CHEMICAL ENGINEERING TRANSACTIONS
VOL. 36, 2014
Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
DOI: 10.3303/CET1436055

CFD Simulation of the Release of LN_2 Inside a Tunnel

Roberto Bubbico, Giorgio Falleni, Barbara Mazzarotta*

Dipartimento Ingegneria Chimica Materiali Ambiente, "Sapienza" Università di Roma, Via Eudossiana 18, 00184, Roma
barbara.mazzarotta@uniroma1.it

The present study is aimed at investigating the dispersion of nitrogen accidentally released from a liquefied nitrogen (LN_2) road tanker, carrying 10.6 t of liquid product, inside a model tunnel. Two severe release scenarios have been assumed, with hole sizes 250 and 700 mm, respectively: under these conditions all the LN_2 present in the tanker is completely discharged in a very short time (less than 2 min, for both scenarios). A CFD (Computational Fluid Dynamics) approach was used to simulate cold nitrogen dispersion. The study cases show that the massive release of liquid nitrogen within tunnels may pose serious hazards also in the case of rather short galleries: the combined effect of very low temperatures and oxygen deficiency may impair people eventually present inside the tunnel from leaving their vehicles and escape safely to the open.

1. Introduction

Liquefied nitrogen (LN_2) is transported by road, into containers or in bulk, in special vacuum insulated vessels at temperatures in the range -196 to -155 °C, and corresponding pressures ranging from atmospheric to about 20 bar. LN_2 is classified according to ADR as a hazardous substance belonging to class 2: if released in the environment, it will evaporate rapidly, forming a very cold cloud, with the potential to cause asphyxiation, if local oxygen concentration falls below 15 % vol. In the open, the influence of ventilation will improve mixing with air, which will rapidly increase both temperature and local oxygen concentration, while more problems may arise inside tunnels, where environmental conditions are less favourable to safe cloud dispersion. ADR code rules the passage of dangerous materials through tunnels, classifying these latter into categories ranging from A to E: liquid nitrogen may pass through all tunnels, except those belonging to category E.

Italy is one of the most mountainous Countries in the world, and a great number of tunnels are present along its road network: only 3 of them are longer than 10 km, but more than 350 are longer than 1 km, and thousands are hundreds meters long. Most hazardous materials, including LN_2, are generally allowed to pass through rather short tunnels (length < 500 m) without any restriction.

In the present work two release scenarios involving the dispersion of nitrogen inside a short (400 m) road tunnel will be examined, using Computational Fluid Dynamics (CFD), in order to assess whether the consequences of such accidents may pose a lethal hazard to people possibly exposed to it.

2. Case study

In the case study a release of nitrogen is assumed to occur from a 19 m^3 road tanker (2 m in diameter and 6 m long), carrying 10.6 t of liquid product, at -195 °C: this temperature is 1 °C higher than nitrogen normal boiling temperature (-196 °C), i.e. the pressure inside the container is just above the atmospheric one. The release is from the bottom of the tanker, which is assumed to be placed in the middle of a tunnel, 400 m long and with 90 m^2 section area (maximum width and height 8 and 12 m, respectively), full of air at 15 °C.

Two severe release scenarios have been simulated using ALOHA 5.4.3 (EPA, 2013), assuming hole sizes 250 (case A) and 700 mm (case B), respectively. According to ALOHA results, the nitrogen, escaped from the tanker at high average rates in a very short time (2 min for case A, at 88.7 kg/s and 1 min for case B, at 177.3 kg/s), immediately forms a mixture of gas and aerosol. Taking into account that also the product

Please cite this article as: Bubbico R., Falleni G., Mazzarotta B., 2014, Cfd simulation of the release of ln2 inside a tunnel, Chemical Engineering Transactions, 36, 325-330 DOI: 10.3303/CET1436055

in liquid phase evaporates very rapidly, for the sake of simplicity, the dispersion was modeled directly assuming that the release is in the gaseous phase.

The release location is set at the centre of the tunnel; no ventilation is assumed, and the possible presence of obstacles on the path of the cloud is not taken into account. The cold nitrogen cloud dispersion has been simulated by adopting a CFD approach, using the commercial Ansys Fluent code: a k-ε turbulence model has been adopted, including chemical diffusion and gravitational effects.

