Fuel Cycle Emissions and Life Cycle Costs of Alternative Fuel Vehicle Policy Options for the City of Houston Municipal Fleet

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Abstract

Municipal fleet vehicle purchase decisions provide a direct opportunity for cities to reduce emissions of greenhouse gases (GHG) and air pollutants. However, cities typically lack comprehensive data on total life cycle impacts of various conventional and alternative fueled vehicles (AFV) considered for fleet purchase. The City of Houston, Texas, has been a leader in incorporating hybrid electric (HEV), plug-in hybrid electric (PHEV), and battery electric (BEV) vehicles into its fleet, but has yet to adopt any natural gas-powered light-duty vehicles. The City is considering additional AFV purchases but lacks systematic analysis of emissions and costs. Using City of Houston data, we calculate total fuel cycle GHG and air pollutant emissions of additional conventional gasoline vehicles, HEVs, PHEVs, BEVs, and compressed natural gas (CNG) vehicles to the City's fleet. Analyses are conducted with the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. Levelized cost per kilometer is calculated for each vehicle option, incorporating initial purchase price minus residual value, plus fuel and maintenance costs. Results show that HEVs can achieve 36% lower GHG emissions with a levelized cost nearly equal to a conventional sedan. BEVs and PHEVs provide further emissions reductions, but at levelized costs 32% and 50% higher than HEVs, respectively. CNG sedans and trucks provide 11% emissions reductions, but at 25% and 63% higher levelized costs, respectively. While the results presented here are specific to conditions

and vehicle options currently faced by one city, the methods deployed here are broadly applicable to informing fleet purchase decisions.

Keywords: fuel cycle emissions, carbon footprint, alternative fuel vehicle, municipal fleet, life cycle costs

1. Introduction

Vehicles are among the leading contributors to air pollutant and greenhouse gas (GHG) emissions, which impact human health and contribute to climate change. The selection of fleet vehicles represents one of the most direct opportunities for local governments in the United States to reduce vehicle emissions, and thus merits consideration as cities like Houston strive to fulfill their pledges to the U.S. Conference of Mayors' Climate Protection Agreement (2014). While the federal government sets vehicle emission standards, cities can choose among vehicles with a wide range of fuel economy or powered by alternative fuels.

Emerging technologies spurred by rising fuel economy standards have yielded several alternative fuel vehicle (AFV) options that could viably be considered for fleet purchases: hybrid electric vehicles (HEV), which use battery technologies to boost the efficiency of a gasoline-fueled vehicle; plug-in hybrid electric vehicles (PHEV), which use a grid electricity-charged battery together with a gasoline engine; battery electric vehicles (BEV), recharged solely by grid electricity; compressed natural gas vehicles (CNGV), which use CNG in an internal combustion engine; and propane or liquefied petroleum gas vehicles (LPGV) (Silva et al., 2009).

AFVs provide benefits such as reduced dependence on imported petroleum and reduced emissions (One Million Electric Vehicles, 2011; Bandivedekar et al., 2008). The Houston-Galveston-Brazoria region fails to meet ozone standards set by the U.S. Environmental

Protection Agency (EPA) to protect human health, and narrowly attains recently tightened standards for fine particulate matter (PM) (Status of SIP Requirements for Designated Areas, Texas Areas by Pollutant, 2016; Texas Recommendation for Area Designation, 2013). Vehicular emissions of nitrogen oxides (NO and NO_2, or NO_x) and volatile organic compounds (VOCs) in the city contribute to this problem by acting as precursors to ozone formation. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions contribute to climate change globally as GHGs.

The City of Houston, Texas, has introduced HEVs, BEVs, and PHEVs into its 10,000+ vehicle municipal fleet as part of its Green Houston efforts, which include a Houston Drives Electric Initiative (2013). According to data provided by fleet manager Jedediah Greenfield (personal communication, August 2016), the City owns over 675 HEVs, 25 BEVs, and 15 PHEVs. The City plans to purchase 45 HEVs and 17 BEVs through the end of the fiscal year in June 2017.

Houston has also recently joined several cities across the United States including Atlanta, Georgia, Indianapolis, Indiana, and San Diego, California, to form the Energy Secure Cities Coalition. This coalition aims to reduce petroleum dependence by transitioning municipal vehicles away from gasoline and diesel, and to share and coordinate information on the transition (Roadmap: Transitioning Municipal Fleets to Alternative Fuel Vehicles, 2016; Energy Secure Cities Coalition, 2016). Likewise, the City has continued its relationship with the U.S. Department of Energy’s Clean Cities program another program aimed at urban sustainability. The City has reduced 128,725 gasoline gallon-equivalents (1 gallon = 3.78 liters) of petroleum use in 2015 (2015 Transportation Technology Deployment Report, 2015). Coupled with this emphasis on reduced petroleum usage comes a relatively abundant supply of North American natural gas, which some cities and corporations have utilized to meet goals of reducing petroleum usage, fuel costs, and emissions (Kahne, 2011; Laughlin and Burnham, 2014;Yang et al., 2013).

Cities weighing fleet options must consider both the environmental and economic implications of those choices. A life cycle or fuel cycle approach allows the most comprehensive and appropriate method for such comparisons (Burnham et al., 2011; Granovskii et al., 2006; Haller et al., 2007; Venkatesh et al., 2011b). Several studies have investigated the costs or environmental impacts associated with AFVs, including some that have investigated their role in municipal government fleets. Gilmore and Lave (2013) looked at total cost of ownership of various AFVs, but did not quantify emissions. Lipman and Delucci (2003) showed life cycle costs associated with HEVs, but not other AFVs. Both Granovskii et al. (2006) and Haller et al. (2007) considered life cycle costs and emissions, but the former did not consider specific cases, and the latter presented results only on VOC emissions, not GHGs or other air pollutants. While Windecker and Ruder (2013) examined costs and GHG emissions of various AFVs in a specific fleet setting, they did not adopt a life cycle approach for costs, nor did they investigate the sensitivity of costs and emissions to factors such as distance driven or electricity mix. Barter et al. (2012) modeled currently available BEV, HEV, PHEV and conventional gasoline vehicle technologies in terms of potential market penetration and subsequent GHG reductions, but did not focus on options for fleets. Luk et al. (2015) compared the GHG impacts and ownership costs of using natural gas in a variety of vehicle technologies including conventional internal combustion, HEVs, and BEVs. Tong et al. (2015) meanwhile examined the GHG consequences of various natural gas pathways for light duty vehicles, including CNG as well as methanol, ethanol, and fuel-cell vehicles. Both recent studies by Luk et al. (2015) and Tong et al. (2015)

though do not look at specific deployment of these vehicles, especially in comparison to commercially available vehicles powered by other fuel pathways. In sum, there are very few studies comprehensively assessing both economic and environmental impacts of vehicle options in a municipal fleet context. Studies of AFV options for fleets are thus necessary to inform cities such as Houston that seek to pursue sustainable transportation planning and municipal fleet management.

Here we use data supplied by the City of Houston to estimate the fuel cycle emissions and life cycle costs associated with gasoline and alternative fuel vehicles in the City's municipal fleet. Vehicle models studied represent models already in the City's fleet or currently available for purchase. A fuel cycle assessment of emissions is conducted to quantify emissions from all stages of the fuel cycle: production, processing, and final combustion. We also compute the life cycle costs of each option, taking into account initial vehicle price, fuel and maintenance costs, and associated infrastructure, offset by vehicle resale values.

2. Methodology (and Data)

2.1 Environmental Methods

2.1.1 Fuel Cycle Assessment Model

Fuel cycle emissions analyses are conducted through the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by Argonne National Laboratory. GREET allows calculations of fuel cycle emissions of gasoline, BEVs, HEVs, PHEVs, CNGVs, and LPGVs with a variety of inputs including U.S. Energy Information Administration (EIA) market projections, renewable and non-renewable electricity mixes, and efficiencies of fuel extraction and processing. The October 2015 release of GREET, the latest available at the time of this analysis, reflects data regarding energy market trends and projections. GREET presents fuel cycle results on a pollutant mass per distance traveled basis. We compute total GHG emissions on a CO_2-equivalent (CO_2e) gram per kilometer basis for each vehicle by using 100-year global warming potentials of 36 and 298 for CH_4 and N_2O, respectively (Myrhe et al., 2013). Fuel cycle emissions were averaged over yearly model runs between 2015 and 2021. The model yields emissions estimates for each vehicle for the three stages of the fuel life cycle: feedstock, fuel, and vehicle operation. Feedstock emissions include emissions at the well or mine as well as emissions from energy used for natural resource extraction. Fuel emissions arise during processing. Both feedstock and fuel emissions values incorporate emissions from transport and distribution of fuel. Vehicle operation includes tailpipe emissions from combustion and evaporative emissions at the vehicle. Previous studies have used earlier versions of GREET to estimate total emissions footprints of various transportation fuels and technologies (Tessum et al., 2014; Luk et al., 2015; Tong et al., 2015). Where available, fuel economy data were obtained from the U.S. Department of Energy's fueleconomy.gov, which provides corrected laboratory-based estimates.

2.1.2 Vehicle Models Analyzed

Vehicle models analyzed (Table 1) span sedans and class 2 trucks (trucks with gross vehicle weight of 6001-10000 pounds, such as Ford F-150). While the sedans analyzed differ in size, weight, and manufacturer, they are an appropriate basis for comparison since all seat five passengers and serve the same purpose of transporting municipal employees.

The Toyota Corolla provides the most attractive combination of initial cost and fuel economy among possible gasoline vehicles considered (i.e., relative to the Honda Civic or the Toyota Camry), and thus is chosen as the conventional vehicle for baseline comparisons for sedans. The Toyota Prius c was chosen as the HEV option for evaluations, since Toyota Prius models form a large portion of HEVs in the City fleet (EV Case Study, 2013). The BEV option is assumed to be the Nissan Leaf, which comprises all BEVs in the current Houston fleet. The only CNGV sedan available at the time of analysis is the CNG Honda Civic.

