Sustainable Fleet Vehicle Options for the City of Houston

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1. Introduction

1.a. Houston Solutions Lab and this grant

The Houston Solutions Lab is a partnership between Rice University and the City of Houston. The mission of the Lab is “to find innovative ways of making the city work better.” As part of the Lab’s 2018 request for proposals, the City’s Office of Sustainability sought proposals that would “help the City plan for longer-term decisions about shifting the City’s fleet to lower emission vehicles.” Our research team was selected to conduct a study under that solicitation. The project applies state-of-the-art methods in life cycle analysis and optimization modeling to inform the City about the financial and environmental impacts of investment decisions in vehicles and associated infrastructure.

1.b. Electric vehicles: general information

The vast majority of vehicles in the United States are conventional vehicles (CVs) that continue to be powered by internal combustion engines using gasoline or diesel fuel. Other options that are less widely used include compressed natural gas (CNG), biofuels, and fuel cells. However, given the evolution of technologies, electric vehicles (EVs) in some form (e.g., plug-in hybrid or fully electric) are likely to provide the most affordable and environmentally friendly alternative to gasoline and diesel.

Cleaner municipal fleet vehicles are one of the top opportunities for cities to reduce greenhouse gas emissions, according to the National Renewable Energy Laboratory.[1] Cleaner vehicles can also improve air quality. However, shifting to EVs will require surmounting substantial barriers, including unfamiliarity with new technologies, higher upfront costs, limited range, and lack of charging infrastructure. Furthermore, with budgets constrained and costs evolving, prudent planning must stage investments

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[1] National Renewable Energy Laboratory. 2016. Estimating the National Carbon Abatement Potential of City Policies: A Data Driven Approach.

to balance vehicle and infrastructure needs while dynamically adapting to changing prices and uncertainty.

Technologies for batteries, EVs, and chargers are rapidly evolving, enabling prices to fall and performance to improve, but with substantial uncertainty about future trends. Industry analysts expect EVs to achieve upfront price parity with gasoline cars by the mid-2020s.[2] By contrast, the United States Energy Information Administration expects a price gap to remain.[3] Prior research published by Dr. Cohan's research group using data from the City of Houston's Fleet Management Department found that EVs had already reached parity in total cost of ownership by 2015, but only if charging infrastructure was already available.[4]

By contrast, recent studies have found little financial or environmental benefit from using CNG as an alternative fuel for cars or buses.[5] For example, while CNG-fueled buses exhibit close to the same capital costs as diesel buses, their higher maintenance and fuel costs mean that their total cost of ownership is approximately 30% greater.[6] Additionally, once methane leaks are accounted for, CNG buses are no better than diesel-fueled buses for climate-warming emissions; by contrast, using natural gas to replace coal, electricity, or heating oil in non-transportation applications yields substantial savings (see Appendix A).[7] CNG sedans suffer from similar challenges and have limited availability. A peer-reviewed publication comparing CNG,

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[2] Electrek (2017). U.S. cities' massive electric vehicle order increases to 114,000 vehicles, ~40 companies competing.
UBS (2017), UBS Evidence Lab Electric Car Teardown – Disruption Ahead?
Bloomberg New Energy Finance (2017), Electric Cars to Reach Price Parity by 2025

[3] U.S. EIA. Annual Energy Outlook 2019.

[4] Sengupta and Cohan (2017). "Fuel cycle emissions and life cycle costs of alternative fuel vehicle policy options for the City of Houston municipal fleet." *Transportation Research Part D*, 54, 160-171.

[5] Lajunen and Lipman (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy*, 106, 329-342.
Vasconcelos et al. (2017). Environmental and financial impacts of adopting alternative vehicle technologies and relocation strategies in station-based one-way car sharing. *Transportation Research Part D*, 57, 350-362.

[6] Ally and Pryor (2016). Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems. *Energy Policy*, 94, 285-294.

[7] Cohan, D.S., and S. Sengupta (2016). Net Greenhouse Gas Emissions Savings from Natural Gas Substitutions in Vehicles, Furnaces, and Power Plants. *International Journal of Global Warming,* 9(2), 254-273.

conventional, hybrid, and electric vehicle options for the City[8] found that CNG vehicles had higher life-cycle greenhouse gas and NO_x emissions and lifetime costs than other options (see figures reprinted in Appendix A). Since the time of that study, more PHEV and EV options have become available, and the performance of batteries has improved, whereas fewer CNG options are available now. For all of these reasons, we focus on electric vehicle options and do not analyze CNG vehicles in this study.

Despite a multi-city solicitation seeking electric models of ambulances, police cruisers, and refuse trucks designed to meet cities' needs,[9] most of these specialty vehicles remain unavailable in electric form. Pickup trucks have also yet to be introduced in electric form from original manufacturers. Thus, for the purposes of this study, we focus on vehicle models that are already available in the near-term. Therefore, the focus will be on sedans and SUVs, for which a range of fully electric and/or plug-in hybrid models are commercially available.

1.c. Chargers: general information

Chargers for electric vehicles come in three varieties: Level 1, Level 2, and Level 3.[10] Level 1 charging involves plugging a cable provided with the vehicle into a standard 120-volt wall outlet. This supplies only about 5 miles of range per hour of charging time, and can take over 20 hours to recharge an electric vehicle. Thus, Level 1 charging is inadequate for typical operation of municipal vehicles.

Level 2 charging uses a 240-volt circuit and can supply about 20 miles of range per hour of charging, or about 180 miles during an 8-hour charge.[11] This makes Level 2 charging adequate for recharging municipal vehicles between uses and fully recharging the vehicles overnight. The higher voltage enables Level 2 chargers to achieve a

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[8] Sengupta, S., and D.S. Cohan (2017). Fuel Cycle Emissions and Life Cycle Costs of Alternative Fuel Vehicle Policy Options for the City of Houston Municipal Fleet. *Transportation Research D*, 54, 160-171. doi:10.106/j.trd.2017.04.039

[9] https://electrek.co/2017/03/15/electric-vehicle-order-114000-vehicles-40-companies-competing/

[10] Union of Concerned Scientists. 2018. Electric Vehicle Charging: Types, Time, Cost and Savings. https://www.ucsusa.org/clean-vehicles/electric-vehicles/car-charging-time-type-cost

[11] https://www.ucsusa.org/clean-vehicles/electric-vehicles/car-charging-time-type-cost

charging efficiency of around 86%, compared to 84% for Level 1 charging.[12] For either type of charger, charging efficiency is enhanced if the battery is less than 90% charged when the charging begins.[13] Level 2 chargers are produced by a growing number of manufacturers and are the most common type of public chargers found in parking garages and retail locations. Level 2 chargers are compatible with any of the models of electric vehicles considered in this study. Teslas require an adapter or a specially designed charger.

Level 3 chargers, also known as DC fast chargers because they use direct current rather than alternating current, can supply 60-80 miles of charge in 20 minutes.[14] That makes them well suited for cars that must be quickly ready for use after extensive driving. However, the installed cost of a Level 3 charger is roughly ten times higher than a Level 2 charger.[15] Furthermore, Level 3 systems provide rapid charging only until a vehicle's battery has been recharged by about 80%; after that point, charging slows to the rate of a Level 2 charger.[16] Thus, for municipal fleet vehicles that only partially deplete their charge on a typical use, the advantages of recharging with a Level 3 charger would be small and the costs would be high.

Based on the above considerations, we recommend Level 2 charging as the most appropriate charging infrastructure for the City to develop to recharge municipal vehicles on-site. In the future, it is possible that networks of Level 3 chargers will become available, enabling off-site charging akin to refueling at a gasoline station. However, as of July 2019, there are only 144 DC fast charging stations available to the public in the state of Texas (less than a dozen of which are in the City of Houston), and

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[12] Vermont Energy Investment Corporation. 2013. An assessment of level 1 and level 2 electric vehicle charging efficiency. https://www.veic.org/documents/default-source/resources/reports/an-assessment-of-level-1-and-level-2-electric-vehicle-charging-efficiency.pdf

[13] Nathaniel Kong. 2018. Exploring electric vehicle battery charging efficiency. https://ncst.ucdavis.edu/wp-content/uploads/2018/09/Kong_NCST-Fellowship-Report.pdf

[14] https://www.energy.gov/eere/electricvehicles/vehicle-charging

[15] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. 2015. Costs associated with non-residential electric vehicle supply equipment.

[16] ChargeHub 2019 Charging Guide.

1,075 Level 2 stations.[17] Thus, gasoline station-style offsite recharging of municipal electric vehicles is not a viable option in the near-term.

Given that Level 2 charging on City property is likely to be the dominant means of charging municipal electric vehicles, choices must be made about the features of the chargers and whether they should be purchased or leased. Options for Level 2 chargers include wall-mounted and pedestal style designs. Pedestal designs are likely to be more durable for long-term use. Dual-port connectors enable two cars to be charged from a single pedestal. Chargers also differ in the amount of data that they collect from the vehicle during charging, and the extent to which they can be programmed to conduct charging at desired times, such as when clean and cheap electricity is available from the grid.

1.d. City of Houston context

Houston is the fourth largest city in the United States by population, totaling 2.33 million people in 2018.[18] It is also the third largest major city in the continental United States by surface area, sprawling across 627 square miles.[19] This vast size means that municipal vehicles may travel longer distances for local use in Houston than in some other cities.

Houston has long been known as the nation's "Energy Capital" for oil and gas, and is poised for leadership in clean energy innovation as well. Houston already leads the nation in municipal purchases of renewable energy, obtaining 92% of its electricity from wind and solar.[20] However, the City still relies on a predominantly fossil fuel fleet for its vehicles.

Air quality is a significant concern in Houston. The Houston-Galveston-Brazoria region currently violates the U.S. Environmental Protection Agency's ambient air quality

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[17] U.S. Department of Energy, Alternative Fuels Data Center, Electric Vehicle Charging Stations website. https://afdc.energy.gov/fuels/electricity_locations.html#/find/nearest?fuel=ELEC

[18] https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk

[19] https://en.wikipedia.org/wiki/List_of_United_States_cities_by_area

[20] https://www.epa.gov/greenpower/green-power-partnership-top-30-local-government, data as of April 22, 2019.

standard for ground-level ozone. The standard is 70 parts per billion of ozone averaged over an 8-hour period. The “design value” for ozone at each air quality monitor is evaluated based on the fourth-highest day each year, averaged over three years. The overall design value for a region is the highest design value at any of its monitors; in other words, all monitors in a region must achieve the 70 ppb limit in order for a region to be in attainment. Based on 2016-2018 data, the design value for the Houston region is 78 ppb, indicating that ozone pollution on peak days must be reduced by at least 8 ppb in order to attain the standard. A total of 13 Houston monitors exceeded a 70 ppb ozone design value during that period, demonstrating that unhealthful ozone levels in the region are widespread.[21] However, the region does attain the fine particulate matter standard at all monitors.

Addressing climate change has become a growing priority for the City of Houston in recent years. Mayor Sylvester Turner is co-chair of Climate Mayors and has committed the City to developing a Climate Action Plan (CAP). Transportation contributed 47% of Houston’s 34.3 million metric tons of CO_2-equivalent emissions in 2014 and thus is a focus of the CAP. A draft of the CAP released in July 2019 sets overall emissions reduction and offset targets of 40% by 2030, 75% by 2040, and 100% by 2050.[22] Reductions in transportation emissions represent the largest share of those targets. Shifting regional fleet vehicles to electric vehicles and alternative renewable fuels is the first component of that plan, along with reductions in vehicle miles traveled and provision of equitable mobility. Two specific recommendations are particularly relevant in the context of our report: 1) “Increase public infrastructure for EV and alternative renewable fuels, installing EV charging stations at public-facing City buildings” by 2025; and 2) “Convert non-emergency, light-duty municipal fleet to 100% EV” by 2030.

The City of Houston is also an active partner in EVolve Houston, which aims to accelerate the adoption of zero-emissions passenger travel and goods movement through electrification. By doing so, EVolve Houston hopes to improve air quality and

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[21] Data from TCEQ, https://www.tceq.texas.gov/cgi-bin/compliance/monops/8hr_attainment.pl
[22] Houston Climate Action Plan: Draft Outline of Recommendations. Released July 25, 2019.

reduce greenhouse gas emissions. Other partners in EVolve Houston include the University of Houston, CenterPoint Energy, NRG, GE, ABB, Chargepoint, EV Box, and Navigant.

According to FY 2019 data provided by its fleet department, the City of Houston owns a fleet of 13,755 vehicles. In addition to the vehicle types that we focus on in this study, the City fleet includes a broad array of vehicles such as forklifts, mowers, and all-terrain vehicles. A small but growing portion of the City's vehicles are operated through its FleetShare program, which was launched in 2012. The program allows City employees to reserve a vehicle online and use it for a designated period of time. The high usage rate of FleetShare vehicles makes them a priority for the deployment of fuel-efficient options. Most FleetShare vehicles had been hybrid Toyota Priuses or electric Nissan Leafs, although most Leafs and chargers were damaged by Hurricane Harvey. Since then, support from Nissan allowed the City to add 27 electric Leafs. That brings the total to 37 electric and plug-in hybrid vehicles, along with 526 conventional hybrid vehicles.[23]

Although this report focuses on the unsubsidized costs of vehicles, the net costs to the City could be reduced if it receives grants and other funding for alternative vehicles. Henna Trewn, an EDF Climate Corps Fellow who worked with the City of Houston Office of Sustainability, compiled a list of 16 funding opportunities for electric vehicles and associated infrastructure. Potential sources of funding include the Texas Commission on Environmental Quality, Houston-Galveston Area Council, Federal Transit Administration, and Federal Aviation Administration. The City may also be eligible for discounted pricing through its participation in the C40 coalition of cities that are addressing climate change. Even without discounts or subsidies, Trewn found that savings in total cost of ownership could be achieved if electric buses were used instead of diesel at the airport and for a downtown shuttle.

