COMPARATIVE STUDY OF THE INHERENT RISKS OF CNG AND DIESEL BUSES/HDVs/GARBAGE TRUCKS IN TUNNELS

Olivier Bordelanne[1], Philippe Liégeois[1], Micheline Montero[1],
Gilles Durand[2], Corinne Berthelot[2]

[1] GDF SUEZ, DRI-CRIGEN, 361 avenue du Président Wilson BP 33 – 93211 Saint Denis La Plaine Cedex, France
[2] on behalf of Association Française du Gaz Naturel pour Véhicules (AFGNV) – French Association for Natural Gas Vehicles, 8 rue de l'Hôtel de Ville – 92200 Neuilly sur Seine, France.

Keywords: Compressed Natural Gas (CNG), Diesel, Buses, Garbage Trucks (GTs), Heavy Duty Vehicles (HDVs), Safety, Tunnels, Risks

1. BACKGROUND

Following past incidents involving CNG buses in France, the BEATT (French Office of Road Transports Accidents) has conducted a study in 2006. Among the conclusions and recommendations mentioned in the study report, the BEATT has suggested that the driving of CNG buses in tunnels usually forbidden to dangerous goods transportation, should be also forbidden.
Due to the negative impact of such recommendations on the CNG market in France where more than 2200 CNG buses, 850 CNG Garbage Trucks (GTs) and more than 100 GNG Heavy Duty Vehicles (HDVs) are operated every day, the AFGNV (French Association for Natural Gas Vehicles) and the Safety and Security of roads management Direction (DSCR) have settled up a working group in charge of building counter-arguments to these recommendations.
This working group has conducted two complete studies aiming at comparing the inherent risks of operating CNG buses, CNG HDVs and CNG GTs in tunnels to the inherent risks of operating Diesel buses, Diesel HDVs and Diesel GTs under the same conditions.

2. AIMS

The objectives of these studies were :

- To analyze the risk of CNG buses/HDVs/GTs being operated in tunnels to identify scenarios of accidents implicating these vehicles and related dangerous phenomena;
- To evaluate the risks of these CNG buses/HDVs/GTs and to compare them to the risks associated to the operation of Diesel buses/HDVs/GTs under the same conditions,
- To expose the security guidelines to minimize the afore mentioned risks in normal operation of CNG buses/HDVs/GTs in tunnels.

3. METHODS

These studies and analysis are built around a risk evaluation approach named Globally At Minimum Equivalent (GAME). With such approach, in case of incertitudes (for example due to a lack of data due to insufficient experiments to establish statistics), the adopted values are the maximum ones for the CNG case in order not to advantage the CNG case versus the Diesel case.

Sensitivity studies have been conducted also, considering:

- Technical requirements adopted in R96M and ECE R110 regulations for CNG buses;
- Several technical characteristics of the industrial vehicles (HDVs and GTs) and their weight (Fully Loaded Total Weight (PTAC));
- Traffic conditions (moving freely/dense).

3.1. Presentations of buses systems

3.1.1. Reference bus: Diesel fuel

The analysis is done by comparison, in terms of equivalent services. Under the chosen conditions, the transport of passengers is conducted by a Diesel bus operating in the environment determined for the study. The fuel tank presents a total capacity of 300 liters. For this study, it has been considered that the tank is full when the event (accident) occurs.

3.1.2. CNG buses

Under the evaluated situation, buses are filled with Compressed Natural Gas (CNG). The CNG bus dimensions are the following : length = 12 meters, width = 2,5 meters, height = 3,3 meters. CNG buses are equipped with 9 gas cylinders of 126 litres each in which natural gas is compressed at 200 bars.

Gas cylinders are composite cylinders, CNG-3 type (with aluminium liner) or CNG-4 type (with polyethylene liner) and they are in connection each other via 9 mm diameter high pressure pipes/tubes.

Thermal fuses are installed at both ends of gas cylinders to avoid over pressure. These fuses are activated when temperature reaches 110°C (T° >110°C). Several types of fuses exist depending on the regulation on which the bus relies on (regulations ECE R110 or R96M).

Valves (solenoid valves), installed on the gas line of the bus, are closed as soon as the engine stops. Safety equipments, which depend on the regulation (ECE R110 or R96M), are listed in the next 2 following paragraphs.

3.1.2.1. *CNG bus (R96M Regulation)*

These buses comply with the R96M Regulation from 1996 which has been modified on the 31st of January 2007.
Each gas cylinder (tank) is equipped with a manual valve and two thermal fuses: one "classical" fuse on the high pressure piping side and one "fast" fuse on the opposite. The manual valve allows isolating one of the cylinders if necessary (e.g. for maintenance purposes) but otherwise this valve is usually open.
The high pressure piping is equipped with two « classical » deported thermal fuses (deported PRDs) and with one solenoid valve. These two "classical" deported thermal fuses (deported PRDs) are the same as the fuses installed on the gas cylinders. The valve is closed when the engines stops.

