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The use of Natural Gas Vehicles in underground facilities: Application to the PARIS-LA-DÉFENSE underground network

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ABSTRACT

Considering the current strong development of natural gas vehicles and their use in many underground infrastructures, this paper focuses on the corresponding risk induced in such situations. It consists in applying the analysis of the consequences of the huge and complex underground network of the La Défense business center, in the suburbs of Paris. The different types of natural gas vehicles were considered, compressed natural gas (CNG) and liquified natural gas vehicles (LNG). Based on existing knowledge in risk analysis, the main dangerous phenomena that can occur for those vehicles, jet fire, vapor cloud explosion, and tank burst, were all considered and modeled for each technology. To evaluate the release source term, the very beginning for both jet fire and flammable cloud characterization, the classic gas release model was used while considering the pressure decrease in the tank to get the mass release time variation. This was mainly interested in estimating the resulting jet fire heat release rate and duration and the corresponding impact on the global heat release curve. As far as vapor cloud explosion (VCE) is concerned, the worst-case situation, more precisely the largest flammable mass is obtained in the first seconds following the release beginning. The specificity for VCE represents the tunnel confinement's influence on the pressure wave propagation. In such an environment, the commonly used multi-energy approach, based on semi-spherical wave propagation is inappropriate, reflexion phenomena should be introduced to provide a better prediction. The consequence modeling shows that, for both technologies, the worst dangerous phenomena remain the tank burst, especially for LNG where the lethal effect may affect most of the people present in the tunnel, for CNG lethal effect should reach 30 m and more for the same tank burst scenario. This huge consequence highlights the importance of preventing its occurrence through the efficiency of dedicated safety measures but also fire prevention since such a tank burst is induced by a fire in the surrounding of the tank. For the jet fire case, the consequences are a global vehicle heat release rate increase, during the gas release, while this could influence the efficiency of the tunnel ventilation, this does not significantly modify the thermal consequences for people. Regarding the vapor cloud explosion, lethal overpressure would affect passengers of the few closest vehicles for LNG and users in an area of 4 to 20 m centered on the vehicle for CNG.

KEYWORD: natural gas for vehicle, jet fire, vapor cloud explosion, tank burst

INTRODUCTION

According to the current global warming, new energy carrier vehicles are currently under strong development. While electric vehicles represent a large proportion of clean vehicles, natural gas vehicles present some advantages since they could provide a larger range and faster charging. They are consequently used to improve public transport solutions in many cities worldwide. In the specific case of Paris, natural gas vehicles represent a significant proportion of clean vehicles to be used in the coming years. Consequently, the safety aspect due to those vehicles should be addressed and,

considering underground facilities could increase the consequences of each accidental situation, those facilities represent a key issue for that new energy carrier development. One of the most complex underground networks near Paris is the La Defense business center, evaluating the influence of using such natural gas vehicles in such an environment is then a challenge. The present paper summarises the evaluation that was achieved. While the key issue concerns bus circulation, the different types of vehicles were considered, by the specific characteristics of all tunnels.

After presenting the natural gas vehicle characteristics, in terms of gas quantity, safety system, and proportion on the road, and the main characteristics of the tunnels in the La Defense-center, this paper focuses on risk evaluation. Regarding this evaluation, for each technology, compressed natural gas, and liquified natural gas, the release mass flow rate computation is first detailed since its importance for jet fire and vapor cloud explosion. Those two last phenomena are then characterized using an algebraic approach, integral model, and specific tools, mainly for wave propagation since free field wave propagation correlation cannot be used in a such confined environment. The tank burst consequences are then evaluated, taking into account, once more, the influence of confinement on those consequences.

VEHICLES AND INFRASTRUCTURES CHARACTERISTICS

Natural gas vehicles

Natural gas as an energy carrier for vehicles evolve quickly, then the first step to evaluate potential accident consists in identifying and determining key characteristics of natural gas vehicles. First, the two fuel storage possible conditions should be distinguished, the most commonly used solution nowadays remains compressed natural gas (CNG) but liquified natural gas (LNG) is under development for long-distance applications, typically for trucks or buses. In CNG vehicles, natural gas is stored in gaseous form compressed to 200 bar while LNG vehicles use cryogenic tanks where the gas is cooled to -162°C at (or near) ambient pressure. According to the current market, CNG is considered for all types of vehicles, i.e., cars, trucks, and buses, while LNG is considered only for trucks and long distances buses.

