PROF. ING. CIRO CALIENDO

ORDINARIO DI STRADE, FERROVIE E AEROPORTI - UNISA

MEMBRO ESPERTO DEL CONSIGLIO SUPERIORE LAVORI PUBBLICI DEL MIT

Seminario

Modelli e metodi per l'analisi del rischio stradale in galleria

28 giugno 2023

Sede Ordine degli Ingegneri della provincia di Salerno

UNIVERSITA' DEGLI STUDI DI SALERNO
DIPARTIMENTO DI INGEGNERIA CIVILE
Prof. Ing. Ciro Caliendo
email: ccaliendo@unisa.it

ANALISI DEL RISCHIO IN GALLERIA IN CASO DI INCENDIO

I maggiori incendi nelle **gallerie stradali europee**:

Incendio nel tunnel del Monte Bianco (1999) con 39 morti

Incendio nel tunnel dei Tauri(1999) con 12 morti

Incendio nel tunnel del San Gottardo (2001) con 11 morti

Spalling

DIRECTIVE 2004/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004

on minimum safety requirements for tunnels in the Trans-European Road Network

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 71(1) thereof,

Having regard to the proposal from the Commission,

Having regard to the Opinion of the European Economic and Social Committee [1],

Having regard to the Opinion of the Committee of the Regions [2],

Acting in accordance with the procedure laid down in Article 251 of the Treaty [3],

[1] OJ C 220, 16.9.2003, p. 26.
[2] OJ C 256, 24.10.2003, p. 64.
[3] Opinion of the European Parliament of 9 October 2003 (not yet published in the Official Journal), Council Common Position of 26 February 2004 (OJ C 95 E, 20.4.2004, p. 31) and Position of the European Parliament of 20 April 2004 (not yet published in the Official Journal).

Decreto Legislativo 5 ottobre 2006, n. 264
"
Attuazione della direttiva 2004/54/CE in materia di sicurezza per le gallerie
della rete stradale transeuropea"

pubblicato nella Gazzetta Ufficiale n. 235 del 9 ottobre 2006 - Supplemento
Ordinario n.195

IL PRESIDENTE DELLA REPUBBLICA
VISTI gli articoli 76 e 87 della Costituzione;
VISTA la direttiva 2004/54/CE del Parlamento europeo e del Consiglio, de 29
aprile 2004, relativa ai requisiti minimi di sicurezza per le gallerie della
rete stradale transeuropea;
VISTA la legge 25 gennaio 2006, n. 29, recante disposizioni per l'adempimento di
obblighi derivanti dall'appartenenza dell'Italia alle Comunità europee. Legge
comunitaria 2005;
VISTA la preliminare deliberazione del Consiglio dei Ministri, adottata nella
riunione del 6 aprile 2006;
ACQUISITO il parere delle competenti Commissioni parlamentari della Camera dei
deputati e del Senato della Repubblica;
VISTA la deliberazione del Consiglio dei Ministri, adottata nella riunione del
22 settembre 2006;
SULLA PROPOSTA del Ministro per le politiche europee e del Ministro dell
infrastrutture, di concerto con i Ministri degli affari esteri, della giustizia,
dell'economia e delle finanze, dell'interno e dei trasporti;
Emana
il seguente decreto legislativo:
Art. 1
(Oggetto e campo di applicazione)
1. Il presente decreto ha lo scopa di garantire un livello minimo sufficiente di
sicurezza agli utenti della strada nelle gallerie della rete stradale
transeuropea mediante la progettazione e l'adozione di misure di prevenzione
atte alla riduzione di situazioni critiche che possano mettere in pericolo la
vita umana, l'ambiente e gli impianti della galleria, nonche' mediante misure di
protezione in caso di incidente.
2. Il presente decreto si applica a tutte le gallerie situate nel territorio
italiano appartenenti alla rete stradale transeuropea, di lunghezza superiore a

Metodi e modelli per lo studio degli incendi nelle gallerie

- **Esperimenti su grande scala** → Costosi, pericolosi e richiedono molto tempo per la loro realizzazione
- **Esperimenti su piccola scala** → A volte non sono in grado di riprodurre le caratteristiche su grande scala
- **Simulazione numerica** → E' uno strumento sempre più utilizzato per riprodurre lo sviluppo di un incendio e quantificarne gli effetti

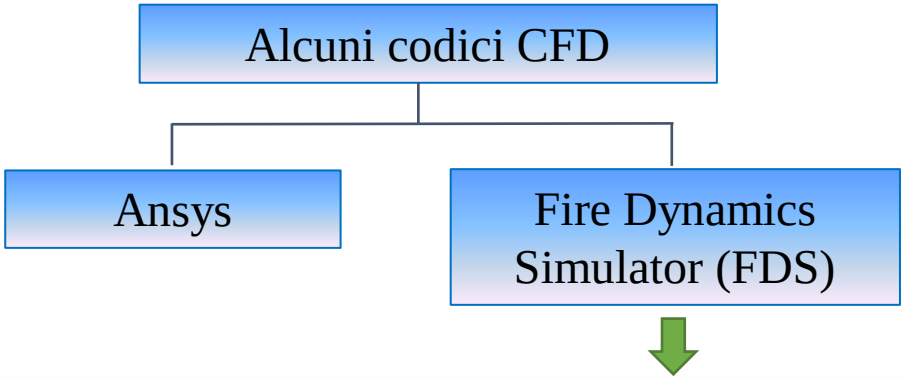
  - **Valutazione** più **rapida** ed **efficiente** dello sviluppo dell'incendio rispetto agli altri due metodi;
  - **Costi ragionevoli**;
  - **Comprendere** meglio le **relazioni** tra **l'incendio** e le **alte temperature**, i **gas tossici** e le **condizioni** di **visibilità** per l'evacuazione delle persone dalla galleria;
  - **Considerare** meglio la **geometria** della galleria, il **traffico**, il **tipo** di **veicolo incendiato**, la **posizione** dell'**incendio** e la **circolazione** di **merci pericolose**.

Modelli di fluido dinamica computazionale (CFD)

La **simulazione numerica** degli **incendi** nelle gallerie si basa generalmente su **modellazione in CFD**, il che porta a:

- **Dividere** il **volume** della **galleria** in **piccole celle** all'interno delle quali vengono risolte le **equazioni fondamentali della fluidodinamica** (equazioni di conservazione della massa, della quantità di moto e dell'energia);
- **I risultati** sono ottenuti **per ogni cella** e riguardano in particolare: **temperatura**, **concentrazione** di **fumi** e **gas tossici**, **velocità** e **direzione** del **flusso d'aria**, ecc.

