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13 March 2015

Additional information for ECE/TRANS/WP.15/2015/6e – Use of Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (CNG) as fuel for vehicles carrying dangerous goods: Focus on CNG safety

Transmitted by NGV Global

Summary

Executive summary: Methane (CH4) has been used as a vehicle propulsion since the mid-1930s, at first predominantly in Italy and today used in more than 20 million over-the-road light and heavy duty vehicles worldwide as well as for non-road vehicles (e.g. construction and recreational) and, most recently, in ships. Vehicles propelled in one method or another by natural gas are called generically *natural gas vehicles* (NGVs). The fuel is used in spark ignited internal combustion engines (SI-ICE) operating independently on *either* methane *or* petrol and are referred to as 'bi-fuel' systems. Compression ignition engines that mix various quantities of diesel fuel and methane are referred to as dual-fuel systems. Engines designed to run *only* on natural gas (spark-ignited) are called 'dedicated' natural gas engines.

Methane can originate from fossil sources or is created from agricultural, urban and human waste in the form of renewable biogas upgraded to biomethane suitable for contemporary vehicles. (It also can be produced synthetically.) Methane can be stored as a gaseous fuel (compressed natural gas – CNG) or in cryogenic form as liquefied natural gas (LNG).

The operational safety of NGV components -- for CNG and LNG vehicles-- and their testing is regulated through the application of the ECE Regulation No. 110 (which also references other international standards such as ISO).

This document presents the safety aspects of natural gas – focused on CNG -- associated with the operation of such vehicles and how the regulations help to ensure a good level of safety when applied properly.

The body of safety literature and studies – private sector and government-sponsored – coupled with documented real-world experiences demonstrate that the use of compressed natural gas (CNG) as a fuel for road vehicles is no more a risk than vehicles fuelled with liquid petroleum fuels. In fact, some of the literature and data indicate that operation on natural gas is safer than petrol or diesel fuel, particularly when involved in hazardous accidents.

Action to be taken: Discussion on the topic, amendment of 9.3.4.4 to include CNG and referencing the respective ECE Regulations.

Related documents: Working Document,Use of Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (CNG) as fuel for vehicles carrying dangerous goods ECE/TRANS/WP.15/2014/16e)

Introduction

In Working Document ECE-TRANS-WP15-2015-6 – "Use of Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (CNG) as fuel for vehicles carrying dangerous goods" AEGPL and NGV Global propose the amending subsection 9.3.4.4 introducing compressed natural gas (CNG) and liquefied petroleum gas (LPG) as fuels alongside liquefied natural gas (LNG) as per the proposal in the working document.

This document refers specifically to the safety aspects of CNG.

Summary of the Properties of Methane/Natural Gas

Methane (CH4) is the principle constituent in natural gas. Methane is a naturally occurring substance as a fossil fuel but also is a renewable fuel that can be made from agricultural waste (plant and animal), human and urban waste, typically through anaerobic digestion. This process results in a mixture including about 50% methane (biogas) that can be upgraded to pipeline quality *bio-methane* for introduction into the normal gas pipeline grid or used directly as a vehicle fuel.

Methane is flammable at ambient pressure and temperatures and has a relatively low ignition temperature; -188°C compared to diesel at 55°C. Methane has the highest of the auto ignition temperatures; 540° C for CNG versus diesel at 210° C[1].

One key feature of natural gas is that it is lighter than air and disperses very quickly. Unlike liquid fuels, natural gas does not pool around the vehicle if it leaks. The concentration rapidly dissipates before the explosive limit is reached (approximately 5% methane-to-air). As such, in case of a potential leak, the risk of ignition of compressed natural gas coming into contact with a hot vehicle part is considerably lower than with diesel. By contrast, diesel has a lower explosive limit of 0.6%, making it more likely to ignite both at lower concentrations and lower auto-ignition temperature.

An overview of the physical properties of currently used vehicle fuels is shown in Table 1 below. A summary of the relative safety aspects of traditional fuels and the gaseous fuels are shown in Table 2.

Table 1: Physical properties (indicative) fuels

Properties	*Petrol*	*Diesel*	*LPG*	***CNG***	***LNG***
Lower Explosive Limit (LEL) –	1.2%	0.6%	1.8%	**5%**	
Upper Explosive Limit (UEL)	7.1%	7.5%	8.5%	15%	
Auto ignition Temperature	246 °C	210 °C	450 °C	540 °C	
Flash point(liquid) ignition point (gas)	-43 °C	55 °C	-104 °C	-188 °C	

[1] Higher auto ignition temperatures for diesel are reported, up to 280 °C.

