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An Evacuation model for risk analysis in Spanish Road Tunnels

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Abstract

In this paper we present EvacTunnel 3.0 an evacuation model design specifically for road tunnels. The model combines coarse network (space discretization) and a microscopic approach for modeling individual behaviors. Based on Monte Carlo methods, the model has the capability to perform multiple simulations by changing random variables of tunnel users such as pre-movement times and walking speeds. The proposed model allows the user to incorporate the effects of fire into the evacuation simulation (importing fire data/results from another model) and, therefore, predicts the number of people directly affected by the smoke (victims). Three verification cases of the proposed model are shown in this paper: 1) risk analysis application, 2) comparison with other evacuation models and 3) a real case application.

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Keywords: *Computer modeling, Evacuation, road tunnels; Real Time; Risk Analysis*

1. Introduction

In recent decades, in Europe alone, tunnel fires have destroyed more than a hundred vehicles causing over 400 deaths and presenting a cost of billions of euro for the European economy (Carvel, 2007). Disasters like the Mont Blanc tunnel fire (Italy–France, 1999) and the other three fires in the Eurotunnel (1996, 2006 and 2008) show that these environments should receive particular attention from designers. Consequently, the European Directive 2004/54/EC (Council Directive, 2004) establishes the requirement of a thorough and detailed risk analysis for the tunnels in the trans-European network in order to achieve the appropriate safety levels and reduce the negative consequences of a hypothetical emergency scenario.

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In this context, several Computational Modelling software packages have been used in recent years as a tool for analysing occupant safety conditions in case of emergency. This is the reason why their application, initially almost exclusively for buildings, is currently being extended to a large number of environments such as aircraft, trains, ships and tunnels. Designers, engineers, researchers often face the problem of performing the safety analysis through the use of a current evacuation model which is not designed specifically to be applied in road tunnel scenarios.

However, road tunnels are unique environments with their own specific characteristics: underground spaces, unknown to users, no natural light, etc. which affect different aspects of Human Behaviour (Boer, 2003, Shields 2004, Worn, 2006) such as pre-evacuation times (e.g. people may show vehicle attachment), occupant–occupant and occupant–fire interactions (Byan, 1977, Di Nemo, 2002, Frantzich, 2004) herding behaviour and exit selection. . Therefore, designers need a deep knowledge both of the characteristics of the model they use (e.g. the modelling method) as well as of its limitations to represent this kind of scenarios.

This paper presents EvacTunnel 3.0 a new evacuation model for road tunnels. The original model was integrated into a Decision Support System for road tunnels (Capote, 2013, Alvear, 2013). Then, this new version has been adapted for its use in risk analyses for road tunnels. In addition to the other main features (Stochastic approach, Individual perspective, simulations in real-time), the present version of EvacTunnel incorporates fire data (Importing fire data/results from another model) and predicts the number of victims due to the smoke.

2. EvacTunnel 3.0 Overview

Based on previous works developed by GIDAI Group (Capote, 2013, Alvear, 2013), EvacTunnel 3.0 employs a stochastic approach in order to simulate the evacuation process in a road tunnel (see table 1). Furthermore, this new model can be applied for risk analysis purpose by considering the consequences of a fire situation in a road tunnel.

Table 1. Characteristics for EvacTunnel 3.0.

INPUTS PARAMETERS FOR EVACTUNNEL 3.0			
	Length to the exit nearest against the traffic [m]		
Tunnel characteristics	Length of traffic congestion in tunnel [m]		
	Number of lanes		
Number of vehicles	By default	By choice	
Type of alarm	Consecutive	Simultaneous	
Method for definition of survival from smoke	Without smoke	Tabulated method	Simulation method
Stochastic simulation parameters	Number of iterations	Percentile to be calculated	

EvacTunnel 3.0 is a freeware object-oriented evacuation model that has the capability to perform several simulations (a minimum of 100 runs) in a few seconds and statistically process the sample of results. Based on Monte Carlo Methods, random samples are generated. In each run each tunnel user has different values of these parameters. After performs n runs, potential outcomes of the scenario are obtained.

Output parameters are total evacuation time, number of people trapped inside the tunnel and number of people affected by the fire. The total evacuation time is determinate by the last person who reaches the exit.

As we can see in table 1, the user should introduce some basic inputs that define the tunnel characteristics - the distance in meters from the location of the accident to the nearest exit (emergency exit or tunnel exit), the length of traffic congestion (queue of vehicles) that occurs before the tunnel is closed and the number of total lanes of the tunnel- and those inputs that determinate the stochastic simulation: (1) the number of iterations and (2) percentile of the results (0.90, 0.95 or 0.99).

