Direct Injection of CNG for Driving Performance with Low CO₂

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Summary

Today's compressed natural gas (CNG) engines in series production use manifold port fuel injection (PFI) of the gaseous fuel. In downsized, boosted engines this results in a loss of low-end torque when compared to a gasoline direct-injected (DI) engine due to lower volumetric efficiency and the inability to perform scavenging. This paper discusses the significant development progress that has been made in the direct injection of compressed natural gas in passenger car engines. The key component of this technology is the CNG DI injector, for which the concept and the development status will be presented. Selected results of the progress on engine and vehicle implementation from two automakers show the potential of the CNG DI combustion technology. With the CNG DI technology, downsizing is possible and an equivalent driving performance in comparison to DI gasoline engines is realized.

1 Introduction

Carbon dioxide (CO₂) emissions from vehicles are now regulated in most of the world's major automotive markets. These regulations are based on the global warming effect of carbon dioxide in the atmosphere, where it increases the heat-trapping capability of the atmosphere, thus providing an impetus toward higher average global temperatures as atmospheric CO₂ concentration rises.

Two fundamental strategies exist for reducing automotive CO₂ emissions: (1) reduce the energy used by the automobile and (2) reduce the carbon-to-energy ratio of the fuel used by the vehicle. The first strategy is heavily in use and involves a large number of efficiency improvement and loss reduction approaches to the powertrain, vehicle aerodynamics, and climate control. The second, fuel-based approach, is a realistic alternative, but carries with it fuel infrastructure considerations that are broad and regional in nature, whether the fuel is electricity or an alternate chemical compound to gasoline or diesel fuel. In addition, a fuel-based approach to CO₂
reduction must consider to the total-cycle CO\textsubscript{2} impact, often described as "well-to-wheels".

It is within the second, fuel-based CO\textsubscript{2} reduction strategy that we focus on compressed natural gas (CNG). CNG offers approximately 25% lower CO\textsubscript{2} emissions at a combustion level than gasoline. In the near-term, natural gas has rapidly growing availability from fossil sources. In the longer term, the outlook for methane generated from renewable sources such as wind and bio-activity is quite positive. Renewable methane can easily be blended into natural gas without any blend limits (versus limits for ethanol in gasoline or FAME in diesel). Thus, a CNG infrastructure can be used for renewable methane without any modifications or restrictions. Existing fossil supplies of natural gas can act as an energy "bridge" to a renewable biomethane future, with a continuous spectrum of blending between fossil and renewable sources of methane being possible along the way.

While CNG is an attractive path, there still remains an opportunity to boost the customer acceptance of CNG vehicles through an upgraded fuel injection system. Today's production CNG vehicles use intake port injection of the CNG fuel, with a resulting loss in low-rpm torque when compared to a gasoline engine. This loss is noticeable to customers, both in the engine performance specifications and in the resulting vehicle on-road drivability. The result is diminished downsizing capability in comparison to modern boosted gasoline direct injection engines. While this low-rpm torque could be created by using a larger displacement engine, multi-stage boosting, or transmissions with increased gear-count, these solutions have a significant negative effect on cost, packaging and weight. As we will show, the use of direct-injected CNG permits restoration of the low-end torque and gives the same performance as a gasoline engine while producing significantly lower CO\textsubscript{2} emissions. Furthermore, a direct injection approach follows the existing trend toward direct injection in spark-ignited engines and allows the fuel conversion to proceed by swapping a gasoline direct injector for a CNG injector.

Direct injection of natural gas offers the following potential advantages versus CNG PFI: reduced fuel consumption through the enhanced downsizing capability of CNG engines on par with modern boosted gasoline direct injection engines, improved torque by avoiding air displacement by the CNG and by the application of scavenging, more effective catalyst heating (analogous to gasoline DI), and easy conversion of gasoline DI engines. The potential and the technical feasibility of CNG direct injection was evaluated and demonstrated within the European NICE and InGAS projects [1,2,3,4], which showed that with direct injection increased low-end torque is feasible and downsizing becomes possible.

2 CNG Direct Injector

The direct-injected CNG vehicle of tomorrow has a strong similarity to today's production CNG vehicles. However, an important enabling component that has been
missing is the direct injector itself. The high flow area required for direct CNG injection, combined with a non-lubricating gaseous fuel, create significant challenges to realize a durable direct CNG injector with low leakage.