The tunnel geometry is modeled using tetrahedric cells, which are usually preferred for curvilinear surfaces. In order to choose the mesh size, some preliminary runs were carried out, which showed that the best compromise between the accuracy of the results and the time required to perform the calculations is obtained with meshes 2 m size; this grid was refined in the release zone, using progressively smaller cells (down to 0.05 m), as shown in Figure 1 for the 0.25 m hole. A total of about 58,000 cells were used to describe the tunnel geometry: such grid resolution is similar to that used in a previous study (Bubbico el al. 2014) concerning the dispersion of toxic chemicals in a 1000 m tunnel, which was modeled using about 72000 meshes, and successfully tested to give grid independent solutions.

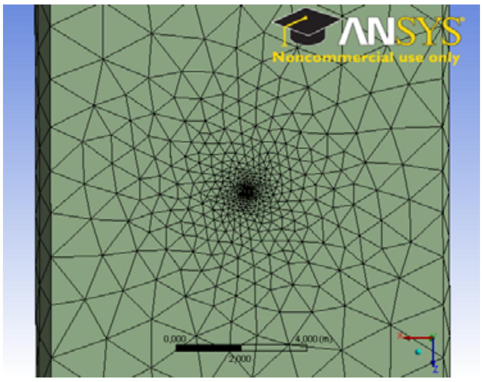

Figure 1: mesh in the proximity of the 0.25 m hole (case A).

The following boundary condition were set: "wall" for walls, ceiling and pavement of the tunnel (assuming a concrete wall 2 m thick) with no heat nor mass flux; "pressure outlet" for tunnel ends, with initial pressure 1 atm and initial temperature 293 K. The turbulence intensity was set as: 10 % for mass flow inlet, with a hydraulic diameter corresponding to that of the hole; 5 % for ambient air at tunnel inlet and outlet, with a hydraulic diameter of 12 m. The temperature of external ambient air was assumed slightly higher (20 °C) than that inside the tunnel (15°C), where initial air velocity and turbulence were set to zero. Discretization method were PISO for pressure-velocity coupling; further details are reported in Falleni, 2013.

Each study case was simulated as a 2 min transient: this time corresponds to the release duration for case A, while, for case B, the release lasts 1 min only: afterwards, the tanker is empty and only the dispersion of the nitrogen cloud occurs. The used time step ranged from 0.001 s, for the initial phase of the dispersion (10 s) to 0.01 s for the remaining time: simulations were stopped 2 min after the release started.

3. Results

With reference to case A, which is the less severe scenario (release from a 0.25 m hole, lasting for all the simulation time) Figure 2 shows the nitrogen concentration profiles on the middle longitudinal plane at 8, 30 and 120 s after the release starts, and that on the tunnel pavement at 120 s. It can be noticed that the gaseous nitrogen, released at the level of the tunnel pavement, has already reached the vault after 8 s: in this early dispersion phase, the effects related to the initial release velocity prevail over the gravitational ones. 30 s after the release starts, cold nitrogen is already stratified on the pavement, reaching a distance of about 65 m from the release point. At the end of the simulation time (120 s) high nitrogen concentrations are observed on the pavement for almost all the tunnel length, even if the cloud has not yet reached tunnel portals; on the middle longitudinal plane, the maximum concentration is always reached on the tunnel vault just over the release point, since the release continues for all the simulation time. However, moving from the release zone toward the tunnel ends, the height of the cold cloud decreases rapidly.

For case B, which is the most severe scenario, all the nitrogen transported in the tanker is released within 1 min; then the dispersion profiles are examined for 1 min further. In the first 60 s (i.e. when the release is taking place), the concentration profiles are qualitatively similar to those of case A, as shown in Figure 3.

