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LETTER

Impact of non-petroleum vehicle fuel economy on GHG mitigation potential

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Abstract

The fuel economy of gasoline vehicles will increase to meet 2025 corporate average fuel economy standards (CAFE). However, dedicated compressed natural gas (CNG) and battery electric vehicles (BEV) already exceed future CAFE fuel economy targets because only 15% of non-petroleum energy use is accounted for when determining compliance. This study aims to inform stakeholders about the potential impact of CAFE on life cycle greenhouse gas (GHG) emissions, should non-petroleum fuel vehicles displace increasingly fuel efficient petroleum vehicles. The well-to-wheel GHG emissions of a set of hypothetical model year 2025 light-duty vehicles are estimated. A reference gasoline vehicle is designed to meet the 2025 fuel economy target within CAFE, and is compared to a set of dedicated CNG vehicles and BEVs with different fuel economy ratings, but all vehicles meet or exceed the fuel economy target due to the policy's dedicated non-petroleum fuel vehicle incentives. Ownership costs and BEV driving ranges are estimated to provide context, as these can influence automaker and consumer decisions. The results show that CNG vehicles that have lower ownership costs than gasoline vehicles and BEVs with long distance driving ranges can exceed the 2025 CAFE fuel economy target. However, this could lead to lower efficiency CNG vehicles and heavier BEVs that have higher well-to-wheel GHG emissions than gasoline vehicles on a per km basis, even if the non-petroleum energy source is less carbon intensive on an energy equivalent basis. These changes could influence the effectiveness of low carbon fuel standards and are not precluded by the light-duty vehicle GHG emissions standards, which regulate tailpipe but not fuel production emissions.

Introduction

The US transportation sector is highly reliant on petroleum fuels such as gasoline [1]. Compressed natural gas (CNG), E85 (85% ethanol, 15% gasoline by nominal volume), and electricity are among the alternatives used [2]. Non-petroleum vehicles can help mitigate petroleum use, but it is important to consider their impact on other sustainability metrics, such as greenhouse gas (GHG) emissions.

The life cycle GHG emissions of alternative vehicle fuels depend on the fuel economy ratings of the vehicles in which they are used. For example, Campbell *et al* [3] compared the use of biomass-derived ethanol and electricity and concluded the latter was favourable in terms of life cycle GHG emissions because of the higher efficiency of battery electric vehicles (BEVs) compared to internal combustion engine vehicles (ICEVs). Luk *et al* [4] and Laser and Lynd [5] subsequently conducted similar analyses but did not reach the same conclusion as Campbell *et al* [3], and both attributed the discrepancies to differences between the vehicles being compared. Among other differences, Luk *et al* [4] increased the fuel economy of ICEVs by assuming they were designed for dedicated ethanol (instead of gasoline) use, while Laser and Lynd [5] reduced the fuel economy of BEVs by analysing batteries large enough (in terms of both energy capacity and mass) to provide driving ranges comparable to ICEVs. Appropriate assumptions will depend on financial and policy considerations, among others, including battery prices and non-petroleum fuel vehicle incentives.

Corporate average fuel economy standards (CAFE), which regulate automaker fleet fuel economy, are increasingly stringent [6]. CAFE also incentivizes (49 US Code 32905–manufacturing incentives for alternative fuel automobiles) the production of non-petroleum fuel vehicles by only accounting for 15% of their energy use when determining compliance [6]. ‘This means that 1 gallon of alternative fuel is treated as 0.15 gallons of fuel, essentially increasing the fuel economy of a vehicle on alternative fuel by a factor of 6.67’ [6]. This incentive can be used by automakers to meet CAFE in lieu of implementing potentially costly fuel efficiency technologies to improve vehicle fuel economy. Anderson and Sallee [7] found that some automakers previously added E85 flex fuel (gasoline with 0%–85% ethanol by nominal volume) capability to their relatively inefficient vehicles to reduce the cost of meeting CAFE. Although CAFE credits for E85 flex fuel vehicles (and other dual fuel vehicles, such as plug-in hybrid electric vehicles) are being reduced to better reflect their actual alternative fuel use (or lack thereof), the credits will remain for dedicated non-petroleum fuel vehicles [6]. The 2015 Honda Civic Natural Gas (NG) vehicle is a dedicated CNG ICEV, which is less fuel efficient than its gasoline counterpart [2]. The CNG vehicle continues to use a less efficient 5-speed automatic transmission, while the gasoline versions have been upgraded to a higher priced (and more efficient) continuously variable transmission [1, 2]. This difference illustrates that CAFE has different fuel economy requirements for petroleum and non-petroleum vehicles, which could affect GHG emissions.

The literature does not examine the impact of dedicated non-petroleum fuel vehicle credits within CAFE on future vehicle life cycle GHG emissions. Cheah and Heywood [8], Knittel [9] and Bandivadikar *et al* [10] excluded dedicated non-petroleum fuel vehicles in their analyses of CAFE. Luk *et al* [11], Curran *et al* [12], Burnham *et al* [13] and Venkatesh *et al* [14] each compared GHG emissions from BEVs and dedicated CNG ICEVs to those of gasoline vehicles but did not account for CAFE.

