PG&E GAS R&D AND INNOVATION

LNG/CNG Transportation Technical Analysis

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RNG, CNG, LNG Background

Renewable natural gas (RNG) can be used as a transportation fuel in the form of compressed natural gas (CNG) or liquified natural gas (LNG).

In terms of natural gas vehicles, LNG is used in less than 5% of natural gas vehicles (NGV) with nearly all used by heavy-duty trucking and some transit buses because LNG allows for a smaller fuel system footprint. CNG is more common among light-duty and medium-duty vehicles. (Alternative Fuels Data Center, 2018)

LNG is the same fuel as CNG but in cryogenic form. At -260 degrees F, the natural gas turns into a colorless, odorless liquid fuel. It is then dispensed to vehicles as a cryogenic liquid. CNG stations tap into the local gas utility lines and compress the gas up to 3,600 psi. The compressed gas is then transferred into high pressure storage cylinders. When fueling, CNG is very like fueling with gasoline and diesel fuel. It does not require special protective gear and minimal training. (Fuel Space, 2014)

If the natural gas is derived from biogas, fuel vehicles require the biogas to be upgraded to higher purity standards. At the tailpipe of a vehicle, biomethane produces the same emissions. However, biomethane/conventional natural gas, when used have shown to give off 40% less GHG, but it will generally get fewer miles to the full tank than a regular gas engine. (Fuel Space, 2014)

Benefits of using RNG as a fuel

RNG qualifies as an advanced biofuel under the Renewable Fuel Standard.

(Definition from https://www.afdc.energy.gov/laws/RFS)

- Advanced Biofuel: Any fuel derived from cellulosic or advanced feedstocks. This may include sugarcane or sugar beet-based fuels; biodiesel made from vegetable oil or waste grease; renewable diesel co-processed with petroleum; and other biofuels that may exist in the future. Nested within advanced biofuels are two sub-categories: cellulosic biofuel and biomass-based diesel. Both biomass-based diesel and cellulosic biofuel that exceed volumes in their respective categories may be used to meet this category. Fuels in this category must demonstrate a life cycle GHG emissions reduction of 50%. (Fuel Space, 2014)

  - Biomass-Based Diesel: A diesel fuel substitute made from renewable feedstocks, including biodiesel and non-ester renewable diesel. Fuels in this category must demonstrate a life cycle GHG emissions reduction of 50%. (Fuel Space, 2014)
  - Cellulosic Biofuel: Any fuel derived from cellulose, hemicellulose, or lignin—nonfood-based renewable feedstocks. Fuels in this category must demonstrate a life cycle GHG emissions reduction of at least 60%.
- In terms of cost, CNG will be less costly compared to LNG. This is mainly due to the cost difference in transporting the fuel to the station. CNG distribution infrastructure is the existing natural gas pipeline system. Whereas LNG must be trucked into the station.

CNG vs. LNG Uses

Usually CNG is better suited for shorter routes and where weight is not an issue. Garbage trucks, for example, are almost always CNG because of the short routes and the variable weight. Longer routes and where weight is continuously maxed out, such as a sand and gravel hauler running 700-mile round trips, LNG should be considered. (Fuel Space, 2014)

Dedicated Engine vs. Bi-Fuel Engine

Dedicated Engine: dedicated system designed to rune exclusively on natural gas. These engines usually run more efficiently than bi-fuel engines. They work well with fleet vehicles that return to a fueling site regularly.

