# ENGINES FOR ALTERNATIVE FUELS

## 1 Introduction

Engines configured for alternative fuels are unlikely to come into widespread use unless they can markedly distinguish themselves in terms of fuel cost, refueling infrastructure, cleanliness of emissions, or being free of $CO_2$. Table 1 compares alternative fuel vehicles (methanol and natural gas vehicles (NGVs)), hybrid vehicles, and electric vehicles (EVs) commercially-produced in Japan. Of the alternative fuel vehicles, NGVs have gained a certain amount of traction, and future growth looks promising.

The movement of Dubai crude oil prices and of the prices of gasoline and diesel in Japan is shown in Fig. 1. The price of Dubai crude oil plunged in the spring of 2016, temporarily dropping to approximately 20 yen/L. However, since a tax of 53.8 yen/L and 32.1 yen/L applies to gasoline and diesel, respectively, alternative fuels could penetrate the market if they can at least remain competitive with those market prices. Currently, there is still no tax applied to compressed natural gas (CNG).

Looking further ahead, the United States and Europe have been focusing on DME (dimethyl ether) due to the possibility of manufacturing it from shale gas or biomethanol. Hydrogen stations are rapidly being built in response to the spread of fuel cell vehicles, and there are rising expectations for the use of hydrogen in engines as well. Other alternatives are also exhibiting their strengths in niche applications, as in the case of the Stirling engine serving as an air-independent propulsion power plant in submarines, which require quietness. This article summarizes the current usage of engines configured for alternative fuels, as well as the progress of research and development.

## 2 LPG Engines

The number of registered vehicles in Japan that run on LPG has been decreasing steadily since peaking at 319,000 in 1991[1]. There were 227,491 registered vehicles at the end of March 2015 (including 5,225 bi-fuel vehicles and 5,093 mini-vehicles), a decrease of just under 7,000 vehicles from the previous year. The reasons for this decline are the rise in LPG prices[2] and the increased fuel efficiency of gasoline vehicles. A significant impact is also attributed to policy of reducing the number of corporate taxis, which represented 80 percent or more of registered vehicles, as well as to the introduction of gasoline hybrid vehicles. LPG stations can be found at approximately 1,600 locations.

On a global scale, there were 13 million vehicles in Europe, 62.2 million in Asia and Oceania, 730,000 in the United States and Central and South America, 210,000 in Africa, and 120,000 in the Middle-East in 2011. At over 2 million vehicles, Turkey, Poland and South Korea stand in contrast to Japan, which remains at around 250,000 vehicles[3].

Research and development on particulate matter (PM) emitted by LPG vehicles after injection in the gas and liquid state[4] has shown that despite differences in PM emissions due to the composition of the fuel and injection method, the amount of PM emitted by LPG vehicles is equivalent or lower than that emitted by gasoline or diesel vehicles compliant with the new long-term regulations.

## 3 Natural Gas Engines

As of April 2016, the number of natural gas vehicles (NGVs) worldwide had reached 22.4 million vehicles. Iran, where they are the most popular, had approximately 4.07 million, followed by China with approximately 3.99 million and Pakistan with approximately 3.7 million. The countries with the highest number of natural gas stations are China, coming first with 6,205 locations, Pakistan, with 2,997 locations, and Iran, with 2,268[5]. In contrast, there were 44,676 NGVs on the roads in Japan as of the end of March 2015[6], and 290 natural gas stations.

Approximately half of the NGVs in Japan are commer-

Table 1 Comparison of alternative fuel, hybrid, and electric vehicles

| Vehicle type | Methanol vehicles | NGVs | Hybrid vehicles | EVs | Number of registered vehicles |
|---|---|---|---|---|---|
| Passenger cars | 0 | 1 579 | 3 948 371 | 39 650 | 39 689 646 |
| Light- to medium-duty vehicles and heavy trucks | 576 | 5 784<br>19 367 | 13 470 | 24 | 5 877 354 |
| Buses | 0 | 1 575 | 978 | 34 | 226 944 |
| Special vehicles | 0 | 3 965 | 6 418 | 38 | 1 682 582 |
| Compact vehicles | 0 | 12 406 | 435 | 15 974 | — |
| Total | 576 | 44 676 | 3 969 672 | 55 720 | — |

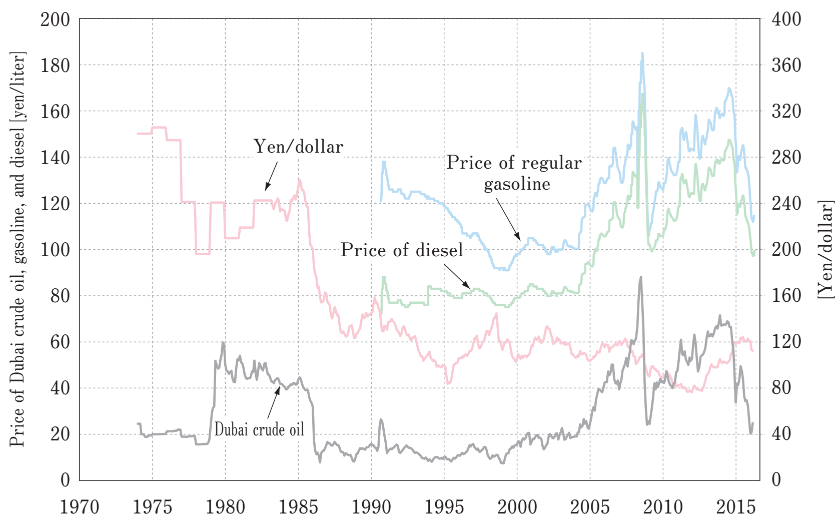


Fig. 1 Movement of Dubai crude oil prices and prices of gasoline and diesel in Japan.