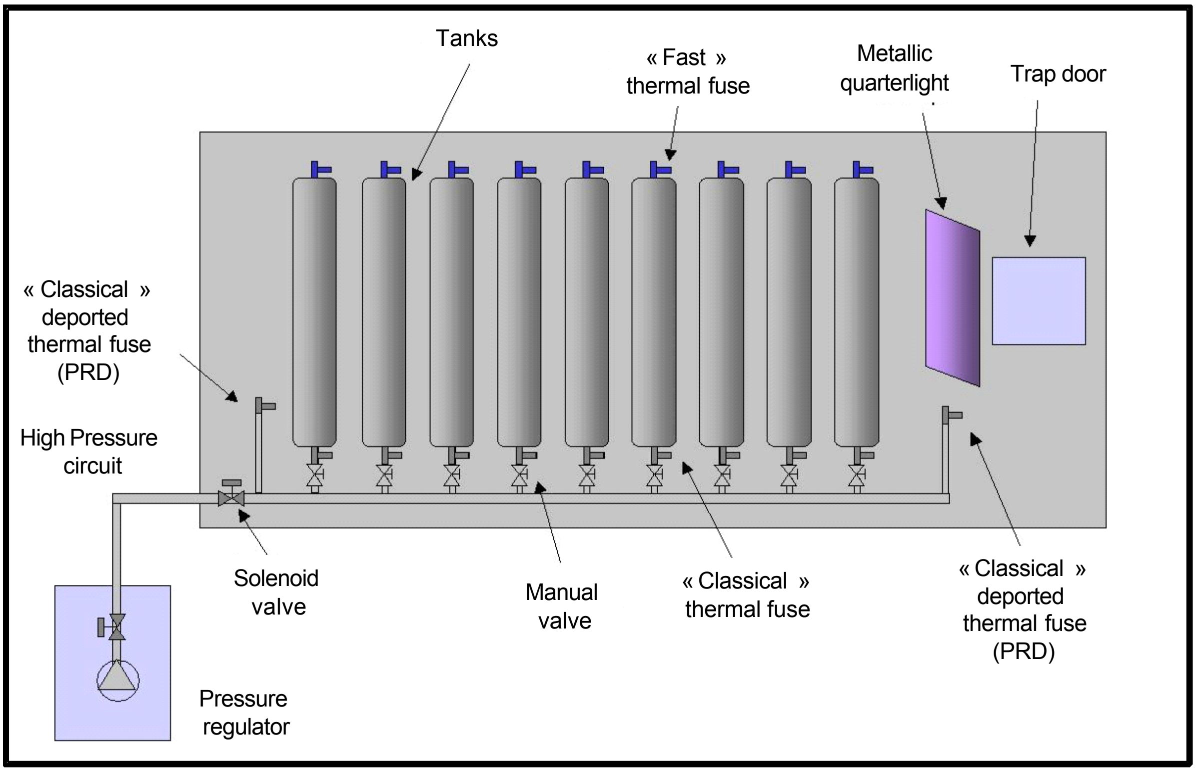

Figure 1 : Schematic representation of a CNG bus complying with R96M regulation.

3.1.2.2. *CNG bus (ECE R110 Regulation)*

These CNG buses comply with the ECE R110 regulation. Gas cylinders tops are equipped with solenoid valves which automatically close when the engine stops. Gas cylinders are equipped with 2 thermal fuses, generally located at both ends. Alternative configuration exist but, in this study we have considered as them equivalent regarding the tests required.

Flow limiters are installed between thermal fuses and solenoid valves. They allow a maximum gas flow of 27 Nm^3/hour in case of wrenching of the high pressure line.

Unlike CNG buses complying with R96M regulation, CNG buses complying with the ECE R110 regulation are not equipped with deported thermal fuses (deported PRDs).

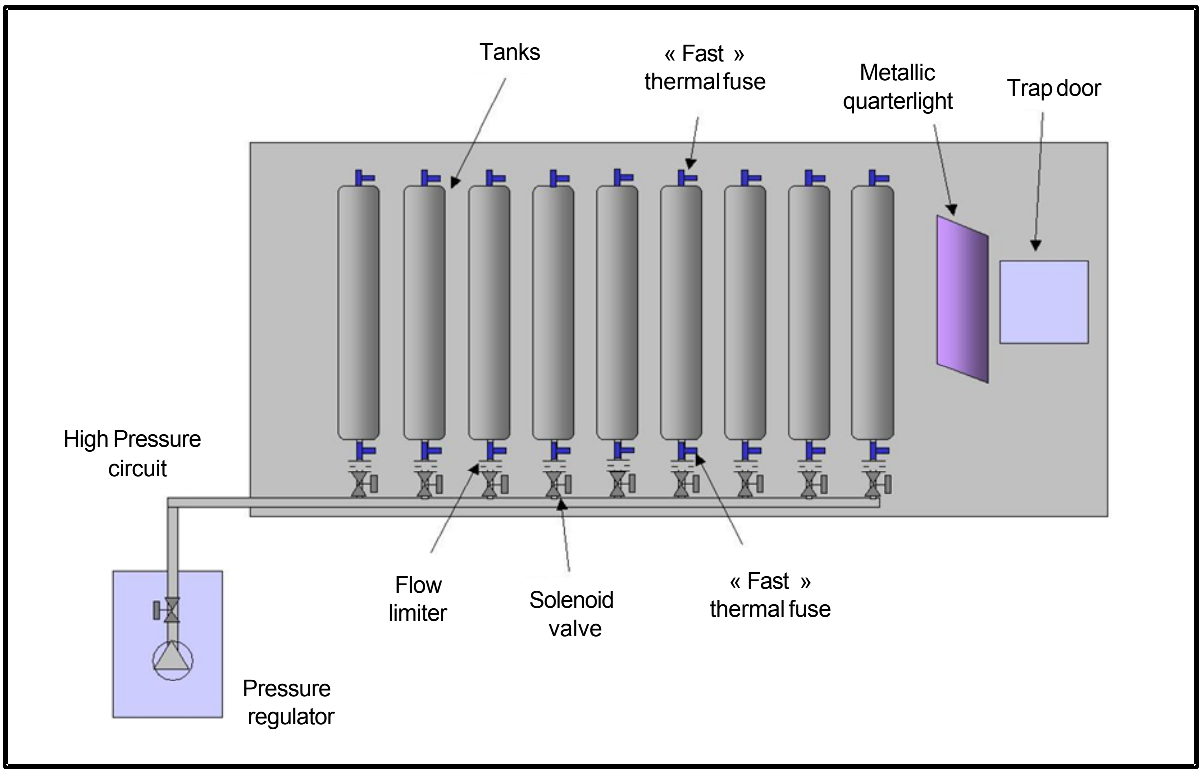

Figure 2 : Schematic representation of a CNG bus complying with ECE R110 regulation.

3.1.2.3. *Additional elements*

The solenoid valves closing when the engine stops is possible thanks to a specific conception of the valve itself. Thermal fuses are generally oriented upwards but for 10% of the cases, these fuses are oriented downwards or towards the gas cylinder itself.

In order to limit the risk of a fire propagation into the bus towards the gas cylinders on the roof via the trap door , most of the CNG buses manufacturers have installed a metallic quarterlight (deflector). We estimate that these dispositions have been taken for 85% of the cases.