We consider one PHEV model, a plug-in Prius available directly from the manufacturer (2015 Toyota Prius Plug-in Hatchback, 2015). The City of Houston deployed PHEVs beginning in 2009 via conversion kits developed by Hymotion for use on Toyota Priuses (Fowler, 2009; Francfort et al., 2009). The plus-in Priuses were at first charged infrequently, but are now charged more regularly. A PHEV has the ability to run off both grid electricity and liquid fuel, differentiating it from an HEV, which cannot use grid electricity. This ability to recharge its battery gives the PHEV two distinct operating modes: charge depleting (CD) and charge sustaining (CS). In CD mode, the onboard PHEV battery recharged with grid electricity is depleted to run the vehicle. During this mode, the gasoline or diesel can supplement electricity from the battery depending on driving conditions. CD mode switches to CS mode when the battery reaches a specific state of charge (SOC). The vehicle then runs on liquid fuel to maintain the battery's SOC, much like a HEV (Silva et al., 2009; Francfort et al., 2009). .

To obtain a single overall fuel cycle emissions footprint for PHEVs we calculate a weighted average of footprints from the charged mode and gasoline-only (CS) mode (Bradley and Quinn, 2010; Gonder et al., 2009, Simpson, 2006). Weights for each mode come from City data indicating refueling events of current retrofitted plug-in Prius vehicles. We compute average daily distance traveled from the yearly odometer readings for the City's PHEV's from July 2015 to June 2016, assuming the vehicles are driven five days per week for 50 weeks per year. Assuming one battery recharge per day (Gonder et al., 2009; SAE, 2010; Shirk, 2011) and a CD mode range of 18 km (www.fueleconomy.gov), we estimate that 27% of VKT would be driven in CD mode and 73% in gasoline-only mode. These calculated proportions were similar to those obtained by from City of Houston data on daily odometer readings and exact dates of gasoline refueling for plug-in Prius vehicles from 2012 to 2014.

The CNG and propane Ford F-150 provide alternative fuel forms of the Ford F-150, which the City uses for its pick-up truck needs. Data were not available for the fuel efficiency of the CNG Ford F-150 at the time of this study. We calculated the fuel efficiency for this vehicle from the fuel efficiency of the gasoline Ford F-150 and the ratio between the fuel efficiencies of the CNG Honda Civic and its gasoline counterpart (i.e., 0.97). We assumed the fuel efficiency of the propane F-150 model to be 16 miles per gasoline gallon-equivalent (2015 Transportation Technology Deployment Report, 2015).

2.1.3 Other Considerations

Tailpipe emission rates were taken from the Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool for NO_x (Table 1). This tool, also developed by Argonne National Laboratory, provides emissions factors based on EPA's Motor Vehicle Emissions Simulator (MOVES) along with U.S. Department of Energy methodology. While GREET's default values for NO_x also come from MOVES, they represent weighted averages over a 30-year lifetime (Cai et al., 2013a), far older than the seven-year lifetime of a City fleet vehicle assumed in this study. Furthermore, values from AFLEET account for vehicle deterioration (Burnham, 2013). Tailpipe GHG emissions were computed by GREET, except tailpipe CH_4 emissions which were taken from EPA testing data (Cai et al., 2013a).

For vehicles that utilize grid electricity (electric Leaf and plug-in Prius), charger efficiency was assumed to be 91.1%, based on a weighted average of level one and level two chargers owned by the City. Level two chargers carry more voltage, allowing faster battery recharge (Chae et al., 2011).

Electricity mix was set based on purchases by the City of Houston, which committed to buy 75% of its electricity from renewable sources through June 2016 (City of Houston Increases Renewable Energy Purchase and Receives Sustainability Certification, 2015). Assuming business as usual, we developed a scenario in which the City continues to purchase 75% renewable energy. The remaining electricity was assumed to be from the Electricity Reliability Council of Texas (ERCOT) grid based on a 2015-2021 electricity mixes projected by the U.S. Energy Information Administration (EIA) in its Annual Energy Outlook 2016. The Outlook incorporates the EPA's Clean Power Plan, which aims to reduce GHG emissions from the U.S. power sector, despite the U.S. Supreme Court's recent ruling putting the plan on hold until further review (Annual Energy Outlook , 2016; Clean Power Plan for Existing Power Plants, 2016). On average, EIA projects electricity from the ERCOT grid to come from coal (31.0%), natural gas (44.5%), nuclear energy (11.2%), petroleum (0.1%), renewable (13.1%) and other sources (0.2%). GREET simulations were run in yearly intervals from 2015 to 2021 to capture the effect of changing market and technology shares on final emissions footprints.

2.1.4 Uncertainty in Upstream Emissions

Recognizing the uncertainty in GHG emissions from fossil fuel extraction and processing, especially for natural gas (Allen et al., 2013; Brandt et al., 2014; Caulton et al., 2014; Schwietzke et al., 2014a; Schwietzke et al., 2014b), we quantified the uncertainty associated with our results using an ensemble of emission factors from eGRID (2015), Venkatesh et al. (2011a), Venkatesh et al. (2011b), and Venkatesh et al. (2012). The Venkatesh studies provide best, 5th percentile and 95th percentile estimates for upstream emissions for each fossil fuel, enabling us to construct uncertainty ranges.

2.2 Economic Methods

2.2.1 Formulae

The net present value (NPV) of overall life cycle costs for each municipal vehicle option was computed by the formula:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{1}$$

where n is the lifetime of the vehicle (assumed to be seven years per communication with the City), C_t is the cost incurred in year t, and i is the discount rate (assumed to be 5% in this study). These calculations took into account initial prices and infrastructure costs (e.g. electric vehicle charging station), yearly fuel costs calculated from annual vehicle kilometers traveled (VKT) and fuel prices as well as any salvage value (negative cost in year n) from the resale of the vehicles (Table 2). This approach to calculating NPV as well as the assumed discount rate has been used in a similar form by Gilmore and Lave (2013). Levelized per kilometer costs were computed by first annualizing the calculated NPV values using the formula of Park (2011):

$$A = NPV \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{2}$$

where A is the annualized equivalent cost (\$/year) of an NPV for n years at a discount rate of i. The levelized cost (¢/km) then comes from this annual cost divided by annual VKT (km/year). We computed Equations 1 and 2 using the NPV and PMT functions in Microsoft Excel.

2.2.2 Input Values

We assumed most vehicle prices to be the most recently available (2015 or 2016) manufacturer's suggested retail prices (MSRP) obtained from various sources including manufacturers' webpages and car review websites (Table 2). While the City does maintain salvage values for vehicles sold from its fleet, it has not sold any relatively new AFVs (e.g. electric Leaf). For consistency, resale values (i.e. how much a vehicle depreciates) therefore come from Edmunds.com as of July 2016 using its salvage value calculator for each vehicle model for the Toyota Corolla and gasoline Ford F-150. For the other sedans, salvage value was scaled according to the initial and salvage values of the Toyota Corolla. We assumed identical salvage values for all Ford F-150 models. Vehicles were assumed to be in "clean" condition and sold to a private party.

We utilized yearly fuel prices from the EIA Annual Energy Outlook 2016, which lists price projections in constant 2015 dollars. Annual VKT values (16,866 for sedans and 15,742 for trucks) reflect the average distance traveled by the respective vehicle type in the City of Houston fleet, from 2015-2016 data. Yearly maintenance costs are average annual values (2015-2016) based on available City data.

For infrastructure costs, we assume one charger would be needed per electric vehicle and one CNG or propane refueling station per 30 vehicles added to the fleet. Zero infrastructure costs are assumed for gasoline vehicles, which the City refuels at commercial stations. The City reports a cost of $11,000 per charger based on infrastructure it installed by 2014. The cost of CNG infrastructure is estimated based on costs paid under U.S. Department of Energy grants for refueling stations (Mitchell, 2015). For propane, we assumed a 1000 gallon refueling station and an average of costs provided by Smith and Gonzalez (2014). Alternate assumptions for infrastructure costs are considered in Section 3.2.2.

3. Results and Discussion

3.1 Fuel Cycle Emissions

3.1.1 GHG Emissions

Figure 1 illustrates results from GREET along with uncertainty ranges from the Venkatesh upstream emissions ranges (see section 2.1.4). The gasoline Corolla emits the most GHGs per kilometer at 209 CO_2e g/km. The HEV Hybrid Prius c emits 134 CO_2e g/km, approximately a 36% reduction in emissions compared to the Corolla. Shifting from HEV to PHEV results in lower emissions (109 CO_2e g/km) for the new plug-in Prius. At 28 CO_2e g/km, the electric Leaf shows the lowest overall footprint among vehicles simulated, a reduction of 87% compared to the Corolla. By contrast, the CNG Civic emits more GHGs (185 CO_2e g/km) than the other AFV sedan options. Trucks as expected had significantly higher fuel cycle foot prints than sedans. Substituting CNG for gasoline in the Ford F-150 cuts emissions by approximately 11%. Replacing the gasoline truck with a propane truck reduces emissions by approximately half as a much, at 6%.

Figure 1 also categorizes emissions by fuel cycle stage. As expected, vehicle operation (tailpipe) determines emissions for all except the electric vehicles. Feedstock emissions become large only for CNG, mostly from CH_4 emissions in obtaining natural gas. While the bars in Figure 1 represent GREET baseline estimates, the dots and error bars substitute the best, 5th and 95th percentile estimates for upstream (feedstock and fuel) estimates from the Venkatesh studies.