Dispersion quality	None	None	medium	High	Medium

Table 2: Summary of safety aspects of various fuels

Properties	*Petrol*	*Diesel*	*LPG*	*CNG*	*LNG*
ECE-Regulation fuel tank	R.34	R.34	R.67-01	R.110-Rev 3	
Leakage after collision	probable (allowed)	probable (allowed)	Improbable	Very Improbable	Very Improbable
Bonfire test of tank	no (only plastic tanks)	no (only plastic tanks)	Yes	Yes	Yes
Bleed (ventilation)	Yes	Yes	No	No	Yes

Description of CNG Vehicle System

Generically speaking, CNG fuel systems are relatively simple in terms of their mechanical and electrical/electronic components. The complexity of natural gas/gasoline systems and more often with heavy duty, dual-fuel natural gas/diesel vehicles relates mostly to the fuel management system and its compatibility with the controls designed for petroleum fuels. The NGV system components are type approved and installed in accordance with UN/ECE Regulations 110. These components include:

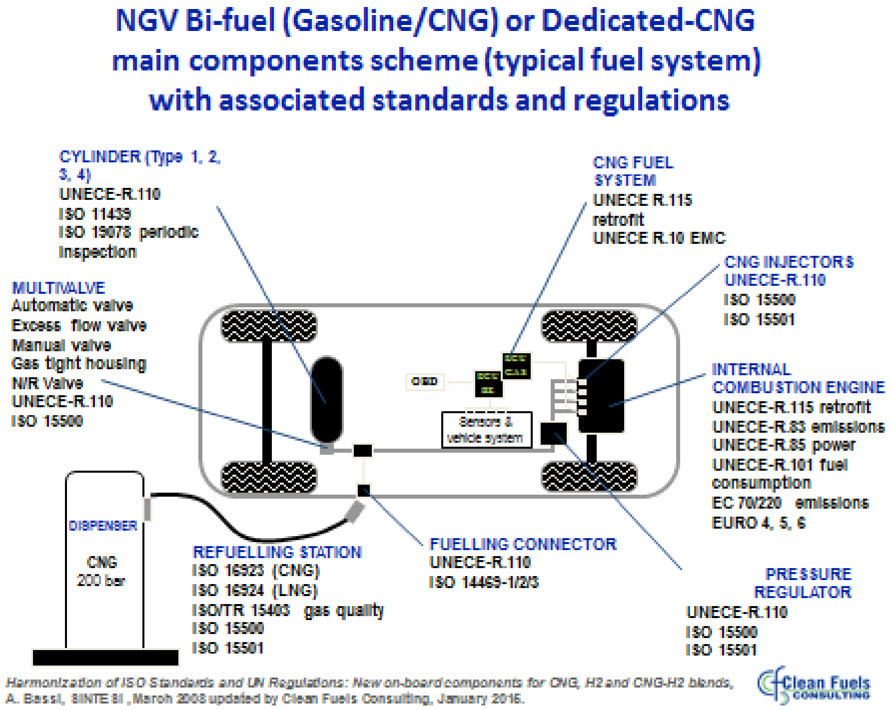
One or multiple CNG cylinders, also including thermal/pressure relief devices (PRDs), excess flow valves, manual valves, and brackets or frames for multiple cylinders comprising the ‘fuel storage system’;

High pressure fuel lines;

Pressure regulator, fuel solenoid valves (one for a gas line/one for petrol) and fuel injector(s).

A schematic of the basic CNG fuel system, along with some of the principle international standards and regulations applicable to the components is shown in Figure 1.

Figure 1: CNG fuel system components & related international standards and regulations



Safety concerns of NGVs most typically reflect issues with the high pressure fuel storage systems. In fact, CNG fuel storage systems are amongst the safest, most robust of any transportation fuel used today. Likewise, CNG cylinders are subject to the most stringent, destructive, and challenging certification testing requirements than those of any liquid fuels. Steel cylinders are tested to 2.5 times the working pressure and as much as 3.65 times the working pressure for CNG cylinders incorporating or made of various composite materials.

Emergency shut-off devices and pressure relief devices are specially designed and installed to maximize safety in the event of an accident or other unforeseen occurrence harmful to the vehicle.