Through focused efforts, Delphi has made significant progress in designing and building such an injector.

2.1 Requirements

Several high-level criteria were used as the starting point for CNG DI injector requirements:

1. Applicable to a passenger car engine which is downsized and boosted
   a. Based on current gasoline engine trends
2. Matches the torque and power of the gasoline version of the engine
   a. For customer acceptance in the market
3. The injector is compatible to mount in the existing gasoline direct injector "pocket" in the cylinder head
   a. Allows an exchange of injectors so that a CNG engine could be created from a gasoline engine with fewer modifications
4. Maximize the range of the vehicle from the CNG tanks
   a. For customer acceptance in the market

Based on these high-level criteria, the following injector-level requirements were established:

- Pressure Range: 6 bar to 16 bar, absolute
- Flow Rate: 6.7 grams/second at 16 bar absolute pressure (Natural Gas)
- Injector Body Diameter: 21 mm
- Injector Tip Diameter: 7.5 mm

The maximum operating pressure of 16 bar was chosen based on several factors:

- Desire to maximize vehicle range.
  - A lower maximum pressure allows more CNG to be used from the tank.
- Desire for a higher flow rate.
  - A higher maximum pressure gives more flow for a given injector nozzle cross section.
- Reduced tip leakage.
  - A lower maximum pressure reduces leakage when closed.

It can be seen that these factors are in opposition to each other - some are better at higher pressure and some are better at lower pressure. Therefore, the choice of maximum pressure is a compromise which was taken carefully. To increase the range of the vehicle on CNG from pressurized CNG tanks, a lower operating pressure is desired to maximize the amount of CNG that can be taken from the tank before the tank pressure drops below operating pressure. This relation is shown in
Figure 1 below, highlighting the percent of the CNG fuel used from the tank versus the maximum operating pressure. For example, if we consider 16 bar as the baseline, there is a 6.6% loss in vehicle range by choosing an injection system having a 30 bar maximum operating pressure. (Note that this is a simplified comparison, with the assumption of no pressure loss between the tank outlet and the fuel rail.)

![Graph showing percent CNG Used from Tank vs. Tank Pressure]

The flow rate target was set based on achieving high power output from the CNG engine. When sizing an injector flow rate for engine power output, the engine-level target must be converted to a per cylinder basis so the injector flow can be determined. The choice of 8 bar operating pressure, currently used by PFI systems, would add approximately 3.6% additional range, as shown in Figure 1. However, meeting the flow rate target at 8 bar pressure would result in too many compromises in the CNG direct injector.

### 2.2 Injector Design Concept Selection

Designing an injector to meet the requirements started with making two fundamental choices: the actuator type and the valve type.

#### 2.2.1 Actuator Selection

The actuator choice was important - it moves the pintle to open and close the valve, thus controlling the fueling event. Most direct injectors today use an electromagnetic solenoid actuator, but some use a piezo-electric actuator. A Pugh analysis was conducted to make the actuator decision, with the key criteria identified as: suitability for large pintle lift to meet the flow target, suitability for long pulse widths, re-use of existing Delphi injector design features where possible, small fuel quantity delivery, complexity of the thermal compensation, and cost. The solenoid is shown as the baseline in the table in Figure 2 below. As can be seen, the piezo-electric actuator...
was rated as better ("+") in one aspect, and worse ("-") in five aspects. On this basis, a solenoid actuator was chosen [5].

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Solenoid</th>
<th>Piezo-electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large pintle lift</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Long pulse widths</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Delphi technical re-use</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Minimum quantity</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Thermal compensation</td>
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<td>-</td>
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<tr>
<td>Cost</td>
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<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>(5) -, (1) +</td>
</tr>
</tbody>
</table>

Fig. 2: Pugh Analysis for Actuator Choice

2.2.2 Selection of Valve Type

Most direct injectors today are inward-opening, multihole injectors. However, some do use an outward-opening valve. Cross section diagrams of both valves are shown in Figure 3 below. The selection of the valve type for the CNG DI injector was based on the consideration that the gas pressure inside the injector would be a maximum of 16 bar, while the in-cylinder pressure could reach 100 bar or more under high engine loads. This negative pressure differential makes an inward-opening valve susceptible to being opened by the cylinder pressure, which is undesirable. In contrast, an outward-opening valve is naturally sealed by higher cylinder pressures. An outward-opening valve was selected on this basis.

