REPRODUCTION OF HUMAN BEHAVIOR IN RISK MODELS – VALIDATION OF THE RELEVANT RISK PARAMETERS BASED ON PROBAND TESTS

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ABSTRACT

Under certain conditions, risk analyses must be carried out as part of the quantitative safety assessment of road tunnels. In addition to object-, traffic- or event-specific parameters, there are also a number of input parameters that are fixed in the risk model and whose variation is usually not planned - this also applies to parameters of human behavior. In the course of various test series on the escape and reaction behavior of road users in road tunnels in the event of an incident, various behavioral parameters were determined and analyzed. The obtained values are compared with the conventional model parameters, used in the Austrian tunnel risk model. In addition to the reduction of the overall risk, based on the currently acquired behavioral parameters, it can be shown that the assessment of self-rescue related safety measures is more or less invariant under the change of behavioral parameters investigated, if a comparative assessment approach is used.

Keywords: tunnel, risk analysis, risk assessment, real life field test, human behavior

1. INTRODUCTION

One main objective of the safety measures in tunnels is to ensure self-rescue in case of an incident. In the course of equipping a tunnel with operational and safety equipment, a quantitative safety assessment using a risk analysis approach must be carried out under certain conditions. Efficient risk models also have modules that depict/ map human behavior. In addition to object-, traffic- or event-specific parameters that are systematically varied, there are also a number of input parameters that are fixed in the model and whose variation is usually not planned/ provided. Among other things, this applies to many parameters for describing human behavior. The basic parameters used in the Austrian tunnel risk model have not been validated or updated since the introduction of the model about 10 years ago.

In the course of a series of tests conducted by the Federal Highway Research Institute (Bundesanstalt für Straßenwesen) on the influence of fire-fighting systems (FFFS) on self-rescue behavior, tests were carried out for the first time in which the reaction and escape behavior of tunnel users was investigated qualitatively and quantitatively [1]. The results provide a basis for checking the data stored in the risk models.

For the first time, the paper will present new insights into evacuation and reaction behavior in connection with the possible updating of risk models.

2. EVACUATION BEHAVIOR IN TUNNELS

In general, the evacuation behavior of persons can be divided into several phases. At the beginning is the pre-evacuation phase, which includes all events before the start of the evacuation and ends with the decision to escape. Of particular interest here is the duration of this phase and which characteristics of the event lead to whether and when the tunnel user decides to escape. In the following evacuation phase it can be distinguished between a pre-movement phase and a movement phase. During the pre-movement phase, the tunnel user searches for information and selects an escape route. The movement phase includes all behavior that the tunnel user displays during the evacuation until he reaches an escape target.

This approach is reflected in the Kuligowski's 4-phase model [2], where the first two phases of Kuligowski correspond to the pre-evacuation phase, the third phase corresponds to the pre-movement phase and the fourth phase corresponds to the movement phase. In phase 1, situational clues are perceived which are interpreted in phase 2 and evaluated with regard to their risk. In phase 3 an action decision is made, which is carried out in phase 4. Based on this pattern, the behavior of tunnel users before and during evacuation is reproduced in the Austrian tunnel risk model. Phases 1 to 3 are represented by a reaction time. Reaction time is understood to mean the realization of the situation as well as the processing and includes the period of time from the vehicle's standstill at the event situation until leaving the vehicle. The movement phase is mainly modelled and determined by different escape velocities. The escape velocity expresses the average speed at which the subject moves out of his vehicle to reach a safe area (here: emergency exit). A more detailed connection to the relevant parameters in the Austrian tunnel risk model is given in section 4.

3. TEST PERSON EXPERIMENTS IN REAL TUNNELS WITH AUTOMATIC FFFS

To gain further insights into the escape and reaction behavior of road tunnels with the system types high pressure foam (foam) and high pressure water mist (water-mist), two real life field tests were conducted with the aim of determining the influence of the FFFS on the behavior and experience of road users [1].