Compressed natural gas (CNG) cylinders are available in a number of different types, weights and sizes to suit different applications. These include:

CNG Type 1: All metal cylinder made of steel. There is no covering other than paint on the outside of the cylinder.

CNG Type 2: A metal cylinder (steel or aluminium) with a partial wrapping that goes around the cylindrical part of the cylinder (hoop wrapped). The wrapping is usually made of glass, aramid or carbon fibre, contained in an epoxy or polyester resin.

CNG Type 3: This type of cylinder is fully wrapped with the same kind of material used for the partial wrapping of a Type 2 cylinder. It has a metal liner, usually an aluminium alloy.

CNG Type 4: This is fully wrapped with the same kind of material used for the partial wrapping of a Type 2 cylinder. This type of cylinder has a plastic liner.

Specific requirements set out in international standards and regulations specific to CNG fuel systems “are based on the unique physical and chemical attributes of CNG.

Specifically for safety considerations, these typically have requirements to include (but are not necessarily limited to):

- Requirements for minimum structural integrity and labelling of high-pressure CNG fuel containers;
- A PRD (pressure relief device) is a one-time-use device triggered by excessive temperature and/or pressure that vents gas to protect the cylinder from rupture, particularly in case of a fire. Temperature-triggered PRDs are mandatory; pressure-triggered PRDs are optional.
- Requirements related to sizing, securement, routing, and protection of PRD vent lines to protect vehicle occupants from—and to minimize—the possibility of venting gas being ignited;
- A manual or remotely activated shutoff valve on each CNG fuel container to isolate it from the rest of the fuel system;
- An additional shutoff valve to isolate all CNG fuel containers from the rest of the fuel system and engine."
- An excess flow valve to shut off or extremely limit the flow of gas escaping from a container in case of a ruptured pipe or main valve.

As with road vehicles of all types, ensure proper installation and regular inspections of fuel system components (lines, valves) can preclude in-use wear and damage."[2]

Global CNG Incident Data Demonstrate Overall Safety

A 2013 study by the U.S. Department of Transportation systematically characterized NGV/CNG accidents, equipment failures and fires from 1976-2010. The data were provided by the Clean Vehicle Education Foundation, the non-profit affiliate of NGVAmerica. The data were collected by a variety of NGV stakeholders and organizations worldwide over the past three decades.[3]

- 138 incidents: 56% U.S.; 44% Europe, Asia, S. America;
- All vehicles included: 51% LDV/Trucks; 38% buses; 11% other commercial vehicles;
- Most problems were with individual NGVs and not a result of any general systemic failures;
- 14 incidents (10%) involved a pressure relief device failure that vented a cylinder but without a fire;

[2] Adapted from, *"Natural Gas Systems: Suggested Changes to Truck and Motorcoach Regulations and Inspection Procedures,"* U.S. Department of Transportation, Federal Motor Carrier Safety Administration, Report number **FMCSA-RRT-13-044,** March 2013.

[3] *Natural Gas Systems: Suggested Changes to Truck & Motorcoach Regulations & Inspection Procedures*, U.S. Dept. Transportation (FMCSA), March 2013, findings based on data from Clean Vehicle & Education Foundation

- 17 vehicles (13%) involved fire but only one (0.007%) was attributed to a failure of the CNG system and none of the cylinders in these incidents ruptured (gas fuel storage safety systems worked as designed);
- Most fires that occurred were started by an electrical short, stuck brakes (which ignited a tire), or leaking gasoline, diesel fuel or hydraulic fluid impinging on a hot engine or exhaust system and was not caused by the CNG fuel or fuel storage systems.

Table 3 summarizes 135 of the 138 incidents reported from 1976-2010 (three incidents from the total lacked enough specific information to be quantified into this table).

Table 3: Summary of NGV accidents 1976-2010

Type of Incident	Number of Incidents (135)	Percentage of Total
Cylinder ruptures	50	37%
PRD release (no fire)	14	10%
Vehicle fire (no cylinder rupture)	17	13%
Accident w/another vehicle	12	9%
Single vehicle accident	6*	4%
Cylinder or fuel tank leak	14	10%
Other	7**	5%
Unknown cause	15+	11%

*5 of these were at low underpasses
** 5 related to operational/maintenance
+12 outside the U.S.

Natural Gas Vehicle Safety in Normal Operations (and in consideration of concerns of ADR)

There are a variety of concerns about CNG in ADR-certified vehicles in the operational phase. But the physical characteristics of CNG and the functional solutions provided to prevent accidents with cylinders during fires make CNG safer than operation with liquid fuels.