Inward-Opening Valve
- Is susceptible to being opened by cylinder pressure
- Requires high spring forces in injector to counteract

Outward-Opening Valve
- Is naturally sealed by cylinder pressure
- Higher flow rates possible

Fig. 3: Inward-Opening Valve and Outward-Opening Valve Considerations
2.3 Injector Hardware Design and Build

Based on the actuator and valve choice, as well as a range of other requirements, several generations of CNG DI injector hardware have been designed, built, and tested. Constant refinement and improvement has taken place in each generation, guided by computational fluid dynamics (CFD) simulation, finite element analysis (FEA), and mechatronic simulations. The fourth generation of the injector is shown in Figure 4 below, and represents a high level of performance and durability. It has a 7.5mm tip diameter and a body diameter less than 21mm, making it packaging compatible with today's gasoline direct injectors.

![Fourth Generation of the Delphi CNG DI Injector](image)

The fourth generation injector features a flow path that has been optimized for high gas flow rates and internal materials and features designed for robust durability. Natural gas does not have the lubricating properties of gasoline or diesel fuel, so special measures are implemented in the injector to ensure that injector performance will be stable over its entire lifetime, even with the larger nozzle opening area necessary with a gaseous fuel.

2.4 Durability Testing

Validation testing of an injector involves a spectrum of tests aimed at evaluating if the injector can withstand the rigors and stresses of an engine-mounted component in an automotive environment that includes vibration and a wide range of hot and cold temperatures. In addition to environmental testing, the injector must also be proven to be durable enough to last the entire useful life of the vehicle. For future injectors that have one injection per combustion event, useful life is typically understood to be in the range of 300 million to 500 million injection events. Three CNG DI injectors were tested to 400 million injection events using dry CNG as the fuel. Figure 5 shows the flow shift of these injectors when characterized with a 7 millisecond injection pulse. As can be seen, at 400 million cycles the flow shift for all three injectors remains inside the +/- 5% limits, indicating that the parts are durable.
The flow shift after cycling is not the only critical durability parameter. The other parameter of primary interest is the tip leakage. Figure 6 shows the evolution of tip leakage performance after durability cycling for generations 1 through 4 of the CNG DI injector, normalized to the leakage of the generation 1 injector as 100%. As can be seen, the GEN1 injector was far above the leakage limit. By GEN2, the leakage had dropped over 80%, by GEN3 it had dropped over 95%, and by GEN4 the tip leakage was within the leakage limit after durability cycling.

Figure 7 below shows the detail of the GEN4 tip leakage progression during a 400 million cycle durability test. All leakage values are inside the limit, and over time the leakage values improve and stabilize at approximately 20% of the limit or less.
The CNG DI injector has met the specifications and durability limits that were set. The pressure range, flow rate, and packaging dimensions have all been met or exceeded, and a small quantity of injectors has passed limited durability testing to 400 million cycles. The next development phase for the injector will focus on (1) optimization of the design and (2) development of the manufacturing processes needed to industrialize the injector for series production.

3 Engine Evaluation of CNG DI

3.1 Engine Overview

Dynamometer experiments were conducted using a current production Ford 1.0 liter GTDI 3-cylinder engine with minor cylinder head modifications to install the CNG direct injection system. The injectors were mounted in a central position in the combustion chamber. The application of the CNG DI system is shown in Fig. 8. The compatible CNG DI injector dimensions allowed the installation of the injector in an unchanged position and orientation relative to the current production engine. In addition this engine was equipped with a CNG port fuel injection system (CNG PFI) to allow a direct comparison during engine testing.
Fig. 8: Application of the CNG DI Injection System to the 1.0 Liter Engine

The boosting system and the combustion system were unchanged relative to the production gasoline DI concept.

3.2 Engine Testing

The experiment was carried out on an engine dynamometer fully equipped with emission and combustion analysis systems to evaluate the combustion system capability that is defined and characterized by the downsizing concept of the base engine.

Fig. 9: Relative Engine Torque: CNG DI, CNG PFI, and Gasoline DI

Figure 9 shows a normalized comparison of the torque behavior in the entire speed range for the CNG direct injection system, the CNG port fuel injection system, and the baseline gasoline direct injection system for reference. Up to an engine speed of
1750 rpm the waste gate of the turbo charger is fully closed and the engine is producing the maximum possible torque. Above 1750 rpm, the targeted overboost torque of the engine is achieved and the waste gate is opened in order to stay at this torque level.

