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Simulation of People Evacuation in the Event of a Road Tunnel Fire

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Abstract

This paper presents basic findings obtained by means of a simulation model for representing an evacuation process from a curved bi-directional Italian road tunnel in the event of a fire. Simulations were carried out by using the STEPS people evacuation model associated with a CFD model simulating the fire. It was found that the evacuation time is primarily influenced by the walking time and to a less extent by the pre-movement time in all scenarios studied. The presence of an alarm system reduced the evacuation time for most the tunnel users, allowing them to reach the tunnel exit in safety.

Keywords: Evacuation model; CFD model; Road tunnel; HGV Fire.

1. Introduction

The severe consequences to people, structures, traffic and environment occurred as a result of the disastrous fire accidents in Alpine tunnels (Mont Blanc tunnel, 1999; Tauern tunnel, 1999; St. Gotthard tunnel, 2001) have shown the necessity of improving the level of safety in the existing tunnels.

For this aim the Directive 2004/54/EC [1] has recommended minimum safety requirements for all road tunnels (with length >500 m) of the trans-European road network (TERN). The Directive has the prime objective of preventing critical events that endanger human life, environment, tunnel structures and equipment; the second is of reducing the consequences of such events by enabling people to rescue themselves, ensuring efficient action by emergency services, protecting the environment and limiting structure damage.

The evacuation process from a tunnel under emergency conditions is a complex phenomenon, which involves considering different factors such as both the physical characteristics of the tunnel and human behaviour. But while the first type of factor is deterministic and consequently easy to insert in an evacuation model, the variables

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related to human behaviour present difficulties in their exact definition due to their intrinsic randomness. The literature presents some studies concerning the influence of the variables related to human factors in road tunnel evacuations. These works [2-5] consider that the time required to escape (evacuation time) may be generally divided into three phases, namely the detection time, the reaction time and the travel time. With reference to these times several human behaviours could be observed during emergency. In addition the interactions between tunnel occupants are also a crucial factor in evacuation process. In fact the user's behaviour is also affected by the others regarding the decision to leave the vehicle and how to escape. In general two main types of interaction groups are formed: "emerging groups" and "established groups". The former group type can naturally arise and dissolve during emergency; while the latter, which is formed by family or friends, is characterized for staying together and ensuring that each member evacuates under safe conditions. In this last case the evacuation time is the same for the whole group, but walking speed is that of the slowest user.

In the light of the above considerations, the people evacuation process has been considered in this paper to deserve a more detailed investigation. In this respect, simulations tools for the prediction of pedestrian movements appear to provide a useful aid for designers and researchers. Nevertheless these simulation tools have been hitherto used prevalently for modelling pedestrian flows in evacuation processes from public or private buildings, whilst they have been performed only few times for application to a road transportation system and more especially in tunnels in the event of a fire.

In the literature several simulation models with associated software are nowadays available as a tool for investigating people safety in the case of an emergency in a tunnel. In general these evacuation models simulate factors belonging to two main categories. The former category is related to physical features such as fire spreading more especially in tunnels, vehicles being involved in the accident, and tunnel geometry. The latter is related above all to human behaviour such as the time to react and leave the vehicle, while moving in a particular direction, choosing both the walking speed and the exit door. In other words, the simulations of people evacuations are generally carried out on the basis of a software using as input the results obtained from a compatible software that models the spread of fire, smoke, and toxic gases, as well as the presence of obstacles and the characteristics of the tunnel [6-11]. However, it is to be said that the majority of these studies do not take sufficient account of the fact that the interaction between fire and evacuation is affected by the vehicles queuing in the tunnel. This acts, in contrast with the condition of isolated vehicles, as an obstacle on the spreading of the fire. In fact the queues of vehicles cause both higher temperatures and a reduced longitudinal velocity in air flow, as well as reducing more rapidly the visibility distance in tunnel thus influencing people evacuation negatively.

As a result, there are at least three main reasons for justifying this paper. The first is motivated by the need to investigate more efficiently the evacuation process due to fire in a tunnel. The second, is the setting up of a simulation model for representing with sufficient realism the evacuation of people from a tunnel under emergency conditions. Finally, the understanding of how the effects of fire may spread from the burning vehicle to other areas of the tunnel taking into account the presence of queuing vehicles and how this interferes with evacuation.

