Supplementary Information for:
Impact of non-petroleum vehicle fuel economy on GHG mitigation potential

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Supplemental Methods

All vehicles in this study are based on a method discussed in the manuscript. Each vehicle includes a base vehicle model developed within Autonomie. All base vehicle models are modified using assumptions from the Vehicle Attribute Model to improve fuel economy and, in the case of compressed natural gas (CNG) vehicles, for CNG use. An overview of this process is illustrated in Figure S1 and discussed below.

Figure S1: Overview of vehicle models

Notes: CAFE = Corporate Average Fuel Economy standards, CNG = compressed natural gas, ICEV = internal combustion engine vehicle, BEV = battery electric vehicle
Base Vehicle Models

Autonomie is used to develop the base vehicle models [1]. This tool simulates vehicle performance (e.g., fuel economy) and estimates manufacturing costs based on detailed component level assumptions (e.g., aerodynamic drag) [1]. The base vehicle models for internal combustion engine vehicles (ICEV) and battery electric vehicles (BEV) are based on Autonomie vehicle templates with gasoline conventional and battery electric powertrains, respectively. Both templates are modified to have a Chevy Equinox-like glider (vehicle without powertrain) [2]. A common glider is selected for comparability and a crossover SUV is chosen to better represent the light-duty vehicle market than a car or truck-based SUV. Different powertrain components (internal combustion engine and electric motor) power ratings are tested for acceleration and fuel economy performance. The component specifications that provide average light-duty vehicle 0-98 km/h acceleration time of 9.3 s [3] are interpolated, along with associated fuel economy ratings presented in Table S1.

Plug-in batteries are a unique aspect of the BEV base vehicle models. Batteries are required to provide sufficient energy and power capacities. Batteries energy capacities are sized (interpolated iteratively alongside the level of added fuel efficiency technologies, as discussed in the following subsection) to provide the targeted 100 km, 300 km and 500 km driving ranges using both high power cells (1041 W and 148 Wh per cell) and high energy cells (800 W and 324 Wh per cell) defined within Autonomie [1]. The lowest price option that can still provide the sufficient power to achieve the 0-98 km/h acceleration time of 9.3 s is selected. The short-distance BEV uses a 32 kWh battery comprised of high power cells. The mid- and long-distance BEVs use 98 kWh and 169 kWh batteries, respectively, comprised of high energy cells.

The price of the base vehicle models are detailed in Table S1, respectively. Prices are based on Autonomie [1] component manufacturing costs. The exception is the price of the charger, which is not included in Autonomie [1] and thus from the Vehicle Attribute Model [4]. A 30% retail price markup to be consistent with the added fuel efficiency technologies, which are discussed in the following subsection [4]. The average of the price ranges are used for the base case results in the manuscript.

Table S1: Fuel economy and price of base vehicle models

| Fuel Economy (2-cycle\(^a\)/5-cycle\(^b\) MPGe\(^c\)) | ICEV      | Short-Distance BEV | Mid-Distance BEV | Long-Distance BEV |
|--------------------------------------------------|-----------|--------------------|------------------|-------------------|
| Price (Low/High Estimate)                        |           |                    |                  |                   |
| Glider                                           | $12000/$1200 | $12000/$1200       | $12000/$1200     | $12000/$1200      |
| Engine/Motor                                     | $2600/$3400 | $1000/$2000        | $1100/$2300      | $1300/$2700       |
| Gearbox                                          | $1500/$2100 | 0/0                | 0/0              | 0/0               |
| Plug-in Battery                                  | 0/0       | $8200/$11500       | $14200/$24100    | $24600/$41800     |
| Charger                                          | 0/0       | $900/$900          | $900/$900        | $900/$900         |
| Other                                            | $1100/$1200 | $2200/$2300        | $2200/$2300      | $2200/$2300       |

\(^a\) unadjusted laboratory rating used for CAFE standard compliance
\(^b\) adjusted rating used for real world fuel consumption and driving range estimate
\(^c\) Miles per gallon gasoline on an energy equivalent basis
Added Fuel Efficiency Technologies