3.2. Presentations of industrial vehicles (Heavy Duty Vehicles (HDVs) & Garbage Trucks (GTs) systems

For the evaluated situations, the industrial vehicles are classified following their Fully Loaded Total Weight (PTAC). Three categories are then identified :

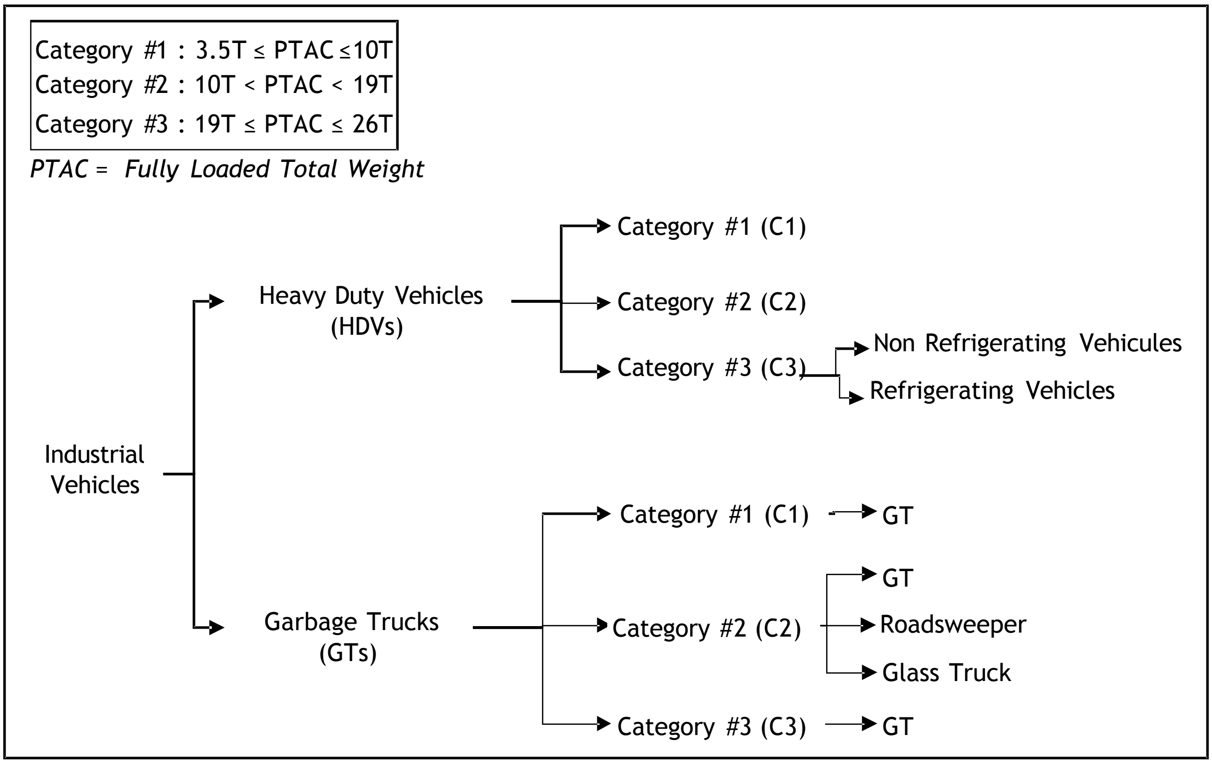

Figure 3 : Industrial Vehicles (HDVs & GTs) decomposition over the 3 categories.

3.2.1. Reference HDVs & GTs: Diesel fuel

The analysis is done by comparison, in terms of equivalent services. Under the chosen conditions as reference, the industrial vehicles are running on Diesel in the environment determined for the study. For this study, it has been considered that the tank is full when the event (accident) occurs.

Categories (PTAC)	**Diesel Industrial Vehicles**	
	Diesel tank volume	**Type of tanks (materials)**
C1 (3,5-10T)	70 to 100 L	Plastiic material (eventually aluminium or Steel)
C2 (10-19T)	115 to 280 L but can be 2x280L	Plastic material, aluminium or Steel
C3 (19-26T)	300 to 800 L but can be 1500L	Aluminium (eventually Plastic or steel)

Figure 4 : Diesel Industrial Vehicles (HDVs & GTs) characteristics.

NB : for these Diesel industrial vehicles, the fuel tanks volume of the HDVs and the GTs have been supposed to be the same for all the categories

3.2.2. CNG HDVs & CNG GTs

3.2.2.1. Characteristics

The location and the volume of the gas cylinders are different for each category defined in Figure 3. Characteristics of the CNG HDVs and CNG GTs are detailed in the following table :

<table>
<tr><th rowspan="2">Categories
(PTAC)</th><th colspan="3">Heavy Duty Vehicles (HDVs)</th><th colspan="3">Garbage Trucks (GTs)</th></tr>
<tr><th>Number & volume of the gas cylinders</th><th>Location of the gas cylinders</th><th>Space available to road</th><th>Number & volume of the gas cylinders</th><th>Location of the gas cylinders</th><th>Dumper/skip Volume</th></tr>
<tr><td>C1
(3,5-10T)</td><td>2 cylinders of 80L + 1 cylinder of 60L + 2 cylinders of 30L Total : 280 L</td><td>2 + 1 in the wheelbases + 2 in Back cabin</td><td>173 à 176 mm</td><td>2 cylinders of 80L + 1 Cylinder of 60L Total : 220L</td><td>2 + 1 in the wheelbasess</td><td>5 to 8 m3</td></tr>
<tr><td>C2
(10-19T)</td><td>6 cylinders of 80L - Total : 480L</td><td>3 in each of the wheelbases</td><td>12t
390 mm under the external cylinders
230 mm under the lowestcylinders
150 mm under the stands

16t
400 mm under the external cylinders
280 mm under the lowestcylinders
200 mm under the stands</td><td>6 cylinders – Total : 480L</td><td>wheelbase</td><td>10 to 12 m3</td></tr>
<tr><td rowspan="3">C3
(19-26T)</td><td>16 cylinders of 80L – Total : 280L</td><td>8 in each of the wheelbasest</td><td rowspan="3">19t
335 mm under the lowestcylinders
265 mm under the stands

26t
360 mm under the lowestcylinders
290 mm under the stands</td><td>4 cylinders of 80L + 4 Cylinders of 70 or 80L = Total : 600L or 640L</td><td>Wheelbases 4 right and 4 left</td><td rowspan="3">14 to 20 m3</td></tr>
<tr><td>8 cylinders of 80L Total : 640L</td><td>4 in the right wheelbase + 2 under front chassis + 2 in back cabin</td><td>4 cylinders of 80L + 2x2 Cylinders of 80L = 640L</td><td>Right wheelbase (4) + Front chassis (2)+ Rear chassis (2)</td></tr>
<tr><td>4 cylinders of 80L + 3 cylinders of 70L – Total : 530L</td><td>4 in the right wheelbase + 3 in back cabin</td><td>4 cylinders of 80L + 3 Cylinders of 70L = 530L</td><td>Right wheelbase (4) + back cabin (3)</td></tr>
</table>

Table 1 : CNG Industrial Vehicles (HDVs & GTs) characteristics.