Interaction between cargo and fuel

Natural gas is an inert, non-toxic, non-corrosive substance. A chemical interaction with the cargo is not possible unless in the case of some catastrophic occurrence if the entire vehicle is completely destroyed (as might be the case with intentional sabotage). Physical interaction with the cargo is restricted to an accident whereby the load is compromised and becomes enflamed or in the case of a catastrophic incident involving a CNG cylinder, which is highly unlikely during the normal installation, operation and maintenance of an NGV done in accordance with international standards, regulations and in accordance with industry best practices.

Effect of fuel spillage on the construction

Should a leak occur the natural gas in the CNG system under normal circumstances will dissipate harmlessly upwards into the atmosphere.

Effect of a cargo fire on fuel system installation

The fire protection of fuel storage systems for CNG is higher than that for liquid fuel tanks due to the pressure relief devices integrated in the tank design. The suitability of each tank-design is verified through crash tests, bon-fire tests and other severe abuse testing. When in a fire situation the fuel cylinders will release fuel in a controlled manner. For the carriage of dangerous goods care shall be taken when placing and orienting the PRD exit points, as has been delineated for CNG or as with LNG trucks, requiring the (gaseous) fuel to be released through a vent stack above and away from the vehicle in R.110.[4]

Possibility of a jet fire in case of gas release

One particular incident with a fire engulfing a CNG bus in the Netherlands (Wassenaar, 2012) resulting in a 'flame thrower effect' from a cylinder that performed as designed has caused concerns about the directional flow of gas released in the event of a fire. NGV stakeholders are examining alternative designs to reduce this effect. But, safety evidence for a gas release from a typical 50 liter (water volume), 200 bar CNG tank (typical of the volumes of CNG storage installed on a passenger car) shows that the flammable jet length of CNG tank diminishes to one meter or less in under one minute through a PRD with a relatively standard opening of about 5mm.[5]. (See Annex 1) Fuel storage on a CNG truck will vary, however, for illustrative purposes the 2014 model IVECO CNG Stralis has four 70 liter tanks and the 2014 model Mercedes Econic 2630 NGT has four, 150 liter CNG tanks. Unlike the bus CNG tanks that are manifolded together, CNG truck tank configurations are not of the same design and release of the entire fuel storage through a single PRD is not typical. Though this changes the dynamics of the fuel release timing based on the study of the 50 liter CNG tank, the release pattern (and in the event of ignition) of both timing and distance indicates a relatively short-time event. Also, these trucks often have protective covers on the tanks that also can act to deflect the 'flame thrower effect'. (See Figures 2 and 3, below)

[4] UN/ECE R.110; 18.6.8. "Venting management system: The primary pressure relief valve shall be piped to a vent stack which extends to a high level. The primary and secondary relief valve outlets shall be protected from fouling by dirt, debris, snow, ice and/or water. The vent stack gas exiting the vent stack or secondary relieve valve shall not impinge on enclosed areas, other vehicles, exterior-mounted systems with air intake (i.e. air-conditioning systems), engine intakes, or engine exhaust. In the case of dual tanks, the primary relief valve outlets piping for each tank may be manifold to a common stack."

[5] *Safety Aspects of CNG Cars*, J.Berghmans, M.Vanierschot, Leuven, Belgium, 2012, delivered to the 2014 International Symposium on Safety Science and Technology.

Figure 2: Mercedes Econic 2630 CNG tanks[6]

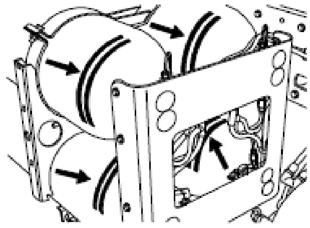


Figure 3:Iveco Stralis CNG tanks[7]

Safety during refuelling operation

Fuelling NGVs is as easy as and safer than fuelling with gasoline or diesel. With CNG there is no release of toxic fumes or potential for spillage associated with liquid petroleum fuels. The fuelling nozzle simply clicks onto the receptacle on the vehicle and is ready to fill. When the cylinder is full, the dispenser automatically shuts off and the fuel connector is removed. Options for fuelling include public stations (many of which are multi-fuel, self-serve), depot-based for fleet applications and home fuelling. Public fuelling is ‘fast fill’ and depot-based can be fast-fill, slow-fill, or both. The main difference between each option is the volume and speed at which the fuel is dispensed and the means of paying for the fuel.

