New energy carriers and additional risks for user safety in tunnels

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NEW ENERGY CARRIERS AND ADDITIONAL RISKS FOR USER SAFETY IN TUNNELS

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INTRODUCTION

Over the last few years, CETU has been performing studies with the aim of evaluating the additional risks for user safety in tunnels caused by new energy carriers (NEC). The first CETU studies enabled the relevant NEC to be identified, along with dangerous phenomena that they may generate. A quantitative assessment of the effects of the phenomena was also conducted, according to vehicle type.

CETU then launched a joint research project with INERIS in order to quantitatively assess risks for user safety in tunnels. The energy carriers taken into account were those identified by CETU: hydrogen, compressed natural gas (CNG), liquefied natural gas (LNG) and electricity. The vehicle types considered were light vehicles, heavy good vehicles and buses.

This article will focus on the methodology of this joint project and present some results concerning light vehicles and heavy goods vehicles. The specific case of buses will not be handled in this paper.

The first chapters will be dedicated to hydrogen. Throughout these chapters, hazard investigations and direct risks will be presented in detail, especially occurrence rate calculations and modelling.
For the other fuel types, only differences with hydrogen or specificities in terms of phenomena and risk will be highlighted and results presented. A last chapter will focus on indirect risks.

In order to differentiate vehicle types, rates will be tested by the number of events per 10^8 km travelled by all vehicle types. This will therefore ensure comparability with the general event rates for ICE (internal combustion engine) vehicles.

HYDROGEN: PRESENTATION AND HAZARD INVESTIGATIONS

Presentation

Hydrogen is currently mainly used as an additional power reserve for electric vehicles. It is then combined with a fuel cell, converting the hydrogen into electricity, and an electric motor.

The current predominant storage method for hydrogen consists in pressurized tank with pressure from 350, type III, to 700 bar, type IV, although other storage systems exist as cryo-compressed or metal hydrides. The storage method studied considered for the present paper was pressurized tank. Each tank is fitted with at least one TPRD (Thermally-activated Pressure Relief Device) to prevent a pressure rise in the tank in the event of an increase in temperature. Their function is to release hydrogen contained in the tank before the mechanical integrity of the tank is lost. It is generally activated around 110°C. One of the purposes of type IV tanks is to permit a loss of tightness in the event of a fire in the immediate vicinity, in order to release the hydrogen. Tests conducted on this type of tank enable the size of the necessary TPRD to be calculated accurately but also demonstrate that burst cannot be fully prevent since a TPRD failure is still possible (cf. [1])
In the case of light vehicles, tanks are generally positioned under the vehicle. In the case of heavy goods vehicles, they are also positioned in the lower part, commonly behind the driver's cab.

Main dangerous phenomena

As in traditional vehicles, a *fire* may concerns a hydrogen vehicle. Assuming the TPRD works correctly, a *jet fire* will break out during the vehicle fire.

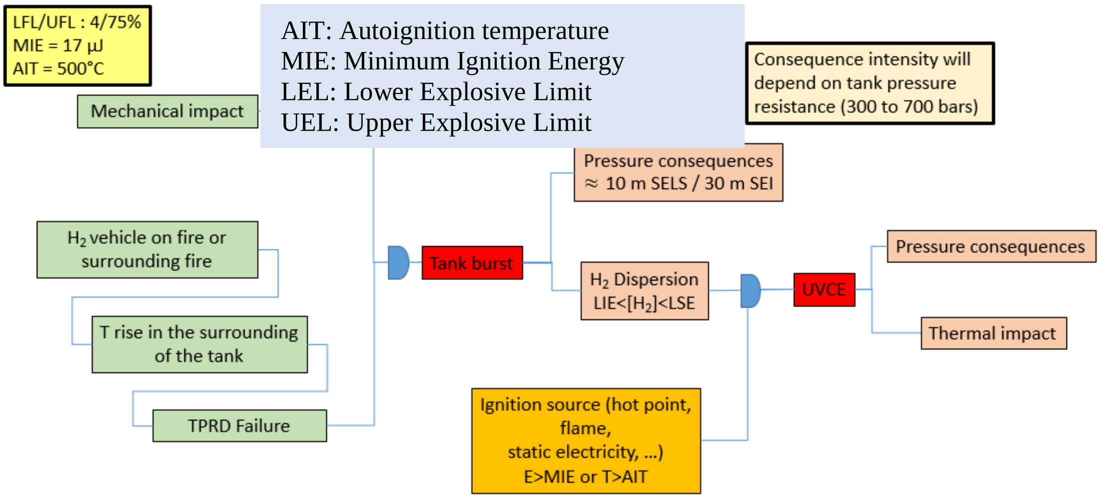
Assuming a TPRD opening without engulfing fire, as the result of a collision or a malfunction during filling (the opening may occur after a certain period of time):

- *A jet fire* will occur if an energetic enough ignition source is present in the immediate vicinity;
- A *VCE (vapor cloud explosion)* will occur if no source of ignition is present in the immediate vicinity, a hydrogen cloud will then be formed and later encountered such an ignition source.