3.2.2.2. CNG installation (ECE R110 Regulation)

These CNG industrial vehicles are complying with the ECE R110 regulation. One of the head of each gas cylinder is equipped with a solenoid valve which closes automatically when the engine stops or when their electric power is lost. These solenoid valves cannot be leaking or blocked on an open position except if a mechanical failure occurs.
A manual valve is put before the solenoid valve. This manual valve is a priority valve vs. the solenoid valve.

Gas cylinders are equipped with thermal fuses nearby the solenoid valve in order to avoid any over pressure. These fuses are melting when temperature reaches 110°C. Some flow limiters are put in parallel to the thermal fuses and before the valves. These limiters regulate the flow at $3Nm^3/h$ for a pressure delta of 100 bars in case of a breach of the high pressure lines/tubes.
The pressure regulator is located nearby the engine, under the cabin or back to the cabin.
Gas cylinders are made of steel, they are type 1 cylinders (type 3 (aluminum liner) and type 4 (polyethylene liner) cylinders are not used for industrial vehicles. The cylinders are connected together via the high pressure circuit/line. The diameter of the tubes varies with the vehicle category. Their bursting pressure is above 450 bars.

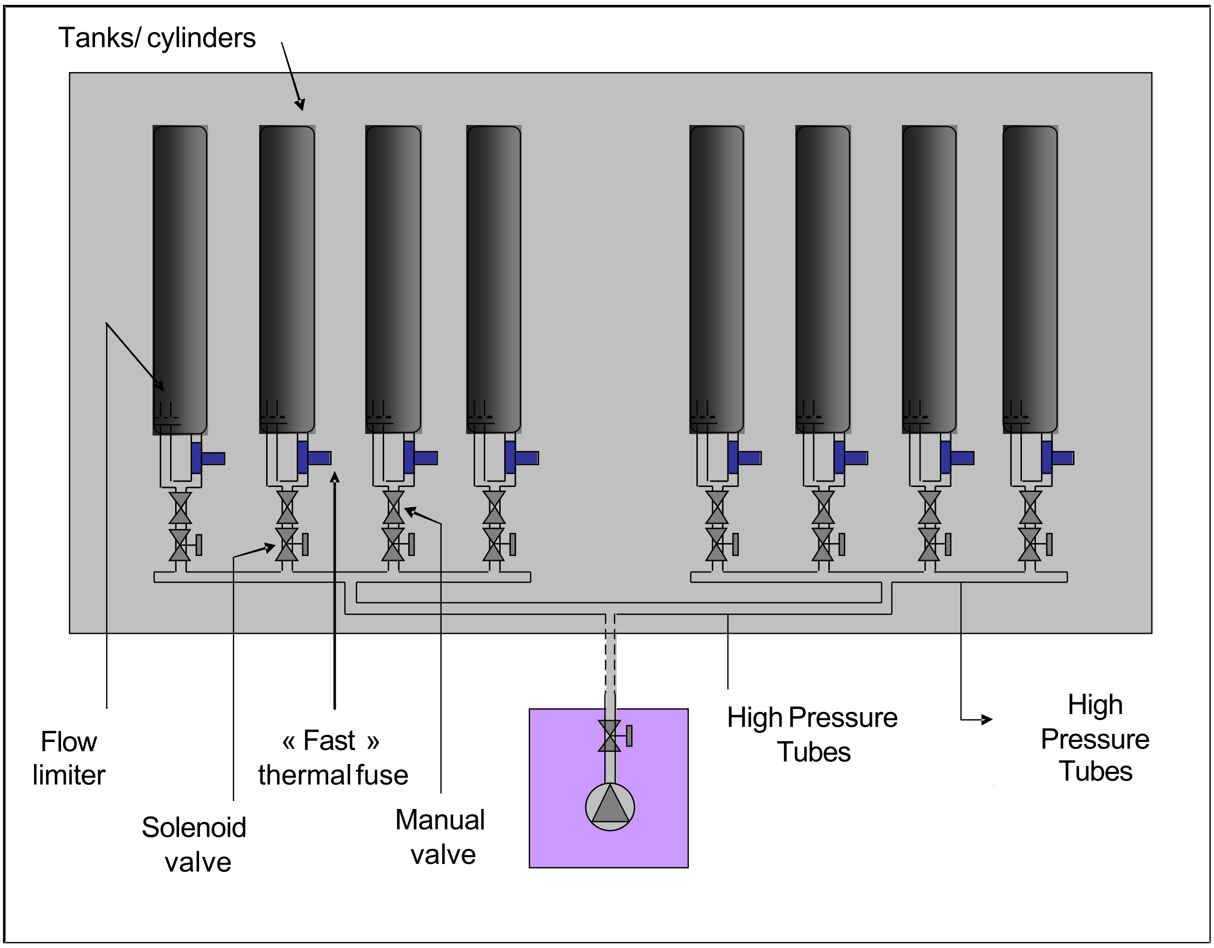

Figure 5 : Schematic representation of CNG HDVs/GTs with ECE R110 regulation.

3.3. Presentation of the tunnel environment

We have decided to consider the situation for which the maximum number of cases are covered. When some data for the vehicle and its environment are missing or incomplete, the upper bound choice has been chosen and applied for the CNG situation.

The tunnel geometry, the traffic data and the ventilation data presented in this document and used for the calculations have been defined in collaboration and after approval of experts of the CETU (French Tunnels Studies Centre).

3.3.1. Tunnel geometry

Characteristics adopted for the tunnel are representative of an urban tunnel, new or renovated, and complying with the current requirements especially in terms of building and exploitation dispositions.

The tunnel considered for this study is 500 meters length and 4.75 meters high. We have considered that the feared event (the accident) occurs at the centre of the tunnel in order to consider the most penalizing case.
The tunnel consists in 2 circulation tracks (roads), one hard shoulder and one pavement. Circulation in the tunnels occurs only on one way.

