OPTIMIZATION OF EMERGENCY EGRESS DOORS IN ROAD TUNNELS

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ABSTRACT

As a general approach, the required maximum spacing between the emergency exits in road tunnels is provided not to exceed 300 m, as stated in NFPA 502. It is also stated that there is not considered to be any minimum exit separation, while most typical exit separations are between 30 m – 200 m and appropriate exit separation distances can only be determined by engineering analysis of emergency egress requirements.
This study focuses on the incident tunnel and aims to analyze the effects of spacing and clear widths of egress doors on evacuation time. To accomplish this, generic tunnel geometries with various length and varying number of lanes are modeled to accommodate different number of vehicles to be present along the tunnel. Egress pathways leading directly to an exit are also modeled for the tunnels with various clear widths exceeding 1.12 m as per NFPA 502. Four types of vehicles are modeled with varying numbers in the tunnels and their initial locations are provided to demonstrate a highly congested (almost stopped) condition with different spacings between each other. The number of motorists is calculated based on the total number of vehicles and additionally increased to provide varying numbers for each scenario. Hence, four variables, *i.e.,* exit door spacing, exit door clear width, egress pathway clear width, total number of motorists are considered to be varying for each scenario. Emergency evacuation simulations are then performed using Pathfinder, to obtain the total evacuation time, *i.e.* RSET (Required Safe Egress Time), for the incident tunnel. Finally, a supervised machine learning algorithm is developed to evaluate the effects of each variable on evacuation time, and the possibility of optimizing the egress doors.

BACKGROUND STUDY AND MOTIVATION

In our previous study, we analyzed to evaluate whether it is possible to extend the distances between cross-passages along metro tunnels [1]. NFPA 130 states the maximum distance between the cross-passages, when they are used in lieu of exits along metro tunnels, to not exceed 244 m. In 2020 Edition, it is also stated that the distance between exits can be increased where supported by engineering analysis [2].

Based on this statement, we performed more than 1000 emergency egress analyses with varying parameters, which are the distance between cross-passages, walkway width, door widths of the rolling stocks, and number of passengers. Our aim was first to analyze the effect of each variable on the total evacuation time, as shown in Figure 1.

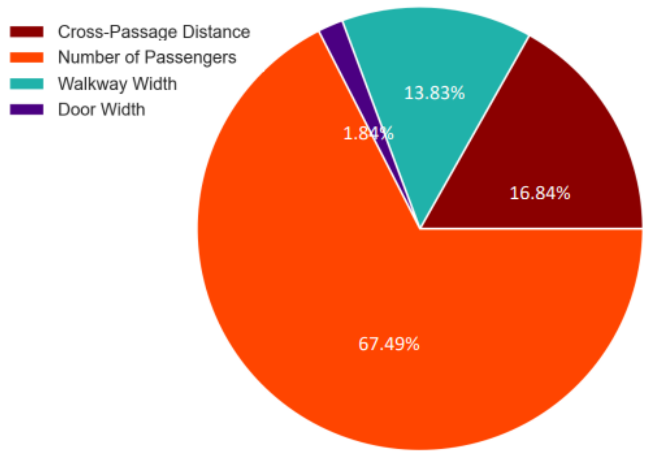

Figure 1: Importance Analysis of Variables on Evacuation Time Along Metro Tunnels.

The results yield that the effect of the number of passengers on evacuation time is 67.49%, while the effect of the distance between cross-passages is 16.84%. If we compare these two variables, it can be stated that the number of passengers has 4 times more effect on the evacuation time than the distance between cross-passages.

Assuming all the other variables are constant, increasing the distance between cross-passages will increase the evacuation time. However, as per the results obtained, the walkway width has 9.25% effect on the evacuation time, which can possibly reduce the evacuation time if increased. Therefore, we focused on increasing the walkway width to increase the flow of the passengers along the walkway, which would eventually reduce the total evacuation time.

The results of this previous study showed that considering the total evacuation time, the distances between cross-passages can be optimized by adjusting the walkway widths which makes it possible to increase the distances between the cross-passages along the metro tunnels, while ensuring that the evacuation time is not exceeded. The conclusion of previous study forms the basis motivation for this study.