Assuming a TPRD malfunctions in a situation of engulfing fire or following a mechanical impact, a *tank burst* is likely to occur.

Event trees – example with tank rupture

Des arbres des causes et conséquences ont permis de préciser les phénomènes identifiés ci-avant, ci-dessous un exemple concernant le tank rupture.



In the study, mechanical impact as a cause of tank rupture was ruled out considering current safety rules for hydrogen tank (cf.[2]).

Furthermore, a pneumatic tank rupture occurs when the pressure inside the tank generates levels of stress above acceptable levels. Pressure increases when temperature increases and when the TPRD malfunctions. To estimate the duration before the burst occurrence, information available in literature was consulted and the results of a series of tests extrapolated (cf.[11]). These tests were carried out on pressurized bottles of hydrogen, nitrogen or helium at pressures ranging from 200 to 700 bar. Assuming, on a conservative estimate, that the length of time is proportional to the energy absorbed, i.e. the product of the incident flow by the area of the tank and by the length of time, it was possible, from these tests, to estimate the length of time before the tank rupture occurred. In the case of an "enveloping" fire such as a vehicle fire (incoming flux 20 to 50 kW/m^2), this time period is between 8 minutes (worst-case value corresponding to very particular circumstances) and 20 minutes. In the case of a fire some meters away (incoming flux 10 kW/m^2), this time period would be 40 minutes. In the case of hot smoke (incoming flow 2.5 kW/m^2), it would be at least 3 hours.

The explosion phenomenon is therefore likely to occur during the user evacuation period in the case of a fire in the vehicle itself but would occur after the evacuation phase in the case of a more distant fire.

Conclusion and future of the study

This first stage has enabled us to accurately quantify the dangers and their causes and effects. It has been particularly useful for calculating probabilities and assessing the consequences of dangerous phenomena. It has also highlighted, for the jet fire and the VCE, the need to distinguish between two cases: that of a phenomenon having the NEC vehicle as its source (direct risk) and that in which the NEC vehicle is impacted by the effects of a fire in another vehicle (indirect risk). While the effects are similar (temperature, excess pressure, etc.), the consequences for users may be significantly different.

HYDROGEN – DIRECT RISKS - FIRE

Occurrence rates

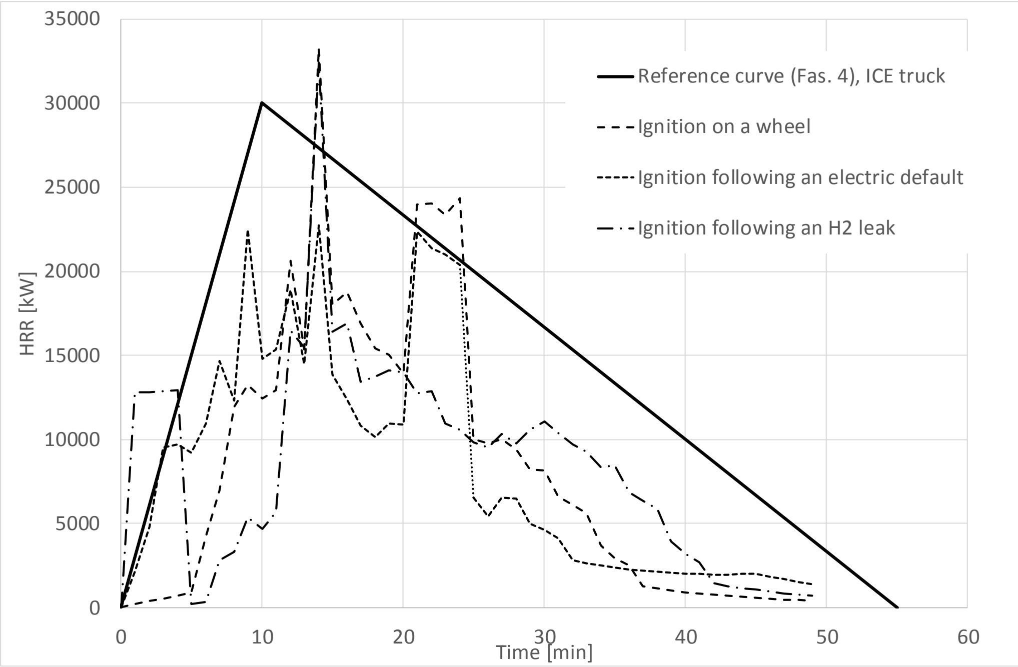
It was thought that the risk of a leakage and ignition of hydrogen would not significantly increase the risk of ignition. It was therefore assumed that the estimated rate of fires in a hydrogen vehicle was the same as for ICE vehicles. In France the rate is 2 for 10^8 veh-km for light vehicles and 3 for 10^8 veh-km for heavy goods vehicles (cf. [3]).

