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VENTILATION IN SHORT TUNNELS AS A RISK MITIGATION MEASURE: "A SHORT TUNNEL CAN BE AS DANGEROUS AS A LONG ONE"

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ABSTRACT

When a tunnel capacity is foreseen by design and in operation results in a higher one, which produces almost permanent queues inside a tunnel, with a combination of light and heavy vehicle traffic, and an emergency management protocol mismatched to the reality of the operation, whether it is a short or long tunnel, with two-way or one-way flow, it is necessary to revisit the concept of tunnel classification based on its length and traffic volume, because a short tunnel can be as dangerous as a long tunnel".

Normally, tunnels between 50 m or less and up to 250 or less than 500 m are defined as short tunnels in the standards that regulate and legislate on road tunnels worldwide. It is also possible to intuit a priori, that short tunnels, being of really minimum lengths, if compared with tunnels defined as long (1000 m and above), do not present comparable risks as those that would be found in the latter. Therefore, the attention to any particularity that a short tunnel may have, during the design phase, is ruled out.

However, with a closer look, it is observed that in general terms from the regulations, short tunnels have been stripped of all series of protections, "possibly" because of the supposed lower level of risk compared to long tunnels. However, the fact that these short tunnels do not have a tangible safety compliance scheme, puts them in a potentially high-risk classification, just like long tunnels. Therefore, they are vulnerable to the shortcomings that can be ensured from a holistic view of safety, whose vision is almost never fulfilled in a project.

1. CONTEXT OF THE PROBLEM

In several design standards and directives, there are stipulated a series of aspects that must be reviewed and taken into account when designing safe tunnels. Many standards [5], define the following factors that influence the tunnel to be more or less safe, among others, such as the following aspects:

- Tunnel length
- Amount of traffic and nature of the traffic (heavy, light, motorcycles, other)
- Dangerous goods
- Longitudinal slopes
- Natural ventilation, with forced ventilation
- One-way or two-way flow
- With or without emergency lane
- With or without drains for hazardous materials
- Emergency plans
- Fire extinguishing, fire detection and fire alarm systems

There are, in turn, numerous methods of risk analysis[6], both qualitative and quantitative risk measurement, there are of course prescribed as the above list, that each of these conditions must be taken into account in a design, however, these factors are usually associated in relation to the length of a tunnel and the amount of traffic, at most. Meanwhile, catastrophic accidents continue to happen as the one reported in the tunnel called "Túnel de la Línea" in Colombia, Latin America, where in a set of 23 tunnels; one of them being only 190 m long, an accident occurred that left at least 7 dead and 30 injured. Then, in several engineering projects, it is found that tunnels between 50 m or less and up to 250 or 300 m, even less than 500 m, -as in the European Directive-, are defined as short tunnels and at the level of standards, more or less requirements are imposed based on the length of the tunnel.

On the other hand, although statistically an admissible margin of fatalities and injuries has been established in road tunnel projects, as used in the approach of risk analysis methodologies such as DG QRAM and others, it is unacceptable to allow the loss of human lives in a context as delimited as a short tunnel, and then there must be analyzed several concepts around the meaning of risk, and the dynamic nature of this for which are applicable in turn, dynamic systems for risk mitigation.

2. DYNAMIC NATURE OF RISK

Any infrastructure made by man and for man, would be meaningless without a use. An infrastructure, be it a high-rise building, a hydroelectric power plant, a bridge, an airport, a road tunnel, etc., would be nothing more than "models" if they did not interact with man, since these are static systems in themselves, and only under interactions with man, dynamic processes are produced, as man uses these infrastructures. Therefore, the interactions between man and infrastructures produce processes that are dynamic, not static. There is no risk associated with the static nature of the infrastructures, but there is a risk associated when man interacts with them. Therefore, it can be said that "risk is dynamic in nature".