This is the context wherein the present work is set. The paper sets out to study an evacuation process from a curved bi-directional road tunnel in which a fire source due to a heavy goods vehicle (HGV) is considered. For this aim the worst fire scenario was investigated, which was identified to be when the HGV was located in the middle of the tunnel length. In this position of the HGV fire, it is assumed that other vehicles queue and come to a halt without overtaking the burning vehicle. In addition people are prevented from escaping with their own vehicles, but they have to leave their cars and walk towards a safe place. Given that along the length of the investigated tunnel there are no emergency exits for the tunnel occupants, the users have to walk on sidewalks in the direction of the exit portals (Portals A or B if they are upstream or downstream of the fire, respectively). However the worst condition for people's safety is more especially studied. This is for the zone downstream of the fire (from the middle of the tunnel and exit B) because, due to the longitudinal ventilation direction of jet-fans, tunnel occupants might be here exposed to hot gases and smoke with the danger of burning or suffocation. For this purpose the simulation tool labelled STEPS for the prediction of pedestrian movement under emergency conditions was used. This evacuation model was associated with a CFD model [12] for simulating fire. In other words simulation of people evacuation was carried out by using as input in STEPS the results obtained from the CFD software that modelled fire, smoke, toxic gases and visibility in the tunnel investigated.

In the light of the above considerations, the present paper is organised as follows: the next section deals with the evacuation model that has been used and its calibration; then the results of simulations are presented and discussed, and an evaluation of people safety is made. Finally, the conclusions and directions of future research are reported.

2. STEPS evacuation model

In this work, the STEPS evacuation model by Mott MacDonald was used to evaluate the evacuation time. It has so far been applied to various types of infrastructure (e.g. airports, exhibition centres, offices, railway stations, shopping malls, stadia, tunnels) for simulating people movement and behaviour in various evacuation conditions [13]. STEPS employs a modern agent-based approach which predicts the movement of discrete individual (virtual people) through three-dimensional space. In agent–based modeling the agents are capable of interacting with the environment and/or other agents following a list of rules that guide their movement. The geometry of the space under consideration is divided into two basic entities: planes and paths. Planes are used to model any surface on which people move (e.g. floors, platforms and stairs). Paths are geometric entities allowing only unidirectional flow in single file which are used for the representation of movements devices. Connections between the planes and paths are provided by exits. The flow rate through an exit is a function of its width and capacity. Planes are divided into discrete entities using Cartesian meshes of chosen size. This mesh serves both as the basis for the free-space movement algorithm and for solving the inter-agent collision problem in the case of people crowds. The mesh size is chosen in general to represent the area occupied by a single person and can be set to different sizes in different locations.

To each agent moving through the domain under consideration are assigned certain basic attributes: free walking speed; awareness of the modelled environment; patience required to make queuing choices; association with other members of a family or friends group; and pre-movement time in the event of an evacuation. Such attributes can be assigned both deterministically and by distribution laws. Randomness is built into the solution procedure both at the level of resolving equally-balanced decisions and in the movement algorithm, so that an ensemble average of several simulations should be used [14].

Moreover, STEPS allows the import of data (e.g. temperatures of hot gases, smoke, toxic gases, etc.) from fire simulation models. In this paper, the CFX by ANSYS [12] was used. Details of the CFD simulations were found elsewhere [11]. The effects on the occupants' movements can be calculated according to some values established in the literature. For example smoke data, imported in terms of smoke extinction coefficient K, can be used to affect walking speeds according to the Jin and Yamada [15] empirical relationships, also reported by PIARC [4] for tunnel fire scenarios. In the presence of smoke the walking speed can be reduced because of both smoke concentration and irritation, from 1.3 m/s (if $K < 0.2\ m^{-1}$) down to 0.3 m/s, as a function of smoke concentrations and properties (i.e. if $K > 1 m^{-1}$ for non-irritating smoke or if $K > 0.5\ m^{-1}$ for irritating smoke). In fact, the walking speed in non-irritant smoke decreases gradually as the smoke extinction coefficient increases, whereas in irritant smoke the speed decreases rapidly due to both the physical obscuration effects and the physiological irritation effect: as people cannot keep their eyes open for a long time without heavily running tears, they inevitably walk zigzag or step by step along the side wall.