The number of people trapped inside the tunnel is a random output variable calculated by the model based on the type and number of vehicles. There are two possible options to define the number and type of vehicles, 1) by default. Based on the length of traffic congestion, the occupancy distance established for each type of vehicle (8 m for cars and 20 m for trucks and buses) and the ratio of each type of vehicle or 2) manually. The user defines the number and type of vehicles trapped inside the tunnel.

As it is explained above, the model randomly calculates the number of people inside a tunnel. This is obtained as a uniform random variable between 1 and 2 for heavy vehicles, 1 and 5 for light vehicles and 20 to 40 for buses.

It should be noted that the flexibility of EvacTunnel permits the user to modify these parameters (ratio of different types of vehicles, length of occupancy and ranges of occupancies).

Similar to previous version of EvacTunnel, the self-evacuation of each tunnel user depends on the following parameters: pre-movement time, travel distance and walking speed.

The tunnel users are uniformly distributed inside the tunnel. Movement is based on straight lines towards the exit shorter distances. No interruptions or stops are simulated once the tunnel users have started to move. Furthermore no groups are considered. The model is based on the mathematical principles described below. Evacuation time of the i-th tunnel user is:

$$t_{e_i} = t_{pm_i} + \frac{d_{mov_i}}{v_{mov_i}} \tag{1}$$

where

t_{pm_i} -pre-movement time (s);

d_{mov_i} -travel distance to the exit (m);

v_{mov_i} -Uninpeded walking speed (m/s).

The pre-movement time (in s) of the i-th user is:

$$t_{pm_i} = t_{alar_i} + t_{resp_i} \tag{2}$$

Where:
t_{alar_i} -Reaction time;
t_{resp_i} -Response time.

Reaction time (t_{alar}) can be obtained as:

- Simultaneous: All the user receives the alarm at same time. Therefore, (t_{alar}) is zero.
- Consecutive. It is assumed that the alarm in propagated as a "domino effect, and it is started by the person next to the accident reaching different locations – and warning the other occupants- during their movement towards the exit with a defined speed and response time. These parameters can be varied by the model´s user in Advanced Options.

$$t_{alar_i} = t_{pm_q} + \frac{d'_{I2} - d_{mov_i}}{v_{mov_q}} \tag{3}$$

Where:

t_{pmq} -Pre-movement time of the first responder close to the accident;

d'_{I2} -Distance from the accident to the exit;

v_{movq} -Walking speed of the first responder.

The default random behavioural variables were extracted from experiments and the scientific literature respectively. The experiments were conducted at the University of Cantabria in a small tunnel at night. The time spent by 32 participants to leave their cars was measured. Participants were not informed about the purpose of the experiments. Each test was performed individually.

The participant was instructed to drive and stop in a specific location on the road. Then, he/she was encouraged to leave the car by the following pre-recorded notification message. “This is an emergency. Please, leave the car and evacuate the tunnel”.

It is worth to say that the mean value of the pre-movement times obtained in the experiments is very close to the one obtained from the experiments conducted by (Norén and Winer, 2003) when both variables “time to leave the car” and “hesitation time” are included. The horizontal walking speed is one of the most studied parameters. There are a lot of data regarding this parameter in the scientific literature. In this case, the walking speed is derived from (Norén and Winer, 2003).

This new approach permits the model´s user to employ EvacTunnel 3.0 for the risk analysis required in the MRAT (Spanish Ministry of Transport, Ministerio de Fomento, 2012). The MRAT establishes a method for obtaining the number of affected persons inside the tunnel and the evacuation routes for specific fire scenarios (see table 2).

Similar to the MRAT, EvacTunnel contains the three alternatives for considering the influence of smoke for tunnel occupant: Without smoke, Tabulated method and Simulation method. It is assumed that if there is not smoke (Without smoke method) there will not be any affected people. For Tabulated method a specific destratification time is set up plus an additional time to the entire length of tunnel. Those tunnel users who are inside the tunnel after this time are considered as victims in the model. The fire scenarios and the values applied by default are shown in Table 2. The user can modify this values in the model.

Table 2. Fire scenarios considered by the MRAT.

