People evacuation in tunnel fires : a cross evaluation of two methodologies

Benjamin Truchot, Christophe Willmann, Joel Guivarch

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Benjamin TRUCHOT[1], Christophe WILLMANN[2], Joel GUIVARCH[2]

[1]INERIS, Verneuil en Halatte, France
[2]CETU, Bron, France

Benjamin.truchor@ineris.fr

ABSTRACT

In France, safety assessment of tunnels is mainly based on a risk analysis called the specific hazard investigation. One of the key issues of these studies consists in modeling people evacuation. The commonly used method for computing the people evacuation consists in evaluating their displacement velocity based on smoke opacity. However, it is obvious that other fire consequences parameters, thermal effects and toxicity, will affect people displacement.

To evaluate whether considering those effects is relevant and could modify conclusions of specific hazard investigations in tunnels or not, two approaches were used in a comparative manner. The first approach is based on currently used method and considers only the smoke opacity. The second innovative approach introduces thermal and toxic consequences on the displacement velocity. It enables considering the toxic dose impact on human being during the evacuation process and the thermal effect together with the visibility.
This new approach also introduces a new method for the evaluation of lethality and user evacuation which are managed with thresholds in the current method. This difference was also considered in the comparison.

Those two approaches were applied on many fire scenarios to compare the conclusions in terms of people trapped or killed by the fire. For each of those scenarios, consequences were evaluated based on a CFD model, for different tunnel geometries, design fires and ventilation strategies. The two most relevant of those scenarios are presented in the present paper.

This comparison shows only minor differences for the specific case of tunnel fire safety. One way to consider the effect of the new methodology should consist in keeping the existing method but modifying the corresponding thresholds for the different quantities relative to fire consequences.

INTRODUCTION

In France, every owner of a tunnel longer than 300 m should have a safety documentation in which the tunnel is described, the safety level is assessed and the operational aspects are explained. The safety assessment is mainly based on a risk analysis, so called specific hazard investigation.

Evaluation of fire consequences on people during the evacuation process is a key issue of specific hazard investigation. Regarding fire impact, several aspects are considered including temperature rise, radiation, smoke toxicity and smoke opacity. All those effects influence the people evacuation process, first through their influence on the displacement velocity and next, for evacuation and lethality. The current method [1] used for Specific hazard investigation only includes threshold to deal with these aspects.

Under a joint project research initiated by the CETU (Centre d'Etude des Tunnels, a national center for tunnel safety) and involving INERIS (Institut National de l'Environnement Industriel et des Risques, a national center for risk industrial risk protection), a new approach was elaborated for determining these impacts. This new approach was based on the last available input of the state of the art, especially the dose concept.

This new approach was compared to the existing one within the study of several scenarios to determine it added value. This article presents this work and it conclusion.

CURRENTLY USED APPROACH

The currently used approach is based on recommendation [1] and best practices of the engineering company.

In the current method, the walking velocity is computed by considering only the local visibility. The impact of CO and temperature is then considered through the possible death of people.

Walking velocity during evacuation process

As mentioned above, in the currently used recommendation, the user walking velocity is calculated based on the local visibility using the following assumption[1]:

- Walking velocity is 1 m/s if local visibility is higher than 20 meters;
- Walking velocity is 0,5 m/s if local visibility is between 5 and 20 meters;
- Walking velocity is 0,3 m/s if local visibility is lower than 5 meters.

While having determine the walking velocity, the evacuation direction is the required to compute the people displacement. People are assumed to go directly to the closest safe evacuation door while the local visibility stays higher than 5 m. When the local visibility becomes lower than this threshold, 50% of users is assumed choosing the wrong way, for instance run toward the fire instead of toward the nearest emergency exit.

User lethality and evacuation

Temperature and toxic fire consequences are used to estimate the available duration for the evacuation process [1]. Fire toxicity is considered through the CO local concentration assuming that users couldn't walk more than 15 min if the CO concentration is higher than 3000 ppm. Regarding thermal effect, following the same approach, it is assumed that user cannot walk more than 15 minutes if local temperature is higher than 80°C.

Concerning the lethality, not considered in [1], additional hypothesis is commonly used and consists in assuming that user die if the CO concentration becomes higher than 5000 ppm or the temperature becomes higher than 100°C. This death is assumed to be instantaneous.

NEW APPROACH

This new approach consists in considering a walking speed as a function of local toxic, thermal and visibility conditions. It mainly also considers the Fractional Effective Dose approach [2].