INTRODUCTION

NFPA 502 is one of the most used standards worldwide in road tunnels. Regarding means of egress, briefly the following requirements are stated [3]:

- the distance between the exit spacings, which is subject to emergency egress analysis, is stated not to exceed 300 m.
- the egress pathway leading to an emergency exit is stated to have a minimum clear width of 1.12 m.
- the doors in the path of egress are to comply with NFPA 101.

This study aims to understand the effects of each variable on the evacuation time along a road tunnel, where cross-passages are used as emergency exits. Walkways, leading to cross-passages are provided with varying widths, and the cross-passage doors are also modeled with varying clear widths. To accommodate various number of motorists in the tunnel, generic road tunnel models having 2-lanes, 3-lanes and 4-lanes are used in the analysis. Finally, the portals at both ends of the road tunnel are also modeled to be used as an emergency exit depending on the traffic condition.

Two different traffic conditions are studied. The first scenario is the emergency condition outside the portal exit of the tunnel. The tunnels are modeled to be occupied by vehicles to reflect an almost stopped (highly congested) condition, and motorists are allowed to use all the emergency exits, *i.e.,* the cross-passages and both portals regardless of the direction of traffic. The second scenario is the emergency condition at the exit portal of the tunnels. The tunnels are modeled to have as many vehicles as possible, as in the first scenario, but the exit portal of the tunnel is assumed to be blocked, hence is not usable as an exit. This scenario is provided to reflect a flowing traffic condition to analyze the case when one of the emergency exits is not usable.

A total of 1080 simulations are performed with varying values of four variables, *i.e.,* the distance between cross-passages, walkway widths, door clear-width, and the number of motorists, using Pathfinder. The evacuation times obtained for each scenario and variable are then used in machine-learning model to analyze the effects of these variables on total evacuation time. Finally, regression analysis is provided using Excel Data Analysis and supervised machine-learning model.

ASSUMPTIONS AND MODEL SETUP

The length of the tunnels is assumed to be 1200 m, from portal to portal and the width of the lanes is assumed to be 3.7 m. The simulations are performed to obtain the total evacuation time, which are gathered to be analyzed with these variables.

Variables

Different generic 2-lane, 3-lane, and 4-lane road tunnels are modeled using Pathfinder, to simulate varying number of vehicles, hence various number of motorists. The number of lanes are not considered as a variable affecting the evacuation time, but rather is modeled to ensure that motorists have enough space to be initialized in the models.

Cross-passages are modeled separately for each model such that:

- For the first set of scenarios, tunnels are modeled with 3 cross-passages, separated by 300 m distance.
- For the second set of scenarios, tunnels are modeled with 4 cross-passages, separated by 240 m distance.
- For the third set of scenarios, tunnels are modeled with 5 cross-passages, separated by 200 m distance.
- For the fourth set of scenarios, tunnels are modeled with 7 cross-passages, separated by 150 m distance.
- For the fifth, and final set of scenarios, tunnels are modeled with 9 cross-passages, separated by 120 m distance.

Therefore, to account for various cross-passage distances, five different variables are modeled and analyzed.

The width of the walkway is modeled to be varying as 1.2 m, 1.4 m, and 1.6 m. These three variables are analyzed in the studies. Moreover, the width of the tunnels and consequently the width of the portals vary with walkway widths, as follows:

- The width of the 2-lane road tunnel, hence the width of the entrance and exit portals, are modeled to be 8.6 m, 8.8 m, and 9 m.
- The width of the 3-lane tunnel, hence the width of the entrance and exit portals, are modeled to be 12.3 m, 12.5 m, and 12.7 m.

- The width of the 4-lane tunnel, hence the width of the entrance and exit portals, are modeled to be 16 m, 16.2 m, and 16.4 m.

The width of the emergency exit doors, leading to the cross-passage is modeled to be 1 m, 1.1 m, and 1.2 m. Hence these three variables are used to analyze the effect of exit door width on total evacuation time. Finally, the width of the cross-passage is modeled to be 2.2 m.

Total Number of Motorists

Four different vehicles are modeled throughout the tunnel:

- Passenger vehicles with 4.5 m in length, 1.8 m in width.
- SUVs with 5.5 m in length, 2 m in width.
- HGVs with 15.5 m in length, 2.4 m in width.
- Busses with 13 m in length, 2.6 m in width.

