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A methodology for the sizing and positioning of emergency exits in tunnels

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Abstract

The reference law for the construction of new tunnels belonging to the Trans-European Road Network currently calls for the implementation of emergency exits when the expected traffic in the tunnel is larger than 2000 vehicles/hour per lane and the length of the tunnel is more than 1000 m. Emergency exits must allow the road users to abandon the tunnel afoot and in safety and to reach a safe place in case of accident or fire. Apart from allowing pedestrian flow outside the tunnel, such exits also have to provide a pedestrian route for access to the tunnel by first aid services. Emergency exits can provide a path toward an emergency tunnel which leads pedestrians to the outside or to shelters with escape routes separated by the tube of the tunnel. The Italian legislative decree n. 264, published on October 5th, 2006, imposes that the distance between emergency exits must not exceed 500 m. Sizing emergency exits can be submitted to the application of the technical norms of prevention and protection by fires. The legislation related to the minimum safety requirements for tunnels of the Trans-European Road Network does not clearly state anything concerning this aspect. This paper proposes a methodology for the verification of correct spatial positioning and sizing of the width of emergency exits of road tunnels, considering such width as a function of the expected vehicular flow for the tunnel, the distance between two emergency exits, the number of lanes in the tunnel and the average coefficient of occupation of the transiting vehicles.

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Keywords: emergency exit; tunnel; prevention and protection by fires; pedestrian flow; vehicular flow

1. State of the art

In the field of road safety and specifically with regards to safety inside road tunnels, the Italian normative datum is represented by the legislative decree n. 264 published on October 5th, 2006, carrying out the Directive 2004/54/EC of the European Parliament and of the Council of April 29th on minimum safety requirements for tunnels in the Trans-European Road Network. The decree dictates the principal norms concerning design, construction, maintenance and exercise to guarantee a minimum safety level to the road users. To realize the safety measures in a tunnel, the Normative systematically considers the aspects of the system related to infrastructure, exercise, users and vehicles considering the following parameters:

- tunnel length;

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- number of tubes;
- number of lanes;
- cross-sectional geometry;
- vertical and horizontal alignment;
- type of construction;
- uni-directional or bi-directional traffic;
- traffic volume per tube (including its time distribution);
- risk of congestion (daily or seasonal);
- access time for the emergency services;
- presence and percentage of heavy goods vehicles;
- presence, percentage and type of dangerous goods traffic;
- characteristics of the access roads;
- lane width;
- speed considerations;
- geographical and meteorological environment.

Besides the limitation of the consequences of accidents, design choices aim to facilitate first aid and the evacuation of users. Specifically, concerning emergency exits, they must allow the users to abandon the gallery afoot and to reach a safe place in case of accident or fire. These exits must also ensure a route of access to the tunnel, afoot, for first aid services. Such exits can consist in:

- direct exits from the tunnel to the outside;
- cross-connections between tunnel tubes;
- exits to an emergency gallery;
- shelters with an escape route separate from the tunnel tube.

Shelters without an exit leading to escape routes to the open air shall not be built.

In any case, in new tunnels, emergency exits shall be provided where the traffic volume is higher than 2000 vehicles per lane per hour. Nevertheless, the legislative decree n. 264 does not point out what the criteria for sizing safety exits must be, confining itself to advising a distance of 500 m as a maximum distance between two emergency exits. Therefore, following a check related to the maximum distance between two emergency exits pointed out by the in force legislation, it is appropriate to propose a methodology for sizing the width of such emergency exits in order to allow pedestrian outflow for the totality of users that could be jammed in a tunnel after an accident or an incident, within a prearranged time. Such verifications are achieved analyzing the behaviour of pedestrians in emergency conditions.

In literature the behaviour of pedestrians is generally described at three levels: strategic, tactical and operational, as found in Hoogendoorn et al. (2001) and CROW (1998). At the strategic level, pedestrian decides what emergency choices he wants to take and in which order. The strategic level holds limited interest for the present paper since the emergency choices that pedestrian takes are obviously forced: to get to the nearest available emergency exit as quick as possible, having a preference for the emergency exits in the opposite direction of that in which the accident has occurred.