User walking speed and direction

The proposed approach is based on the international work on the fire consequences on people regarding their evacuation capability [2]. This international standard gives information about the impact of fire on evacuation capability. It clearly shows that both toxic and thermal fire consequences will affect people during the evacuation process. This standard however does not link the fire consequences parameters with displacement velocity. This link was proposed by some authors [3] for different application based on the following formulae:

$$v = v_0 . f_1(K_s). f_2(\rho). f_3(T)$$

Such a formula enables to consider all the three parameters of fire consequences on people displacement velocity. In this formula, $f_1(K_s)$ is a velocity correction function depending on the extinction coefficient, $f_2(\rho)$ is a similar function that depends on toxicity and, finally $f_3(T)$ is the function that gives the modification as a function of temperature.

The visibility effects on people walking velocity is based on existing data [5] and considering that smoke from fire in tunnel are irritant ones. $f_1(K_s)$ can then be expresses as follow:

$$f_1(K_s) = \max(f_{1_{min}} , -67.154.K_s^3 + 55.033.K_s^2 - 14.876.K_s + 2.3133)$$

The extinction coefficient is then based on CO_2 concentration and local temperature [1]: $K_s = 83000.[CO_2]/T_g$. One of the key issue regarding the impact of visibility is the minimum value when opacity is the only effect on people. Regarding available data [5], the minimum appears to be 0.3 m/s. A minimum value of 0.3 m/s appears as the most relevant one regarding the present objective and the tunnel context.

The objective of the toxic influence on people moving velocity is to consider not only CO impact but all other compounds that could be in smoke as hydrogen chloride, sulfur dioxide and others. Following ISO 13571 approach [2] it is then possible to build an equivalent CO toxicity to be considered in the toxic impact on people evacuation. Considering that velocity becomes 0 when the FED [2] reach 1, that corresponds, for this specific case of application to a toxic dose of 35 000 ppm.min. In the current approach, the considered dose is 3000 ppm during 15 min, this means 45 000 ppm.min. the evolution of velocity correction as a function of CO concentration can be written as follow:

$$f_2(d_{CO}) = \min(1; -0.289. \ln(d_{CO}) + 3.0604)$$

Following [3][4], the temperature correction function could be written as follow:

$$f_3(T) = \begin{cases} v_0 & T_0 < T < T_{\sigma 1} \\ v_0 + \dfrac{(v_{max} - v_0)\left(\dfrac{T - T_{\sigma 1}}{T_{\sigma 2} - T_{\sigma 1}}\right)^2}{v_{max}} & T_{\sigma 1} < T < T_{\sigma 2} \\ v_{max} . \left[1 - \left(\dfrac{T - T_{\sigma 2}}{T_d - T_{\sigma 2}}\right)^2\right] & T_{\sigma 2} < T < T_d \end{cases}$$

Then, thresholds should be defined. The first one, $T_{\sigma 1}$ corresponds to the minimum velocity that could affect people, it was fixed to 30°C. Then, in this approach, the velocity is supposed to increase because peoples become aware about the risks while the temperature is under $T_{\sigma 2}$, that was fixed to 60°C. Then, between $T_{\sigma 2}$ and the lethal temperature, T_d, the velocity is supposed to decrease because of the temperature effect on human beings. T_d was fixed to 120°C. One main difference with the model described in [3] is the maximum velocity, originally fixed at 5 m/s, it was reduced, for the present approach to 1.6 m/s which appears more coherent with feedback experience concerning road tunnel evacuation. It is also assumed that, if the visibility is lower than 5 meters, 50% of people head in the wrong direction.

User lethality and evacuation regarding heat and radiance

Considering lethality implies computing both thermal and radiative effects. However, in the context of road tunnel evacuation process, it can be demonstrated that radiative effects should influence people only in the surrounding of the fire. Radiation from the smoke could, in some specific case, influence people but it is currently impossible to take such an effect into account since the impossibility to model their effect with precision enough with existing models in the context of road tunnels. Consequently, only the convection impact is used, its effect is evaluated through the following formula [2]:

$$X_{FED}^{th} = \int_{t_1}^{t_2} (\frac{1}{t_{conv}}).dt \text{ with } t_{conv} = (4.1.10^8).T(t)^{-3,61}$$

In this equation X_{FED}^{th} represents the thermic dose that impacts user between times t_1 and t_2. In the 13571 ISO standard, the thermic dose is only related to the direct effect on the body for instance burns. When building the new method for evacuation velocity computing, it is then assumed that the evacuation is not possible anymore when $X_{FED}^{th} = 1$.

Based on a similar approach than incapacitating approach, lethal effects should consider both convective and radiative effect. The corresponding thresholds are based on a temperature of 120°C for convective effects and a radiance of 5 kW/m² for radiative effect [9].

