INTEGRATION OF NEW ENERGY CARRIERS IN FRENCH SPECIFIC HAZARD INVESTIGATIONS: OVERVIEW OF PRINCIPAL ISSUES

Christophe Willmann, Pauline Charles
CETU, French tunnel study centre, FR

DOI 10.3217/978-3-85125-996-4-32 (CC BY-NC 4.0)

ABSTRACT

A national work group comprising specialists in specific hazard investigations has been set up by the CETU with the aim of adapting specific hazard investigations to the new energy carriers vehicles. Two main adaptations have been made. The first concerns the adaptation of the criticality matrix ranking, so as to take into account the specificities of gas dangerous incidents in terms of frequency and severity. The second concerns the adaptation of the detailed scenario analysis to take account of two dangerous incidents involving gas, kinetic vapour cloud and tank rupture explosions, which are more instantaneous than fires (the dangerous incident that is the most feared in tunnels).

Keywords: risk analysis, new energy carriers, adaptation.

1. INTRODUCTION

The French Centre for Tunnel Studies (CETU) has been working on the impact of new energy carriers (NEC) in underground space for many years. A joint research project with INERIS has enabled a quantitative assessment of the additional risks of these vehicles.

As they are already present in traffic, it was necessary to integrate them into the safety management system. The approach used began with adapting the risk analysis conducted for French tunnels (known as the specific hazard investigation) so as to take into account these new vehicles.

To handle this topic, CETU set up a work group of national specialists in specific hazard investigations. The work is still in progress but almost finalized. The main issue was to find a work methodology and ways to integrate quantitative risk assessment results (from the CETU-INERIS study [3]) into the specific hazard investigation methodology which is scenario-based ([1]). After a short reminder of the specific hazard investigation methodology, the paper will explain how the main difficulties related to the specificities of NEC vehicles were overcome in the adaptation process.

2. SPECIFIC HAZARD INVESTIGATION METHODOLOGY

A specific hazard investigation is a French methodology for analysing risks related to user safety in road tunnels. In this method, the tunnel is considered as a system, which includes the users, equipment, environment, operator, maintenance and emergency services. The approach is scenario-based [1]. Unlike a system-based approach, only a few relevant scenarios are chosen and analysed in detail. The main goal is to identify potential hazards related to the tunnel, analyse in detail how the system mitigates them, and, if necessary, propose improvements to address the weaknesses identified.

A specific hazard investigation is divided into five phases, which will be presented overleaf (details can be found in [2]).

2.1. The tunnel and its environment

This section of the investigation describes the tunnel and its environment. In general, the following aspects are relevant:

- tunnel characteristics;
- location of the operating centres and emergency centres in relation to the tunnel;
- natural environment (geology, hydrogeology, meteorology, etc.);
- human environment (population and nearby activities including temporary ones);
- roads: main routes and their usual traffic conditions;
- traffic composition;
- any other aspects considered relevant.

2.2. Functional description of the tunnel

This section highlights the link between the safety functions and the principal structural elements, equipment and operating arrangements to ensure their effective performance.

2.3. Identification of hazards and choice of scenarios

The first step of this section is the identification of hazards and dangerous incidents that they may entail. An exhaustive inventory of potentially dangerous incidents is drawn up, for example LV fire or HGV fire. They are then ranked in a criticality matrix, combining their presumed frequency and severity. The matrix has five columns, for five classes of severity. For example, class I corresponding to "Minor or none" means there is only material damage, class II "Significant", implies slightly injured persons and class III "Critical", could lead to seriously injured persons or less than 5 fatalities.

The matrix resulting from the above severity and frequency classes is shown in Figure 1.