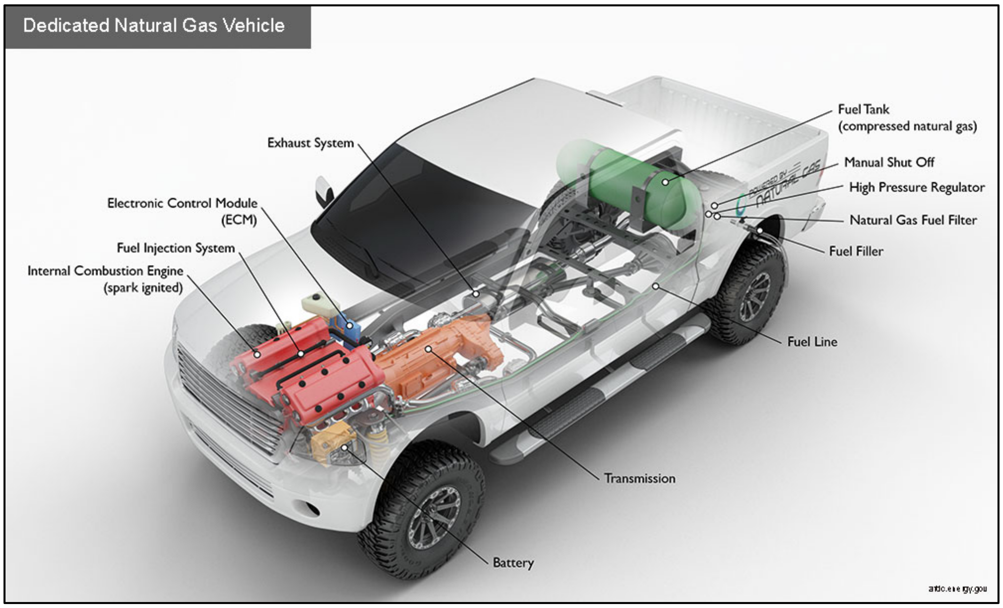


Figure 1 Illustration of a dedicated natural gas vehicle (Alternative Fuels Data Center, 2018)

(https://www.afdc.energy.gov/vehicles/how-do-natural-gas-cars-work)

Bi-Fuel Engine: system that can be run on natural gas or conventional fuel (diesel or gasoline) but not both at the same time. For a bi-fuel engine, you will need to install a separate tank to your vehicle. A common location to place the tank is in the trunk.

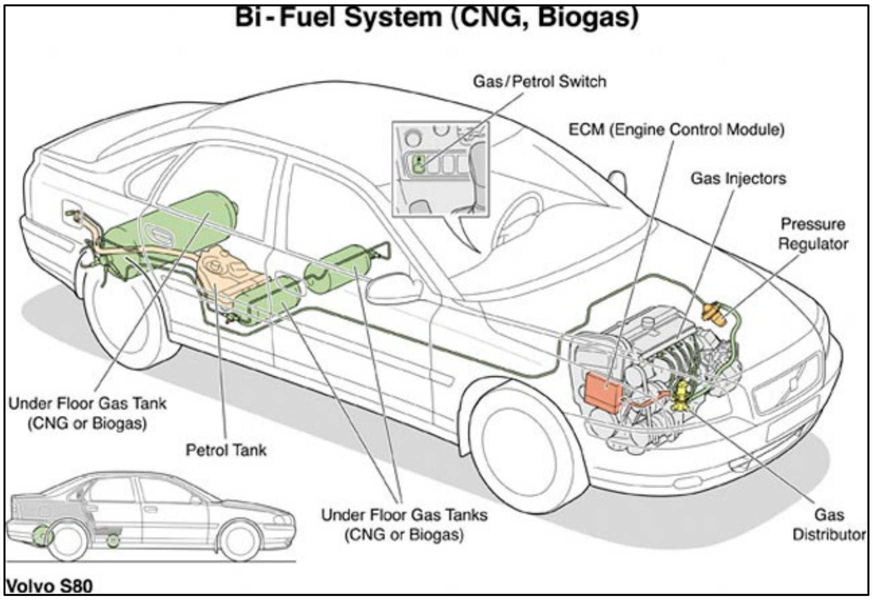
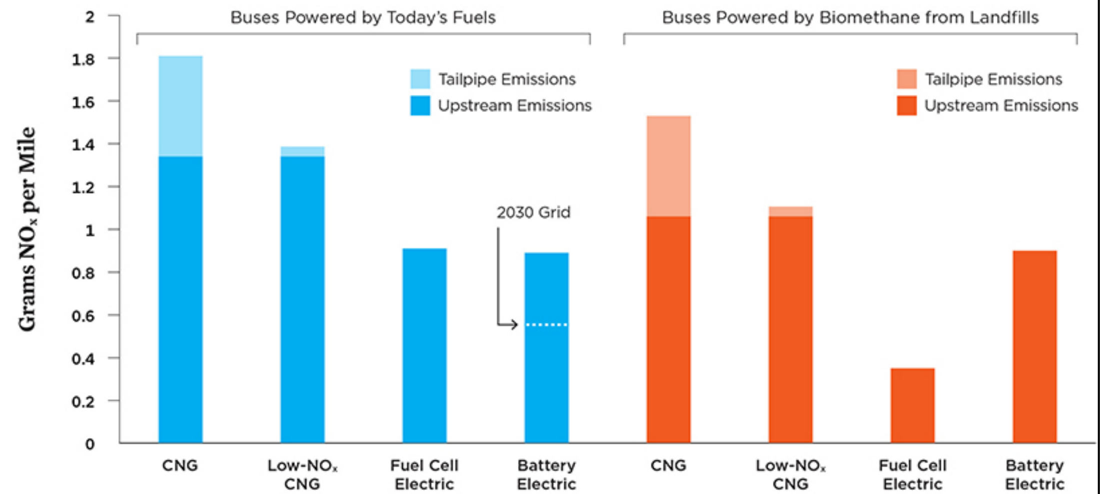


Figure 2 Bi-Fuel System (CNG, Biogas)

(http://www.greencarcongress.com/2004/10/volvo_bifuel_s8.html)

Light-duty sedans, pick-ups and some smaller medium-duty trucks are either dedicated or bi-fuel, whereas medium-duty and heavy-duty engines are dedicated only.