The gas quantity in CNG vehicles is an important parameter that strongly varies. For cars, the gas quantity typically varies by a factor larger than two, between 8 kg in a Dacia Duster GNV to 19 kg in an Audi A4 G-Tron. When including light commercial vehicles, less than 3.5 t in this list, the mass of gas could reach 70 kg with the Piaggio NP6. For trucks and buses, the gas quantity is larger again, reaching up to 250 kg. Using LNG leads to doubling the natural gas mass in the tanks.

To provide first information about the probability of an accident involving natural gas vehicles, their proportion on the traffic should be considered. An analysis achieved in France [1] mentions that 27,000 natural gas vehicles were used in France in 2021 august the first, for a total number of vehicles of around 45 million, this means that natural gas vehicles, mainly CNG currently represent about 0,05%. The expected number of natural gas vehicles is 54,000 in 2028. This average proportion should however be used carefully since CNG is more used for infrequent vehicles, Figure 1, having in mind that cars represent 70% of the used vehicles. The proportion of natural gas light commercial vehicles is typically bout 0,15%, representing three times the average value. Furthermore, due to the clean public transport policy, natural gas buses are more and more used and may represent a significant proportion of buses in the coming years.

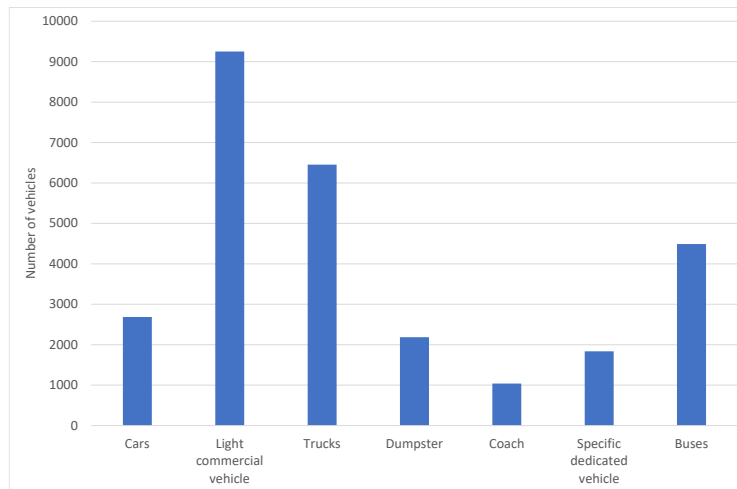


Figure 1: Natural gas vehicles for various categories.

The La Défense underground network

The public institution "PARIS LA DEFENSE" manages the whole development of the business district of La Défense near Paris. Due to its design inherited from the 60s with a pedestrian slab, the district includes numerous underground infrastructures from quite classic tunnels to multipurpose underground structures. A map of the La Defense center is reproduced in Figure 2.

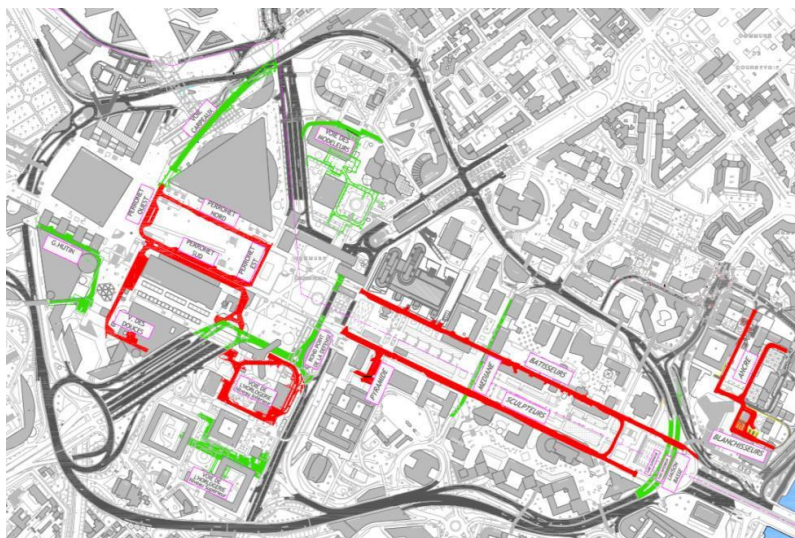


Figure 2: La Defense district, tunnels, and underground facilities are marked in red or green.