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[23] Henna Trewn. 2019. Electrification EVolution: Electric Vehicle Policy and Projects in Houston.

2. Overview

In this report, we present the results of a life-cycle analysis of the costs and environmental impacts of various traditional and electric options for sedans, pickup trucks and sports utility vehicles (SUVs) that are suitable for municipal use. We then conduct optimization modeling to explore how purchases of electric vehicles might be staged over a multi-year period to minimize overall costs.

Section 3 presents our methods for identifying available vehicle options and assessing their life-cycle financial and environmental impacts. Section 4 presents the results of those analyses. Section 5 presents the methods and results for the optimization modeling.

3. Methods

3.a. Meetings with City officials to discuss scope and priorities

Work for the project officially began on September 1, 2018. Meetings with City officials to discuss the scope and details of the project were held on September 4, 2018 in the Fleet Management Division office; on December 13, 2018, February 14, 2019, and June 19, 2019 via phone; and on March 19, 2019 at Rice University. A meeting to discuss a draft of this report was held at Rice University on September 11, 2019.

3.b. Analyzing City of Houston data

Three important sources of information provided by the City of Houston defined the parameters of our model: (1) the City's capital improvement purchasing plan for 2020-24, which showed the funding approved for new vehicle purchases by vehicle type and year (Table 1); (2) the desired daily range and functions for each vehicle type (Table 2); and (3) data for the maintenance costs (Table 3), fuel costs and yearly miles driven for each vehicle in the fleet in 2018 (Figure 1). The daily range and functionality constraints enabled us to identify fully-electric vehicle models that would fit the City's needs, and to estimate the percent of drive time that plug-in hybrid vehicles could operate in electric mode. The cost and mileage database allowed us to project annual miles driven for new vehicles as well as to make maintenance and fuel cost predictions. Notably, since the number of miles driven and the maintenance costs varied linearly over the age of vehicle for each vehicle class, we estimated lifetime mileage and maintenance costs using the average values for each year of the vehicle's 7-year lifetime. Additionally, the City provided average electricity and gasoline costs to use as parameters when extrapolating new vehicle expected costs (e.g., the City paid $0.078/kWh for electricity and $2.01/gal for gasoline in FY 2018). The four vehicle classes covered in this study were sedans, sport utility vehicles (SUVs), pickup trucks, and vans, and each was analyzed separately within the City dataset. However, due to a lack of electric options for pickup trucks and vans, only sedans and SUVs are considered in our optimization analysis.

The budget data from the capital improvement purchasing plan was used in our optimization model. We used the total funds per year available for purchasing vehicles in each class as constraints on that model.

Table 1. City of Houston vehicle purchasing plan. All costs are in 2019$.

Vehicle Class	Vehicle Size	Yearly Budget									
		2019		2020		2021		2022		2023	
		Budget ($)	# Vehicles	Budget ($)	# Vehicles	Budget ($)	# Vehicles	Budget ($)	# Vehicles	Budget ($)	# Vehicles
Sedan	Full	$2,080,000	100	$2,137,000	103	$2,080,000	100	$2,080,000	100	$2,080,000	100
	Intermediate	$534,890	31	$324,735	15	$276,990	13	$241,490	11	$330,240	16
SUV	Mini	$200,000	6	$140,000	4	$210,000	6	$245,000	7	$210,000	6
	Standard	$11,012,555	279	$11,018,555	279	$11,018,555	279	$11,018,555	279	$11,018,555	279
	Full	$37,800	2	$0	0	$0	0	$0	0	$0	0
PUT	1/2T	$558,503	20	$373,504	13	$373,504	13	$403,837	14	$464,503	16
	3/4T	$338,000	13	$359,000	8	$359,000	8	$281,000	7	$125,000	5
	1T	$129,537	1	$0	0	$0	0	$0	0	$0	0
Van	Cargo	$251,450	3	$80,000	2	$80,000	2	$80,000	2	$80,000	2
	Passenger	$23,595	1	$0	0	$0	0	$0	0	$0	0

Table 2. The expected range and seating capacity for each vehicle class. Taken from City of Houston vehicle class descriptions.

Vehicle Class	Vehicle Size	Daily Mileage Range (mi)	Seating Capacity
Sedan	Compact	50-80	4
	Standard, Full	75-100	5
SUV	Standard, Extended	50-80	6-8
Pickup truck	1/2T, 3/4T, 1T, Crew	50-80	2-4
Van	Cargo	50-80	1
	Passenger	75-100	5-20

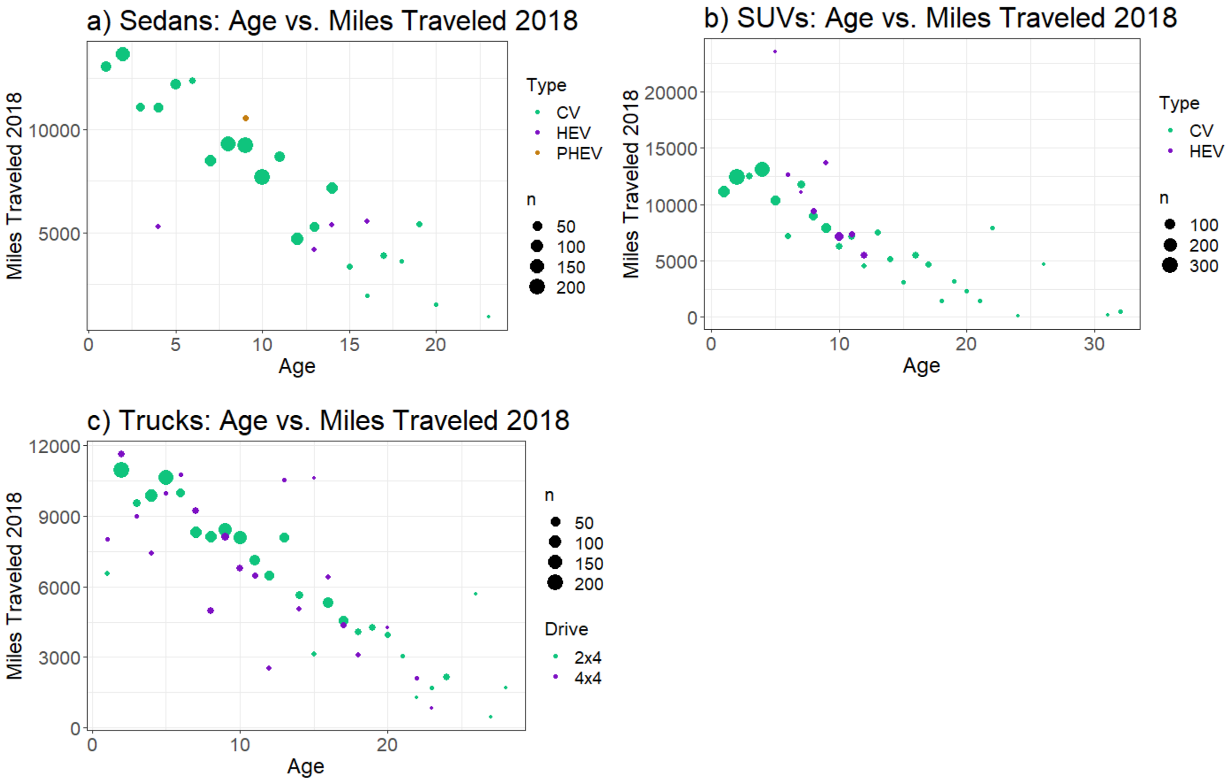

Figure 1. Average miles driven by a) sedans, b) SUVs and c) pickup trucks in 2018 based on vehicle age. Vehicles that were not driven in 2018 were excluded from the calculation. No distinction was made between vehicle usage types (e.g. general use vs. patrol sedans).

Table 3. The expected per-mile maintenance cost for a) sedans, b) SUVs and c) pickup trucks for conventional vehicles. Calculated by tabulating the total maintenance cost over total miles driven for each vehicle class and age.

Vehicle Age (yrs)	Average Maintenance Costs ($/mi)			
	Sedans	PUTs 2x4	SUVs	PUTs 4x4
1	0.0778	0.0232	0.1689	0.0676
2	0.0873	0.0929	0.1141	0.1492
3	0.1975	0.1599	0.2302	0.5313
4	0.2748	0.1369	0.2498	0.1158
5	0.1909	0.1716	0.2526	0.3253
6	0.2021	0.1556	0.3499	0.1587
7	0.3707	0.2728	0.2128	0.5601

3.c. Available vehicle options

3.c.i. Sedans

Vehicle models were chosen for 2019 model year comparisons by considering models already in use by the City and comparable models with similar specifications, prices, and emission characteristics (Table 4). We selected the Toyota Camry gasoline vehicle (conventional vehicle; CV); Toyota Camry hybrid (hybrid electric vehicle; HEV); Toyota Prius Prime plug-in hybrid (PHEV); and the Nissan Leaf and Nissan Leaf e+ electric vehicles (EV) due to their low cost and high efficiency relative to other vehicles available on the market. We looked at both the Nissan Leaf and the Nissan Leaf e+ EVs because of their difference in range: the Nissan Leaf has a 40 kWh battery which provides an electric range of 151 miles while the Nissan Leaf e+ has a 62 kWh battery with 256 miles of range. Information on vehicle prices was obtained from Edmunds.com. Information on energy efficiency was obtained from the Environmental Protection Agency (EPA) website, http://fueleconomy.gov. Data from these sources were input into the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model. It should be noted in particular that the listed efficiency of the Toyota Prius Prime PHEV is a combined value of two separate efficiency values for each of its operational modes. In the electric mode (sometimes called charge-depleting (CD) mode), the vehicle draws power solely from the battery. In the hybrid mode (sometimes called charge-sustaining (CS) mode), the vehicle draws power from both the battery and gasoline combustion. The electric-mode efficiency for the Toyota Prius Prime is 250 Wh/mi, and the hybrid-mode efficiency is 54 mpg.

Table 4. Specifications for sedan models compared in this study. Highlighted vehicles were used in the analysis based on a combination of affordability and greater fuel economy.

Type	Vehicle Model	Latest Model Year	General Vehicle Specs			CV/HEV/PHEV Specs	PHEV/EV Specs		
			Seating	MSRP	Curb Weight (lbs)	Gasoline Efficiency (mpg)	Electric Efficiency (Wh/mi)	All-electric Range (mi)	Li-ion Battery Size (kWh)
EV	Chevrolet Bolt	2019	5	$36,620	3563		280	238	60
EV	Ford Focus	2018	5	$29,120	3640		300	115	23
EV	Nissan Leaf	2019	5	$29,900	3433		300	151	40
EV	Nissan Leaf e+	2019	5	$36,550	3780		300	256	62
PHEV	Chevrolet Volt	2019	5	$33,520	3519	42*	310**	53	18
PHEV	Ford Fusion Energi	2018	5	$36,595	3986	42*	330**	21	7
PHEV	Hyundai Sonata	2019	5	$33,400	3247	39*	340**	27	10
PHEV	Kia Optima	2019	5	$35,390	3230	40*	330**	29	10
PHEV	Toyota Prius Prime	2019	4	$27,350	3375	54*	250**	25	9
HEV	Honda Insight	2019	5	$22,930	3000	52			
HEV	Toyota Prius	2018	5	$24,980	3075	52			
HEV	Honda Accord	2019	5	$25,320	3428	48			
HEV	Toyota Camry	2019	5	$28,150	3472	52			
CV	Toyota Camry	2019	5	$23,845	3296	34			
CV	Honda Accord	2019	5	$23,720	3208	33			
CV	Chevrolet Malibu	2018	5	$22,090	3135	30			

*gasoline MPG of PHEV models represents efficiency in hybrid mode.
**electric Wh/mi of PHEV models represents efficiency in electric mode.
EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, and CV = conventional gasoline vehicle.

3.c.ii. SUVs

The SUVs considered in this study were selected by cross-referencing currently owned SUVs with available 2019 models and comparing price, efficiency, and capacity (Table 5). As with sedans, information on price and energy efficiency was obtained from Edmunds.com, fueleconomy.gov, and manufacturers' websites.

Table 5. Specifications for SUVs compared in this study. Highlighted vehicles were used in the analysis.

Type	Vehicle Model	Latest Model Year	General Vehicle Specs			CV/HEV/PHEV Specs	PHEV/EV Specs		
			Seating	MSRP	Curb Weight (lbs)	Gasoline Efficiency (mpg)	Electric Efficiency (Wh/mi)	All-electric Range (mi)	Li-ion Battery Size (kWh)
EV	Hyundai Kona Electric	2019	5	$36,950	3715		280	258	64
PHEV	Mitsubishi Outlander	2019	5	$35,795	4178	25**	450*	22	-
PHEV	Subaru Crosstrek	2019	5	$34,995	3726	35**	380*	17	-
PHEV	Ford Explorer	2020	7	-	-	-	-	25	-
HEV	Toyota Highlander	2019	8	$37,320	4398	29			
HEV	Ford Explorer	2020	7	$52,280	4969	24			
CV	Toyota Highlander	2019	8	$31,680	4134	22			
CV	Volkswagon Atlas	2019	7	$30,895	4242	19			
CV	Mitsubishi Outlander	2019	7	$24,695	3351	27			
CV	Subaru Crosstrek	2019	5	$21,895	3113	25			
CV	Hyundai Kona	2019	5	$19,990	2890	30			
CV	Ford Explorer	2019	7	$32,765	4345	24			

*gasoline MPG of PHEV models represents efficiency in charge-sustaining mode.
**electric Wh/mi of PHEV models represents efficiency in charge-depleting mode.
EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, and CV = conventional vehicle.