Life cycle NO_X emissions from transit buses, by vehicle and fuel type. The lowest life cycle emissions of nitrogen oxides (NO_X) from biomethane results from generating electricity or hydrogen for use in battery or fuel cell electric vehicles. Source: Chandler, Espino, and O'Dea 2017.

Figure 3 Life cycle NOx emissions from transit buses, by vehicle and fuel type (https://www.ucsusa.org/biomethane-transportation)

CNG vehicles function the same way gasoline-powered vehicles with spark-ignited internal combustion engines (ICE) in the following steps:

- The fuel-air mixture is compressed and ignited by the spark plug. Typical pressure is 3,600 psi.
- Natural gas is stored in a fuel tank, usually in the back of the vehicle.
- The CNG fuel system transfers high-pressure natural gas from the fuel tank to the engine. The fuel storage and delivery system is the main difference between CNG vehicles and ICE vehicles.
- Pressure is reduced to match the engine fuel injection system
- The fuel is introduced to the intake manifold or combustion chamber

Typical modifications for CNG vehicles include hardened exhaust and valve seats. These changes do not impact the visual appearance of the engine, nor do they impact maintenance schedules. The expected after-market conversion cost to upgrade to a natural gas vehicle varies between $20,000 and $50,000 based on the amount of fuel storage installed. (Lyden, 2014)

Main Differences between CNG and ICE Vehicles

- Natural gas is much more sensitive to spark quality and voltage, so maintenance of these parts to be protected from heat and other damage is critical.
- Main difference in maintenance is that the fuel storage tank needs to be inspected at regular intervals, after accidents, or when there is suspected damage.
- Since natural gas burns cleaner than conventional gasoline, the oil in natural gas engines should last longer.

There are about 50 manufacturers that produce 100 models of light, medium, and heavy-duty vehicles and engines. (Lyden, 2014)

Medium Duty

- CNG powered vans and shuttles are in use in major cities and airports.
- Regional haul and distribution, pick-up and delivery, food and beverage, and utility are good candidates for medium duty CNG vehicles.
- It is expected that CNG vehicles will be more common among light duty and heavy duty, however this will have meaningful impacts on the medium duty vehicle technology, which will bring costs down over time.

Heavy Duty

- Intercity buses, transit buses, school buses, refuse trucks, motor homes, combination trucks
  On tractor units, the CNG tanks are typically mounted on the frame rails, behind the cab, or a combination of the two.
- Currently one in five new transit buses in America is fueled by natural gas (Fuel Space, 2014). By consuming large volumes of fuel and emitting large amounts of exhaust, transit buses have strong reason to be switched to compressed natural gas.

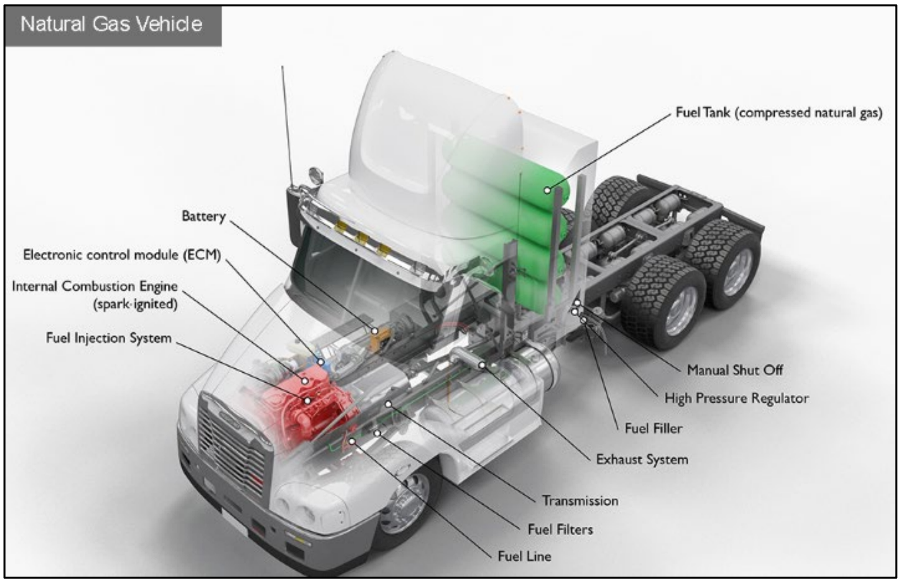


Figure 4 Illustration of a natural gas truck (Alternative Fuels Data Center, 2018)