The rightmost side lane is modeled to be occupied mainly by heavy vehicles and busses and their number is intentionally kept the same for each tunnel. Passenger vehicles and SUVs are also distributed on this lane to make it fully occupied and are distributed along the other lanes. The stopping distance between the vehicles longitudinally is modeled to be between 0.5 – 1 m to provide as many vehicles as possible, and to be considered as possible egress route between the lanes. Motorists are then initialized in the model to be placed at either side of the vehicles, either between the lanes, or towards the tunnel wall. For this, occupant sources are used in the models.

The total number of motorists is directly proportional with the total number of vehicles. As this value is considered one of the variables in the analysis an approximate minimum and maximum values are determined such that, each passenger car and SUV are assumed to have 1.4 person, each HGV to have 1 person, and each bus to have 40 persons [4]. The total number of each vehicle that is modeled along the tunnels is shown in Table 1.

Table 1: Total number of motorists

2-LANE ROAD TUNNEL			
	Total number	Motorists per vehicle	Total number of motorists
Passenger vehicle	238	1,4	334
SUV	136	1,4	191
HGV	34	1	34
Bus	34	40	1360
TOTAL			1919

3-LANE ROAD TUNNEL			
	Total number	Motorists per vehicle	Total number of motorists
Passenger vehicle	476	1,4	667
SUV	272	1,4	381
HGV	34	1	34
Bus	34	40	1360
TOTAL			2442

4-LANE ROAD TUNNEL			
	Total number	Motorists per vehicle	Total number of motorists
Passenger vehicle	714	1,4	1000
SUV	408	1,4	572
HGV	34	1	34
Bus	34	40	1360
TOTAL			2966

By applying approximately 10% margin to the calculated minimum and maximum numbers, total number of motorists is assumed to vary between 1750 – 3250, hence numbers within this range are used to populate motorists for each scenario. Travel speed of motorists is assumed to not exceed 0.62 m/s (37.7 m/s).

Scenarios and Data Collection

As explained in the previous sections, simulations are performed with varying distances between cross-passages, walkway widths, exit door widths, and number of motorists; hence in total four different variables are considered. **Error! Reference source not found.** summarizes the number of variables considered in the simulations, for one set of simulations a total of 135 scenarios are performed. In total, eight sets of simulations, *i.e.,* 1080 number of simulations are studied, four for highly congested traffic, and four for flowing traffic conditions.

Table 2: Total Number of Variables

	Number of lanes	Distance between cross-passages	walkway width	exit door width
	2 3 4	300 240 200 150 120	1,2 1,4 1,6	1 1,1 1,2
Number of variables	3	5	3	3

Total number of motorists is randomized for each scenario to vary within the range as explained previously. Therefore, prior to the regression analysis, four independent variables are the distance between the cross-passages, walkway width, exit door width, and the number of motorists.

Generated Models

Sample generic 2-lane and 4-lane tunnels, for both traffic conditions modeled in Pathfinder, are shown in Figure 2. The occupant sources are modeled along the tunnel to be at either side of the vehicles, and the whole tunnel roadway surface is considered as part of the egress route. In the simulations, to obtain consistent results, no pre-movement time is considered.