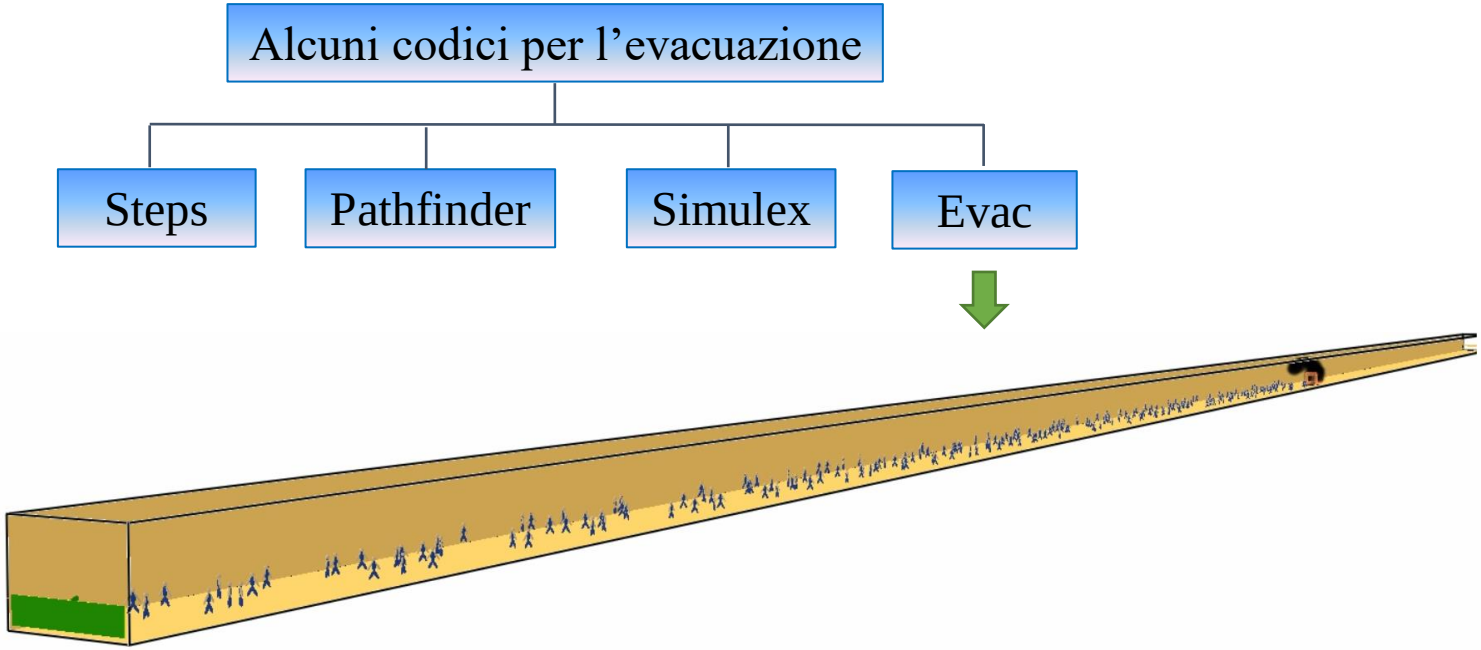
L'accuratezza dei **risultati** è influenzata dai **modelli fisici utilizzati nella simulazione**, dalle **dimensioni dell'incendio** e dalla **finezza della griglia**.



Metodi e modelli per l'evacuazione delle persone

Sono stati sviluppati diversi **strumenti** di simulazione per la **previsione dei movimenti degli utenti in caso di emergenza**.

Questi software utilizzano generalmente come **input** i **risultati ottenuti** da un **modello CFD**.



ANALISI DEL RISCHIO IN GALLERIA

Approcci analisi del rischio

- **Approccio basato sugli scenari** → Analizza un insieme definito di scenari rilevanti, con un'analisi separata per ciascuno di essi
- **Approccio di sistema** → Analizza un sistema complessivo in un processo integrato, includendo tutti gli scenari rilevanti e producendo indicatori di rischio per l'intero sistema. **Quest'ultimo è generalmente utilizzato**

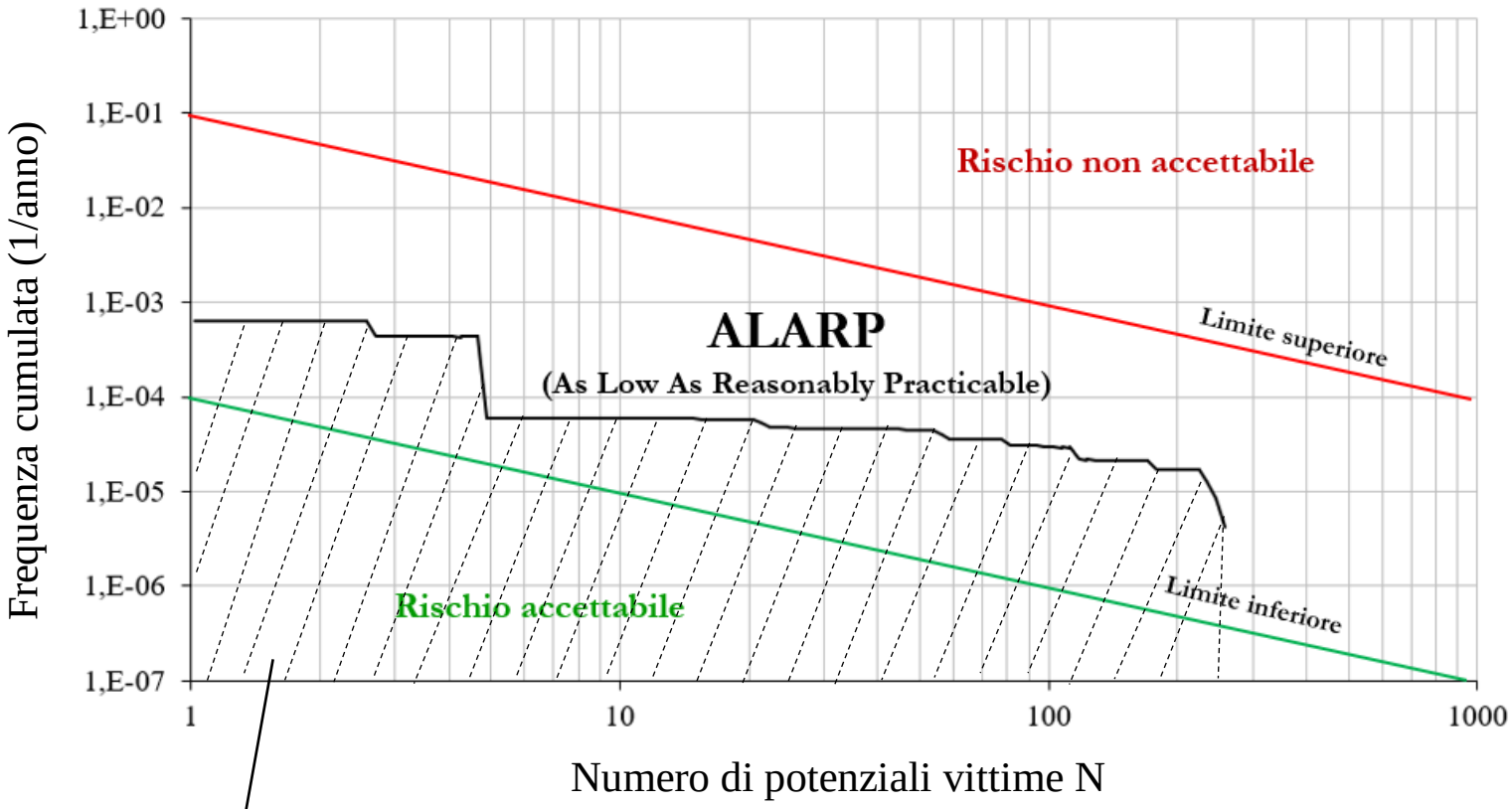
In un'**analisi del rischio** si possono considerare **vari tipi di rischio**, come ad esempio:

- Danni ad un **gruppo specifico di persone** (**rischio sociale**);
- Danni ad una **singola persona** (**rischio individuale**);
- Danni **materiali** e **ambientali**.