The tunnel characteristics vary between each in terms of dimensions, length varies typically for about 100 m to 800 m, in terms of traffic, between around 150 veh/j to more than 20 000 veh/j but also in terms of proportion of each type of vehicle with some tunnels dedicated to buses, some with numerous delivery zones, i.e., a large proportion of light commercial vehicle and trucks with few cars and some with a large majority of cars. Furthermore, the potential number of people that could be inside the tunnel in case of an accident having in mind that bus stops are in some tunnels.

RISK ANALYSIS FOR CNG AND LNG VEHICLES

Before going any further in risk evaluation, identifying dangerous phenomena for each natural gas technology is mandatory. This paragraph describes the identified phenomena for both CNG and LNG.

CNG vehicles

As mentioned earlier, CNG consists in using natural gas stored in a pressurized manner, around 200 bars. The main safety measure for this type of storage is a TPRD (Thermally Pressure Release Device) that consists of a venting line automatically opened, after a certain delay, when the surrounding temperature reaches 120°C. using, commonly, a eutectic metal. Specific risk analysis was proposed in the literature and shows that new dangerous phenomena should be considered when such vehicles are present [2][3].

The first event that should then be considered is a leak on the gas line that could be induced by either a breach on this line or an undesired opening of the venting line. Such an event would induce a pressurized gas release with either a jet fire, in case of immediate ignition or a vapor cloud explosion (VCE) in case of delayed ignition. In this second case, VCE, a jet fire can be formed after the explosion, but the associated flow rate will be reduced since a significant proportion of the gas would be involved in the explosion.

Another phenomenon to be considered is the tank burst that could result in a choc that reduces its mechanical resistance of it, or a surrounding temperature rise, i.e., a pressure rise in the tank, together with the venting line opening system failure.

LNG vehicles

The number of risk analysis studies is less numerous in the literature while previously mentioned papers provide some valuable information.

It should be first reminded that the safety system to prevent pressure rise in the tank differs from the CNG one, pressure valve is used for the LNG tank, which means that the physical quantity that triggers the safety system differs between the two systems. However, potential additional dangerous phenomena are quite similar. The first event to be considered is consequently an unexpected opening of the safety line that implies LNG release. Such a release may then imply a jet fire or a VCE depending on the ignition sequence. A burst of the tank remains also possible in case of tank heat exposure and safety valve(s) non-opening.

CONSEQUENCES MODELING FOR CNG VEHICLES

Evaluation of the mass flow rate

As discussed in the previous paragraph, for both CNG and LNG vehicles, jet fire, vapor cloud explosion, and tank burst were considered and modeled. For both jet fire and vapor cloud dispersion and explosion, the first step consists in determining the mass flow rate evolution and leak duration considering the evolution of the physical conditions in the tank. Then, based on this mass flow rate, jet fire consequences and explosive mass can be estimated.

The mass flow rate is estimated based on the tank pressure, the estimated release diameter, 2 or 4 mm, based on the Birch model [4]. To use such a model, it should be first evaluated whether the flow is choked or not:

$$\frac{P_{res}}{P_{amb}} \geq \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

Then the mass flow rate through the opening is computed:

$$q_g = C_d \times A_b \times \psi \times \sqrt{\rho_g \times P_{rés} \times \gamma \times \left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}$$

Where ψ is 1 if the flow is choked and, if the flow is not choked, is:

$$\psi = \sqrt{\frac{2}{\gamma - 1} \times \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} \times \left(\frac{P_a}{P_{rés}}\right)^{\frac{2}{\gamma}} \times \left(1 - \left(\frac{P_a}{P_{rés}}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

At each time step, the released mass is removed from the tank and the new resulting pressure inside the tank is estimated to get the mass flow rate evolution over time. An example of such mass flow rate evolution is reproduced hereafter in Figure 3.