This study compares the well-to-wheel GHG emissions of a set of hypothetical model year 2025 vehicles. A gasoline ICEV that meets the 2025 fuel economy target within CAFE is used as a reference vehicle. It is compared to a set of dedicated non-petroleum fuel vehicles with different fuel economy ratings, but all vehicles exceed the fuel economy target. Some of the vehicles exceed the target because of the dedicated non-petroleum fuel vehicle incentives within CAFE. Ownership costs and BEV driving ranges are estimated to provide context as these can influence the vehicles automakers choose to produce and consumers choose to purchase. The study results aim to inform stakeholders about the potential impact of CAFE standards on GHG emissions, should non-petroleum fuel vehicles displace increasingly fuel efficient petroleum vehicles.

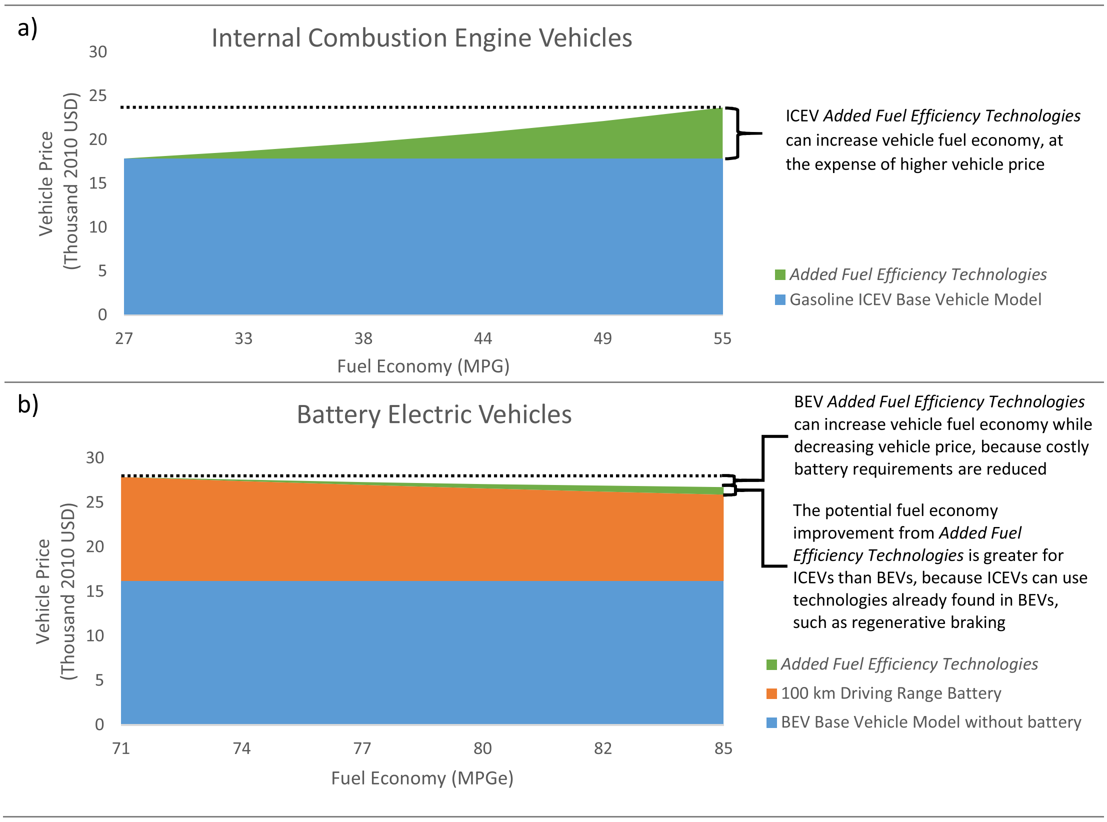
Methods

This study analyses the well-to-wheel GHG emissions of a set of hypothetical model year 2025 petroleum and non-petroleum fuel vehicles that meet or exceed fuel economy targets within CAFE. The non-petroleum fuels in this study are CNG and electricity, which are the only two fuels used by model year 2015 dedicated non-petroleum fuel vehicles available in the US for consumer purchase [2]. Ownership costs (consisting of the vehicle price and the net present value of lifetime fuel and maintenance costs) and BEV driving ranges are estimated for context. Other intangible costs that can influence automaker and consumer decisions, such as range anxiety [15, 16], are beyond the scope of this study. Base case estimates are developed using the assumptions described in the subsections below, and are supported by sensitivity, uncertainty and scenario analyses. All financial data are presented in 2010 USD.

Vehicle models

All vehicles are modelled using complementary software tools developed with industry input. Autonomie [17] is a vehicle simulation model developed by Argonne National Laboratory in conjunction with General Motors to analyse specific vehicle technologies, including the cost, fuel economy and acceleration performance of particular ICEV and BEV designs. The vehicle attribute model [18] is a spreadsheet model developed by General Motors to analyse the relationships among vehicle characteristics, including the incremental cost of fuel economy improvements.