The tactical level pertains to the short term decisions given the emergency situation at the strategic level. Planning the pedestrian route belongs to the tactical level (known the origin of the pedestrian, he chooses his own final destination). The same considerations for the strategic level are valid. At the operational level, a pedestrian takes instantaneous decisions for the period immediately following, in line with the decisions he took at the tactical level. A great part of the decisions established at the operational level concern pedestrian's behaviour, that has been widely described in scientific literature. In fact, in literature it is possible to find numerous empirical data taken from all over the world. Pedestrian behaviour is largely described as dependent on the motive of the move and on the type of infrastructure. Pedestrian speeds vary because of the external conditions, with an average speed close to 1.34 m/s. Pedestrian movement has been described at the submicroscopical level as "movement of the leg" (Weidmann, 1993). The movement is characterized by an oscillatory motion in which the speed of movement depends on the frequency of the leg, approximately 2 Hz. However, pedestrian outflow is usually described from microscopic and macroscopic variables, in reference to variables such as trajectories and spacing (microscopic) as well as flow, speed and density (macroscopic).

Considering a pedestrian flow in static and homogeneous conditions, the following relationship is valid for every type of flow and equally to the fundamental relationship of vehicular outflow:

$$q = k \cdot v \tag{1}$$

where:
q [*people/s*] is the flow;
k [*people/m²*] the density and v [m/s] the average speed of the outflow.

The speed of pedestrian flow seems to follow a normal distribution with an average of 1,34 m/s and standard deviation of 0,37 m/s. In Weidmann (1993), speed is on average 1,34 m/s, with varying speeds between 0,97 m/s and 1,65 m/s. As density increases, the various factors that influence the free outflow speed have a smaller effect in the walking speed of pedestrians (Mitchell and Smith, 2001).

Table 1 Characteristics of unimpeded, capacity and jammed pedestrian flows derived for level walkways (Daamen, 2004).

Source	Unimpeded	Capacity	Jammed
AlGadhi et al. (2001)			k_j>7,0
Fruin (1971)	k<0,5		k_j>5,0
O'Flaherty & Parkinson (1972)	k<0,6	q_c=1,29 u_c=0,68 k_c=1,89	
Pauls (1997)	k<0,5		k_j=4,0 - 5,0
Pushkarev & Zupan (1975)		q_c=1,67 u_c=1,11 k_c=1,5	k_j=2,5 - 5,0
Sarkar & Janardhan (1994)		q_c=1,53 u_c=0,74 k_c=2,1	k_j>4,2
Virkler & Elayadath (1994)		q_c=1,03 - 1,2 u_c=0,75 - 0,82 k_c=1,3 - 1,8	
Weidmann (1993)	k<0,5	q_c=1,23 u_c=0,7 k_c=1,75	k_j>5,4

The speed of pedestrian flow also depends on the travel purpose. The highest speed is for job movements (1,45 - 1,61 m/s), followed by commuters (1,34 - 1,49 m/s), shoppers (1,04 - 1,16 m/s) and pedestrians walking for leisure (0,99 - 1,10 m/s). In Roddin (1981) a free walking speed is considered 1,5 m/s for commuters and 1,75 m/s for students. In pedestrian flows with different travel purposes, the speed variation grows to more than 0,5 - 1,0 m/s (O'Flaherty and Parkinson, 1972).

The speed of pedestrian flow is also strongly dependent on the age of pedestrian. If 0 to 20% of pedestrians are elderly (65 years or more) the average speed is 1,2 m/s. If the percentage of elderly pedestrians is greater than 20%, the average speed of the flow decreases to 1,0 m/s. Conditions of free outflow on sidewalk are generally considered to be at a speed of 1,5 m/s (HCM, 2000).

Table 2 Observed walking speeds in uncongested corridors (source: Daamen, 2004).