3. Validation of the evacuation model

The STEP model is here validated by means of a comparison with data of evacuation tests performed in one of the tubes of the Benelux tunnel in Rotterdam (Netherlands) [16]. The tunnel tube is one-way, more than 1 km long, almost 10 m wide with driving lanes of 3.5 m width and an escape strip of 1.5 m next to either wall, and also with 12 emergency exits. In the tests a truck slowed down and stopped in the middle of the tunnel, blocking about 40 cars in both driving lanes. Some time after the truck had stopped, an alert hazard announcement was first made via the loudspeakers in the tunnel, then the drivers (the only person in each car) were told to evacuate the tunnel. The tests differ in the position of the cars in the tunnel with respect to the HGV and the emergency exit.

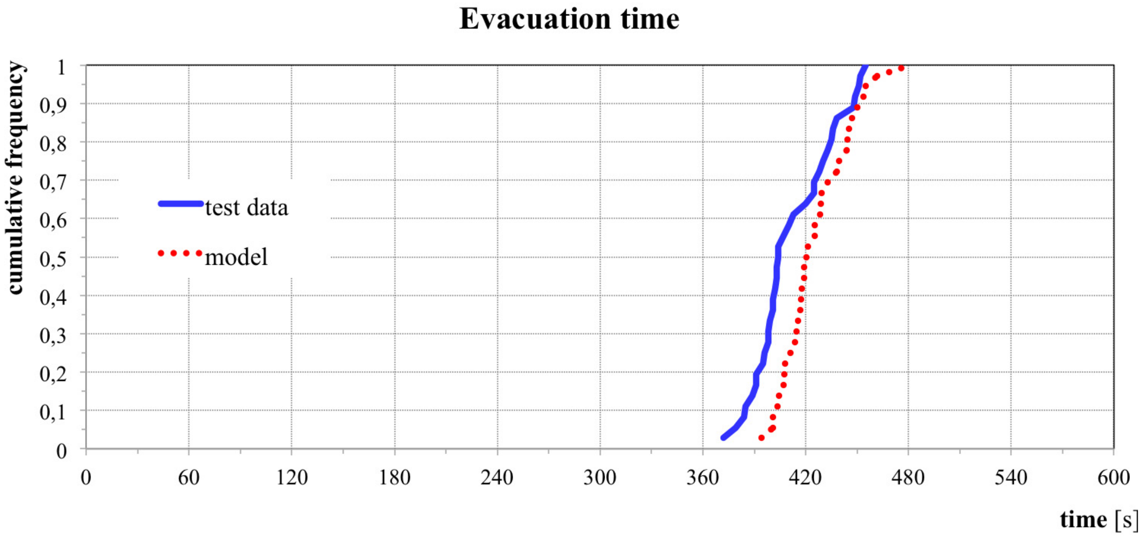

Figure 1. Comparison between evacuation time from evacuation test and modelling

We carried out simulations of the evacuation process of the reported tests, and performed a sensitivity analysis of STEPS numerical parameters (time step and grid size). As input data of the model (i.e. walking speed, pre-movement time) the distribution function of parameters was used as obtained from tests.
An example of results obtained is shown in Figure 1. A good prediction of test data was obtained: the evacuation time was overestimated by the model, differences of about 15 s between test data and simulations were observed. These differences were assumed in this work to be within acceptable tolerance levels.

4. Case of study

4.1. Tunnel description

The investigated tunnel is located in the South of Italy along a rural road (S.S.145) which connects the cities of Castellamare di Stabia and Sorrento. The tunnel, labelled Varano, is a curved bi-directional road tunnel, 1.2 km long, 10.5 m wide and 5.5 m high, with an almost uniform upward slope of 2%. At present, it has neither emergency exits for people nor alarm systems triggering evacuation in the event of a fire accident. However, it is equipped with two lay-bys in order to provide a safe place for parking broken down vehicles and, hence, prevent tailbacks. The tunnel is going to be improved in compliance with the Directive 2004/54/EC [1], with a longitudinal ventilation system that will be able to provide efficient forced airflow in the ascending direction, both in ordinary traffic conditions and in the case of fire emergency, when a linear heat detection system will activate all fans. These future features of the tunnel were taken into account in the simulations. More especially the ventilation system is assumed to be constituted by eight pairs of axial jet fans with a direction of air flow from the Portal A to B. The tunnel has a rectangular cross section with two lanes (Figure 2).