However, geometrically ill-conceived works impose conditions on the dynamics of a process from the outset, and to the extent that the statics of the infrastructures affect the dynamics of a process, the risk will vary in range, and therefore, it will oscillate between the dynamic and the static, the latter being a restriction imposed from the outset on the dynamics of the processes due to the invariable nature of their nature. In synthesis, the errors in the geometric design of tunnels, which have been identified in the norms, regulations or design guides, such as exaggerated lateral and longitudinal slopes, narrow radii of curvature, gauges, platforms, shoulders and lane widths, absence of emergency evacuation tunnels, inaccuracy of information and data of the traffic study, lack of characterization of dangerous goods, etc., impose per se, a restriction on the design of tunnels, impose per se, a restriction to the fulfillment of the goal of having a safe tunnel, thus transferring its potential risk to the dynamic systems of the processes that have to manage its variables to modulate the risk, control it or minimize it. According to the above, it is not correct to dimension and design the dynamic systems without first taking into account the non-compliances, at least regulatory, of the infrastructures, as if we were starting from an ideal structure, since then, we will have deficiently dimensioned systems for the attention of the risks in the operation of the tunnel.

3. DYNAMIC SYSTEMS

Understanding that the processes happen by the interaction of man on the infrastructures (static), that is; man puts in use the structures to its service, example; when a road tunnel starts operating, then, the dynamic systems are all those that collaborate in a variable way in the time to modulate the risks that are generated by the interaction between the vehicles, the occupants, and the infrastructure itself. The dynamic systems will be: ventilation systems[8], detection systems, and fire extinguishing systems when they must be activated, ITS, signaling, communications, emergency brigades when they are activated, etc. These are all the resources and systems that assist in a continuous and sustained manner over time the management of vehicular traffic through the tunnel or road corridor, and will vary in behavior and performance according to the variation of the events generated by the vehicles in transit.

In this way, the dynamic systems will only act according to some input variables, which initially would not satisfy previous requirements, such as a bad geometric design, and therefore, the sizing and specifications of the dynamic systems will never be adequate to satisfy safe operating conditions of the tunnel.

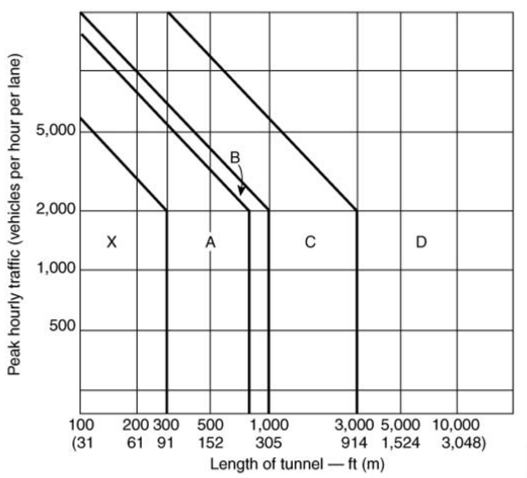
We have established then, that geometrically poorly dimensioned infrastructures impose restrictions to the fulfillment of the safety goals by the dynamic systems, so it can be deduced that no matter how many safety systems and emergency plans are available, the intrinsic risk of the previous non-compliances underlies and where the dynamic systems are not perfectly adjusted to the variables of the traffic regime, then, any kind of consequences as catastrophic as the ones happened in a tunnel of only 190 m in length could occur.

4. RISK MITIGATION SYSTEMS

It should be defined that the need of ventilation for short tunnels is prescribed for sanitary needs, that is, only natural ventilation is required to guarantee the sufficient quantity of oxygen in the air and the cleaning of the air through the dissolution of contaminants in the normal operation of the tunnel. But under the definition of natural ventilation, the benefit of ventilation as a safety mechanism for a fire or smoke evacuation situation occurring in a short tunnel is practically ruled out. It should be shown then, the reasons why forced ventilation is required for certain short tunnels.

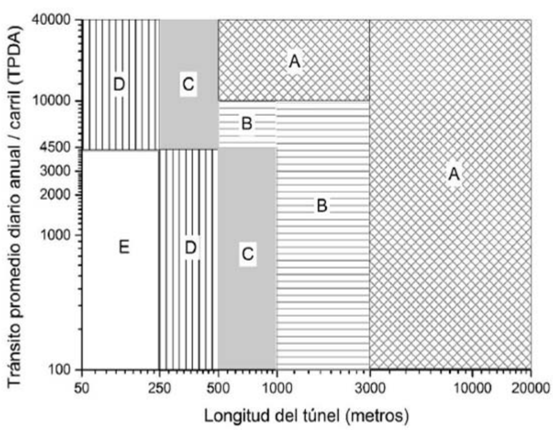
According to NFPA 502 [3], short tunnels are specifically defined as being between 31 [100 ft] and 91 m [300 ft] in length and are only intended to handle traffic of about 5,000 vehicle-hours/lane, as shown in Figure 1 below:

Figure 1: Tunnel Classification according to NFPA 502



Source: NFPA 502, 2020 edition

Figure 2: Tunnel Classification according to the Tunnel Manual, Colombia.