Source	Mean speed [m/s]	Standard deviation [m/s]	Location
CROW (1998)	1,40		Netherlands
Daly et al. (1991)	1,47		United Kingdom
FHWA (1988)	1,2		United States
Fruin (1971)	1,4	0,15	United States
Hankin & Wright (1958)	1,6		United Kingdom
Henderson (1971)	1,44	0,23	Australia
Hoel (1968)	1,50	0,20	United States
Institute of Transportation Engineers (1969)	1,2		United States
Knoflacher (1995)	1,45		Austria
Koushki (1988)	1,08		Saudi Arabia

Source	Mean speed [m/s]	Standard deviation [m/s]	Location
Lam et al. (1995)	1,19	0,26	Hong Kong
	1,25		Sri Lanka
Morral et al. (1991)	1,4		Canada
Navin & Wheeler (1969)	1,32		United States
O'Flaherty & Parkinson (1972)	1,32	1,0	United Kingdom
Older (1968)	1,30	0,3	United Kingdom
Pauls (1987)	1,25		United States
Roddin (1981)	1,6		United States
Sarkar & Janardhan (1994)	1,46	0,63	India
Sleight (1972)	1,37		United States
Tanariboon et al. (1986)	1,23		Singapore
Tanariboon Guyano (1991)	1,22		Thailand
Tregenza (1976)	1,31	0,30	United Kingdom
Virkler & Elayadath (1994)	1,22		United States
Yong (1999)	1,38	0,27	United States
Estimated overall average	1,34	0,37	

2. Methodology for the analysis of pedestrian outflow in emergency

Considering a uniform vehicular flow in a road tunnel, in an emergency the flow stops and the vehicles form a queue. The car occupants can in some cases decide, after a while, to abandon the vehicle becoming consequently pedestrians fleeing the tunnel. Therefore, sizing and localizing pedestrian emergency exits must necessarily start from an analysis of the distinctive parameters of pedestrian outflow in emergency conditions. For instance, it is necessary to examine the existing link between speed and density, flow and density as well as flow and speed of the outflow. As flow and density of pedestrian tide increase, speed and movement easiness decrease. Overcoming a critical value of density, flow and speed quickly decrease.

Pedestrian outflow model must allow the determination of the outflow speed, depending on density and having a fixed outflow direction. It is possible to use the Greenshields theory to model pedestrian flow, establish the free outflow speed and hypothesize a linear link between speed and density:

$$v = v_0\left(1 - \frac{k}{k_L}\right) \quad (2)$$

where:
v_0 [m/s]is the free outflow speed;
k [people/m^2] is the flow density and k_L [people/m^2] is the limit density.

In such a hypothesis, considering the case of an isolated pedestrian, speed is that of free outflow under emergency conditions. The free outflow speed has been determined through simulations of outflow under emergency conditions for isolated pedestrians, on a plain and a straightaway. The achieved values come to an average of 3,2 m/s with a standard deviation of 0,6 m/s, considering that the isolated pedestrian, in emergency conditions, continues at a brisk pace.

Another indispensable parameter for determining the outflow speed is pedestrian density. Considering as a limit value 4 people/m^2 (HCM, 2000), density is defined beginning from the suitable space among the queued cars. Although, for the analysis of pedestrian outflow, the concept of lane is not perfectly usable since it has been shown that pedestrians don't walk following preset lanes. In emergency conditions the behaviour of pedestrians is comparable to that of the vehicular outflow. In fact, it is necessary to define a free section of outflow considering the road section and the presence of vehicles in queue. However, the section that will be counted must be clear of the shy away distance. The following table displays some of the shy away distances in literature.

Table 3 Shy away distances of pedestrians (Daamen, 2004)

Criterion	Distance [cm]	Source
Concrete walls	35-45	CROW (1998)
	45	De Neufville & Grillot (1982)
	15	Pauls (1987)
	40	Van Soeren (1996)
	25	Weidmann (1993)
Metal walls	20	Weidmann (1993)
Obstacles	40	Van Soeren (1996)
	10	Weidmann (1993)
Opposite flows	60	De Neufville & Grillot (1982)
Pedestrian	27,5	Knoflacher (1987)
Platform edges	80	Van Soeren (1996)

In fact, pedestrians maintain a minimum distance from the side obstacles, depending on typology and conditions of the side obstacles and on the easiness of movement for pedestrians themselves. In literature such a distance generally varies from 10 to 80 cm. For the considered outflow conditions it is possible to consider a shy away distance of 40 cm which is the value typically used by many authors to consider the free space between pedestrians and side obstacles. In other cases such distances are measured as adjacent to side walls.