Public fuelling of CNG is much like fuelling with gasoline or diesel. The driver pulls up to a dispenser, switches the engine off and then connects the nozzle to the receptacle.

Fuelling usually takes about the same amount of time as a gasoline or diesel vehicle, though if demand is particularly high, a resulting pressure drop may extend this time until the compressor is able to re-fill the stationary fuel storage containers at the station.

There are a variety of safety provisions associated with NGV fuelling. Some fuelling nozzles have an isolator fitted, which prevents the engine from being switched on while connected to the dispenser. In case of a drive-away without disconnecting the nozzle, break-away couplings disconnect the hose from the dispenser sealing off the dispenser as well as the hose. In the unlikely event of a hose rupture, an automatic shutoff valve (excess flow valve) will stop the flow of natural gas from the normal fuel coupling or high pressure hose. Dispensers are equipped with safety valves in their base, which close off the passage of gas to the refuelling stations fuel system in the event of damage to the dispenser (if it is knocked over).

Public fuelling stations are usually supplied either by piped natural gas (just like at home), or by ‘tube trailers’. A station supplied by a tube trailer is part of a ‘mother-daughter’ system, where the fuel is compressed at the centrally-located mother station and delivered via the tube trailer to the daughter station. Mother-daughter systems are usually used when piped natural gas is not available. Another fuelling option is Liquid-to-Compressed Natural Gas (L-CNG), which can offer LNG to vehicle or provides an option to vaporize the LNG

[6] Photo: Daimler website.

[7] *(Diagram: Iveco Stralis Supplement to Body Builder Instructions)*

into CNG, relying on pumped LNG instead of compression, as vaporization acts to compress the gas into a CNG tank.

CNG Compatibility with Operations at Liquid Petroleum Fuel Terminals

"Several bulk fuel terminal operators in the United States raised concerns regarding the safety of allowing spark-ignited natural gas fuelled tractors to fill "under the rack". These concerns appear to be based on several aspects of spark-ignited engines, including: 1) The potential for spark or electric arc to serve as an ignition source; 2) The temperatures of certain exhaust system components serving as an auto-ignition heat source for flammable or combustible liquids e.g., gasoline or diesel; 3) Uncertainty about risks from retrofit---kit modifications that are not original equipment; and 4) The potential for venting of compressed natural gas (CNG) or liquefied natural gas (LNG) tanks to create a flammable or explosive environment under the racks.

The Clean Vehicle Education Foundation (CVEF) (U.S.A.) in consultation with tractor and engine manufacturers, fleet operators, natural gas vehicle (NGV) experts, and other expert parties, has attempted to systematically address concern in a paper published in July 2013. They have carefully concluded that there is no diminished margin of safety associated with the operation of spark-ignited NGVs in the terminal area, specifically including the area under terminal loading rack. In summary, CVEF has found: 1) The modern "solid state" design of natural gas engines, including coil on plug encapsulated high voltage systems mitigate the risk of stray spark or arc that may have been associated with earlier generations of spark-ignited gasoline engines; 2) Current diesel engine exhaust component temperatures are and have been well above the auto-ignition temperature of gasoline and diesel for years, with no known incidents. The fact that certain NGV exhaust components are comparatively above this auto-ignition temperature poses no identifiable incremental risk, making NGVs no less safe than diesel engine technology in this regard; 3) Natural gas retrofits in the market today provide for direct injection of natural gas with diesel into compression engines, with the diesel compression ignition providing the source for natural gas ignition. Hence, they operate in a manner similar to diesel engines (i.e., no spark plugs, and similar exhaust system components and temperatures.)"[8]

NGV Safety in Maintenance Facilities

Safety in maintenance facilities of compressed gas fuelled, large-scale was evaluated in the March 2014 report by Sandia Laboratories summarizes Phase I work for existing NGV repair facility code requirements. [9] A Hazardous and Operability study was performed to identify key scenarios of interest that included releases from LNG 'boil off' and, for both LNG and CNG, purging of fuel tanks for purposes of general maintenance. A fourth scenario was also performed where the entire contents of a 700 L, fully pressurized (250 bar) CNG cylinder were released into the NGV maintenance facility due to the activation of a thermally triggered PRD. "Scenario analyses were performed using detailed simulations and modelling to estimate the overpressure hazards from HAZOP defined scenarios. The results from Phase I will be used to identify significant risk contributors at NGV

[8] *"Compatibility with Operations at Liquid Petroleum Fuel Terminals,"* Clean Vehicle Education Foundation (U.S.A.), July 2013.