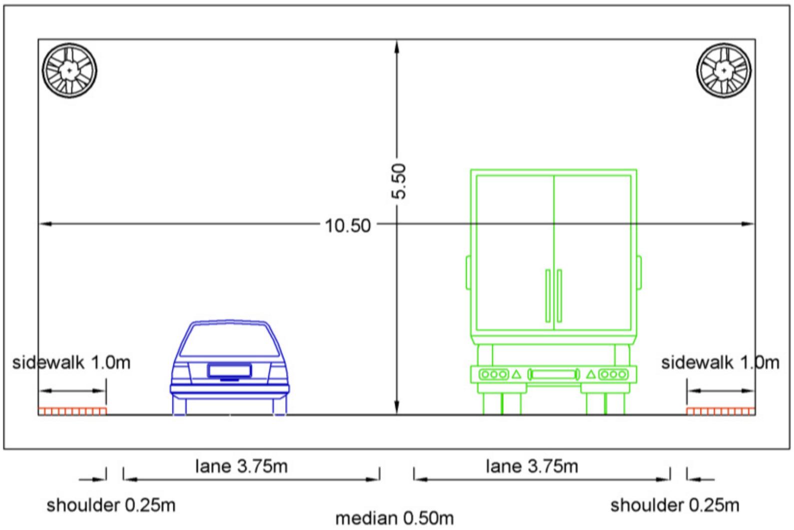

Figure 2. Cross section of the tunnel (median in two continuous strips marked on the pavement).

The annual average daily traffic (AADT) is more than 10,000 vehicles per day for each traffic direction, with a percentage of heavy vehicles slightly less than 5%. The speed limit for vehicles is 50 km/h.

4.2. Scenario

An emergency scenario under congested traffic was assumed as follows: a HGV, driving in the upward direction, comes to a halt and catches fire (HRR peak of 50 MW) at the tunnel centre, causing a queue on each fire side.
A number of 78 cars (carrying two persons per car) is supposed to queue up and stop, maintaining a minimum distance from the vehicle in front of about 2 m, up to the tunnel downstream portal, which is reached by the queue after 5 min from the fire start.
People caught up in the traffic jam downstream the HGV fire can be considered as being unable to leave the tunnel by car. Since along the length of this tunnel there are no emergency exits, people evacuation is assumed to occur along the tunnel sidewalk in the direction of the exit portals. The evacuation process, however, is worse for people who are in the zone downstream of the fire because, due to the longitudinal ventilation direction of jet-fans, they might be exposed to hot gases and smoke with the danger of burning or suffocation. Therefore, in the following only this evacuation route is considered (from the middle of the tunnel length to portal B). The maximum distance to walk to reach exit B is 590 m. In Figure 3, an example of STEPS snapshots for the simulated scenario is reported during the first minutes of the people's escaping.

