EVS27
Barcelona, Spain, November 17–20, 2013

Fuel Efficiency Benefits of Electrified CNG Vehicles

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Abstract

According to Natural Gas Vehicles for America, more than 120,000 vehicles in the United States now run on compressed natural gas (CNG). Around the world, however, there are now more than 8.7 million natural gas vehicles (NGVs)—so the United States has only 1.4% of all CNG vehicles. In addition, vehicle electrification is seen as an effective way to improve vehicle fuel efficiency. This study evaluates the benefits of CNG as compared to gasoline based on state-of-the-art technologies for a wide variety of powertrain configurations, including conventional; start-stop systems; mild hybrids; pre-transmission full hybrid electric vehicles (HEVs); single-mode power-split vehicles; single-mode power-split 10-mi all-electric range (AER) vehicles; and General Motors' Voltec (an extended-range electric vehicle [E-REV]) with a 40-mi AER. State-of-the-art engine maps for both gasoline and CNG generated from the same engine were used for the simulation. First, the impact of switching from gasoline to CNG without any engine resizing is analysed. Next, all of the CNG vehicles, which were sized to meet the same Vehicle Technical Specifications (i.e., performance, grade) as the gasoline vehicles, are compared. The impacts on fuel efficiency of the different fuels are then compared.

Keywords: Modeling, Alternative fuel, control system, ICE (internal combustion engine)

1 Introduction

In 2010, the United States imported about 49% of the petroleum it consumed—two-thirds of which is used to fuel vehicles in the form of gasoline and diesel. With much of the world's petroleum reserves located in politically volatile countries, the United States is vulnerable to supply disruptions. However, because U.S. natural gas reserves are abundant, this alternative fuel can be domestically produced and used to offset the petroleum currently being imported for transportation use.

Natural gas vehicles (NGVs) are similar to gasoline or diesel vehicles with regard to power, acceleration, and cruising speed. The driving range of NGVs is generally less than that of comparable gasoline and diesel vehicles because, with natural gas, less overall energy content can be stored in the same size tank as the more energy-dense gasoline or diesel fuels. Extra natural gas storage tanks or the use of LNG can help increase range for larger vehicles.

The objective of the study is to evaluate the fuel efficiency benefits of electrified CNG vehicles for a wide range of powertrain configurations, including conventional as well as several electric drive vehicles such as start-stop, full HEVs and PHEVs. Autonomie [1], developed by Argonne National Labs, will be used to perform the simulations.

2 Approach

2.1 Powertrain Configurations

For the study, seven different powertrain configurations for midsize vehicles were selected, including the following:

- Conventional
- Conventional with a start-stop system with assist (i.e., a micro hybrid)
- Mild hybrid
- Pre-transmission parallel for hybrid electric vehicles (HEVs)
- Power-split for HEVs
- Power-split for plug-in HEVs (PHEVs) with a 10-mile all electric range (AER)
- Extended-range electric vehicles (E-REVs) with a 40-mile AER

2.2 Engine Comparison

To enable a fair comparison of the gasoline and compressed natural gas (CNG) fuels, two proprietary datasets for gasoline and CNG generated from the same engine have been provided by an original equipment manufacturer (OEM) representing the state-of-the-art technologies. Figure 1 shows the difference in peak power between both fuels. The ratio between the peak power of the CNG and the gasoline is 0.82. It is also of note that the engine reaches its peak power at lower speed when using CNG instead of gasoline.

Most of the difference in peak power levels occurs at “low loads” where the engine is operated most of the time (Figure 1 shows this difference start to become more pronounced by 1,000 rotations per minute [RPM]). At speeds of around *2,000 RPM*, the engine will provide *22.5%* more power when using gasoline than when it uses CNG. Therefore, a loss of performance of the vehicle can be expected when using CNG as fuel. This result occurs in the case of the Honda Civic GX, which uses the same engine technology as its gasoline-powered “sister,” the Honda Civic. The peak power of the GX is *110 HP* compared to *140 HP* for the gasoline-powered Civic.