Moreover, dotted bars for the PHEV and BEV models show the increase in emissions should the City discontinue its renewable electricity purchases post-2015. These values are an average of 2016-2021 GREET runs, where electricity comes from the ERCOT grid. For the plug-in Prius models, the decrease in renewable energy increases overall footprint by 22%. Meanwhile, the electric Leaf would increase GHGs more than three-fold in this situation. We also simulated a second scenario isolating the role of natural gas. For the electricity-powered vehicles, we ran GREET where only natural gas-sourced electricity fueled the vehicles. In this case, emissions from the Leaf would increase by approximately 2.6 times, while emissions from the Plug-In Prius would increase by about 18%.

The Venkatesh uncertainty calculation substitution yields higher estimates for CNG, but only narrow uncertainty for gasoline vehicles, whose emissions are dominated by vehicle operation. Venkatesh best footprint estimates are about 3% higher than GREET estimates for both the CNG Civic and CNG F-150, suggesting the GREET model's continued performance in constraining life cycle natural gas emissions. The substitution raises estimates for the electric Leaf by approximately 53%. While uncertainty in emissions from natural gas (which forms on average 11.2% of the electricity used to power this vehicle), does contribute to this high number, more likely GREET assumes a less polluting grid than the calculations used to derive the uncertainty ranges, which uses emission factors from the ERCOT grid in 2012. The uncertainty ranges for the cases of 100% natural gas electricity as well as the CNG-only vehicles show this more clearly. For hypothetical 100% natural gas case, the center of the uncertainty range sits 30% higher than the estimate from GREET, but center of the uncertainty range for the CNG Civic or CNG F-150 does not sit as highly. Therefore we conclude GREET's assumptions, which assume underlying projections for electricity generation technology in the ERCOT, cause such a large difference between GREET estimates and the best estimates from Venkatesh et al. studies.

Likewise, we calculated the uncertainty in propane emissions by attributing proportion to U.S. propane production derived from natural gas production and petroleum production. This attribution likely introduced the difference seen in GREET's estimates and the center of the uncertainty ranges.

3.1.2 NO_x Emissions

In addition to GHGs, the GREET model calculates fuel cycle emissions of NO_x, SO_2, CO, and VOCs. We focus on NO_x, the leading target of Houston's efforts to attain federal ozone standards (Figure 2). The electric Leaf again has the lowest overall total emissions, and HEVs and PHEVs emit less than gasoline or CNG. Due to increasingly stringent NO_X limits imposed by EPA in recent years, only a small fraction of the sedan emissions come from the tailpipe where it would mostly strongly impact local air quality and exposure. Trucks emit far more NO_x than sedans, due to greater horsepower and lower fuel economy.

3.1.3 PHEV GHG Emissions and Sensitivity Analysis

The new plug-in Prius is more efficient across operating modes, and achieves nearly 80% reduction in emissions by operating in charged mode, assuming the City continues its 75% renewable electricity purchases (Figure 3). Under ERCOT grid electricity, emissions would be nearly equal for each mode. A hypothetical case of a PHEV powered only by ERCOT natural gas-fired electricity would provide a 15% reduction in emissions from gasoline-only operation.

The distance traveled between full battery recharges also inherently affects the average fuel cycle emissions of PHEVs. To investigate the effect of distance traveled on fuel cycle emissions, we plot PHEV emissions savings compared to the gasoline Corolla as a function of distance traveled between battery recharges (Figure 4). The constant portions of each curve represent the emissions savings per kilometer during each PHEV's charged mode. In this mode, the plug-in Prius provides savings of 168 CO_2e g/km. Emissions savings then asymptotically approach emissions savings if the vehicle ran only in gasoline-only mode (75 CO_2e g/km).

3.2 Life Cycle Costs

3.2.1 Levelized Cost

Figure 5 illustrates seven-year life cycle levelized costs for each vehicle model according to four main cost categories: effective vehicle price, associated infrastructure, fuel, and maintenance. Effective vehicle price is the initial vehicle price minus the discounted resale value at the end of the seventh year.

The levelized cost of the hybrid Prius c (27.4 ¢/km) is similar to that for the gasoline Corolla (27.1 ¢/km), as its fuel cost savings nearly balance its higher vehicle price. Note that Table 2 assumes a historically low price of gasoline ($2.06/gallon) and the City’s exclusion from federal fuel taxes. The City is exempt from all federal fuel taxes, but only exempt from state excise taxes on CNG (Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG), 2015; Fuel Tax Credits and Refunds, 2016). Texas does not have excise taxes on propane used in motor vehicles (Liquefied Gas, 2015). Costs are substantially higher for the electric Leaf (36.2 ¢/km), CNG Civic (33.9 ¢/km), and plug-in Prius (41.0 ¢/km). Similarly, the CNG (57.4 ¢/km) and propane (49.2 ¢/km) F-150 cost substantially more than the traditional gasoline F-150 (35.3 ¢/km). However, much of the cost differential results from the infrastructure costs assumed for AFVs, as examined in the following section.

3.2.2 Sensitivity Analyses of Levelized Cost

We consider several sensitivity scenarios to explore how alternate assumptions affect the incremental costs of each AFV relative to its gasoline counterpart (Figure 6). In Figure 6, dots show the cost increment under baseline assumptions, while the bars show results under alternative assumptions for gasoline prices (±50%), electricity prices (±50%), CNG prices (±50%), discount rate (0%-10%), yearly VKT (±50%), and infrastructure costs (-100%).

The scenario of zero infrastructure costs would apply if infrastructure was already available or could be attained via a grant. In that case, the CNG Civic would cost 3.6 ¢/km less than the gasoline Corolla, while the Leaf would cost 2.5 ¢/km less Since electricity and CNG represent only a small fraction of the costs of operating AFVs (Figure 5), the overall cost differentials are relatively insensitive to these costs (Figure 6). Results are somewhat more sensitive to gasoline prices, since fuel constitutes a larger share of costs for conventional sedans and trucks. For the comparison between the gasoline and propane F-150, sensitivities to propane and gasoline prices are similar, due to the similar fuel costs and fuel economies for these vehicles. Meanwhile, higher VKTs favor AFVs due to fuel savings of electricity or CNG relative to gasoline (Figure 6).

3.3 Discussion

Our results show the emissions and cost impacts that can be expected for various AFV purchases that the City of Houston could consider for its municipal fleet. The HEV Prius c achieves a 36% GHG reduction but a slightly higher cost relative to a conventional gasoline Corolla. Greater emissions savings can be achieved by the BEV Leaf and new PHEV Prius, but at substantially higher costs. The plug-in Prius provides the greater versatility of gasoline operation when needed, while the more conventional hybrid Prius c offers partial emissions savings at far lower cost than the BEV or PHEV. Both PHEVs and BEVs have sufficient range to operate in electric mode for short daily distances (134 km for the BEV, and 18 km range in electric mode for the PHEV), but the PHEVs offer extended range in gasoline mode when needed. Since the fully electric Leaf offers more emissions savings yet similar costs to the new plug-in Prius, it may be the better choice for applications where fully electric operation is practical. However, the environmental benefits of both of these plug-in options depend on the City continuing its purchases of renewable electricity. Under ERCOT grid electricity, emissions savings would narrow and would be similar to those of the Prius c hybrid.

The CNG Civic yields far less emissions savings than any of the other AFV sedans. The CNG F-150 is similar to the CNG Civic in the percentage emission reduction it achieves relative to its gasoline counterpart. However, the emission savings from CNG vehicles depend on assumptions of methane emissions from natural gas. The version of GREET used here reflects fugitive methane emissions estimates by EPA in 2013 (Burnham et al., 2013). Some other studies indicate higher levels of methane leaks from local distribution (Brandt et al., 2014; Jackson et al., 2014; Phillips et al., 2013) or upstream production of natural gas (e.g., Petron et al., 2012; Turner et al., 2015). As shown by Cohan and Sengupta (2016), the differences in fuel cycle emissions of gasoline and CNG vehicles are within the uncertainty ranges of methane leaks.

4. Conclusion and Policy Implications

This study analyzed the total fuel cycle emissions (carbon footprints in grams greenhouse gases per km traveled) and levelized cost (U.S. dollars per km traveled) impacts of alternative fuel vehicle (AFV) options for the City of Houston fleet through comparisons to conventional, gasoline-powered sedans and trucks. All the AFV options achieve greenhouse gas (GHG) savings relative to conventional vehicles. Among sedans, battery-electric vehicles (BEV) running solely on electricity followed by plug-in hybrid vehicles (PHEV), running on grid electricity as well as gasoline, achieve the most emissions reductions. Hybrid electric vehicles (HEV), which run on gasoline and electricity generated onboard, as well as compressed natural gas vehicles (CNG), achieve the third and fourth greatest emissions reductions, respectively. The emission savings of the plug-in vehicles depend on the City continuing its purchases of ~75% renewable electricity. Among trucks, CNG trucks emitted less than propane-powered trucks, when compared to a conventional gasoline truck.

Levelized cost analysis shows AFVs to have higher costs than conventional gasoline fleet vehicles. However, most of the difference arises from infrastructure costs. Without these costs, electric vehicles would be comparable in cost to gasoline sedans, and CNG sedans would achieve cost savings. Thus, policies or grants that facilitate development of electric charging or CNG refueling infrastructure could be crucial to municipal fleet decisions. This is especially true since upfront costs can be a substantial barrier to adoption of alternative technologies.

For natural gas, an important policy consideration is whether deployment of CNG vehicles adds to overall natural gas consumption or shifts it from other sectors. A shift could occur either directly, if natural gas supplies are limited (an unlikely scenario in the short term, given the abundance of shale gas in the U.S.), or indirectly if greater CNG use raises the cost of natural gas to other users such as power plants. Cohan and Sengupta (2016) showed that using natural gas to replace coal-fired electricity or heating oil furnaces each achieves far more emissions reductions than CNG vehicles. Thus, even a small amount of displacement from these uses would negate any emissions benefits of CNG vehicles.