Table 1: Number of test persons (pairs) for each experimental setting

Parameter	Including activation of FFFS	Without activation of FFFS
foam	16	14
water-mist	28	26
Pairs	3(6)	3(6)

Table 1 shows the number of participants, separated by persons who experienced an activation of the FFFS and the number of those who served as so-called control subjects. In a random, yet controlled set-up, the escape behavior of the participants inside and outside the vehicle was observed. Participants drove a car into the tunnel and were confronted with a simulated accident with smoke propagation. After stopping the vehicle on approaching the accident, an announcement requested them to evacuate. In case of the subjects of the event group "with FFFS" the FFFS was activated for 2 minutes during the announcement (see Figure 1).

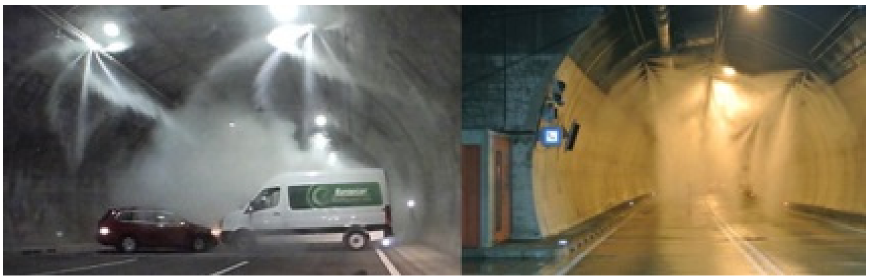

Figure 1: Experimental situation after activation of FFFS – Foam (left) – Water mist (right)

The participants had 3 minutes from the start of the announcement to react. The trial ended when one of the following criteria occurred: Attempt to make an emergency call via mobile phone; turning the vehicle; reaching certain targets: Emergency exit, emergency call station;

the test person remains in the vehicle for 3 minutes; getting out and remaining in the scenario for 3 minutes. Figure 2 shows the experiment set-up in the tunnel.

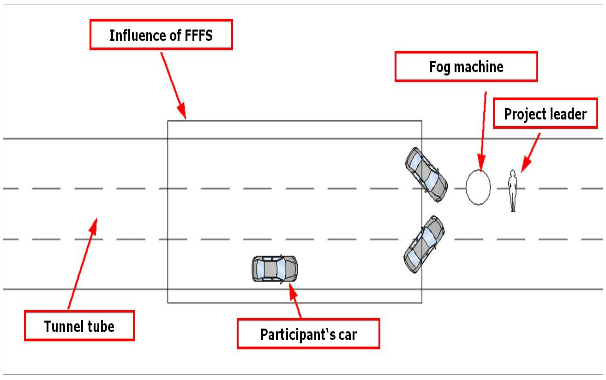

Figure 2: Schematic representation of experiment set-up

4. PARAMETER COMPARISON AND DISCUSSION

The Austrian tunnel risk model TuRisMo 2.0 according to [3] forms the basis for the investigation of the influence of representative behavioral parameters on risk models. TuRisMo is based on an integrative approach which allows a detailed analysis of road tunnels as an overall system, including the evaluation of a variety of risk mitigation measures. A detailed description of the Austrian tunnel risk model can be found, for example, in [3], [4] and [5], the implementation of a FFFS (water mist) and the illustration of its effectiveness in the tunnel risk model can be found in [6].

The modelling of evacuation procedure and in particular of human behavior during such, is based on four basic assumptions:

- Persons in the tunnel begin self-rescue when a) they are prompted to do so by suitable installations by the operating personnel or b) visibility falls below a critical value due to the concentration of fire smoke.
- Persons who are requested to escape by the operating personnel need a certain reaction time to actually leave the vehicle.
- Persons escape with a statistically distributed walking speed to the nearest emergency exit but never over the fire site.
- A certain percentage of people do not leave the vehicle's location despite limited visibility or request for self-rescue.

These assumptions are represented by three model parameters, namely – reaction time (time to perceive, process and decide) – escape velocities (demographically inspired velocity distribution) and share of non-evacuating persons (because of reduced mobility, injuries or impropriate behavior).

