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Model of people evacuation from a road tunnel

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ABSTRACT

This paper deals with the evacuation from a road tunnel. We have focused on the possibilities of using technological equipment for evacuation of people. The first part deals with the definition of the evacuation issue. The evacuation of people comes when an accident is found. It consists of informing people in a tunnel and providing possibilities for evacuation. At this moment, the technological equipment of road tunnel plays an important role. Using it, we can reduce the time needed to people in the tunnel to start their evacuation.

The next part aims at presenting a mathematical tool, which is used to calculate the evacuation time. This will be employed to create a model of evacuation.

The conclusion contains a design of the evacuation model. We compare two types of models. The first is called a hydraulic model, which is a form of the current model. This model is a mathematical expression of the behaviour of people. The second type of model is called an individual model. It is a microscopic model, which takes into account an individual human behaviour. This model will be used to create and display the simulation of the evacuation. Models will provide a quantitative numerical output and a graphical output in the form of graphs.

KEYWORDS: road tunnel, evacuation of people, fire, mathematical tools, model of evacuation, technological equipment, simulation

1. Introduction

The fire in road tunnel is considered to be the greatest danger situation for a road user. Just insignificant number of events that occur in a tunnel is accompanied by the fire. The consequences of the fire cause high risk to human life and health. The smoke as a consequence of fire can spread only in the tunnel tube because the tunnel is basically an enclosed building. So, all people in tunnel are in danger, no just the people that are close to the fire. It is necessary to detect break out of the fire as soon as possible and provide all persons in the tunnel with this information in an understandable way. These persons leave the area after they realize the risk and after that the evacuation starts. Persons can use different evacuation possibilities: road, evacuation paths, evacuation roads and escape passages. The main barriers in an evacuation part are crashed vehicles and other vehicles. The evacuation is however necessary in another dangerous events as well. The example of such event is an act of terrorism, for instance. Nevertheless, this paper is focused on the evacuation of persons in the case of fire [1].

2. Definition of the person evacuation problem

The rise of the emergency situation and a process of the evacuation are shown in the Fig. 1. A detection phase starts after the rise of the fire or, in general after the rise of the emergency event. The fire is observed either by persons and reported by pressing the fire-alarm button or phone call in SOS booth. The fire can be also detected by the electronic fire alarm system and the electronic fire system turns on the fire alarm [2].

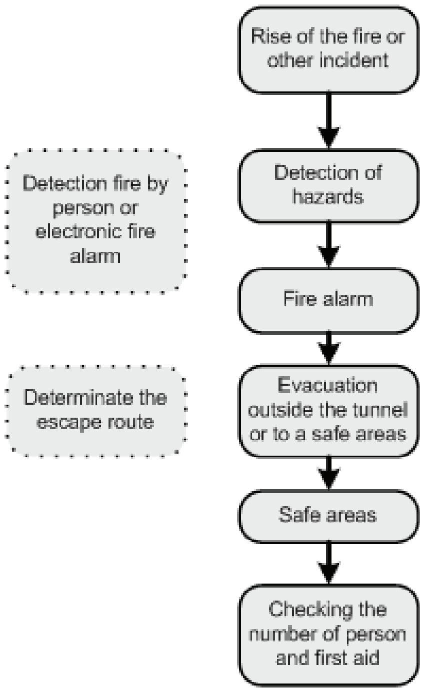

Fig. 1. Rise of the fire and evacuation process
Source: [2]

Persons in the tunnel are warned by an acoustic and an optical actuators and their evacuation outside the tunnel or to a safe areas starts. After the evacuation, the check of the number of persons and first aid take place. The person evacuation in the tunnel is an object evacuation. The object evacuation is an evacuation of a small number of construction objects. The object evacuation is a long term evacuation, from the time point of view. It is necessary to keep persons out of the tunnel until the fire is not extinguished and the smoke is not ventilated [1].