Scenarios	S1	S2	S3	S4	S5
Vehicles involved	1 LV	1 LV/1HV	1 LV/1 B	1 HV/ 1 B	2 LV
	8 MW	30MW	15 MW	30 MW	100 W
Destratification time (s)	300	247	260	247	77
Additional time (s)	60	60	60	60	45
Total destratification time (s)	360	307	320	307	122

For Simulation method, EvacTunnel is prepared for loading an Excel file with the following data: 1) distance from the accident to the different points inside the tunnel (in meters), 2) t1, the time when tenability limits are reached 3) t2, the time when tenability limits are over. The tenability limits are assumed by the model user (i.e. based on FED, visibility, etc.). The following part of this paper presents different stages of verification and application cases of EvacTunnel 3.0. It should be noted that this version of the model is available in GIDAI´s website for its use (http://www.gidai.unican.es/Download.html).

3. Comparison with MRAT

For this application case, this epigraph presents the comparison of EvacTunnel 3.0 with the Tabulated method (MRAT). This will show the verification of this model for risk analysis purpose.

3.1. MRAT description. Tabulated model

It should be noted that the MRAT uses a deterministic approach that requires some predefined inputs and assumptions. For this application case it is assumed that a fire in car (scenario 1) has caused a traffic congestion of 150 m and the distance from the fire to the entrance is 400 m. (see figure 1). 34 light vehicles are in the traffic congestion and based on the occupancy presented in the MRAT – 1.5 persons for light vehicles- it is obtained that a total of 25.5 persons for each lane are trapped inside the tunnel.

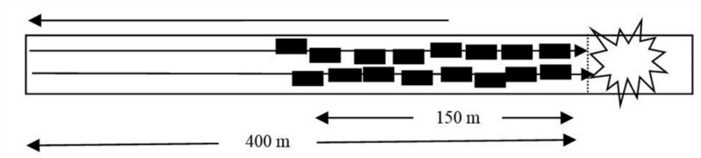

Fig. 1. Layout for the comparison between EvacTunnel and MRAT for tabulated model.

The MRAT analyses the occupant evacuation routes considering the following assumptions:

- The response time of occupants directly involved in the accident is 90 s.
- The response time for other users is 15 s. once their vehicles are stopped in the queue.
- The walking speeds are: V_{e1}*= 1 m/s without smoke* and V_{e2}*= 0.5 m/s with reduced mobility*

Furthermore some equations are proposed for obtaining the evacuation routes from each vehicle. The evacuation routes are defined by three sections (space-time):

- Section 1. Point 1 to 2. Response time of the user.
- Section 1. Point 2 to 3. Evacuation without smoke.
- Section 3. Point 3 to 4. Evacuation with reduced visibility.

3.2. Results

Based on MRAT, the figure 2 shows the evacuation routes obtained from each vehicle trapped inside tunnel.

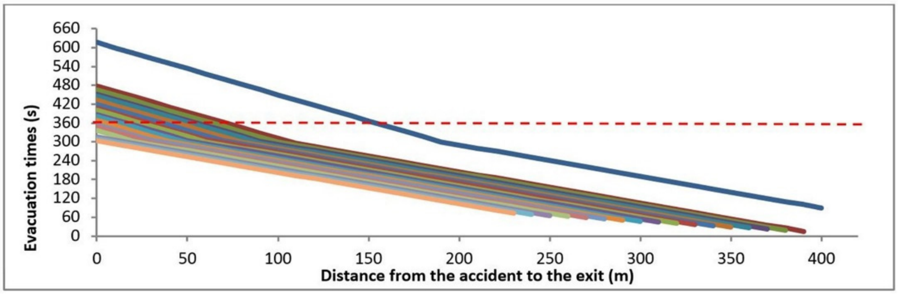

Fig. 2. Evacuation routes obtained with MRAT.

It should be noted that EvacTunnel is a stochastic model; this means that its inputs parameters are random and they are defined by a probability distribution function and its statistical parameters (mainly the mean value and the standard deviation). In order to see that the model´s results are consistent with MRAT´s results, EvacTunnel has been calibrated to simulate as a deterministic model by considering the standard deviation near zero. Some assumptions have to be made for comparing both models:

For EvacTunnel 3.0, a total of 35 cars trapped in the tunnel were considered (1 vehicles directly involved in the accident and 34 trapped in the queue). It was assumed a simultaneous alarm with a response time of 15 s. and a walking speed of 1 m/s. Table 3 shows the results from MRAT and EvacTunnel.

Table 3. Comparative analysis of MRAT and EvacTunnel for tabulated model.