Consequences

The effects of fire were modelled by taking the sum of the individual heat release rates of each of the elements making up the vehicle. The spread kinetics were taken into account in view of the fact that fire spread would only occur in the case of two adjacent elements. This kinetic energy also depends on parameters such as the point of ignition or neighboring parameters. As described in [12] this method consists in summing the contribution of each individual burning elements of the vehicle while introducing a parametric delay to account for the propagation phenomenon. Since the uncertainties of such an approach several experimental comparisons were previously published and highlight the capability of the model to compute an evaluation of the HRR peak value together with the fire duration. For the present situation that concerns hydrogen-powered vehicle, a large number of situations were modelled, producing different curves which were used to reconstruct the linearized fire curve.

The contribution of the jet fire was also taken into account. Regarding the lack of detail information, several configurations were studied with different diameter for the TPRD and a range of tank pressure between 350 and 700 bar. The heat release rate of the jet fire was then estimated to 12.6 MW with a one-minute duration for light vehicles. For heavy goods vehicles, the presence of several tanks was introduced, the heat release rate of the jet fire was still around 12.6 MW since the TPRD diameter is identical but the duration was enlarged to 4.5 minutes. These hypotheses can be considered as worst-case scenarios for the different configurations stated above. One must keep in mind that some configurations may lead to greater theoretical heat release rates for jet fire but over very short periods for which the actual heat release rate value will therefore be highly transient. Moreover, after the curve linearization, since the amount of energy is the same, the resulting differences would not be significant.

Using this evaluation of the jet fire HRR (Heat Release Rate) and using the method proposed by [12], the HRR curve for hydrogen-powered heavy goods vehicles was built, see figure hereafter. In this figure, several curves corresponding to different fire ignition situations on hydrogen-powered heavy goods vehicles are compared with the reference curve for ICEs.



Analysis of the curve shows that the thermal effects are not exacerbated. In fact, the peaks in the heat release rate linked to the activation of the TPRD are of very short duration and the rest of the curve is below the theoretical ICE curve. Furthermore, the tanks are situated in the lower part of the vehicles and the TPRD activation temperature is 110°C. Therefore, if users are still near to the vehicle when the jet fire breaks out, they would already be unable to evacuate considering 120°C as the threshold for which human body endure lethal effects.
As far as the toxic effects are concerned, the chemical compounds released by a fire of such a hydrogen-powered vehicle would be identical to those produced by an internal combustion engine vehicle, as hydrogen combustion produces water vapor.
It was therefore concluded that, when the TPRD operates, the effects of a fire in a heavy goods vehicle with a hydrogen tank are similar to those of a traditional vehicle.
Using the same method, the conclusion is identical for light vehicles.

HYDROGEN – DIRECT RISKS – JET FIRE RESULTING FROM A COLLISION OR A MALFUNCTION DURING FILLING

The case of a jet fire following a vehicle fire has already been considered in the preceding section dealing with fire.
This part focusses on a jet fire situation occurring as the result of a collision or a malfunction during the filling of the tank, without engulfing vehicle fire.

Occurrence rates

In accordance with the specific situation considered, the jet fire is triggered by the activation of the TPRD immediately after a collision or possibly after a malfunction during filling with an associated delay. In these two configurations, an ignition source is required to establish a jet fire. To evaluate the occurrence rate for such a situation, the proportion of the vehicle type in the traffic and the penetration rate of hydrogen must obviously be taken into account. This leads to the following formula:

$$\tau_{JF} = P_{inf\_ouv} . \tau_{type\_veh} . \tau_{penetration} . (\tau_{accident} . P_{ouv_{sur_{choc}}} + \tau_{d\_remp}) \qquad [1]$$

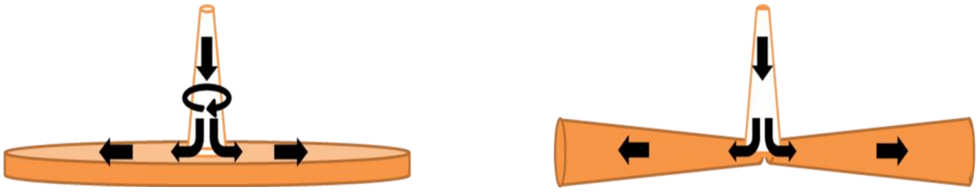
In this equation, following symbols were used:

- P_{inf_ouv} is the probability of ignition on activation of the TPRD. P_{inf_ouv}, is assumed equal to 0.9 with regard to the properties of hydrogen and in particular its very low MIE.
- τ_{type_veh} is the existence rate of the type of vehicle considered in the traffic: 0.95 for light vehicles, 0.05 for heavy goods vehicles.
- $\tau_{penetration}$ is the proportion of hydrogen vehicles in the car population. A value of 2% of the population by 2030 and 10% by 2050 currently appears to be a value curve (cf. [44]). 100% was also considered in the study in a comparison purpose.
- $\tau_{accident}$ is the accident rate, 41 for 10^8 veh-km in France
- $P_{ouv_{sur_{choc}}}$ is the probability of the TPRD opening as the result of a collision. It is presumed to be 0.02, assuming that only 20% of accidents cause personal injury and that only 10% of these accidents are violent enough to result in the opening of the TPRD
- τ_{d_remp} is the estimated TPRD opening rate a certain period of time after a malfunction during filling. It was assumed, in the absence of experience, that this would occur in 1 vehicle in a 100 in the course of the life of the vehicle, i.e. 1 for $1.5\text{x}10^{7}$ veh-km (150,000 km travelled on average by vehicles during it life). Assuming that the occurrence of the phenomenon is independent of presence in a tunnel, this probability should be modified to take into account the ratio of the tunnel length to the length of the road network, i.e. $5\text{x}10^{-4}$ in France. With these assumptions, τ_{d_remp} is equal to 1 for $3\text{x}10^{10}$ veh-km.