The analysis of pedestrian flow is generally based on the study of speed, density and average flow of groups of people. If pedestrian density increases in space and time, it can reach the value of limit density for which the outflow stops. The phenomenon that defines the achievement of the limit density can occur when fleeing pedestrians move toward the emergency exit, increasing the density along the route up to the limit value as a result of the pedestrians that get out from vehicles and start moving, as a large platoon, toward the exits. Therefore, emergency exits must be placed at such a distance so as to avoid the aforementioned condition.

3. An application for unidirectional tunnels with two lanes

The calculation of the maximum distance between consecutive emergency exits is based on the following affirmations:

- the speed of free flow v0, determined through simulations, is 3,2 m/s;
- the limit density kL is 4,0 people/m2;
- the entering vehicular flow is considered constant and equal to 2000 vehicles/h per lane;
- the free section for pedestrian outflow, for highways with two lanes per direction (Italian legislation type A), net of the encumbrance of the stopped vehicles and the shy away distance of 40 cm among pedestrians and obstacles, is about 4 m;
- the occupation coefficient of the car is assumed to be equal to 5 people/vehicle.

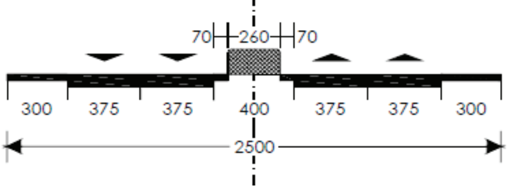

Figure 1 Typical section for highways type A suburban (Ministerial decree 5/11/2001)

Table 4 Outflow parameters in the calculation sections

Section	Progressive [m]	People in section	k [p/m^2]	v [m/s]	Walk time [s]	Q [p/s]
1	50	100	0,5	2,8	17,9	5,6
2	100	200	1,0	2,4	20,8	9,6
3	150	300	1,5	2,0	25,0	12,0
4	200	400	2,0	1,6	31,3	12,8
5	250	500	2,5	1,2	41,7	12,0
6	300	600	3,0	0,8	62,5	9,6
7	350	700	3,5	0,4	125,0	5,6
8	400	800	4,0	0,0	-	-

Knowing the speed of pedestrian flow, it is possible to calculate the walk time for every section 50 m long. The maximum distance between emergency exits must be set in correspondence with the value of density that involves the achievement of the critical density. In fact, in correspondence with such a value, the maximum flow is obtained and a further increase in density involves a reduction of the flow, that tends to-wards the unstable branch of the outflow curves. Figures 2 and 3 show the maximum flow in correspondence to the density value of 2 people/m^2, which is equal to 12,8 people/s at a speed of 1,6 m/s. Such a value is obtained at a distance of 200 m from the place of danger.

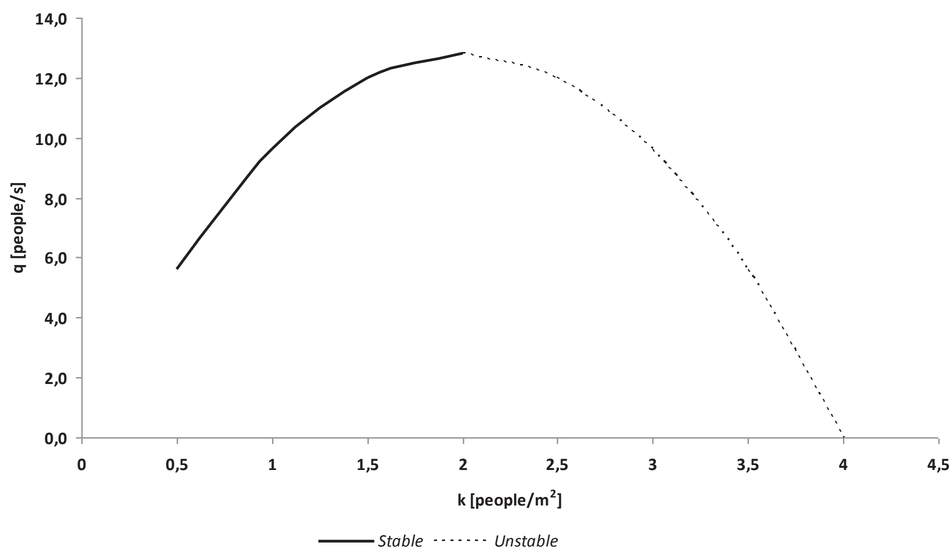

Figure 2 Link between density and pedestrian flow.