The Vehicle Attribute Model [4] estimates the incremental price of fuel economy improvements based on the aggregation of different fuel efficiency technologies (e.g., lightweight materials and hybrid electric powertrain components) forecasted to be commercially available in future model years. This tool is used to model added fuel efficiency technologies. The price of these incremental fuel economy improvements are added to the base vehicle models. The fuel economy of ICEVs are improved to meet 2015, 2020 and 2025 Corporate Average Fuel Economy (CAFE) standards [5], respectively, for a 4.5 m² Chevy Equinox-like footprint [2], as discussed in the manuscript. The fuel economy of BEVs are improved to the maximum forecasted to be feasible within the Vehicle Attribute Model [4], which was determined iteratively to be a more cost-effective means to provide the driving ranges targeted in this study than further increasing battery capacity. The price of fuel economy improvements are estimated with Equation S1 from the Vehicle Attribute Model [4], which is based on an aggregation of individual technologies from the Energy Information Administration [6]. The incremental fuel economy and vehicle price of added fuel efficiency technologies are shown in Table S2. The average of the price ranges are used for the base case results in the manuscript.

Equation S1: Price of added fuel efficiency technologies

\[ P = \frac{b}{k} (e^{kFE} - e^k) \]

Where:

\( P \)= incremental price [\$]

\( b \)= price parameter [\$], 947 to 2623 for ICEVs and 1.03x10⁻⁶ to 1.27x10⁻³ for battery electric vehicles

\( k \)= price scaling factor [dimensionless], 0.7 to 0.9 for ICEVs and 15 to 18 for battery electric vehicles

\( FE_o \)= Initial fuel economy [MPG]

\( FE \)= Improved fuel economy [MPG], limited by technological options to a maximum of 121% and 20% greater than the initial fuel economy for internal combustion engine and battery electric vehicles, respectively

Table S2: Incremental fuel economy and price from added fuel efficiency technologies

|                       | Low-Efficiency ICEV | Mid-Efficiency ICEV | High-Efficiency ICEV | Short-Distance BEV | Mid-Distance BEV | Long-Distance BEV |
|-----------------------|--------------------|--------------------|----------------------|--------------------|-----------------|-------------------|
| Fuel economy improvement over base vehicle model (Low/High) | 25%                | 54%                | 93%                  | 20%                | 20%             | 20%               |
| Price (Low/High Estimate) | $700/$1500          | $1700/$3500        | $3400/$7000          | $500/$1200         | $500/$1200     | $500/$1200        |

Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle
CNG Modifications

The Vehicle Attribute Model [4] is used to model modifications of gasoline ICEVs modifications for CNG use, which is not possible within Autonomie [1]. Engine modification costs range from $500 to $2000 and result in a thermal efficiency improvement of 14%, but additional fuel tank mass offsets some of this benefit [4]. A stainless steel fuel tank has a fixed cost of $290, a variable cost of $40 per Lge (liter gasoline energy equivalent) and a mass of 4 kg per Lge [4]. A carbon fibre fuel tank has a fixed cost of $320, a variable cost of $40 per Lge (liter gasoline energy equivalent) and a mass of 1 kg per Lge [4]. Fuel economy is reduced by 6% per 10% increase in vehicle mass [4]. Fuel tank size is scaled to provide an average light-duty vehicle driving range of 600 km [4]. The range in price and fuel economy from the modifications are shown in Table S3, with higher fuel economy associated with higher vehicle price. The average of these ranges are used for the base case results in the manuscript.

Table S3: Incremental fuel economy and price from CNG modifications

|                      | Low-Efficiency ICEV | Mid-Efficiency ICEV | High-Efficiency ICEV |
|----------------------|---------------------|---------------------|----------------------|
| Fuel economy improvement over base vehicle model (Low/High) | 6%/12%              | 8%/12%              | 9%/12%              |
| Price (Low/High)     | $2400/$4000         | $2100/$3700         | $1800/$3400         |

Notes: ICEV = internal combustion engine vehicle
CAFE and Light-Duty Vehicle Greenhouse Gas Emissions Standards

The vehicles in this study comply with both CAFE and Light-Duty vehicle Greenhouse Gas Emissions standards [5], as shown in Figure S2. Some vehicles have fuel economy performances that exceed fuel economy targets within CAFE standards, while others require non-petroleum fuel credits for compliance.