Nel campo delle gallerie, viene comunemente utilizzato il rischio sociale.

- Il **rischio sociale** può essere espresso in termini di numero atteso di vittime all'anno (EV) o come curva nel diagramma F-N.
- La **curva F-N** mostra la relazione tra la frequenza (F) e le conseguenze (in termini di vittime) (N) dei possibili incidenti.

Esempio curva F-N con regione ALARP per l'Italia con riferimento alle gallerie

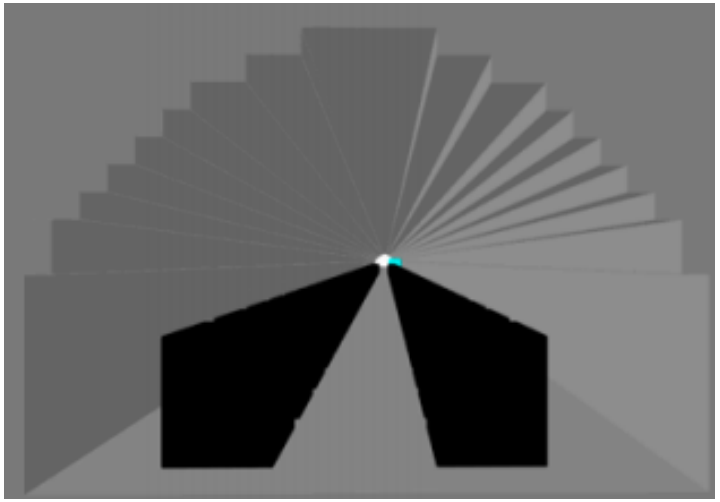


$$Valore\ atteso\ del\ rischio\ (EV) = \int_1^{\infty} F(N)\, dN$$

Analisi del rischio basata sull'uso dei codici FDS+Evac

Dati di input FDS:

- Sezione della galleria stradale;
- Tipologia di ventilazione;
- Lunghezza della galleria (L);
- Posizione delle uscite di emergenza;
- Caratteristiche plano-altimentriche della galleria;
- Posizione e dimensione dei veicoli in coda.



Scenari di incendio:

- Posizione del veicolo incendiato nel tunnel (1/4 L, 1/2 L, 3/4 L).
- Velocità massima di rilascio del calore (HRRmax): 8 MW (due autovetture), 30 MW (autobus), 50 MW (veicolo commerciale pesante) e 100 MW (veicolo commerciale pesante).

Analisi del rischio basata sull'uso dei codici FDS+Evac

applied sciences

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Article

Risk Analysis of Road Tunnels: A Computational Fluid Dynamic Model for Assessing the Effects of Natural Ventilation

Ciro Caliendo *, Gianluca Genovese and Isidoro Russo

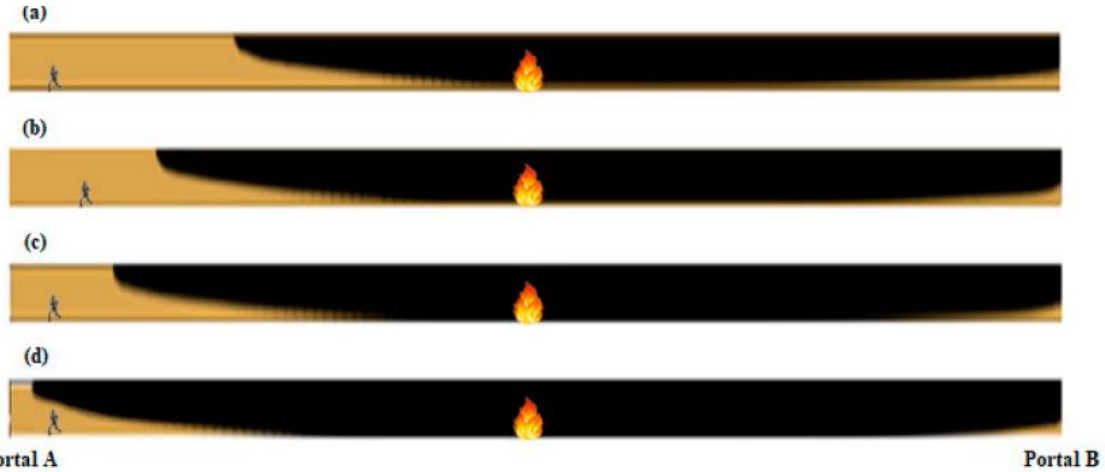
Department of Civil Engineering, University of Salerno, 84084 Fisciano, Salerno, Italy; ggenovese@unisa.it (G.G.); isrusso@unisa.it (I.R.)
* Correspondence: ccaliendo@unisa.it; Tel.: +39-8996-4140

Abstract: We have developed an appropriate Computational Fluid Dynamics (CFD) model for assessing the exposure to risk of tunnel users during their evacuation process in the event of fire. The effects on escaping users, which can be caused by fire from different types of vehicles located in various longitudinal positions within a one-way tunnel with natural ventilation only and length less than 1 km are shown. Simulated fires, in terms of maximum Heat Release Rate (HRR) are: 8, 30, 50, and 100 MW for two cars, a bus, and two types of Heavy Goods Vehicles (HGVs), respectively. With reference to environmental conditions (i.e., temperatures, radiant heat fluxes, visibility distances, and CO and CO_2 concentrations) along the evacuation path, the results prove that these are always within the limits acceptable for user safety. The exposure to toxic gases and heat also confirms that the tunnel users can safely evacuate. The evacuation time was found to be higher when fire was related to the bus, which is due to a major pre-movement time required for leaving the vehicle. The findings show that mechanical ventilation is not necessary in the case of the tunnel investigated. It is to be emphasized that our modeling might represent a reference in investigating the effects of natural ventilation in tunnels.