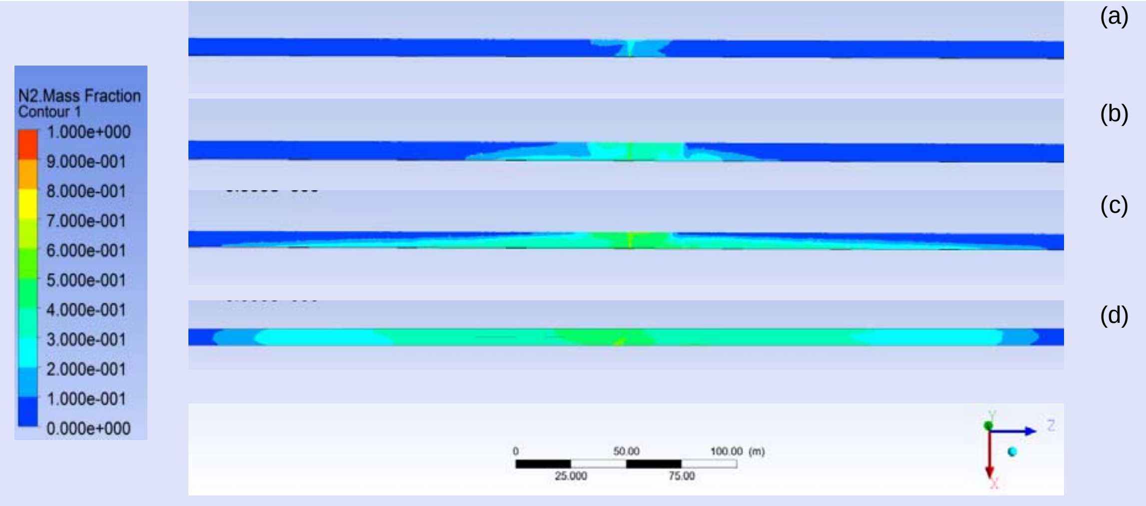

Figure 2: nitrogen concentration for case A: along the middle longitudinal plane of the tunnel: (a) after 8 s; (b) after 60 s,(c) after 120 s; (d) on the tunnel pavement: after 120 s.

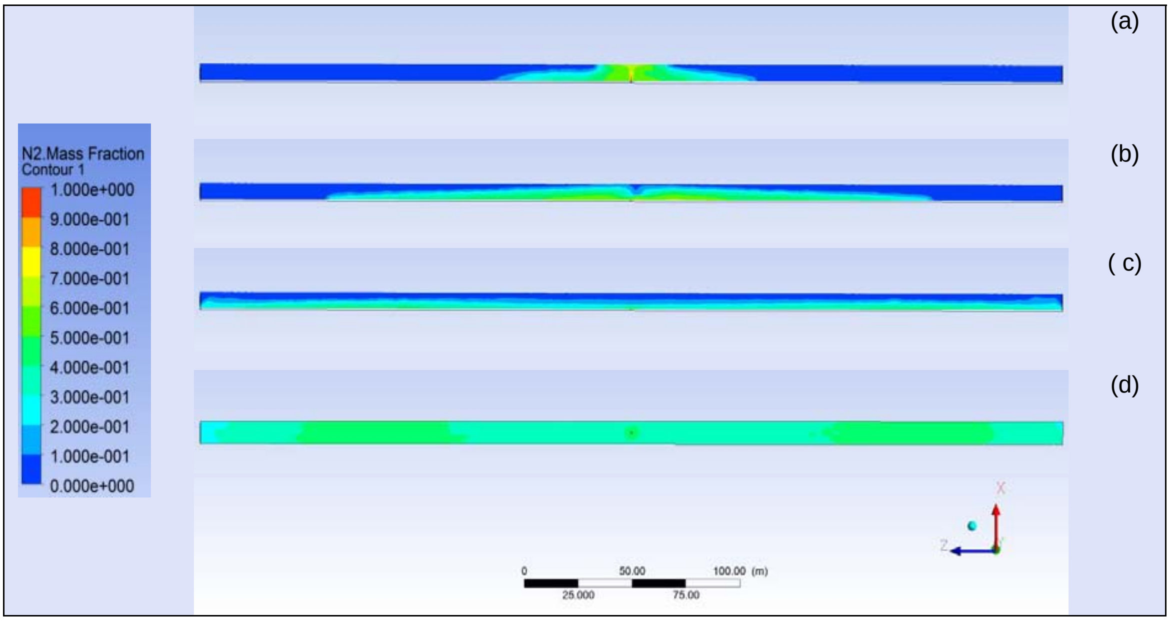

Figure 3: nitrogen concentration for case B: along the middle longitudinal plane of the tunnel: (a) after 30 s; (b) after 60 s,(c) after 120 s; (d) on the tunnel pavement: after 120 s.

However, the concentration values are higher (see Figure 2, for comparison) and the cloud takes up a large portion of the tunnel volume. In fact, 60 s after the release starts, cold nitrogen has already spread over about 70 % of the tunnel length and, afterwards, it continues to move towards the tunnel ends, even if at a reduced velocity, progressively stratifying over the pavement. As a matter of fact, as the release stops, nitrogen concentration on the tunnel vault reduces rapidly to zero. At the end of the simulation (120 s), the nitrogen cloud has reached the tunnel portals, stratifying in the lower third of their height (see Figure 4). Inside the gallery, after the release stops, the minimum height of the cold nitrogen cloud is around 2.1 m, i.e. higher that the height of an average person.