	I Minor or None	**II Significant**	**III Critical**	**IV Catastrophic**	**V Major Catastrophe**
A Very frequent					
B Frequent					
C Occasional					
D Rare					
E Very rare					
F Extremely rare					

Figure 1: Criticality matrix

Fires incidents are more numerous in this matrix than those related to other hazards (accidents, breakdowns) because they are more impacted by the vehicle type (HGV, LV, dangerous goods vehicle). Moreover, they are of greater interest for the objectives of the specific hazard investigation as they provide better knowledge of how the system is able to address and mitigate the danger and how this system can be improved.

The second step is the choice of scenarios. This begins with the choice of dangerous incidents, based on the matrix. Dangerous incidents are then combined with contextual parameters to define a scenario. These contextual parameters are for example the location of the incident, the traffic conditions and the initial air flow velocity. In general, only between 4 and 8 scenarios are selected for detailed analysis, which would not be possible if the number of scenarios is too high. This set of scenarios must be representative and instructive.

2.4. Analysis of the scenarios

Each scenario starts with the dangerous incident chosen previously, and continues with sequences of events until the end of users' evacuation.

In the case of fire, the first step in this analysis is to choose the hypothesis related to user behaviour (walking speed related to visibility, influence of temperature and toxicity, etc.) and fire modelling. The analysis is then conducted by using a space-time graph that illustrates the fire's development and the users' trajectory which are influenced by air opacity, temperature, heat radiance, and toxicity.

2.5. Summary

This section of a specific hazard investigation contains a summary of what has been learned from the scenarios and a summary of their consequences. It also evaluates the system's level of safety especially by qualitatively assessing its ability to address the hazards. Then, if necessary, proposals for improvement are made.

3. ADAPTING THE METHODOLOGY TO THE SPECIFICITIES OF NEC-RELATED DANGEROUS INCIDENTS

As explained in [3], new propulsion energies that raise the most concern for user safety are gases: hydrogen, compress natural gas (CNG) and liquid natural gas (LNG)[1]. They can cause specific dangerous incidents in addition to classic incidents that also occur with vehicles powered by petrol or diesel (accident and fire). These dangerous incidents specific to gas are jet fires or VCE (vapor cloud explosions) both resulting from a collision, a malfunction during tank filling, or tank rupture following fire[2]. They will be called "gas dangerous incidents" in the following sections of the present article.

Because of their specificities, gas dangerous incidents can't be treated in a specific hazard investigation methodology in the same way as accidents and fires. These specificities also provide new opportunities in terms of risk assessment. The following sub-sections explain these specificities and how the steps of the methodology can be adapted to integrate them.

3.1. Adaptation of the ranking in the criticality matrix to the frequency and severity of gas dangerous incidents

The first step in the methodology significantly impacted by the specificities of gas dangerous incidents is the identification of hazards and choice of scenarios. Both frequency and severity of gas dangerous incidents have specificities that need to be analysed to determine if it is possible to integrate them in the criticality matrix presented in 2.3 or if another approach should be developed.

---

[1] Apart from a very specific batteries, the only specific incident related to Li-ion batteries (assuming a battery capacity of 80 kwh), is thermal runaway, which has a non-significant impact on user safety, even if it would be difficult to extinguish by firefighters.

[2] A jet fire following a fire doesn't have a significant additional impact on users' safety apart if the gas vehicle is a bus. A tank rupture following a collision was assumed to be very unlikely given the shield effect of the other part of the vehicles and the strong resistance of the tanks required by regulation.

Frequency specificities and related issues

The frequencies of classic dangerous incidents (accident and fire) and gas dangerous incidents are calculated based on occurrence rates. However, the occurrence rates of classic dangerous incidents are based on a dangerous incidents data base, whereas the occurrence rates of gas dangerous incidents are calculated with formula. Although the proportion of gas vehicles in French traffic has seen a significant increase over the past few years, it remains very low. Therefore, the gas dangerous incidents data base isn't large or reliable enough to base occurrence rates on.