For comparability, each petroleum and non-petroleum vehicle selected for this analysis is based on a common *base vehicle model*—a crossover SUV that represents the fastest growing market segment in the North America. The *base vehicle model* features a powertrain scaled to provide a 0–96 km h^{-1} acceleration time of 9.3 s to match the US Model Year 2013 light-duty vehicle average [19]. The *base vehicle model* has a 4.5 m^2 footprint (wheelbase multiplied by track width) and an associated 2025 CAFE laboratory fuel economy target of 53 mpg [6]. Autonomie [17] is used to develop *base vehicle models* because this level of detail cannot be modelled with the vehicle attribute model [18]. *Base vehicle models* are upgraded with *added fuel efficiency technologies*, as shown in figure 1. The term *added fuel efficiency technologies* is used here to describe the use of technologies (including lightweight



ICEV *Added Fuel Efficiency Technologies* can increase vehicle fuel economy, at the expense of higher vehicle price

BEV *Added Fuel Efficiency Technologies* can increase vehicle fuel economy while decreasing vehicle price, because costly battery requirements are reduced

The potential fuel economy improvement from *Added Fuel Efficiency Technologies* is greater for ICEVs than BEVs, because ICEVs can use technologies already found in BEVs, such as regenerative braking

Figure 1. Relationship between vehicle price and fuel economy for (a) internal combustion engine vehicles and (b) battery electric vehicles.

materials and hybrid electric powertrains, among others) that can be used to improve the fuel economy of the *base vehicle model*. The vehicle attribute model [18] is based on a comprehensive collection of *added fuel efficiency technologies* and is used to estimate the price of fuel economy improvements. The specific technologies themselves are not fully detailed in the vehicle attribute model [18].

The petroleum vehicle in this study is referred to as the *gasoline high-efficiency ICEV*. Autonomie [17] was used to estimate the fuel economy and price of a base vehicle model with a conventional gasoline powertrain. The vehicle attribute model [18] was used to estimate the prices of *added fuel efficiency technologies* required to improve the fuel economy rating to meet the 2025 fuel economy target for a Chevy Equinox-sized vehicle footprint. The high-efficiency ICEV uses both lightweight materials and a hybrid electric powertrain. Note that ICEV is used here to broadly describe vehicles that are propelled by internal combustion engines, as a means to distinguish them from BEVs, which have the unique design considerations illustrated in figure 1.

The non-petroleum fuel vehicles in this study are similar to the gasoline high-efficiency ICEV. Differences include powertrain modifications and other attributes that account for the use of different fuels (e.g., high pressure CNG fuel tank, plug-in battery). The CNG high-, mid- and low-efficiency ICEVs use differing levels of *added fuel efficiency technologies* (based on the vehicle attribute model [18]) although these vehicles exceed the fuel economy target due to non-petroleum vehicle incentives. Therefore, CNG vehicles may, but are not required to, use the *added fuel efficiency technologies* found in the gasoline high-efficiency ICEV. The long-, mid- and short-distance BEVs have different battery sizes, and are all more fuel efficient than the ICEVs. Key vehicle characteristics are compared in table 1 and a detailed discussion is provided in the supplementary information.

Operation and maintenance

Well-to-pump (fuel production) GHG emissions detailed in table 2 are default GREET [20] values for 2025 gasoline, CNG and NG derived electricity. The latter is the fastest growing source of electricity generating capacity in the US [1]. Electricity produced from higher and lower carbon intensity energy sources is also examined because GHG emissions are affected by the location where the BEVs are charged and the source of electricity. Scenario analyses are conducted to illustrate the importance of this source of variability.

Pump-to-wheel (fuel use) carbon dioxide emissions are shown in table 2. Methane emissions depend on vehicle emissions control systems and GREET

Table 1. Model year 2025 vehicle fuel economy performance modelled with Autonomie [17] and vehicle attribute model [20].

Vehicle	Fuel economy	Price	Description
Gasoline high-efficiency ICEV	41 MPGe[a] (5.7 l/100 km)	\$23 000	• Gasoline vehicle upgraded with lightweight glider and hybrid electric powertrain to achieve fuel economy rating[b] that meets 2025 CAFE fuel economy target
CNG high-efficiency ICEV	46 MPGe[a] (0.16 GJ/100 km)	\$26 000	• CNG[c] version of gasoline vehicle upgraded with lightweight glider and hybrid electric powertrain to achieve fuel economy rating[b] that meets 2025 fuel economy target
CNG mid-efficiency ICEV	36 MPGe[a] (0.20 GJ/100 km)	\$23 000	• CNG[c] version of gasoline vehicle upgraded with lightweight glider to achieve fuel economy rating[b] that meets 2020 fuel economy target
CNG low-efficiency ICEV	29 MPGe[a] (0.25 GJ/100 km)	\$22 000	• CNG[c] version of gasoline vehicle with fuel economy rating[b] that meets 2015 fuel economy target
NG short-distance BEV	85 MPGe[a] (23 kW h/100 km)	\$49 000	• BEV with 32 kW h battery that provides 100 km driving range, which is comparable to bestselling Model Year 2014 BEV (130 km Nissan Leaf) [21]
NG mid-distance BEV	78 MPGe[a] (26 kW h/100 km)	\$36 000	• BEV with 98 kW h battery that provides 300 km driving range, which is comparable to near future BEVs planned by major automakers (e.g., 320 km Chevy Bolt) [22]
NG long-distance BEV	70 MPGe[a] (30 kW h/100 km)	\$27 000	• BEV with 170 kW h battery that provides 500 km driving range, which is comparable to gasoline ICEVs (560–820 km) [5]

[a] Estimate of real world (5-cycle) fuel economy presented on a miles per gallon of gasoline energy equivalent (MPGe) basis.