There are many forms of the object evacuation implementation. In the case where persons must leave the tunnel it is a person leaving evacuation. In the case where persons can stay in safe areas we are talking about inner form of building evacuation. The person leaving form of evacuation is typical for road tunnels. The evacuation problem can be partly solved by inner form of evacuation where the tunnel contains two tubes; the second tube can be used as a safe area. The tunnel tubes are independent zones separated by the fire-resistant doors and a pressurized ventilation system. Persons who passed through the fire-resistant doors are considered to be evacuated, therefore safe. Persons in the safe areas can get first aid and wait for the IRS to come [3]. There are additional negative fire-related factors that occur after the fire. The main are:

- Products of combustion,
- Lack of oxygen,
- Flame,
- Heat,

State of the art research showns that the most persons had died because of products of combustion and burned after their death.

The composition of gases and their quantity depends on the chemical composition of combustible materials and the type and amount of oxidizing agents. Organic and inorganic combustibles are composed mainly of carbon, hydrogen, sulfur, phosphorus and nitrogen. There are oxides in the flue gas. The fire also leads to formation of pyrolysis products, such as hydrocarbons, hydrogen cyanide, etc. Most of these substances are toxic to humans and exposition to these substances has fatal consequences. There are small particles of carbon, tar and other solids among the combustion products as well. The smoke is a compound of solid dispersion particles with a size 10^{-5} to 10^{-7} cm dispersed in the gaseous products of combustion. The higher the amount of fine solid particles is, the more irritation it causes to the respiratory tract, eyes and more reduced the visibility is. The amount of smoke particles and the resulting optical density of smoke depend primarily on the type of burning material. It is necessary to dilute the smoke with clean air to improve the visibility. A gradual decline of the oxygen is a direct result of ongoing oxidation reaction which leads to the lack of oxygen. There is 21 % of oxygen in the air in normal conditions and it falls to 10% – 14% due to the fire. Reduce of oxygen leads to breathing problems and to loose of the ability to make logical decisions.

Flames are the main outcome of an oxidation of the flammable gases in space. The release of flammable gases goes on even if there is not enough oxygen in the space and flames are moving outside the burning area. This flow of the flames can easily spread the fire to significant distances. The heat is a product of the fire with vital impact on the spread of the fire. The fire temperature can easily exceed 1000 °C. The temperature of fully developed fire is always higher than 500 °C. The specific temperature that human body can survive depends from the contact time. The effects mentioned above affect the persons in road tunnels [4].

3. Factors that affect the evacuation of persons

The main factors which affect the evacuation in tunnel:

- Mental condition of the people in risk,
- Physical condition of the people in risk,
- Construction of the tunnel,
- Technological equipment of the tunnel.

The mental status of the people is one of the main factors affecting the evacuation. An another important factor is location of both persons and the fire. Sometimes persons even must pass through the fire in order to reach the safe place. In this case persons can make a decision not to evacuate themselves but wait for help instead. This situation can happen in case of back-forward-propagation of the fire. The opposite situation is if the persons are located in the safe place but make a decision to leave it, e.g. when one truck driver left the safe place to take a cell phone. Another example of irrational behavior is if person reject to leave SOS cabin and cross smoked space to reach a safe place. SOS cabin do not protect against smoke or heat. Some studies shows that persons are phone to go back than to pass through smoke-covered place and reach safe place. An average opacity when persons decide to return is 3 meters, and women are returning more often than men. Furthermore a panic can occur when persons do not feel safe or secure. The person protection is more complicated if persons do not have sufficient information about fire building security, evacuation options and about an existience of escape routes. The panic can also occur when persons just thinks that there is a fire in the tunnel. The risk of panic is rising with falling capacity of the escape routes and with the higher density of persons. The panic does not occur if a flow of evacuating persons move from place of fire to the safe place but the panic occurs when this flow stops. The physical condition of evacuating persons has significant impact on the evacuation. The evacuation is the easiest if persons are between 20 and 40. The ability to move is falling as the age is rising. Persons younger than 20 tend to underestimate the risk of fire. Other situation is when persons are older or not able of movement. These persons tend to act passively and tend to succumb to the fear and became mentally immobile.