Source: Manual for the Design, Construction, Operation and Maintenance of Road Tunnels, 2021 edition.

Additionally, these tunnels are classified as "X", and have Mandatory Requirements (MR) and Conditionally Mandatory Requirement (CMR) protection and safety considerations, which can be summarized in table A.7.2 "Minimum Road Tunnel Fire Protection Reference Guide". But it is relevant that this standard recommends that absolutely, for "all" tunnel lengths, the respective engineering analysis must be developed, where at least each of the following aspects must be taken into account.

(1) New installation or modification of an existing installation.

(2) Modes of transport using the facility

(3) Anticipated traffic volume and mix

(4) Restricted vehicle access and egress

(5) Fire emergencies ranging from minor incidents to major catastrophes (6) Potential fire emergencies ranging from minor incidents to major catastrophes (7) Fire emergencies ranging from minor incidents to major catastrophes

(6) Potential fire emergencies including, but not limited to, the following.

(a) At one or more locations within or on the facility

(b) In the vicinity of the facility

(c) At facilities at a great distance from the emergency response facilities

(7) Exposure of the emergency systems and structures to elevated temperatures

(8) Traffic congestion and control requirements during emergencies (9) Emergency protection elements

(9) Fire protection elements, including, but not limited to, the following

(a) Fire alarm and fire detection systems

(b) Standpipe systems

(d) Water fire extinguishing systems; (e) Ventilation systems

(e) Ventilation systems

(f) Emergency communication systems

(g) Protection of structural elements

(10) Components of facilities, including emergency systems (11) Evacuation and rescue requirements

(11) Evacuation and rescue requirements

(12) Emergency response time (13) Access points for vehicles

(13) Access points for emergency vehicles (14) Emergency communications to emergency responders (15) Access points for emergency vehicles

(14) Emergency communications to appropriate agencies (15) Location of facilities, including emergency systems (16) Emergency communications to appropriate agencies

(15) Location of facilities, such as urban or rural (level of risk and response capability)

(16) Physical dimensions, number of traffic lanes and roadway geometry

(17) Natural factors, including prevailing wind and pressure conditions

(18) Expected loading

(19) Impact on buildings or landmarks near the facility (20) Impact on the facility

(20) Impact on the facility from external conditions and/or incidents (20) Impact on the facility from external conditions and/or incidents

(21) Traffic operating mode (unidirectional, bidirectional, switchable or reversible).

From the above, and according to the "X" classification for short tunnels, the following means or safety resources are considered mandatory (MR):

- Structural elements of the tunnel protected to fire.
- Traffic control
- Emergency response plan

And as conditionally mandatory (CMR), the following safety means or resources:
- Emergency communications systems

However, of all the above, not a single system that is part of the fire protection for short tunnels, among others, for example, the ventilation system, is included. The following are the systems that are part of the fire protection in this standard, but could be others or similar in other standards:

- Fire vehicle.
- Piping network system for hose connections, hose cabinets or hydrants.
- Fire department water storage.
- Fire Department connections.
- Fire pumps
- Manual fire extinguishers
- Fixed water-based fire extinguishing system.
- Emergency ventilation system
- Drainage system
- Hydrocarbon detection
- Environmental hazards due to substances and fuels

COLOMBIAN STANDARD [4]

In the Colombian standard called the "Manual for the Design, Construction, Operation and Maintenance of Road Tunnels, 2021 edition, short tunnels are classified as "E", and are considered between lengths of 50 to 250 m, for traffic volumes of 100 to 4500 TPDA (Average Daily Annual Daily Traffic/Lane), see graph 2 above.

