} is not affected by the technological systems, the overall objective of the proposed model is to determine the remaining two time parameters. The evaluation of the quality of fire sensors is primarily based on laboratory and field tests. Donghil and Byoungmoo (2009) describes tests of flame and smoke detection in laboratory conditions, big field tests of fire sensors were performed in the Runehamar tunnel (Aralt and Nilsen, 2009), and fire tests in undersea tunnels are described in Nilsen et al. (2001).

The challenge in designing a fuzzy system is their identification and calibration. The designer of a fuzzy model has to propose decision rules, and set the optimal number as well as parameters of the particular membership functions (MFs). This is in general very difficult and requires expert knowledge or large set of representative data. The different methods of fuzzy system identification were nicely summarized for example by the already mentioned work from Babuska (2002).

In this paper, we propose a solution suitable for estimation of time of heat detection by a Linear Fire Sensor (LFS) without the need for performing practical fire field tests. The approach is demonstrated on the FM1 (temperature identification), even though it has been used also for the model FM2 depicted in Fig. 1. In order to determine the time t_{FS}, the fuzzy module FM1 uses four input variables as denoted in the following equation: