THE INNOVATION BEHIND THE CNG/PETROL BI-FUEL-HYBRID VEHICLE

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- IN PURSUIT OF THE ULTIMATE ECO-FRIENDLY CAR -

1. Background

Since Kyoto Protocol was agreed, many industries have been tackling CO_2 emission reductions, and the transportation industry is no exception. The amount of CO_2 emissions from the transportation industry peaked around 2001, and although it has been on a decreasing track, it is still responsible for about 20% of total CO_2 emissions, and therefore, the reduction of CO_2 exhaust from automobiles is a critical problem. The Government of Japan enacted the “Act on the Rational Use of Energy”, the so-called “Energy Saving Act”, to improve the efficiency of energy consumption. In order to realise this goal, car makers have been developing fuel-efficient vehicles such as the petroleum-fueled hybrid, and introducing them to the market one after another.

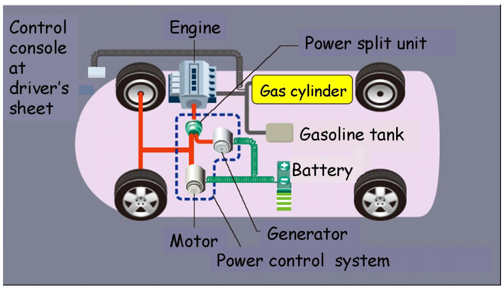
Using natural gas for automobile fuel, with its CO_2 emissions the lowest among fossil fuels, it is possible to reduce CO_2 emissions by approximately 10% to 20% in comparison with petrol-fueled cars of the same model. Furthermore, in comparison to petrol -powered automobiles of the same class, petrol hybrid cars can reduce CO_2 emissions by approximately 50% (Source: Tokyo Gas Co., Ltd.). By combining the CO_2 reduction effects of natural gas fueled vehicles with the highly efficient driving mechanisms of hybrid systems, we sought to produce a vehicle with further improved CO_2 reductions. Moreover, in the production of this vehicle, we chose to utilise natural gas and petrol as a bi-fuel, with the aim of securing a longer cruising distance.

2. Aims

By combining the CO_2 reduction effects of natural gas fueled vehicles with the highly efficient driving mechanisms of hybrid systems, we aimed to produce a vehicle with further improved CO_2 reductions. Moreover, in the production of this vehicle, we chose to utilise natural gas and petrol as a bi-fuel, with the aim of securing a longer cruising distance.

3. Methods

3. 1: The selection of a base vehicle



For our base vehicle, we selected the Toyota *SAI* (DAA-AZK10; Displacement: 2.36L; Total length: 4.605m x width: 1.770m; marketed in the US as *HS*), taking into account the following: 1) its latest hybrid mechanisms; and 2) the vehicle's surplus trunk space following the installation of the compressed natural gas (CNG) cylinders.

3. 2: Basic specifications

In designing our bi-fuel hybrid vehicle, we included a fuel supply system for natural gas vehicles which utilised petrol hybrid cars as its basis to show the ability of natural gas vehicles to reduce CO_2 emissions. Although there were many precedents for the conversion of petrol vehicles to natural gas vehicles, and its reliance already proven, there was almost no precedent for the conversion of a petrol hybrid car to a natural gas car.

Tokyo Gas assisted in determining the vehicle's specifications, and the vehicle's development was conducted in cooperation with HKS Co., Ltd. (HKS; Fujinomiya City, Shizuoka Prefecture), a company possessing experience in the production and selling of bi-fuel system kits which alternatingly utilise CNG and petrol. We developed the sub computer for CNG to utilise petrol hybrid engine control unit (ECU), and designed the layout for the main parts such as the cylinder, regulator, and injector, and installed them. We also ensured that exhaust performance complied with emission standards, and improved engine performance when driving with CNG. The major specifications for this undertaking were as follows:

- A hybrid system utilising the base vehicle's latest hybrid mechanisms.
- Specifications to utilise the bi-fuel of CNG/petrol to secure a longer cruising distance.
- Compliance with emission standards for light and medium weight cars (JC08H + JC08C) when driving with CNG.
- Secured engine performance with CNG and the utilization of lightweight cylinders to improve fuel consumption.

3. 3: Remodeling of the vehicle

Utilising the original petrol system of the base vehicle, we modified the vehicle by adding CNG fuel system parts to the car.