An important caveat to note is that the decisions taken by the City may have little effect at the margin on total nationwide fleet GHG emissions. Jenn et al. (2016) showed that given the way Corporate Average Fuel Economy (CAFE) regulations provide favorable accounting for automobile manufacturers to sell AFVs, increased AFV adoption can allow other vehicles to emit more GHGs. Nonetheless, AFVs provide the City an avenue to lessen impacts on local air quality.

The fuel prices and vehicle operation conditions assumed here are specific to the City of Houston municipal fleet. However, the methods used here could readily be extended to other vehicle options and input assumptions. Such analyses can help fleet managers make informed decisions about the purchase and deployment of vehicle options for optimizing environmental and economic outcomes.

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***Highlights (for review)**

- Costs and emissions compared for alternative fuel vehicles
- Application to City of Houston municipal fleet using broadly applicable methods
- Hybrid electric vehicles cut greenhouse gases by 36% and reduce costs
- Battery electric and plug-in hybrid vehicles minimize emissions but increase costs
- Compressed natural gas vehicles yield little emissions benefits

Table 1

Table 1. Vehicle models simulated with the GREET model grouped by vehicle class: sedans (top) and trucks (bottom). All information from manufacturers' webpages unless otherwise noted.

Make/Model	Year	Fuel	Fuel Economy[a]	Curb Weight[b] (lb)	Tailpipe NO_x Emissions[c] (g/km)
Toyota Corolla	2015	Gasoline	32 mpg	2,855	0.056
Toyota Prius c	2015	Gasoline (HEV)	50 mpg	2,500	0.045
Toyota Prius Plug-In	2015	Gasoline/Electricity (PHEV)	95 mpge[c] (Electricity) 50 mpg (Gasoline)	3,194	0.000 (Electricity) 0.045 (Gasoline)
Nissan Leaf	2015	Electricity	114 mpge	3,243	0.000
Honda Civic	2015	CNG	31 mpge	2,754	0.056

Make/Model	Year	Fuel	Fuel Economy[a]	Curb Weight[d] (lb)	Tailpipe NO_x Emissions[c] (g/km)
Ford F-150	2016	Gasoline	16 mpg	4,051	0.060
Ford F-150	2016	CNG^	15.5[#] mpge	4,051	0.060
Ford F-150	2016	Propane^	16* mpge	4,051	0.060

[a] Adjusted laboratory value from fueleconomy.gov unless otherwise noted; mpg: miles per gallon, mpge: miles per gallon equivalent. 1 mile = 1.6 km; 1 gallon = 3.78 L

[b] From Edmunds.com (accessed July 2016) unless otherwise noted. Curb weight defined by EPA Glossary (2013) as vehicle weight with fuel and equipment, but without passengers. 2.2 lb = 1 kg

[c] From AFLEET (2016) developed by Argonne National Laboratory

[d] From Ford Specifications (2016) accessed July 2016, assuming negligible weight of alternative fuel tank and two-wheel drive

*Based on City of Houston information submitted to U.S. Department of Energy Clean Cities Coalition. See 2015 Transportation Technology Deployment Report.

^CNG and propane vehicles come with option as gasoline bi-fuel vehicle. Assuming fuels cannot be used simultaneously, footprints of bi-fuel vehicles will average of footprints of single-fuel vehicles. See Priddle (2015), Edelstein (2015), Ford F-150 (2015), 2016 Ford CNG F-150 5.0L. (2015). First Compressed Natural Gas and Propane-Capable 2016 Ford F-150 rolls off the line at Kansas City (2015).

[#] Scaled value using fuel economies of gasoline and CNG Honda Civic models

Table 2

Table 2. Manufacturers' suggested retail prices (MSRP), infrastructure costs, and annual vehicle miles traveled (VMT) for each vehicle model.

Vehicle	MSRP[a]	Infrastructure Costs	Resale Value[c]	Maintenance Costs[d]	Annual VMT	Fuel Prices ($/GGE)[l]
Gasoline Corolla	$19,865	-	$9,044	$1,609	16,866	2.06
Electric Leaf	$32,000	$11,000[b]	$14,569	$216	16,866	2.95
Hybrid Prius c	$21,838	-	$9,942	$1,670	16,866	2.06
New Plug-in Prius	$31,194	$11,000[b]	$14,202	$1,002	16,866	2.95/2.06
CNG Civic	$20,110	$10,128 [g]	$9,156	$1,132	16,866	1.51
Gasoline F-150	$28,135[m]	-	$16,299	$1,953	15,742	2.06
CNG F-150	$36,200[i]	$11,105[g]	$16,299	$1,953	15,742	1.51
Propane F-150	$36,200[i]	$1,750[j]	$16,299	$1,953	15,742	1.96

[a] From Edmunds.com (accessed July 2016) unless otherwise noted.

[b] From City of Houston data assuming one charger per vehicle purchased

[c] From Kelley Blue Book (2014) accessed July 2014; for sedans all other resale values are scaled to resale value of Toyota Corolla

[d] Average maintenance costs per vehicle from City of Houston data and Edmunds.com (accessed July 2014).

[e] Includes base 2009 MSRP and retrofit costs. From 2009 Toyota Prius (2014) and Fowler (2009).

[f] Assumed same as 2009 Prius without PHEV conversion

[g] Based on model presented in Mitchel (2015) and based on purchase of 30 vehicles

[h] Assumed to be same as 2013 model

[i] Includes base 2016 MSRP of gasoline F-150 and retrofit costs. See Priddle (2015).

[j] From Smith and Gonzales (2014) and based on purchase of 30 vehicles

[k] Assumed same as gasoline F-150

[l] Gasoline gallon-equivalent 1 gallon = 3.78 L. From EIA Annual Energy Outlook 2016. Average of sales-weighted average prices for 2015-2021 for the region including Texas, minus federal and state excise taxes where applicable.

[m] From Ford.com build your own tool

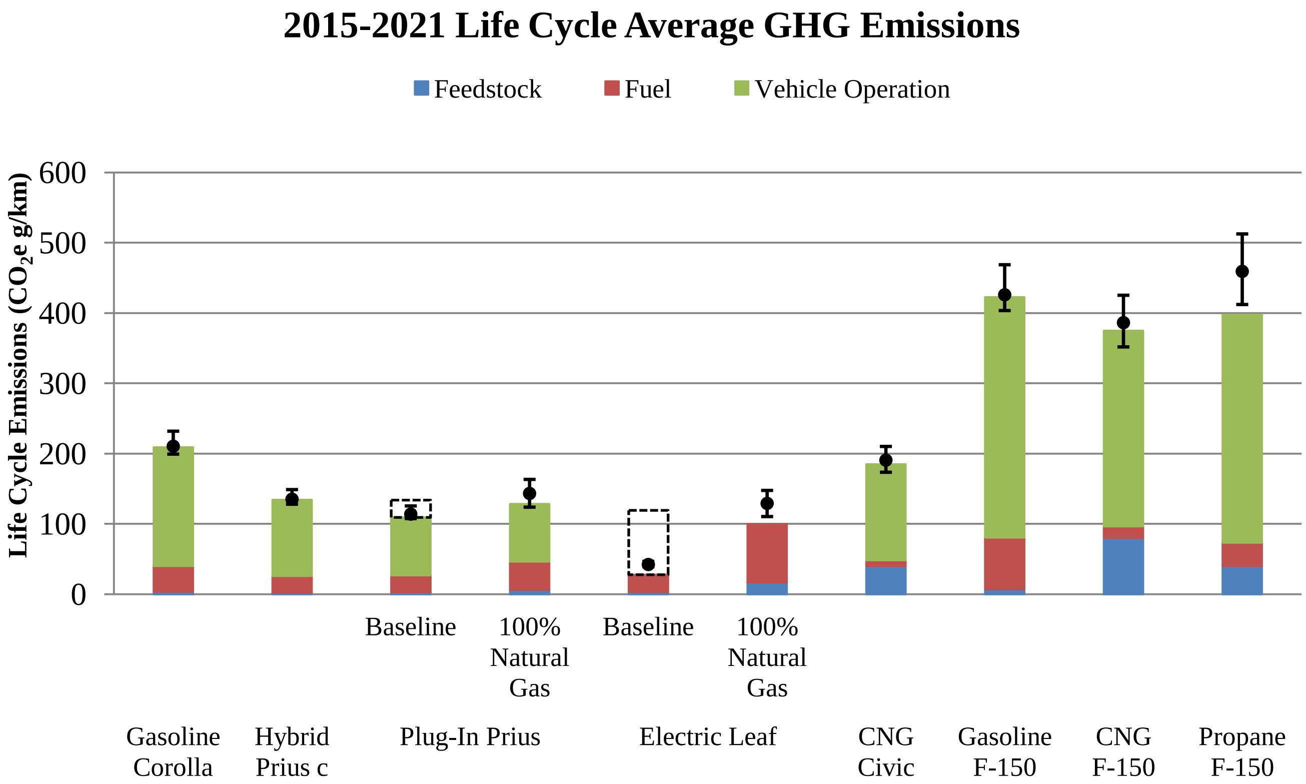


Figure 1. Fuel cycle CO_2e emissions estimates from GREET (solid bars) with best, 5th percentile, and 95th percentile upstream emissions from the Venkatesh studies (error bars and dot). Dashed bars show emissions under ERCOT grid electricity.