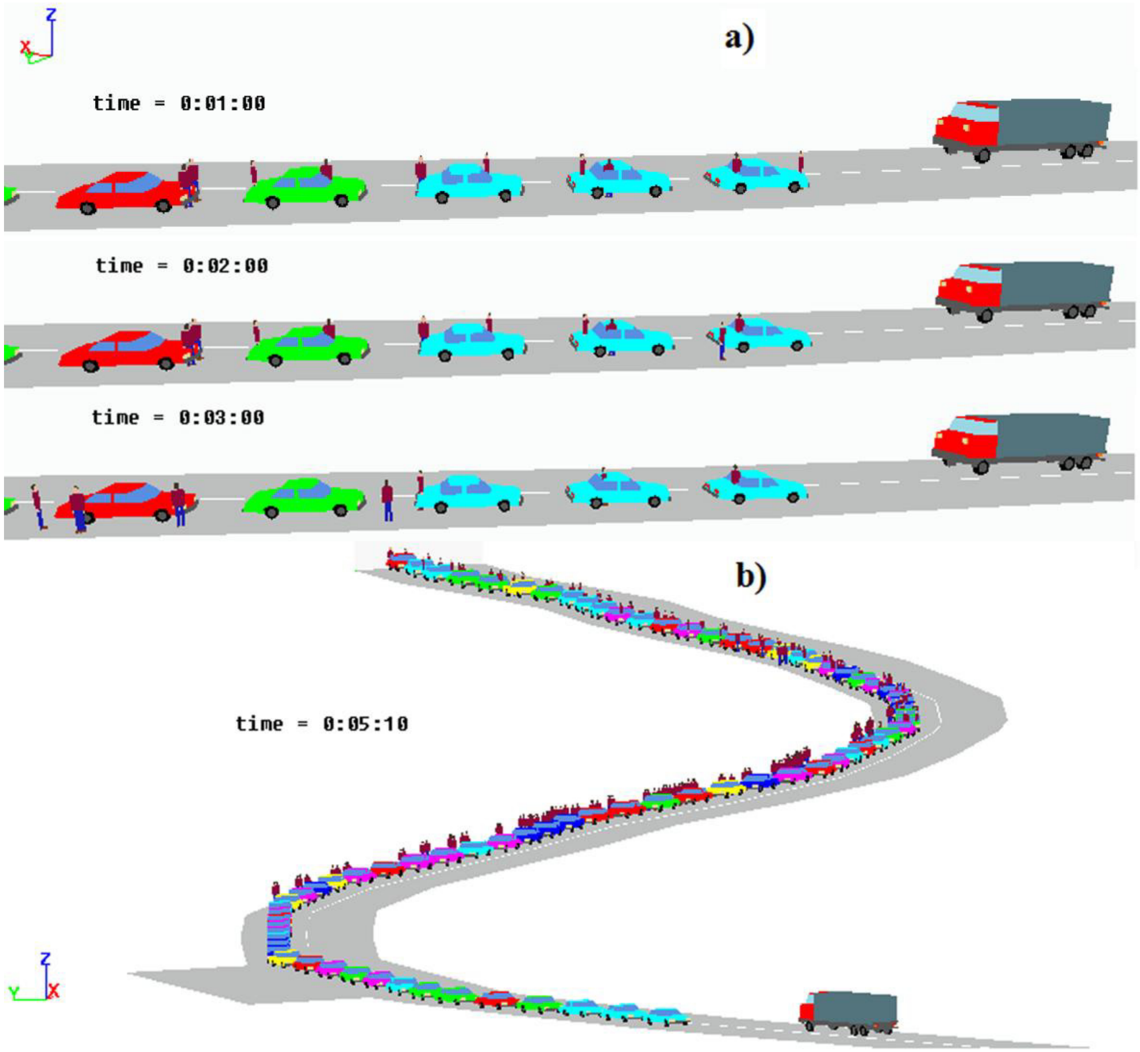

Figure 3. STEPS snapshots: a) near the burning HGV; b) along the downstream tunnel section completely full of vehicles.

4.3. Simulation Settings

Egress simulations by STEPS were carried out for 6 scenarios, differing in behavioural features, characteristic times and dependence on fire-induced smoke (see Table 1).

After the start of the fire, three time occasions were considered for each person: i) the time when the car is still in motion; ii) the pre-movement time (the time for detecting, alerting, reacting and leaving the vehicle); iii) the walking time required to reach a safe place. The times during which the cars are still in motion fall in the range 1-309 s, with cars gradually stopping every 4 s from the one closest to the HGV up to the farthest one. The pre-movement time and walking speed were assumed to be random variables. The pre-movement time was firstly simulated for the Scenarios 1-4 (Table 1) by assuming for each person a normal distribution with: mean=120 s, σ= 30 s, minimum= 30 s, maximum= 210 s [10]. Then for Scenarios 5-6 (Table 1), a fire alarm system was assumed to be activated by the heat detection system 2 min after the fire starts, according to CFD fire simulation results. The time to react and leave a car after the signal alert was assumed equal to 0.5 min, in agreement with PIARC [4]. Therefore, simulations were carried out by setting the pre-movement time equal to 0.5 min for the people in the cars stopping after the alarm, and 2.5 min for people in the 30 cars stopping before the alarm. All occupants' initial positions are assumed to be close to the vehicles, hence, the pre-movement time includes the time required to leave the car. In all the scenarios the tunnel sidewalk is defined as the evacuation walking plane to which all the car planes, corresponding to the starting point of evacuation, are connected by exits. Occupant load of 2 people (unimpeded adults) per car and standard dimensions of cars (4.5 x 2m^2) were assumed. Grid size equal to 0.5 m and time step of 0.1 s were used. With reference to the walking speed, according to PIARC [4] this lies in the range 0.5-1.5 m/s. In this work, an unimpeded walking speed was assumed for each person according to a normal distribution [10] with: mean= 1.25 m/s, σ= 0.3 m/s, minimum= 0.95 m/s, maximum= 1.55 m/s.