4.1. Derivation of the model parameters from the test subjects' experiments

The data on self-rescue and evacuation behavior recorded in the course of the trial were analyzed with regard to the behavioral parameters used in the Austrian tunnel risk model. Due to the consistent homogeneity of the data sets without activating the FFFS, the statistical analysis for this case was carried out on the basis of the combined data set of both tunnels. When the FFFS was activated, response times, escape velocities and proportions of non-evacuating persons were investigated separately for the two tunnels with the different FFFS types in order to identify tunnel-specific and system-specific influences. The results of the analysis are presented in Table 2 together with the values normally used in the Austrian tunnel risk model.

Table 2: Analysis of real person test data with and without activation of FFFS

Parameter	without activation of FFFS		including activation of FFFS	
	TurRisMo standard value	Experimental results	Experimental results (foam)	Experimental results (water-mist)
Reaction time	53 seconds	30 seconds	54 seconds	40 seconds
Escape velocities	1.15 m s^{-1}	1.9 m s^{-1}	1.7 m s^{-1}	2.6 m s^{-1}
Share of non-evacuating persons	3 %	2 %	13 %	32 %

The Austrian tunnel risk model takes account of reaction time and the proportion of non-running persons in the Austrian tunnel risk model in terms of an average value. For this reason, the values shown in Table 2 already correspond to the values used in the parameter study, cf. Section 6; in contrast, the escape velocities are taken into account in the risk model via a discrete probability distribution. The distribution applied as standard is based on assumed escape velocities which are differentiated according to age and gender and taken from the evacuation model BuildingExodus, cf.[7] as well as on the demographic distribution of the Austrian population[8]. In the course of the parameter study, this distribution is replaced by the discrete actual distribution of the escape velocities from the test persons. Both distributions are shown in Figure 3.

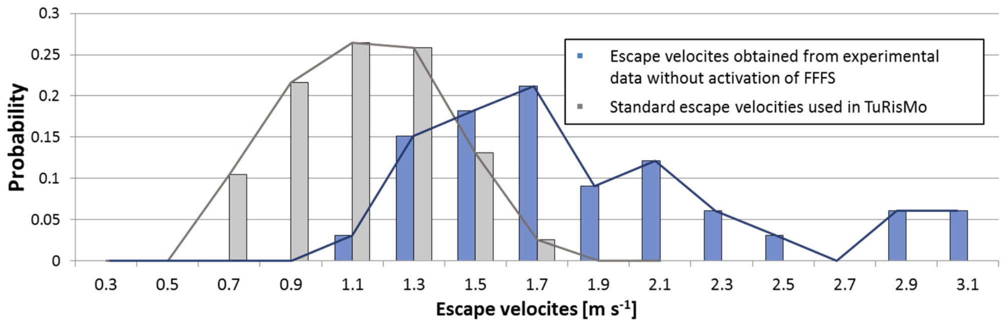

Figure 3: Probability distribution of escape velocites

4.2. Discussion of model input parameters and general validity

4.2.1 Response times

The normally assumed response time of approximately 60 seconds in the Austrian risk model, which includes the time from stopping the vehicle and following the self-rescue request to leave the vehicle, can be regarded as conservative, even without comparison with the significantly shorter response times from the test subjects. Nevertheless, it must be noted that the test persons were confronted with an experimental set-up and were aware of the experimental character of the situation. A certain expectation and thus a - in comparison to a real situation - faster reaction can therefore be assumed. The resulting response times of 30-54 seconds are therefore to be regarded as optimistic.

4.2.2 Escape velocities

The actual escape velocities determined from the two studies are comparatively high and deviate significantly from the standard values usually used in risk analyses. Particularly striking is the fact that, contrary to other assumptions (see[9],[10],[11]), particularly high speeds were recorded in the case of very limited visibility. Some of the respondents literally ran out of the danger zone. With regard to this behavior, it should be noted that the presence in the area of the activated water mist (high walking speeds were mainly encountered with this type of plant) is unpleasant and therefore the drive to leave this area quickly is high. It should also be borne in mind that the limitation of visibility (and its effect on escape velocities) in the experimental set-up cannot be directly transferred to the conditions of a real fire (effect of the FFFS combined with dense fire smoke was not investigated).