5. STATIC SYSTEMS AND DYNAMIC

We have defined in the "dynamic nature of risk", that we have static and dynamic systems. The static systems are the infrastructures and the dynamic systems are all the resources that materialize according to the real time in the event of a contingency. If we review the mandatory requirements that a short tunnel must meet, such as "structural elements must be protected against fire", this is not a dynamic element against the contingency of an accident or a fire inside the short tunnel. And regarding the "traffic control" and the "emergency response plan", since these are very dependent on human decision making, they are subject to the risk of failure by not meeting the expectations that are necessary to cover, when an accident and/or fire occurs in a tunnel, in general, short or long length. The same happens with the "emergency communications systems", which result from the decision to implement them or not, according to the criteria of the engineering analysis proposed in standards such as NFPA 502.

Although an engineering analysis must be developed on a mandatory basis for any length of tunnel, it is not yet clear when, what, and why, some, all, or no systems, both static and dynamic, should be implemented to address safety.

Accordingly, at the very least, it should be clear that the systems, resources, and dynamic means to deal with a contingency for an automobile accident and/or fire in the tunnel will be those that can be made available in real time and materially, such as ventilation systems, water jet discharges from hoses or fixed water-based extinguishing systems, manual extinguisher discharges on a vehicle that is on fire or overheated and will soon cause a spreading fire. Therefore, it is of vital importance, before establishing for every tunnel the need to develop an engineering analysis, and beyond defining what is mandatory, and what is conditionally mandatory in safety equipment for a tunnel, is to recognize the nature of the static and dynamic systems that are part of the safety of a tunnel that is put into operation, where not even all risk analysis models are able to cope with these circumstances [11].

6. ANALYSIS OF THE SITUATION

In view of the clear evidence shown by the statistics in the reports that are permanently published worldwide, there are still accidents due to vehicular collisions at the entrance of a tunnel, accidents with or without fire, many of them with catastrophic results due to the loss of human lives. It is necessary then, to understand that the structures or infrastructures already built, or to be built, that once poorly executed do not comply at least prescriptively with some or many geometric parameters such as those already mentioned above, and in addition, certain resources or systems are also static in nature to contribute to safety, then, it is also necessary to understand that they must be recognized as dynamic systems, that those systems that contribute materially and in real time to safety, such as emergency ventilation, water jet discharges, and manual extinguishing, should be recognized as dynamic systems, in order to consider a reclassification of tunnels[10] to include both forced ventilation and fire extinguishing.

6.1. CATASTROPHE IN A 190 M LONG TUNNEL

In a 190 m long tunnel, there were no water-based extinguishing systems, no manual fire extinguishers, and even less forced ventilation. At the same time, an engineering analysis considered that other resources or fire protection systems were unnecessary. The communication systems were those that corresponded to communication via radios between surveillance personnel on the outskirts of each tunnel, and an emergency plan[7], possibly not adjusted to the changing reality of traffic depending on the time of day and the special vacation dates, where the number and intensity of travelers moving through a road corridor designed to mobilize mostly freight vehicles increases. Therefore, light vehicles and cargo vehicles shared the same road corridor, which also consisted of 23 tunnels, all with different lengths.

An accident occurred inside the tunnel, which was only 190 m long and had a negative slope, when a tractor-trailer with no brakes collided with a line of vehicles inside the tunnel. Several of the light vehicles were carrying families, as well as intermunicipal buses full of passengers, but also cargo vehicles, so that the light vehicles were trapped in the middle of the cargo vehicles, producing a human "sandwich", which as a result of the accident left at least seven dead and 30 injured, according to official news reports and the rescue corps that attended the accident.

6.2. EFFECTS OF THE VEHICLE COLLISION

After the vehicle collision, several light vehicles were ejected at the gauge level downstream of the tunnel, while others were trapped in the middle of the tractor-trailers, which remained with their engines running after the collision. The tractor-trailer that collided spilled the material it was carrying, such as engine lubricating oils and brake fluids. Minutes after the accident, visibility inside the tunnel was lost due to fumes from the burning engines, possibly also due to the combined combustion of the oil and brake fluid spills. The death of the people could have been caused by asphyxiation and intoxication[9], in addition to the mechanical impact.