3.c.iii. Pickup trucks and vans

Very few models of non-CV pickup trucks and vans were available at the time of this analysis. In particular, insufficient information was found on currently available hybrid or electric van options to allow a quantitative cost and emissions comparison. We instead provide a qualitative account of manufacturers' plans to release electric and hybrid pickup truck and van models in the coming years.

With respect to pickup trucks, this study includes a comparison between the Ford F-series and the Dodge Ram line. In particular, we compared the specifications and pricing of truck models with and without the addition of a mild-hybrid engine to calculate fuel economy savings from, and price premiums on, currently-marketed pickup trucks with hybrid engines. Additionally, we looked at the information available from manufacturers regarding expected release dates for electric and plug-in hybrid pickup trucks. Information about available vans was found from Edmunds, fueleconomy.gov, and manufacturers' announcements, and is summarized in Table 6.

Table 6. Specifications for pickup models compared in this study. Highlighted vehicles were used in the analysis.

Type	Vehicle Model	Vehicle Size Class	Latest Model Year	General Vehicle Specs			Fuel Economy (mpg)
				Seating	MSRP	Payload Capacity (lbs)	
CV	Chevrolet Colorado	4x2 1/2T Crew	2019	4	$26,700	-	22
CV	Ford F-150	4x2 1/2T	2019	2	$29,000	5000	22
CV	Ram 1500	4x2 1/2T	2019	4	$34,135	6730	22
CV	Ford F-250	4x2 3/4T	2019	3	$33,150	4150	15
CV	Ram 2500	4x2 3/4T	2019	3	$33,395	4050	14
HEV	Ford F-150	4x2 1/2T	2019	2	$30,745	3000	22
HEV	Ram 1500	4x2 1/2T	2019	4	$35,385	6730	23
CV	Chevrolet Colorado	4x4 1/2T Crew	2019	4	$32,000	-	19
CV	Ford F-150	4x4 1/2T	2019	2	$34,395	5000	20
CV	Ram 1500	4x4 1/2T	2019	4	$37,635	6410	21
CV	Ford F-250	4x4 3/4T	2019	3	$35,945	3730	15
CV	Ram 2500	4x4 3/4T	2019	3	$36,295	4050	14
HEV	Ram 1500	4x4 1/2T	2019	2	$38,885	6410	22
HEV	Ford F-150	4x4 1/2T	2019	4	$35,390	5000	21

HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle.

3.d. Gathering information about charging options

Our research team met with City of Houston officials to understand their priorities for charging infrastructure, and with Michael Conklin of CenterPoint Energy and Shivkumar Kalyanaraman of GE Power Conversion to explore technological options for multi-vehicle charging. Conversations with City fleet department officials indicated that the department plans to have a dedicated charging spot for each electric or plug-in hybrid vehicle in its FleetShare program. Officials told us that leasing a dual-port charger at an annual cost of $700 per vehicle ($1400 per system per year) was the preferred option identified so far. All subsequent analysis in this study uses that annual cost per vehicle. It should be noted that there are less-expensive charging options available in the market, and it is possible that the City might adopt those in the future, which would alter the results in Section 4.

3.e. Electricity and fuel costs

Two kinds of vehicle fuels were considered in this study, namely E10 gasoline and electricity. E10 is a blend of 10% ethanol and 90% gasoline and is the most widely available liquid fuel on the market today across the United States. Sources of electricity vary by location. The City of Houston is the top purchaser of renewable energy among US local governments, purchasing 1.07 billion kWh of cleanly-generated electricity annually.[24] This amount makes up 92% of the City's retail electricity purchases, which was reflected in our model assumptions regarding the GHG and NO_x emissions from electricity production per-vehicle. It was assumed that the remaining 8% of electricity purchased by the City was produced from the same composition of fuel types as that of Electric Reliability Council of Texas (ERCOT) retail electricity. Prices were taken from the reported rates paid by the City, which were $0.078/kWh for electricity and $2.01/gal for unleaded gasoline in FY2018. The ERCOT electricity mix was obtained from the ERCOT Capacity and Demand Reserves report.[25]

3.f. Maintenance costs

Maintenance costs for conventional vehicles were calculated based on City data for 2018 (Table 3). Data were screened to include only vehicles that were driven and not sold in 2018, and for which the difference in the M5 and FuelForce mileage calculations was less than 500 miles. Removing vehicles with large discrepancies between M5 and FuelForce measurements filtered out the vehicles whose reported values were outliers.

It is not yet possible to directly compute maintenance costs for electrified vehicles in the City fleet over a full vehicle lifetime. Thus, we turn to the literature to develop estimates for the maintenance costs of PHEVs and EVs relative to conventional vehicles. Estimates were found in both the peer-reviewed and gray literature, and from preliminary data reported by New York City. Across those studies, estimates of the maintenance costs of electrified vehicles as a percentage of those for conventional

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[24] https://www.epa.gov/greenpower/green-power-partnership-top-30-local-government-0

[25] http://www.ercot.com/content/wcm/lists/167023/CapacityDemandandReserveReport-May2019.pdf

vehicles range from 47-90% for PHEVs and 13-76% for EVs (Table 7). The lower maintenance costs of PHEVs and EVs than conventional vehicles is to be expected, since operation in electric mode results in less wear and tear on moving parts as in the internal combustion engine of a CV. All of the studies that considered both PHEVs and EVs found that the EVs have lower costs. That likely results from the fact that EVs avoid the need for internal combustion engines altogether. However, the exact amount of maintenance savings remains highly uncertain. Most of the PHEV and EV models have been introduced or upgraded too recently to have an extensive track record of their maintenance in use by city fleets or elsewhere.

Table 7. Literature review of maintenance costs of PHEVs and EVs relative to CVs.

Study	**Basis**	**Ratio PHEV/CV**	**Ratio EV/CV**
New York City 2018[26]	Weighted average of actual costs for NYC fleet vehicles in 2018	47%	21%
Sengupta and Cohan 2017[27]	Edmunds.com and City of Houston fleet data	62%	13%
Palmer 2018[28]	Modeled estimates for Texas	90%	76%
Logtenberg 2018[29]	Vincentric fleet cost estimates for Canada	N/A	53%
Al-Alawi and Bradley 2013[30]	Maintenance cost model for 25-mile range PHEV mid-sized sedan (first 7 years)	84%	N/A
Al-Alawi and Bradley 2013	Maintenance cost model for 25-mile range PHEV mid-sized SUV (first 7 years)	88%	N/A
EPRI 2013[31]	Maintenance costs of Chevy Cruze, Chevy Volt (PHEV) and Nissan Leaf (EV) for 140,000 miles	52%	22%

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[26] https://www1.nyc.gov/assets/dcas/downloads/pdf/fleet/NYC-Fleet-Newsletter-255-March-8-2019-Reducing-Maintenance-Costs-With-Electric-Vehicles.pdf

[27] Sengupta, S., and D.S. Cohan (2017). Fuel Cycle Emissions and Life Cycle Costs of Alternative Fuel Vehicle Policy Options for the City of Houston Municipal Fleet. *Transportation Research D*, 54, 160-171. doi:10.106/j.trd.2017.04.039

[28] Palmer et al. 2018. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Applied Energy*, https://doi.org/10.1016/j.apenergy.2017.10.089.

[29] Logtenberg et al. 2018. Comparing Fuel and Maintenance Costs of Electric and Gas Powered Vehicles in Canada. Available at https://www.2degreesinstitute.org/reports/comparing_fuel_and_maintenance_costs_of_electric_and_gas_powered_vehicles_in_canada.pdf

[30] Al-Alawi, B.M., and T.H. Bradley. 2013. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. *Applied Energy*, 103, 488-506.

[31] EPRI 2013. Total cost of ownership model for current plug-in electric vehicles. http://www.ehcar.net/library/rapport/rapport079.pdf

The literature values showed significant variation, and the differences in methodologies meant that no one study proved most appropriate for application to the City of Houston maintenance cost projections. Thus, we decided to use the average of the available literature values for PHEV and EV maintenance costs. Based on those averages, we assumed that maintenance costs for PHEVs would be 67.4% of those for CVs, and for EVs they would be 37% of those for CVs. Note that all but one of the estimates in Table 7 is specific to sedans. Given the lack of information on the expected maintenance costs of non-conventional SUVs and pickup trucks, we applied the same percentages across vehicle types.

For HEVs, the City did not have enough HEV sedans that were 7 years old or older to enable us to compute city-specific estimates about the relative maintenance costs for these vehicles. Palmer (2018)[32] found that HEV and PHEV maintenance costs are similar. Thus, we assume that maintenance costs for HEVs would be 67.4% of the maintenance costs for CVs, as computed above for PHEVs.

3.g. The GREET and AFLEET models and underlying assumptions

GREET is a pair of life-cycle models developed by Argonne National Laboratory to compute greenhouse gas and air pollutant emissions from vehicles. The GREET fuel-cycle model computes emissions from fuel production ("well to pump") and vehicle operation ("pump to wheels" or "tailpipe"); together, these emissions are known as well-to-wheels fuel-cycle emissions. The GREET vehicle-cycle model computes emissions from the manufacture and disposal of vehicles. Being able to tally all of these components of emissions is important in comparing internal combustion engine vehicles, whose emissions come from all stages, with electric vehicles, which produce no tailpipe emissions but typically require more energy for vehicle manufacture due to their large battery size. The parameters modified from the default GREET values for this analysis are detailed in Table 8.

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[32] Palmer et al. 2018. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Applied Energy*, https://doi.org/10.1016/j.apenergy.2017.10.089.

Table 8. Parameters modified from their default values in the GREET model.

GREET Parameters Modified	**Vehicle Types***
Fuel Economy	CV, HEV, EV
Fuel Economy (Charge-depleting)	PHEV
Fuel Economy (Charge-sustaining)	PHEV
Daily Mileage	PHEV
Electric Range	PHEV, EV
Car Weight	EV
Car Battery Weight	EV
Car Battery Chemical Composition	EV
NOx Emissions Factors	CV, PHEV, HEV

* EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle.

AFLEET is a tool produced by the Argonne National Laboratory to assess the environmental and cost impacts of electrifying vehicle fleets. Nitrogen oxide (NOx) emissions factors were calculated using the AFLEET model because GREET NOx emissions factors represent emissions over a 30-year vehicle lifetime, which is far greater than the 7-year lifetimes assumed for city vehicles. AFLEET model factors can be scaled based on expected vehicle lifetime, which is one of the model's input parameters along with fuel economy and annual miles traveled.

3.h. Linear programming optimization model

In formulating a long-term plan for shifting the City's fleet to low emission vehicles, there were a number of potential variables and constraints to be considered. The optimization problem has been expressed as a linear program solved using the Simplex method (in Gurobi) to incorporate as many of those variables as possible, while still remaining computationally feasible (any increase in the number of variables can lead to an exponential increase in solution time). A linear program is formulated such that an objective function is minimized or maximized for a selected range of decision variables which are multiplied by their associated costs over a range of indices. That objective function is then bounded by a set of constraints over subsets of those indices. This general approach has been used in the past for other related fleet utilization and replacement problems.

For the integration of low-emission vehicles into the City of Houston fleet, the most straightforward objective function was to minimize lifetime costs of ownership. Those costs could be purely economic, limited to the costs incurred by the City, or could include the social costs of greenhouse gases and air pollution and associated health impacts. The basic decision variables were the numbers of vehicles to keep, release, or purchase each year. However, there are many choices that could have been made for the indices of those variables, including the duration of the long-term purchasing plan, the assumed end-of-life outcomes for the vehicles, and how many alternative vehicle types must be considered for each subcategory. For example, when a vehicle reaches the end of its useful life, it could be replaced by a conventional fuel vehicle, a hybrid vehicle (either traditional or plug-in), or by a fully electric vehicle. Of course, a vehicle can also be replaced before the end of its useful life, but that primarily affects the salvage value, not the underlying decision variable. The aforementioned costs assigned to each decision variable include the purchase price, fuel costs, and annualized operation and maintenance costs.

The constraints applied to the problem were both practical and economic. Practical constraints include that for each subcategory of fleet vehicles, there is an assumed utilization that relates to both time and distance demands. Additionally, there is a maximum age that each vehicle can reach. Economic constraints related both to operational budgets and funds for new purchases, and how those funds might be supplemented by secondary programs such as Volkswagen settlement funding. There are both first costs and annual costs for each variable, which include discount rates for changes in time. Moreover, the costs associated with the variables are also indexed; for example, a conventional vehicle has fuel costs associated with gasoline prices, while an electric vehicle has operational costs tied to electric rates. Fully electric vehicles or plug-in hybrids also incur costs related to charging infrastructure.

With the exception of near-term prices, all of the costs used in the model were based on assumptions for future values of vehicle purchase prices and operational costs (both economic and environmental). The effect of variations in all of these costs must also be considered in determining the best return on investment for the transition of the city fleet. Given the size of the formulated problem, it was useful to examine a variety of scenarios to quantify the influence of uncertainty in the selection of the costs.

4. Results

4.a. Scope of available options for vehicles and charging infrastructure

4.a.i Sedans

The 2019 MSRPs and efficiencies for the sedans selected for analysis and optimization were shown in the highlighted rows of Table 4. To calculate the overall efficiency and fuel costs of the Toyota Prius Prime PHEV, we used the vehicle's all-electric range to calculate the proportion of miles that would be expected to be traveled in electric mode, in which the vehicle runs on electricity only, versus hybrid mode, in which the vehicle runs on gasoline. Based on the average daily mileage of 65 miles for a compact sedan in the City fleet and the Prius Prime's all-electric range of 25 miles, we determined that for a given trip the average proportions of miles driven in each mode would be 0.38 for electric mode and 0.62 for hybrid mode.