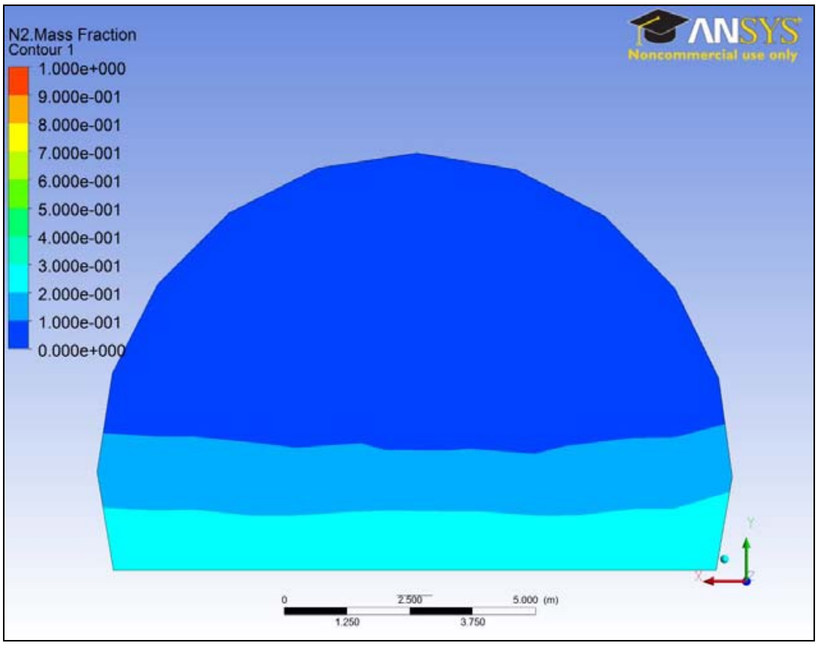

Figure 4: nitrogen concentration for case B after 120 s at the tunnel portals.

Temperature profiles were examined as well (Falleni, 2013) and are shown in Figure 5 at time 60 s: of course, their general trend reflects that of nitrogen concentration, taking into account that the released product is very cold (78 K ≅ -195 °C). Accordingly, the minimum temperature inside the tunnel is observed in the release zone, and it is as low as 140 K (-133 °C). For case A, in a portion of tunnel about 40 m long, for all the simulation time, the temperature is below 170 K (-103 °C). For case B, as long as the release takes place, a not negligible portion of the tunnel (about 40 m long after 30 s) experiences very low temperatures, ranging from 120 to 140 K (from -153 to -133°C). When the release stops (at time 60 s), the low temperature zone has already become considerably larger, and, afterwards it progressively extends to the whole tunnel, with temperatures around 220 K (-53°C): the temperature remains low due to the poor heat exchange efficiency with the surrounding air, especially after the end of the release, when the cloud slows down.

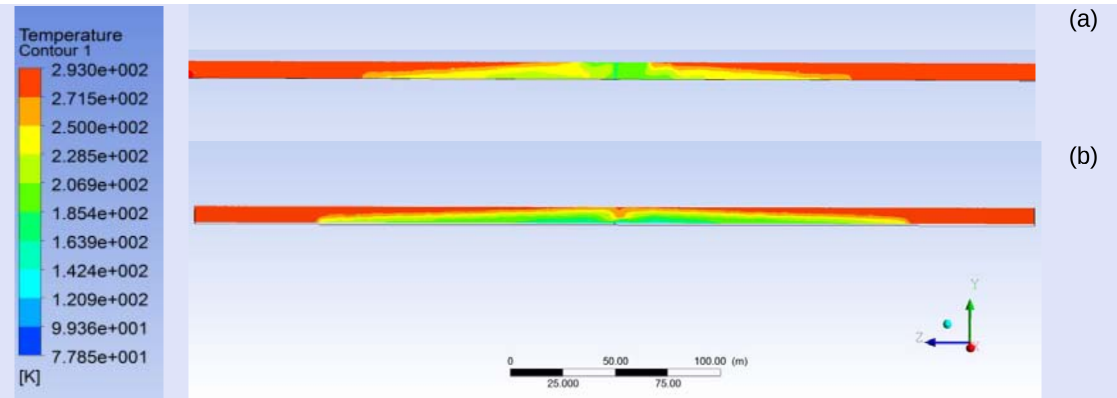

Figure 5: temperature profiles for along the middle longitudinal plane of the tunnel after 60 s; (a) case A; (b) case B.