For each evacuation scenario 35 runs were carried out. This number of runs was identified as that required to obtain a satisfactory accuracy (a significance level of 0.05) of resulting normal distributions.

The effect of behavioural features (e.g. unrelated people or "family" groups for two occupants each car) was also assessed. The behaviour of "family" groups considers, as has been aforementioned, that people stay together and ensure that each member has been evacuated safely, so as a result their walking speed corresponds to the slowest user while response times and evacuation routes is the same for the whole group.

Finally, the effect of the fire-induced reduced visibility at eye level on walking speed was investigated by importing smoke data from CFD simulations. Fire simulations were carried out by means of the CFD software CFX by ANSYS [12]. Details of simulation software and settings were found in a previous work [11]. In the simulations the longitudinal slope of 2% of the tunnel was considered, the effects of forced ventilation were taken into account, with the effect of the queuing of vehicles on the fire development and the spreading of smoke and hot gases. In particular, CFD results in terms of smoke concentration at eye level along the egress path were here used to calculate the extinction coefficient (K) by Eq 1-2, assuming for HGV: smoke yield y_s~ 0.025 kg/kg; mass optical density D_m~ 100 m^2/kg [17]. Light obscuration due to smoke is expressed by the extinction coefficient K (m^{-1}) or of optical density D (m^{-1}) in Eq. 1, as a measure of the attenuation in intensity I of a light beam passing through a distance L (m) of smoke:

$$\frac{I}{I_0} = e^{-KL} = 10^{-DL} \tag{1}$$

The optical density D can be expressed in terms of smoke properties:

$$D = D_m \frac{C_s}{y_s} \tag{2}$$

where D_m is the mass optical density (m^2/kg), C_s is the smoke concentration (kg/m^3) and y_s the smoke yield (kg/kg). During the evacuation of each person STEPS uses the imported K values at the corresponding position along the egress pathway to evaluate the walking speed according to Jin & Yamada relationships [15].

The main conditions of simulated scenarios are summarized in Table 1.

Table 1. Summary of the evacuation conditions for the simulated scenarios

Scenario	Family	Pre-movement time [s]	Maximum unimpeded walking speed [m/s]	Smoke
1	NO	mean= 120; σ= 30; min= 30; max= 210	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	NO
2	YES	mean= 120; σ= 30; min= 30; max= 210	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	NO
3	YES	mean= 120; σ= 30; min= 30; max= 210	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	Non-irritant
4	YES	mean= 120; σ= 30; min= 30; max= 210	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	Irritant
5	YES	Related to alarm system and car position	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	Non-irritant
6	YES	Related to alarm system and car position	mean= 1.25; σ= 0.3; min= 0.95; max= 1.55	Irritant

5. Results

5.1. Evacuation times

In Table 2, for each scenario investigated mean data gathered over runs in terms of characteristic times (i.e. the time when car is in motion, the pre-movement time, the walking time and the evacuation time) and of average walking speed are reported. Statistical treatment analysis of data over all the 156 users involved provides estimation of mean, standard deviation, minimum and maximum.

Table 2. Statistical treatment over all 156 people of individual means over runs of characteristic times and average walking speed

		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
car in motion time [s]		Deterministic values in the range 1-309 s depending on car position along the tunnel					
pre-movement time [s]	Mean	119	120	120	119	fixed values in the range 30-149 s	fixed values in the range 30-149 s
	Std.Dev.	13.4	6.1	5.8	6.1		
	Minimum	90	105	107	106		
	Maximum	143	137	139	135		
walking time [s]	Mean	216	250	264	420	241	305
	Std.Dev.	125.5	134.9	145.7	252.5	142.3	241.5
	Minimum	2	13	19	19	4	4
	Maximum	451	487	540	899	512	873
evacuation time [s]	Mean	**490**	**524**	**539**	**695**	**449**	**514**
	Std.Dev.	42.6	45.4	55.5	162.0	86.5	194.9
	Minimum	413	442	441	447	342	342
	Maximum	590	602	657	1021	662	1023
average walking speed [m/s]	Mean	1.2	1.1	1.00	0.7	1.1	1.0
	Std.Dev.	0.06	0.09	0.07	0.06	0.03	0.18
	Minimum	1.1	0.7	0.5	0.6	1.0	0.6
	Maximum	1.4	1.2	1.1	0.9	1.2	1.2