One major concern about incorporating fully electric vehicles into the city fleet is whether their ranges would be sufficient to support daily usage between charges. For this reason, we modeled two models of the Nissan Leaf: the standard EV model with a 40 kWh battery and 151 mile range, and the e+ model with a 62 kWh battery and 256 mile range in 2019. Both of these ranges are comfortably beyond the typical daily mileage of City vehicles.

4.a.ii SUVs

Commercial SUV types included CVs, HEVs, PHEVs and an EV. The five models selected for analysis offer relatively affordable SUVs with both traditional and alternative fuel options, which makes direct comparison possible.

The most affordable standard-size plug-in hybrid SUVs that we identified were the Mitsubishi Outlander 2019 and the Subaru Crosstrek, which we included alongside their traditional non-hybrid counterparts of the same make. Likewise, the only all-electric SUV available in the US for under $50,000 was the 2019 Hyundai Kona Electric, which we also included alongside its CV counterpart. It should be noted that while the CV Outlander seats seven, the PHEV Outlander seats only five; additionally, all Subaru and Hyundai models have a seat limit of five passengers. This reduction in seating should be considered in purchasing decisions. We selected the Ford Explorer and Toyota Highlander 2019 models for comparison due to their competitive pricing, their current presence in the City fleet and the availability of both CV and HEV models for comparison.

An overview of the MSRP and efficiency of selected SUV models was shown in the highlighted rows of Table 5. Currently, hybrids and EVs are sold at a premium relative to CVs, with the magnitude of that premium varying greatly depending on the manufacturer. In particular, the HEV Ford Explorer retails for $19,500 more than the CV Ford Explorer with no increase in fuel economy. This is likely because Ford’s hybrid is offered with several non-optional luxury features, ramping up the price and increasing the vehicle weight enough to cancel out the efficiency gains from using a hybrid engine. The Toyota, Mitsubishi, and Subaru vehicles all retail with more modest price increases for the hybrid models but with appreciable increases in efficiency. Finally, the Hyundai EV model is $16,600 more expensive than the corresponding CV, a significant premium, but its fuel economy of 120 mpge is a marked improvement over the 30 mpg fuel economy of the CV.

An additional parameter required to calculate costs and emissions for PHEVs is the proportion of time spent in each operating mode. This was calculated by using the average expected daily range of an SUV used by the city of Houston (65 mi) and determining the proportion of that range travelled in electric mode based on each vehicle’s all-electric range. The Mitsubishi Outlander PHEV has a range of 22 miles, meaning the proportions of the average trip travelled in each mode would be 0.34 for electric mode and 0.66 for hybrid mode. The Subaru Crosstrek PHEV has a range of 17 miles, meaning the proportions would be 0.26 for electric mode and 0.74 for hybrid mode. The proportion of travel conducted in electric mode could be increased if the PHEV is recharged between uses when it is checked out from the FleetShare program multiple times in a day.

4.a.iii. Pickup trucks and vans

Purchasing options for EV and PHEV pickup trucks and vans are currently limited. We therefore collected information on models that manufacturers are planning to produce in the future. Since insufficient information exists regarding the future efficiencies for these new vehicles compared with currently available CV models, pickup trucks and vans were excluded from our optimization model.

The only two pickup trucks available in the U.S. in 2019 were CVs and mild hybrids. Ford has confirmed the release of a full hybrid-electric F-150 in 2020[33] and also announced the development of an all-electric F-150,[34] although the release date of the latter has yet to be announced. Unlike regular hybrid powertrain systems, mild hybrids are incapable of full-electric propulsion; thus mild hybrid engines are less efficient than regular hybrids but still more efficient than CVs. There are two mild hybrid-electric pickup truck models currently available in the U.S. at a competitive price point. One is the 2019 Ram 1500 fitted with an eTorque engine, which has a combined fuel economy of 19 mpg compared with the 17 mpg of the non-hybrid model. The other, a Ford F-150 with an EcoBoost engine, has the same 19 mpg fuel economy. The highlighted rows of Table 6 presented these fuel economies and the listed retail prices for the 2019 Ford and Ram pickup trucks with and without hybrid engines. A fuel cost comparison revealed only a negligible decrease in fuel costs when using a mild hybrid versus a conventional internal combustion engine.

The mild hybrid engines from both Ford and Dodge are only available for pickup trucks in the 1/2-ton weight class; 3/4-ton and 1-ton models are only available with internal combustion engines. Since we could not find any information from manufacturers indicating possible future hybrid options for medium-/heavy-duty trucks, we considered only 1/2-ton trucks in our analysis.

In the case of vans, *Inside EVs* reports that Ford plans to release an all-electric Transit in Europe in 2021[35] and is promising to retain the same payload as current

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[33] https://www.caranddriver.com/news/a15343872/electrified-icons-ford-mustang-and-ford-f-150-hybrids-coming-by-2020/

[34] https://www.caranddriver.com/news/a25933730/ford-f-150-electric-pickup-truck-confirmed/

[35] https://insideevs.com/news/343761/2021-ford-transit-electric-van-everything-we-know/

gasoline-powered vans while using a 76 kWh battery that will provide a range of 124 miles. That comfortably exceeds the 50-80 mile daily use range sought by the City. *Inside EVs* also reports that other full-size all-electric vans have been announced for Europe by Mercedes-Benz[36] and VW,[37] but there has been no indication of when, if ever, these vehicles will be made commercially available in the United States. Unfortunately, the only cargo vans or transit vans announced for future release in the United States are CVs.

4.b. Cost comparisons

4.b.i. Sedans

The life cycle cost of vehicles was divided into four parts: purchase price, lifetime fuel costs, lifetime maintenance costs, and (in Section 4c) social costs related to vehicle emissions. The MSRPs of the sedans for this study can be seen in Table 4. We assumed the discount rate to be zero, since the City told us its nominal rate for borrowing is 2%. That matches the inflation rate target set by the U.S. Federal Reserve and implies a real interest rate near 0%. A larger discount rate would favor vehicles with lower initial costs.

Table 9 shows the per-mile fuel costs and lifetime fuel costs for sedans. The results show that fuel for CVs costs almost 3 times as much per mile as electricity for EVs. This is reflected in the lifetime fuel costs for each vehicle, with EVs saving approximately $3,000 on fuel relative to the traditional CV option. For maintenance costs, we took the CV costs from current City data. Note that fuel costs are much lower than maintenance costs overall (Table 9).

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[36] https://insideevs.com/news/335868/how-mercedes-benz-intends-to-go-all-electric-with-its-vans/

[37] https://electrek.co/2018/04/13/mercedes-benz-esprinter-all-electric-van/

Table 9 Projected lifetime fuel costs by sedan type.

	Type	Average Fuel Costs ($/mi)	Total Fuel Costs	Total Maintenance Costs
Nissan Leaf	EV	0.022	$1,794	$11,737
Nissan Leaf e+	EV	0.022	$1,794	$11,737
Toyota Prius Prime	PHEV	0.030	$2,451	$13,927
Toyota Prius	HEV	0.039	$3,167	$13,927
Toyota Camry	CV	0.059	$4,843	$15,416

Figure 2 compares retail, fuel, maintenance, and charging infrastructure costs over the lifetime of the vehicles. The per-vehicle cost for the City to lease charging infrastructure is assumed to be $700/year for both EVs and the PHEV, based on communication with City officials. That is based on a dual-port system with extensive data gathering, and with a charge-ready parking spot always available for each electrified fleet vehicle. Because the 7-year cost of this charging equipment alone ($4,900) is higher than the 7-year cost of fuel for the conventional vehicle (approximately $4,800), it more than negates the lower cost of electricity than gasoline. Thus, the most expensive vehicle to purchase and maintain is the Nissan Leaf e+, the EV with the largest range, while the least expensive vehicle is the Toyota Prius HEV, with a $7,241 difference in cost between the two (Figure 2). Notably, both the HEV and the base model of the Nissan Leaf are less expensive in terms of lifetime costs than the CV, with the savings in maintenance as the most influential factor in the differential. Further, without the $700/year leasing cost for electric vehicle charging infrastructure, the Nissan Leaf EV base model and the Toyota Prius Prime PHEV would both be cheaper than the CV option, with the Leaf cheaper than both the HEV and the CV.

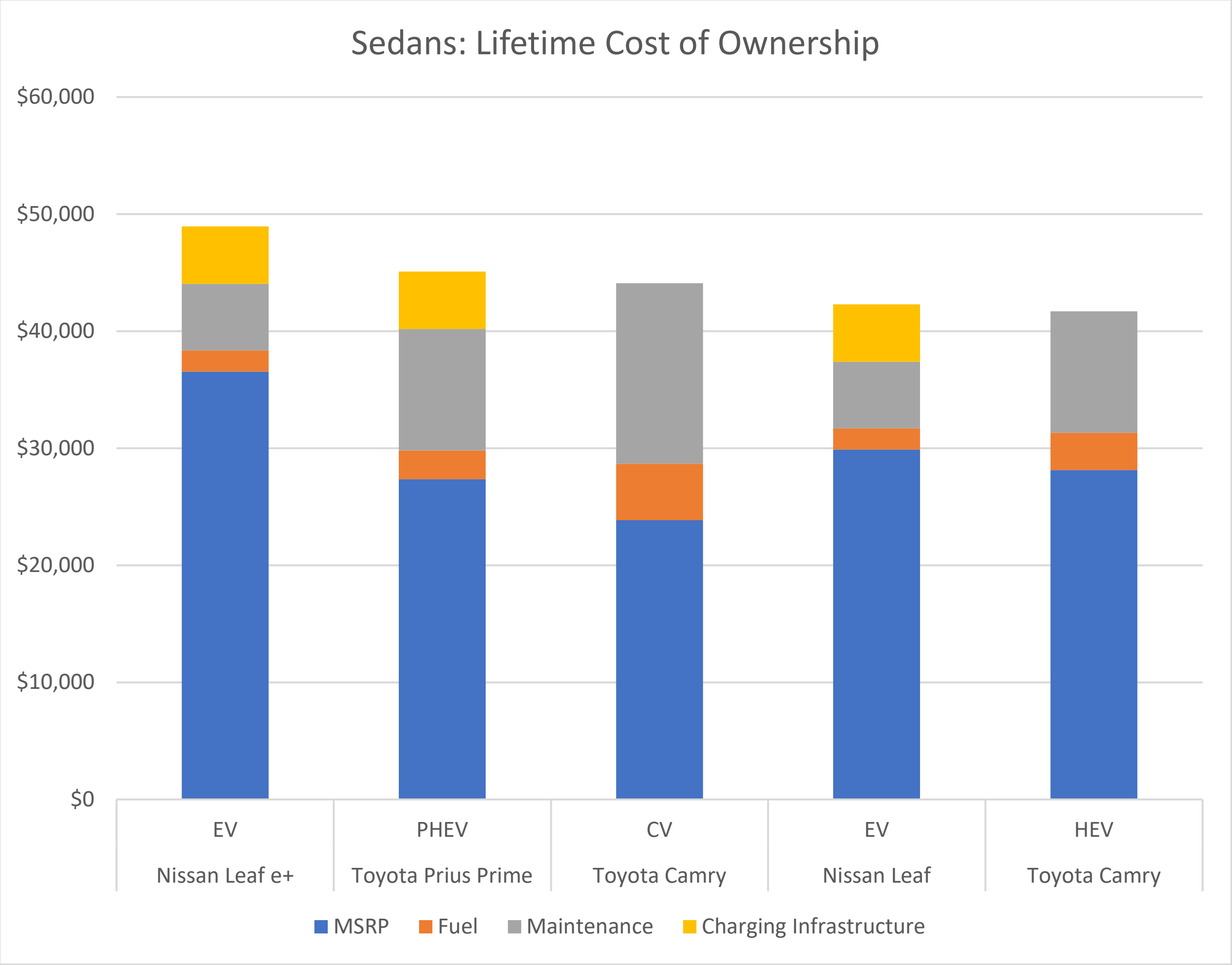

Figure 2. Lifetime costs of ownership for sedans broken down by expense category. A 7-year lifetime was assumed. We used City-reported values for fuel costs, and calculated overall levelized maintenance costs and expected lifetime mileage. MSRPs were the retail prices with no discounts. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle

Note that the above cost assessment does not include salvage value. The City of Houston reported that they received an average of $946 in salvage value for retired vehicles in 2018, but since only gasoline vehicles were retired, we were unable to make a comparison across vehicle types. The expected salvage values of EVs in general are unknown, since affordable EV sedans and SUVs have not been on the market long enough to result in reliable estimates.

4.b.ii. SUVs

Our initial cost-comparison of SUV models accounted for initial retail prices, lifetime fuel costs, and expected maintenance costs. The fuel cost comparison in Table 10 suggests that, over a 7-year lifetime, purchasing the Kona Electric EV will result in the maximum potential fuel savings of $3,126 over its CV counterpart, which is less than the $4,900 lifetime cost for charging infrastructure. The PHEV models of the Mitsubishi Outlander and Subaru Crosstrek yield even less fuel cost savings than their CV counterparts, and still require costly charging infrastructure. Fuel costs for the Ford Explorer HEV are the same as for the Ford Explorer CV, because the fuel economy for the two vehicles is the same. However, the hybrid version of the Toyota Highlander yields some fuel savings.

Table 10. Lifetime fuel costs for SUVs over a 7-year lifetime, excluding the cost of charging infrastructure. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle and CV = gasoline vehicle.