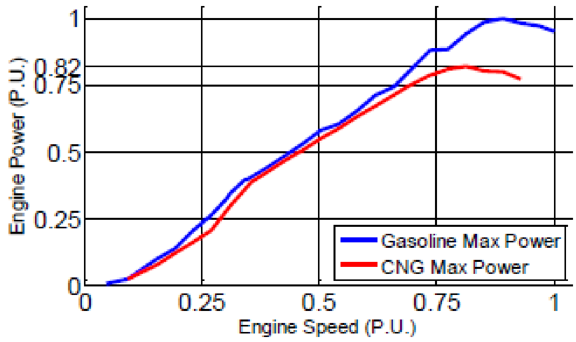

Figure 1. Engine Peak Power Comparison

To provide a fair comparison of the two fuels, two cases will be studied for the fuel efficiency impact, as follows:

- Without any engine resizing (i.e., vehicle performance levels will be different), and
- With CNG engine resizing (i.e., vehicle performance levels will be the same).

2.3 Vehicle Sizing

When resized via simulation, the vehicles are required to meet certain Vehicle Technical Specifications (VTSs). For conventional vehicles, the VTSs are as follows:

- Minimum time for an acceleration is from 0 to 60 mph in 9 seconds;
- Minimum time to execute passing a vehicle (i.e., accelerating from 50 to 80 mph) is 9 seconds; and
- Vehicles are sized to perform a 6% grade at 65 mph at gross vehicle weight.

In addition, for full HEVs,

- Minimum engine peak power is 70% of the maximum between requirements from acceleration and grade performance levels; and
- Regenerative power must be captured on the Urban Dynamometer Driving Schedule (UDDS) cycle.

For PHEVs, additional VTSs include that the vehicle must be able to run the UDDS on electric mode for the PHEV 10 and a US06 (or Supplemental Federal Test Procedure [SFTP]) for the E-REV.

Automated vehicle-sizing algorithms are used to rigorously define the characteristics (i.e., power, energy, weight) of each component of the vehicle to provide consistent results.

All of the vehicles were sized to provide the same range on the combined drive cycle. Because the weight of the CNG tank depends on its capacity, publicly available information was used as an input to the simulation. Figure 2 shows the relationship between values for tank capacity and weight used in the simulation.

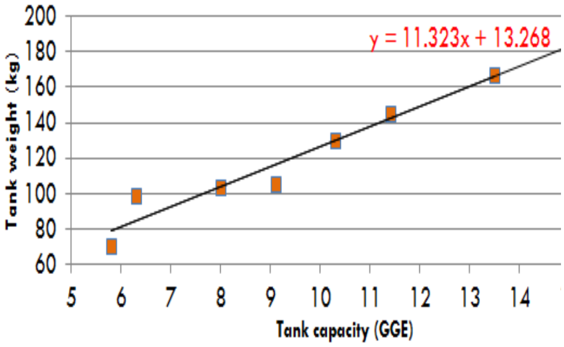

Figure 2. CNG Tank Weight

2.4 Driving Cycles

The UDDS and the Highway Fuel Economy Test (WHFET) driving cycles were used to perform the simulations. All of the results are derived by assuming hot conditions.

3 Simulation Results

3.1 Vehicle Sizing Results

As previously discussed, in addition to assessing the gasoline vehicles (Case 1), two cases for the CNG vehicle have been simulated:

- Without any engine resizing (Case 2), and
- With CNG engine resizing (Case 3).

Figure 3 shows the differences in vehicle test weights between the gasoline vehicle and the CNG vehicles both with (Case 3, shown in red) and without (Case 2, shown in blue) resizing. The addition of CNG tanks leads to an additional weight ranging from 90 to 158 kg.