4.2.3 Share of non evacuating persons

In view of the comparatively low data set from the real tests, the shares of non-running persons of 3% in the risk model and 2% in the test persons without activation of the FFFS can be interpreted as equivalent. In the Austrian risk model non-volatile persons remain at the vehicle's location for the entire simulation period of 900 seconds and are thus exposed to the dangers of heat and flue gases over a long period of time. The interpretation that all test persons who did not initiate an escape reaction within the duration of the experiment (180 s) would not initiate an escape over a period of 900 seconds even in an actual fire is therefore presumably conservative. In addition, it can be assumed that the decision to flee and leave the vehicle is facilitated by the perceivable real threat and the observation of other refugees (group effect).

5. PARAMETER STUDY – EFFECT OF HUMAN BEHAVOIR ON THE QUANTITATIVE ASSESSMENT OF SAFETY MEASURES

The effect of a change in evacuation behavior parameters on the absolute risk values of a model tunnel, calculated with the Austrian tunnel risk model, has already been investigated in prior studies [13]. As a result of the parameter improvement, with respect to experimental obtained data, a reduction of approx. 25% of the overall risk value for a more or less generic bidirectional model tunnel without FFFS has been found. More diverse results were obtained for the same model tunnel if the effects of FFFS are taken into account. A detailed discussion of the change in absolute risk and about the possible effect of FFFS activation on human behavior can be found in [13]. Although the absolute risk value may change with a change in evacuation behavior parameters, the comparative assessment method used in the Austrian tunnel risk model is considered to be very robust against variation of background parameters.

5.1. Model tunnel

In order to investigate the influence of changed behavioral parameters on the outcome of risk assessments and to examine the invariance with respect to the variation of background parameters, the Austrian tunnel risk model is applied to a 1000-metre long bi-directional model tunnel, which characteristics are summarized in Table 3.

Table 3: Model tunnel – relevant parameters

Parameter	Value
length	1000 m
inclination	3 %
traffic type	Bi-directional traffic

emergency exit distance	500 m
traffic volume	20.000 veh/day
traffic composition	14.5 % hgv, 0.5% bus

5.2. Results

Starting from the characteristics of the model tunnel, specific parameters were varied to reflect the action of four risk mitigation measures. The changed parameters are shown in Table 4 for the reference model tunnel as well as for the tunnel including different risk mitigation measures.

Table 4: Model implementation of risk mitigation measures

Risk mitigation measure	Parameter	Value in reference case	Value after application of measure
Additional emergency Exit	Emergency Exit Distance	500 m	333 m
Improved incident detection	Detection time	37 s	7 s
Portal barriers	Time until tunnel closure	90 s	60 s
Smoke extraction system	Ventilation system	Longitudinal	LL + Smoke Extraction

Two risk assessments were carried out based on the same set of reference tunnel and risk mitigation measures. In the first study standard evacuation parameters which are normally used in the Austrian tunnel risk model were applied. These parameters were changed in the second study, according to the findings of the person experiments described in chapter 4, c.f. Table 2 and Figure 3. Within each risk assessment the four risk mitigation measures were evaluated and the resulting risk values were compared to the reference risk profile arising from the reference model tunnel. The results are depicted in Figure 4 and Figure 5. Due to more optimistic behavioral parameters, the risk values arising from adapted evacuation parameters lead to consistently lower risk expectation values. Standard behavioral parameters lead to risk values between 0.221 (reference case) and 0.132 (smoke extraction) expected fatalities per year. In contrast, risk expectation values between 0.171 (reference case) and 0.128 (smoke extraction) were found for adapted behavioral parameters. The overall risk reduction arising from variation of behavioral parameters is in good agreement with the findings of prior studies [13]. On Average 18% risk reduction in the present, compared to 25% in the prior one.