Shipping/Rail

- Marine LNG ships have natural gas stored a liquid. The boil-off gas is then sent to dual fuel engines where it is burned. Steam turbine systems have been very common on LNG powered ships. These ships need to be heavily insulated to maintain a -260 ° F temperature and keep the natural gas in liquid form. (CAT, 2018)
- LNG is an advantageous fuel for ships because of the tight emission regulations.

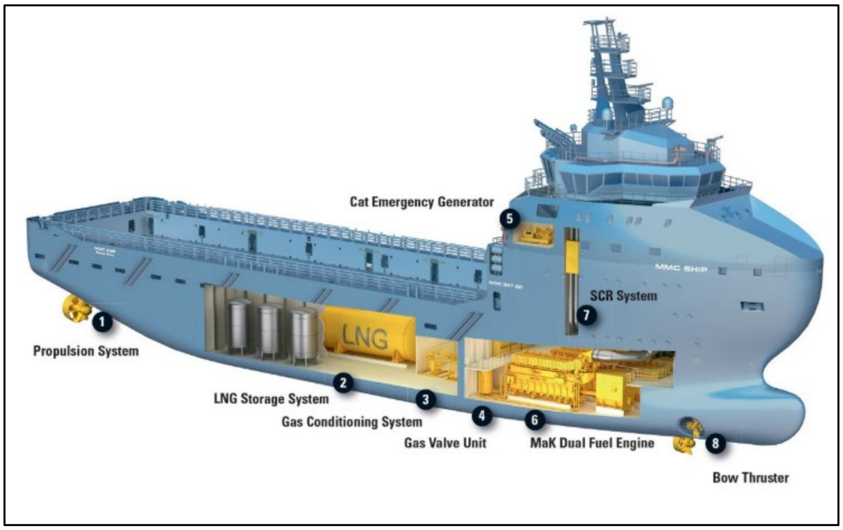


Figure 5 Illustration of an LNG powered ship (CAT, 2018)

- Locomotives are starting to use CNG as well. The Napa Valley Wine Train recently retrofitted a diesel engine to run on compressed natural gas. Most CNG locomotives are diesel engine systems that have been converted to use compressed natural gas generators to generate the electricity that drives the traction motors. Some CNG locomotives can fire their cylinders only when there is demand for power, which will actually make them more energy efficient than conventional diesel engines.