The occurrence rate of fire is 0.9 per 10^8 $veh.km$ for light vehicles and 3 per 10^8 $veh.km$ for heavy goods vehicles [4], and the occurrence rate of CNG tank rupture is given by the formula below.

$$R_{Burst} = \tau_{penetration} * \tau_{type\_veh} * \tau_{veh\_fire} * P_{malfuncion\_TPRD} \qquad (1)$$

where: τ_{type_veh} is the existence rate of the type of vehicle considered in the traffic, $\tau_{penetration}$ is the proportion of CNG vehicles in the car population, τ_{veh_fire} is the occurrence rate of fires in the type of vehicle considered, $P_{malfunction\_TPRD}$ is the probability of a malfunction of the TPRD. More details can be found in [3].

Because of a totally different approach in term of occurrence rate calculation, the uncertainties of frequencies are significantly different between gas dangerous incidents and classic dangerous incidents. This therefore raises the question of the integration of these two frequency types in the same matrix.

Severity specificities and related issues

The severity of classic dangerous incidents, especially fires, is expressed in the number of users losing their self-evacuation capacity by applying the principles outlined in [5]. In the context of a fire in a tunnel, which is the dangerous incident that is mainly investigated in the methodology (see. 2.3), a user losing self-evacuation capacity will quickly die if not helped. Hence, because of the arrival time of rescue services (up to 30 min after the loss of self-evacuation capacity), the number of users losing their self-evacuation capacity is often converted by practitioners into the number of deaths.

In line with French regulations [6], the severity of gas dangerous incidents is expressed as the number of users subjected to significant lethal effects. A user subjected to significant lethal effects is a user that has a certain probability of dying, but death is not certain. For instance, the significant lethal effect threshold of an overpressure is 200 mbar, as stated in [6], whereas the overpressure that kills by lung rupture is between 900 and 1500 mbar, depending on the medical sources. At 200 mbar, lung disorder resulting in death could happen to people who already have health problems or poor physical condition (direct effect) or users could get killed by falling on the ground or being hit by flying pieces from tunnel equipment or vehicles (indirect effect). There are various direct and indirect effects and their impact on the body is complex given the huge variety of health conditions. Therefore, [6] doesn't provide the possibility of deducing a number of deaths from a number of users subjected to significant lethal effects.

As the severity of gas dangerous incidents is not expressed in the same unit as for classic dangerous incidents, they cannot be directly ranked in the same matrix.

Overcoming the issues by a specific integration of gas dangerous incidents into the matrix

To resolve the two issues previously mentioned, two options were investigated.

The first consists in having two separate criticality matrixes: one for classic dangerous incidents and a second for gas dangerous incidents. This will avoid ranking dangerous incidents that have frequencies with different uncertainties (first issue) and severities with different units (second issue) within the same matrix. However, this has two strong disadvantages. Firstly, the selection of dangerous incidents will be made more difficult and subject to more mistakes. Secondly and principally, the overview of risks offered to stakeholders by a unique dangerous incidents matrix will be lost.

A second option is to find a solution to integrate the gas dangerous incidents into the single matrix.

Concerning frequency, as explained in 2.3, the criticality matrix is organized with frequency classes and severity classes. That means that two events of the same matrix cell belong to the same frequency class and are considered equivalent in term of frequency for the dangerous incidents selection. Generally, the difference between the lower value of a frequency class and the higher one is an order of magnitude (for example between 1 event in one year and 10^{-1} event in one year for class “B”). Even uncertainties higher than 100% are thus unlikely to change the frequency ranking of a dangerous incident[3]. Therefore, the difference in terms of uncertainty between classic dangerous incidents and gas ones is unlikely to change the ranking of these dangerous incidents in frequency classes. Hence, it was eventually stated that it is acceptable to rank classic and gas dangerous incidents together in the frequency classes.