Figure 1 B&W

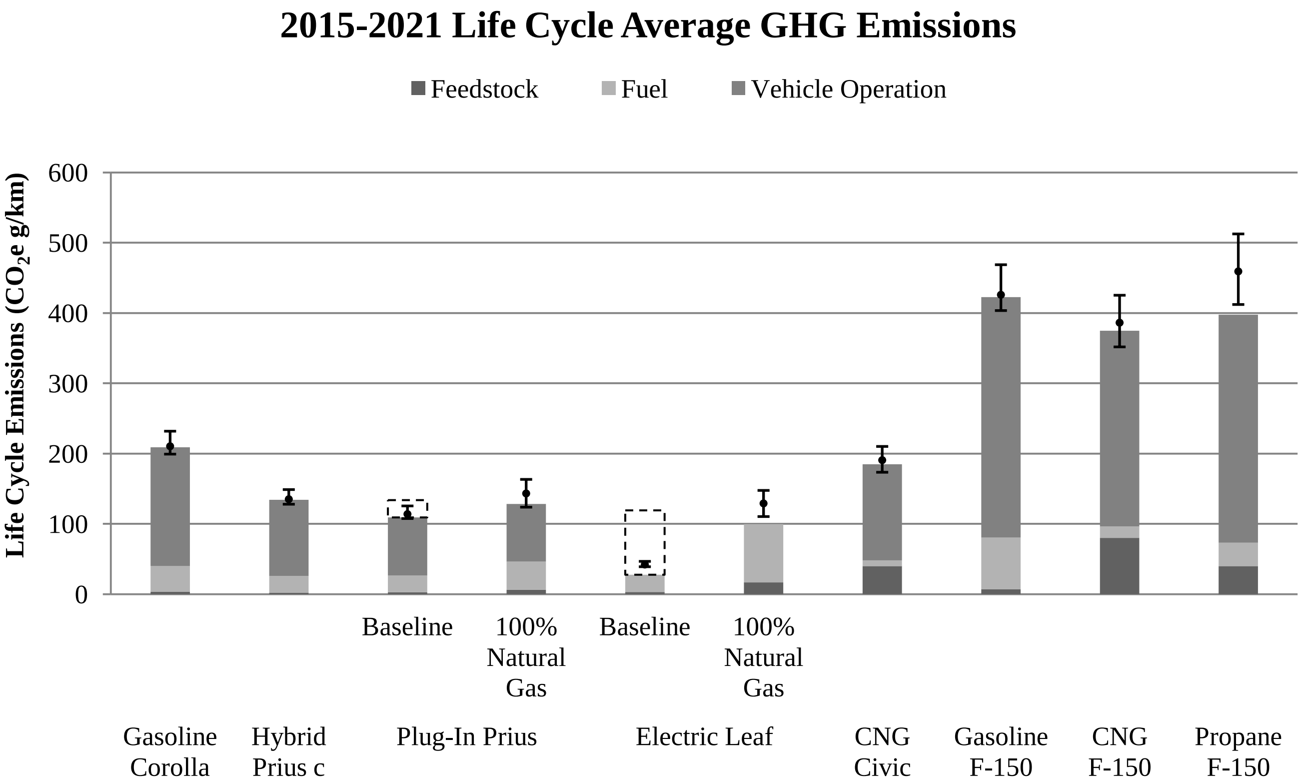


Figure 1. Fuel cycle CO_2e emissions estimates from GREET (solid bars) with best, 5th percentile, and 95th percentile upstream emissions from the Venkatesh studies (error bars and dot). Dashed bars show emissions under ERCOT grid electricity.

Figure 2

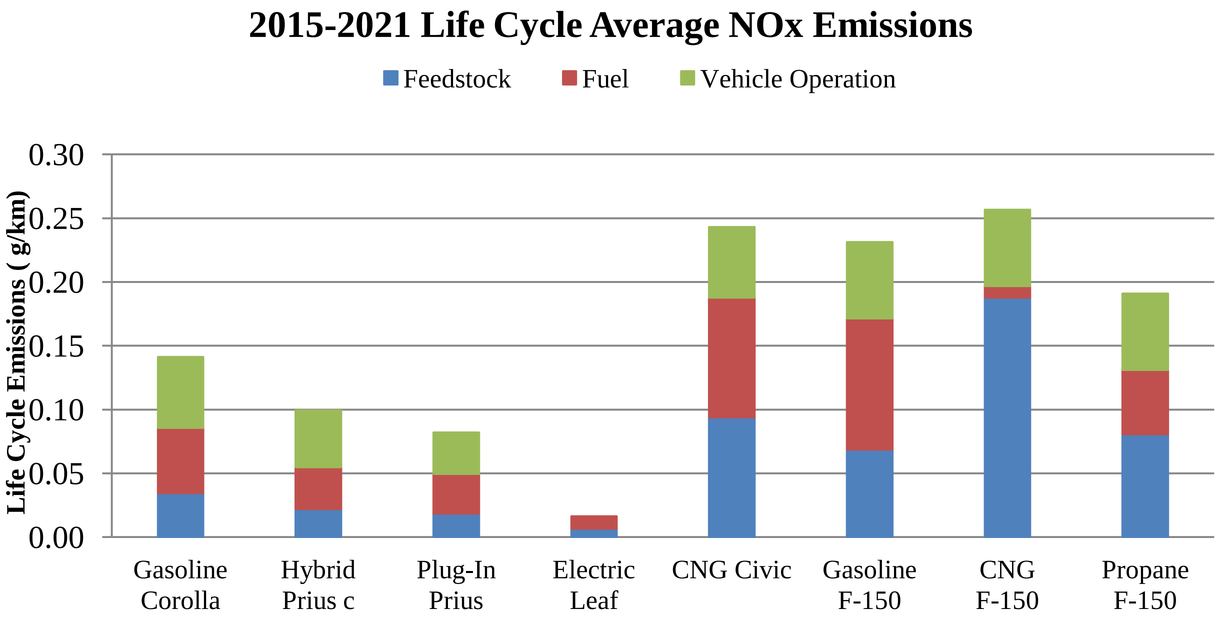


Figure 2. Fuel cycle average NOx emissions.

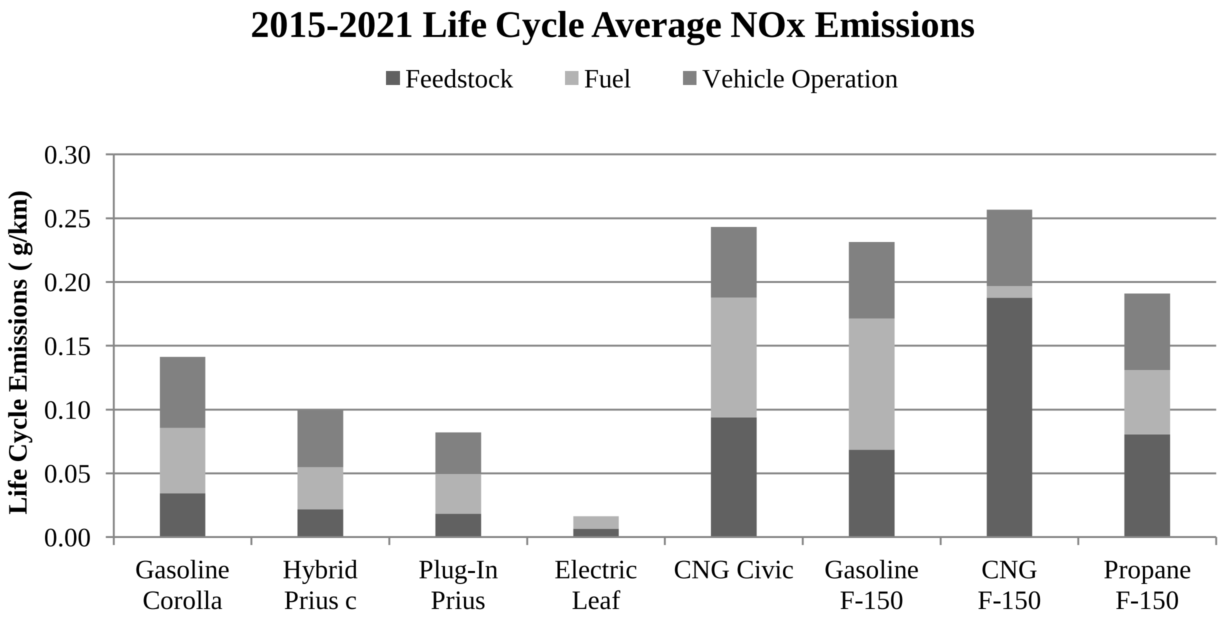


Figure 2. Fuel cycle average NOx emissions.

Figure 3

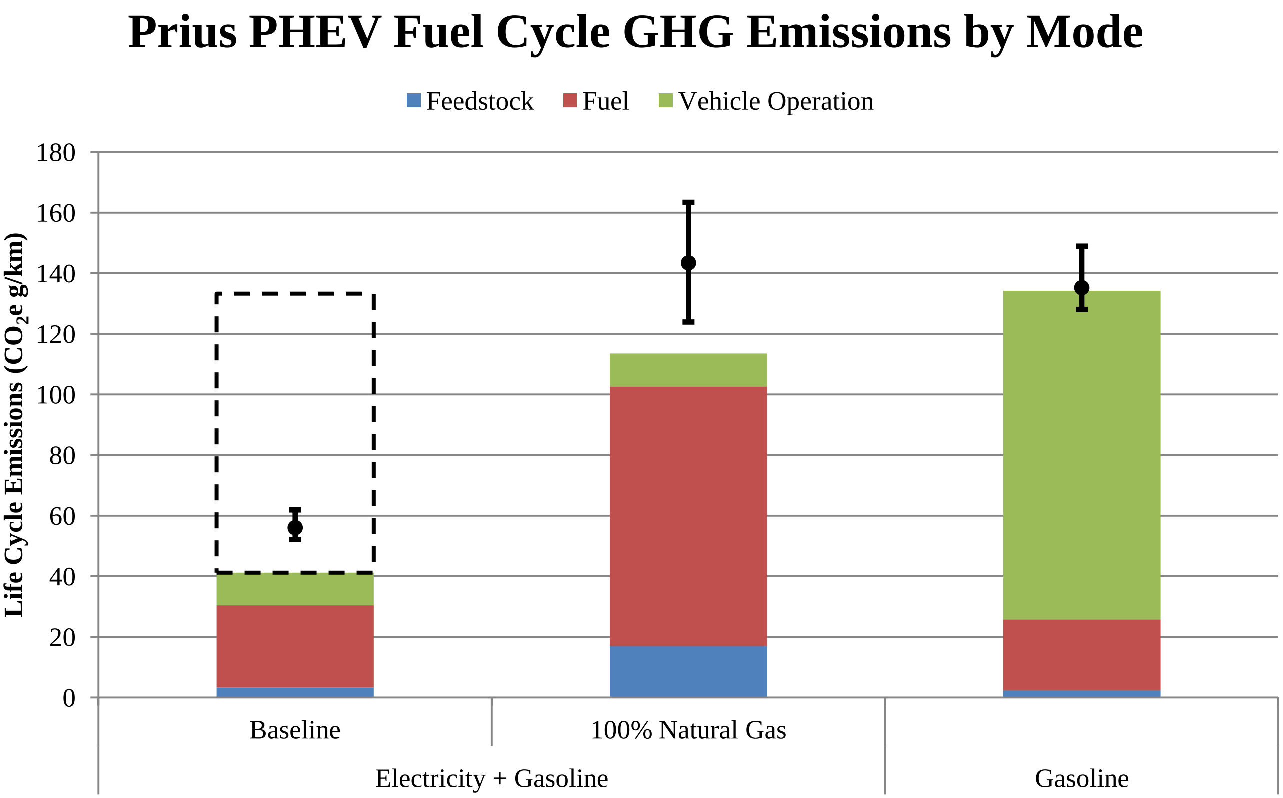


Figure 3. Fuel cycle emissions of the PHEVs by operating mode. Solid bars show GREET results with best, 5th percentile, and 95th percentile upstream emissions from the Venkatesh studies. Dashed bar shows grid electricity if City discontinues its 75% renewables commitment

Figure 3 B&W

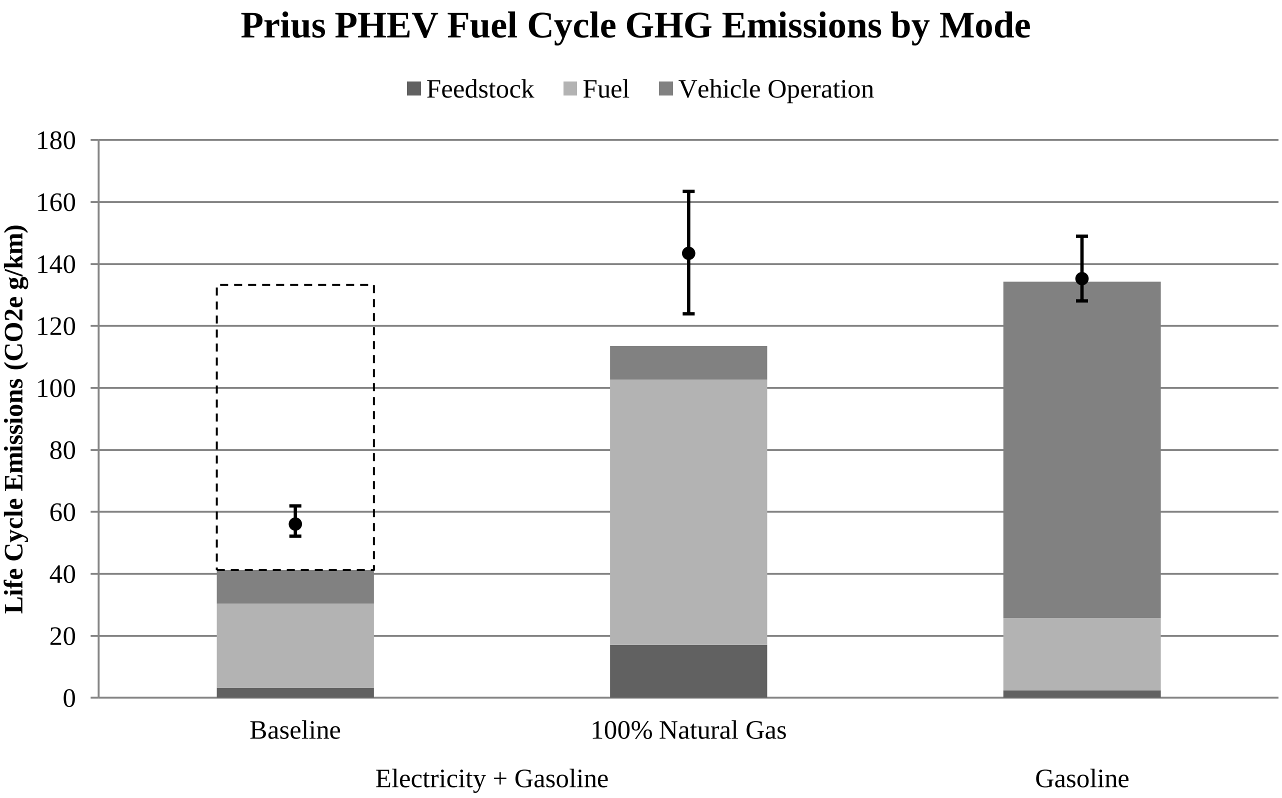


Figure 3. Fuel cycle emissions of the PHEVs by operating mode. Solid bars show GREET results with best, 5th percentile, and 95th percentile upstream emissions from the Venkatesh studies. Dashed bar shows grid electricity if City discontinues its 75% renewables commitment

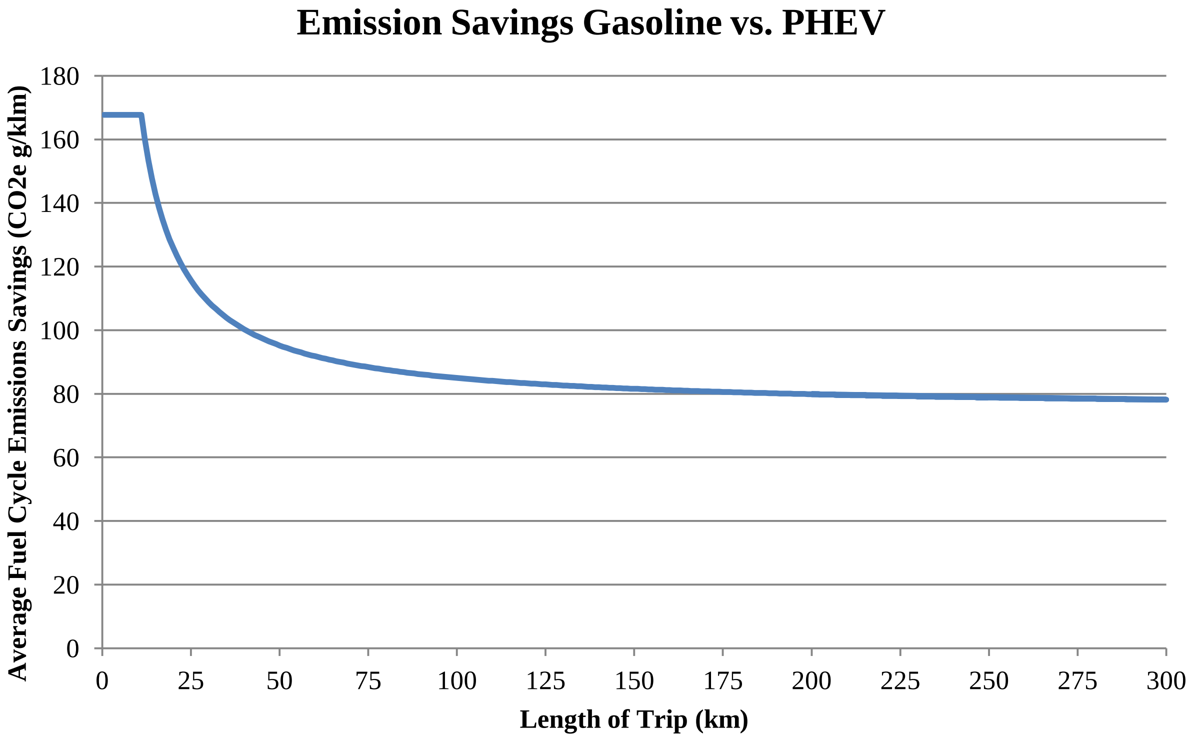


Figure 4. Effect of distance traveled between recharges on emissions savings of PHEVs relative to the gasoline Corolla.