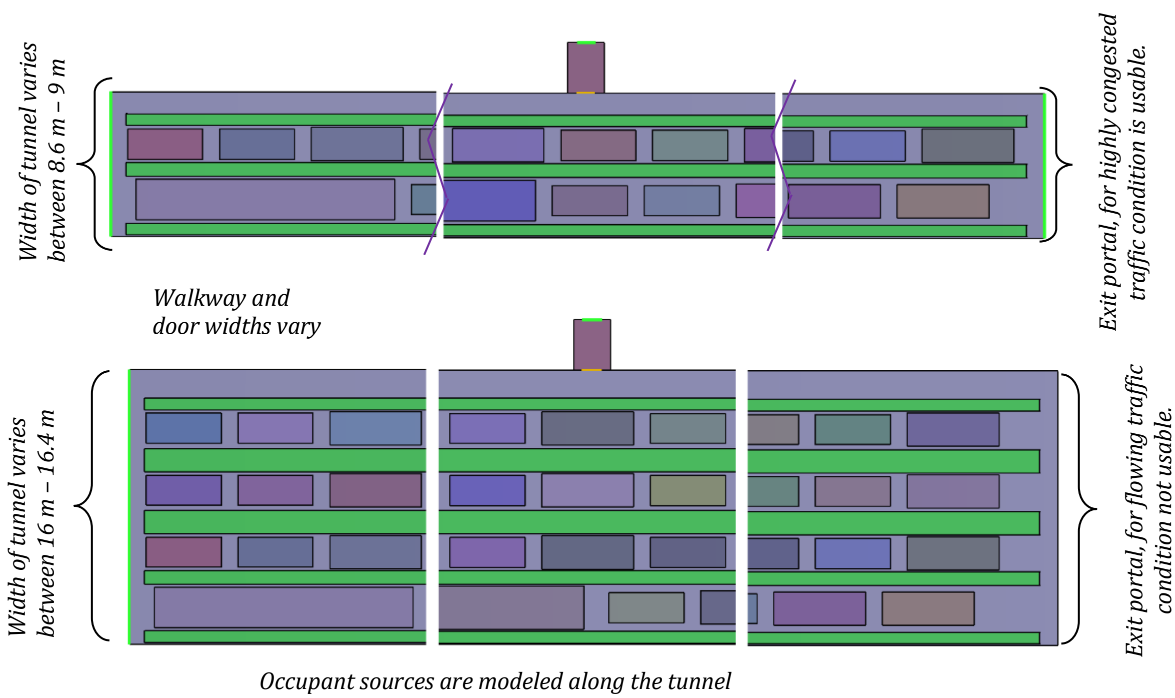

Figure 2: Sample Generic 2-Lane and 4-Lane Models

RESULTS AND DISCUSSION

Simulations are performed with four different variables and total evacuation times for each scenario are obtained and tabulated, as shown in Table 3. The results for each traffic condition are split into train and test dataset for machine learning algorithm to analyze the effect of each variable on the evacuation time. Finally, to estimate the relationship between the variables and the evacuation time, regression analysis is applied using Excel Data Analysis, and supervised machine learning algorithms for each traffic condition, separately.

Table 3: Results of the Simulations

Data Analysis	SIMULATION DATA for stopped traffic						Machine Learning Model
	sim_run	**dist_CP**	**width_ww**	**width_ED**	**no_ppl**	**evac_time**	
100% Values for Data Analysis	1	300	1.2	1	1962	834.7	67% / 70% / 80% Values for Train Dataset
	2	300	1.2	1.1	1817	676.5	
	3	300	1.2	1.2	2123	695.1	
	4	300	1.4	1	1949	887	
	5	300	1.4	1.1	2002	763.9	
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	.	.	.	.	.	.	
	376	240	1.6	1	2274	784.7	
	377	240	1.6	1.1	2387	735.9	
	378	240	1.6	1.2	2469	690.2	
	379	200	1.2	1	2433	740.9	33% / 30% / 20% Values for Test Dataset
	380	200	1.2	1.1	2637	655.6	
	381	200	1.2	1.2	2559	628.9	
	.	.	.	.	.	.	
	.	.	.	.	.	.	
	.	.	.	.	.	.	
	536	120	1.4	1.1	2965	492.3	
	537	120	1.4	1.2	3052	446.3	
	538	120	1.6	1	2779	518.8	
	539	120	1.6	1.1	2907	476.4	
	540	120	1.6	1.2	2999	427.2	