Such results give a first overall indication of the assessed features:
i) unrelated people (Scenario 1) are able to reach the tunnel exit in a shorter time when compared to family groups (Scenario 2): the estimated mean values of total evacuation time are 490 s and 524 s, respectively;
ii) the presence of smoke affects the egress process by reducing the walking speed, to a greater extent in the case of irritant smoke: the mean of the total evacuation time is 539 s in the case of non-irritant smoke (Scenario 3) and 695 s in the presence of irritating smoke (Scenario 4), respectively, in comparison with the value of 524 s in the absence of smoke (Scenario 2); the average walking speed is estimated to be reduced from 1.1 m/s with no smoke to 1.0 m/s with non-irritant smoke, down to 0.7 m/s in the presence of irritating smoke;
iii) the presence of a fire alarm system, for triggering the evacuation process, shortens the egress process in comparison with scenarios with stochastic pre-movement times: the mean evacuation time is 449 s in the case of non-irritant smoke (Scenario 5) and 514 s in the presence of irritating smoke (Scenario 6) in contrast to 539 s (Scenario 3) and 695 s (Scenario 4), respectively.
In all the scenarios investigated the evacuation time is primarily influenced by the walking time and to a less extent by the pre-movement time.

In Figure 4, the distribution function of evacuation times are reported for all scenarios. In the absence of smoke (Scenario 2) almost all the people leave the tunnel within 10 min, whereas the presence of non-irritating smoke (Scenario 3) delays total tunnel evacuation by about 1 min. On the other hand, irritant smoke (Scenario 4) causes a more significant reduction in walking speed, so that all tunnel occupants can be estimated to exit the tunnel approximately 17 min after the fire start in contrast to non-irritant smoke where all users can exit the tunnel within 11 min. Similar total evacuation time values are observed in the presence of an alarm system (17 min and 11 min respectively for Scenario 5 and 6) although some people start to evacuate earlier.

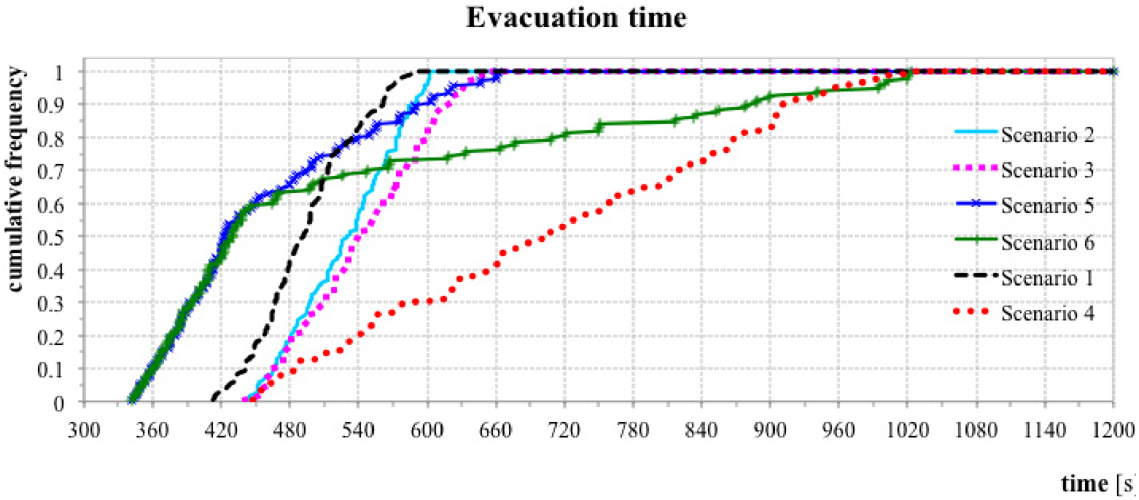

Figure 4. Function of cumulative distribution of the evacuation time for simulated scenarios

5.2. Acceptable safety criteria for tunnel user survival in the event of fire

In the event of a tunnel fire several factors could affect tenable conditions for people, and dangerous effects could be due to hot and toxic combustion gases as well as to radiation [4,18]. CFD results in terms of temperature, radiant heat flux and toxic gases concentrations predicted along the egress path were here used, in order to evaluate the risk of impaired escape, incapacitation or even death due to asphyxiation, hyperthermia or severe burns. These values with STEPS results in terms of people position over time allows the determination of ASET (available safe escape time). These values refer to the person closest to the HGV when the fire started, and so exposed to the most severe fire-induced conditions and also needing to walk the maximum distance to the tunnel exit portal.