3. 3. 1: Outline of the CNG fuel supply system structure

The main CNG components consist of a receptacle, a CNG cylinder, a regulator, a delivery assembly, a sub computer, and a controller, among others.

a) Receptacle (for CNG)

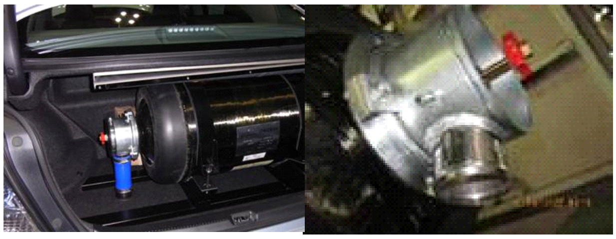
The receptacle is used to connect the nozzle of the CNG dispenser to the fuel pipe of the car, when you fill the car with fuel. Most Japanese natural gas vehicles usually install receptacles at the same place as petrol-fuel vehicles. However, this vehicle needs to utilise the original receptacle for petrol to be converted to one for a CNG-petrol bifuel car as there is not enough space to install receptacles for both CNG and petrol on the vehicle. Therefore, we decided to install it in the engine compartment, a procedure that is commonly followed in overseas. This also gives the added advantage of preventing the accidental start of the engine while filling because the bonnet is open.

b) CNG cylinder

One fiber reinforced plastics 77.7 liter composite cylinder (24.8MPa, D:408mm X L:870mm X W:25.7kg) is installed in the trunk. In accordance with the specifications for receptacles and other CNG parts set at 20MPa, the filling pressure has been set to 20MPa and the filled volume 5.5m^3.

Not only does the relatively larger capacity of the cylinder improve cruising distance, but its lightweight contributes to improved fuel consumption and engine performance. In order to prevent gas inflow to the inside of the vehicle in the case of a gas leak around the cylinder valve, the gas is released through the duct connected to the sealed semi container case, which secures the gas tight around the cylinder valve.

(Installed cylinder)

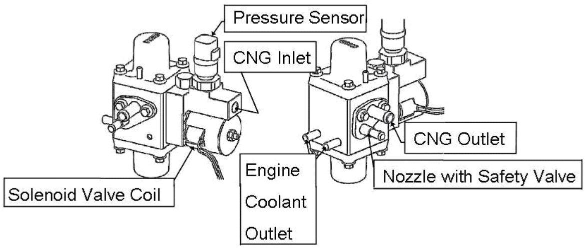


(Semi container case)

c) Regulator (for CNG)

A regulator is installed at the back left of the vehicle under the trunk and lies downstream of cylinder, and it reduces the pressure of CNG (highest pressure is 20MPa), and supplies the decompressed CNG to the injector at around 250kPa.

The regulator has a monolithic structure comprised of a solenoid valve and a pressure sensor. Engine coolant water is circulated to prevent freezing while gas is decompressed.

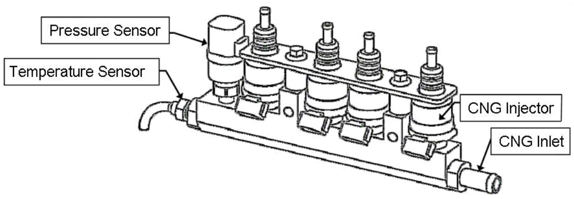


d) Fuel filter

A fuel filter is installed in the low-pressure fuel line between a regulator and a delivery assembly that screens out compressor oil from CNG and to prevent oil-mist from adhering to injector sheet. In comparison with installations in high-pressure piping, choosing parts that have a higher capture rate and lower pressure loss is vital.

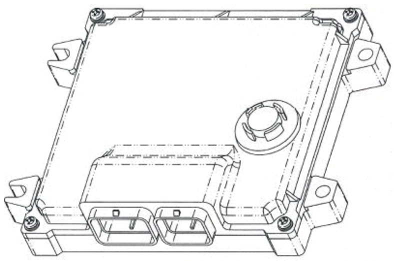
e) Delivery assembly (for CNG)

The delivery assembly is installed near the engine intake manifold together with a fuel pressure sensor, a fuel temperature sensor, and a delivery pipe holding the CNG injectors, which requires high performance, high reliance and low-noise.



f) Sub computer (for Bi-fuel)

The sub computer is installed under the floor mat of the navigator seat. This sub computer contr ols the switch between CNG and petrol operations, optimum air-fuel ratio control in CNG operations, ignition timing, and the main stop and fuel shut off valves. Additionally, with a self-diagnostic function, if any CNG operational failure is detected, it features a fail-safe function to display error codes, close the main stop valve, and switch to petrol operation mode.