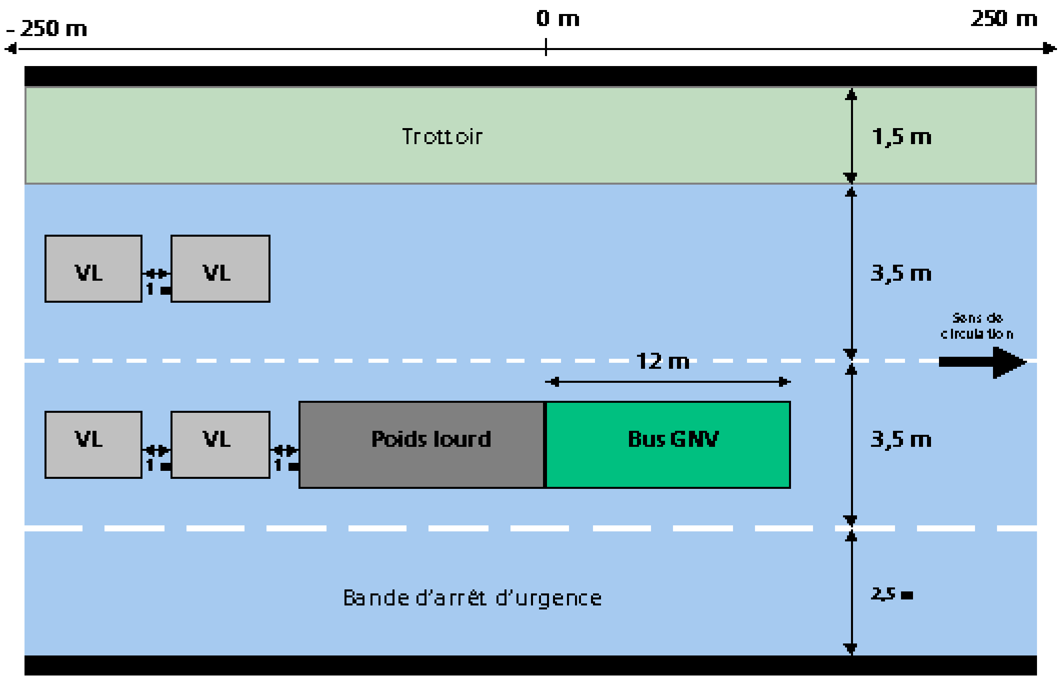

Figure 6 : Schematic representation of the tunnel (planar view).

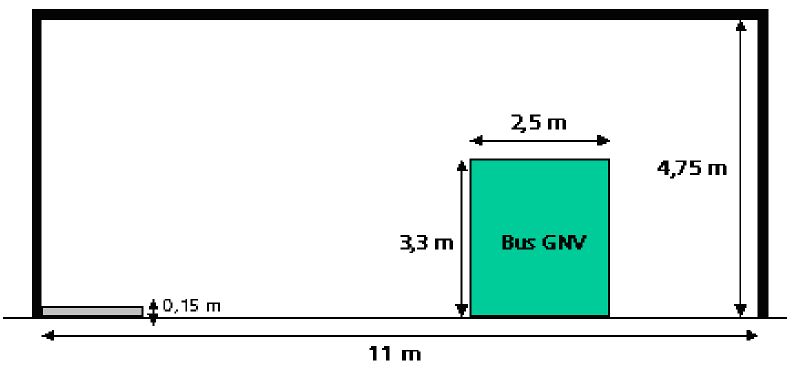

Figure 7 : Schematic representation of the tunnel (profiling view).

3.3.2. Traffic conditions

In order to better represent all the different traffic conditions, 2 types of traffic conditions have been considered:

◊ Dense traffic : 3000 vehicles/hour, running at 10 km/h. This hypothesis brings, in case of a collision, to low energy impacts (but possibly generating gas leaks). For the study, we have considered that the bus is carrying 100 persons.

◊ Moving freely traffic : 1000 vehicles/hour, running at 60 km/h. This hypothesis brings to high energy impacts in case of collisions (possibly generating a breach of the high pressure piping line or event conducting to the wrenching of the cylinders rack on the top of the roof of the CNG bus).

For the study, we have considered that the bus is carrying 30 persons. For the industrial vehicles, we have considered that for the HDVs only 1 person is on board (the driver) while for the GTs we have considered that 3 persons are on board (the driver + 2 passengers).

Experts from the CETU (French Tunnels Studies Centre), agrees with the hypothesis of a ratio of 10% of heavy duty vehicles in these traffic conditions. Frequently, heavy duty vehicles are not allowed to overtake other vehicles when in tunnels. Then, we have considered a ration of 20% of heavy duty vehicles running on the right-hand road in the tunnel. Transportation of dangerous goods in tunnels is forbidden.

3.3.3. Tunnel ventilation (venting system)

Different types/configurations of ventilation/venting systems co-exist in tunnels.

3.3.3.1. Natural ventilation

This effect corresponds to the ventilation/venting effect naturally created by the difference of atmospheric conditions between both ends of the tunnel. This effect generally occurs in urban area but it has not been integrated/considered for this study.

3.3.3.2. Piston effect ventilation

This effect occurs when air masses are put into motion by vehicles traffic. The air current/flow inducted by piston effect relies between 1 m/sec (under dense traffic conditions) and 3 m/sec (under moving freely traffic conditions). This air-flow/venting effect gradually decreases when vehicles slow down or even stop in the tunnel.

In order to consider a precise value of the piston effect air-flow speed, experts from CETU have conducted calculation with the CAMATT software. Results of these calculation show that, under moving freely traffic conditions, the air flow speed reaches 60 km/hour :

- Initial air-flow speed is 3,6 m/sec, which reinforce the choice of a 3 m/sec value in order to consider the upper bound scenario in the CNG case,
- 40 seconds after the accident (collision), the air-flow speed is still 3 m/sec, then superior to 2,5 m/sec,
- If we « maximize » the value of the piston effect air-flow speed up to 3 m/sec when the accident occurs, the air-flow speed is still around 2,5 m/sec 40 seconds after the accident1.

3.3.3.3. Mechanical ventilation

Mechanical de-fuming (de-smoking) systems are mandatory in news tunnels longer than 300 meters. This obligation also runs when tunnels are renovated. Two mechanical venting systems have to be considered :

◊ Health/sanitary ventilation, under normal operation conditions, which is installed in order to evacuate polluting emissions from vehicles in the tunnel,

◊ De-fuming/de-smoking ventilation in case of fire in the tunnel. This mechanical de-fuming ventilation is started by a security agent which activates a pre-programmed scenario adapted to the event as soon as the fire is detected. Usually, this de-fuming mechanical ventilation is started at T0+2min (T0 : accident or fire detected/seen) and the de-fuming regime is usually stabilized at about T0+4min.

Two types of mechanical ventilation exist :

◊ Lengthwise ventilation pushes the air in the same direction of the circulation thanks to accelerating systems (reference value of the created air-flow speed= 3 m/sec),

◊ Cross-ventilation extracts the air at the roof of the tunnel (reference air-flow speed 160-200m^3/sec).