The Light-Duty Vehicle Greenhouse Gas Emissions Standards [7] are designed to reduce tailpipe CO2 emissions, while maintaining methane and nitrous oxide emissions, which are already relatively low. Some vehicles have CO2 emissions below CO2 targets within Light-Duty Vehicle Greenhouse Gas Emissions standards, while others require credits for compliance. The EPA [7] expects automakers to receive credits from the use of less GHG intensive air conditioner refrigerants (among other incremental improvements not captured in 2-cycle fuel economy tests).

![Figure S2: Comparison of vehicle fuel economy to CAFE standards and tailpipe CO2 emissions to GHG standards](image)

Notes: CAFE = Corporate Average Fuel Economy standards, CNG = compressed natural gas, ICEV = internal combustion engine vehicle, BEV = battery electric vehicle
Operating Costs

The fuel prices in this study are based on all six forecast scenarios from the 2015 Annual Energy Outlook and are illustrated in Figure S3 [6]. The Reference scenario is used for the base case results.

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**Figure S3**: Fuel price scenarios from the Annual Energy Outlook [6]
Maintenance costs are based on the powertrain-specific expenses and their frequencies itemized in Table S4. The data is primarily based on research from Oak Ridge National Laboratory [8] but with the addition of CNG-specific modifications. Other expected maintenance costs (e.g., tire replacements) not specific to powertrain type, which are estimated to have a lifetime cost of $2600 [8] and are assumed to be applicable to all vehicles in this study.

Table S4: Powertrain-specific maintenance costs from Oak Ridge National Laboratory [8]

|                      | Cost  | Gasoline High-Efficiency ICEV\(^a\) | CNG High-Efficiency ICEV\(^b\) | CNG Mid- and Low-Efficiency ICEV\(^b\) | BEV\(^b\) |
|----------------------|-------|------------------------------------|---------------------------------|----------------------------------------|-----------|
| Motor Oil & Filter Change | $80   | /12,000 km                         | /24,000 km                      | /16,000 km                             | n/a       |
| Air Filter Replacement  | $50   | /50,000 km                         | /50,000 km                      | /50,000 km                             | n/a       |
| Spark Plug Replacement  | $220  | /100,000 km                        | /100,000 km                     | /100,000 km                            | n/a       |
| Timing Chain Adjustment | $350  | /160,000 km                        | /160,000 km                     | /160,000 km                            | n/a       |
| Brake Pad Replacement  | $460  | /160,000 km                        | /160,000 km                     | /80,000 km                             | /160,000 km |
| CNG Tank Inspection\(^e\) | $200  | n/a                               | /60,000 km                      | /60,000 km                             | n/a       |

\(^a\)Maintenance schedule from Oak Ridge National Laboratory for gasoline hybrid electric vehicles [8], which utilizes an electric motor to assist the internal combustion engine and thus has less frequent engine-related maintenance requirements than gasoline conventional vehicles

\(^b\)Maintenance schedule from Oak Ridge National Laboratory for gasoline fuelled conventional vehicles [8], with the exception of oil change frequency being doubled (16,000 km [9] vs 8,000 km) to account for differences in gasoline and CNG fuel properties

\(^c\)Maintenance schedule from Oak Ridge National Laboratory for gasoline hybrid electric vehicle [8], with the exception of oil change frequency being doubled to account for differences in gasoline and CNG fuel properties

\(^d\)Maintenance schedule from Oak Ridge National Laboratory for plug-in hybrid electric vehicle [8], with the exception of internal combustion engine-related maintenance requirements, which battery electric vehicles do not have

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

\(^e\)CNG Tank Inspection cost and frequency are based on discussion [10] and owner’s manual maintenance schedule [9] for the Honda Civic CNG
Crystal Ball

The Monte Carlo analyses were conducted with Crystal Ball software [11]. The input parameters are provided in Table S4. Results are based on simulations of 10,000 trials. The sensitivity of ownership costs and GHG emissions to the Monte Carlo analysis variables are shown in Tables S5 to S8.