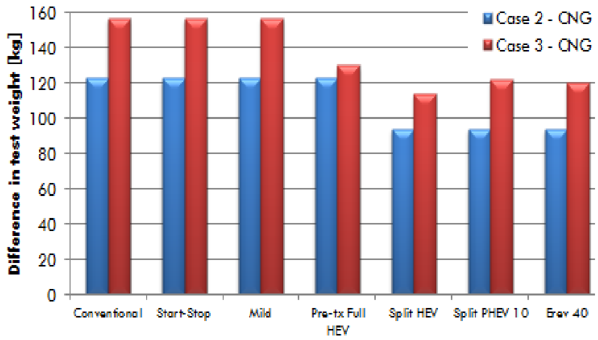

Figure 3. CNG Vehicle Test Weight Difference Compared to Conventional Gasoline (Case 1)

The CNG vehicles are heavier, mainly because of their gas tanks. The differences between the two CNG cases occur mainly because of the engine weight. Indeed, the engine has a lower power density when it uses CNG and therefore will be heavier when it is resized to have the same peak power as the gasoline (Case 3).

When using CNG in the same engine technology as that used in the gasoline vehicle, there will be a loss of power. Figure 4 summarizes the lower levels of power when using CNG.

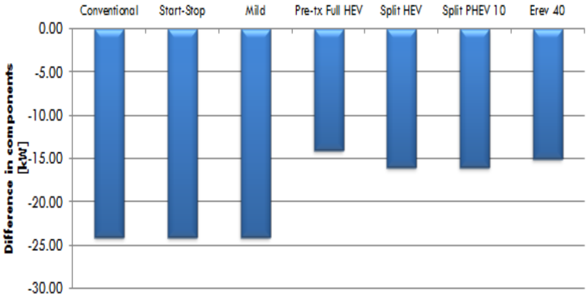

Figure 4. Engine Power Difference to Meet the Same VTS

Without resizing, this extra weight and losses of power will inevitably lead to a loss of performance levels for the unsized CNG vehicles as compared to the gasoline vehicles, as summarized in Figure 5.

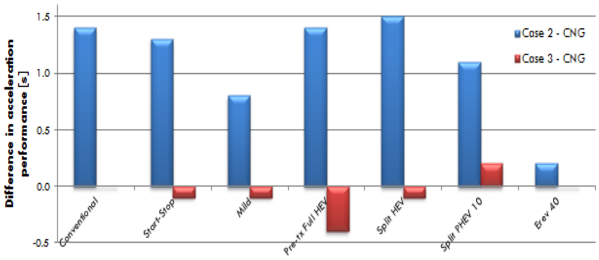

Figure 5. Performances Differences for Case 2 and Case 3 Vehicles compared to Case 1 Vehicles

The vehicles' main characteristics and performance specifications are provided in Appendix A.

3.2 Vehicle Efficiency

Figure 6 and Figure 7 show the values of gasoline-equivalent fuel consumption of the different powertrain configurations under study. Despite the differences in weights of the test vehicles, the gasoline-equivalent fuel consumption of each configuration for each case is comparable, mostly for high degrees of hybridization.