For this study, mechanical ventilation has been considered as lengthwise ventilation (case most representative of urban area tunnels). Then, the de-fuming ventilation speed has been considered at 3m/sec.

3.3.3.4. Resulting ventilation

Under dense traffic conditions :

- Piston effect ventilation air-flow speed at T0 (when the accident occurs) : 1 m/sec
- Lengthwise mechanical ventilation started at T0+2min and stabilized at about T0+4min, air-flow speed : 3 m/sec

Under moving freely traffic conditions : ventilation evolves over the time depending on different scenarios:

- Piston effect ventilation air-flow speed at T0 (when the accident occurs) : 3 m/sec

[1] *These results reinforce the hypotheses taken for the gas inflammation calculations conducted thereafter for which we have considered a 40-second delay to characterize the size of the gas cloud when emitted at constant flow.*

Lengthwise mechanical ventilation started at T0+2min and stabilized at about T0+4min, air-flow speed : 3 m/sec

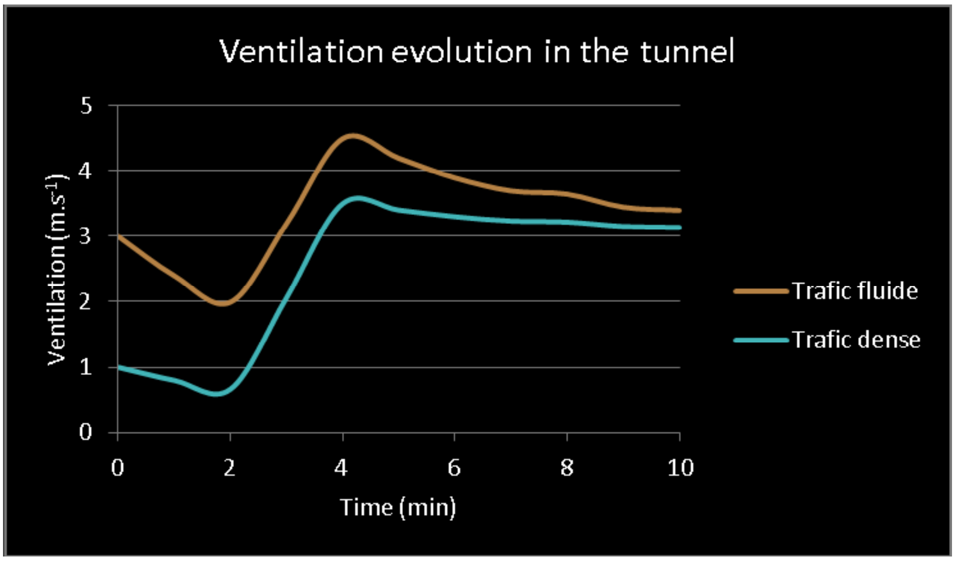

Figure 8 : Ventilation evolution in the tunnel.

4. RESULTS

4.1. Probabilities Comparison for buses

The following table presents a summary of the probabilities for the different cases (scenarios) studied **for diesel buses, CNG buses** complying with R96M regulation and CNG buses complying with ECE R110 regulation.

Cases	Central feared event / Dangerous phenomena	Probability for Dangerous phenomena (per vehicle)	
		Free traffic	Dense traffic
Diesel	Fire / Bus and gasoil fire	9,9E-10	2,1E-09
CNG R96M	Leak / Inflammation	6,2E-11	4,7E-10
	Breach / Torch	7,9E-12	0,0E+00
	Breach / Vapour Cloud Explosion (VCE)	7,9E-12	0,0E+00
	Breach / Anoxia (lack of oxygen)	3,2E-10	0,0E+00
	Fire / Torches from fuses	9,7E-10	2,4E-09
	Fire / Gas cylinder bursting	2,4E-17	6,0E-17
CNG ECE R110	Leak / Inflammation	6,2E-11	4,7E-10
	Breach / Torch with limited flow	4,7E-17	0,0E+00
	Breach / Torch	2,4E-23	0,0E+00
	Breach / VCE	9,2E-24	0,0E+00
	Breach / Anoxia (lack of oxygen)	3,7E-22	0,0E+00
	Fire / Torches from fuses	9,7E-10	2,4E-09
	Fire / Gas cylinder bursting	4,9E-14	1,2E-13

Table 2: Probability of events for Diesel and CNG buses

One can see that the most probable/likely events for CNG buses are the gas inflammation by release of the thermal fuses installed on the vehicle to avoid a gas pressure increase in the cylinders. In addition, under dense traffic conditions, low speeds of the vehicles in the tunnel reduce the energies generated in case of a collision, which has brought the working group to exclude the probability that a breach occurs (probability = 0/vehicle). Probabilities of the other dangerous phenomena (leak, fire) slightly increases when traffic is getting denser.

When comparing phenomena occurrence between CNG buses complying with R96M regulation and CNG buses complying with ECE R110 regulation, it appears that probabilities of occurrence are lower for the CNG buses complying with ECE R110 regulation, except for the gas cylinders bursting phenomena: manual valves which are usually in open position and located at both ends of the cylinder (for the R96M configuration), can represent an additional security barrier in case of a widespread bus fire and in case this fire is not detected by the two thermal fuses located on the same cylinder.

4.2. Seriousness Comparison for buses

The following table presents a summary of seriousness evaluated and associated to the different studied phenomena for Diesel buses, CNG buses complying with R96M regulation and CNG buses complying with ECE R110 regulation. One can see that the event for which the seriousness if **the highest for CNG buses would be the bursting** of one of the gas cylinders in the case of a widespread bus fire and in the case that simultaneously, several thermal fuses are not activated.

Cases	Central feared event / Dangerous phenomena	Phenomena Seriousness	
		Free traffic	Dense traffic
Diesel	Fire / Bus and gasoil fire	0,34	0,86
CNG R96M	Leak / Inflammation	0	0
	Breach / Torch	0,10	/
	Breach / Vapour Cloud Explosion (VCE)	0,022	/
	Breach / Anoxia (lack of oxygen)	0,0001	/
	Fire / Torches from fuses	0,10	0,26
	Fire / Gas cylinder bursting	8,7	12,1
CNG ECE R110	Leak / Inflammation	0	0
	Breach / Torch with limited flow	0,029	/
	Breach / Torch	0,10	/
	Breach / Vapour Cloud Explosion (VCE)	0,10	/
	Breach / Anoxia (lack of oxygen)	0,0001	/
	Fire / Torches from fuses	0,10	0,26
	Fire / Gas cylinder bursting	8,7	12,1

Table 3: Phenomena seriousness for Diesel and CNG buses

4.3. Global Risks levels Comparison (criticalities) for buses

To complete the analysis, the risks levels (criticalities) of the different considered events are evaluated by multiplying each case probability by its seriousness. Results are summarized in the table and figures below.