Table S5: Monte Carlo and Sensitivity Analyses Assumptions

| Assumption                        | 5th/50th/95th Percentile Assumption | Distribution                                                                 |
|-----------------------------------|--------------------------------------|------------------------------------------------------------------------------|
| Operation                         |                                      |                                                                              |
| ICEV Fuel Economy                 | 80%/100%/120% of base case           | Weibull distribution based on fuel economy from GREET 2015 [12]              |
| BEV Fuel Economy                  | 80%/100%/120% of base case           | Weibull distribution based on fuel economy from GREET 2015 [12]              |
| Lifetime Years                    | 7/17/27 years                        | Discrete distribution based on US statistics from Transportation Energy Data Book [13] |
| Lifetime Vehicle km Travelled     | 90,000/180,000/240,000 miles         | Discrete distribution based on US statistics from Transportation Energy Data Book [13] |
| Discount Rate                     | 4%/8%/20%                            | Discrete distribution based on discount rates from Argonne National Laboratory [14] |
| Fuel Price                        | Not Applicable                       | Discrete uniform distribution based on 2015 Annual Energy Outlook price forecasts scenarios illustrated in Figure S3 [6] |
| Vehicle Design                    |                                      |                                                                              |
| Base Vehicle Model Price          | 16%/50%/84% of difference between high and low price estimates | Triangular distribution on prices from Autonomie [1] |
| Fuel Efficiency Improvement Costs | 16%/50%/84% of difference between high and low price estimates | Triangular distribution based on prices from Vehicle Attribute Model [4] |
| CNG Modification Costs            | 16%/50%/84% of difference between high and low price estimates | Triangular distribution on price range from Vehicle Attribute Model [4] |
| Battery Costs                     | 16%/50%/84% of difference between high and low price estimates | Triangular distribution on prices from Autonomie [1] |
| Fuel Production                   |                                      |                                                                              |
| Gasoline Production GHGs         | 97%/100%/103% of base case           | Normal distribution based on gasoline refining efficiency from GREET 2015 [12] |
| CNG Production GHGs              | 98%/100%/102% of base case           | Triangular distribution based on CNG compression efficiency from GREET 2015 [12] |
| NG Electricity Production GHGs    | 63%/100%/105% of base case           | Triangular distribution based on 0-100% market share of combined cycle electricity generation efficiency from GREET 2015 [12] |

Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle
Sensitivity Analysis

The sensitivity of ownership costs to vehicle price variables are examined in Figure S4. The gasoline and CNG high-efficiency ICEVs utilize added fuel-efficiency technologies to the greatest extent and thus are the vehicles most sensitive to the price of these technologies. The long-distance BEV has the largest batteries and thus its results are most sensitive to battery price.

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**Figure S4: Sensitivity analysis results for vehicle price variables**

*Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas*
The sensitivity of ownership costs and GHG emissions to real world fuel economy are examined in Figure S5. Gasoline high-efficiency ICEV ownership costs are most sensitive to changes in fuel economy because it has the highest fuel costs. CNG low-efficiency ICEV GHG emissions are most sensitive to change in fuel economy because it has the highest base case GHG emissions, which is a results of using the most fuel, on an energy equivalent basis.

![Figure S5: Sensitivity analysis results for real world fuel economy](image)

Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas
The sensitivity of ownership costs to vehicle longevity and discount rate is examined in Figure S6. The gasoline high-efficiency ICEV is most sensitive to these variables because it has the highest fuel, maintenance, and thus operating costs. Note that GHG emissions in this study do not depend on vehicle longevity because they are compared on a per km basis.

**Figure S6: Sensitivity analysis results for vehicle longevity and discount rate**

**Notes:** ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas
The sensitivity of ownership costs and GHG emissions to vehicle longevity and discount rate is examined in Figure S6. The gasoline high-efficiency ICEV is most sensitive to fuel price scenario because of volatile oil prices. NG BEVs are most sensitive to fuel production efficiencies, due to the wide range of efficiencies among natural gas combined cycle facilities.