Using this formula and these assumed values for the various parameters, a hydrogen technology penetration rate of 2% lead to an estimated occurrence rate of $1.41\text{x}10^{-2}$ for 10^8 all types veh-km in a light vehicle and $7.41\text{x}10^{-4}$ all types veh-km in a heavy goods vehicle for a jet fire situation triggered by a collision or a malfunction during the tank filling.

Consequences

As mentioned previously, the hydrogen tank is located on the lower part of light and heavy goods vehicles. Consequently, the jet resulting of the TPRD opening will be directed to the ground, resulting in a specific shape of the fire. A specific methodology was developed for calculating thermal impact consequences. It consists in converting the descending vertical jet fire into a horizontal jet fire at ground level with a flow distribution as illustrated hereafter. This was obtained by assuming the mass conservation and creating two symmetric jet fires with an individual mass flow rate equals to half of the one computed at the TPRD opening.



Schematic diagram of an impinging jet fire: actual situation (left) and modeled situation (right).

Several configurations were studied with different TPRD diameter and different tank pressure, from 350 to 700 bar. This shows that the length of the flame is between 3 and 8 m around the discharge point and that any user impacted by the flame will be subjected to lethal effects. Since the location of tanks and their possible configurations are the same for light vehicles and heavy goods vehicles, this result is valid for both types of vehicle. Considering one vehicle every 10 m and 1.5 users per vehicle, cf. [3], 1.5 users would therefore be likely to be subjected to lethal effects. This result should however be put into perspective in view of the very short duration of the jet fire: about 1 minute for light vehicles and 4.5 minutes for heavy goods vehicles.

HYDROGENE – DIRECT RISK – VAPOUR CLOUD EXPLOSION

Occurrence rates

In accordance with the specific case under consideration, the VCE results from a vehicle collision causing the opening of the TPRD or by the opening of the TPRD following a malfunction during filling. Whatever the triggering phenomenon is, no ignition should be present near the opening to let the dispersion, and later, after delayed ignition, the explosion to occur. Following a similar approach to that previously used for the jet fire, the occurrence rate could be estimated by

$$\tau_{UVCE} = P_{non\_\inf\_ouverture}.\tau_{type_{veh}}.P_{inflammation_{nuage}}.\tau_{penetration}.(\tau_{accident}.P_{ouv_{sur_{choc}}} + \tau_{d\_remp}) \quad [2]$$

Terms $\tau_{type_{veh}}$, $\tau_{penetration}$, $\tau_{accident}$, $P_{ouv_{sur_{choc}}}$, and τ_{d_remp} are the same as in the case of the jet fire (cf. above). The new terms are explained below:

- $P_{non\_inf\_ouverture}$ is the probability of non-ignition on opening of the TPRD. $P_{non\_inf\_ouverture}$ is assumed equal to 0.1 with regard to the properties of hydrogen and in particular its very low MIE
- $P_{inflammation\_nuage}$ is the probability of ignition of the hydrogen cloud formed after the opening of the TPRD without ignition. $P_{inflammation\_nuage}$ is assumed to be equal to 1 due to the presence of numerous ignition sources in the tunnel (electrical equipment, lighting, ventilation equipment, etc.), the low energy needed for ignition and the calculated cloud sizes (15m long, 4m in diameter).

With a hydrogen technology penetration rate of 2%, the estimated occurrence rate of a VCE is 1.56×10^{-3} for 10^8 all types veh-km in a light vehicle and 8.23×10^{-5} all types veh-km in a heavy goods vehicle.

Consequences

As for the jet fire, several configurations were studied with different TPRD diameter and different pressures, from 350 to 700 bar. The worst-case configuration for the VCE is a 4 mm leak at a pressure of 700 bar for a hydrogen mass of 3.33 kg in the tank.

A situation, that corresponds to free field dispersion, was modeled using the integral software Phast v6.54. To reproduce a tunnel-like situation, the wind speed was set to 1 m/s with a flat profile. The maximum flammable mass is therefore about 770 g of hydrogen mixed with air at a concentration between the LFL and the UFL. The distance to the calculated LFL in the open is in the order of 20 m.

If an ignition source with ignition energy greater than the minimum ignition energy (17.5 μj) is present in the cloud zone where the concentration is greater than the LFL (4%) and less than the UFL (75%), the cloud will explode.