[b] CAFE fuel economy target for vehicle with a Chevy Equinox-like footprint (4.5 m^2) [23] in model year 2025 is 53 MPG but is based on unadjusted laboratory (2-cycle) tests, which produce higher ratings than adjusted real world (5-cycle) estimates [6].

[c] CNG modifications facilitate higher engine compression ratios and thus thermal efficiencies [24].

Notes: CNG = compressed natural gas, NG = natural gas-derived electricity, ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, all prices in 2010 USD.

assumes gasoline vehicles emit 0.006 g CH_4 km^{-1}, while methane emissions from CNG vehicles are ten times higher [20]. Nonetheless, vehicle methane emissions are negligible when compared to well-to-wheel GHG emissions [20].

Operating costs are comprised of fuel and maintenance costs. These costs are based on a 290 000 km lifetime driving distance (GREET default value for SUVs [16]), spread over 17 years (median consumer vehicle age [11]) and discounted at a rate of 8% (vehicle attribute model default value [21]). Table 2 presents 2025 fuel prices sourced from the 2015 Annual Energy Outlook [1]. Fuel prices in later years and maintenance schedules are detailed in the supplementary information.

Sensitivity, uncertainty and scenario analyses

Variables examined in the sensitivity, uncertainty and scenario analyses are selected based on results of studies that evaluated uncertainty in GHG emissions of vehicles using NG-derived fuels/electricity [11–14]. Probability distribution functions for the variables examined are provided in the supplementary information. For example, fuel prices are particularly volatile, and they are based on a discrete uniform distribution of the six forecast scenarios within the 2015 Annual Energy Outlook [1]. The variables are examined individually in the sensitivity analysis and collectively in the uncertainty (Monte Carlo) analysis, the latter conducted using Crystal Ball software and simulating 10 000 trials. A scenario analysis is also conducted to analyse the use of other non-petroleum energy sources (coal, biomass and landfill gas). This is done to distinguish this major source of variability [20] among the many other sources of uncertainty, such as real world fuel economy [11]. Incremental results are presented to capture correlations between vehicles with different attributes.

Results and discussion

This study compares the ownership costs and well-to-wheel GHG emissions of a set of hypothetical model year 2025 vehicles that meet or exceed (in the case of non-petroleum vehicles) CAFE fuel economy targets. Some non-petroleum fuel vehicles may have lower fuel economy performance than the reference *gasoline high-efficiency ICEV*, but exceed CAFE fuel economy

Table 2. Year 2025 GHG emissions from GREET 1 2015 [16] and fuel prices from Annual Energy Outlook 2015 [1].

Fuel	Well-to-pump GHGs	Pump-to-wheel CO_2[a]	Fuel price	Description
Gasoline	17 kg CO_2eq GJ^{-1}	72 kg CO_2 GJ^{-1}	\$24 GJ^{-1} (\$3.00 gge^{-1})	• Emissions based on 90% gasoline (16% oil sands/84% conventional crude) and 10% corn ethanol (9% wet mill/91% dry mill, includes both indirect land use change and biogenic carbon sequestration) by nominal volume • Price based on West Texas Intermediate crude oil spot price of \$87 per barrel
Compressed natural gas (CNG)	18 kg CO_2eq GJ^{-1}	56 kg CO_2 GJ^{-1}	\$16 GJ^{-1}	• Emissions based on US feedstock (58% conventional/42% shale gas, includes methane leakage with 100 year global warming potential of 30) • Price based on natural gas Henry Hub spot price of \$5.60 per mmBtu
Natural gas-derived electricity (NG)	119 kg CO_2eq GJ^{-1}	0 kg CO_2 GJ^{-1}	\$32 GJ^{-1}	• Emissions based on US natural gas facilities (88% combined cycle/12% steam or gas turbine), which is the fastest growing source of electrical generating capacity in the US [1] • Price based on US delivered electricity price of \$0.11 kW^{-1} h^{-1}

[a] Methane emissions are modelled in GREET as function of vehicle driving distance and not as a fuel characteristic.

Notes: gge = gallon gasoline equivalent (lower heating value), all prices in 2010 USD.

targets because of incentives for non-petroleum fuel use. The results show that CNG vehicles that have lower ownership costs than petroleum vehicles and BEVs with long distance driving ranges can exceed 2025 CAFE standard fuel economy targets. However, this could lead to CNG vehicles and BEVs that are less efficient and heavier than the petroleum vehicles, respectively. Thus, these non-petroleum vehicles could have higher well-to-wheel GHG emissions than petroleum vehicles on a per km basis (even if the non-petroleum energy source is less carbon intensive on an energy equivalent basis).