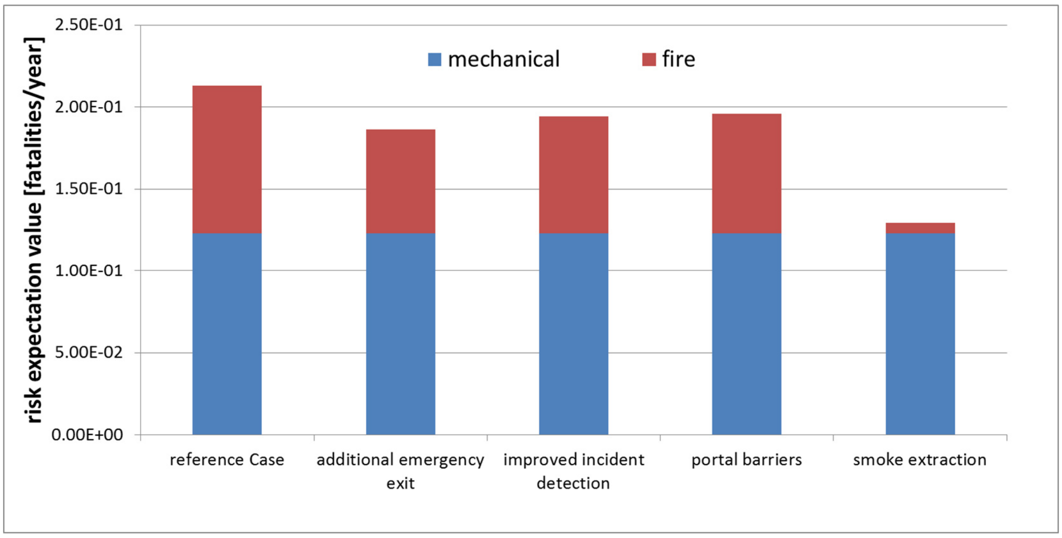

Figure 4: Risk values with respect to standard behavioral parameters

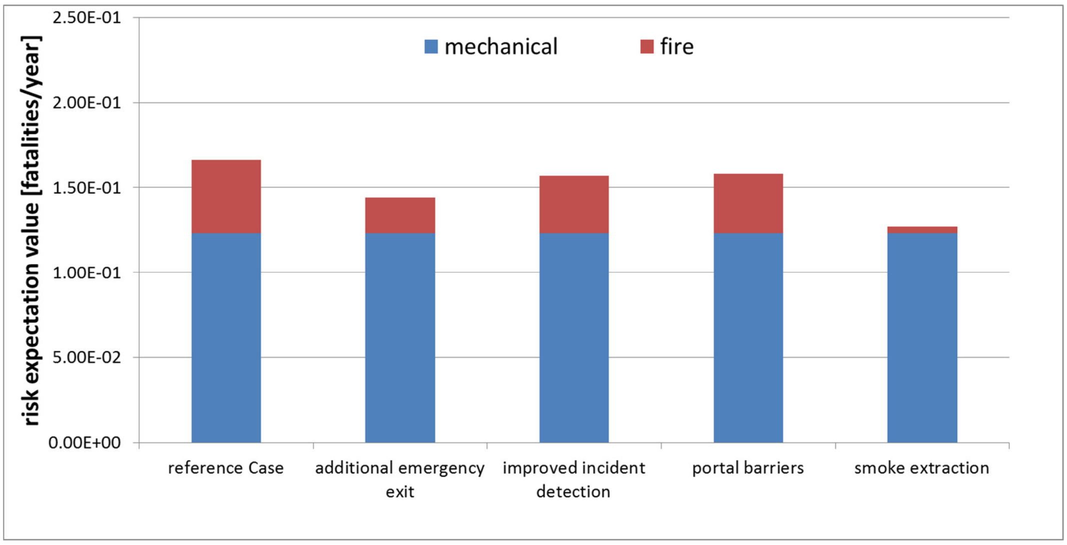

Figure 5: Risk values with respect to behavioral parameters based on person experiments

In the application of the Austrian risk model, decisions are made based on the relative comparison of reference risk profile, which is given from the application of the risk model on a reference tunnel, and the risk value of the actual tunnel. The actual tunnel may include notable deviations from regulatory guidelines as well as additional measures. Since parameter variations, which do not favor specific measures or tunnel designs, will cancel out in this kind of relative assessment approach, the Austrian tunnel risk model is believed to be very robust against parameter uncertainties. In order to investigate this behavior, the risk reductions due to risk mitigation measures, as they result from the risk model, is compared in Figure 6, for the two choices of behavioral parameters (standard parameters and experimentally obtained parameters). It is found that three of the investigated measures – improved incident detection, portal barriers and smoke extraction system – lead to almost exactly the same percentage of (fire) risk reduction for both choices of behavioral parameters. Only risk reduction following from an additional emergency exit increases from approximately 30% to 50%, if the optimistic behavioral parameters are used. However, also for this case risk reductions are comparable (same order of magnitude). Thus, the robustness of the comparative risk assessment approach is confirmed.