Cases	Central feared event / Dangerous phenomena	Risks Levels	
		Free traffic	Dense traffic
Diesel	Fire / Bus and gasoil fire	**3,4E-10**	**1,8E-09**
CNG R96M	Leak / Inflammation	0	0
	Breach / Torch	7,9E-13	/
	Breach /Vapour Cloud Explosion (VCE)	1,7E-13	/
	Breach / Anoxia (lack of oxygen)	3,2E-14	/
	Fire / Torches from fuses	9,7E-11	6,2E-10
	Fire / Gas cylinder bursting	2,1E-16	7,2E-16
	Total	**9,8E-11**	**6,2E-10**
CNG ECE R110	Leak / Inflammation	0	0
	Breach / Torch with limited flow	1,4E-18	/
	Breach / Torch	2,4E-24	/
	Breach /Vapour Cloud Explosion (VCE)	9,5E-25	/
	Breach / Anoxia (lack of oxygen)	3,7E-26	/
	Fire / Torches from fuses	9,7E-11	6,2E-10
	Fire / Gas cylinder bursting	4,2E-13	1,4E-12
	Total	**9,7E-11**	**6,2E-10**

Table 4: Global risks levels comparison for Diesel and CNG buses

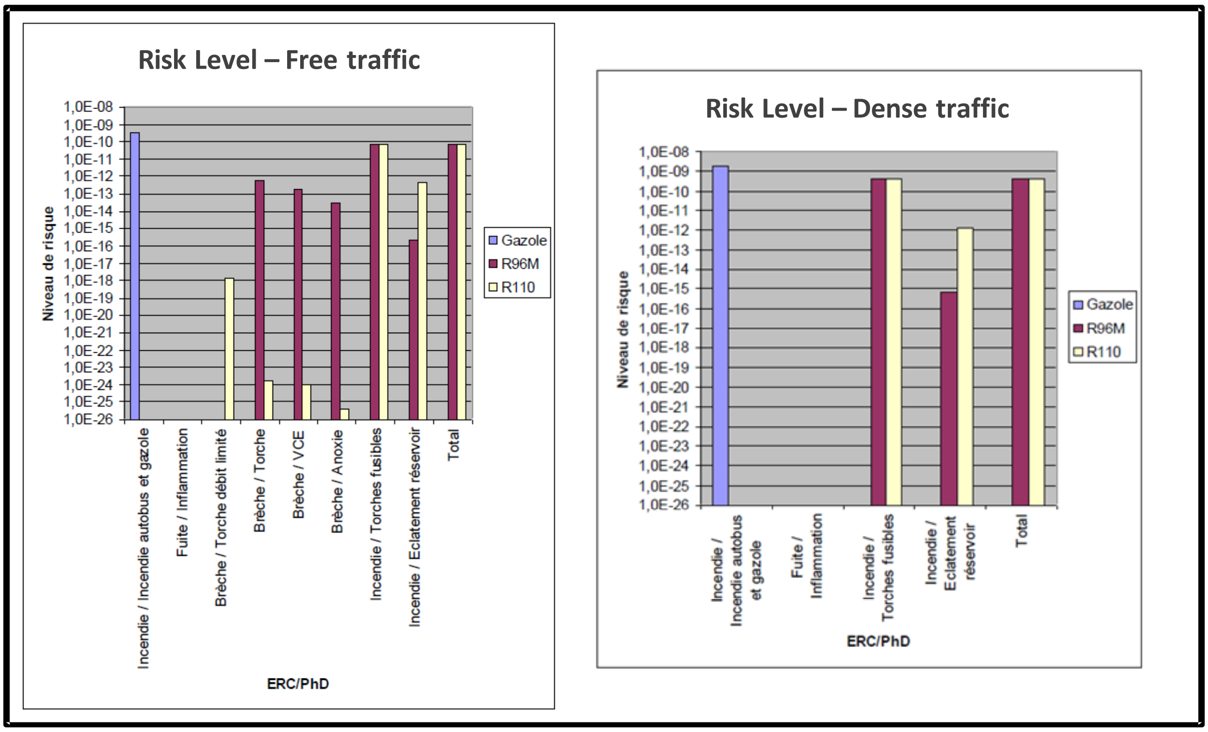

Figure 9: Risk Levels for Diesel and CNG buses

4.4. Global Risks levels Comparison (criticalities) for Industrial Vehicles

The global risks levels comparison in the case of the Industrial Vehicles (i.e. Heavy Duty Vehicles (HDVs) and Garbage Trucks (GTs)), running in the tunnel, for the reference fuel (Diesel) and for the CNG is summarized in the following figures and table.

Case	Central feared event / Dangerous phenomena	Crticalities of Dangerous Phenomena					
		Free Traffic			Dense Traffic		
		3,5-10T	10-19T	19-26T	3,5-10T	10-19T	19-26T
Diesel HDVs	Fire / Gasoil fire	1,18E-10	2,27E-10	4,85E-10	4,08E-10	7,97E-10	1,70E-09
Diesel GTs	Fire / Gasoil fire	3,73E-10	5,15E-10	8,69E-10	1,31E-09	1,80E-09	3,05E-09
CNG HDVs ECE R110 regulation	Leak / Inflammation	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Breach / Torch or fire ball with limited flow	1,16E-17	7,18E-18	5,74E-17	0,00E+00	0,00E+00	0,00E+00
	Breach / Torch o fire ball with important flow	9,84E-23	5,80E-23	1,69E-22	0,00E+00	0,00E+00	0,00E+00
	Breach /Vapour Cloud Explos	9,12E-24	4,35E-24	1,16E-23	0,00E+00	0,00E+00	0,00E+00
	Breach / Anoxia	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Fire / Torches from fuses	4,54E-11	5,61E-11	6,15E-11	1,75E-10	2,17E-10	2,38E-10
	Fire / Gas cylinder bursting	2,83E-16	3,39E-16	9,04E-16	2,23E-15	2,66E-15	7,10E-15
	Total CNG HDVs	**4,54E-11**	**5,61E-11**	**6,15E-11**	**1,75E-10**	**2,17E-10**	**2,38E-10**
	gap (Diesel -CNG)/Diesel %	**61**	**75**	**87**	**57**	**73**	**86**
CNG Garbage Trucks (GTs) ECE R110 regulation	Leak / Inflammation	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Breach / Torch with limited flow	1,93E-18	9,38E-18	1,77E-17	0,00E+00	0,00E+00	0,00E+00
	Breach / Torch with Important flow	1,95E-22	4,44E-22	7,65E-22	0,00E+00	0,00E+00	0,00E+00
	Breach Vapour Cloud Explos	4,83E-24	9,66E-24	1,29E-23	0,00E+00	0,00E+00	0,00E+00
	Breach / Anoxia	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Fire / Torches from fuses	3,77E-10	4,30E-10	5,56E-10	1,47E-09	1,67E-09	2,16E-09
	Fire / Gas cylinder bursting	2,06E-16	4,11E-16	5,48E-16	1,62E-15	3,23E-15	4,31E-15
	Total CNG GTs	**3,77E-10**	**4,30E-10**	**5,56E-10**	**1,47E-09**	**1,67E-09**	**2,16E-09**
	gap (Diesel -CNG)/Diesel %	**-1**	**16**	**36**	**-12**	**8**	**29**