The GHG emissions and ownership cost results are shown in figures 2 and 3, respectively. In each figure, the base case results are presented in part (a), incremental results for each non-petroleum vehicle relative to the reference gasoline high-efficiency ICEV are presented in part (b) to highlight similarities and differences, and finally, Monte Carlo analysis results in the form of cumulative distribution functions are shown in part (c). In the latter, the point at which a curve crosses the y-axis (shown as a vertical line in the middle of the plot) is the probability that a non-petroleum vehicle will have lower GHG emissions or ownership costs than the reference gasoline high-efficiency ICEV.

CAFE could lead to the use of non-petroleum energy sources that are less carbon intensive than petroleum on an energy equivalent basis, but result in higher GHG emissions on a per km basis

Figure 2(a) shows the use of CNG in model year 2025 vehicles can result in higher, similar or lower well-to-wheel GHG emissions than the gasoline high-efficiency ICEV (160 g CO_2eq km^{-1}), depending upon whether CNG is used in the low-, mid-, or high-efficiency ICEV. Although CNG is a less carbon intensive fuel than gasoline on an energy equivalent basis, a low vehicle fuel economy can increase CNG use to the point that well-to-wheel GHG emissions can exceed those for a gasoline vehicle. Figure 2(c) shows the GHG emissions from the CNG high- and mid-efficiency ICEVs are likely to be lower than those of the gasoline high-efficiency ICEV (probability near 100%), while those of the CNG low-efficiency ICEV are very unlikely to be lower than those of the gasoline high-efficiency ICEV (probability near 0%).

The base case estimates of GHG emissions from the NG BEVs (110–130 g km^{-1}) are all lower than those of the gasoline high-efficiency ICEV. However, the long-distance BEV is less likely to be able reduce GHG emissions than BEVs with smaller batteries when uncertainties are taken into account. Whether or