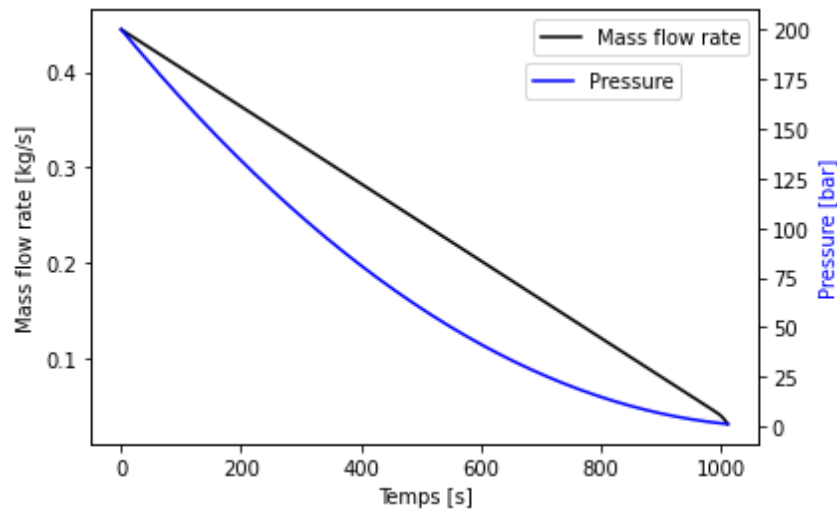


Figure 3: Example of mass flow rate evolution, case of a 245 kg tank, release through a 4 mm diameter.

In this approach, the tank cooling effect that results from the leak is neglected, leading to a slightly overestimated flow rate after a certain amount of time. The source term for explosive cloud formation and jet fire is known.

Jet fire modeling

Jet fires should be considered in two aspects: the consequences of the jet fire itself and its influence on the global heat release rate (HRR), which could, for underground infrastructure, modify the ventilation design.

For cars and vehicles with downward-directed openings, Regarding the consequences of the jet fire itself, an integral approach was developed. This approach is based on a representation of the jet fire by two horizontal flames assuming that the flow deviates when impinging the ground, Figure 3. The flame length is estimated by assuming that the mass flow rate is divided into two flames.

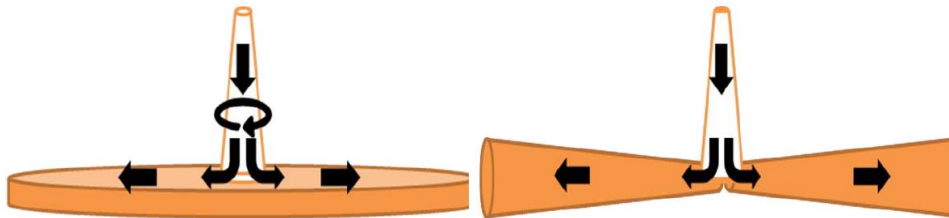


Figure 4: Schematic view of the jet fire simplified model.

Two configurations were modeled, with the same 200 bar pressure inside the tank, but two different diameters, 2 and 4 mm. Those two cases lead respectively to 116 and 465 g/s flow rate and flame length of 3.4 and 6.2 m. The associated flame length for such a case would be respectively 3.4 and 6.2 m, those values correspond to the safety distance.

On top of the jet fire itself, the influence of the gas release on the global vehicle fire should be considered. An example of such a modified curve is plotted hereafter in Figure 4.