The construction of the tunnel has a significant impact to person protection. The first is the right location of escape routes. The escape routes should have be placed at visible places to have psychological impact to evacuees. Building construction, escape exits doors, constitute barriers to avoid the spread of the smoke, the fire and the heat. We can divide tunnel to zones and protected areas using them. The lighting and ventilation plays a vital role as well. The risk of panic rise in case the light or ventilation is not sufficient [1][11].

3.1. Technological tunnel equipment

We can divide technological equipment of the tunnel according to evacuation impact as follows:

- Equipment for detecting the fire or other emergency,
- Equipment for informing persons in the tunnel,
- Equipment for informing about evacuation possibilities and to provide evacuation possibilities.

The dividing is shown in the Fig. 2. The fire detection equipment includes video surveillance, electric fire alarm, SOS booths and system for opacity measuring.

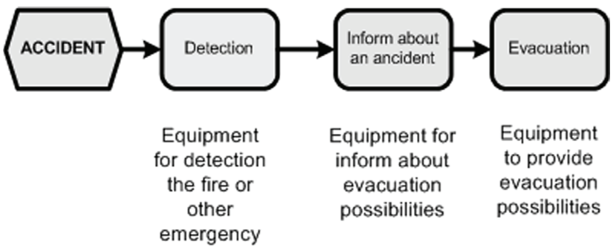

Fig. 2. Dividing of technological equipment
Source: [1]

The important properties of video surveillance systems include surface coverage and ability to act automatically. The cameras are important not only for discover the fire but for management action as well. The electronic fire alarm system is an essential element for the detection of fire. It turns out that it is not enough just to measure the actual temperature at the ceiling of the tunnel: measuring of its growth is also important. Sensors in the tunnel must cover the entire length of the tunnel tube. The linear detectors of electronic fire alarm are being used to this purpose. It is possible to cover some places such as escape corridors, service rooms by point detectors. Height of the tunnel, the location of the sensor and air velocity in the tunnel influence the time of detection. SOS cabins are important part of the tunnel security because they are used to establish emergency communication with the tunnel dispatcher. In addition to verbal connections, SOS cabins allows communication with dispatcher by using the buttons that are able to establish direct communication with IRS. The distance between the cabins, cabin equipment and their marking is also important [7].

The system for opacity measuring is part of an integrated fire identification system. The measuring device is designed to measure the carbon monoxide, nitrogen oxides and other products of combustion. Optical air pollution caused by combustion fumes from internal combustion engines, but also from fire. Radio and communications equipment, sound distribution equipment, optical and acoustic beacons are being used to inform persons in the tunnel.

Radio and communications equipment enable using of mobile phones in tunnels, including eCall (automatic notification of an accident). This system allows communication with people in the tunnel over radio receivers in vehicles thus the operator can provide exact instructions to persons in the tunnel what reduce the evacuation time.

The dispatcher can provide information and instructions using sound equipment. The average clarity is required. The escape routes can be equipped with sound equipment to avoid clumping of people at the door of escape corridors and to better control the evacuation process.

The acoustic beacons belong to novel elements of tunnel security so they are not in technical standards and so they are implemented rarely. The first acoustic beacons have been used in tunnel under the Mont Blanc for the first time. The acoustic beacons produce a sound or combination of sound which allows better orientation in tunnel with reduced opacity caused by smoke. The acoustic beacons are located next to escape routes.

The marking of distance to the evacuation routes, tunnel lighting and ventilation of the tunnel are information evacuation equipment [1],[6],[7].

4. Evacuation time

The prediction of movement of persons is an essential aspect of the evaluation their safety. The evacuation is considered to be safe if required safe egress time (RSET) is smaller than available safe egress time (ASET).

$RSET \leq ASET$

RSET is composed of sub-intervals:

$RSET = t_d + t_v + t_{rz} + t_u$

Where:

$t_{rz} = t_r + t_z$,

t_d – time from the beginning of the fire to the fire detection (minutes),

t_v – time form the fire detection to the start of the evacuation (minutes)

t_r – time from the start of the evacuation start to decision of the person to evacuate (minutes)

t_z – time from the decision of the person to evacuate to real evacuation (minutes)

t_u – estimated evacuation time (minutes)

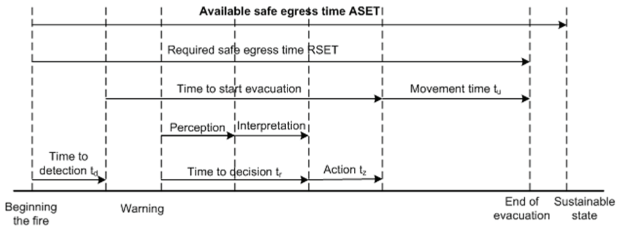

Fig. 3. Available safe egress time ASET

Source: [5]

ASET is shown in Fig. 3 [5].