The overpressure distances from the explosion were calculated using the multi-energy model. This model used, as an input, the hydrogen flammable mass, computed above, and a violence index. Considering hydrogen is a highly reactive product, i.e. an important fundamental flame speed, and considering that, in tunnel, flow might be strongly turbulent, the violence index was set to 10. One should remain that the multi-energy model is based on the computation of a hemispherical propagation of the pressure wave. In a tunnel configuration, wave propagation will obviously be first hemispherical, before the wave reaching the wall. Then, this hypothesis of spherical propagation is no more valid as soon as the wave reaching the walls. However, it was assumed that a spherical propagation reproduces as possible the loss of energy related to the phenomena of diffraction, reflection off the walls and interaction with any obstacles. The lethal effects distance, i.e. a 140 mbar overpressure, would therefore be 25 m on either side of the explosion, i.e. a total length of 50 m in the tunnel.

On the basis of the hypotheses of section 4 (one vehicle every 10m and 1.5 users per vehicle, cf. [3]), 16 to 32 people would be subjected to lethal effects in a 1000 m long two-lane tunnel according to traffic hypotheses. This distance is principally related to the leakage diameter, the results are therefore the same for light vehicles and heavy goods vehicles. Furthermore, in view of the size of the cloud, only the results corresponding to an explosion impacting the walls were taken into account.

HYDROGENE – DIRECT RISK – TANK RUPTURE

Occurrence rates

In accordance with the special case considered, tank rupture results from a fire where there has been a malfunction of the TPRD causing pressure in the tank to build up beyond its mechanical resistance. The formula corresponding to the occurrence rate of such a phenomenon is therefore:

$$\tau_{Eclatement} = \tau_{penetration} * \tau_{type\_veh} * \tau_{incendie\_veh} * P_{défaillance\_TPRD} \qquad [3]$$

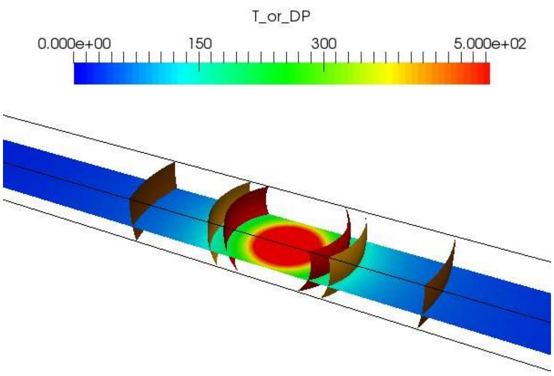
Terms $\tau_{type_{veh}}$ and $\tau_{penetration}$ are the same as in the case of the jet fire (cf. above). The new terms are explained below:

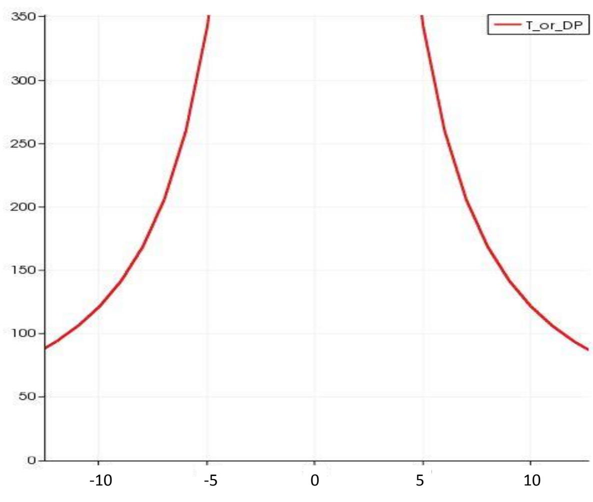
- $\tau_{incendie\_veh}$ is the occurrence rate of fire in the type of vehicle considered: 2 for 10^8 veh-km for light vehicles and 3 in 10^8 veh-km for heavy goods vehicles (cf. [3]),
- $P_{défaillance\_TPRD}$ is the probability of a malfunction of the TPRD. In the absence of feedback on TPRD reliability, it is assumed that the probability of TPRD malfunction is the same as that of a sprinkler head, as the opening mechanism is very similar, in the order of 0.001.

With a hydrogen technology penetration rate of 2%, the estimated occurrence rate of a tank rupture is 3.8×10^{-5} for 10^8 all types veh-km in a light vehicle and 3.10×10^{-6} all types veh-km in a heavy goods vehicle.

Consequences

The consequences of tank rupture were evaluated assuming a 50-litre tank with a 700 bar internal pressure. Two types of consequences were considered: pressure effects related to the blast and pressure effects related to the explosion of the flammable cloud formed following release of the gas.
The pressure consequences obtained for this phenomenon are illustrated in the figure hereafter, it is represented, on the left, in the plane 2 m above the ground. From this figure, the decrease in excessive pressure at 2 m above the ground was calculated and is plotted on the right figure.





The lethal pressure effects resulting from the blast occur up to about 10 metres either side of the tank, i.e. 20 metres of tunnel.
With regard to the effects of excessive pressure corresponding to the cloud explosion, the flammable mass would be close to the total mass present in the tank, i.e. about 3 kg. The associated lethal effects would therefore occur up to 50 meters either side of the tank, i.e. 100 meters of tunnel. In view of the properties of hydrogen, a cloud explosion is almost certain (cf. VCE). The lethal effects of pressure and excessive pressure are obviously not cumulative.