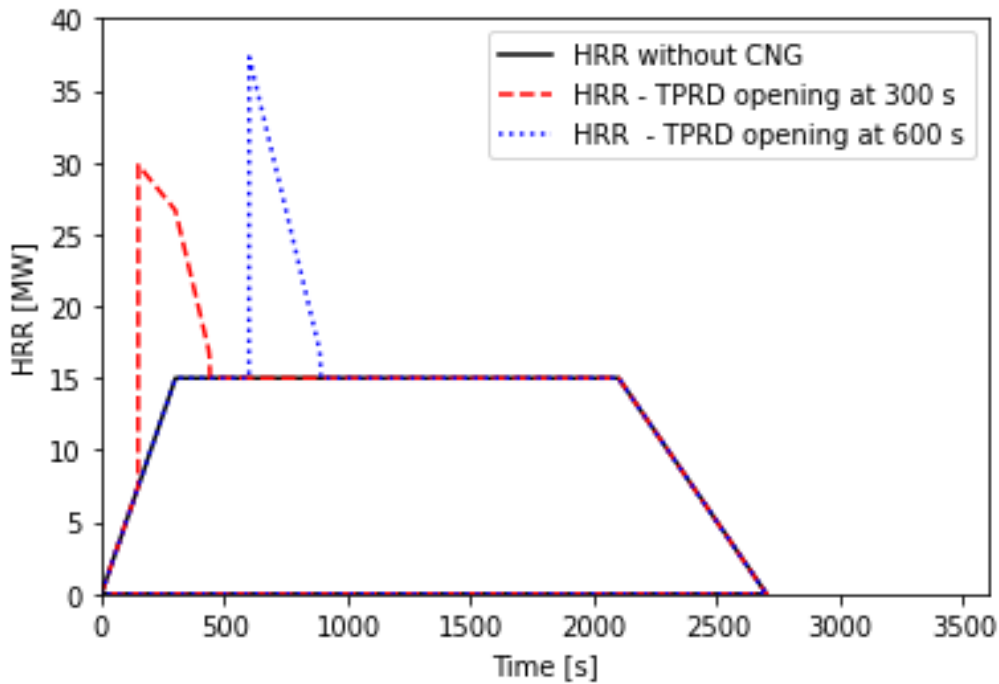


Figure 5: Example of modified HRR curve for a light commercial vehicle with 70 kg of gas.

While the evaluation of the impact of the jet fire on the HRR for ventilation design purposes is just a conversion of the mass flow rate in terms of HRR based on the heat of combustion, the specific consequences of the jet fire itself should be specifically addressed. This was done using both an adapted integral approach and a computational fluid dynamics model to consider the specific characteristics of the underground facilities, mainly the geometry.

Vapor cloud explosion

Considering the vapor cloud explosion, a dispersion model, coupled with experimental data, enables determining the flammable mass. Then, the multi-energy method [5] is used to determine the initial explosion pressure. Having in mind that the multi-energy curve corresponds to hemispheric wave propagation in an open environment, a semi-empirical wave propagation code was used to predict the overpressure distribution in the infrastructure.

To evaluate the flammable mass, the integral tool Phast [6] was used. The code enables computing the gas dispersion in a given airflow. The velocity profile was set to flat with a constant value along the tunnel height for this specific application. The source term in the code is represented by the tank itself, at a given pressure with a leak diameter, it includes a mass flow rate module that enables computing the leak characteristics based on the initial tank conditions that lead to the worst situation. This first step provides the flammable cloud characteristics including the gas concentration, Figure 5, and the flammable mass. The computed flammable mass for this 4 mm in-diameter case is about 20 g.

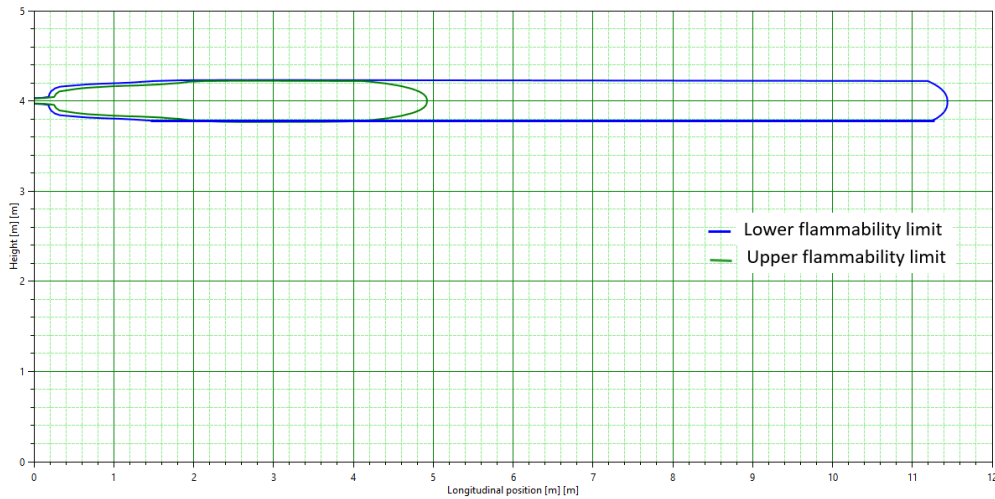


Figure 6: Example of gas concentration in case of TPRD opening, flow velocity 1 m/s, 4 mm in-diameter, pressure 200 bar.

This approach is then simplified and does not consider the possible jet impingement on the tunnel walls or ceiling. The resulting flammable mass would be strongly modified in such a case. Experimental data indicate that the multiplication factor between a free jet and impinging one would be between 2 and 10 [7]. Therefore, to take into account the possible jet impingement in this risk evaluation, 10 was chosen as the multiplication factor to cover all the situations including the worst one. The flammable mass for impinging the jet was then fixed to 10 times the free jet one, which means 200 g.