Concerning severity, as explained before, the severity of gas dangerous incidents is expressed as the number of users subjected to significant lethal effects. The probability that such users will die is non-negligible but unknown, which means that the only possible assumption is that this probability is between 0 and 1. Therefore, if n users are subjected to lethal effects of a given gas dangerous incident, the number of deaths will be between 0 and n. It is likely that the users still alive after being subjected to significant lethal effects will be seriously injured. Therefore, to rank this gas dangerous incident in the severity classes together with the classic dangerous incidents, it is possible to consider that it belongs to the classes between the critical one (seriously injured persons or less than 5 fatalities) and the one including n deaths. For example, according to [3], a CNG vapour cloud explosion (VCE) will subject up to 9 users to significant lethal effects, so it belongs to both critical class and catastrophic class (between 5 and 50 deaths) as illustrated in green in Figure 2.

I Minor or none	**II Significant**	**III Critical**	**IV Catastrophic**	**V Major catastrophe**
		🟩	🟩 CNG VCE	
			HGV fire	

Figure 2: Example of gas dangerous incident ranking in the criticality matrix

This second option was therefore chosen by the work group.

3.2. A possible calculation of generic severities that provides the opportunity to have a generic risk assessment of gas dangerous incidents

In the step dedicated to hazard identification and scenario choice, the severity of classic dangerous incidents is only estimated based on expert judgement in a generic way, independent of the tunnel characteristics. Therefore, this estimation is a wide range of possible values rather than a precise one, which is enough to classify the dangerous incident in a

---

[3] Only uncertainties close to 1000% are likely to do so.

severity class that covers an order of magnitude. Of course, by using a quantitative approach (see. 2.4), the scenario analysis enables this first estimation to be more accurate.

[3] gives results from modelling, with a reasonable worst-case geometry (60 m2 section, 6 m heigh, 10 meters wide) that enable a far more precise estimate of the severity of gas dangerous incidents by taking into account certain tunnel characteristics (for example the number of lanes). [3] also enables the frequency of each gas dangerous incident to be calculated. Thus, it is possible to have a more precise risk assessment of gas dangerous incidents (see.Table 1) than the one given by the criticality matrix (see 2.3).

Table 1: Extract of the risk assessment table of hydrogen dangerous incidents

Energy	Dangerous incident	Vehicle type	Frequency (penetration rate[4] of 2%)	Number of users subjected to significant lethal effects
H2	VCE	LV	8,32E-05	15 to 25
		HGV	5,80E-06	15 to 25
		Bus	4,47E-07	15 to 25 + bus passengers
	Tank rupture	LV	1,12E-06	15 to 25
		HGV	2,52E-07	15 to 25
		Bus	1,94E-08	15 to 25+ bus passengers

3.3. A detailed scenario analysis that has to be adapted to gas dangerous incident kinetics

The choice of scenarios

Gas dangerous incidents follow a collision or a fire. Therefore, the collision scenarios and the fire scenarios chosen for all vehicles types will be used as a basis to study gas dangerous incidents. Indeed, as explained in [3], apart from these gas dangerous incidents that can occur, there is no significant differences between a collision or a fire involving a classic vehicle and these same incidents with a gas-powered vehicle.

Kinetic issues

A fire takes from minutes to tens of minutes to develop. This enables an analysis of the progressive impact of the fire and safety measures on users (see 2.4). The order of magnitude of the kinetics of VCE and tank ruptures is up to the second, so very little can be expected from such analysis. This raises the question of the added value of such an analysis in case of VCE or tank ruptures, as these dangerous incidents are already assessed in a generic way (see 3.2).

To address this issue, VCE and tank ruptures were handled differently. Indeed, even if their kinetics have nearly the same order of magnitude, their occurrence time is significantly different. A VCE is likely to happen from few seconds to one or two minutes after the collision, whereas a tank rupture is likely to happen from 8 to 20 minutes after a collision [3].