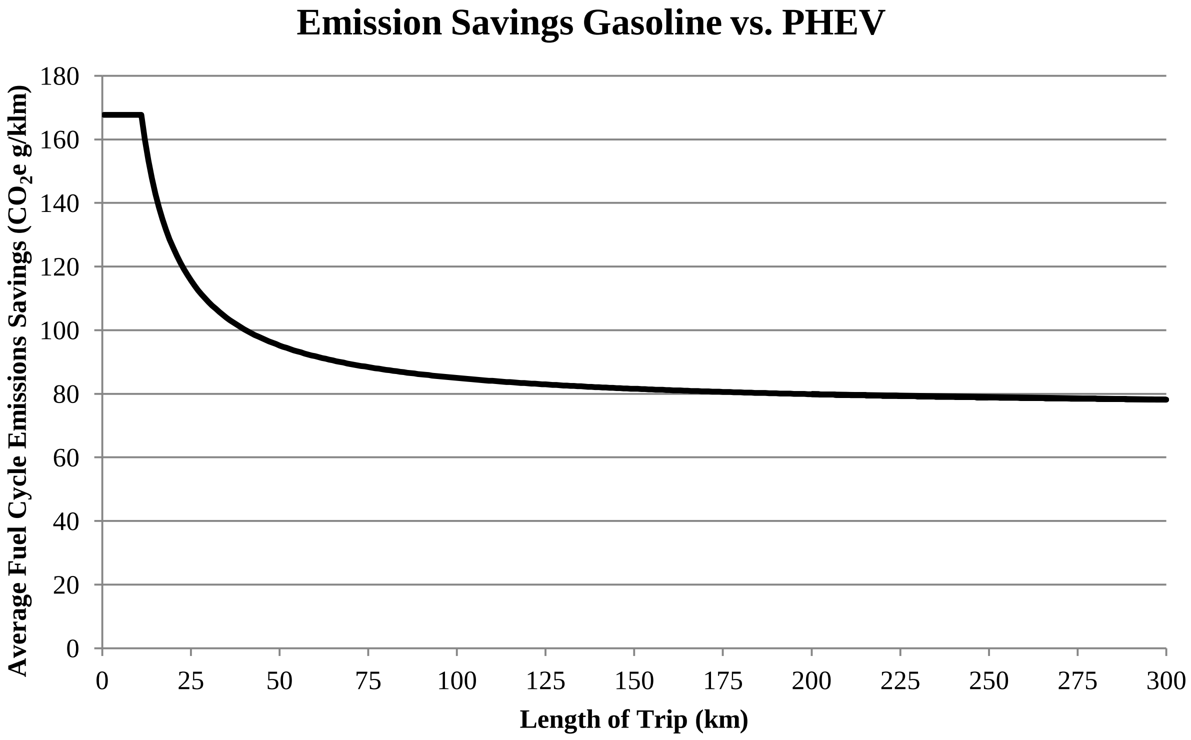


Figure 4. Effect of distance traveled between recharges on emissions savings of PHEVs relative to the gasoline Corolla.

Figure 5

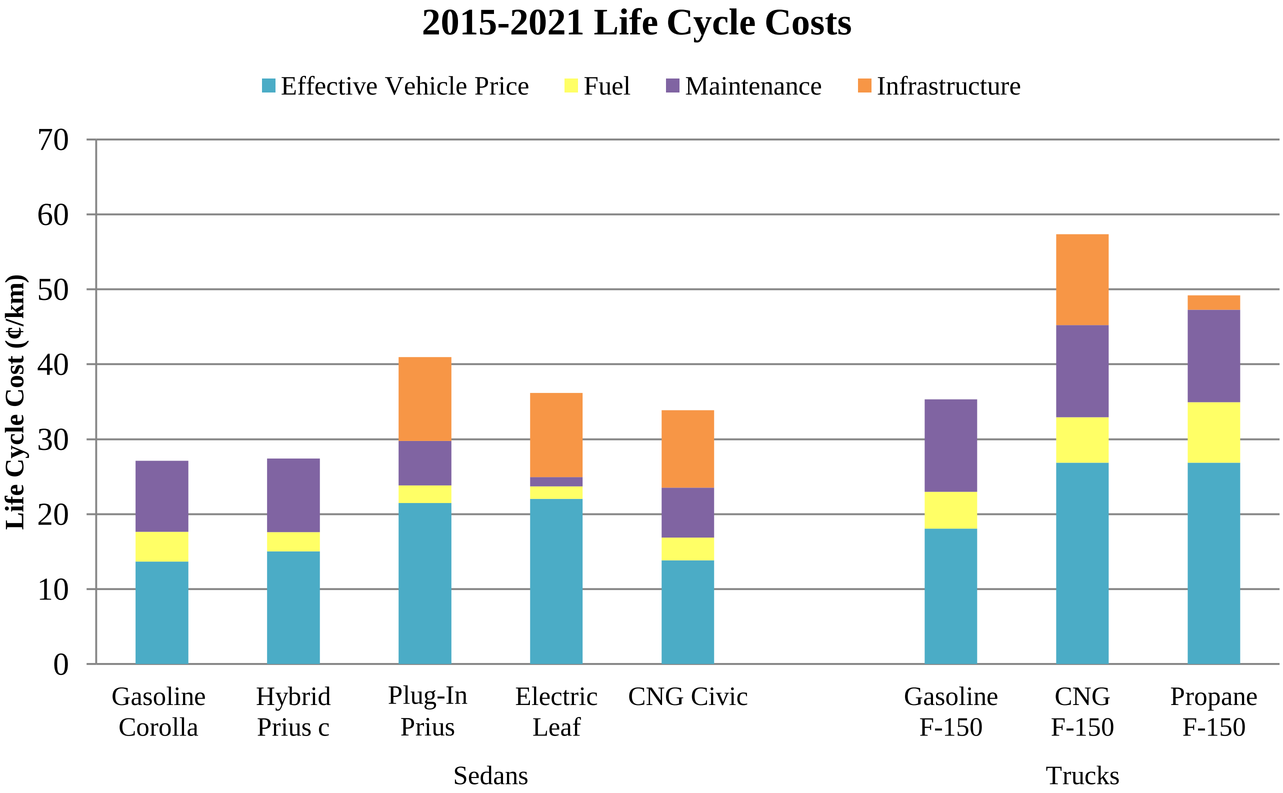
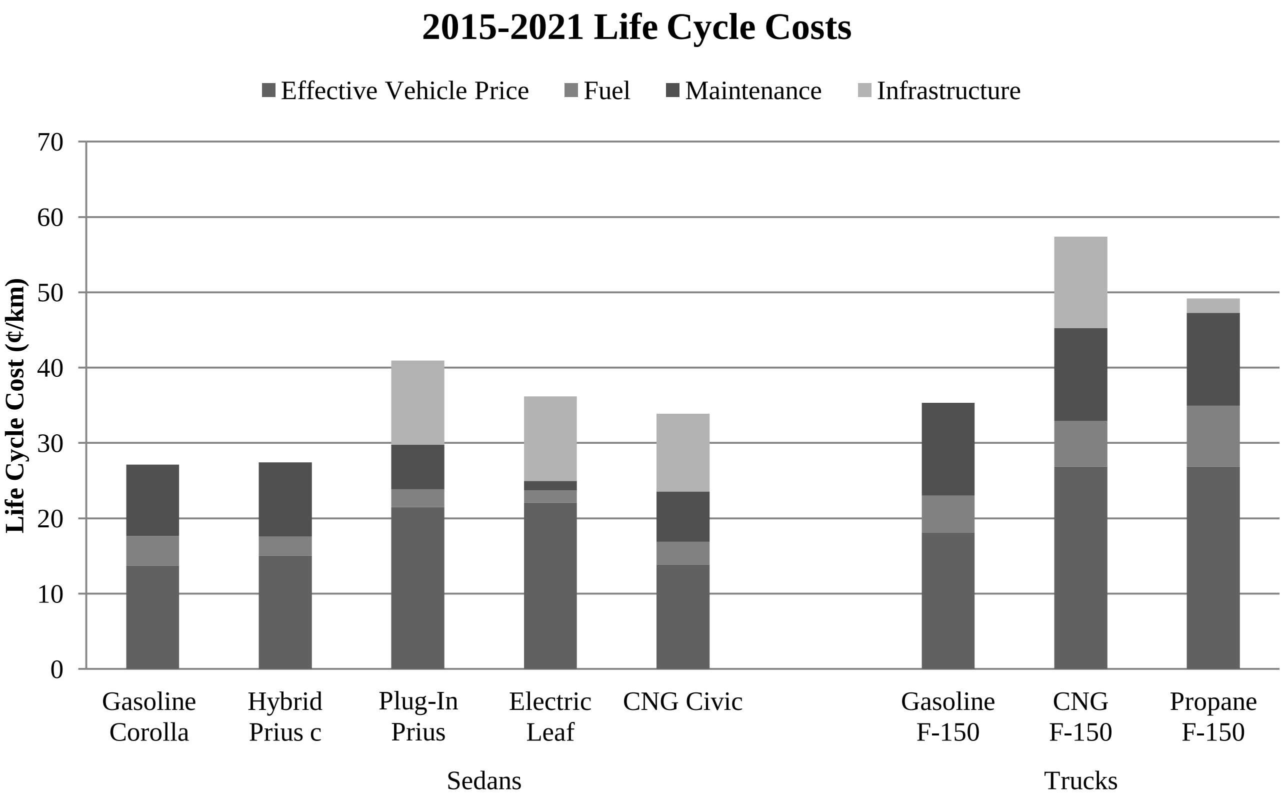


Figure 5. Levelized life cycle cost for each vehicle model.

Figure 5 B&W



2015-2021 Life Cycle Costs

Figure 5. Levelized life cycle cost for each vehicle model.