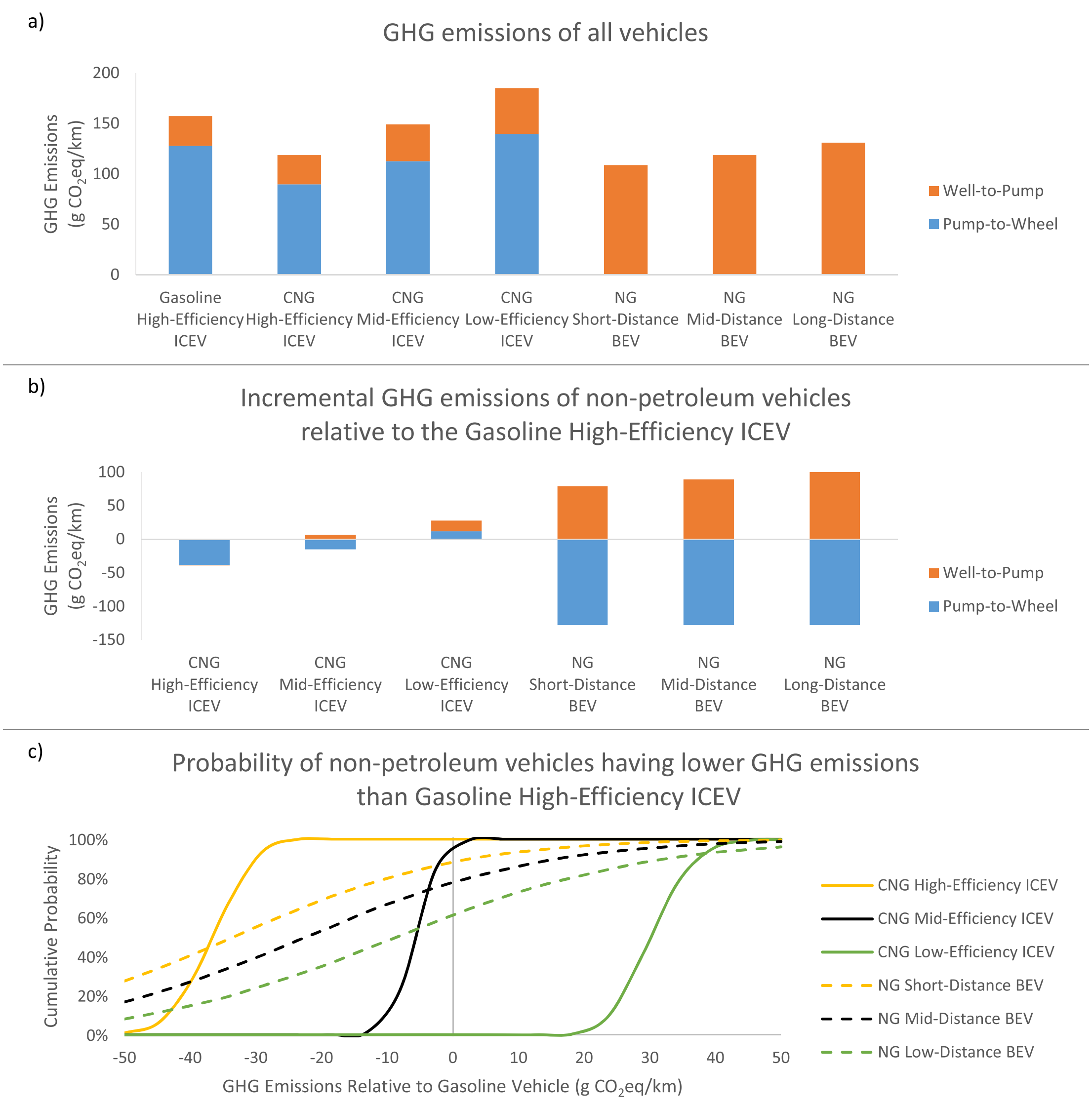


Figure 2. Well-to-wheel (a) GHG emissions of all vehicles, (b) incremental GHG emissions of non-petroleum vehicles relative to the gasoline high-efficiency ICEV, (c) cumulative distribution function of incremental GHG emissions of non-petroleum vehicles relative to the gasoline high-efficiency ICEV. Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas-derived electricity, other sources of electricity are examined using scenario analyses and the results are presented in the supplementary information.

not reductions will occur depends on factors including NG-derived electricity production efficiency (36%–60%). Not shown in figure 2, are sources of electricity other than NG that could significantly change results. As shown in the supplementary information, the exclusive use of coal for electricity production can result in BEVs having higher GHG emissions than the gasoline high-efficiency ICEV, regardless of driving range, whereas the use of renewable energy for the BEV means lower GHG emissions are very likely. However, for electricity grids that rely on NG or a mix of sources, BEVs with larger batteries are less likely than those with smaller batteries to be able to mitigate GHG emissions by displacing gasoline vehicles.

Model year 2025 CNG vehicles can have lower vehicle price and ownership costs than gasoline vehicles that meet CAFE

Figure 3(a) shows the base case ownership costs are approximately $35 000 for each of the three CNG vehicles, which are less than the $36 000 costs of the gasoline high-efficiency ICEV. Figure 3(b) shows that the similarity in CNG vehicle ownership costs is due to a trade-off between CNG vehicle price ($22 000–$26 000) and both fuel ($5000–$8000) and maintenance costs ($5000) because *added fuel efficiency technologies* increase vehicle price while reducing both fuel and maintenance costs (e.g., hybrid electric powertrains require fewer oil and brake pad changes than conventional powertrains). However, CNG