La figura mostra la diffusione del fumo in caso di incendio a metà della lunghezza del tunnel (420 m dal portale di ingresso):

- I risultati dell'esposizione ai gas tossici e al calore lungo il percorso di evacuazione hanno dimostrato che gli utenti della galleria possono evacuare in sicurezza nel caso esaminato;
- Inoltre, i risultati hanno anche dimostrato che la ventilazione meccanica non è necessaria in questo caso. Perché è una galleria corta L<1 km

L = 850 m



8 MW

30 MW

50 MW

100 MW

Analisi di rischio in galleria

Consiglio Superiore dei Lavori Pubblici

Commissione Permanente per le Gallerie
ex art. 4 del D.Lgs. n. 264/2006

DELIBERAZIONE DELLA
COMMISSIONE PERMANENTE PER LE GALLERIE
DEL 6 FEBBRAIO 2020

ALLEGATO B

GALLERIE DELLA RETE STRADALE ITALIANA TRANSEUROPEA
NON CONFORMI ALLA SCADENZA INDICATA ALL'ARTICOLO 10, COMMA 7,
DEL D.LGS. N. 264 DEL 2006

MISURE TEMPORANEE PER LA
LIMITAZIONE DELL'ESERCIZIO
EX ARTICOLO 4, COMMA 10, DEL D.LGS. N. 264 DEL 2006

Analisi del rischio basata sull'uso dei codici FDS+Evac

Caso di una canna di galleria stradale unidirezionale utilizzata per il traffico bidirezionale quando la canna adiacente è chiusa per lavori di manutenzione, riparazione e/o adeguamento.

applied sciences

MDPI

Article

Risk Analysis of One-Way Road Tunnel Tube Used for Bi-Directional Traffic under Fire Scenarios

Ciro Caliendo *, Isidoro Russo and Gianluca Genovese

Department of Civil Engineering, University of Salerno, Fisciano, 84084 Salerno, Italy; isrusso@unisa.it (I.R.); ggenovese@unisa.it (G.G.)
* Correspondence: ccaliendo@unisa.it; Tel.: +39-8996-4140

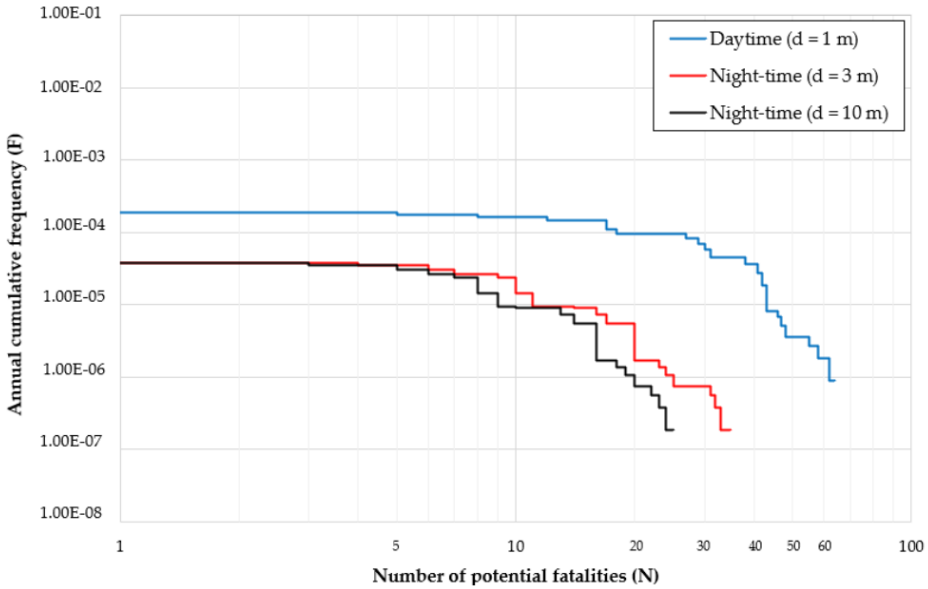
Abstract: We have set up a Computational Fluid Dynamics (CFD) modeling, and performed a user evacuation model, for evaluating the risk level in one-way road tunnel tube when used for bi-directional traffic in particular circumstances. The simulations were carried out by considering both peak-hour traffic volumes during the day and off-peak hours overnight. The investigated one-way tube is ventilated by natural ventilation only, and has a length of less than 1000 m. With reference to the worst environmental conditions, which are downstream of the fire due to the direction of natural ventilation, the consequences on escaping users, caused by different types of burning vehicles located in various longitudinal positions along the tube, are shown. The results prove the positive effects on environmental conditions (in terms of temperature, visibility distance, CO and CO_2 concentration) along the user evacuation path when the tube is used for bi-directional traffic at night rather than daytime. Only for the case of 100 MW fire and in the proximity of the exit portal, the last escaping user might be affected by a visibility distance and CO concentration exceeding the threshold values. In this special case, countermeasures for reducing smoke concentration or emergency services at the portals should be provided. However, the quantitative risk analysis, based on a probabilistic approach, showed that the F-N curve of the tube when used for bi-directional traffic with reference to the night always lies below that of the daytime, and the reduction in the risk level is between 80 and 100% for the night traffic compared to daytime one. It is to be focused on the fact that our modeling may represent a reference in investigating the effects of hourly traffic volumes on the risk level in tunnels and may help decisionmakers in understanding when to temporarily close a tube for maintenance, repair, or rehabilitation activities and use the adjacent tube for bi-directional traffic.

check for updates

Citation: Caliendo, C.; Russo, I.; Genovese, G. Risk Analysis of One-Way Road Tunnel Tube Used for Bi-Directional Traffic under Fire Scenarios. *Appl. Sci.* **2021**, *11*, 3198. https://doi.org/10.3390/app11073198

I risultati dell'analisi quantitativa dei rischi hanno mostrato che:

- La curva F-N della canna utilizzata per il traffico bidirezionale con riferimento alla notte è sempre inferiore a quella del giorno;
- La riduzione del livello di rischio è compresa tra l'80 e il 100% per il traffico bidirezionale notturno rispetto a quello diurno.



ANALISI DEL RISCHIO IN GALLERIA

Analisi del rischio basata sull'uso di FDS+Evac

Efficacia di un veicolo di emergenza dotato di un sistema di acqua micronizzata per contrastare la fase di crescita dell'incendio nelle gallerie stradali

Si ipotizza che il sistema ad acqua micronizzata modifichi le curve di incendio originali (cioè quelle di HRR_{max} pari a 8, 15 e 30 MW) intercettando la legge lineare della fase di crescita dell'incendio a 8, 6 o 4 MW.

applied sciences MDPI

Article

A Numerical Study for Assessing the Risk Reduction Using an Emergency Vehicle Equipped with a Micronized Water System for Contrasting the Fire Growth Phase in Road Tunnels

Ciro Caliendo *, Gianluca Genovese and Isidoro Russo

Department of Civil Engineering, University of Salerno, Fisciano, 84084 Salerno, Italy; ggenovese@unisa.it (G.G.); isrusso@unisa.it (I.R.)
* Correspondence: ccaliendo@unisa.it; Tel.: +39-(89)-964140