cial vehicles such as trucks, buses, or garbage trucks. Of the trucks, the majority are light- to medium-duty vehicles designed for short- or medium-distance transportation. In this context, Isuzu Motors Limited announced the Giga CNG in December 2015[7] (Fig. 2). This addition of a completed vehicle heavy-duty CNG truck to the market to complement modified vehicles sold by Kyodo Co., Ltd., is expected to increase the use of NGVs for long-distance transportation. In addition, events such as the opening of the first combined gasoline and L-CNG station in Japan at the Keihin Truck Terminal in March 2016 hint at future more widespread use of NGVs in the commercial vehicles sector.

Many papers on the latest research on natural gas engines have been released in and outside Japan. Reports concerning natural gas engines presented at the 26th Internal Combustion Engine Symposium held from December 8 to 10, 2015[8], included research on the impact of hydrogen and carbon dioxide on knock resistance (Osaka Gas Co., Ltd.), research investigating the effects on combustion and fuel efficiency with CI engine (Toho Gas Co., Ltd., GDEC Co., Ltd., Oita Univ. and Chiba Univ.), research investigating the effects on exhaust emission and fuel efficiency with dual fuel engine to use diesel fuel and CNG (Kyoto Univ. and Waseda Univ.).

There is also a Ministry of Land, Infrastructure Transport and Tourism project pursuing research on boil-off gas countermeasures as part of research to commercialize heavy-duty LNG vehicles with a long-distance cruising range.

As millions of NGVs are spreading in cities around the world, there are expectations that Japan will also not only see existing CNG vehicles become more popular, but also the early appearance of new NGVs, including LNG vehicles.

## 4 Hydrogen Engines

Hydrogen can be produced from renewable energy sources such as sunlight or wind power and, depending on the selected primary energy source, it is strongly expected be a next-generation fuel that effectively contributes to resolving the issues of global warming, environmental pollution, and energy resource depletion faced by the planet. This has led to Japan leading the world in re-