It is assumed that the mass of gas per tank is the same regardless of the type of vehicle. In addition, only the explosion of one tank is considered. It is highly unlikely that a malfunction would affect both tanks. Furthermore, if the blast from a tank or the explosion of the resulting cloud impacts a tank, the effects will not be concurrent.

On the basis of the hypotheses of section 4 (one vehicle every 10m and 1.5 users per vehicle, cf. [3]), for light vehicles and heavy goods vehicles, these two phenomena would lead to 16 to 32 people being subjected to lethal effects in a 1000m long two-lane tunnel depending on traffic hypotheses. These results should be put into perspective in view of the theoretical time period before the blast (8 to 20 minutes in the case of an enveloping or neighboring fire) and the self-evacuation of users.

CNG – PRESENTATION, HAZARDS and DIRECT RISK

Like hydrogen, CNG is stored in pressurized tanks fitted with a TPRD with temperature activation at 110°C. Storage pressure is 250 bar. The two possible TPRD configurations were taken into account.

The dangerous phenomena are the same as for hydrogen.
The event trees are the same as for hydrogen with regard to causes and effects. The parameters are different however: The MIE is 300μJ, the AIT is 537°C, the LEL and the UEL are 5% and 15% respectively.
The hypotheses, methods, approaches and formulas used to establish the probabilities and consequences of dangerous phenomena are the same as for hydrogen and will therefore not be repeated. The results are different due to the nature of the gas.

For the probabilities in particular, although the formulas used are the same, the value of some parameters are different, as specified below:

- *Jet fire*: due to the properties of CNG, the probability of ignition during opening of the TPRD (P_{inf_ouv}) is taken to be 0.1
- *VCE* : due to the properties of CNG, the probability of non-ignition on opening of the TPRD (P_{inf_ouv}) is taken to be 0.9 and the probability of ignition ($P_{inflammation\_nuage}$) of the cloud is 0.5

The occurrence rate for a fire in a CNG-powered light vehicle and in a CNG-powered heavy goods vehicle are 2 for 10^8 veh-km and 3 for 10^8 veh-km respectively. The thermal effects are similar to those of an ICE vehicle of the same type. The toxic effects of a CNG fire are comparable with that of an ICE fire.
The occurrence rates and consequences of other phenomena are specified in table 1 assuming a CNG technology penetration rate of 2%.

1.

phenomena	***Light vehicles***		***Heavy good vehicles***	
	Nbr/10^8 all types veh.km	Users subjected to lethal effects	Nbr/10^8 all types veh.km	Users subjected to lethal effects
Jet fire	$1{,}56.10^{-3}$	1,5	$8{,}23.10^{-3}$	1,5
VCE	$7{,}04.10^{-3}$	3 à 9	$3{,}71.10^{-4}$	3 à 9
Tank rupture	$3.8\text{x}10^{-5}$	9 to 17*	$3\text{x}10^{-6}$	9 to 17*

* These results should be put into perspective in view of the theoretical period of time before the blast (8 to 20 minutes in the case of an enveloping or neighboring fire) and the self-evacuation of users.

LNG – PRESENTATION, HAZARDS and DIRECT RISKS

Unlike hydrogen and CNG, LNG is stored in semi-refrigerated liquid form at pressure in the order of 10 bar and temperature of about -130°C. An insulating layer is necessary to maintain the temperature of the tank. LNG is currently mostly used for heavy goods vehicles destined for long-distance transportation.
A 560 liter tank has capacity to store about 182 kg of natural gas, allowing an operating range of over 1000 km. 450 liter tanks are also used. In the case of light vehicles, tanks are expected to hold about 60 liters.
Tanks are fitted with two valves tarred at 16 bar (T_{liq}=-130°C) and 24 bar (T_{liq} =-100°C) respectively to prevent a build-up of pressure and thereby reduce the risk of explosion. For the record, under atmospheric pressure, the liquefaction temperature of natural gas is -162°C. The vapor pressure of natural gas at -50°C is over 100 bar.

The phenomena are the same as for CNG. The hypotheses, methods, approaches and formulas used to establish the probabilities and consequences of the phenomena are also the same.
The event trees are the same as for CNG with respect to causes and effects, the valve opening criteria being used in place of the criteria for TPRD.

The hypotheses, methods, approaches and formulas used to establish the probabilities and consequences of the phenomena are the same as for CNG. The results are different owing to the nature of storage (liquid rather than gaseous) and different safety systems (valves rather than TPRD).

For the probabilities in particular, although the formulas used are the same, the value of certain parameters are different as specified below:

- *Jet fire*: in view of the properties of LNG, the probability of ignition on opening of the TPRD (P_{inf_ouv}) is taken to be 0.05 in respect of the properties of LNG and in particular the temperature at the discharge point, in the order of -120°C in the tank, -161°C in the jet.
- *VCE:* in view of the properties of LNG and the discharge characteristics, the probability of non-ignition on opening of the TPRD (P_{inf_ouv}) is taken to be 0.95 and the probability of ignition of the cloud ($P_{inflammation\_nuage}$) is 0.2. In particular, for such a two-phased leakage, the temperature of the flammable mixture would be less than 0°C. The energy to be provided in such conditions is therefore greater than that necessary for mixtures at ambient temperature.
- *Tank rupture*: the probability of valve malfunction is assumed to be 0.01 (cf [5]). Since there are two valves, the probability of malfunction of both valves ($P_{défaillance\_soupapes}$) is 10^{-4}.