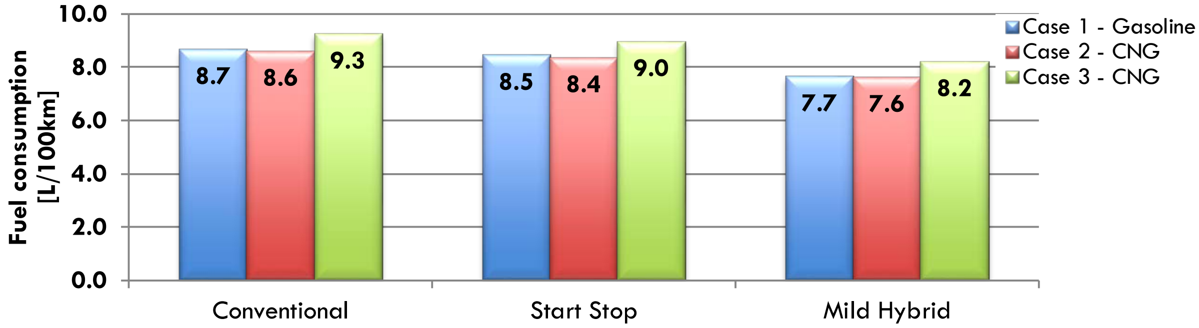

Figure 6. Conventional and Mild HEV

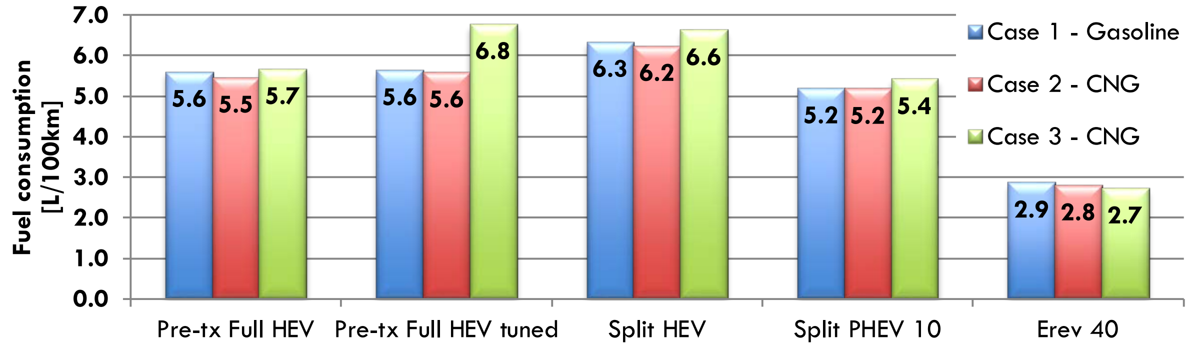

Figure 7. Full HEVs and PHEVs

Figure 8 shows the percentage of gasoline-equivalent fuel savings when using CNG as compared to the gasoline usage of the same configuration. The results show that the resized CNG vehicles will consume more fuel in the range of 1.8% to 6.9% except for the pre-transmission tuned vehicle, which will consume 21.4% more fuel than its gasoline counterparts. The non-resized E-REV will deliver savings of 3.4% as compared to its gasoline counterpart despite not having been sized. This result occurs because of the higher peak efficiency of the engine when it uses CNG. This higher efficiency also benefits the resized E-REV, which will bring almost 7% of savings in fuel usage. Moreover, the sizing revealed that there are not drastic differences between the two engine powers (86 kW for gasoline and 91 kW for the non-resized case).

Further analysis shows that hybridization enables users to operate the engine at higher average efficiency, as shown Figure 9.

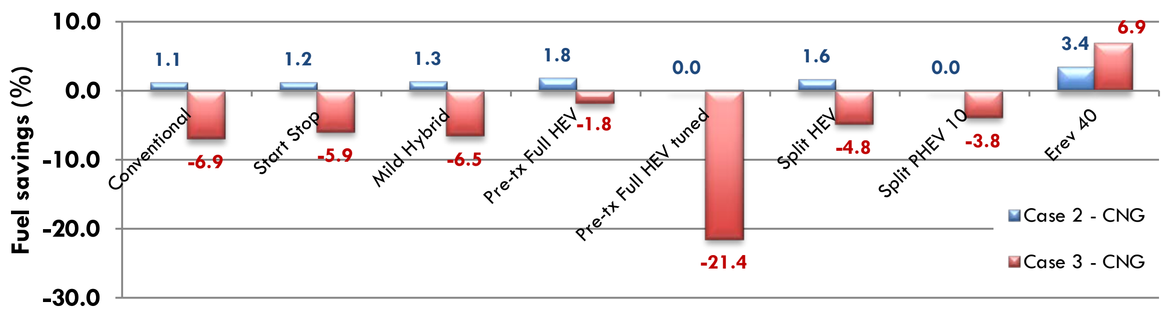

Figure 8. Percentage of CNG Fuel Savings of Gasoline Equivalent Configurations as Compared to the Gasoline Vehicles of the Same Configuration