4. Discussion

Modeling the release of a liquefied gas inside a tunnel is not an easy task and, as a matter of fact, up to now, the attention of the researchers appears to be mostly focused on general fire hazard inside tunnels. The literature reports the results of some experiments carried out within instrumented tunnels, either on reduced (Lönnermark & Ingason, 2005; Vianello et al., 2012) or full scale (Eureka, 1995).A number of CFD simulation works calculating the profiles of temperature and combustion products concentration are also available: Woodburn and Britter (1996) simulated a tunnel fire, Hu et al. (2006) and Zhen and Ingason (2012) estimated the maximum ceiling temperature, Migoya et al. (2011) focused on the heat release rate, and Wang (2012) examined the propagation of heat and smoke in a full-scale tunnel. On the contrary, just a few works, concerning CFD simulation of the dispersion of low-temperature toxic substances in tunnels are reported, and, according to the author's knowledge, no experimental data are available. Hall (2001) studied the release of chlorine in a tunnel, emphasizing that the results provide only a qualitative picture of some aspects of the dispersion; Bubbico et al. (2014) modeled the release of ammonia and chlorine in a tunnel, pointing out some interesting aspects (for example, the influence of gas density and diffusivity) and giving a preliminary contribution to the study of cold toxic gases dispersion in tunnels. The present work, which is based on a similar approach, is mainly oriented at understanding whether the massive release of liquid nitrogen may represent a hazard to people inside a tunnel where transit of such tankers is not subject to any limitation.

From this point of view, the results of the simulations point out that people eventually present in a rather large portion of the tunnel may be exposed to the threats of asphyxiation, due to the high concentration of nitrogen (especially in the correspondence of the tunnel floor), which markedly dilutes the oxygen content in the air, and that of low temperature. When oxygen concentration falls below 18 % vol., the volume of inspired air decreases and the heart accelerates its beats; below 15-16 % vol. people feel dizzy, experience fatigue, apnea, and difficulties in coordinating movements and in taking decisions (AIDI 2010); a further decrease of oxygen concentration causes faint and, after some time, death.

With reference to the most severe accident (case B), 1 min after the release beginning, a mass concentration of nitrogen in the range 30-40 % is established along about 300 m of the tunnel (see Figure 3), from the pavement to a height (2.1 m) higher than that of an average person. The increased concentration of nitrogen gives rise to a remarkable decrease of residual oxygen concentration, which, in that region, will range from 12.5 to 14.6 % vol., values which are largely insufficient to sustain an effective respiration. Therefore, it is likely that exposed population will encounter serious obstacles to undertake the proper actions to protect themselves and safely escape from the tunnel. Asphyxiation risks are noticeably reduced by decreasing the scale of the accident. For the less severe release (case A) a much smaller extension (40 m) of the tunnel portion with a dangerously high nitrogen concentration is observed (see Figure 2); moreover, moving from the release point, the height of the stratified nitrogen cloud becomes rapidly lower than that of an average person.

Low temperature may cause hypothermia and exposure, for body temperatures below 35 and 24-26 °C, respectively: the former condition is reversible, but the latter is irreversible and lethal for its effects on heart and respiratory functionality. The individual capacity to withstand very low temperatures may be variable and is affected by factors such as humidity and air velocity: in the literature (Parmeggiani, 1983) the level of hazard has been related to the Equivalent Chill Temperature (ECT), as shown in Table 1.

Table 1: Equivalent Chill Temperature (ECT) and its effect on exposed people

ECT	Hazard
> 0°C	Null
-30°C < ECT < 0°C	Limited: false self confidence, which may cause impulsive behaviors
-58°C < ECT < -30°C	Moderate: may cause freezing of the exposed parts of the body within 60 s
ECT < -58°C	High: rapid freezing within 30 s of exposure

In the case of absence of wind, as assumed in the present study case, ECT values coincide with the actual temperature. With reference to the study cases, where no forced ventilation is assumed, in both cases very cold temperatures (below -100 °C) are reached in a tunnel portion about 40 m long centered on the release point (see Figures 5 and 8). Such temperatures may cause severe impairing effects to the population, especially in the case of the larger release, since almost all the tunnel will be at temperatures as low as -50 °C.