One of the key issues of the multi-energy model consists in determining the explosion level that gives the initial overpressure. To ensure representation of the worst possible situation, level 6 was considered for the multi-energy simulation, such a level implies an initial maximal overpressure of 500 mbar. Reminding that the multi-energy method is based on hemispheric flame propagation, a specific model, DIFREX, that includes wave reflection on structures was used. This model is based on the same propagation correlations but with considering reflection phenomena. An example of overpressure resulting from such a VCE is plotted in Figure 6.

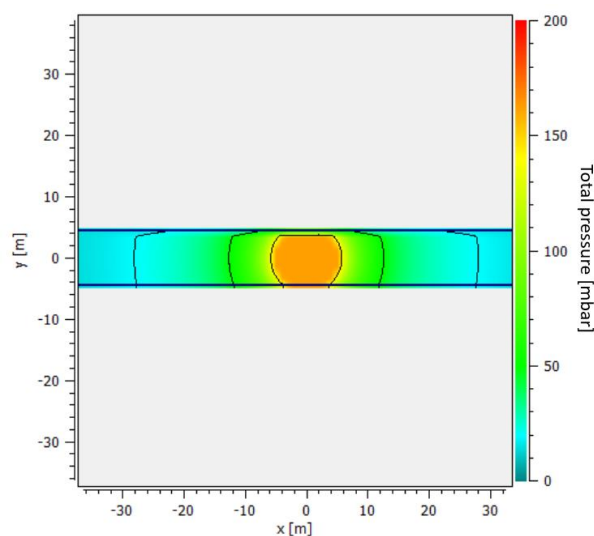


Figure 7: Overpressure in the tunnel, top view, for a 200 g of flammable mass explosion.

This modeling enables one to conclude that the significant lethal effects (200 mbar according to the French regulation), remain in the close vicinity of the vehicle, typically 4 m for the impinging situation. These distances are similar for all types of vehicles since the flammable mass is governed by the release diameter and the tank pressure which do not differ from one type of vehicle to another one.

It should be noted that, given the unavoidable uncertainties of the modeling, the value evaluated in the CETU/INERIS study in the general case [3] is considered a high estimate (20 m). The tunnel length considered for significant lethal effects is therefore 4 to 20 m.

Tank burst

A similar approach is used to model the consequences of tank bursts. The initial pressure is given by the tank characteristics and the semi-empirical code enables evaluating the overpressure distribution in the tunnel. Given the potentially severe consequences of such an event, the delay before the tank burst is also estimated for a range of situations, based on available experimental data, and using thermodynamic analysis.

These simulations should be translated in terms of risk, considering the presence of people in each infrastructure. Then, an occurrence probability should be estimated considering the probability of the initial event, for example, the sudden opening of a thermally activated pressure release device, with or without ignition, and the estimated traffic data for natural gas vehicles.

A similar approach has been conducted for indirect risk, evaluating the potential consequence of a distant fire, modeled thanks to a classical CFD approach, on a natural gas vehicle. Then, when required, the specific consequences induced by the natural gas vehicle, such as a tank burst typically, were estimated with the same approach as for the direct risk.

CONSEQUENCES MODELING FOR LNG VEHICLES

Jet fire

For the LNG case, the main important data is that the pressure inside the tank is close to the atmospheric one, the product is maintained in the liquid phase thanks to the cooling, and the temperature is about -160°C. When considering a 4 mm in-diameter hole, the opening section of the pressure valve, and assuming a full liquid flow through this valve, the mass flow rate would be about 21 g/s, leading to a 1 MW fire. For a cryo-compressed tank, with a product stored at 10 bars and -120°C, the mass flow rate would increase to 33 g/s, which means a 1.5 MW jet fire. The jet fire itself does not have any specific consequences that differ from the vehicle fire.

The main difference with CNG which lead to quick emptying is the LNG tank emptying would take about 1 hour, meaning that the global heat release rate for the vehicle fire would be 1 to 1.5 MW increased during the whole fire duration.

Vapour Cloud Explosion

Based on the same mass flow rate, 21 g/s, the flammable mass was estimated to be 45 g thanks to the Phast tool. Considering the multiplication factor for impinging jet, the flammable mass would reach 450 g. Based on the same approach as for CNG, i.e., coupling the multi-energy method to determine the initial overpressure and the wave propagation code DIFREX, the overpressure evolution in the tunnel can be computed, and distances are quite similar to those estimated for CNG.