The occurrence rates for a fire in an LNG-powered light vehicle and in an LNG-powered heavy goods vehicle are 2 for 10^8 all types veh-km and 3 for 10^8 all types veh-km respectively. The thermal effects are similar to those of an ICE vehicle of the same type. The toxic effects of an LNG fire are comparable with that of an ICE fire.

The occurrence rates and consequences of other phenomena are specified in table 2 assuming an LNG technology penetration rate of 2%.

2.

phenomena	*Light vehicles*		*Heavy good vehicles*	
	Nbr/10^8 all types veh.km	Users subjected to lethal effects	Nbr/10^8 all types veh.km	Users subjected to lethal effects
Jet fire	$7{,}82.10^{-4}$	1,5	$4{,}12.10^{-5}$	1,5
VCE	$2{,}97.10^{-3}$	1,5	$1{,}56.10^{-4}$	1,5
Tank rupture	$3{,}8.10^{-6}$	12 à 225	3.10^{-7}	4 à 17

* These results should be put into perspective in view of the theoretical time period before the blast (8 to 20 minutes in the case of an enveloping or neighboring fire) and the self-evacuation of users.

ELECTRICITY – PRESENTATION, HAZARDS AND DIRECT RISKS

Electric vehicles use batteries as an energy source. They can be based on different technologies but their operating principle is always based on the use of two oxidation and reduction reactions in each of two electrodes. Li-Ion batteries are mainly used and have been the subject of numerous studies and tests. This was the only type of battery considered in the study. LMP (lithium metal polymer) technology has been identified as presenting a special risk. Lithium in metal form has the specific properties of spontaneous combustion in contact with air and violent reaction on contact with water. This type of technology promotes the formation of dendrites that could cause an internal short circuit. A polymer electrolyte is installed to reduce this formation and reduce the risk of leakage or vapor release. But no independent test or study has enabled the effectiveness of this measure to be verified.

For electric vehicles, as for ICE vehicles, the main risk is fires. The presence of a battery in vehicles introduces a new potential ignition point for a fire. In particular, the presence of a battery in a warm atmosphere could lead to its thermal runaway leading to its ignition, and then the ignition of the vehicle. The temperature value liable to trigger a thermal runaway is assumed to be 150°C in view of the influence of the load status and several elements stated in literature (cf. [6,7,8] [8]). The time before runaway on reaching the temperature of 150°C is assumed to be 10 minutes on the basis of various tests (cf. [9][9] and [10] [10]). Feedback shows that immediate or delayed fire ignition is possible after a collision, but this is rare.

Unlike other NEC, no phenomena other than fire need to be considered for batteries.

The hypotheses, methods, approaches and formulas used to establish the probabilities and consequences of the phenomena are the same as for the other energy sources.

In the absence of a vehicle population of sufficient size and a feedback period of sufficient length, it has been assumed that the estimated occurrence rate of fire in an electric vehicle is the same as for ICE vehicles, i.e. 2 for 10^8 veh-km for light vehicles and 3 for 10^8 veh-km for heavy goods vehicles.

To compare the thermal effects of an electric vehicle and an ICE vehicle, the method used shows that there is no significant difference between the two types of vehicle.
Furthermore, various tests carried out on electric vehicles and internal combustion vehicles show that there are no significant differences in terms of toxic emissions between the two types of vehicle, even though a fire in the battery is liable to give off hydrofluoric acid. These toxic emissions should be put into perspective in view of the other sources of toxic emissions from a vehicle (regardless of its type): plastics, seats, air-conditioning components, etc.