	MRAT	**EvacTunnel 3.0**
Affected	36	39
Evacuation time (s)	354.98	359.40

As we can see in table 3, the results from EvacTunnel 3.0 are consistent with MRAT results. The mean values of evacuation times are close (they differ less than 5 s.). Furthermore, the number of affected people is also nearby.

The small difference between the two methods (8.3% for the number of affected people) is caused due to EvacTunnel considers the number of people trapped inside the tunnel as a random variable (it should be noted that EvacTunnel permits the model´s user to define the number of vehicles but not the number of people inside those vehicles). In general, this verification test showed that EvacTunnel works correctly and it obtains consistent results for risk analysis purpose.

4. Comparison between EvacTunnel and other evacuation models

In this section we present a comparison analysis between EvacTunnel and other current evacuation models: STEPS (Mott McDonald), Pathfinder (Thunderhead Engineering, 2009) and GridFlow (Bensilum, 2003). The evacuation consists of an accident in the center of the tube obstructing the access to the cross passage. The evacuation is modelled considering the moment in which the vehicles are stopped, queuing behind the vehicles involved in the accident. It is assumed a total of 54 vehicles trapped in the tunnel: 49 light vehicles (cars) and 5 heavy vehicles (trucks). The occupation load is assumed to be 1 person per heavy vehicle. For light vehicles a load factor of 2.32 is considered. Therefore, 119 occupants are considered for the simulations. Two tests are presented. In Test 1, no behaviour is performed in order to check that the simulation of movement is working satisfactorily. In Test 2 a behaviour comparison is performed. Table 4 displays the evacuation times obtained in Test 1. The evacuation times are very similar between the models. The Percent Error (PE) is not higher than 1% between the proposed model and the models of the comparison. The small differences are found due to the random distribution of the occupants who are further from the tunnel portal (their start position). Results from Test 1 show that basic movement components of EvacTunnel work adequately.

Table 4. Results of Test 1 (s): 1 run.

Model	Evacuation time
Pathfinder	260
STEPS	257
GridFlow	258
EvacTunnel	262

Test 2 provides an opportunity to validate the proposed model against other evacuation models. In this test the scenario has been run 100 times to capture stochastic variations in the results. The implementation of pre-evacuation times in GridFlow, STEPS and Pathfinder models has been done using the criterion of distance from the accident as it is considered by the proposed model. In this way a consecutive response of the occupants has been considered. In order to implement this, the tube was divided into 13 zones (20 m length) with different population groups and pre-movement time distributions. In GridFlow these zones were implemented by different spaces connected by links (inlet and outlet). In STEPS this was done by using locations on the plane. In Pathfinder rectangular rooms were used. The pre-movement times have been assigned using normal distribution laws. In Zone 1 it was assumed a pre-movement time distribution with a mean of 170 s and a standard deviation of 17.5s. Then, the mean value has been increased by 13 s per zone in order to reproduce the same “domino effect” applied by the proposed model. The same unimpeded walking speed distribution has been assigned for all occupants in all models. This is a normal distribution with a mean value of 1.20 m/s and a standard deviation of 0.20 m/s. Figure 3 shows the cumulative distribution functions of evacuation times and Table 5 displays a comparison of the mean, maximum, minimum and 95 th percentile of total evacuation times obtained by the models.

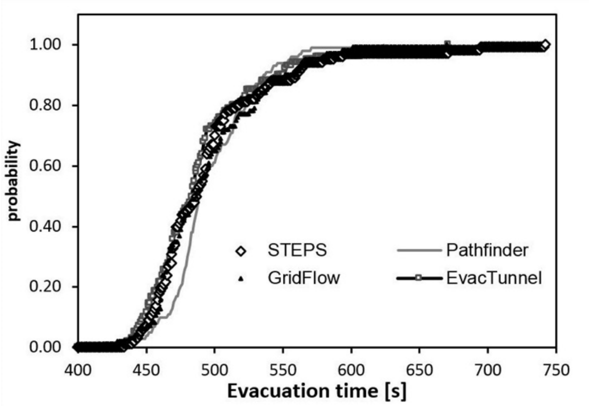

Fig. 3. Cumulative distribution functions of total evacuation times.

Table 5. Results of Test 2 (s): 100 runs.

	Pathfinder	STEPS	GridFlow	EvacTunnel
Mean	497	496	495	491
S.D.	31	50	42	44
Range	429-624	434-742	419-670	434-671
Perc. 95th	554	580	570	587

The predicted evacuation times do not vary significantly among each model and their curves are very similar. In this case the evacuation time was driven by the interactions between pre-movement time and the travel distributions.