User lethality and evacuation regarding toxicity

Evaluating the fire toxic effect on people requires first defining the nature of the impact, incapacitation, non-reversible effects or lethality. Several methods were then developed for those different applications as the ISO 13571 [2] one for incapacitation or the large bonfire non-reversible and lethal effects in the context of land use planning [7]. When dealing with fire in tunnels, which means in confined space, the distinction between the different types of gas, asphyxiant and irritant, should be considered as proposed in [2]. This approach consists in computing through the Fractional Effective Dose, FED, for asphyxiant gases, and Fractional Effective Concentration, FEC, for irritant gases. This evaluation is based on specific thresholds to determine the incapacitation and should be adapted for lethality.

Then, to consider lethality, the lethal dose of CO, $5,09.10^9$ ppm[2,27].min, shall be considered. However, while CO is not the only gas to be produced by the fire, other gases as to be considered by modifying the CO source term as a function of real fire emissions following, for example the methodology described in [8]. This method consists in increasing artificially the CO emissions by a factor representative of the relative toxicity of other gases. To illustrate, if a gas with a lethal threshold twice the one of CO, the CO equivalent will be twice this gas quantity. The main limit of such an approach is that it considers a constant ratio between toxic gases along the whole fire. It is also important to note that, in this dose evaluation, the breathing rate increase due to CO_2 is not considered.

COMPARAISON BETWEEN THE TWO APPROACHES

Several scenarios were chosen and analyzed with the two methods and the results have been evaluated (mainly number of deaths).

Choose of scenarios

In this project among twelve fire scenarios studied and 6 were chosen for their relevance for the comparison. A scenario is relevant when consequences for users are realistic and sever enough to involved the assumptions of the two methods and evaluate their impact on the results (mainly number of death). The scenarios modelled were based on two geometries. The first corresponds to the French Talant tunnel, nearby Dijon and is assumed to be longitudinally ventilated. Different fire standard curves were modeled for this tunnel, from 30 to 200 MW with different initial conditions and ventilation strategy. The second is a fictitious square section tunnel with a transvers ventilation system. Only 100 MW fire was modeled for this tunnel with considering 2 fire positions. While the objective of the present paper is not to evaluate the method but to provide some examples of application, only two scenarios are presented in paragraphs hereafter, Talant-2 and Talant-4.

Complementary common hypothesis for the two approaches

While the existing and new approach use different hypothesis for people walking velocity and people lethality, additional required hypothesis should be identical for a comparison purpose. For each approach, the required time for people to evacuate their car, after having decided to do so, is fixed to 90 s [1], this time is supposed reaching 300 s for a bus evacuation.

Then, the alarm process should be defined. In the present article, people are supposed to decide to evacuate their car when the visibility decreases near the ground 150 m in front of us.

Modeling and graphic representation

Consequences modeling were achieved using the FDS, version 6, fire code [6]. The tunnel geometry was fitted to be representative of the Talant existing tunnel, nearby Dijon in France. This circular shape tunnel is 630 m long, 10 m width and the maximum height is 8 m. One of the specificities of this tunnel is the 6% slope, considering that the traffic is going down. For numerical modeling cells were 0.5x0.25x0.25 m³. For the analysis, all quantities were considered 1,5 m above ground.

The Talant-2 scenario analysis

This case corresponds to a 100 MW fire with an initial counter pressure about 20 Pa that induces a 1 m/s air velocity in the opposite direction of the traffic. Considering a congestion case, the fire ventilation was chosen to maintain the smoke stratification, which means a fire ventilation of 1 m/s in the direction of the traffic. The people evacuation process is represented on Figure 1. On these pictures, continuous line represents people who evacuate in the correct direction, i.e. in the opposite of the fire; dotted line represents persons who evacuate in the wrong direction because of the low visibility; the vertical line marks the death for the person considering lethal criteria are reached.

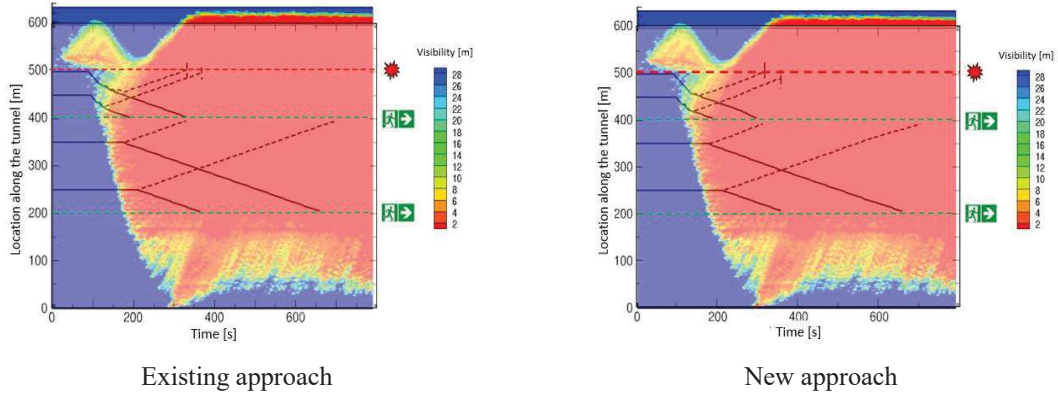| Existing approach | New approach |

Figure 1 : Visibility along time and space together with people evacuation for both evacuation model.