It is at such a distance that the position of the emergency exits appear optimal. Considering the situation in which an emergency is verified in front of the emergency exit, pedestrians must be able to reach the previous exit covering a distance not greater than 200 m by foot. In fact, if the distance were greater than this, the outflow would become unstable producing a congestion phenomena. It is now possible to define the size of the emergency exits using the methodologies proposed by the norms of fire prevention.

People to be evacuated *P* is:

$$P = P(k; v; q; l) \qquad (3)$$

where:

k: density of pedestrian flow [people/m^2];
v: speed of pedestrian flow [m/s];
q: pedestrian flow [people/s];
l: length of pedestrian route [m].

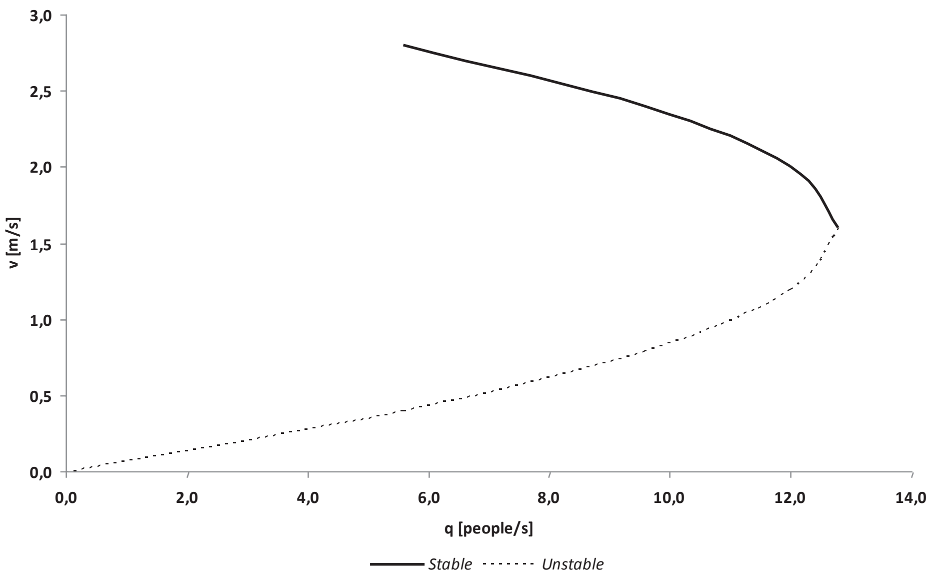

Figure 3 Link between flow and pedestrian speed.

Width of emergency exits *L* is:

$$L = \frac{P}{50} \cdot 60\,[cm] \tag{4}$$

Considering the results reported in table 4, in correspondence of the section stated at the progressive 200 m an overcrowding of 400 people occurs. Therefore, to allow the evacuation 8 modules of 60 cm (enough width to the transit of a person) are necessary, equal to 480 cm. It is possible to note that after Progressive 400 m, people in section are equal to 800 and traffic jam conditions are reached for the pedestrian outflow. As a consequence, the distance between two emergency exits prescribed by the *Guide for the Planning of Safety in Tunnels* (ANAS, 2006), equal to 300 m, is within this limit. Concerning the EU Directive, it is possible to calculate as, using a lower car occupancy rate (eg. 4 people/car), also a 500 m distance between two exits could be acceptable.

4. Conclusions

Current European legislation establishes, for the Trans-European Road Network, the placement of emergency exits to a non superior distance of 500 m. The *Guide for the Planning of Safety in Tunnels* (ANAS, 2006) establishes that tunnels of new constructions must be endowed with emergency exits at a distance not greater than 300 m, when the volume of daily traffic surpasses 2000 vehicles/h per lane. The same manual points out that the maximum distance set by the law between two emergency exits (500 m) is only at the border of risk acceptability.

Considering the achieved results, it appears more congruous to place the emergency exits at intervals depending on the actual pedestrian flow present in the tunnel, with the purpose to avoid pedestrian outflow reaching conditions of congestion. Knowing the distance between the emergency exits, it is possible to define the width of the exits given the number of people that have to be evacuated.

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