At lower engine speeds, e.g. 1500 rpm, the CNG PFI engine loses more than 30% of its torque when compared to the gasoline DI mode. Through application of direct-injected CNG, approximately 2/3 of the torque loss can be recovered right away, as long as the spark setting is optimized for efficiency. By adding moderate spark retard, the turbine speed can be increased through higher heat flux into the exhaust, resulting in a boost increase. In other words, the torque loss by reduced combustion efficiency is more than offset by the torque rise due to higher boost pressure. As a consequence, the maximum torque in CNG DI mode nearly matches gasoline DI.

Spark timing with gasoline fuel is determined by the borderline of knock, while during CNG operation the engine is running fully knock free and near the thermodynamic optimum. As a consequence of the knock limitation, the point of 50% mass fraction burned (50% burn angle) for gasoline is in the range of 20° to 30°CA ATDC and thus considerably retarded from the optimum range of 8° to 10°CA ATDC, as can be seen in Fig. 10. With CNG, both PFI and DI, spark angle is not knock restricted but is instead limited above 1500 rpm to approximately 15°CA ATDC due to limited peak pressure capability of the engine hardware. In order to increase the low-end torque for CNG DI operation, a combustion retard of the same magnitude needs to be applied below 1750 rpm.

![Fig. 10: Comparison of 50% Burn Angle for CNG vs. Gasoline](image)

As displayed in Fig. 11, the low-end torque enhancement of CNG DI vs. CNG PFI is mainly achieved by the injection of CNG into the cylinder after the intake valve is closed ("IVC"). During CNG PFI operation, the CNG displaces air on the intake stroke and cylinder filling is reduced, resulting in a loss of torque. With CNG DI injection it is
possible, up to approximately 2000 rpm, to inject the complete CNG mass required for full load operation directly into the cylinder after IVC. Therefore, the cylinder can be filled completely with pure air as with gasoline DI operation and the energy associated with the CNG system pressure is not wasted by expansion down to manifold pressure level. This operation mode requires an injector designed to meet the volume flow requirements. Fig. 11 shows that the effect of the late injection is significant. At 1000 rpm an early start of injection (SOI) of 250° BTDC reduces the maximum torque by more than 15%, at 1500 rpm even by more than 25%.

![Fig. 11: CNG DI: Start of Injection (SOI) Timing Effect on Engine Torque](image)

For engine speeds above 2000 rpm, the required injection time becomes longer than the available time after IVC and a part of the CNG needs to be injected before IVC. But, this effect does not lead to any torque loss because the turbo charger is already able to produce enough manifold pressure to compensate for the reduced cylinder filling effect. This effect can be observed in Fig. 12 which displays the relative manifold pressure over crank speed. Above 2000 rpm, with CNG the turbocharger must produce a manifold pressure approximately 10% above the gasoline DI level to compress the CNG in addition to the intake air and maintain engine torque.

Below 2000 rpm there is no unused charging potential. The manifold pressure of CNG PFI is significantly lower than for gasoline DI operation, which leads to considerable torque loss. With CNG DI and late combustion settings the manifold pressure can be brought back nearly to gasoline DI level because of injection completely after IVC.
In Fig. 13 the engine efficiency of the three fueling modes is compared. With gasoline DI, only up to 32% efficiency is achieved. The main reason for the much lower gasoline efficiency is the knock limited late combustion phasing. For CNG operation, better combustion phasing is used over the whole engine speed range, resulting in higher efficiency.

CNG PFI operation peaks at 35% and CNG DI reaches 35.5% at two points. CNG DI efficiency exceeds the CNG PFI efficiency by approximately 0.5% to 1% over much of the speed range. Below 2000 rpm, the torque-optimized spark setting with CNG DI sacrifices efficiency for torque increase. The slightly better efficiency of CNG DI versus CNG PFI can be partly explained by the more favorable burn duration and ignition delay as shown in Fig. 14 and Fig. 15.
While CNG PFI combustion is significantly slower than gasoline DI combustion, CNG DI combustion has an even shorter ignition delay than gasoline. The following burn duration is namely not as fast as gasoline DI but considerably faster than CNG PFI.
Another reason for the high engine efficiency level of the CNG DI configuration is the superior combustion efficiency achieved with CNG DI. As shown in Fig. 16, approximately 99% combustion efficiency is achieved over the complete engine speed range.