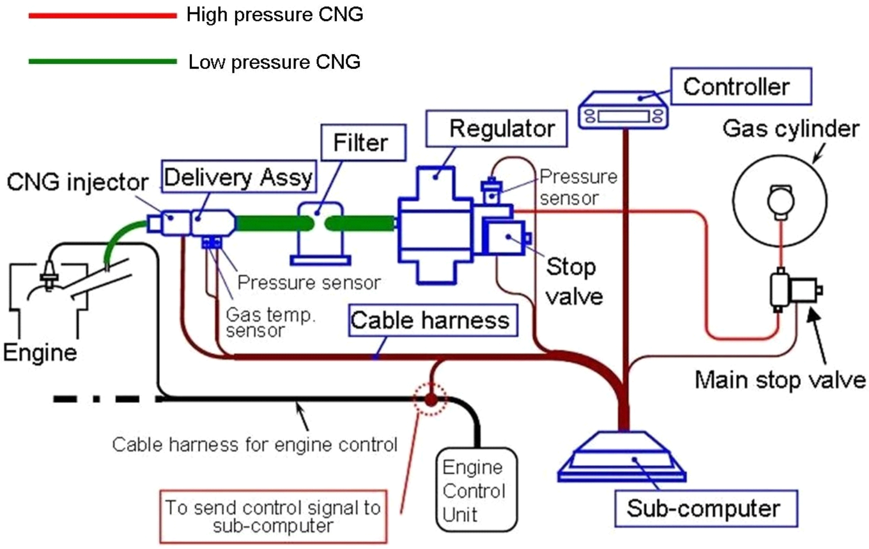


g) Controller (for Bi-fuel)

The controller is installed in the coin compartment of the driver seat. The controller includes a switch for shifting between CNG and petrol operations and features a function to monitor the remaining amount of CNG (pressure), which can be displayed as both pressure (MPa) and level. Furthermore, the system can also display present fuel efficiency (km/m^3) while driving with CNG and, with a self-diagnostic function, if any CNG operational failure is detected, it features a fail-safe function to display error codes on the monitor.

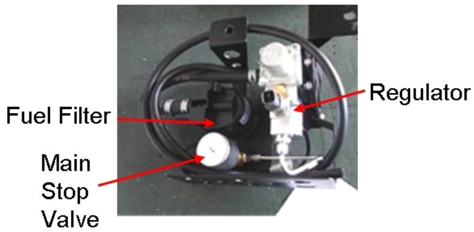
h) Wire harness kit (for Bi-fuel)

As the following figure illustrates, a wire harness kit for the bi-fuel system connects the sensors and components, including the sub computer, which is also connected to the ECU in petrol operation. And, in order to realise higher reliance and shorten the assembling time, all joints have been connected with couplers.



i) Main valve and Fuel shutoff valve (for CNG)

The main valve, installed near the CNG cylinder valve, and the fuel shutoff valve, constructed into the regulator, are solenoid valves which shut off the CNG in the case of an emergency and shut down the engine.



3. 3. 2: Operational mode control: between CNG and petrol

This vehicle can operate on both CNG and petrol. Principally, the sub computer controls the usage of CNG and petrol automatically in accordance with coolant temperature and engine revolutions, and the driver can also freely switch between fuels while driving.

a) Control in starting

A usual CNG-petrol bi-fuel vehicle is started by petrol-fuel. And after that, the vehicle shifts to CNG operations automatically, when all of the following conditions are realised: coolant temperature exceeds 80 degree Celsius while driving; engine revolutions per minute exceed 1000rpm; and CNG pressure exceeds 0.8MPa. When the engine restarts after it has been heated enough, because all these three conditions are met, the vehicle shifts to CNG operation immediately.

However, as this vehicle is a hybrid, when cold starting, the vehicle is started by its motor. While driving, the engine will be started by petrol. The vehicle shifts to CNG operations when the following conditions are realised: coolant temperature exceeds 40 degree Celsius while driving; engine revolutions per minute exceed 1200rpm; and CNG pressure exceeds 1.0MPa.

b) Control in re-starting

The sub computer records the operational mode when the vehicle's engine is stopped.
Upon restart, the sub computer resets the vehicle to the operational mode utilised at the time the engine was stopped.