According to the asphyxiation gas model by Purser [19], dangerous conditions due to toxic concentrations were never achieved. On the other hand, the severe hazard due to convective heat exposure and above all to radiant heat may endanger and impair escape before the people reached the tunnel exit portal. The fractional dose of total heat acquired during exposure can be calculated using Equation 3, with the tenable limit predicted when the FED for heat equals 1:

$$FED = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t \qquad (3)$$

where t_{Irad} and t_{Iconv} are the time to incapacitation due to radiant and convective heat according to the relevant exposure-time curves, respectively.

The ASETs for people nearest the fire in the event of the various scenarios resulted as follows: in all the scenarios, the time to incapacitation by total heat was predicted as being equal to ~450 s (causing pains) and equal to ~510 s (producing severe burns) both in the case of non-irritant smoke and of irritant smoke. No

significant differences in the ASETs in the presence of the alarm system were predicted for the assessed first person, since his pre-movement time is approximately the same in the event of all four scenarios. The comparison between the ASET and the required safety egress time (RSET) showed that lethal conditions may occur for the tunnel users in the event of the hypothesized fire scenarios.
Indeed, in the presence of an alarm (Scenarios 5 and 6) 60^{th} percentiles of evacuation time are less than 450 s (ASET for pains) which means that these people have been evacuated safely, while more than 70^{th} percentiles are less than ASET for severe burns, hence, these people during evacuation are incapacitated by pain due to heat.
On the contrary, longer evacuation times are needed without an alarm system, hence all the people suffered pain due to the heat. Among them those that evacuated before severe health effects (3° burns) are much more for the scenario 1 than for the other scenarios.

6. Conclusions

This research was motivated prevalently by the need to make an analysis of people evacuation process from a curved bi-directional road tunnel in which a fire source due to heavy goods vehicle was considered. For this aim the worst scenario was investigated, which was identified to be when the HGV was located in the middle of the tunnel length. People were assumed to be prevented from escaping with their own vehicles, but had to abandon their cars and walk along sidewalks in the direction of the exit portals. In particular the worst condition for people's safety was investigated which, due to the longitudinal ventilation of jet-fans, corresponds to the area downstream of the fire. In order to achieve the objective, the STEPS software for simulating people's evacuation process was used in conjunction with the fire simulation CFX code. On the basis of these simulations the conclusions given below may be drawn.
The evacuation time is primarily influenced by the walking time and to a less extent by the pre-movement time in all the scenarios investigated. The mean of the total evacuation time was found to be 539 s in the case of non-irritant smoke and 695 s in the presence of irritating smoke, in comparison with the value of 524 s, found in the absence of smoke.
The presence of smoke affects the egress process by reducing the walking speed, to a greater extent in the case of irritant smoke. The average walking speed was estimated to be reduced from 1.1 m/s with no smoke to 1.0 m/s with non-irritant smoke, down to 0.7 m/s in the presence of irritating smoke.
The presence of an emergency ventilation system is able to partially control the evolution of smoke during the fire. On the contrary, the presence of an alarm system can reduce the evacuation time for most tunnel users, allowing them to reach the tunnel exit in safety. When an alarm system is present the mean evacuation time was found to be 449 s in the case of non-irritant smoke and 514 s in the presence of irritating smoke, respectively.

The comparison between the available safe escape time (ASET) and the required safety egress time (RSET) showed that lethal conditions may occur for the tunnel users in the event of the hypothesized fire scenarios.
Although the authors are confident that through carrying out an appropriate analysis they have simulated with sufficient realism the people evacuation process from the tunnel in the event of a fire, there are still some points of interest worth investigating. Further research is needed to allow a more definitive analysis of fire safety in tunnels. This should include more fire scenarios (i.e. tanker burning) and user behaviour (e.g. that of disabled people), as well as analysing in greater detail the effect of fire parameters on the escape process, in order to assess the critical distance from the fire for a safe evacuation in all scenarios. Fast and reliable suppression systems, and/or smoke control systems, should also be better investigated. Therefore, future studies should make these additional developments possible.

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