Vehicle Model	**Lifetime Fuel Costs ($)**			
	CV	**HEV**	**PHEV**	**EV**
Ford Explorer	$6,809	$6,809		
Toyota Highlander	$7,428	$5,635		
Mitsubishi Outlander	$6,053		$5,102	
Subaru Crosstrek	$6,537		$3,940	
Hyundai Kona	$5,448			$1,622

Additionally, we looked at the expected maintenance costs of the different SUV models by first determining both expected lifetime mileage and expected maintenance costs per mile for SUVs from vehicle data provided by the City, and then extrapolating the expected reduction in maintenance costs from available literature on sedan maintenance as explained in Section 3.f. Figure 3 shows that of the selected models, the only alternative-fuel vehicle less expensive than the CV counterpart was the Toyota Highlander HEV. For now, reductions in fuel and maintenance costs do not outweigh the cost of charging infrastructure and the difference in purchase price.

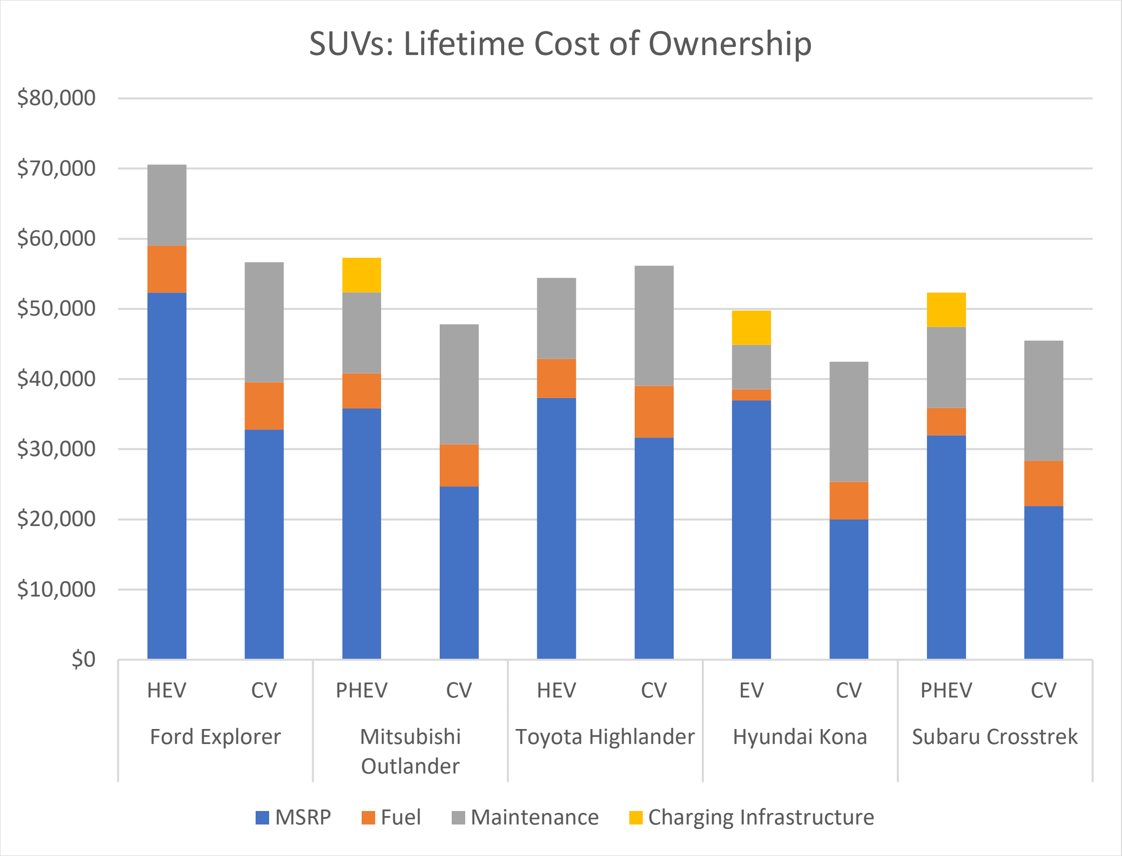

Figure 3. Lifetime costs of ownership for SUVs of different models and fuel types broken down by expense category. A 7-year lifetime was assumed. We used City-reported values for fuel costs and included the $700 per-year per-vehicle cost for leasing charging infrastructure for EVs and PHEVs. We calculated overall levelized maintenance costs and expected lifetime mileage using City vehicle usage data. MSRPs were the retail prices with no discounts. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle.

4.b.iii. Pickup trucks

As with sedans and SUVs, the purchase price, projected fuel costs and projected maintenance costs were used to determine the lifetime costs of ownership. Table 11 below shows the lifetime fuel costs for the different pickup truck models. The HEV costs are either equal to or slightly lower than the CV models. Because the increases in fuel economy are modest in mild hybrids, the relative decrease in fuel costs are less than the decreases seen in both SUVs and sedans.

Table 11. Lifetime fuel costs of CVs vs. HEVs for both two- and four-wheel drive models of the pickup trucks. Seven-year lifetime and FY2018 fuel prices assumed. HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle.

Vehicle Model	**Drive Type**	**Lifetime Fuel Costs ($)**	
		CV	**HEV**
RAM 1500	2x4	$6,204	$5,935
Ford F-150	2x4	$6,204	$6,204
RAM 1500	4x4	$6,500	$6,204
Ford F-150	4x4	$6,825	$6,500

Figure 4 shows the lifetime cost of ownership of the trucks. For both the Ford F-150 and Ram 1500, the HEVs have a lower cost overall than the CVs for 4x4 and 2x4 drive PUTs. The initial price premium on mild hybrid engines is compensated for by the lower maintenance costs of hybrid systems. Thus, purchasing pickup trucks with the mild hybrid engine option will save money overall in the City's operating budget.

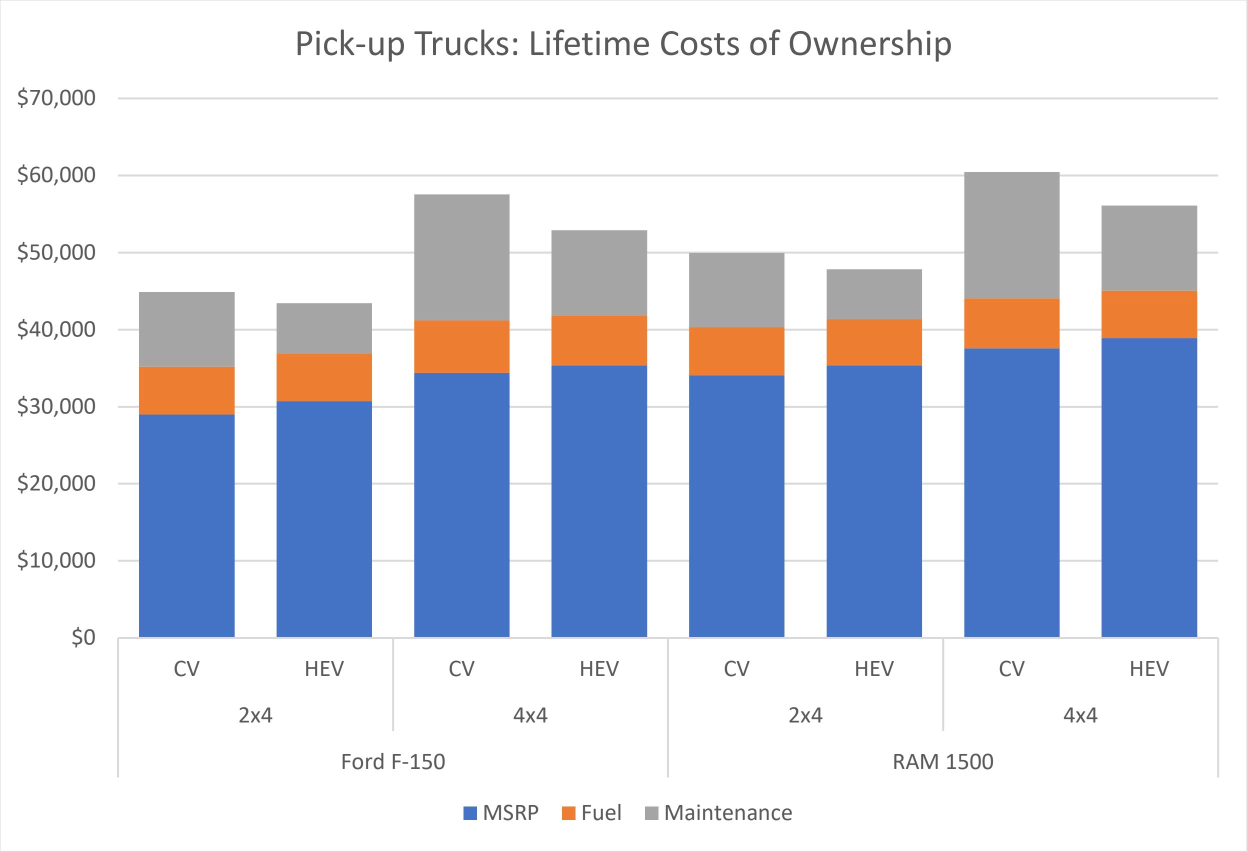

Figure 4. Lifetime costs of ownership for various pickup truck models separated by category of expense. Seven-year vehicle lifetime and average city pickup truck usage assumed. HEV = hybrid-electric vehicle, and CV = conventional gasoline vehicle.

4.c. Environmental comparisons

The two kinds of vehicle emissions modeled in this study were greenhouse gases (GHGs) and NO_x. Since the effects of GHGs in promoting climate change are not localized, we looked at the emissions created over the entire vehicle life cycle. Specifically, we modeled projected emissions from vehicle component production; vehicle assembly, disposal and recycling (ADR); well-to-pump fuel processing; and vehicle operation. By contrast, for NO_x, the impacts on air pollution and health are local, so only direct emissions from vehicle operation were considered.

To put the NO_x impacts in context, we ran both the AP3 (Air Pollution Emission Experiments and Policy model, version 3)[38] and EASIUR (Estimating Air pollution Social

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[38] https://public.tepper.cmu.edu/nmuller/APModel.aspx

Impact Using Regression)[39] reduced-form air pollution impacts models. Each model estimates the monetized value of health impacts resulting from a ton of pollution released from any given location in the United States. AP3 computes impacts via the formation of ground-level ozone and fine particulate matter (PM) from NO_x, whereas EASIUR considers only PM formation from NO_x. For ground-level NO_x emissions released from Harris County, the two models give the results shown in Table 12. Thus, the monetized value of NO_x is $2,719/ton in AP3 and $7,235/ton in EASIUR. These estimates should be seen as conservative, because they neglect the direct impacts of breathing NO_2 and impacts beyond health, such as crop damage caused by ozone. Taking the ozone results from AP3 (since ozone is neglected by EASIUR), and the PM results from the average of the two models, we estimate an overall impact of NO_x emissions from Harris County to be $5,304/ton.

Table 12. Impact per-ton of NOx emissions released from Harris County, as simulated by the AP3 and EASIUR models.

Model	**Ozone from NO_x**	**PM from NO_x**
AP3	$653	$2,066
EASIUR	NA	$7,235

4.c.i. Sedans

Figure 5 presents the life cycle emissions of the different sedan models examined in this study. The hybrid and all-electric models all outperformed the CVs in terms of lifetime emissions. The EVs had significantly lower emissions than the other vehicles, not only due to lack of tailpipe emissions but also due to the fact that most of the electricity purchased by the City is from renewable sources.

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[39] https://barney.ce.cmu.edu/~jinhyok/easiur/

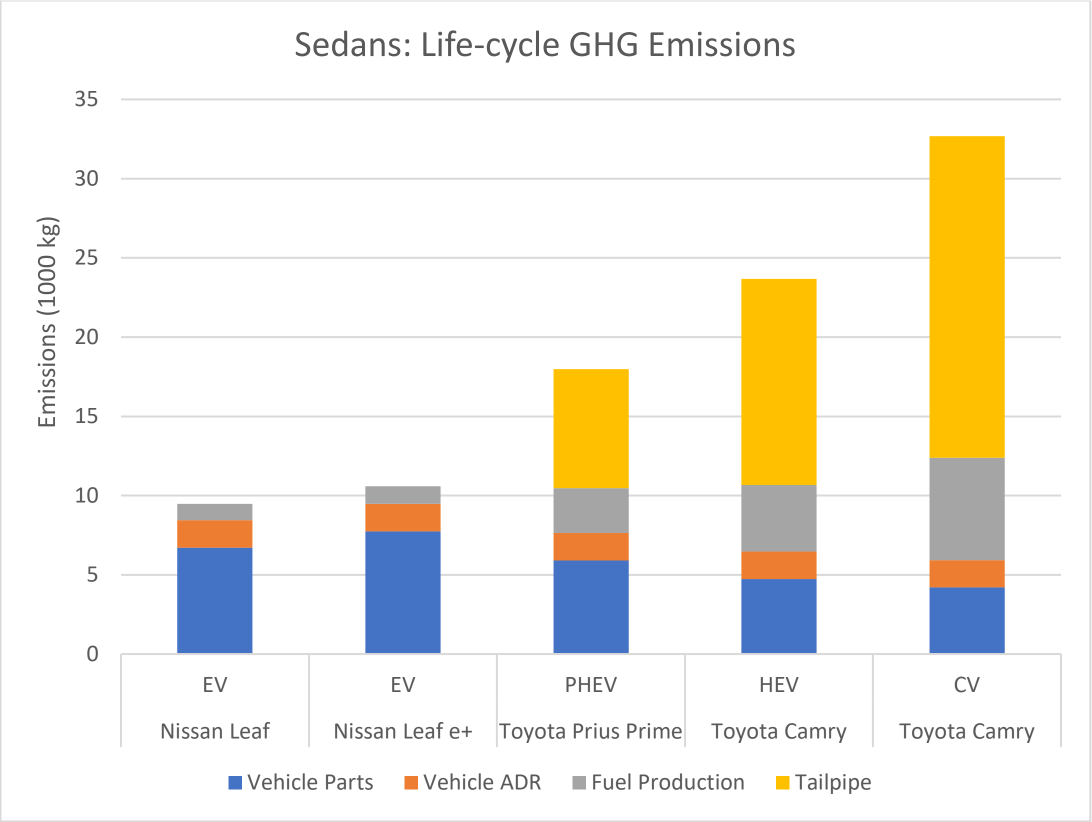

Figure 5. Projected lifetime GHG emissions for all sedan types. Seven-year lifetime and average city sedan usage was assumed. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle and ADR = assembly, disposal and recycling.