- When the vehicle's engine was stopped while driving with CNG, the vehicle is restarted by CNG.
- When the vehicle's engine was stopped while driving with petrol, the vehicle is restarted by petrol.

c) Automatic fuel switching control when CNG level is low

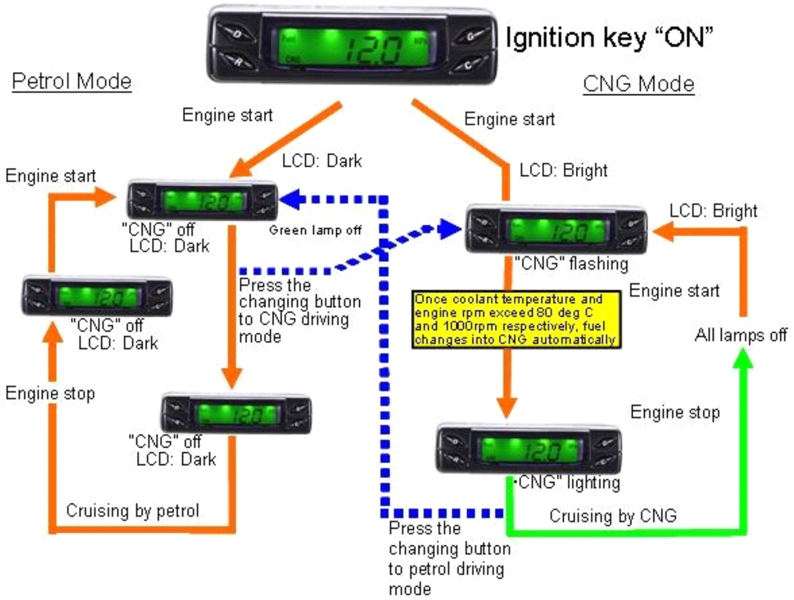
- When CNG pressure falls below 1.0MPa in motion, the vehicle automatically switches to petrol mode with displaying [**ENP**] on the controller monitor.
- The vehicle switches to CNG mode when the CNG is refilled and the engine restarted.
- The controller monitor switches to display the present CNG pressure level. And, at the same time, [**CNG**] sign is switched from flushing to lighting.

d) Free switching

- Petrol operation ➔ CNG operation

  When the driver pushes [**C**] button and the preconditions of CNG driving are met, the driver can shift to driving with CNG.
- CNG operation ➔ Petrol operation

  When the driver pushes [G] button, the driver can shift to driving with petrol in any driving situation.



(Free switching sequence)

3. 3. 3: Air-fuel ratio control

For air-fuel ratio control when driving with CNG, the sub computer detects signals for injection time periods and ignition timing of the petrol injector from the base vehicle's ECU, oxygen sensor output, engine coolant temperature, throttle opening, and vehicle speed signals, among others. The sub computer then calculates the difference between the fuel components of petrol and CNG, adjusts injection periods of the CNG injector, and controls the injection and ignition timing for optimum timing in CNG operation.

4. Results

4. 1: Tests

Tokyo Gas has been running performance tests on public roads. The test driver is an expert at driving the same size, class and type of vehicles.

Although the acceleration is usually a disadvantage in CNG-fueled vehicles, the engine and the motor in this vehicle work together to provide the power to pick up speed, so the driving feeling is improved. The interior of this vehicle has remained exactly the same as the original design of the base car, with the exception of the controller installed in the coin compartment.

4. 1. 1: A change the switch from petrol to CNG

So far, an improvement has been made during the performance tests. As explained before, this vehicle shifts to CNG operations when the following conditions have been realised.

- CNG operation mode is selected by the controller

- Coolant temperature exceeds set temperature
- Engine revolution speed exceeds set speed
- CNG pressure exceeds 1.0MPa

However, while driving on regular roads, under some circumstances, we found that the vehicle did not often shift to CNG operations. Upon investigation, we discovered that this condition was seldom realised because, due to much lower outside air temperature in some seasons the coolant temperature was rarely exceeding the set temperature of 80°C thereof.

In order to counter this finding, we lowered the set temperature of the coolant to 40°C. In doing so, with the exception of cold starting, the engine is started by petrol, and within a few seconds the vehicle shifts to CNG operations. As a result, the total length of driving with CNG has been increased.

4. 1. 2: Other improvements

a) Improvement of compression ratio

We included a fuel supply system for natural gas vehicles utilising *SAI* as its base car, and made no modifications to its engine at all.

Because CNG originally has a very high octane content compared with petrol, a CNG-fueled engine hardly knocks even when it is driven at a high compression ratio. On the other hand, this vehicle is driven with the original base car's engine, meaning that it is driven at the compression ratio set for a petrol-fueled engine; therefore, the efficiency cannot be achieved higher.