Below 3500 rpm, the combustion efficiency of CNG PFI operation is lower because of CNG blow-through, which is unavoidable with the PFI injection system. For CNG DI, the blow-through is minimized and high combustion efficiency can be maintained. For gasoline DI, the combustion is more retarded than for CNG. This leads to high exhaust temperatures, even when the overlap is increased. The high exhaust enthalpy helps to boost the turbocharger, but degrades combustion efficiency due to higher valve overlap. Above 3500 rpm, the combustion efficiency with both CNG injection systems is significantly higher than with gasoline. This is due to more advanced CNG combustion, which leaves more time for post reactions.

### 3.3 Summary - Engine Testing

The presented results highlight the benefits of CNG direct injection. The separation of air and gas is the key for high specific performance in combination with high torque in the lower speed range. CNG DI also avoids the need to use other torque-enhancement countermeasures like enlargement of the engine displacement or the use of more advanced boosting systems.

Specific optimizations of the entire combustion system to utilize CNG in the best way will follow in a future phase of development. This will contain the matching of the boosting system and the orientation of the charge motion relative to the CNG injection. The high level of knock resistance of CNG, in combination with direct injection, will also enable further thermodynamic efficiency improvements through a
higher compression ratio. Modifications of the base engine structure to cope with increased pressures, as well some further optimization of the injection relative to charge motion, also have significant future potential.

4 Vehicle CO₂ Reduction

4.1 Engine Overview

The Mercedes-Benz B200 NGD vehicle currently in series production is equipped with a monovalent 2.0 liter CNG engine with intake port injection having a power output of 115 kW and a peak torque of 270 Nm [6]. A 1.6 liter engine was designed with a CNG direct injection combustion system that exhibits the same full-load performance. The engine remained almost unchanged and is comparable with the 1.6 liter gasoline version (Fig. 17). Even the turbocharger was left unchanged; it is the same as on the 2.0 liter CNG engine. Only the DI gasoline injectors, together with the fuel rail and the high pressure pump, were replaced by the CNG injection system (Fig. 18). Fig. 19 shows the cylinder head with the Delphi Gen 4 CNG injectors installed in a central position.

Fig. 17: Mercedes-Benz Turbocharged I4 Engine – M 270
4.2 Advantage of CNG DI vs. CNG PFI

Figure 20 shows a comparison of the full-load curves of the 1.6 liter engine with intake port injection and with direct injection of CNG. The highlighted area shows the additional potential that can be tapped with direct injection of CNG [7].
4.3 Injector Durability in Engine Testing

During engine testing at Daimler, the GEN 4 injectors have proven their durability in a number of tests. Single injectors reached a running time of almost 2000 hours, and the run time of all GEN 4 injectors at Daimler sums up to approximately 20,000 hours. A special, demanding endurance test of over 1000 hours duration was carried out and all four injectors survived the testing.

4.4 The Path to Vehicle CO₂ Reduction with CNG DI

Today, CNG engines for passenger cars are, in most cases, variants of gasoline engines with only minor modifications. To fully exploit the advantages of natural gas fuel properties it is essential to design a dedicated CNG engine. To achieve maximum fuel efficiency, lowest exhaust emissions, and best performance, the combustion system has to be adjusted for the special characteristics of natural gas. Direct injection, increased compression ratio, and increased peak pressure capability are important elements to be included. Further downsizing of the natural gas engine leads to a fuel consumption improvement of approximately 7% in the NEDC drive cycle. In conjunction with other measures like increased peak pressure capability and application of part load operation strategies, a substantial reduction of the CO₂ emissions of about 16% compared to state-of-the-art engines is feasible (see Figure 21). The systematic refinement of the injection components and CNG direct injection combustion system offers the potential for reducing CO₂ emissions to levels similar to those of diesel engines. This makes CNG as an alternative fuel a highly interesting proposition for the next phase in the optimization of combustion engines.
Fig. 21: CO$_2$ Emissions Improvements for Different Engine Layouts, NEDC Cycle

4.5 Vehicle Results with CNG Direct Injection

The prototype engine with CNG direct injection was installed in the current Mercedes-Benz B-Class natural gas vehicle (B 200 NGD, Fig. 22). The gasoline fuel system was deactivated - hence the test vehicle was designed for mono-fuel operation. As a result, a good and robust operating performance was observed.