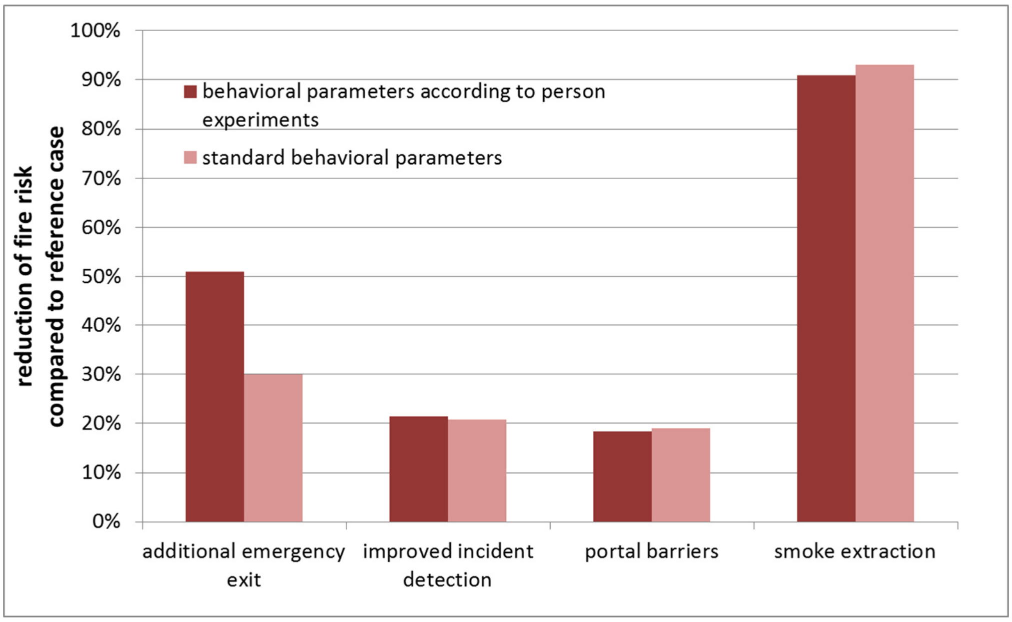

Figure 6: Reduction of fire risk compared to reference case

6. DISCUSSION AND CONCLUSION

The test data show both significantly higher escape velocity and much shorter reaction times compared to conventional model input parameters. Nevertheless, it should be noted that these good results may also be due to the fact that the test situation was a test situation and the test persons were aware of it. Due to the expectations regarding the confrontation with an incident, the situation alone in the tunnel and the claim to accomplish this task well, influences on the result cannot be ruled out. Nevertheless, it is still necessary to make an estimate between the fundamentally conservative, conventional assumptions and the nevertheless very optimistic results with regard to escape speeds and reaction times. This conclusion can be drawn independently of the installation or activation of a FFFS.

Contrary to this, the proportion of non refugees must be discussed differently. Without activation of the fire-fighting system, the value of 3% stored in the risk model corresponds well with the evaluations of the test persons, whereas activation of the FFFS shows a significant increase in the proportion of non-evacuating persons. Even if the proportion of persons who are not reacting is presumably overestimated due to certain restrictions with regard to the short duration of the experiment and, in some cases, the lack of a group effect, it is advisable to discuss the consideration of this effect in the risk assessment and to consider suitable countermeasures to compensate for the escapism.