However, because CNG operations are the main mode for this vehicle, in order to improve the engine efficiency more, we must develop and use a higher compression ratio engine to match the higher octane content of CNG.

b) Durability of the main valve

The main valve, a solenoid valve, is installed in near the cylinder valve to shut off CNG. This valve is required to meet the Japanese standard for the structure of CNG vehicles and the following conditions:

- The main valve can be operated from the driving seat.
- The main valve automatically shuts off when the engine stops.
- Other conditions

To improve fuel consumption, this vehicle has a system to stop the engine when the accelerator is released even while driving. When we drive a usual petrol-fueled vehicle, the engine starts at a starting point and stops at the destination, so that the main valve opens and closes only once for each trip. However, the engine of this vehicle starts and stops numerous times, and the main valve also does the same in time with the engine while driving.

Although the main valve currently used has the top class durability in Japan of 30000 times, we are not certain of how many times the engine will actually start and stop, and also the main valve will repeat opening and closing; therefore, we don't know how long its duration is. For each drive, we need to count how many times the engine starts and stops. Meantime , we need to keep a close eye on the condition of the main valve at periodical inspections.

4. 2: Estimated vehicle capability

4. 2. 1 : CO_2 reduction effects

We are trying to use the low CO_2 emissions per unit calorific value of natural gas as an advantage, and reduce CO_2 emissions from the vehicle. The calculated value for fuel efficiency based on the base vehicle's catalogue value of 23km per liter (10-15 mode) is 29.8km/m^3. Based on this figure, CO_2 emissions are calculated as in Table 1.

(Table 1: CO_2 reduction effects)

	Gasoline-powered vehicle	Gasoline Hybrid vehicle	CNG Bi-fuel Hybrid vehicle
Fuel efficiency	11.5 km/l	23.0 km/l	29.8 km/m ^{3}
	(same class vehicle)	(catalogue)	(calculated by Tokyo Gas)
CO_2 emissions coefficient	2.32 kg/l	2.32 kg/l	2.29 kg/m ^{3}
	(Act on Promotion of Global Warming Countermeasures)	(Act on Promotion of Global Warming Countermeasures)	(calculated by Tokyo Gas)
CO_2 emissions per 1km cruising	202 g	101 g	77 g
% of CO_2 emissions	100	50	**38**

In comparison with petrol hybrid vehicles, our bi-fuel hybrid vehicle can achieve a maximum reduction in CO_2 emissions of approximately 20%, and, in comparison with ordinary petrol cars, a maximum reduction of approximately 60%.

4. 2. 2 : Cruising distance of bi-fuel vehicle

In designing this CNG hybrid vehicle, we utilising a petrol hybrid car and added a fuel supply system for natural gas vehicles, leaving the original base car's petrol fuel system intact, which makes driving with petrol also possible. In other words, this vehicle is also a bi-fuel car that can be driven freely switching between CNG-fuel and petrol-fuel.

Because it is a bi-fuel car, the cruising distance of this vehicle was improved significantly, enabling it to be driven in areas where natural gas stations are few or none. And, in comparison with CNG mono-fuel vehicles, because this vehicle can be driven on CNG until the CNG cylinder runs out completely without worry, the number of times required for refueling has been reduced.

The calculated value for cruising distance based on catalogue values is approximately 1,700km (CNG: 450km; and petrol: 1,250km) when both CNG and petrol have been filled.

(Table 2: Cruising distance)

	CNG	Gasoline
Fuel efficiency	29.8 km/m^3	23.0 km/L
Fuel consumption	15.5 m^3	55 L
Calculated value for cruising distance	461 km	1,265 km
Total calculated cruising distance	1,726 km	

4. 3: Actual fuel consumption

Fuel consumption measurements were conducted using the fill-up method, for two different driving sections: on general roads and on motorways; and by using two kinds of fuel: bi-fuel and petrol.

4. 3. 1: Methods for measurement

The fill-up method was used for measurements of fuel consumption, filling the petrol tank and the CNG tank prior to testing. Following each driving test, each of the fuel tanks was filled again with petrol and CNG respectively, and the refueled amounts of petrol and CNG were recorded as the amounts of consumed fuel. Each of the measurements was conducted by selecting between two different fuel modes (petrol mode and bi-fuel mode) and two different driving sections (general roads and motorways), respectively.

4. 3. 2: Fuel modes

For measurement, modes were set as follows.