Abstract: We performed Computational Fluid Dynamics (CFD) modeling, and simulated a people evacuation process from a tunnel in the event of a fire, for evaluating the potentialities of using, as a temporary safety measure, an emergency vehicle equipped with a micronized water system for contrasting the fire growth phase. The structure investigated is a one-way road tunnel with only natural ventilation, and with a length less than 1000 m. The tunnel is assumed at present to be affected by refurbishment works for making it comply with the minimum safety requirements of the European Directive 2004/54/EC. In particular, it is considered that it has not yet been provided with hydrants, and with the sidewalks and the emergency exit which are still under construction. This means that users are forced to use the road carriageway for escaping from the tunnel if a fire occurs. The CFD findings have shown that the use of the micronized water system might lead to a significant improvement in the environmental conditions along the escape route since the tenability limits of temperature, radiant heat flux, CO and CO_2 concentration were found to be better satisfied. Additionally, the visibility distance was shown to increase, even though it was found to be higher than the acceptable threshold value only in a few cases. However, the quantitative risk analysis based on a probabilistic approach, which was combined with a method currently used in Europe for assessing the risk due to the transit of only dangerous goods, shows that the final cumulative F-N curves related to the micronized water system always lie below those without the mentioned system, and in addition, they are always contained within the limits of the ALARP region. It is to be stressed that our paper might represent a reference in showing the effectiveness of the micronized water system as a temporary safety measure. However, it is desirable that the Tunnel Management Agencies accelerate the refurbishment works for making road tunnels definitively safer for users in a short period of time.

check for updates

Citation: Caliendo, C.; Genovese, G.; Russo, I. A Numerical Study for Assessing the Risk Reduction Using an Emergency Vehicle Equipped with a Micronized Water System for Contrasting the Fire Growth Phase in Road Tunnels. *Appl. Sci.* **2021**, *11*, 5248. https://doi.org/10.3390/app11115248

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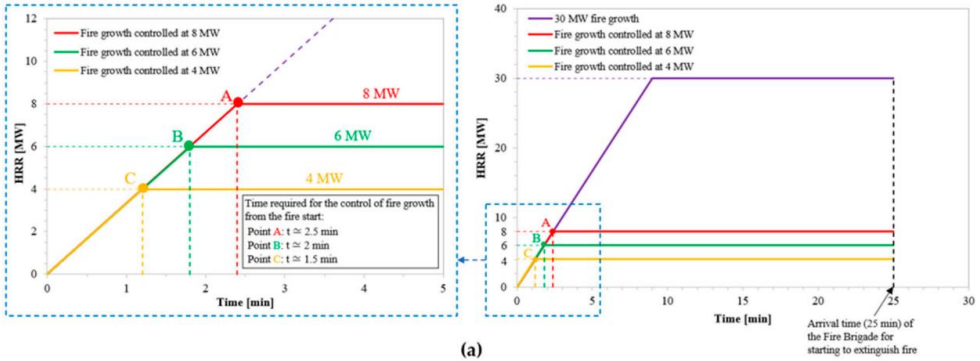
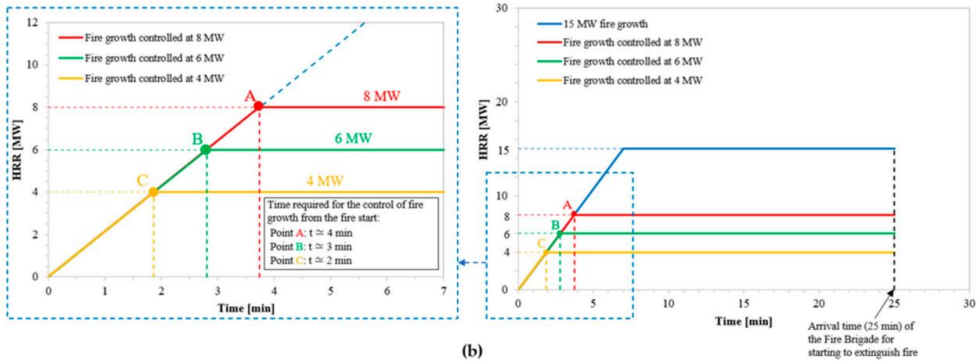


(a)

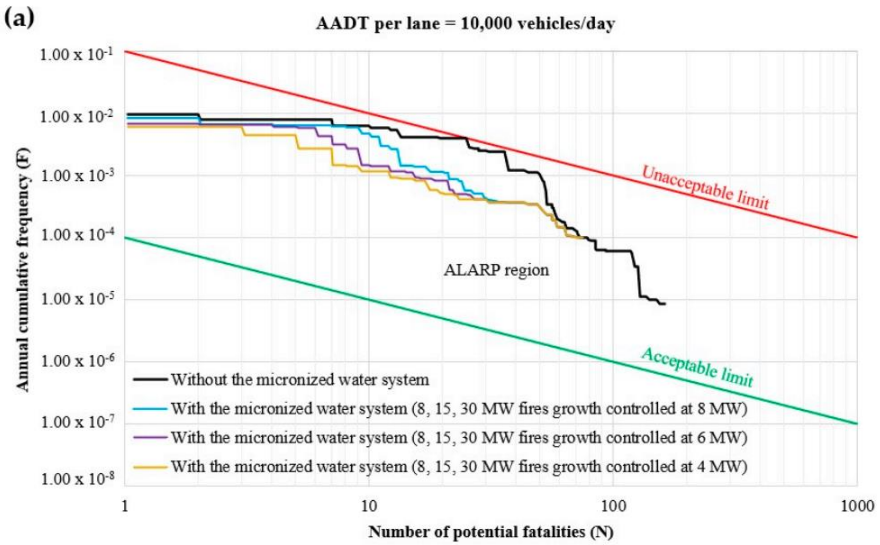


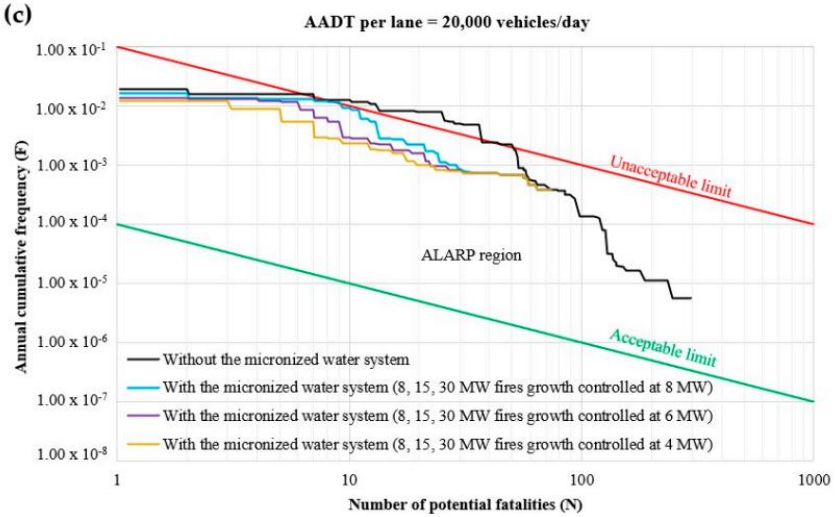
(b)