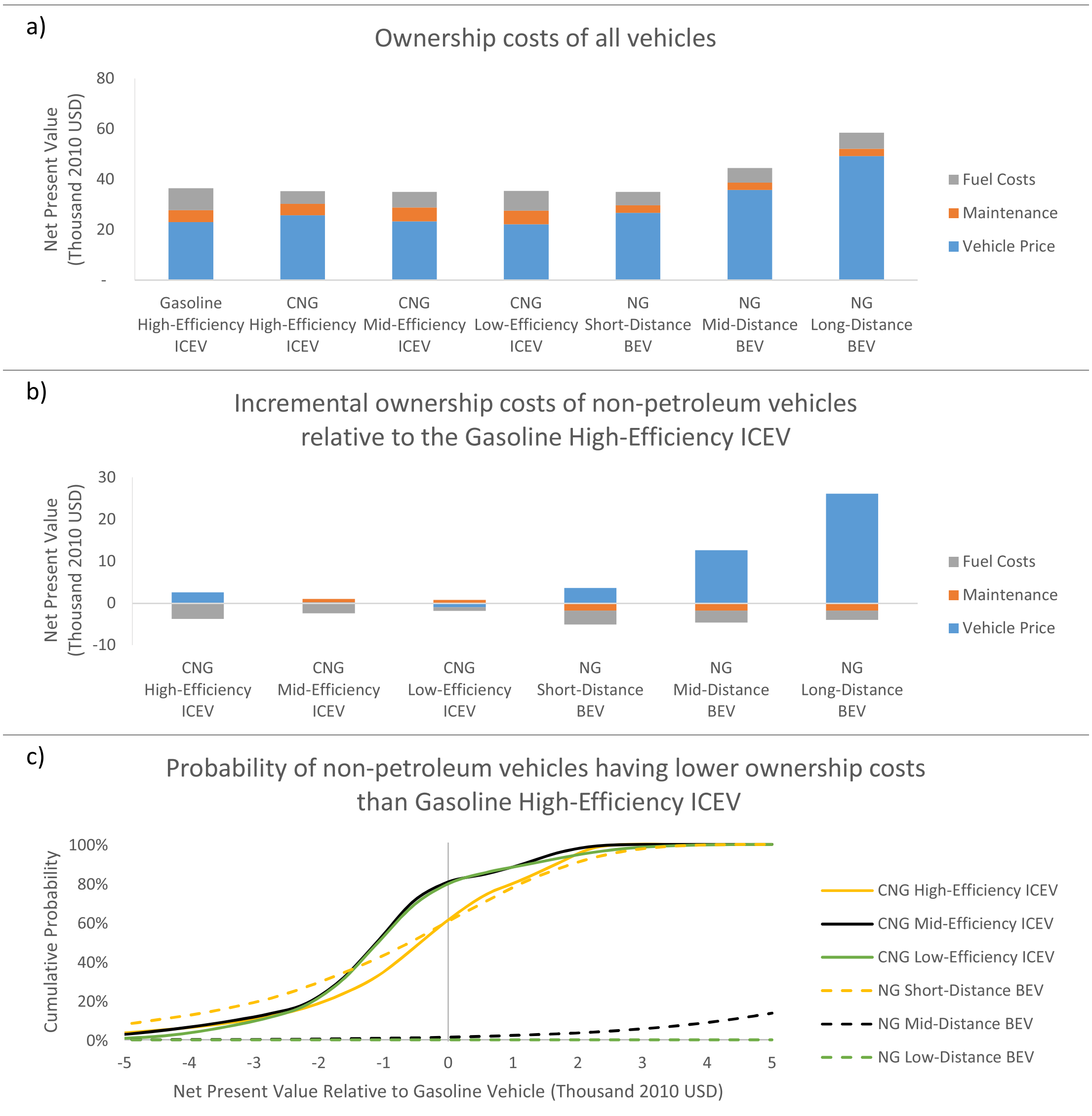


Figure 3. Life cycle (a) ownership costs of all vehicles, (b) incremental ownership costs of non-petroleum vehicles relative to the gasoline high-efficiency ICEV, (c) cumulative distribution function of incremental ownership costs of non-petroleum vehicles relative to the gasoline high-efficiency ICEV. Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas-derived electricity, other sources of electricity are examined with scenario analyses presented in the supplementary information, base case discount rate is 8%.

vehicle ownership costs could be higher than those of the gasoline high-efficiency ICEV if, for example, fuel prices from the Low Oil Price Scenario in the 2015 Annual Energy Outlook [1] are used. The impacts of other variables are examined in the sensitivity analysis in the supplementary information. Among CNG vehicles, the high-efficiency ICEV has the highest vehicle price and is thus most dependent on high oil prices and low NG prices to offset the additional upfront cost. As a result, figure 3(c) shows that when uncertainties are taken into account, among CNG options, CNG use in a high-efficiency ICEV is the least likely (60%) to have lower costs than the gasoline high-efficiency ICEV. Therefore, although automakers could produce (and consumers could subsequently purchase) CNG vehicles that are as fuel efficient as gasoline vehicles that meet the 2025 fuel economy target, there is no clear financial incentive to do so because less fuel efficient CNG vehicles have lower vehicle prices and are more likely to have lower ownership costs.

The above findings provide insights into the rationale behind design decisions made regarding real world CNG vehicles. As noted previously, the CNG version of the model year 2015 Honda Civic is less efficient than gasoline models [2]. This dedicated CNG vehicle does not require fuel economy improvements to meet CAFE and continuing to use older, less efficient technologies means lower vehicle price, and potentially total ownership costs. Thus, there is a financial incentive for consumers to purchase CNG vehicles that are less fuel efficient than gasoline vehicles, and for automakers to produce vehicles to meet this demand.

Decreasing battery costs could result in model year 2025 BEV with short driving ranges having lower ownership costs than gasoline vehicles that meet the CAFE fuel economy target

Figure 3(a) shows that the base case ownership cost for the NGCCe short-distance BEV ($35 000) is less than that of the gasoline high-efficiency ICEV. Figure 3(b) shows that this is because the higher short-distance BEV price is more than offset by savings in fuel and maintenance costs. This is not the case with the mid-, and long-distance BEVs, which have much higher vehicle prices and, therefore, ownership costs ($35 000–$59 000). Vehicle prices are higher for the BEVs with longer driving ranges because they have batteries with a larger energy capacity, increasing vehicle mass and lowering fuel economy. As shown in figure 3(c), it is extremely unlikely (probability near 0%) that the mid- or long-distance BEVs will have lower ownership costs than the gasoline high-efficiency ICEV, even when taking into account uncertainties in fuel, battery and other costs (as illustrated in the supplementary information).

The above findings provide insights into design decisions for real world plug-in electric vehicles. Automakers offer plug-in vehicles with the option of extended driving range, at the expense of lower fuel economy and higher vehicle price. The model year 2015 Tesla Model S is a BEV available with 330 km ($69 900 and 95 MPGe) and 420 km ($79 900 and 89 MPGe) driving ranges [2]. There is also the option of gasoline plug-in hybrid electric powertrains as a means of extending plug-in electric vehicle driving ranges in lieu of larger batteries, though the internal combustion engine system that provides the additional functionality also adds to vehicle mass and reduces fuel economy. The model year 2015 BMW i3 is available as a BEV with an all-electric range of 130 km ($42 400 and 124 MPGe) and as a gasoline plug-in hybrid electric vehicle with a combined gasoline and electric range of 240 km ($46 250 and 117 MPGe when operating on electricity) [2]. Thus, the financial attractiveness of plug-in electric vehicles (both BEV and plug-in hybrid electric vehicles) compared with gasoline vehicles depends in large part on vehicle driving range. The driving range required will depend on the requirements and expectations of individual drivers, including driving patterns and access to charging infrastructure.