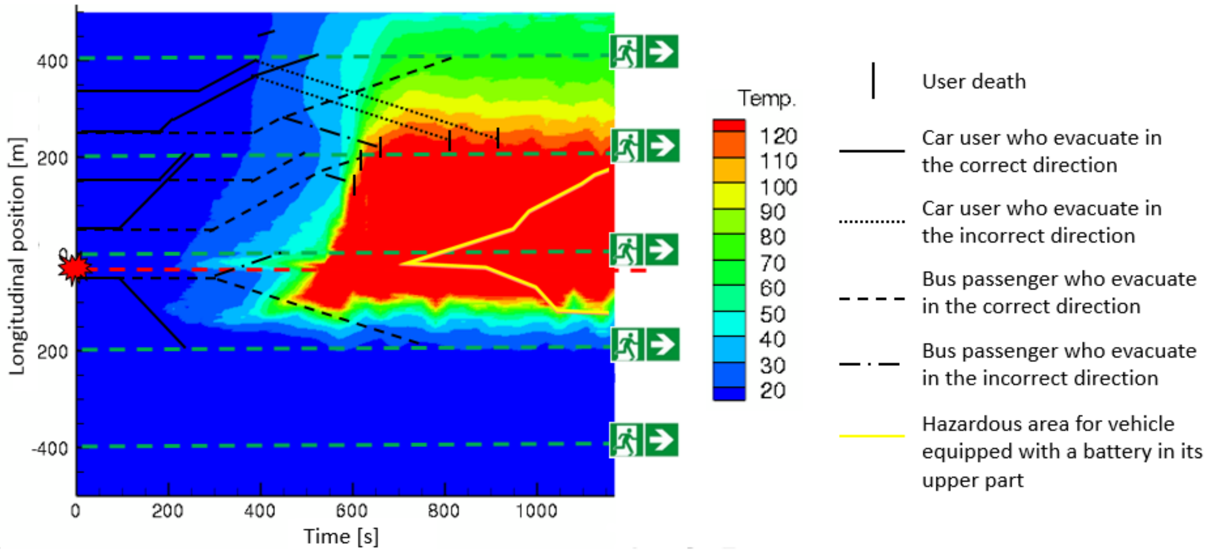
INDIRECT RISKS

In the open air, in the event of a fire, smoke naturally rises. In an underground environment, it is confined and moves through the structure before removal through the portals or via a dedicated system. If an NEC vehicle lies in the path of this smoke, the heat could give rise to one of the phenomena identified above: jet fire, VCE in the case of gas and thermal runaway of a battery. The tank rupture phenomenon can be ruled out as it would occur after the evacuation of users or after their death (3-hour delay cf. above).

The aim was to identify the additional risks for users for each energy type, namely the occurrence rates of an NEC phenomenon following a distant fire and the number of users subjected to the lethal effects of this phenomenon who would otherwise have survived. A user subjected to the lethal effects of the NEC phenomenon who would have been subjected to the lethal effects of the fire was not therefore accounted for.

To assess this indirect risk, the French specific hazard investigations approach was used (cf. [3]). In some situations this risk is almost nil (for example: longitudinally ventilated, one-way, uncongested tunnel). Representative scenarios of plausible situations in which this risk is in principle significant were studied, varying the traffic system (one-way, two-way, congested, etc.), the type of tunnel, the type of ventilation, the heat release rate of the fire and the speed of the initial air current.

The scenarios were analyzed by means of space-time graphs (cf. below) representing change in the fire-related parameters over time and in space (temperature, toxicity, visibility), the movement of users and conditions for triggering phenomena (in yellow below the risk of thermal runaway of a battery for example).



For light vehicles or heavy goods vehicles

This analysis shows that, for both light vehicles and heavy goods vehicles, the additional risk is negligible for all phenomena regardless of the energy source. These phenomena would actually occur after the evacuation of users or in conditions incompatible with their survival. The positioning of tanks (lower part) or batteries (under the bonnet) and the conditions for triggering phenomena explain this result.

CONCLUSIONS

The collaborative study carried out by CETU and INERIS has verified that the occurrence and consequences of a fire in an NEC vehicle was not significantly different from a fire in an ICE vehicle when the safety systems operate properly. The occurrence rates and lethal effects of phenomena specific to NEC vehicles were then assessed. The results for a penetration rate of each technology of 2% and a rate of heavy goods vehicles of 5% are given in table 3.

3.

	Light vehicles		*Heavy good vehicles*	
	Nbr/10^8 all types veh.km	Users subjected to lethal effects	Nbr/10^8 all types veh.km	Users subjected to lethal effects
hydrogene				
Jet fire	$1{,}41.10^{-2}$	1,5	$7{,}41.10^{-4}$	1,5
VCE	$1{,}56.10^{-3}$	16 à 32	$8{,}23.10^{-5}$	16 à 32
Tank rupture	$3{,}8.10^{-5}$	16 à 32	3.10^{-6}	16 à 32
CNG				
Jet fire	$1{,}56.10^{-3}$	1,5	$8{,}23.10^{-3}$	1,5
VCE	$7{,}04.10^{-3}$	3 à 9	$3{,}71.10^{-4}$	3 à 9
Tank rupture	$3{,}8.10^{-5}$	9 à 17*	3.10^{-6}	9 à 17*
LNG				
Jet fire	$7{,}82.10^{-4}$	1,5	$4{,}12.10^{-5}$	1,5
VCE	$2{,}97.10^{-3}$	1,5	$1{,}56.10^{-4}$	1,5
Tank rupture	$3{,}8.10^{-6}$	12 à 225	3.10^{-7}	4 à 17

Electric vehicles powered by Li-ion batteries are not sources of specific phenomena. Other types of batteries could be used, such as those based on LMP (lithium metal polymer) technology but there are no independent studies and tests dealing with this question.

The specific phenomena mentioned above may occur in an NEC light or heavy good vehicle in a tunnel if it is affected by hot smoke from a third party fire (indirect risk). But they would not cause further deaths either because the phenomena would occur after the evacuation of users or because the users would already be dead as a result of the fire.

The case of NEC buses could lead to different findings and results

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