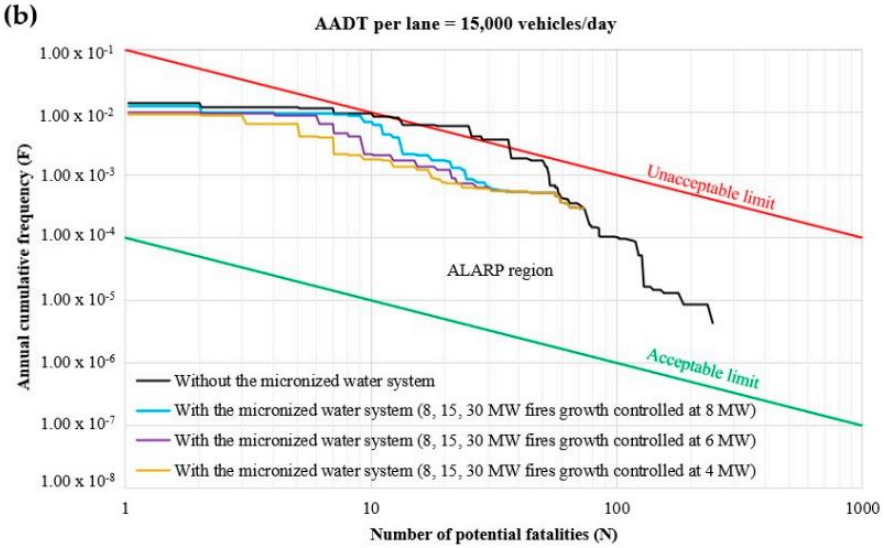
Prof. Ing. Ciro Caliendo, email: ccaliendo@unisa.it

Analisi del rischio basata sull'uso dei codici FDS+Evac

- I risultati mostrano l'efficacia del veicolo di emergenza posizionato ai portali del tunnel e dotato di un sistema di acqua micronizzata quando viene utilizzato come misura di sicurezza temporanea.
- Tutte le curve F-N rientrano nella regione ALARP per i diversi volumi orari di traffico investigati: VHP = (a) 1000, (b) 1500, e (c) 2000 veic/h.







Analisi del rischio basata sull'uso dei codici FDS+Evac

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Contents lists available at ScienceDirect

IATSS Research

Research Article

A 3D CFD modeling for assessing the effects of both longitudinal slope and traffic volume on user safety within a naturally ventilated road tunnel in the event of a fire accident

Ciro Caliendo *, Gianluca Genovese, Isidoro Russo

Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II, 132-84084 Fisciano, SA, Italy

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User safety

ABSTRACT

A 3D Computational Fluid Dynamics (CFD) model was set up to investigate the effects of the longitudinal slope on the risk level of users in naturally ventilated unidirectional road tunnels in the event of a fire accident. These tunnels, which in general do not require any mechanical ventilation system, have a length <1 km and their natural ventilation is due to the difference of pressure at the portals and/or the piston effect of the unidirectional traffic flow. Fire accidents related to vehicles characterized by different maximum Heat Release Rates ($HRRs_{max}$), situated at different locations from the entrance portal of the tunnel, were simulated by varying the longitudinal slope (i), as well as by applying both a positive and negative pressure difference (ΔP) between the entrance and exit portals to also consider any adverse wind conditions, or neglecting that (i.e., $\Delta P = 0$). The combined effects of Peak Hourly Volumes (PHVs) were also investigated in the Quantitative Risk Analysis (QRA), which based on a probabilistic approach, considered as a risk indicator the annual cumulative frequency (F) of having a certain number of potential fatalities (N). The longitudinal profiles of temperature, radiant heat flux, toxic gases concentrations, and visibility distance upstream of the burning vehicle along the escape route (i.e., sidewalks) are reported and compared with the acceptability limits to verify if the environmental conditions are tolerable for user safety while escaping from the tunnel towards the entrance portal or the emergency exit located in the middle of the tunnel length. The results showed that the number of dangerous scenarios for user safety increased in the event of adverse wind (i.e., $\Delta P < 0$) and/or negative gradients (i.e., $i < 0$). The QRA indi-cated the combinations of i, ΔP, and PHV for which the annual cumulative frequency (F) of having a given number of potential fatalities (N) was not acceptable. By providing additional points of knowledge in the field of fire safety engineering, this paper might serve in the design of the vertical alignment of naturally ventilated tunnels with a length <1 km, as well as in the strategies of management and traffic control.

PHV	1100 vehicles/h per lane			1750 vehicles/h per lane			2400 vehicles/h per lane		
i \ ΔP	+5 Pa	0 Pa	-5 Pa	+5 Pa	0 Pa	-5 Pa	+5 Pa	0 Pa	-5 Pa
+4%	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
+2%	Acceptable	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability
0	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability
-2%	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Conditioned Acceptability	Not Acceptable
-4%	Conditioned Acceptability	Conditioned Acceptability	Not Acceptable	Conditioned Acceptability	Not Acceptable	Not Acceptable	Not Acceptable	Not Acceptable	Not Acceptable

I risultati hanno mostrato che:

- Il numero di scenari pericolosi aumenta in caso di vento contrario ($\Delta P < 0$) e/o pendenze negative ($i < 0$).
- L'analisi quantitativa del rischio ha mostrato le combinazioni di i, ΔP e volume orario di punta (PHV) per le quali il livello di rischio non è accettabile. Ciò avviene per PHV=1100 veicoli/h per corsia quando i = -4% e ΔP = -5 Pa; per PHV = 1750 veicoli/h per corsia quando i=-4% e ΔP= 0 o ΔP=-5 Pa; per PHV =2400 veicoli/h per corsia quando: i=-4% indipendentemente dalla differenza di pressione tra i portali, e per i = -2% quando ΔP = -5 Pa. Per i restanti casi esaminati, il livello di rischio è accettabile, oppure si riscontrano situazioni di accettabilità condizionata.

Analisi della resilienza di infrastrutture stradali e gallerie

applied sciences

MDPI

Article

Resilience Assessment of a Twin-Tube Motorway Tunnel in the Event of a Traffic Accident or Fire in a Tube

Ciro Caliendo *, Isidoro Russo and Gianluca Genovese

Department of Civil Engineering, University of Salerno, Fisciano, 84084 Salerno, Italy; isrusso@unisa.it (I.R.); ggenovese@unisa.it (G.G.)
* Correspondence: ccaliendo@unisa.it; Tel.: +39-(89)-964140

Abstract: We have developed a traffic simulation model to quantitatively assess the resilience of a twin-tube motorway tunnel in the event of traffic accident or fire occurring within a tube. The motorway section containing the tunnel was investigated for different possible scenarios including its partial or complete closure. The functionality of the road infrastructure, in the case of an accident in one of the two tubes (each tube presents two lanes with unidirectional traffic under ordinary conditions), was assumed to be recovered both by using the remaining undisrupted lane of the tube interested by the disruptive event (only one lane is closed) and reorganizing the traffic flow by utilizing the adjacent tube for bi-directional traffic (both lanes are closed). The effects of an alternative itinerary individualized in the corresponding open road network were also examined. The level of functionality of the system during the period in which the tube is partially or completely closed was computed as the ratio between the average travel time required to reach a given destination from a specific origin before and after the occurrence of the disruptive event. The resilience metrics were assumed to be resilience loss, recovery speed, and resilience index. The best scenario was found to be the partial closure of the tube in contrast to the complete one. However, in order to contain the negative effects on the functionality of the motorway section due to the complete closure of the tube, it is worth highlighting how the traffic by-pass before the entrance portal of the closed tube should be open in a very short time by the tunnel management team to allow for the quick use of the adjacent tube for bi-directional traffic. An additional improvement, with reference exclusively to passenger cars traveling through the adjacent unblocked tube, might be obtained by activating the variable message signs, located at a sufficient distance from the motorway junction before the entrance portal of the closed tube, in order to suggest an alternative route to heavy good vehicles (HGVs) only. Whereas, when the alternative itinerary is used by all vehicles traveling towards the blocked tube (i.e., both passenger cars and HGVs), this redirectioning of the motorway traffic flow was found to be characterized by an excessive travel time, with it therefore not being advisable. The results obtained might be useful as a decision-making support tool aimed at improving the resilience of twin-tube tunnels.