[9] This section is adapted and taken directly from (in "quotes") "*Analyses in Support of Risk-Informed Natural Gas Vehicle Maintenance Facility Codes and Standards: Phase I*", SANDIA REPORT, SAND2014-2342, March 2014.

maintenance facilities, and are expected to form the basis for follow-on quantitative risk analysis work to address specific code requirements and identify effective accident prevention and mitigation strategies."

"From velocity maps within the NGV maintenance facility, ventilation currents were observed to form recirculation regions when they interacted with the vehicle or roof rafters, which could distort the release plumes and generate flammable mixture accumulation regions. However, for the scenarios investigated, little sensitivity was observed for ventilation or roof supports due to the short durations of the releases relative to the ventilation rates and the propensity of the support structures to enhance mixing. Accordingly, for the low-flow release scenarios that involved a dormant LNG blow-off or a CNG fuel system purge, the flammable masses, volumes, and extents were low, and the flammable regions disappeared shortly after the conclusion of the leaks. Moreover, predicted peak overpressures indicated there was no significant hazard expected."

In the high volume release of gas scenario the modelling indicated that, "Two peaks were observed in the flammable mixture time-histories. The first peak occurred 68 seconds into the release where vessel flow rates were still relatively high and previously expelled mixture accumulated in flammable concentrations along the ceiling. The second peak occurred at the end of the accepted simulation results and was attributed to increasingly cool and dense exit plumes that had slower mixing rates. For both peaks, there was roughly 0.5 kg of natural gas predicted to exist in flammable regions, which for the facility examined could produce an overpressure of around 2.2 kPa—enough to break glass, but not much else. It was noted that flammable mass values would likely further increase beyond if the leak dispersion characteristics were properly modeled. **However, even a conservative estimate for the expanded overpressure potential is still below the threshold required for significant harm."**

Operation in Tunnels

In 1989, two natural gas utilities and the New York State Energy Research and Development Authority jointly funded a comprehensive, $1.2 million safety analysis of fuel-related accidents in tunnels.

Conclusion: *modern tunnel environments, fanned by high-powered ventilation systems would quickly remove and disperse gaseous fuels safely above ground in the event of an accident.*[10]

In 1994, a report done to address the prohibition of NGVs in tunnels in Boston, Massachusetts also concluded that the risk for CNG is less significant than for gasoline. "The comparison of the gasoline and CNG dispersion calculations demonstrated that *the size of the flammable region from an incident involving a CNG fuelled van is significantly smaller than the flammable region from a comparable incident involving a gasoline fuelled van* as long as the effective ventilation velocity is on the order of 0.10 m/s or higher." [11]

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[10] *Safety Analysis of Natural Gas Vehicles Transiting Highway Tunnels*, Shaaban, S H, Ebasco Services Incorporated, New York, 1989.

[11] *"Dispersion of CNG Fuel Releases in Naturally Ventilated Tunnels,"* Center for Fire Safety Studies, Worcester Polytechnic Institute, Mass., November 1994

In 2010 a comparative study of the inherent risks of *CNG and Diesel Buses/Heavy Duty Vehicles (HDVs) and Garbage trucks (GTs) in Tunnels* was published by the French Association for Natural Gas Vehicles (AFGNV). [12] Two studies were carried out:

- Risk of CNG buses/ Heavy Duty Vehicles (HDVs) & Garbage trucks (GTs) being operated in tunnels to identify scenarios of accidents and related dangerous phenomena;
- Risks of these CNG buses/HDVs/GTs and comparison of them to the risks associated to the operation of diesel buses/HDVs/GTs under the same conditions.

The studies concluded that:

- For buses moving in a tunnel, when considering the 10 first minutes after the accident occurs, 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. 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. Considering the period of 1 hour following the accident, the global risk level of a CNG bus is 1.4 times inferior than the global risk level of a diesel bus. In the case of HDVs, the global risk level of CNG HDVs is 61% less than the global risk level of 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 with CNG HDVs than with diesel HDVs.
- For the studied scenarios, it appears that CNG vehicles (buses, HDVs, garbage trucks) are as safe as the equivalent diesel vehicles operating in tunnels.