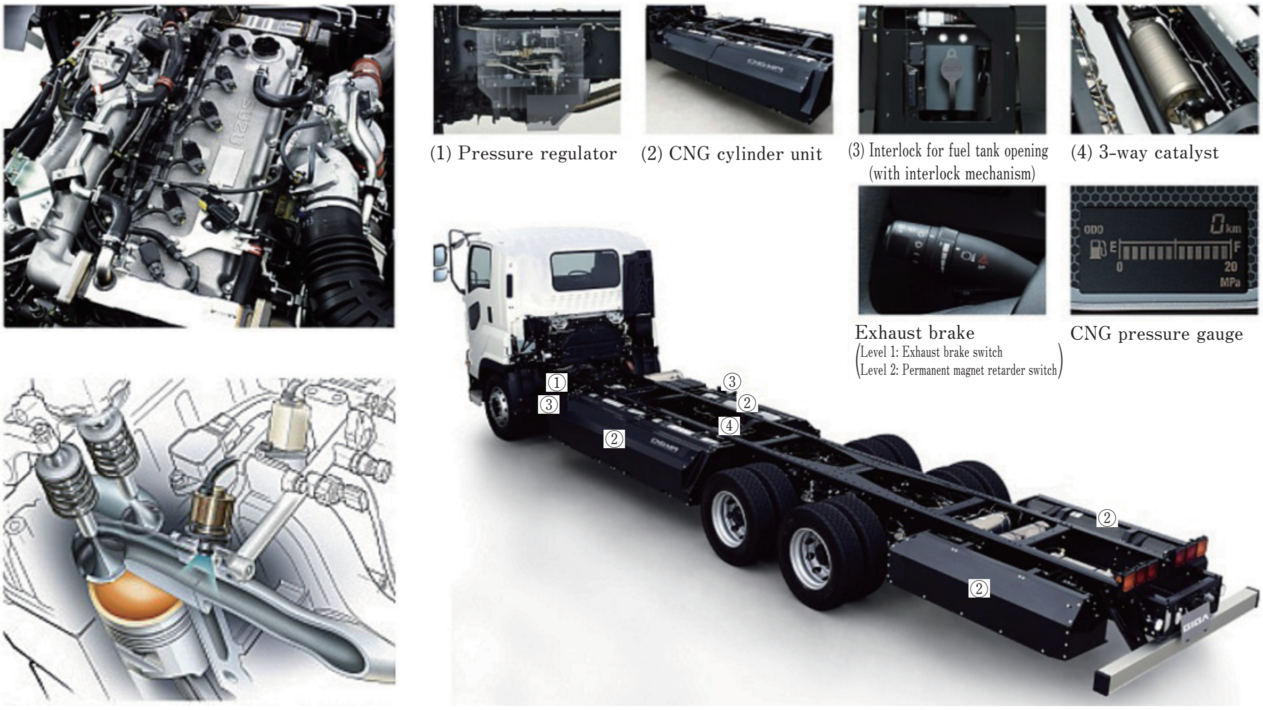


Fig. 2 Isuzu Motors Giga CNG heavy-duty natural gas truck

leasing fuel cell vehicles that use hydrogen as fuel with the release of the Toyota Mirai[9] in December 2014 and the Honda Clarity in March 2016.

In contrast, hydrogen engines are similar to fuel cells in that they also represent a power fueled by hydrogen, and since they can leverage well-established technologies while using existing materials and production equipment, they are seen as having a high potential for commercialization at a lower cost, making them the object of worldwide research and development[10].

Currently, the use of a combustion system based on direct injection into the cylinders has largely solved past issues such as backfiring or the low output unique to gas-based engines, and the combustion system to apply in high output engines is gradually taking shape. In addition, mitigating the production of NOx under high load operating conditions and further improving thermal efficiency have been clearly identified as issues that have to be solved to commercialize hydrogen engines.

In 2015, both in and outside Japan, reports concerning the research and development of hydrogen engines focusing on the above further improvements in thermal efficiency and mitigation of NOx production stood out. In Japan, Tokyo City University is conducting research to revise injection timing and jet shape, as well as improve thermal efficiency by reducing cooling loss, an issue described as inescapable in hydrogen engines, using a rich mixture combustion system that significantly reduces NOx emissions through ignition and combustion of the jet during or immediately after injection[11]. Similarly, Kindai University is performing research to improve thermal efficiency and reduce NOx emissions via high pressure hydrogen jet combustion in rotary engines[12][13]. Outside Japan, research on the injection of water to reduce NOx production under high load operating conditions has been presented by the University of Michigan in the United States[14]. With regard to core technologies that support the performance development of hydrogen engines, Okayama University published a paper concerning the numerical analysis of the shape and other patterns of hydrogen jets injected into the combustion chamber[15], while Tokyo City University has published research on the measurement of thermal flux to ascertain the characteristics of cooling loss[16]. As shown above, the course of the research and development of hydrogen engines has essentially been determined.

## 5 Dimethyl Ether (DME) Engines

In the U.S., Oberon Fuels and the Volvo Group are continuing field testing aimed at more widespread adoption of DME trucks[17], While in the EU, FVV, Ford and Oberon Fuels have announced the start of new research on the potential application of DME as fuel for passenger vehicles[18]. Since DME is a biofuel using wood or organic waste as raw materials, or a renewable energy that can be manufactured using natural energy sources, and is perceived as a future automobile fuel that will contribute to reducing $CO_2$ emissions.

In Trinidad and Tobago, a project to manufacture methanol from the rich supply of natural gas and convert it into DME fuel for transportation has been launched[19]. The project aims to reduce that country's dependence on petroleum imports as well as the burden imposed on the government by diesel subsidies.

In Japan, field tests on public roads have been conducted after obtaining ministerial authorization, and a technical standard proposal for DME vehicles has been drafted based on the resulting data. The Ministry of Land, Infrastructure Transport and Tourism officially announced the applicable standards in January 2015, opening the door for the type approval and registration of remodeling of DME vehicles in Japan. In June 2016, a DME truck compliant with the safety regulations became the first such registered vehicle[20].

## 6 Stirling Engines

Commercially available Stirling engines are used in compact combined heat and power (CHP) systems for homes, power generation achieved through ligneous biomass combustion or the combustion of low calorific biogas generated by waste from sewage, excrement or landfill processing plants, and solar power generation relying on sunlight concentrated through parabolic mirrors as a source of high temperature heat. The generators used for those applications are the 1 kW-class free piston engine by MEC of the Netherlands, the 3.5 kW and 7.5 kW-class free piston engines by Qnergy of the U.S., and the 10 kW-class single-acting alpha-type V-cylinder arrangement engine by Cleanergy of Sweden. Production volume for these engines ranges from a few dozen units to, at most, about 3,000.

One special application is the air-independent propulsion Kockums 75 kW-class 4-cylinder double-acting engine for submarines. They are produced from knockdown kits by Kawasaki Heavy Industries Ltd., and four engines were commissioned for, and refitted to, the Kokuryu Soryu-class submarine.

Examples of original engines being developed in Japan include the e-stir Co., Ltd. generator that uses relatively low-temperature waste heat from plants, the Suction Gas Engine Mfg. Co., Ltd. biomass combustion generator, and the Momose Kikai Sekkei KK ligneous biomass combustion generator for use in emergencies, which uses from wood stoves. Those engines have an output ranging from 0.2 to 10 kW or so, and are only available on a made-to-order basis.

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