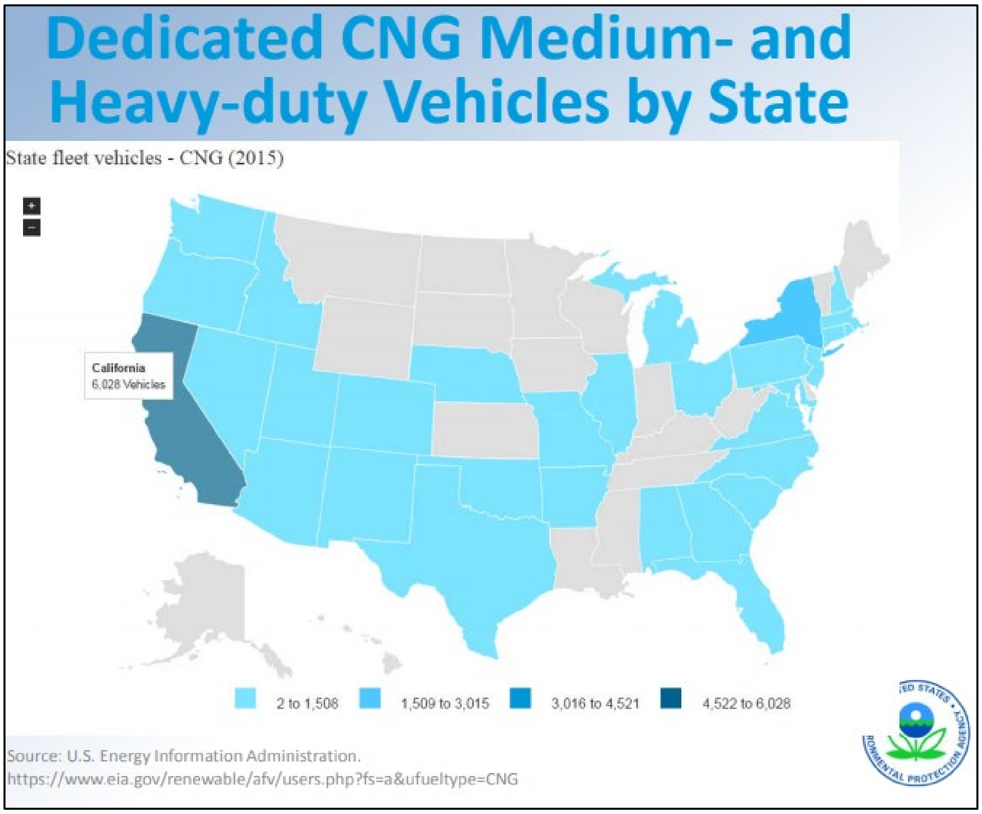


Figure 6 Dedicated CNG Medium- and Heavy-duty Vehicles by State (MOVES, 2017)

Hurdles/Challenges

- The lack of natural gas infrastructure, however this is growing. There are currently over 1,600 CNG and 140 LNG fueling stations in the US (Fuel Space, 2014)
- For CNG, more space is required on the vehicle for fuel storage. CNG takes up more space per GGE (gasoline gallon equivalent). One solution to this problem is to have factory-built CNG vehicles that install the tanks under the body of the vehicle.
- Some states have a more developed natural gas refueling infrastructure, however more investment is needed to increase the pace of construction. The same infrastructure will be used for biomethane and compressed conventional natural gas.

- When fueling CNG at a fast rate, a unique problem occurs called heat of compression. Heat of compression means that when compressed gas is dispensed into a fuel tank at a high rate it gets very hot.
- LNG is a cryogenic liquid, so it requires more training as well as protective eye wear and gloves. LNG makes more sense if you have a dedicated fueling fleet with fueling personnel. Since LNG is not compressed, there is no issue with heat of compression. One issue that is experienced is called boil off. Since LNG is stored at -260 degrees F, it can heat up. When this happens, it starts to boil in the tank and will eventually vent off. Typically not an issue because LNG vehicles are not left idle for weeks at a time after fueling.
- For LNG, the tanks contain high energy content, so there is an explosion hazard in case of a gas leak. LNG is a relatively new fuel source, so there is limited experience handling and working with it.

Opportunities for PG&E

CNG stations are tapped directly from the gas utility pipeline infrastructure. For PG&E this can represent a new market and revenue stream. The fueling process begins with the gas utility connection of the site where fueling of natural gas will take place. At this location, gas is metered, but there are a few steps that are required to make the gas suitable to be "vehicle-ready".

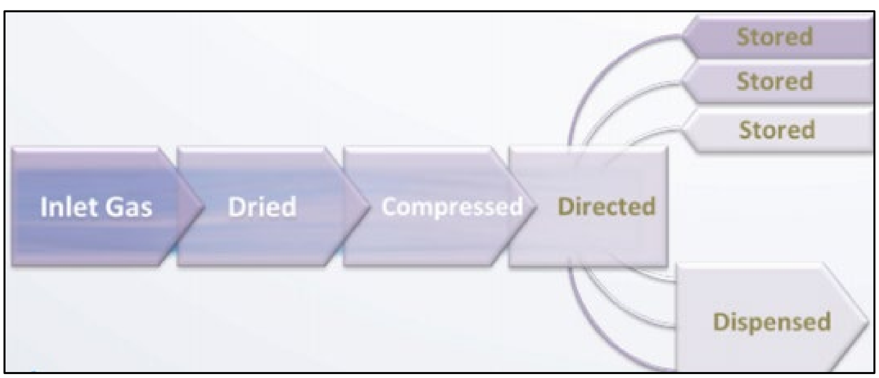


Figure 7 Pathway of CNG from CNG stations

Biomethane for Transportation: Current Projects in the US

Landfill Biogas:

- Waste Management's Altamont Landfill near Livermore, CA
- St. Landry Parish Landfill in Washington, LA
- Joint Water Pollution Control Plants in Los Angeles, CA

Dairies/Livestock Operations:

- Hilarides Dairy in CA
- Fiar Oaks Dairy in IN

Wastewater Treatment Plant:

Janesville Wastewater Treatment Plant in WS

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