Furthermore, transient behavior is improved, resulting in excellent values for vehicle acceleration as shown in Fig. 23. The downsized, direct injected CNG engine is 0.3 seconds faster from 0 to 100 km/h.
Regarding emissions, natural gas engines not only show a lower amount of CO$_2$ in comparison to gasoline engines as a result of the more favorable hydrogen/carbon ratio, but they also produce very low particulate matter exhaust emissions. The primary reason is that there is no wall wetting in the combustion chamber and no subsequent vaporization of fuel from the internal surfaces. Inhomogeneity of the air-fuel mixture, another source of particulate matter, is also minimized. For the Mercedes-Benz B-class, Figure 24 shows a comparison of particulate number emissions in the NEDC during gasoline and natural gas operation. Appropriately equipped gasoline vehicles are currently capable of complying with the upcoming lower limit value for particulate emissions of $6\times10^{11}$ particles/km scheduled to take effect in 2017. Figure 24 shows that natural gas vehicles, whether equipped with PFI or DI, are far below this limit and also far below the level of gasoline operation.
5 Conclusions and Outlook

The 2020 and 2025 CO$_2$ targets require dramatic improvements in powertrain efficiency. CNG is one sustainable solution to reduce CO$_2$ compared to gasoline engines. Through direct injection, CNG as a fuel becomes an attractive alternative in terms of fuel consumption, driveability, and emissions.

5.1 Technology

The key component for CNG direct injection is the injector itself. The solution is an outward-opening solenoid injector with an operating pressure of up to 16 bar. This pressure gives the opportunity to use most of the stored CNG in the tank, giving good vehicle range. The injector is on a path toward readiness for a series production development.

The engine and car test results by Ford and Daimler show the benefits of this solution. Low end torque behavior is similar to gasoline applications and downsizing can be used. The driveability is equivalent to gasoline vehicles and the technical risk for using CNG DI technology in series production cars is low compared to other alternative powertrains. Improvements of the combustion system lead to further benefits and lower CO$_2$ when compared to today's CNG vehicles. Thus, CNG DI technology has the potential to meet the CO$_2$ levels of Diesel engines. Regarding particulate emission, the CNG DI technology shows very low values and is comparable to CNG PFI engines.

5.2 Infrastructure

Every alternate fuel must be supported by fueling station infrastructure. This is a universal requirement for alternate fuels and not unique to CNG. Fueling points can be added at filling stations, similar to the paradigm for gasoline or diesel fuel, or, in countries which have a natural gas distribution for home heating, filling points can be added at home, similar to the electric vehicle charging paradigm.

Regarding filling stations, the European Commission proposed a directive in 2013 which requires member states to bring forward the expansion of fueling infrastructure for alternative energies. Specifically concerning natural gas, the European Commission proposed that the "member states shall ensure that a sufficient number of publicly accessible re-fuelling points are available, with maximum distances of 150 km, to allow the circulation of CNG vehicles Union-wide by 31 December 2020 at the latest" [8]. This, along with other measures, will help address gaps in CNG fueling infrastructure, making natural gas vehicles more attractive to customers.

In the United States, over 1300 public and private filling stations exist, but the lack of proximity to most drivers is still a practical limitation to wider customer acceptance. However, many people in the United States have natural gas as their fuel for home heating. With progress in cost-effective home CNG refueling technology, there may yet be a technological solution that opens up CNG to a broad cross-section of the population.
5.3 Fuel Price

In the United States, CNG prices on a “GGE” (gallon of gasoline equivalent) basis are stable since 2005, and roughly 40% lower than gasoline or diesel fuel since 2011, as can be seen in Figure 8. Expected lower, more stable pricing is one clear advantage of CNG as a fuel in the near- to mid-term. In Germany, CNG as a transportation fuel has tax benefits which the current German government plans to continue.

![U.S. Average Retail Fuel Prices](image)

Fig. 25: Historical Comparison of United States Fuel Pricing [9]

Internal combustion engines are expected to power most vehicles for many years to come. CNG reserves worldwide are currently at over 100 years at today's usage rate and exceed oil reserves significantly. Through direct injection, a combustion engine utilizing CNG as a fuel becomes an equal performer to gasoline and diesel.

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7 References