6.3. VICTIM RESCUE

For the rescue of the victims, the "external" emergency response personnel entered through the downstream portal of the tunnel, that is, at the lowest altitude of the tunnel. However, due to the obstruction of the vehicles trapped in the tunnel and close to the entrance portal, the rescue of the victims had to be done through the upstream portal of the tunnel, that is, at the highest altitude of the tunnel, as well as the extraction of the vehicles involved in the collision. This shows that, given the circumstances of the accident, where there is a short tunnel, also with a negative longitudinal slope, the rescue actions of the occupants were under the most adverse conditions of toxic and irritating fumes, because the rescue could not be downstream of the incident, due to the vehicular obstruction of the entire tunnel. However, there was no forced ventilation to mitigate the risk of death by asphyxiation and/or poisoning, nor was there an extinguishing system to cool the overheated and still burning engines after the multiple collisions.

7. VENTILATION AS A DYNAMIC SYSTEM FOR RISK MITIGATION

It is documented in many specialist papers, statistics published by the different PIARC technical committees, and others, the serious events that can take place in short tunnels [1], a brief non-exhaustive list of accidents involving fires or just accidents, is presented below:

ACCIDENTS WITH/WITHOUT FIRES IN SHORT TUNNELS [2]

					Damage		
Year	Tunnel	Country	Tunnel Length m (ft)	Fire Duration	People	Vehicles	Structure
1967	Suzaka	Japan	244 (800)	11 h	2 injured	12 trucks	-
1968	Moorfleet	Germany	243 (800)	1 h	-	1 truck	Serious
1976	Crossing BP	France	430 (1,410)	1 h	12 injured	1 truck	Serious
1987	Gumefens	Switzerland	343 (1,125)	2 h	2 dead	2 trucks, 1 van	Slight
1989	Brenner	Austria	412 (1,350)		2 dead, 5 injured		
1993	Serra Ripoli	Italy	442 (1,450)	2h 30 min	4 dead 4 injured	5 trucks 11 cars	Limited
1996	Isolla delle Femmine	Italy	148 (485)	-	5 dead 20 injured	1 tanker, 1 bus, 18 cars	Serius
2001	Guldborg-sund	Denmark	460 (1,509)	-	5 dead 6 injured		
2022	La Línea	Colombia	190 (623)	-	7 dead 30 injured	1 truck, 5 cars 3 buses	-

According to the context of the present document, the ventilation system is a dynamic system that must be considered for short tunnels due to the following circumstances that a priori may not be identifiable:

1- Longitudinal slope of the short tunnel greater than 3% finally constructed.
2- Dangerous goods content of the vehicle(s) involved.
3- Production of fumes due to combustion or spillage of hazardous materials from the vehicles involved.
4- Condition of the engines left running after the collision.
5- Unavailability of water for the cooling of the burning engines, to avoid the start of possible combustions of the crashed vehicles.
6- Difficulty for the emergency brigades to reach the exact spot due to the obstruction of the accident vehicles and the line of vehicles formed before and after the tunnel.
7- Rescue and extraction of the injured in the most unfavorable conditions upstream of the accident, under conditions of smoke either from fire or combustion of the spills, or smoke emission from the burning engines.

8. CONCLUSIONS

- Each design standard for the safety of road tunnels has defined a different length for the so-called short tunnels, ranging from 30 m to less than 500 m. This is a very wide range where the length of the tunnels can vary. This is a very wide range where there may be other conditions that are difficult to control through prescriptive design or through risk analysis.
- The infrastructure of a tunnel and the roads that connect to its entrance are static systems, because they have no variation or adjustment after operation.
- The interactions between man and infrastructure produce processes that are dynamic, not static.

- There is no risk associated with the static nature of the infrastructures, but there is a risk associated when man interacts with them.
- Dynamic systems are all those that collaborate in a time-varying manner to modulate the risks generated by the interaction between vehicles, occupants and the infrastructure itself.
- The dynamic systems will be: ventilation systems, detection systems, fire detection and extinguishing systems when they must be activated, ITS, signaling, communications, emergency brigades when they are activated, etc. They are all the resources and systems that assist in a continuous and sustained manner over time the management of vehicular traffic through the tunnel or road corridor, and will vary in behavior and performance according to the variation of the events generated by the vehicles in transit.
- The ventilation system is a dynamic system that should be considered for short tunnels, and therefore, a systematic review of the worldwide regulations should be initiated, with respect to the classification of tunnels that only prescriptively links the parameters of length and traffic volume.
- A conventional risk analysis methodology does not resolve design singularities by virtue of the interaction of static systems and dynamic systems.

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