Conclusions

The body of safety literature and studies – private sector and government-sponsored – coupled with documented real-world experiences demonstrate that the use of compressed natural gas (CNG) as a fuel for road vehicles (including ADR-certified trucks) is as safe as liquid petroleum-fuelled vehicles. In fact, some of the literature and data indicate that operation on natural gas is safer than petrol or diesel fuel, particularly when involved in hazardous accidents.

Nevertheless, all combustible fuels must be handled safely and with adequate precautions to reduce the risk of accidents and dangerous situations. As with all fuel and fuelling systems, there is a constant learning process based on unforeseen incidents, equipment failures, errors in materials production, equipment fabrication, distribution and installation of systems on vehicles. Increased training is available and new research is being done to mitigate risks. The NGV industry worldwide maintains vigilance and caution in order to promote and assure the highest levels of safety as the market for NGVs expands. As such, there should be no prohibitions on the use of CNG for the widest possible variety of transport vehicles, including ADR-certified trucks.

[12] *"Comparative study of the inherent risks of CNG and Diesel Buses/Heavy Duty Vehicles (HDVs) & Garbage Trucks (GTs) in Tunnels"*. Olivier Bordelanne – GDFSUEZ. 8th June 2010, (PowerPoint presentation to NGVA Europe conference, Rome).

Annex 1

Safety Aspects of CNG Cars, J.Berghmans, M.Vanierschot, Leuven, Belgium, 2012, delivered to the 2014 International Symposium on Safety Science and Technology

2.2.1. CNG

(1) Jet fire

Table 3 lists the flow rate of natural gas as a function of the leak diameter assuming a constant tank pressure of 200 bar. The natural gas will mix with the air and will produce jets which are partially flammable. To give an impression of the size of these jets the location where the lower (LEL) and the upper flammability limit (UEL) is reached in the jet is plotted in figure 2 for a very small leak (1 mm diameter) and in figure 3 for a leak of 5mm diameter. When the tank safety device opens a release opening of some 5mm is created.

Table 3. Outflow from a 200 bar CNG tank.

Leak diameter(mm)	Flow rate(kg/s)	Flow rate (m^3/s)	Duration outflow (s)
1	0,027	0, 038	1890
2	0,108	0,155	470
5	0,680	0,971	75
10	2,718	3,88	17,5

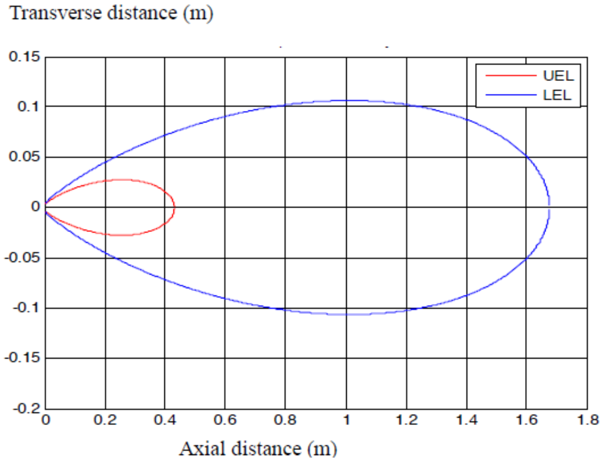

Fig. 2. CNG jet from 1mm leak (m) .

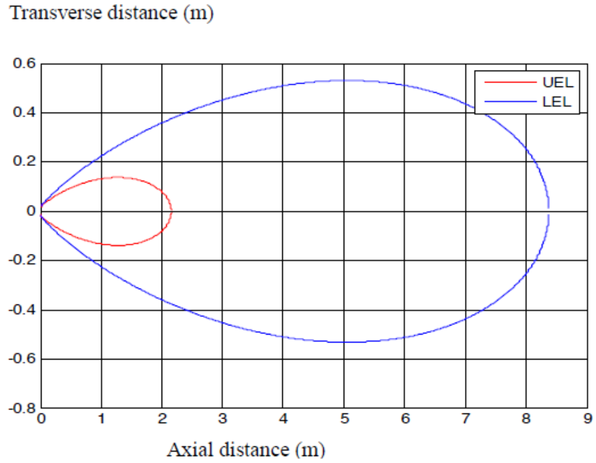

Fig. 3. CNG jet from 5mm leak .