5. Application case: Cristo Redentor Tunnel

As a real application case, the Simulation method of EvacTunnel was employed in Cristo Redentor Tunnel. The aim of this study was to analyse the impact of implementing emergency passages and other safety elements for a fire situation into the tunnel. Cristo Redentor is a bidirectional tunnel that links two countries, Chile and Argentina. The length of the tunnel is 3,080 m.

5.1. The evacuation scenarios

The application case consisted of a fire (truck) in the Chilean side. The following two scenarios were considering:

- Scenario 1 – Emergency exits are not considered and evacuation flows are against the fire for each sides of the tunnel (see figure 4).
- Scenario 2 – three emergency exits are considered (see figure 4).

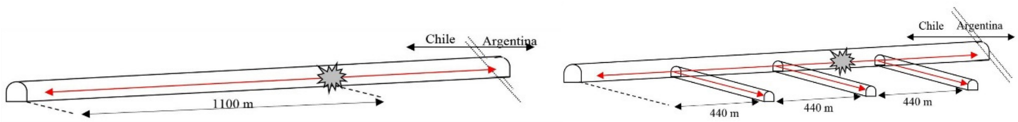

Fig.4. Layout of Scenario 1 and 2 considered for the application case.

5.2. Inputs

Based on these initial scenarios, table 6 shows the considered scenarios.

Table 6. Application scenarios considered for evacuation analysis

Scenario	Type of traffic	ADT	Type of vehicles (%)		
			LV	HV	B
1.1	High	1438	39	58	3
1.2	Extremely High	3096	73	25	2
1.3	HGV	-	0	100	0
2.1	High	1438	39	58	3
2.2	Extremely high	3096	73	25	2
2.3	HGV	-	0	100	0
LV = Light vehicles, HV = Heavy vehicles (trucks), B = Buses ; ADT – average daily traffic					

Three types of traffic were considered:

- High. This is the 95th percentile of the average daily traffic in 2009, 2010 and 2011.
- HGV (heavy good traffic). Only the heavy good traffic is considered with the maximum occupancy level.
- Extremely high. This corresponds with the maximum intensity (registered on October, 29th 2011).

Based on the average length for cars, trucks and buses, table 7 shows the number of vehicles by considering the areas located on each side of the fire.

Table 7. Number of vehicles trapped in the tunnel.

Traffic direction	Chile-Argentina				Fire	Argentina-Chile			
Type of traffic	C	T	B	Total		C	T	B	Total
High	28	41	2	71		10	15	1	26
Extremely high	71	24	2	97		26	9	1	36
HGV	-	55	-	55			20		20

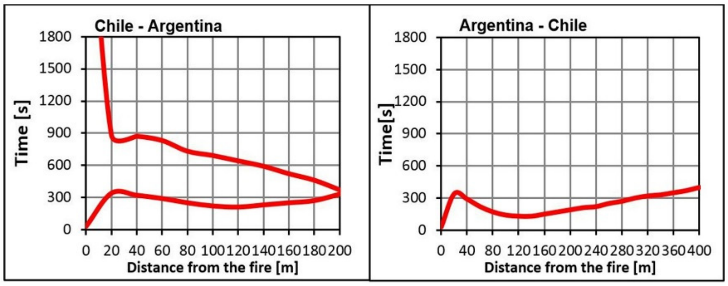

Fig. 5. Tenability curves for Cristo Redentor tunnel.

Figure 5 displays the tenability curves implemented in EvacTunnel. These curves are based on previous results from FDS model - the assumed criterion was the visibility values lower than 10 m, for 1.8 m. The following assumptions were considered:

- Occupants do not evacuate by car.
- It is assumed a self-rescue process for those users that are capable to start the evacuation by foot.
- Users with reduced mobility are not considered (disabled people, injured, etc.).
- Occupants select the closest exit.

5.3. Results

A total of 100 simulation were run for each scenario. The results shown in table 8 correspond to Chilean side. Figure 6 shows the cumulative distribution function for total evacuation time in Scenarios 1.1, 1.2 and 1.3 (without emergency passages) and Figure 7 displays the results for Scenarios 2.1, 2.2. and 2.3. It should be noted that the evacuation times corresponds to those users that were not affected by the fire.

Table 8. Statistical parameters for total evacuation times (min).