The added value of a detailed analysis for a VCE

When a VCE occurs, nearly all the users will still be in their vehicle when impacted by the effects, maybe in a vehicle that is still running. This is very different from the fire scenario in which, unless in rare cases, most users affected by the fire would be outside their vehicles trying to evacuate. For a fire it makes sense to perform the analysis based on the space-time graphic described in chapter 2.4. However, such an analysis is obviously not relevant if all

---

[4] proportion of the NEC energy in the car population

users are in their vehicle when impacted by an explosion. Nevertheless, it could be interesting to analyse the actual location of the vehicles in the significant lethal area of the VCE when it occurs and the consequences for their passengers. In this analysis, vehicles already stopped and vehicles still running have to be distinguished, as the distance between stopped vehicles is far lower than the distance between vehicles still running. The generic severity assessment of VCE (see 3.2) is based on the worst-case scenario in which the significant lethal effect area is full of vehicles stopped. This type of detailed analysis will therefore give a more accurate perspective of the possible results for a representative scenario.

The added value of a detailed analysis for a tank rupture

As reminded in 3, it was assumed in [3], that a tank rupture will only be triggered by a fire. As indicated above, this will happen between 8 to 20 minutes after the gas vehicle catches fire, which means that users would already have started the evacuation process because of the fire. It is therefore of interest to investigate the impact of the tank rupture on the self-evacuation process. To do so, the significant lethal effect area should be integrated into the space time graph presented in 2.4, as illustrated in Figure 3. Then, the specific impact of this area should be analysed, especially to assess if it increases the severity of the initial fire or not. The generic severity assessment of a tank rupture is based on the worst-case scenario in which all the passengers of the vehicles in the significant lethal effect area don't evacuate, so are all subjected to these effects. This type of detailed analysis will give a more accurate perspective of the possible results for a representative scenario.