Based on the above results, it is clear that people directly exposed to a LN_2 release inside a tunnel (for example, those trying to escape on foot, rather than staying inside their vehicle), will be at high risk of suffering very serious damages, due to both low oxygen concentration and low temperature. Furthermore, under the assumed accidental scenarios (which are not unlikely in case of a road accident) the dangerous conditions will establish in a very short time, comparable with, or even shorter than, the reaction time which can be expected from scared and untrained people.

5. Conclusion

The release of a liquefied gas inside a tunnel is something rather different, and much less studied, than a tunnel fire: modeling problems arise due to the rapid phase change occurring after the discharge and to the low temperature, which implies gravitational effects; moreover, the results of the simulations cannot be presently compared with experimental data. Accordingly, any work on this subject can be regarded as a preliminary study and the results, although computationally correct, may be subject to uncertainties deriving from the adopted simplifying assumptions. However, the present study shows that, even inside a rather short tunnel (400 m), a large spill of liquid nitrogen may cause severe consequences to people in transit, since the oxygen concentration will fall below 15 % and the temperature below -50 °C in a large portion of the tunnel. Asphyxiation risk appears particularly high in the proximity of the release zone, where the very low temperatures (below -100 °C) will also severely impair people capability of leaving their vehicles and escaping on foot toward the tunnel ends. Remaining inside the vehicle, with external air circulation closed, until temperature and oxygen level rise again, can be the most effective way to safely escape from the consequences of such an accident. These preliminary results make evidence that LN2 tankers may represent a not negligible risk source inside a tunnel. However it is believed that this issue still requires a more detailed analysis removing the presently adopted simplifying assumptions: in particular, the influence of the large aerosol fraction should be assessed, and the likely presence of obstacles, of a slope of the tunnel, and of the ventilation system should also be introduced in the simulations.

Acknowledgements

The authors are indebted with Benedetta De Caprariis for her contribution to the set-up of the CFD model.

References

AIDII, 2010, TLV e IBE ACGIH 2010, Italian Journal of Occupational and Environmental Hygiene, 1,1, Supplemento, 214-220.

Bubbico R., Mazzarotta B., Verdone N., 2014, CFD Analysis of the Dispersion of Toxic Materials in Road Tunnels, Journal of Loss Prevention in the Process Industries, 28, 47-56.

EPA, Environmental Protection Agency, Office of Emergency Management, 2013, ALOHA 5.4.3.

Eureka, 1995, Fire in Transport Tunnels: Report on full-scale tests, EUREKA-Project EU499: FIRETUN studiengesellshaft Stahlanwendung eIV. D - 40213 Dusseldorf, Germany.

Falleni, G., 2013, Simulazione CFD di dispersione di azoto a seguito di incidente ad autocisterna in galleria, Tesi di laurea magistrale in Ingegneria Chimica, Università di Roma “La Sapienza”, Rome , Italy.

Hall, R. C., 2001, Modelling Dense Gas Dispersion in tunnels, Contract Research Report 359/2001, WS Atkins Consultants Limited, Crown, Norwich; Great Britain.

Hu, L. H., Huo, R., Peng, W., Chow, W. K., & Yang, R. X., 2006, On the Maximum Smoke Temperature Under the Ceiling in Tunnel Fires. Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research, 21(6), 650 - 655.

Lönnermark, A., & Ingason, H., 2005, Gas Temperatures in Heavy Goods Vehicle Fires in Tunnels, Fire Safety Journal, 40, 506-527.

Migoya, E., Garcia, J., Crespo, A., Gago, C., Rubio, A., 2011, Determination of the Heat Release Rate Inside Operational Road Tunnels by Comparison with CFD calculations, Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research, 26(1), 211-222.

Parmeggiani, L., 1983., Encyclopaedia of Occupational Health and Safety, International Labour Office, Ginevra, Switzerland.

Vianello, C., Fabiano, B., Palazzi, E., Maschio, G., 2012, Experimental Study on Thermal and Toxic Hazards connected to Fire Scenarios in Road Tunnels, Journal of Loss Prevention in the Process Industries, 25, 718-729.

Wang, H. Y., 2012, Numerical and Theoretical Evaluations of the Propagation of Smoke and Fire in a Full-Scale tunnel, Fire Safety Journal, 49, 10-21.

Woodburn, P. J., & Britter, R. E. (1996). CFD simulations of a tunnel fire part I. Fire Safety Journal, 26(1), 35-62.

Zhen, L. Y., Ingason, H., 2012, The Maximum Ceiling Gas Temperature in a Large Tunnel Fire, Fire Safety Journal, 48, 38-48.