Table 5: Criticalities comparison for Diesel and CNG Industrial Vehicles

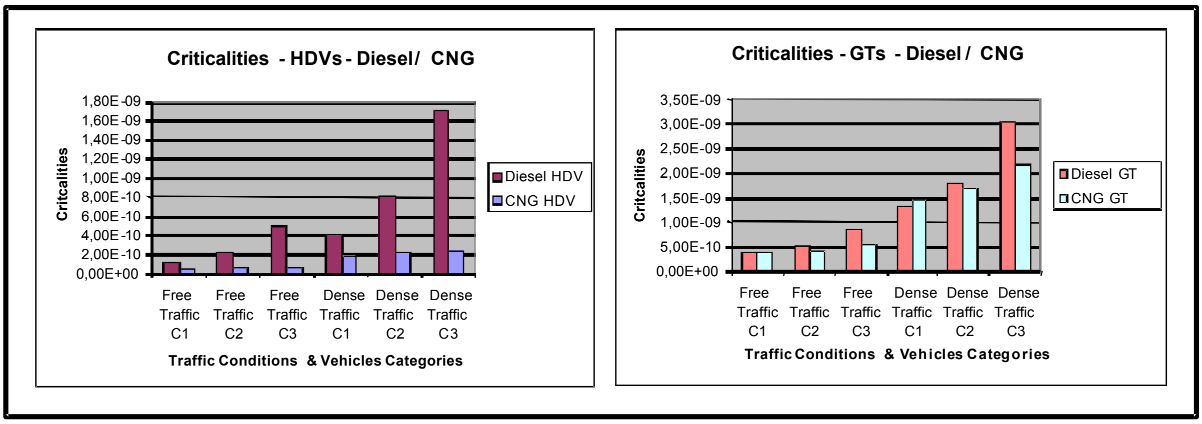

Figure 10: Risk Levels for Diesel and CNG HDVs & GTs

Criticalities depend not only on the fuel (Diesel vs. CNG), but also on the vehicle category.

4.4.1. Heavy Duty Vehicles (HDVs)

For HDVs, without any dangerous goods being transported (except the fuel on board), criticalities are less important for CNG vehicles than for Diesel vehicles. The risk level reduction for CNG vehicles in comparison to Diesel vehicles is between 61% for the C1 category (3,5 – 10 T) and 87% for the C3 category, under free traffic conditions.

Dense traffic conditions are less favorable than free traffic conditions for CNG vehicles due to a higher probability to have CNG leaks that could get on fire and leading to a general fire in the tunnel.

4.4.2. Garbage Trucks (GTs)

Only one case is not favorable to CNG, with C1 category of vehicles under dense traffic conditions. Under free traffic conditions, the gap between CNG and Diesel is not significant (-1%) and no conclusion can be driven. This unfavorable case for CNG is due to the faster kinetics of reaction at the beginning of the fire in the case of CNG vehicle. This faster kinetics make the fuses melting and thus the entire combustion of the loaded materials, accelerating the production of fumes in comparison to Diesel vehicles.

For all the Garbage Trucks (GTs), when considering that there are as many Diesel and CNG vehicles in operation, for each category, and considering that the traffic conditions are 1/3 of dense traffic and 2/3 of free traffic, the total criticalities gap is around 17% in favor to CNG in comparison to Diesel.

5. CONCLUSIONS

When a bus moves in a tunnel, **quantitative analysis shows that the global risk level of a CNG bus is about 3 times inferior to the global risk level of a Diesel bus**, when considering the 10 first minutes after the accident occurs. This results remains the same whatever the traffic conditions (moving freely or dense traffic).

In the case of a CNG bus, the dominant term in the whole risk et the widespread fire with all the thermal fuses being started. When the entire bus is on fire and when this fire is not under control, comparison of the kinetics of the 2 cases (Diesel vs. CNG), following the calculation method of the present study, shows that:

- Considering the fact that the combustion delay, in the case of CNG, is more spread over the time than in the case of Diesel (13 min to be compared to about 6 min for the combustion of the gasoil slick), **the power pick of the fire is 2 times inferior for the CNG case than for the Diesel case**;
- The **average production of fumes** over the 10 first minutes following the accident **is much lower – about -80% - in the CNG case than in the Diesel case**;

- When considering the volume of fumes produced over 1 hour following the accident, **the total volume of fumes is about 30% smaller in the CNG bus case than in the Diesel bus case**, which represents **a global risk level 1,4 times inferior for the CNG bus than for the Diesel bus** (even without considering the toxicity details of the fumes of which composition is very penalizing for the Diesel case).

Among all the situations/scenarios analyzed in this study, the term which has the maximum risk weight over the different risks for a CNG bus, is the widespread fire of the bus. The risk level being determined in terms of fumes production, the global analysis and all the conclusions remain the same even when the tunnel section varies.

In the case of HDVs, the global risk for CNG HDVs has been evaluated in comparison to Diesel HDVs: this **risk is 61% less important with CNG HDVs than with Diesel HDVs** (free traffic conditions – HDVs from 3.5 to 10 tons). For the **heavier HDVs (from 19 to 26 tons), the risk is 87% less important with CNG HDVs than with Diesel HDVs**.

3. Acknowledges

Authors would like to thank all contributors, representatives of MEDDTL and DSR office, CETU Centre and SECTOR Company.