In summary, the comparison of the parameter values stored in the model and the parameter values derived from the test persons shows a fluctuation range within which the real expected value is likely to be found (nota bene: in reality, however, a large fluctuation range can be expected in individual cases as well [12]). It can be stated that, on the one hand, the courses of action as depicted in risk models are close to the actual challenges that refugees have to overcome. On the other hand, the few behavioral parameters introduced for specific modelling and derived on the basis of plausibility considerations and empirical reports are well in line with the evaluations of the real tests. The parameters currently used in practice for mapping human behavior tend to be conservative, resulting in an overestimation of the absolute value of the fire risk.

However, parameter variations which do not favor specific measures or tunnel designs, cancel out, if the assessment is based on a comparative approach and both, reference profile and risk value of the tunnel, are calculated with the same background parameters. The study shows that this is the case for the presented change in behavioral parameters. The risk reduction due to specific counter measures, which are themselves connected with the self-rescue process, is more or less invariant with respect to the adaption of the told parameters. It can therefore be concluded that risk models which are using comparative assessment criteria, as in the case of the Austrian tunnel risk model, are robust against parameter uncertainties. These findings can contribute in improving confidence in such models.

It is nevertheless necessary to continuously check existing models whether they are up-to-date with regard to all input parameters and to make adjustments to new findings if necessary. This process can help to ensure the quality and validity of such models. In addition to the evaluation of behavioral patterns in real-life accidents and fires, realistic experiments in real tunnel facilities provide a valuable contribution along this path.

7. REFERENCES

[1] Mühlberger, A, Plab, A. & Probst, T. (2016). Analyse des Reaktions- und Flucht-verhaltens von Tunnelnutzern bei einer aktivierten Brandbekämpfungsanlage anhand von Realversuchen (FE 15.0607/2014/ERB). Unveröffentlichter Projektbericht der Universität Regensburg im Auftrag der Bundesanstalt für Strassenwesen, Deutschland.

[2] Kuligowski E.: The process of human behavior in fires: US Department of Commerce, National Institute of Standards and Technology, 2009.

[3] Österreichische Forschungsgesellschaft Straße-Schiene-Verkehr: RVS 09.03.11 Tunnel-risikoanalysemodell, Wien, 2015.

[4] Forster C., Kohl B., Wiesholzer S.: Methodologies for accurate risk modeling in the context of integrted quantitative risk analysis, 16th ISAVFT, BHR Group, Seattle, 2015.

[5] Nakahori I., Sakaguchi T., Kohl B., Forster C., Vardy AE.: Risk assessment of zero-flow ventilation strategy for fires in bidirectional tunnel with longitudinal venitlation, 16th ISAVFT, BHR Group, Seattle, 2015.

[6] Bundesanstalt für Straßenwesen: Wirksamkeit automatischer Brandbekämpfungsanlagen in Straßentunneln (FE 15.0563/2012/ERB).

[7] Ando K., Ota H., Oki T.: Forecasting the flow of people, Railway Research Review, Vol. 45, No. 8, 1988.

[8] Statistik Austria: Statistisches Jahrbuch 2003, Verlag Österreich, Wien, 2004

[9] Mayer, G.: Brände in Straßentunneln: Abschätzung der Selbstrettungsmöglichkeiten der Tunnelnutzer mittels numerischer Rauchausbreitungssimulation. Dissertation, Aachener Mitteilung Straßenwesen, Erd- und Tunnelbau, Heft 47, 2006.

[10] Jin, T.: Irritating effects on fire smoke on visibility, Fire Science and Technology, Vol. 5 No 1, S. 79-90, 1985.

[11] Galea E.R., Lawrence P.J., Gwynne S., Filippidis L., Blackshieds D., Cooney D.: Building Exodus – The evacuation model for the building industry. Theory Manual, Fire Safety Engineering Group, University of Greenwich, London, 2017

[12] Martens, M.H.: Modelling Human Behaviour in Tunnels – Expectations and Reality. In: 4th International Conference "Tunnel Safety and Ventilation", Graz, 2008.

[13] Kohl, B., Lehan, A., Senekowitsch, O.: Abbildung des menschlichen Verhaltens in Risikomodellen für Tunnelbrände: Validierung relevanter Eingangsparameter auf Basis von Probandenversuchen, Proceedings of STUVA-Conference 2017, Stuttgart, pp 405-411.