Time from the beginning of the fire to the fire detection depends on the fire detection equipment. Time form the fire detection to the start of the evacuation depends on the fire safety equipment, security management and reaction of the people. The time from the evacuation starts to evacuation execution is a significant time delay in the evacuation time. This time includes decision-making process and time to evacuation execution.

A perception is the time period in which person observe warning. An interpretation is the time interval when persons evaluate the severity of warning and there is a decision-making. Persons find additional information which is significant for their decision in this period. The time from execution of the evacuation is a time interval in which persons carry out a series of measures which they consider before making an evacuation be necessary, for example, meeting children, gathering valuables, documents and so on.

The most significant events affecting the time form the beginning of the evacuation to evacuation execution include:

- The way to fire alarm – it is usually declared by a technical device. Clearly audible warning message broadcast sound device or a radio transmitter is considered to be the most effective method. Warning sirens sound signals are less effective because they require more time, when people gather information about an event.
- Visual approach - decision-making process can be greatly influenced by behavior of others in the tunnel.
- Training - training of persons intended to respond to warning signals is largely influencing a decision-making process.
- Social relations - in the emergency situation, the person will first try to gather family members and persons who have a close relationship. Such activity takes some time, especially if they are close relatives of the incident together.
- Service stuff – good and rapid personnel response may significantly reduce time required to beginning the evacuation

Estimated time between beginning of the evacuation to evacuation execute is estimated at less than 1 minute if the information of the occurrence of an emergency to gets to people through the broadcast warning messages. In case of acoustic signal it is 4 minutes.

The estimated evacuation time is the period when there is a movement of people via object to the open air or in another safe place. A hydraulic model is used to estimate this time [5].

The analysis of movement process is typically focused on evaluation of time necessary to overcome a certain distance and transit time of communication nodes. Persons are generally not moving in direct contact with structures that limit the escape route during the evacuation. So, the effective width of escape route is reduced by the nominal width which is not used as a following formula shows:

$$We = W - \Delta W, \qquad (1)$$

where:

We – Effective width of the communication (m)

W – Nominal width of the communication (m)

ΔW – Ineffective part of the communication (m)

Ineffective width of the communication is different from the barrier to barrier, for example, it is 150 mm next to doors, 200 mm around the corridors, 100 mm for other barriers and 460 mm for wide passages [5].

The size of the person-flow depends from the number of persons and their size. The size of persons depends on age, body size and clothes. The real layout of man is only slightly different from an ellipse whose axes are formed by width and thickness of a man. The average areas per persons are listed in Tab. 1.

The density of people can be expressed by the equation:

$$D = \frac{\sum_{j=1}^{m} E_j}{\sum_{i=1}^{n} S_i} \qquad (2)$$

where:

D – Density of persons (person * m^{-2}),

E – Number of persons,

S – Area of space (m^{-2}) [8][9].

Table 1. The average areas per persons

Age, clothes and luggage	Area (m^2.person^{-1})
Children	0,04 - 0,06
Adolescent	0,06 - 0,09
Adults	
- wearing light summer clothes	0,100
- wearing an average clothes	0,113
- wearing heavy winter clothes	0,125
Adult wearing average clothes	
-with a carry-on luggage	0,180
-with a suitcase	0,240
-with a backpack	0,260
-with a heavy luggage	0,390
-carrying one child	0,200
-accompanied by one child	0,260
-with luggage and accompanied by one child	0,320

Source: [9]

If the people start to group together in evacuation corridor, the density of the people in the given corridor start to rise and the people will lose their ability to move freely. Their movement will be determined by the movement of flow of the entire group instead. If the density is lower than 0,54 os.m^{-2}, then the persons are able to move independently on other persons. If the density is higher than 3,8 os.m^{-2}, then the movement of the persons will stop completely. The dependency of persons movement speed from the people density can be seen in the (Fig. 4).