The release of gas will lead to a decreasing tank pressure as is shown in figure 4 for a tank of 50 liter and a leak diameter of 5mm. This in turn leads to a decreasing length of the gas jet as shown in figure 5. Table 3 lists the time necessary to reduce the tank pressure to 1,1 bar for a 50 liter tank.

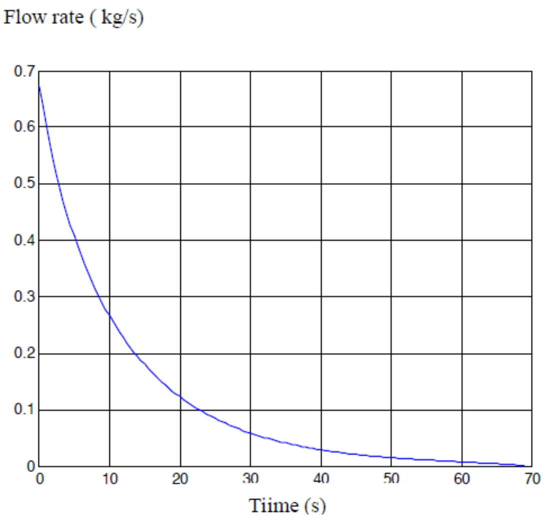

Fig. 4. Flow rate evolution during a gas leak.

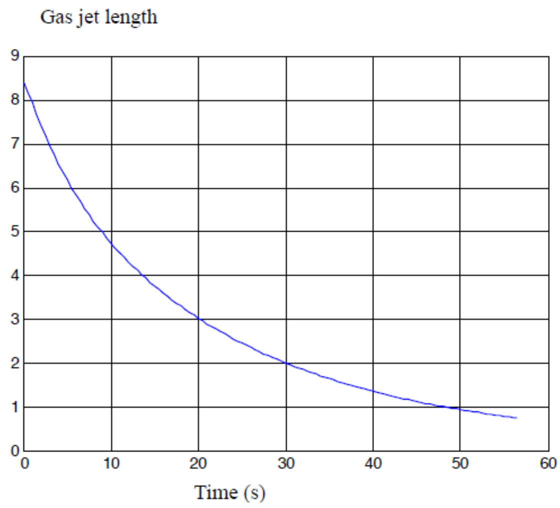

Fig. 5. Flammable jet length evolution during a gas leak.

When a jet is ignited a jet flame occurs. Table 4 gives the dimensions of the flame when the tank pressure is 200 bar and the outflow is horizontal. In this table also the distance from the flame where the heat radiation is 10 kW/m^2 is listed. At such high radiation level people can suffer severe burns resulting in death.

Table 4. Flame dimensions from a leak at 200 bar.

Leak diameter (mm)	Flame length(m)	Max flame width (m)	Distance to 10 kW/m^2 (m)
1	2,5	0,2	3
2	4,5	0,5	5
5	10,0	1,5	12
10	18,2	3,1	24

Fig. 6 shows the evolution of the length of the jet flame from a 5 mm diameter leak.

Jet flame length (m)

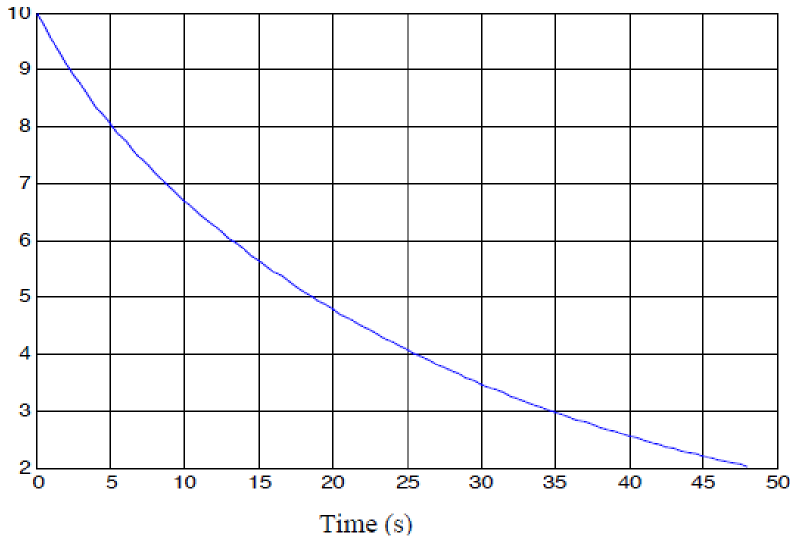

Fig. 6. Jet flame length evolution.