As highlight by the table below, this first comparison shows that, for this case, a modification of the evacuation hypothesis does not affect the conclusion relative to the capability of people to evacuate. The deaths are only users who have headed in the wrong direction because of visibility conditions.

		deaths number (time)	
		current approach	New approach
Talant-2	incapacity	6 (≈300 s)	6 (≈300 s)
	lethality	6 (≈300 s)	6 (≈300 s)

Table 1 Talant 2 - deaths number with the current and the new approach

The Talant-4 scenario analysis

This case corresponds to a 200 MW fire with an initial counter pressure about 20 Pa that induces a 1 m/s air velocity in the opposite direction of the traffic. It is considered that no fire ventilation is activated for that case. The people evacuation process is represented on Figure 2. As for figure 1, on these pictures, continuous line represents people who evacuate in the correct direction, i.e. in the opposite of the fire; dotted line represents persons who evacuate in the wrong direction because of the low visibility; the vertical line marks the death for the person considering lethal criteria are reached.
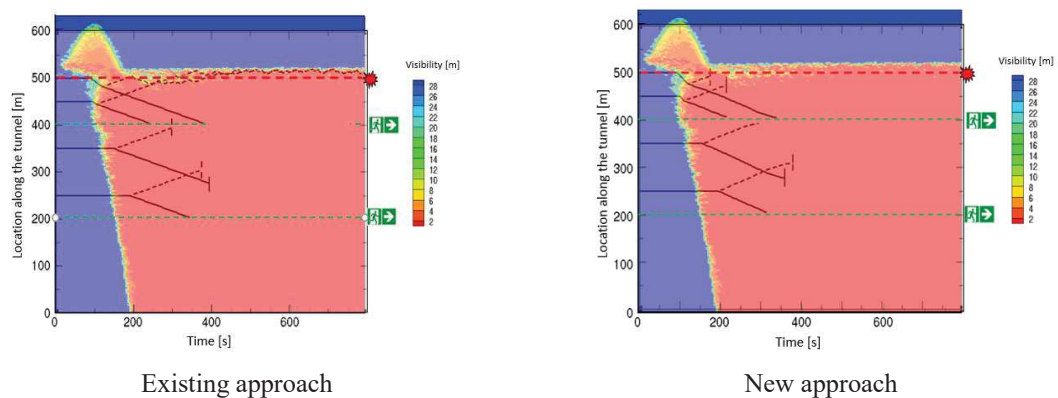

| Existing approach | New approach |

Figure 2 : Visibility along time and space together with people evacuation for both evacuation model.

For this second configuration, the deaths number is also the same for the current approach and the new approach. It must however be pointed out that the deaths are only users who have headed in the wrong direction because of visibility conditions.

		deaths number (time)	
		current approach	New approach
Talant-4	incapacity	34 (≈400 s)	34 (≈200 to 400 s)
	lethality	34 (≈400 s)	34 (≈200 to 400 s)

Table 2 - Talant 4 - deaths number with the current and the new approach

CONCLUSIONS

Regarding the state of the art, the new approach enables an improvement in terms of considering main fire consequences (visibility, temperature and toxicity) on people evacuation and lethality.

This new approach however is more complicated than the current one. Especially, it cannot be easily implemented in specific hazard investigations, the risk analysis on which safety tunnel evaluation is based. Indeed, to implement it, this approach should be considered together with the fire dynamic evolution.

In addition, the study of several scenarios chosen to highlight the impact of fire consequences parameters on users have shown only minor differences in terms of lethality between the current approach and the new one. This could be explained by the specificities of road tunnel evacuation and the general assumptions made in the specific hazard investigations, having in mind that these general assumptions are identical for both approaches. Indeed, with these specificities and assumptions, people do not stay long enough in average conditions of temperature or toxicity to have their velocity or survival conditions affected regarding the concepts of the new approach (dose concept for instance).

It is also crucial, for such modelling, to be aware about human behavior and movement capability in smoke.

Furthermore, these minor differences could be reduced by modifying the thresholds used in the current approach. CETU currently works on these modifications by involving the stakeholders of safety hazard investigations.

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