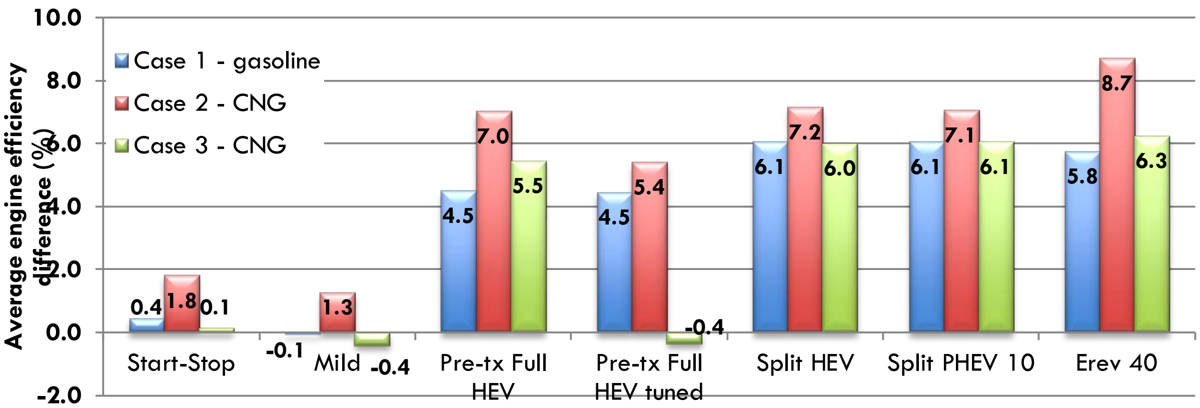

Figure 9. Average Differences in Engine Efficiency Levels (red and green) Compared to Efficiency of Conventional Gasoline Engine (blue)

4 Conclusions

The objectives of the study were to quantify the impacts of using CNG fuel as compared to gasoline on vehicle efficiency for different levels of hybridization. Seven powertrain configurations for midsize vehicles considered, including conventional micro and mild HEV and full HEV, as well as two PHEVs. The vehicles have been defined to represent the potential savings of using CNG in current or near-term technologies. Two proprietary maps of the same engine technology using CNG and gasoline were used to allow a fair comparison.

In addition to the gasoline reference case, two additional options were considered: in one, the CNG engines were not resized to meet the same VTSs as used in the gasoline vehicle; in the other, the vehicles have the same VTSs.

The following conclusions can be drawn from the study based on the methodology and the assumptions considered:

- Hybridization appears to have the potential to lower the fuel consumption penalty of CNG vehicles, especially when the vehicle-level control strategy takes advantage of CNG benefits.
- When the engine is not resized, CNG vehicles show a significant loss in performance (e.g., by taking an additional 0.7 to 1.5 sec for a 0-to-60-mph acceleration); however, fuel economy is only slightly affected (up to a 2% benefit).
- When the CNG engine is resized to meet the same VTSs as the gasoline vehicles, the fuel consumption penalty ranges from 0 to 7%.

Acknowledgments

This work was supported by DOE's Office of Vehicle Technologies. The support of David Anderson is gratefully acknowledged. The submitted manuscript has been created by the UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

Reference

[1] Argonne National Laboratory, "Autonomie," http://www.autonomie.net/. Accessed Jan. 2012.

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Appendix A: Vehicle Characteristics and Performance Specifications

The tables below provide data used for each powertrain configuration in the simulated test for Cases 1, 2, and 3.