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Citation: Caliendo, C.; Russo, I.; Genovese, G. Resilience Assessment of a Twin-Tube Motorway Tunnel in the Event of a Traffic Accident or Fire in a Tube. *Appl. Sci.* **2022**, *12*, 513. https://doi.org/10.3390/app12010513

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Principali risultati

- Lo scenario migliore corrisponde alla chiusura parziale del fornice rispetto a quella completa;
- In caso di chiusura completa di un fornice, l'apertura tempestiva dei by-pass, i quali consentono l'uso del fornice adiacente per traffico bidirezionale, è tale da ridurre significativamente la perdita di resilienza;
- Sia in caso di chiusura parziale che completa, l'utilizzo di un percorso alternativo per i soli mezzi pesanti rappresenta una appropriata strategia per incrementare la resilienza;
- L'utilizzo di un percorso alternativo per tutti i veicoli in caso di chiusura completa di un fornice non è consigliabile nel caso in cui l'itinerario alternativo è già interessato da traffico intenso perché i tempi di percorrenza risultano elevati.

Analisi del rischio basata sull'uso dei codici FDS+Evac

applied sciences

MDPI

Article

A Simultaneous Analysis of the User Safety and Resilience of a Twin-Tube Road Tunnel

Ciro Caliendo *, Gianluca Genovese and Isidoro Russo

Department of Civil Engineering, University of Salerno, 84084 Fisciano, SA, Italy; ggenovese@unisa.it (G.G.); isrusso@unisa.it (I.R.)

* Correspondence: ccaliendo@unisa.it; Tel.: +39-(89)-964-140

Abstract: This study complements our previous work with a simultaneous analysis of user safety and road tunnel resilience. We developed a computational fluid dynamics (CFD) model and simulated the corresponding egress process to evaluate the risk level of users exposed to different types of fire, such those which might occur on the undisrupted lane of a partially closed tube tunnel due to a traffic accident, or in the adjacent tube when used for two-way traffic in the case of the complete closure of the tube involved in the accident. The CFD results showed that: (i) better environmental conditions were found with the partial closure of the tube rather than the complete one; (ii) additional benefits can be achieved by activating variable message signs (VMSs) that suggest an alternative itinerary for heavy good vehicles (HGVs) only; (iii) safety issues for human health may arise only in the case of a 100 MW fire, occurring during the complete closure of the tube and the use of the parallel one for two-way traffic. The findings of the CFD simulations were subsequently used to perform a quantitative risk analysis (QRA) based on a probabilistic approach. The findings of the QRA were found to be consistent with those obtained by the tunnel resilience analysis. In particular, the lowest risk level for user safety was found with the partial closure of the tube instead of the complete one, and by activating the VMSs to redirect HGVs only towards an alternative itinerary. This finding was found to correspond to a higher resilience index of the tunnel (i.e., a lower resilience loss due to a traffic accident occurring in a tube). This study increases our knowledge on certain relevant aspects of the operating conditions of tunnels and can serve as a possible reference for tunnel management agencies (TMAs) in their choice of the most appropriate arrangement to recover the functionality of a tunnel taking into account both user safety and resilience at the same time.

Keywords: road tunnels; user safety; resilience index; recovery strategies; computational fluid dynamics; quantitative risk analysis

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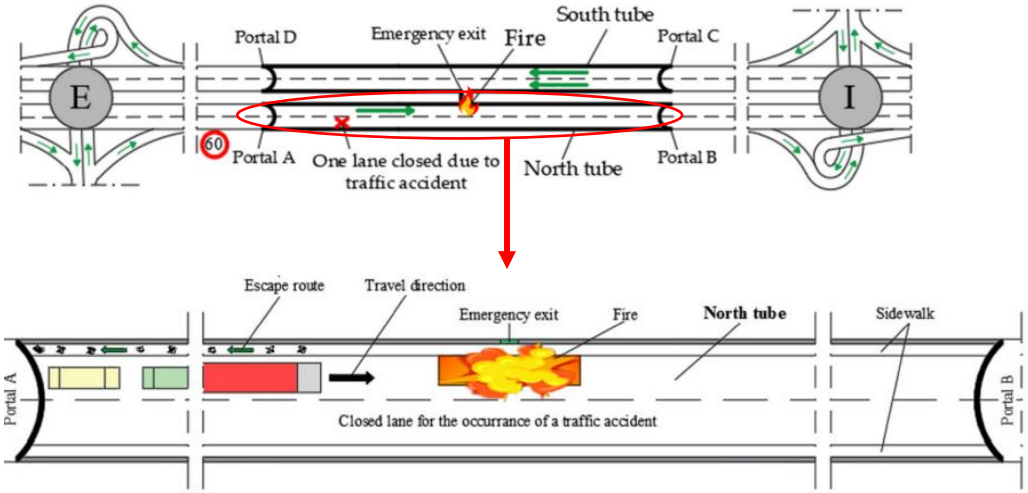
Citation: Caliendo, C.; Genovese, G.; Russo, I. A Simultaneous Analysis of the User Safety and Resilience of a Twin-Tube Road Tunnel. *Appl. Sci.* **2022**, *12*, 3357. https://doi.org/10.3390/app12073357



Principali risultati

- La chiusura completa di un fornice insieme con la strategia di controllo del traffico, che consiste nel deviare i soli mezzi pesanti su un percorso alternativo, è tale da contenere la perdita di resilienza e allo stesso tempo garantire un adeguato livello di sicurezza nel fornice utilizzato per traffico bidirezionale perché è scongiurato il pericolo di incendi di grosse dimensioni che potrebbero essere causati dai veicoli pesanti o da quelli che trasportano merci pericolose.