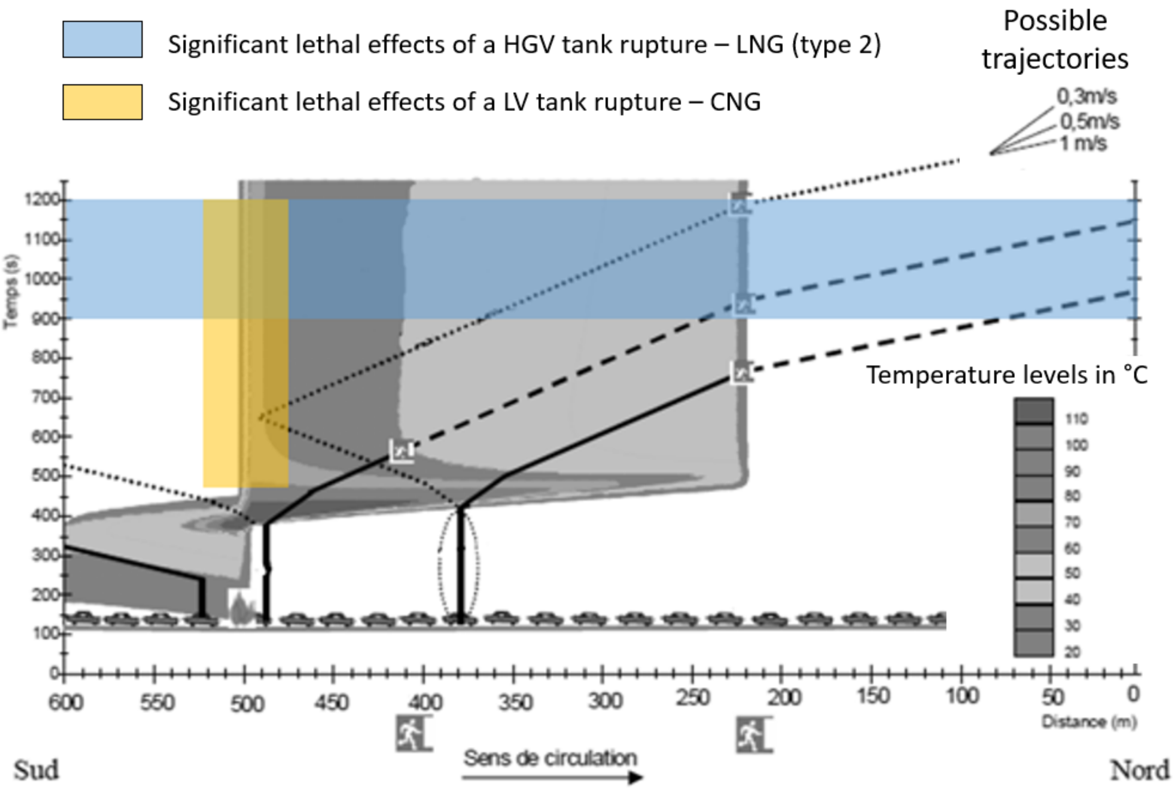

Figure 3: Example of gas dangerous incident integration in the space time graph of a scenario

In the analyses, one should be cautious to not overestimate the impact of the tank rupture. Indeed, in Figure 3, the significant lethal effects represented by the blue and yellow rectangles correspond to all possible time occurrences of the rupture. However, if this happens, it would happen only once. For instance, an LNG tank rupture could happen between 900s and 1200s. The users that may be subjected to lethal effects are the ones on the three trajectories that cross the blue rectangle, whereas if the tank rupture happens at 1150s, only one trajectory would be impacted, as the users on the two others will have evacuated.

4. SUMMARY AND CONCLUSION

Two main issues were identified and solved when adapting the French specific hazard investigation methodology to NEC.

The first concerned an apparent incompatibility of the frequencies and severities of gas dangerous incidents with the criticality matrix. Concerning frequencies, this issue was solved by stating that the difference in terms of uncertainties between classic dangerous incidents and gas ones are non-significant in terms of frequency ranking because this ranking is done in classes that each cover an order of magnitude. Concerning severity, n users subjected to significant lethal effects[5] means that at best there are seriously injured users and at worst n deaths. This makes it possible to rank gas dangerous incidents in one or more classic severity classes that are based on injuries and deaths.

The second issue involved taking into account the specific kinetics of gas dangerous incidents in the detailed scenario analysis. For a VCE, that could occur very quickly after a collision, the detailed analysis should consist in studying the location of the vehicles in relation to the gas-powered vehicle, taking into account that certain vehicles would have stopped and others would still be running. For a tank rupture, that would occur a certain time after a fire, the significant lethal effects area of this gas incident will be integrated into the space-time graph used to analyse the fire. The detailed analysis of the impact of the tank rupture on users should then be performed and take into account their self-evacuation.

Moreover, the quantitative results from the CETU-INERIS study (see [3]) offered the opportunity of adding a somewhat systemic approach to the scenario-based approach of the specific hazard investigation in sense of [1].

These main adaptations now need to be consolidated and backed up by a document that will clearly explain how the steps of the methodology have to be adapted.

5. REFERENCES

[1] "Risk analysis for road tunnels", PIARC technical committee C3.3 Road tunnel operation, 2008
[2] « Fascicule 4 des Guides des dossiers de sécurité des tunnels routiers », CETU publication, 2003
[3] Willmann,C, Truchot B, "New energy carriers and additional risks for user's safety in tunnels", ISTSS 2020 Munich

[4] "Pannes, accidents et incendies en tunnel routier, éléments statistique", reference document, CETU publication, February 2022, 25 pages,

[5] ISO 13571, « Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data », 2012.

[6] Arrêté du 29 septembre 2005 relatif à l'évaluation et à la prise en compte de la probabilité d'occurrence, de la cinétique, de l'intensité des effets et de la gravité des conséquences des accidents potentiels dans les études de dangers des installations classées soumises à autorisation.
NOR: DEVP0540371A - Version consolidée au 08 décembre 2017, 2005

---

[5] meaning that there is a non-negligible probability that they will die but their death is not certain