Scenario	**Mean**	**S.D.***	**Percentile 95**
1.1	31.86	7.59	45.93
1.2	35.49	8.95	52.17
1.3	28.47	8.16	45.92
2.1	2.87	0.14	3.05
2.2	2.93	0.14	3.15
2.3	2.79	0.22	3.07

*S.D.= Standard Deviation

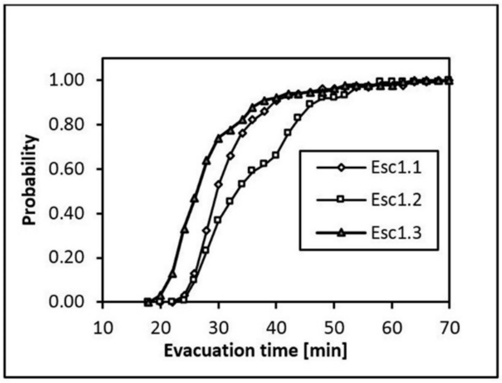

Fig. 6. Cumulative distribution function of total evacuation times for scenarios 1.1, 1.2 and 1.3.

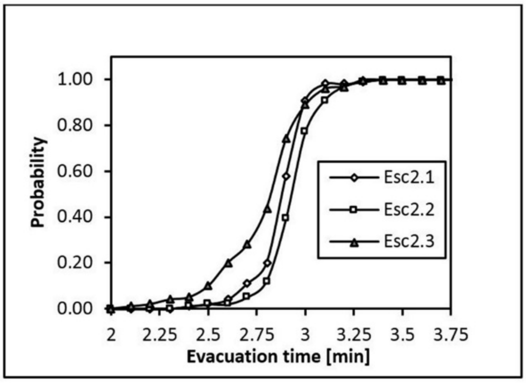

Fig. 7. Cumulative distribution function of total evacuation times for scenarios 2.1, 2.2 and 2.3.

Table 9 presents the statistical parameters of the number of affected occupants in each scenario. The results shows that for those scenarios that include emergency passages (Scenarios 2.1, 2.2 and 2.3) the number of occupants that are affected by the fire was drastically reduced. As we can see in table 8, the number of affected occupants was reduced by 66% for Scenarios 2.1 and 1.1, 57% for scenarios 2.2 and 1.2 and 33% for scenarios 2.3 and 1.3.

Table 9. Statistical parameters for the number of affected occupants inside the tunnel.

Scenario	**Type of traffic**	**Mean**	**S.D.***	**Perc.95**
1.1	High	144	15	166
2.1		50	7	64
1.2	Extremely high	196	33	249
2.2		84	18	113
1.3	HGV	43	6	53
2.3		28	4	34

*Standard Deviation

6. Conclusions

A new evacuation model that can be applied for risk analysis purpose is presented in this paper. EvacTunnel 3.0 obtains the total evacuation time and the number of people trapped inside the tunnel.

Furthermore, for fire situations the model considers the effects of smoke and the ventilation method employed and analyses the possible consequences in terms of number of affected people (dear or injured). It should be noted that the proposed model can be also used for other application such as performance base assessments and/or risk analysis. EvacTunnel 3.0 presents some advantages over traditional risk analyses and other evacuation models:

- It is a specific evacuation model for road tunnels that permits to define the tunnel characteristics from some basic inputs.
- This model has the capability to perform multiple simulations (over 1000) in a less than 5 s.
- It is easy to use and its flexibility permits the model´s user to modify the inputs at any time in a simple manner.
- The stochastic character allows to analyse different emergency scenarios and its possible consequences.
- EvacTunnel statistically treat the sample and obtains the percentile of the total evacuation time and the number of people trapped inside the tunnel for a defined confidence level.
- It simulates fire situations by considering a simple input data and obtaining the number of affected people. This model can be applied for risk analysis purpose.

Different verification and comparison stages have been presented in this paper in order to show the confidence of EvacTunnel. To verify it, a comparative analysis were made between the model and the Spanish MRAT for the *Tabulated method.* The results for evacuation time and number of affected people showed that this new approach can be applied for risk analysis purpose. The next step compared the results of EvacTunnel with other current evacuation models (Without smoke). Two tests were performed and the comparison showed that results from EvacTunnel are consistent with current evacuation models (STEPS, PathFinder and Gridflow) and the model works correctly. Finally as a real application case, EvacTunnel was used in Cristo Redentor Tunnel. Considering a fire situation based on FDS results (using *Simulation method*), EvacTunnel has been used for analyzing the impact of employing emergency exits inside the tunnel. It showed the advantages of using emergency exits by obtaining that the evacuation times and the number of people affected can be drastically reduced – up to 66 % -.

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