(Table 3: Fuel modes)

Fuel mode	Fuel(s) used	Controller setting
Petrol mode	Only petrol	Petrol mode from start to finish
Bi-fuel mode	Parallel use of petrol and CNG	CNG mode from start to finish

4. 3. 3: Driving sections

(Table 4: Driving sections)

Driving sections	Driving distance	Driving state	Driving route
General roads	Approx. 90km	Round trip between inner-city and suburb districts using mainly major arterial roads.	Tokyo Gas, Hamamatsu-cho Building → Route 20 → Route 16 → Tokyo metropolitan road No.29 (Shin-Okutama kaido) →Route 20 → Tokyo Gas, Hamamatsu-cho Building
Motorways	Approx. 220km	Round trip between an inner-city district and a local city using mainly the Metropolitan Expressway and other motorways.	Tokyo Gas, Hamamatsu-cho Building → Shimbashi IC →Route 6 (Mukojima Line) →Misato → Mito IC; returning to the starting point using the same course.

(Note: Driving conditions)

- Driver only
- Measurements taken under actual traffic situations on the driving routes.

4. 3. 4: Test results

(Table 5: Test results*1)

Fuel	Driving section	CNG filled volume	Petrol filled volume	Driving distance	Volume of energy consumption*2	Volume of CO_2 emissions*3
		m^3	L	km	MJ/km	kg/km
Bi-fuel	General roads	9.35	3.40	211	2.6	0.139
	Motorways	26.06	5.40	672	2.0	0.107
Petrol	General roads	—	11.65	183	2.2	0.148
	Motorways	—	10.50	220	1.7	0.111

(*1) Calculated using the total values for each fuel mode and driving section.

(*2) Converted the volumes of CNG and Petrol to the volumes of energy consumption; CNG: 45MJ/m^3N, Petrol: 34.6MJ/L

(Calculated base on the Act on Promotion of Global Warming Countermeasures. Gas is calculated using Tokyo Gas compositions, during normal conditions.)

(*3) CO_2 emission factor; CNG: 2.29kg-CO_2/m3N, Petrol: 2.32kg-CO_2/L
(Calculated base on the Act on Promotion of Global Warming Countermeasures. Gas is calculated using Tokyo Gas compositions, during normal conditions.)

- Bi-fuel mode consumed more volume of energy but emitted less CO_2 versus the petrol mode driving for unit distance.
- For CO_2 reductions in the bi-fuel mode, a 6% reduction for general roads and a 4% reduction for motorways were achieved.

4. 3. 5: Discussion

In estimates of calorific value conversions for petrol and CNG, bi-fuel was estimated to reduce CO_2 emissions by approx. 20%. However, actual results attained from testing measured to be between 4% and 6%.

The followings were possible reasons for these results.

- Since CNG, which can be used with high-compression engines, was used with an engine designed with a compression ratio for petrol, the fuel consumption rate was possibly reduced: With the other manufactured petrol-fuel car and CNG-fuel car, the compression ratio for the petrol model is 10.5, while that for the CNG model is 12.0.
- In the bi-fuel mode, the petrol fill volume is significantly larger in comparison to the fuel consumption of CNG. This is considered to be a result of possible errors in measuring petrol fill: Currently, we rely on the automatic stopping functions of dispensers for fuel fill.
- In consideration of these results, for increased accuracy of measurement, we will need to improve our methods for petrol fueling in the future: Since petrol was used only for the brief time to start and to warm up the engine, very little petrol was actually thought to have been used, and refueled volume was also considered to have been a lot smaller in reality. There may also have been errors in refueling with fuel tank fluid levels and fuel dispenser sensors. In the future, we would like to reduce these possible errors through a decrease in the frequency of fueling.

5. Summary

Though natural gas vehicles are mainly used for trucks in Japan, Tokyo Gas Co., Ltd. desires to contribute to the popularization of natural gas vehicles for private automobiles through the introduction of its CO_2 reduction effects for its Bi-fuel-Hybrid vehicles. This natural gas hybrid vehicle indicates that it can contribute to reductions in CO_2 emissions and diversifications in fuels in the transport sector by combining the low CO_2 emissions per unit calorific value, one of the advantages of natural gas, with the highly efficient driving mechanism of the motors and engines of a hybrid system, which has long been developed primarily for gasoline cars.

In the future, we aim to further reduce this vehicle's GHG emissions through continued analyses of fuel consumption, an accumulation of information related to parts durability, and through further improvements to achieve lower fuel consumption, lower pollution and higher reliability. Additionally, through the sharing information related to this vehicle's development, we endeavor to work with automobile manufacturers to introduce and develop the CNG hybrid car as one of their models of vehicles.