Data Analysis	SIMULATION DATA for flowing traffic						Machine Learning Model
	sim_run	**dist_CP**	**width_ww**	**width_ED**	**no_ppl**	**evac_time**	
100% Values for Data Analysis	*541*	300	1.2	1	1961	1283.8	67% / 70% / 80% Values for Train Dataset
	542	300	1.2	1.1	1817	991.8	
	543	300	1.2	1.2	2123	1034.3	
	544	300	1.4	1	1949	1224.6	
	545	300	1.4	1.1	2001	1119.1	
	.	.	.	.	.	.	
	.	.	.	.	.	.	
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	916	240	1.6	1	2423	1224.4	
	917	240	1.6	1.1	2418	1056.4	
	918	240	1.6	1.2	2458	938.6	
	919	200	1.2	1	2509	1090.5	33% / 30% / 20% Values for Test Dataset
	920	200	1.2	1.1	2596	994.6	
	921	200	1.2	1.2	2642	901.1	
	.	.	.	.	.	.	
	.	.	.	.	.	.	
	.	.	.	.	.	.	
	1076	120	1.4	1.1	2975	668.6	
	1077	120	1.4	1.2	3022	607.3	
	1078	120	1.6	1	3106	786.9	
	1079	120	1.6	1.1	3189	712.4	
	1080	120	1.6	1.2	3237	649.2	

Highly Congested (Almost Stopped) Traffic Model

The tabulated results are introduced to a Machine Learning algorithm to analyze the effect of the independent variables on the evacuation time using gradient tree boosting model. The importance percentages of the variables are shown in Figure 3.

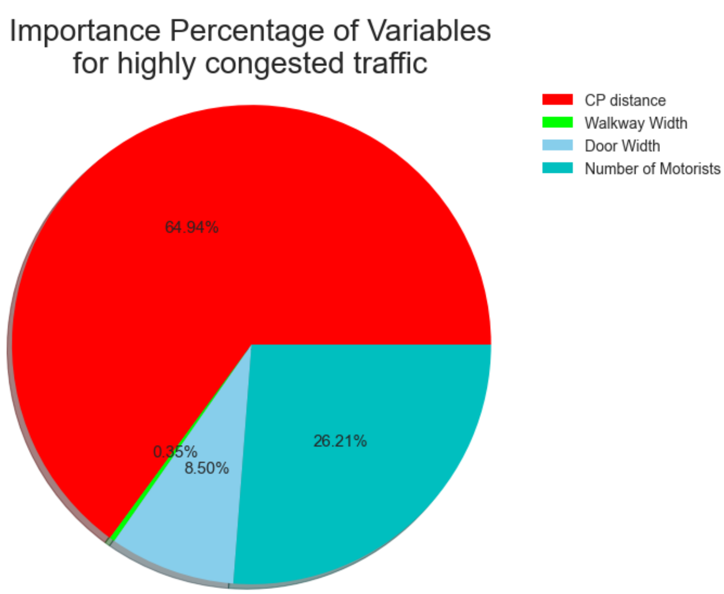

Figure 3: Importance Percentage of Variables for Stopped Traffic Condition

Based on the results obtained for highly congested traffic condition, the most effective variable is observed to be the distance between cross-passages, which has approximately 64.9 % effect on total evacuation time. The effect of the number of motorists on total evacuation time is observed to be approximately 26.2 %. Therefore, it can be stated based on the analyses that, the distance between cross-passages has 2.48 times more effect on the evacuation time than the number of motorists.

The effect of door width is observed to be 8.5 % and is about 13% of the effect of the distance between cross-passages when compared. Finally, the effect of walkway widths is observed to be approximately 0.3%, which can be considered as negligible.

Tabulated data is then studied in linear regression data analysis, using ordinary least squares. The results of the analyses are shown in Table 4 and the equation generated using the intercept and coefficients is also shown as follows:

Table 4: Summary of Linear Regression Analysis for Highly Congested Traffic Condition

	coef	std err		
Intercept	364.3563	32.585	R-squared:	0.965
dist_cp	2.9379	0.030	Adj. R-squared:	0.965
width_ww	14.1543	11.673	F-statistic:	3680.
width_door	-860.1854	23.349	Prob (F-statistic):	0.00
no_ppl	0.2505	0.004	Log-Likelihood:	-2810.8
			AIC:	5632.
			BIC:	5653.

$$ET_{hct} = 365.36 + (2.94 \cdot dist\_CP) + (14.15 \cdot ww) + (-860.19 \cdot dw) + (0.25 \cdot no\_ppl) \qquad (1)$$

<u>Flowing Traffic Model</u>

The effect of the variables on the evacuation time is shown in the figure.