Figure S7: Sensitivity analysis results for fuel price and production

Notes: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas
Supplemental Results

The Monte Carlo analysis results presented in Figures 3 and 4 as cumulative distribution functions and discussed in the manuscript are presented histograms here in Figure S8. The ownership costs and well-to-wheel GHG emissions from using CNG or natural gas-derived electricity (NG) can be higher or lower than those of the gasoline high-efficiency ICEVs.

**Figure S8:** Histogram of incremental ownership costs and well-to-wheel GHG emissions relative to gasoline use

*Notes:* ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, NG = natural gas
The Monte Carlo analysis results for the alternative scenarios discussed in the manuscript are presented in Figure S9. The GHG emissions from each of the renewable CNG ICEVs and biomass-derived electricity BEVs are lower than those of the gasoline high-efficiency ICEVs. The GHG emissions from each of the coal-derived electricity BEVs are higher than those of the gasoline high-efficiency ICEVs.

**Figure S9**: Histogram and 90% confidence intervals (CI) of incremental well-to-wheel GHG emissions relative to gasoline use for vehicles using renewable compressed natural gas, biomass electricity or coal electricity

**Notes**: ICEV = internal combustion engine vehicle, BEV = battery electric vehicle, CNG = compressed natural gas
Supplemental Discussion

Effectiveness of low carbon fuel standards depends on their ability to capture differences in vehicle fuel economy

The California Low Carbon Fuel Standard (LCFS) attempts to capture differences in fuel economy ratings of vehicles using petroleum and non-petroleum fuels with *energy economy ratios* [15]. These ratios are calculated by dividing the fuel economy of new non-petroleum vehicles by the fuel economy of otherwise similar petroleum vehicles, and are periodically revised [15]. *For example, they compare the average fuel economy of the Nissan Leaf and Chevy Volt to the average fuel economy of the Nissan Versa and Chevy Cruze. These values may not be representative of future vehicles.*

The current California LCFS energy economy ratios are 1.0 and 3.4 for CNG and electricity, respectively [15]. The energy economy ratios in this study, using the base case fuel economy estimates for all vehicles, range from 0.7 to 1.1 for CNG and from 1.7 to 2.1 for electricity. This is because gasoline vehicles require fuel economy improvements to meet 2025 CAFE standards, while dedicated non-petroleum fuel vehicles do not. Additionally, automakers are producing electric vehicles with longer driving ranges and are thus heavier. The results in Figure 2c show that non-petroleum vehicles with lower fuel economy, and thus lower energy economy ratio, are less likely to be able to reduce GHG emissions. In particular, should the CNG energy economy ratio fall to 0.7, CNG may no longer be considered a low carbon fuel (despite having relatively a low carbon intensity on an energy equivalent basis) because CNG use would be unlikely to have lower GHG emissions than the Gasoline High-Efficiency ICEV, on a per km basis (probability near 0%).

The Light-Duty Vehicle Greenhouse Gas Emissions Standards do not regulate life cycle emissions

Current CAFE fuel economy targets were developed alongside the Light-Duty Vehicle Greenhouse Gas Emissions Standards [7], which regulate tailpipe emissions. Although non-petroleum fuel vehicle credits for meeting the GHG Emissions Standards are being phased out, the use of non-petroleum fuel vehicles that result in higher life cycle GHG emissions than gasoline vehicles is still permitted within this policy. CNG is a less carbon intensive fuel than gasoline, which enables CNG vehicles that are less fuel efficient than gasoline vehicles to comply with the same GHG targets. Higher fuel use in the CNG vehicle corresponds to having higher fuel production – and thus higher life cycle – GHG emissions than the gasoline vehicle. This is also an issue for BEVs, which lack tailpipe emissions. However, the GHG standards will incorporate electricity production emissions should plug-in electric vehicle sales surpass thresholds. There is no equivalent provision for CNG vehicles. The Supplementary Information illustrates how the vehicles in this study comply with the GHG Emissions Standards.
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