Figure 6

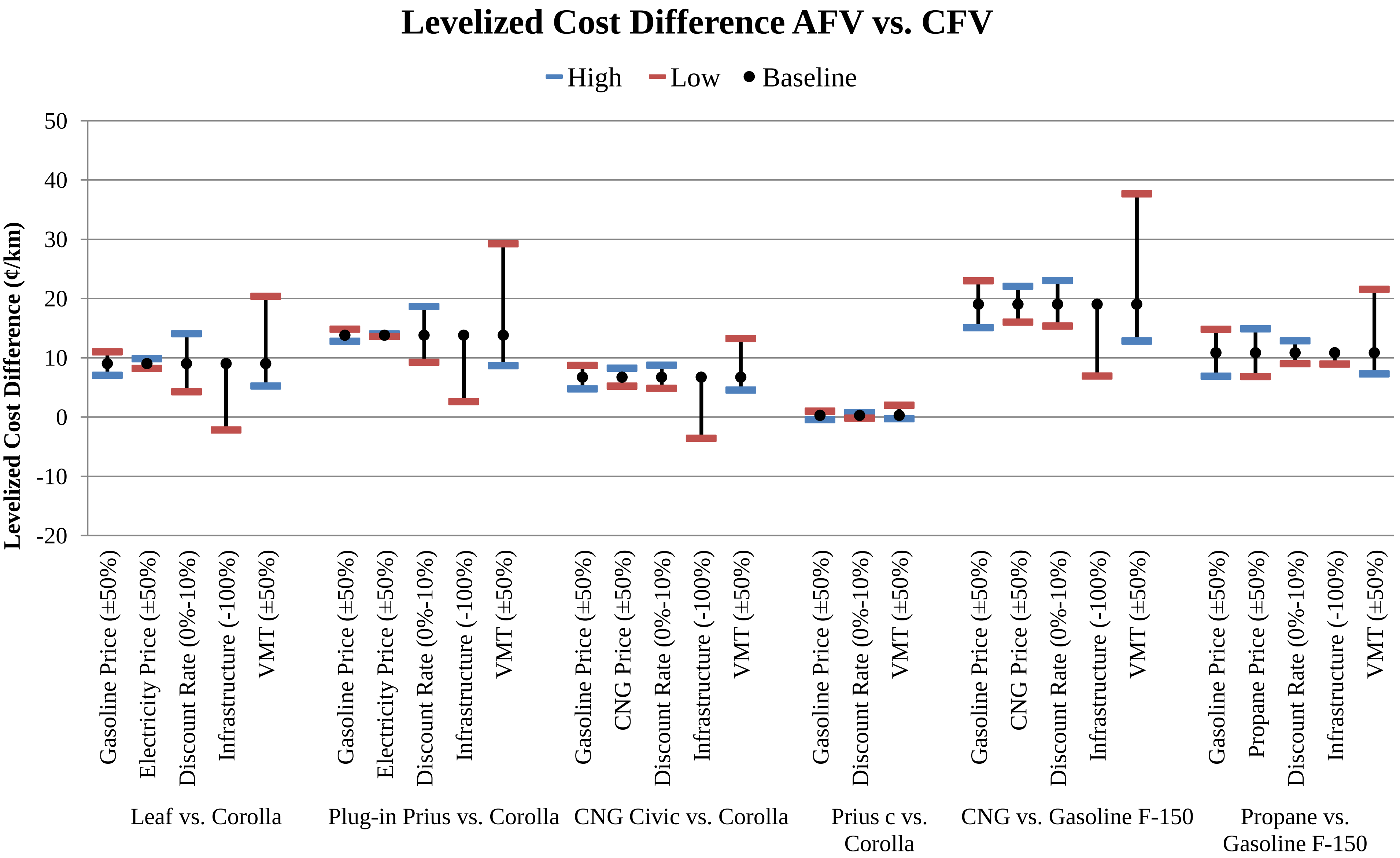


Figure 6. Sensitivity plot of levelized cost differentials to assumptions of fuel prices, discount rate, infrastructure costs, and miles traveled.

Figure 6 B&W

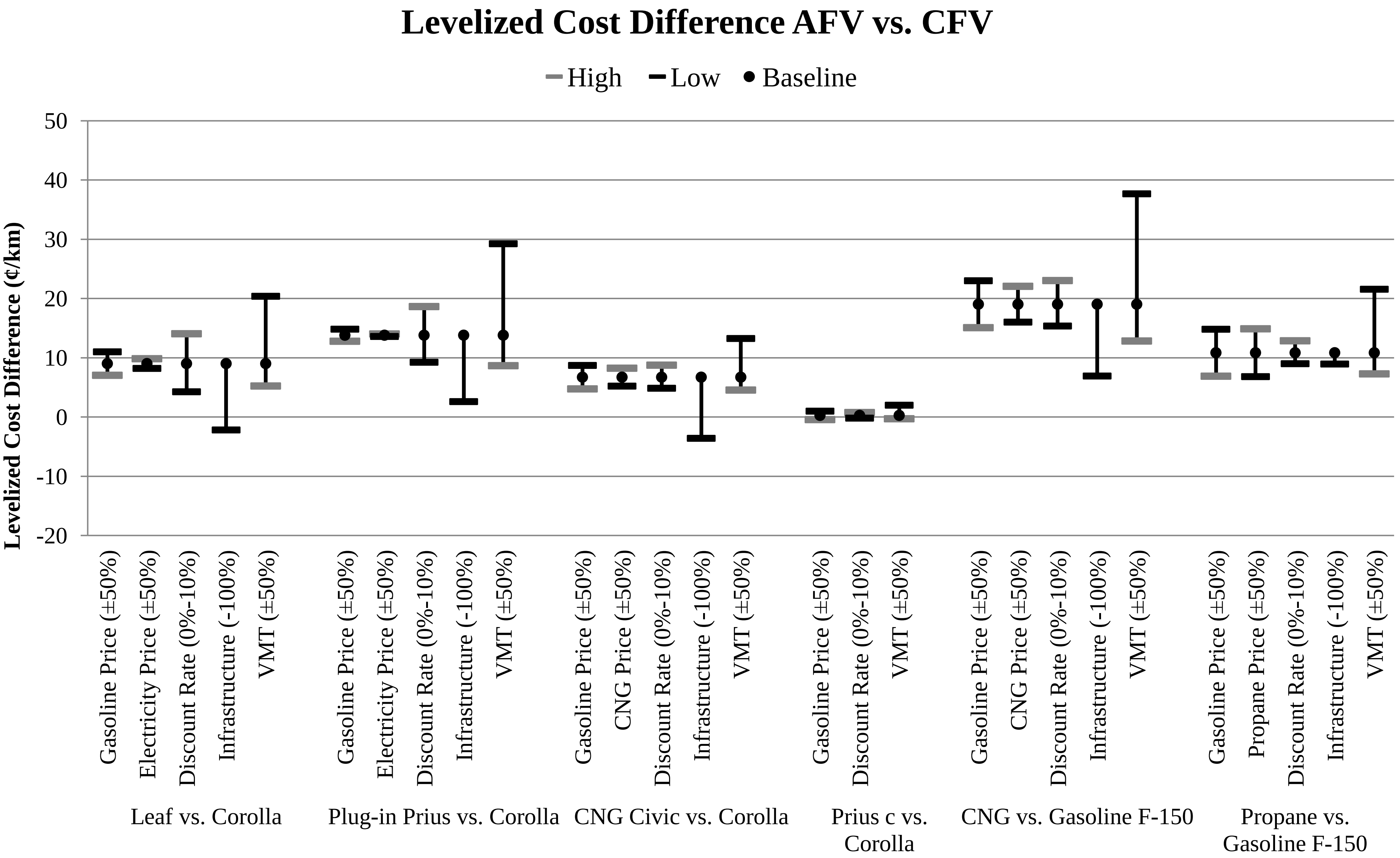


Figure 6. Sensitivity plot of levelized cost differentials to assumptions of fuel prices, discount rate, infrastructure costs, and miles traveled.

April 29, 2017

Dear Editor,

We appreciate the thoughtful comments of the Reviewer and the opportunity to revise the paper in response to those comments. Below, we note each of the Reviewers' comments (in italics), followed by our responses. We are confident that the revisions and responses fully address the Reviewer's comments and that the paper now merits publication in Transportation Research D. We look forward to the publication of this manuscript.

Thank you,

Shayak Sengupta and Daniel Cohan

No major revision is needed.

Line 283, change "do" to "does"

This has been corrected

Line 393, change "achieve" to "achieves"

This has been corrected.

Reviewer #3: This is a well executed example of a broader class of studies that tend to miss an important fundamental point: in the current policy environment, it is more or less futile for individuals, companies, or local governments to try and reduce GHG emissions by choosing higher-efficiency vehicles like hybrids. Operating as we do today and for the foreseeable future in a vehicle market that is constrained by CAFE standards, a fleet operator who stocks up on Priuses only serves to relax the fuel economy standard for the rest of Toyota's (CAFE-constrained) fleet. In all likelihood, the actual fuel economy of the national vehicle fleet will not change at all. Since fuel economy standards are size-based, the way to actually cut GHG emissions is to choose a smaller vehicle, which has the effect of tightening the manufacturer's CAFE standard, at the margin.

It would be good to acknowledge this limitation.

That said, choosing a lower-emitting vehicle can still be very good for local air quality.

This limitation along with appropriate citation has been acknowledged in lines 395-399 of the revised manuscript.

l. 144 - it's not clear what "creating a charged mode" means here. Also, you said in l. 135 that you consider one PHEV model, but here you refer to "both PHEV models in this study."

This has been clarified and corrected

l. 156 you refer again to "charged mode." Is this a typo? It seems you mean "charge depleting mode."

This has been corrected.

l. 155 is 18 km the charge depleting range (the actual distance traveled before entering CS mode) or is it some kind of equivalent electric-only range? (I ask since the Prius uses blended mode operation and only rarely operated in electric-only mode)

We clearly cite the 18 km range as the CD mode according to the EPA with relevant citation. The description of the CD mode is given in the previous paragraph.

l. 187 Clean Power Plan? Better get this published soon… ☹

We leave this as is.

l. 226 It doesn't seem reasonable to assume that other vehicles (especially other powertrains) will have the same ratio of salvage value to initial price. Why not just use Edmunds to look up salvage values for all of them?

There was not a consistent pattern in how Edmunds evaluated AFVs vs. conventional gasoline vehicles. Leafs depreciate fast while Teslas hold their value, and relative depreciation rates are likely to be dependent on future gasoline prices and how AFV technologies continue to evolve. Therefore we chose to use our straightforward approach and keep the methods as is.