Table A1. Case 1 – Vehicles with a Gasoline Engine

Vehicles	Test Weight [kg]	Tank Capa-city [gal]	Engine Power [kW]	Motor 1 Power [kW]	Motor 2 Power [kW]	ESS[a] Power [kW]	ESS Total Energy [kWh]
Conventional	1,538	17	136	–	–	–-	–
Start-Stop	1,553	17	136	5	–	–	–
Mild Hybrid	1,563	17	136	15	–	15	–
Pre-transmission Full HEV[a]	1,558	17	80	40	–	34	1.5
Split HEV	1,602	13	89	67	49	29	1.1
Split PHEV[a] 10	1,645	13	92	68	51	52	3.8
E-REV[a] 40	1,850	13	86	128	86	159	15.2

[a] ESS = Energy Storage System; HEV = hybrid electric vehicle; EREV = extended-range electric vehicle;
HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle.

Table A2. Case 1 – Vehicle Performances for Conventional Gasoline Engine

Vehicles	Acceleration: 0–60mph [sec]	Passing: 50–80mph [sec]	Combined AER[a] [miles]
Conventional	9.1	7.6	–
Start-Stop	8.8	7.1	–
Mild Hybrid	8.3	7	–
Pre-transmission Full HEV	8.7	8.1	–
Split HEV	9.1	7.9	–
Split PHEV 10	8.3	7.3	10.6
E-Rev 40	7.1	7.8	35.9

[a] AER = combined unadjusted all-electric range – combined driving range of the vehicle on EV mode.

Table A3. Case 2 – CNG Vehicles without Engine Sizing

Vehicles	Test Weight [kg]	Tank Capa-city [GGE]	Engine Power [kW]	Motor 1 Power [kW]	Motor 2 Power [kW]	ESS Power [kW]	ESS Total Energy [kWh]
Conventional	1,661	10	112	–	–	–	–
Start-Stop	1,676	10	112	5	–	–	–
Mild Hybrid	1,686	10	112	15	–	15	–
Pre-transmission Full HEV	1,681	10	66	40	–	34	1.5
Split HEV	1,696	8	73	67	49	29	1.1
Split PHEV 10	1,739	8	76	68	51	52	3.8
E-Rev 40	1,944	8	71	128	86	159	15.2

GGE = gallon gas equivalent.

Table A4. Case 2 – Vehicle Technical Specifications (VTSs) for CNG Vehicles without Engine Sizing

Vehicles	Acceleration: 0–60mph [sec]	Passing: 50–80mph [sec]	Combined AER [miles]
Conventional	10.5	9.8	–
Start Stop	10	9.1	–
Mild Hybrid	9.1	8.8	–
Pre-transmission Full HEV	10.1	10.5	–
Split HEV	10.6	10.1	–
Split PHEV 10	9.4	8.7	10.1
E-REV 40	7.3	8.3	34.7

Table A5. Case 3 – Main CNG Vehicle Characteristics with Engine Sizing

Vehicles	Test Weight [kg]	Tank Capa-city [GGE]	Engine Power [kW]	Motor 1 Power [kW]	Motor 2 Power [kW]	ESS Power [kW]	ESS Total Energy [kWh]
Conventional	1,695	10	137	–	–	–	–
Start Stop	1,710	10	137	5	–	–	–
Mild Hybrid	1,720	10	137	15	–	–	–
Pre-transmission Full HEV	1,688	10	86	44	–	38	1.6
Split HEV	1,716	8	94	69	56	31	1.2
Split PHEV 10	1,767	8	97	71	58	56	4
E-REV 40	1,970	8	91	134	91	166	16

Table A6. Case 3 – Vehicle Technical Specifications (VTSs) for CNG Vehicles with Engine Sizing

Vehicles	Acceleration: 0–60mph [sec]	Passing: 50–80mph [sec]	AER [miles]
Conventional	9.1	7.6	–
Start-Stop	8.6	7.2	–
Mild Hybrid	8.2	7.6	–
Pre-transmission Full HEV	8.2	7.1	–
Split HEV	9	7.8	–
Split PHEV 10	8.5	7.4	10.5
E-REV 40	7.1	7.9	36.4