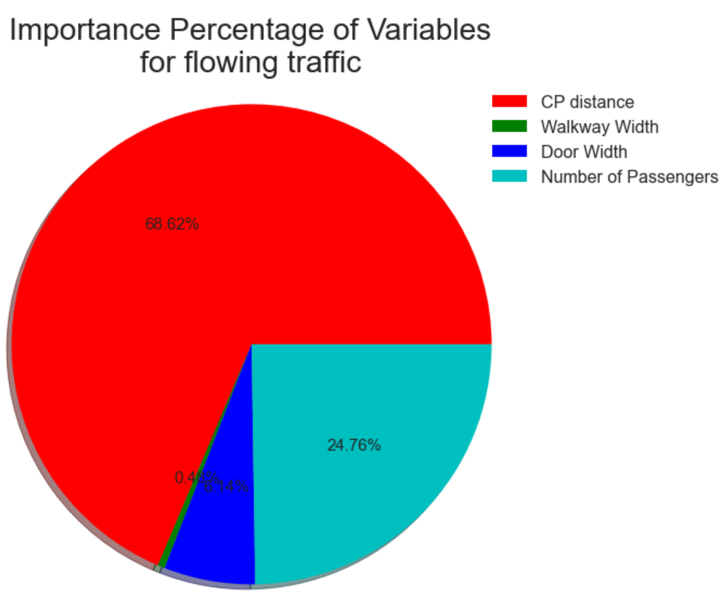

Figure 4: Importance Percentage of Variables for Flowing Traffic Condition

Based on the results obtained for flowing traffic condition, the most effective variable is observed to be the distance between cross-passages, which has approximately 68.6 % effect on total evacuation time. The effect of the number of motorists on total evacuation time is observed to be approximately 24.8 %. Therefore, it can be stated based on the analyses that, the distance between cross-passages has 2.77 times more effect on the evacuation time than the number of motorists.

The effect of door width is observed to be 6.1 % and is about 9% of the effect of the distance between cross-passages when compared. Finally, the effect of walkway widths is observed to be approximately 0.5%, which can be considered as negligible.

Tabulated data is then studied in linear regression data analysis, using ordinary least squares. The results of the analyses are shown in Table 5 and the equation generated using the intercept and coefficients is also shown as follows:

Table 5: Summary of Linear Regression Analysis for Flowing Traffic Condition

	coef	std err		
			R-squared:	0.965
Intercept	386.2012	49.606	Adj. R-squared:	0.965
no_CP	4.7489	0.046	F-statistic:	3683.
width_ww	37.0773	18.068	Prob (F-statistic):	0.00
door_width	-1266.0099	36.292	Log-Likelihood:	-3046.6
no_ppl	0.3778	0.007	AIC:	6103.
			BIC:	6125.

$$ET_{ft} = 386.2 + (4.75 \cdot dist\_CP) + (37.08 \cdot ww) + (-1266.01 \cdot dw) + (0.38 \cdot no\_ppl) \qquad (2)$$

Discussion

The results show that for road tunnels, the most effective variable on evacuation time is, by far the distance provided between the exits and the least effective variable is the walkway width, which can be considered almost negligible. Comparison of the results yield that the distance between cross-passages affects the evacuation time, 2.48 and 2.77 times more than that of the number of motorists for highly congested and flowing traffic conditions, respectively. Although the number of motorists modeled in the simulations can be assumed to be within a considerable range, this result shows exactly the opposite of what we found in our previous study. However, using the Equations 1 and 2, and keeping the walkway width and the number of motorists constant, it is possible to obtain the same evacuation time by increasing the door width for extended exit distances.

REFERENCES

When references are used in the text, tie them to an alphabetical (by principal author) list of references to be included as the last item of your paper. The format commonly used in scientific literature follows:

[1] Bulut, B., Hansen, M.Y.B.L., (2023), "Extending Cross-Passage Distances", 10th International Symposium on Tunnel Safety and Security.

[2] NFPA 502 (2020), "Standard for Road Tunnels, Bridges, and Other Limited Access Highways"

[3] NFPA 130 (2020), "Standard for Fixed Guideway Transit and Passenger Rail Systems"

[4] RVS 09.03.11 (2015), "Tunnel Risk Analysis Model"