Tank burst

This situation corresponds to a failure of the pressure valve to prevent the tank burst in case of fire in the surrounding. In such a case, the product inside the tank will be heated and, consequently, the pressure inside the tank will rise, following the vapor pressure curve. For cryogenic storage, the tank sizing leads commonly to a 16 bar pressure resistance. Reaching 16 bar inside the tank implies the product reaches -113°C in terms of temperature, which means about 50°C heating. When the tank resistance is no more able to resist the internal pressure, the tank will open, releasing the whole product mass into the ambient, having in mind that, in ambient conditions, the product would be gaseous and not liquid, it will consequently vaporize immediately and form a fireball, this is typically a BLEVE phenomenon.

When such an event occurs, it induced two different types of consequences, overpressure and thermal. The overpressure consequences can be estimated in that case using a classic tank burst approach based on the Brode Energy [8] expressed by:

$$E_{Brode} = \frac{(P_{rupt} - P_0) \cdot V}{\gamma - 1}$$

In this equation, P_1 is the tank burst pressure, P_0 is the ambient one, and V is the tank volume and γ the heat capacities ratio of the pressurized gas. According to the tank volume and pressure, the resulting Brode energy remains small enough to have neglectable pressure consequences for this phenomenon, except in the close vicinity of the vehicle.

The second type of consequence, the thermal effect, is more difficult to estimate. Some BLEVE models are available [5] but consider that the fireball is developing in a free environment. Such an approach might be adapted for tunnel application considering that the volume of the fireball will be maintained in the tunnel, but the shape will change. It is important to note here that this approach may overestimate the fire volume since the air entrainment will differ in the tunnel situation, this is not included in the model. This however enables getting some order of magnitude of the potential consequences through the tunnel length potentially affected by the flame. It depends on the tunnel section; some examples of results are provided hereafter in Table 1.

Tank volume [m ³]	Fireball computed volume [m ³]	Tunnel section [m ²]	Tunnel length potentially affected by the flame [m]
0,9	69 500	50	1 390
0,9	69500	120	580
0,7	54 000	50	1 080
0,7	54 000	120	450

Table 1: Example of tunnel length potentially affected by the fireball in case of LNG tank BLEVE.

While some uncertainties remain according to the precise characteristics of the events, these results show that such a tank burst in a tunnel would have dramatic consequences, most of the people located in the tunnel when it occurs would be exposed to lethal effects.

Hopefully, BLEVE is not an instantaneous phenomenon and, depending on the surrounding fire intensity, it would occur after several minutes.

CONCLUSIONS

This paper addresses the risks induced by introducing natural gas vehicles in tunnels, using the various characteristics of the La Defense underground network. Based on the modeling of the three main dangerous phenomena, jet fire, vapor cloud explosion, and tank burst, it shows that:

- for CNG and LNG vehicles, the jet fire's significant lethal effects remain in the vicinity of the natural gas vehicle itself, whatever the vehicle is, which may be an issue for non-empty buses.
- for CNG, the significant lethal effects area of a vapor cloud explosion would have a size of 4 to 20 meters centered on the natural gas vehicle and would affect passengers of the few closest vehicles.
- for LNG, the vapor cloud explosion's lethal consequences remain limited without consequences on other vehicles.
- for CNG, the significant lethal effects area of a tank burst would have a size between 4 and 20 meters centered on the natural gas vehicle and more than 30 meters for certain vehicles that have a bigger tank (250 l instead of 50 l). This phenomenon should occur 8 min or later after fire ignition. So, it's likely that users would have self-evacuated and rescue services would mainly be at risk.
- for LNG, the significant lethal effects area of a tank burst would be several hundreds of meters long, due to thermal effects (fireball) rather than overpressure. Depending on the tank insulation and the number of valves (one or two), the time between the fire's start and the phenomenon's

occurrence will be the same as for CNG or occur more rapidly. Further research is needed to clarify this point.

- in the specific context of La Défense configuration, the indirect risk does not strongly modify conclusions reached for direct risk.

There are two main conclusions. Firstly a tank burst could have huge consequences: significant lethal effect area between 4 and 30 m for CNG vehicles and hundreds of meters for LNG. Secondly, the significant lethal effect area of a CNG VCE is between 4 and 20 meters. Considering that a tank burst results in a fire in the tank surrounding and having in mind that the tank burst delay will depend on the thermal flux received by the tank, all measures used to prevent fire in the tunnel are one more type of critical issue.

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