NO_x emissions are harmful to health, both directly via the health impacts of NO_2 and indirectly via their role in the formation of ozone and particulate matter pollution. We considered NO_x emissions only from vehicle operation, since those are released from tailpipes that are often near other drivers and pedestrians (Figure 6).

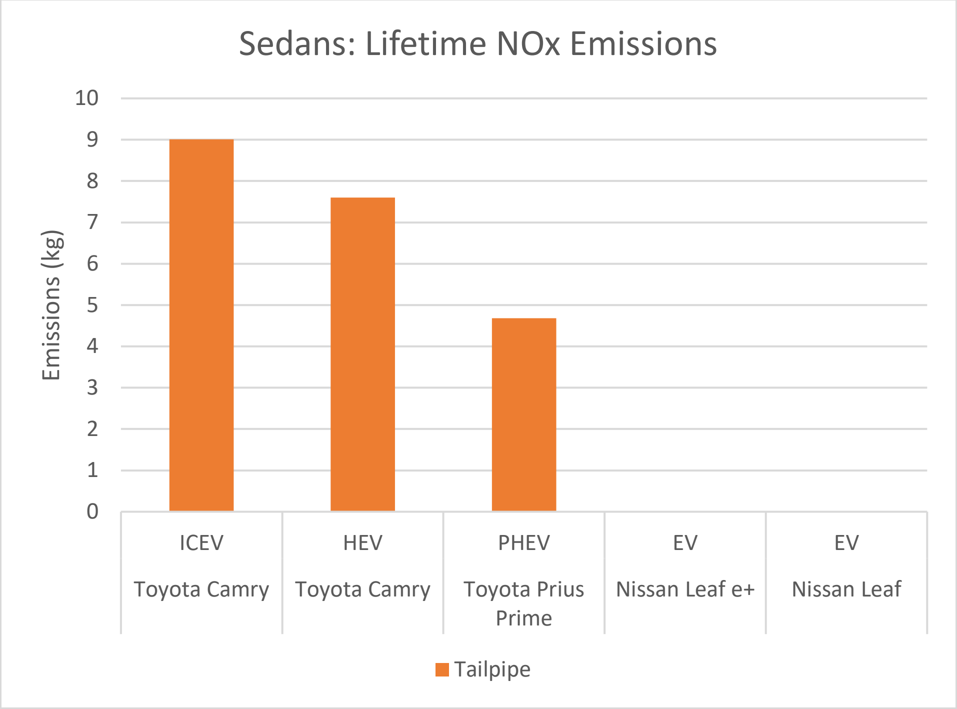

Figure 6. Lifetime sedan NO_x tailpipe emissions by vehicle type. Assumes a 7-year vehicle lifetime with average City use. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle,and CV = conventional gasoline vehicle.

4.c.ii. SUVs

We found that hybrid-electric and full-electric SUVs produced lower GHG emissions than all gasoline-powered SUVs (Figure 7). The higher emissions from the manufacture of hybrid and electric vehicles was more than offset by significant reductions in tailpipe GHG emission for all models except for the Ford Explorer.

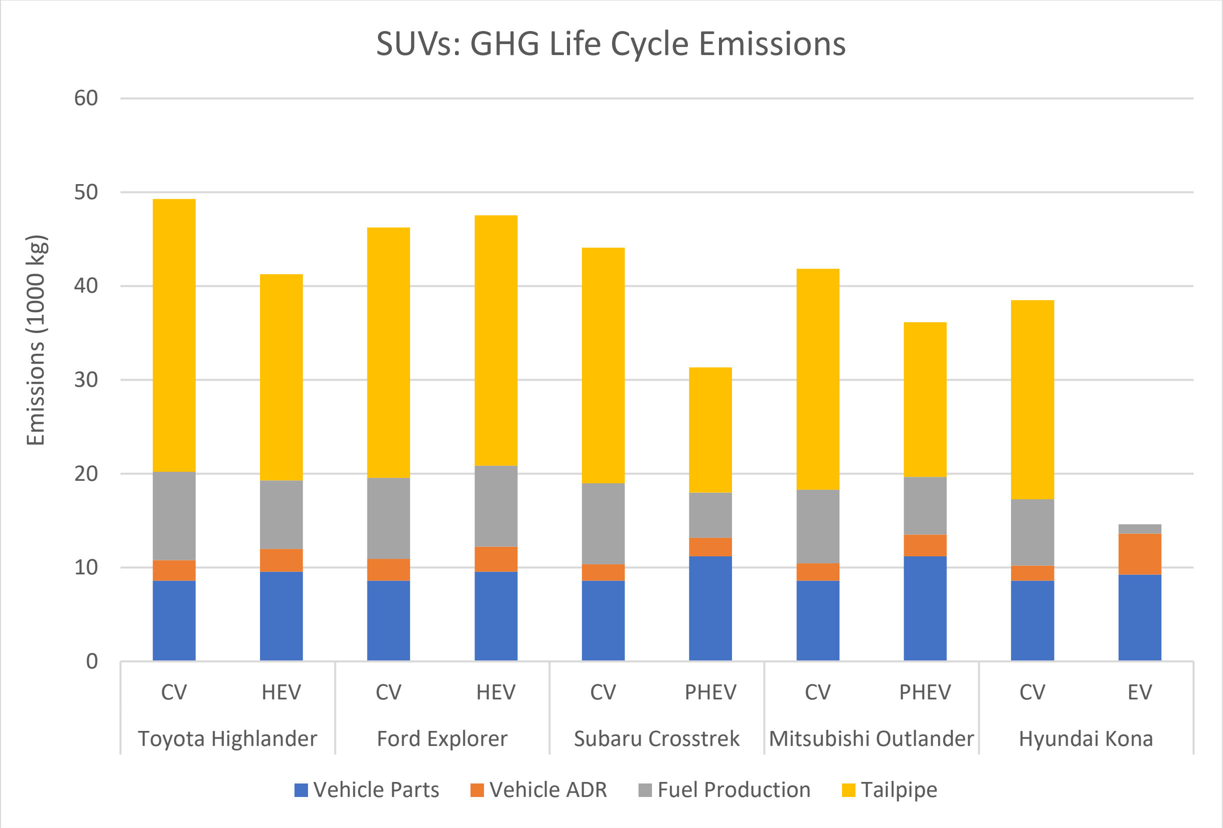

Figure 7. Lifetime greenhouse gas emissions for SUV models broken down by stage in the vehicle life cycle. Seven-year lifetime was assumed for all vehicles as well as average usage for City of Houston vehicles. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle and HDR = vehicle assembly, disposal and recycling.

Similar to our results for sedans, we found that tailpipe NO_x emissions were lower for all-electric and hybrid SUVs than for traditional SUVs across all vehicle brands (Figure 8).

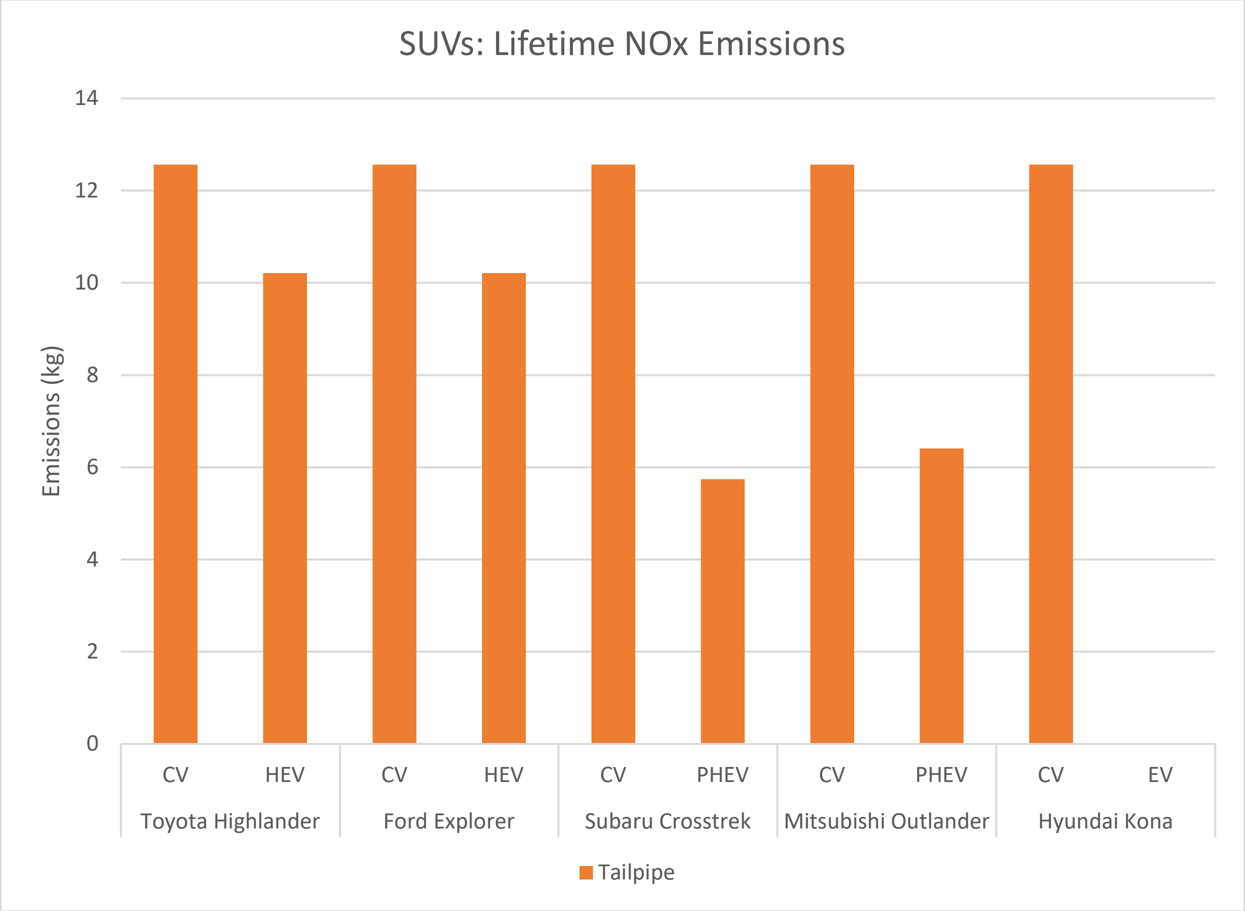

Figure 8. Average per-mile tailpipe NO_x emissions from SUVs. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle,and CV = conventional gasoline vehicle.

4.c.iii. Pickup trucks

We first analyzed greenhouse gas emissions by the CVs and HEVs with either two-wheel or four-wheel drive by both pickup truck manufacturers. Figure 9 shows that the HEVs produced lower emissions than the CVs for both drive-types, with the difference in emissions being more pronounced for the four-wheel drive pickup trucks.

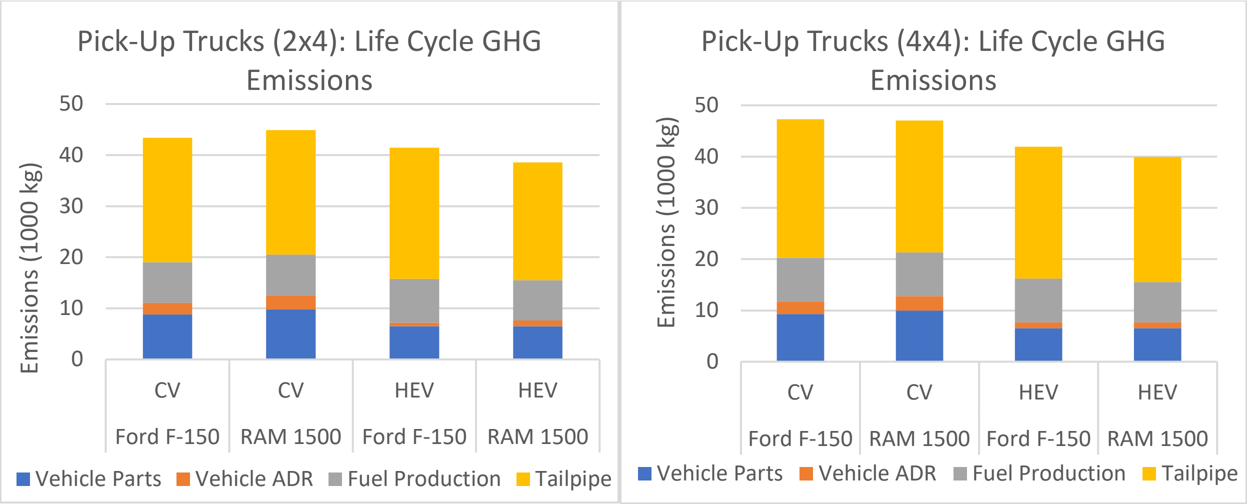

Figure 9. Lifetime greenhouse gas emissions of 2-wheel and 4-wheel drive pickup trucks respectively. Assumes a 7-year vehicle lifetime with average City use. HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle.

Additionally, Figure 10 shows that pickup trucks with mild hybrid powertrains emit around 100 mg/mi less NO_x than conventional pickup trucks.