Analisi del rischio dei veicoli che trasportano idrogeno

Risk Analysis, Vol. 41, No. 9, 2021 DOI: 10.1111/risa.13653

Quantitative Risk Assessment on the Transport of Dangerous Goods Vehicles Through Unidirectional Road Tunnels: An Evaluation of the Risk of Transporting Hydrogen

Ciro Caliendo* and Gianluca Genovese

A quantitative risk analysis (QRA) concerning dangerous goods vehicles (DGVs), including also vehicles for the transport of liquid hydrogen (LH_2TVs), running through unidirectional motorway tunnels was performed. An event tree was built, and a wide parametric analysis based on different geometric and traffic characteristics of tunnels was carried out. The effects of the annual average daily traffic (AADT) per lane, the tunnel length (L), the percentage both of heavy goods vehicles (HGVs) and DGVs (for a given 7% of LH_2TVs) were investigated. The results in terms of social risk, as expressed by *F/N* curves and the expected value (EV), show an increased risk level with the presence of the hydrogen transported, and with certain *F/N* curves that might also lie above the acceptability limit. This means that additional safety measures should be implemented in order to reduce the risk level or that, alternatively, appropriate strategies of traffic control systems should be taken. A statistical modeling for developing a predictive method of the EV is also performed. The outcomes show that the regression coefficients have the signs expected. In particular, the EV increases with the tunnel length (L), the AADT, and the percentage both of HGVs and DGVs. However, the magnitude of estimated coefficients indicates that the expected value EV increases more with the traffic (AADT per lane, HVGs, or DGVs) than the tunnel length. The application of the approximate method might help the Tunnel Management Agencies (TMAs) in making quick decisions, at a preliminary stage, about temporarily allowing, forbidding or limiting the circulation of DGVs and/or LH_2TVs through tunnels; and subsequently investigating in greater depth the potential hazards due to the transport of hydrogen in the worst cases individualized.

KEY WORDS: Dangerous goods vehicles; predictive model; quantitative risk analysis; road tunnels; transport of hydrogen

Principali risultati

- Il valore atteso del rischio (EV) incrementa all'aumentare della lunghezza della galleria, TGM, e percentuale di veicoli pesanti e veicoli che trasportano merci pericolose.
- La presenza di veicoli che trasportano idrogeno liquido può incrementare il livello di rischio di alcune tipologie di gallerie fino a livelli inaccettabili.
- Tale incremento può variare tra il 3% e il 15% fino al 27% se si considera un traffico di $15.2 \cdot 10^8$ tonn · km all'anno.
- Il maggiore incremento di rischio dovuto ai veicoli che trasportano idrogeno è stato riscontrato per bassi valori del TGM e gallerie corte.

Simulazione dello spalling del calcestruzzo dovuto ad un incendio in galleria con il codice FDS

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Research Paper

A 3D computational fluid dynamics model for assessing the concrete spalling of a tunnel lining in the event of a fire

Ciro Caliendo *, Isidoro Russo

Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II, 132-84084 Fisciano, SA, Italy

ARTICLE INFO

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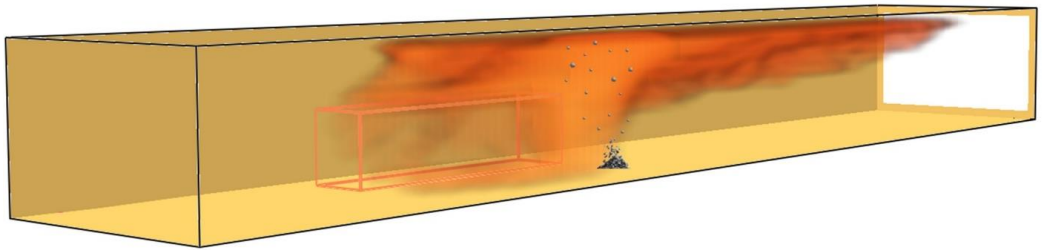
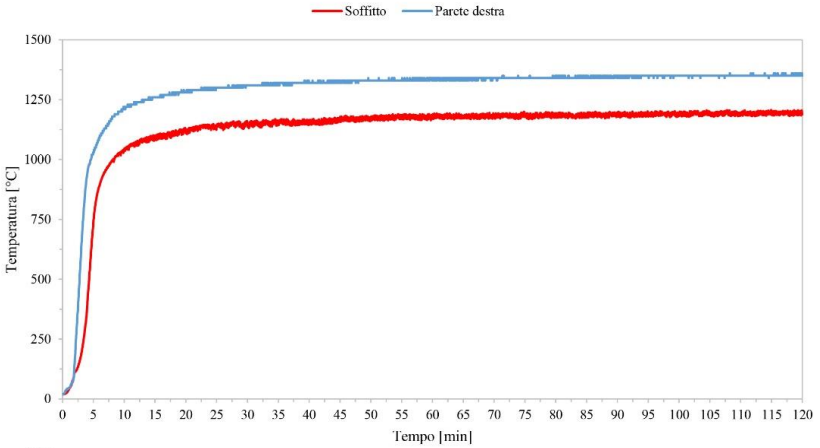
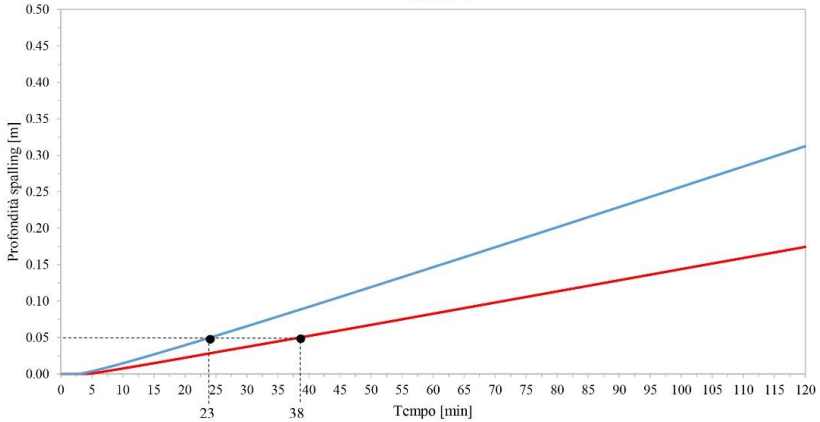
ABSTRACT

A 3D Computational Fluid Dynamics (CFD) model is presented to assess the entity and extension of concrete spalling induced by a fire in a road tunnel, simulating the material loss by means of eliminating elements exceeding a pre-fixed critical temperature. In the proposed 3D CFD model, spalling was assumed to occur when the temperature of the front surface of the infinitesimal elements in which the thickness of the tunnel lining was discretized reaches a pre-fixed critical temperature. The results showed that the fire-induced damage may be underestimated if the material loss in not considered in the spalling analysis. Moreover, the depth and extension of spalling were affected by the value of the critical temperature used as a criterion for element elimination. The maximum depth of spalling at the ceiling was found to be 6–19 cm. The maximum depth of the spalling on the right wall of the tunnel was found to be 17–33 cm. This study increases the state-of-the-art about the entity and extension of the concrete spalling in road tunnels mechanically ventilated, and it can serve to recommend the use of more fire-resistance concretes or fire protection coatings.



I risultati hanno mostrato che, nell'ipotesi che la temperatura di inizio dello spalling sia di 380 °C, la profondità massima dello spalling dopo 2 h dall'inizio dell'incendio è di 30 cm (parete destra) e 15 cm (soffitto).





Alcuni **riferimenti**

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GRAZIE PER L'ATTENZIONE

Prof. Ing. Ciro Caliendo, email: ccaliendo@unisa.it