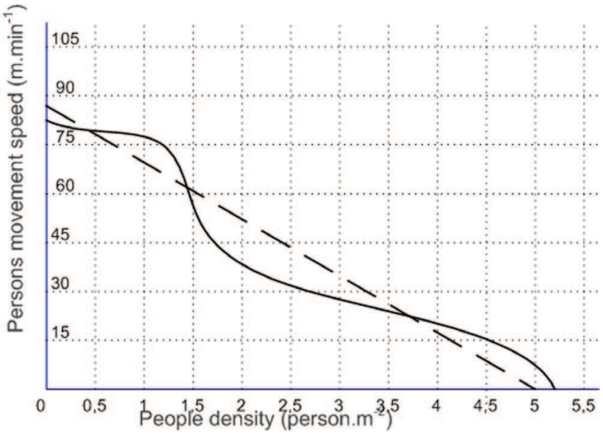

Fig. 4. The dependency of persons movement speed from the people density
Source: [10]

The movement speed of persons depends on physical disabilities of individuals. The values of the movement speed of the specifically disabled persons listed in the Tab. 2 have been determined for the movement of the individual, not the entire group [10].

5. Evacuation model of the person in road tunnel

Models that serve an evaluation of the evacuation of persons can be in general divided to hydraulic models (flow models) and individual models (microscopic models).

5.1. Hydraulic model

Hydraulic model is the simpler one and nowadays it is used more often. It assumes with a lot of approximations, therefore it is necessary to subject its results to validation. Model itself can be created through description of the simple aspects of behaviour and movement, using mathematical equations. Some of them are described in this paper. The model is based on empirical data and empirically determined equations. The model reflects individual parameters, such as time before start of the evacuation, people density, distance to escape exits, effects of various obstacles in the evacuation way (e.g. stopped cars in a tunnel) [11][12].

The model can be used to rather accurate evaluation of the time of evacuation, given accepted assumptions. However, the use of this method is limited if the large number of persons is assumed with. The model should also take into consideration aspects of the human behaviour, e.g. when the persons do not take the shortest path to exit or there are disabled persons present in the tunnel.

Table 2. The values of the movement speed of the specifically disabled persons

Type of limitation	Horizontal communication
	m.s-1
Electric wheelchair	0,89
Manual wheelchair	0,69
Crutches	0,94
Walking stick	0,81
Walker	0,57
Without aid	0,95
Without disabilities	1,25

Source: [10]

5.2. Individual model

Individual model regards an evacuation as an interaction of individuals and simulates real environment conditions that closely describe the reality. The model can be created by description of the various aspects of the human behaviour. An individual is considered to be an active object with its properties. The individual's behaviour is described either by simple rules if – condition – then – activity, or by specific degree of uncertainty. The latter allows us to employ the fuzzy logic to describe the objects more realistically in behavioural perspective. The basic rules include:

- object moves towards the closest exit,
- object moves around the obstacles using the shortest path possible,
- object keeps minimal distance from another objects,
- another objects are by the object considered as obstacles,
- object re-evaluates the rules in each time step,

individuality of the object is taken into consideration (age, gender, disability, degree of physical comfort etc.) [11],[12].

6. Conclusion

This paper deals with an evacuation of the people from a road tunnel. We assume with a scenario, in which persons that are present in the tunnel are endangered by a fire or other extraordinary event. We set a boundary for the evacuation problem and contemplate factors that affect the evacuation process. A special attention has been given to technological equipment that can decrease an evacuation time. Their effects on the evacuation time need to be quantified through a mathematical model. A mathematical apparatus that describes behaviour of the flow of people during the evacuation is presented in the paper. The same apparatus will be used and implemented in the form of mathematical model on a computer. The results must be validated, either by comparison with the result of existing evacuation models or through comparison with the experimental data obtained during real tests.

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