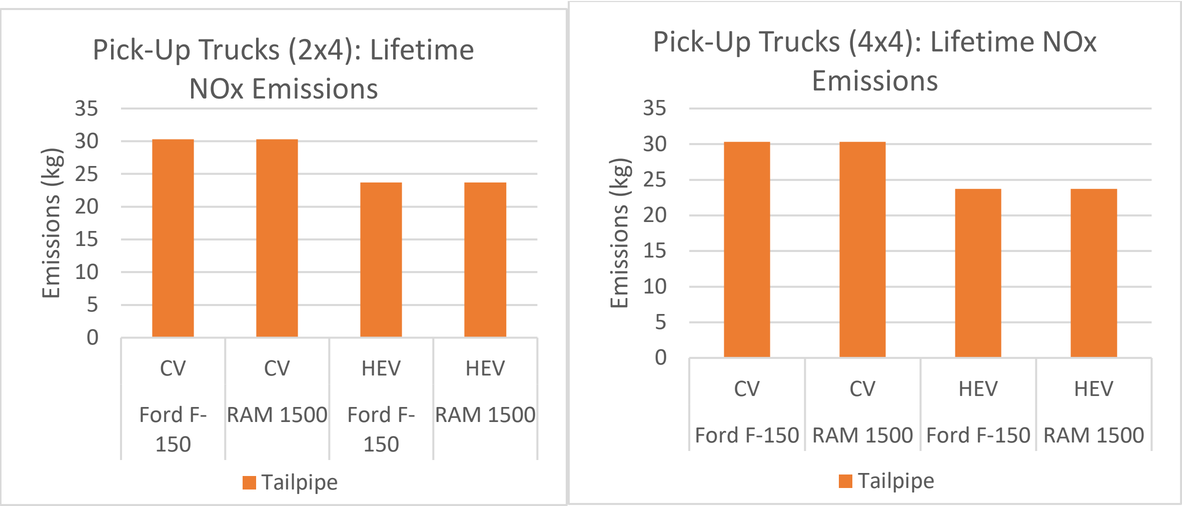

Figure 10. Average lifetime NO_x tailpipe emissions of 2-wheel and 4-wheel drive PUTs. Assumes a 7-year vehicle lifetime with average City use. CV = conventional gasoline vehicle, HEV = hybrid-electric vehicle.

5. Optimization

5.a. Methods

Since cost-competitive options were found for all vehicle types (CV, HEV, PHEV, EV) for sedans, but electric options remain substantially more costly for SUVs and unavailable for pickup trucks, we focus our optimization on sedans. Table 13 shows the parameters required as inputs to the optimization model. Optimizations were completed that represent a variety of economic and technological forecasts, so many of these parameters' values were varied over multiple runs, as specified in the case descriptions in Sections 5.b. and 5.c. However, the parameters with listed values were held constant across all cases and are described below.

Table 13. Parameters used in optimization model. References to tables are made when the inputs used varied by year or vehicle type and are given elsewhere in this report. An * indicates that this assumption was varied over several optimized scenarios.

Category	Parameter	Value
City Vehicle Usage	Miles Travelled per vehicle	*
	Mileage Demand	16,917,503 mi
Costs	Vehicle Purchasing Budget	See Table 1
	Vehicle Purchase Price	*
	Per-Mile Operation & Maintenance Cost	*
	Salvage Revenue	$0
	Emissions Cost per Ton of GHG	$51
	Discount Rate	0%
Emissions	Vehicle Production Emissions	*
	Vehicle Utilization Emissions	*
	Vehicle ADR Emissions	*

To find total sedan mileage demand, we used the vehicle-level usage data provided by the City of Houston, which included 2031 total vehicles. We then looked at vehicles whose M5 and Fuel Force mileage counters showed a difference of less than 500 miles to ensure reliable usage data. We then calculated the average yearly miles traveled by these vehicles, which was 8330 miles, and multiplied this by the total number of sedans owned to arrive at a total City demand of 16,917,503 miles.

We did not include a salvage value in our optimization because there is insufficient information to determine what differences will be between salvage values of traditional gasoline vehicles and hybrid or electric vehicles. As noted earlier, we assumed a discount rate of 0%, since the City's 2% nominal rate matches the 2% inflation rate targeted by the U.S. Federal Reserve, suggesting a real interest rate near zero. The $51 cost per ton of GHG emissions was taken from the Department of Transportation's estimate of the social cost of carbon in 2019 under its mid-range (3%) societal discount rate.[40]

Future Vehicle Cost Projections

Projections of future vehicle costs for years 2020-2025 were calculated using projected change in average MSRP by vehicle fuel type from the International Council on Clean Transportation (ICCT).[41] The projections were scaled based on the 2019 vehicle prices for the models used in our analysis. Future vehicle efficiencies were obtained from the Energy Information Administration's (EIA's) 2019 Annual Energy Outlook (Table 14). Those projections assumed that fuel economy would continue improving through the 2025 model year under Obama-era rules, which may be rolled back by President Trump. If fuel economy standards are rolled back, then smaller scaling factors should be used for CVs and HEVs. For future rounds of our analysis, we also intend to consider price and fuel efficiency projections from the National Renewable Energy Laboratory's Electrification Futures Study[42] and the BNEF Electric Vehicle Outlook 2019.

Table 14. Scaling factors for future fuel economy of CVs and HEVs. Taken from EIA's 2019 Annual Energy Outlook. HEV = hybrid-electric vehicle and CV = conventional gasoline vehicle.

	2019	2020	2021	2022	2023
CV	1.00	1.04	1.09	1.14	1.18
HEV	1.00	1.05	1.10	1.15	1.18
PHEV	1.00	1.00	1.00	1.00	1.00
EV	1.00	1.00	1.00	1.00	1.00

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[40] https://www.transportation.gov/sites/dot.gov/files/docs/Tiger_Benefit-Cost_Analysis_%28BCA%29_Resource_Guide_1.pdf

[41] https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf. Detailed data was provided by Nic Lutsey.

[42] https://www.nrel.gov/docs/fy18osti/70485.pdf

The resulting projections for undiscounted purchase price and 2019 operational costs are shown in Tables 16 and 9, respectively, with Figure 11 providing a graphical comparison.

Table 16. Expected MSRPs for vehicles of each type by model year. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle.

Vehicle Type	**Year**				
	2019	**2020**	**2021**	**2022**	**2023**
EV (150 mi)	$29,900	$28,400	$27,000	$25,800	$24,700
EV (250 mi)	$36,600	$34,500	$32,800	$31,100	$29,700
PHEV	$33,500	$33,300	$33,100	$32,900	$32,800
HEV	$28,200	$28,300	$28,300	$28,300	$28,300
ICEV	$23,800	$23,900	$23,900	$23,900	$23,900

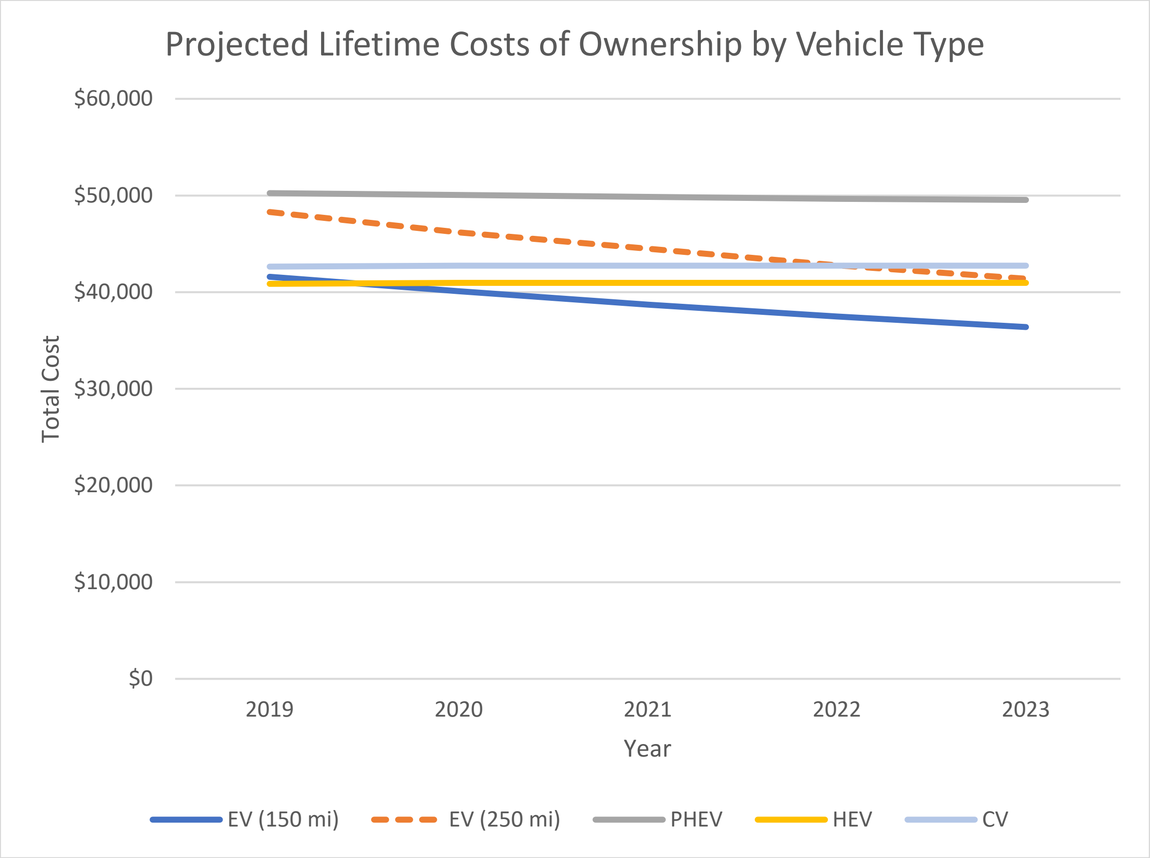

Figure 11. Projected total vehicle costs over time, excluding the cost of emissions. Assumes a 7-year vehicle lifetime. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle.

Future Vehicle Emissions Projections

Projected changes in vehicle efficiency from the EIA, as well as projected changes in EV battery prices and vehicle weights, were used as input into the GREET model to calculate expected emissions for each sedan for each model year; the results can be seen in Figure 12.

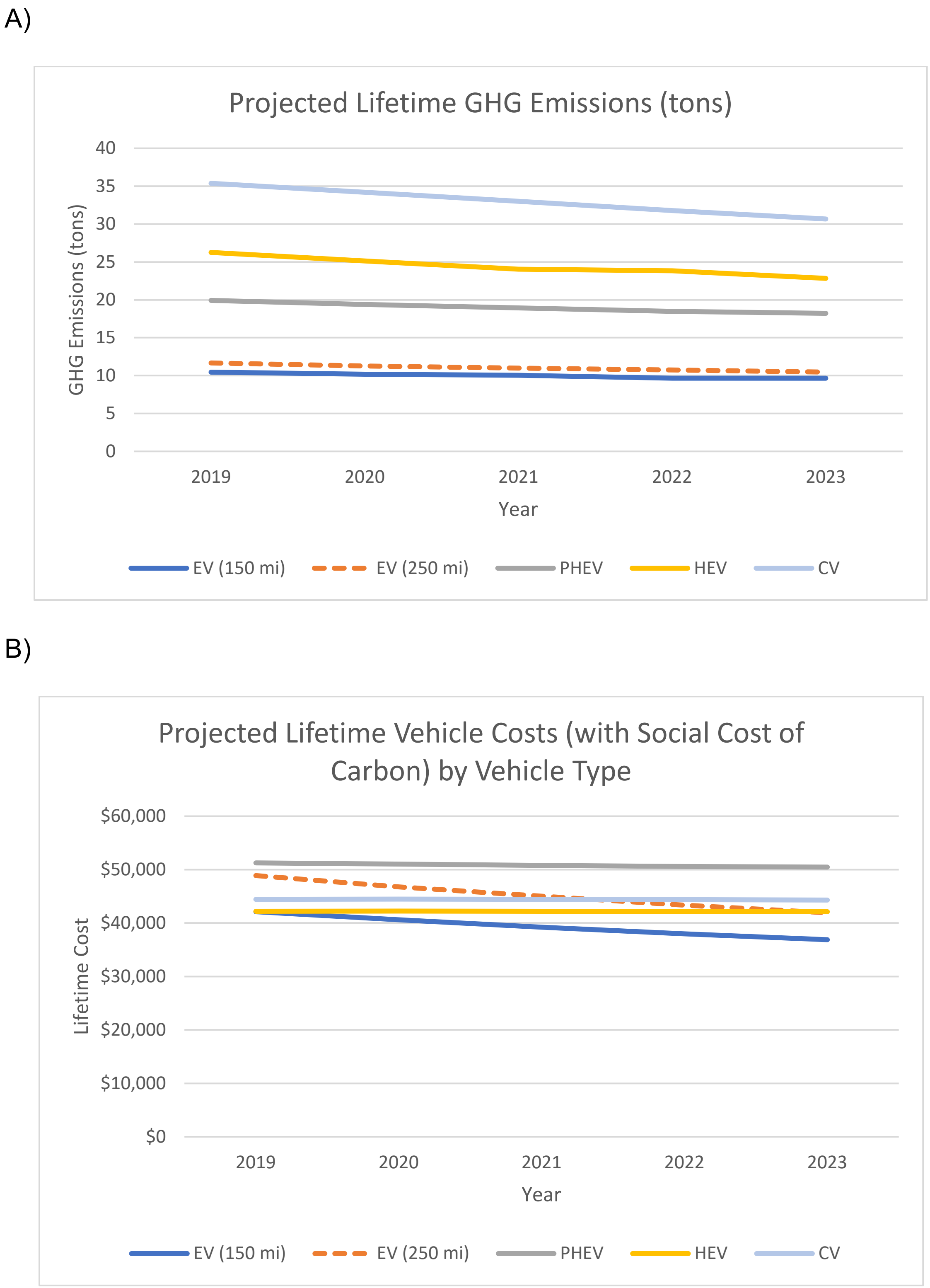

Figure 12. A) Projected GHG emissions and B) projected lifetime costs including GHG costs for vehicles of different fuel types based on purchase year, assuming a 7-year lifetime. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle

5.b. Results

We ran our optimization model for sedans with assumptions from the scenarios listed in Table 17. In future work, we plan to also consider cases with tax credits or grants available for EVs, alternate assumptions for fuel costs, and alternate assumptions for mileage driven.