The fuel economy of vehicles using different fuels will likely have different rates of change over time

The well-to-wheel GHG emissions of alternative fuel vehicles depend on how vehicle designs respond to increasingly stringent fuel economy targets. The results in figure 3 provide context in the form of vehicle prices, fuel and maintenance costs, which influence the design decisions of automakers and purchase decisions of consumers. The results suggest that, for CNG vehicles, there is a financial incentive to maintain a low vehicle purchase price, which means limiting the incorporation of fuel efficiency technologies needed in gasoline vehicles to meet increasingly stringent fuel economy targets.

There are other factors that will influence the fuel economy ratings of BEVs and gasoline vehicles. Figure 3 shows the detrimental impact of increasing BEV driving range on fuel economy [18]. Additionally, unlike with CNG ICEVs, many powertrain (as opposed to glider) technologies that can improve future gasoline ICEV fuel economy may not be transferable to BEVs; for example, most current gasoline ICEVs could benefit from the addition of regenerative braking, which BEVs already have [1]. This means that between 2015 and 2025, fuel economy improvements in gasoline vehicles will exceeds the maximum potential improvement in BEV fuel economy, as estimated by the vehicle attribute model [18]. During this time period, the Energy Information Administration [1] forecasts that the fuel economy of conventional gasoline vehicles will improve by 44%, while that of BEVs (with a 160 km driving range) will increase by only 4%. Therefore, over time, the fuel economy rating of gasoline vehicles likely approach the high fuel economy already present in BEVs.

Stakeholders should be aware of the real world policy implications of changes to vehicle fuel economy over time

Stakeholders examining alternative vehicles and fuels should be aware of the impact of increasingly stringent fuel economy targets. This may be a particular issue for the evaluation of plug-in electric vehicles, whose fuel economy advantage (on an energy equivalent basis) over gasoline ICEVs will likely decrease over time. Nordelöf *et al* [25] conducted a review of electric vehicle life cycle assessments and found that temporal assumptions were often not stated. Thus, for example, when Kennedy [26] reviewed the scientific literature and proposed that countries should aim to reduce electricity generation emissions to 600 t $CO_2e\ GW^{-1}\ h^{-1}$ or less, so that plug-in electric vehicles could be used to mitigate GHG emissions by displacing gasoline vehicles, there was a lack of temporal context. The vehicle fuel economy forecasts by the Energy Information Administration [1] suggest that the maximum electricity generation emissions needed to ensure vehicle GHG reductions may vary over time. Our results show that even the use of electricity with a carbon intensity of less than the threshold proposed by Kennedy [26] (NG-derived electricity base case GHG emissions of 460 t $CO_2e\ GW^{-1}\ h^{-1}$), could result in higher GHG emissions on a per km basis than a gasoline vehicle designed to meet the 2025 fuel economy target. Findings based on historical or currently available vehicles could quickly become outdated as increasingly fuel efficient gasoline vehicles are produced. This study aims to inform stakeholders about the potential impact of CAFE on the ability for non-petroleum fuel vehicles to mitigate GHG emissions, by displacing increasingly fuel efficient petroleum vehicles.

Changes in vehicle fuel economy could influence the effectiveness of low carbon fuel standards. This type of policy is based on assumptions regarding vehicle fuel economy comparisons to facilitate estimates of life cycle GHG emissions. A discussion of California's low carbon fuel standard [27] is provided in the supplementary information.

The potentially high life cycle GHG emissions from non-petroleum vehicles modelled in this study can arise in spite of US light-duty vehicle GHG emissions standards [28]. This policy was developed in conjunction with CAFE and is thus designed to capture changes to vehicle fuel economy over time. However, tailpipe GHG emissions are regulated and not life cycle GHG emissions. Further discussion of this policy is provided in the supplementary information.

Conclusions

The life cycle GHG emissions of alternative fuels are dependent upon the fuel economy ratings of the vehicles in which they are used. Thus it is important to consider that the relative fuel economy ratings of vehicles can change over time, in part because CAFE include credits for non-petroleum fuel use. The results of this study illustrate how CNG vehicles that have lower ownership costs than petroleum fuel vehicles and BEVs with long distance driving ranges can exceed the 2025 CAFE fuel economy target. However, this could lead to lower efficiency CNG vehicles and heavier BEVs that could have higher well-to-wheel GHG emissions than gasoline vehicles on a per km basis, even if the non-petroleum energy source is less carbon intensive on an energy equivalent basis. These changes could influence the effectiveness of low carbon fuel standards and are not precluded by the light-duty vehicle GHG emissions standards, which do not regulate fuel production emissions. This study aims to inform stakeholders about the potential impact of CAFE on the ability for non-petroleum fuel vehicles to mitigate GHG emissions, by displacing increasingly fuel efficient petroleum vehicles.

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