Table 17. List of scenarios covered in our analysis and descriptions of the varied parameters.

Scenario	Description
Base Case	Assumed average sedan usage and no change in fuel prices after 2019. Used projected prices with no discounts applied. Ran without costs associated with emissions projected by GREET.
Social Costs of Emissions Included	Assumed average sedan usage and no change in fuel prices after 2019. Used projected prices with no discounts applied. Ran with costs associated with GHG emissions projected by GREET.

We used the total estimated MSRP for each vehicle type and model year and constant yearly operating costs as described in the methods. One important note is that due to the set-up of the optimization model, we needed to determine the total miles driven yearly by sedans in the Houston fleet. Because we also needed to specify a maximum age for vehicles, which for our study was seven years, and because the budget for new vehicle purchases is too low to immediately replace all fleet miles driven by currently-owned vehicles older than seven years, in order to run the model we assumed that total annual miles driven to be 10.5 million miles, while data from CoH showed around 16.9 million miles driven annually by sedans. The 10.5 million mile value was the greatest mileage (to the nearest 500,000) that the model could accept while still returning a valid result.

Our first analysis (base case) excluded costs due to emissions and looked at the optimal purchase plan given current vehicle life cycle costs. The results are shown in

Table 18. The same results were obtained when including the social cost of GHG emissions in the optimization model, as those costs were too small to substantially sway results.

Table 18. Optimized sedan purchasing plan with base case assumptions and no costs related to emissions included. EV = electric vehicle, PHEV = plug-in hybrid-electric vehicle, HEV = hybrid-electric vehicle, CV = conventional gasoline vehicle

Sedan Type	**Purchase Year**				
	2019	**2020**	**2021**	**2022**	**2023**
CV	62	42	87	0	0
PHEV	0	0	0	0	0
HEV	0	0	0	0	0
EV	0	0	0	75	65

From the table, it can be seen that CVs continue to be the most cost-effective option through 2021. This is primarily due to the initial costs of the vehicles: even though we predicted that short-range EVs would achieve lower lifetime costs than CVs by the year 2020, the relative savings were from reduced maintenance costs and not MSRP. Because the CoH vehicle purchasing budget is separate from the operations and maintenance budget and the model required all seven-year-or-older vehicles to be replaced, the higher starting prices of EVs meant that not enough could be purchased to satisfy unmet mileage demand until 2022. If PHEV costs indeed remain approximately flat as projected by ICCT (Figure 12), then they will not become a preferred option, especially since charging infrastructure costs (if assumed to be $700/year) outweigh potential fuel cost savings. Lower cost options for charging infrastructure would enhance the affordability of PHEVs and EVs. Additionally, maintenance and fuel savings increase for EVs relative to CVs the longer the vehicles are owned, so increasing the expected vehicle lifetime would make electric sedans even more competitive.

6. Conclusions and Recommendations

This study has reviewed the options for conventional, hybrid, plug-in hybrid, and electric vehicles that are available to meet the needs of the City of Houston fleet. Electric options are available only for sedans and SUVs, so we focused our attention on those vehicle types. Electric models of pickup trucks and vans are likely to become available in a few years, but insufficient information is available for analysis at this time. Several key conclusions emerge from our analysis:

1. Fully electric and plug-in hybrid models of sedans and SUVs are currently available that can meet the City's needs for range and capacity. For sedans, the base model of the Nissan Leaf has adequate range and is more affordable than the extended range (e+) option, while the Toyota Prius Prime provides a viable option for a PHEV. For SUVs, the Hyundai Kona EV and Mitsubishi Outlander and Subaru Crosstrek PHEVs satisfy the required mileage range.
2. For sedans, lifetime costs of ownership are similar across the CV, HEV, PHEV, and base-level EV models considered here (Figure 2). Thus, slight changes in assumptions will alter the ranking of options.
3. For SUVs, electric and plug-in hybrid options are available, but in most cases are not yet as affordable as conventional SUVs (Figure 3).
4. Charging infrastructure costs of $700 per vehicle per year, as estimated for an option under consideration by the City, would exceed the fuel savings from replacing gasoline vehicles, given the low cost of fuel assumed here (Figures 2 and 3). Thus, more affordable chargers and/or grants will be crucial for the cost competitiveness of EVs. Opportunities to purchase chargers outright, rather than leasing them for an annual fee, deserve closer attention.
5. Maintenance costs exceed fuel costs for most City vehicles, and thus are crucial to cost comparisons. Our literature review (Table 7) found that HEVs and PHEVs are likely to yield moderate savings, and EVs major savings, compared to conventional vehicles. This deserves a closer look as the City gains more experience in maintaining alternative vehicles and more data become available.
6. Even at current fuel and charger costs, our optimization suggests there is likely to be a turning point within the next five years when mid-range EVs will supplant CVs as the least-cost option for sedans. How soon that transition

comes will depend on how quickly EV purchase prices fall and whether a more affordable option for charging infrastructure is found.

Appendix A: Assessments of CNG vehicles in prior studies

A 2017 peer-reviewed paper by Shayak Sengupta and Daniel Cohan based on City of Houston fleet data found that CNG vehicles do not yield benefits in terms of emissions or costs, as shown in the following three figures. [43]

S. Sengupta, D.S. Cohan / Transportation Research Part D 54 (2017) 160–171 165

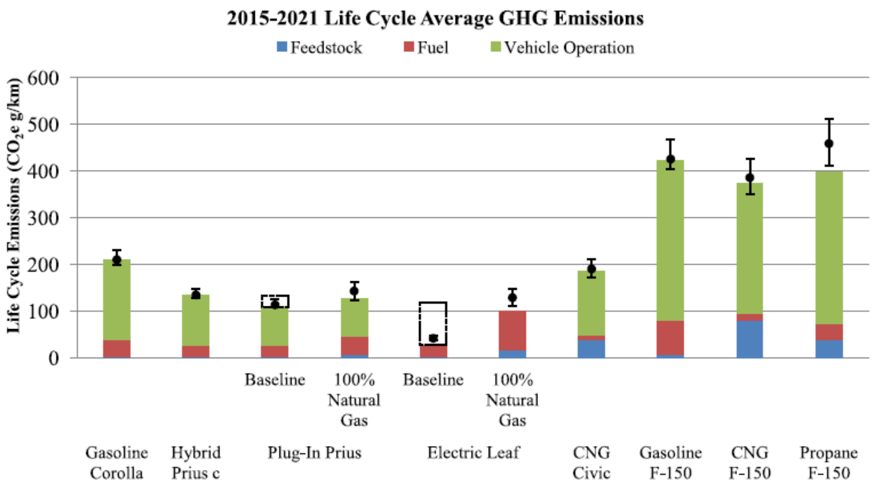

Fig. 1. Fuel cycle CO_2e emissions estimates from GREET (solid bars) with best, 5th percentile, and 95th percentile upstream emissions from the Venkatesh studies (error bars and dot). Dashed bars show emissions under ERCOT grid electricity.

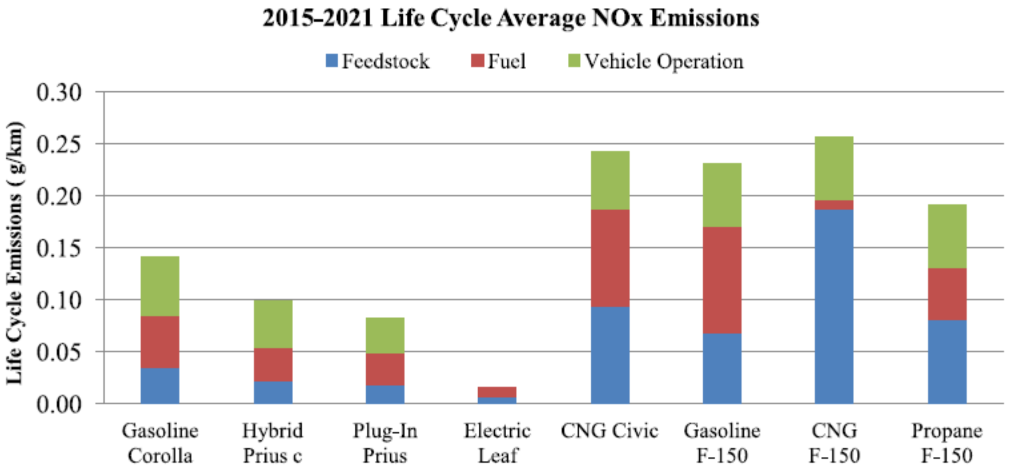

Fig. 2. Fuel cycle average NOx emissions.

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[43] Sengupta, S., and D.S. Cohan (2017). Fuel Cycle Emissions and Life Cycle Costs of Alternative Fuel Vehicle Policy Options for the City of Houston Municipal Fleet. *Transportation Research D*, 54, 160-171. doi:10.106/j.trd.2017.04.039

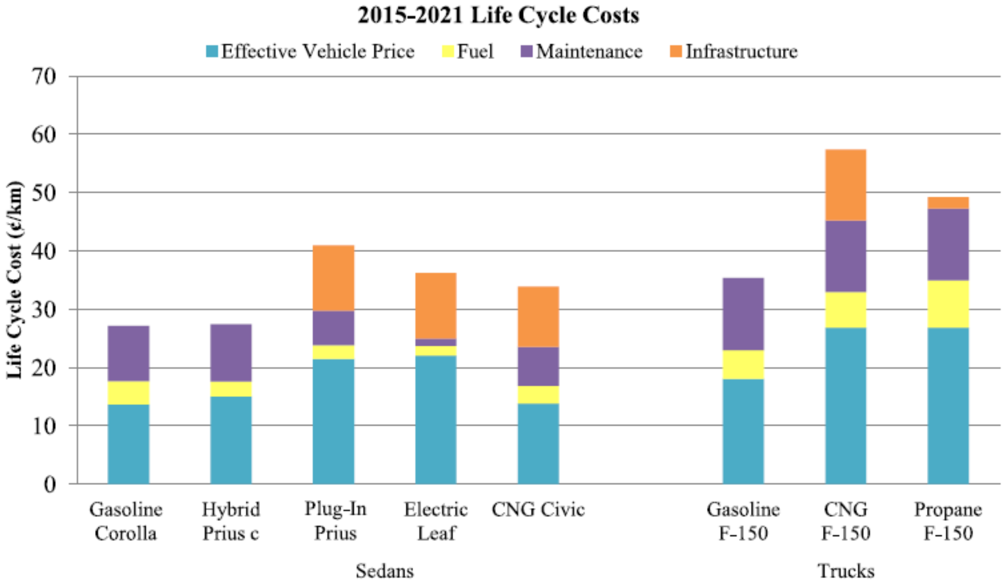
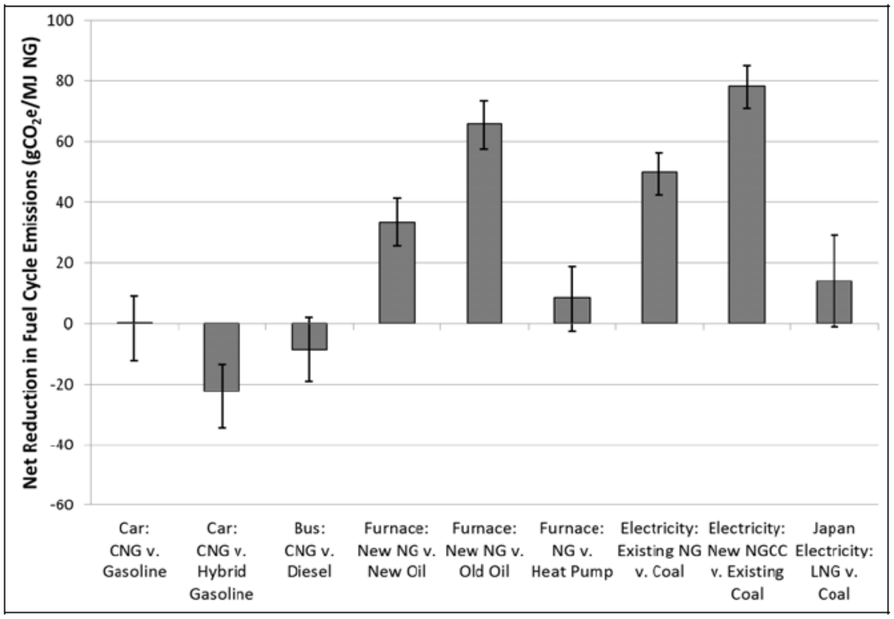


Fig. 5. Levelized life cycle cost for each vehicle model.

A 2016 peer-reviewed paper by Daniel Cohan and Shayak Sengupta[44] found that CNG vehicles yield no net greenhouse gas reductions versus gasoline or diesel, whereas substituting natural gas for coal electricity or heating oil yields reductions.

Figure 5 Net emission reductions ($gCO_2e/MJNG$) per natural gas used in substitutions for other fossil fuel, and uncertainty due to 95th–5th percentile uncertainty in natural gas upstream emissions



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[44] Cohan and Sengupta. 2016. Net greenhouse gas emissions savings from natural gas substitutions in vehicles, furnaces and power plants. *International Journal of Global Warming.* 9(2), 254-273.