Cambridge Clean Fleet Initiative

2030 GHG Reduction Scenarios and Proposed Target

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List of Abbreviations

Abbreviation	Term
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool
BAU	Business-as-usual
CCS	Carbon capture and sequestration
DOE	Department of Energy
DPW	Department of Public Works
EIA	Energy Information Administration
EV	Electric vehicle
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWh	Gigawatt-hours
HEV	Hybrid electric vehicle
HHV	Hybrid hydraulic vehicle

Abbreviation	Term
IR	Idle reduction
ISO	Independent system operator
kg	Kilogram
MWh	Megawatt-hour
MOVES	Motor Vehicle Emission Simulator
NPV	Net present value
PHEV	Plug-in hybrid electric vehicle
RGGI	Regional Greenhouse Gas Initiative
SUV	Sport utility vehicle
TCO	Total cost of ownership

I Executive Summary

In 2016 the Department of Public Works (DPW) began a Clean Fleet initiative that supports the City of Cambridge's 2050 carbon neutrality goals under the Metro Mayors Climate Commitment[1] and complements the City's Net Zero Action Plan.[2] To address fleet GHG emissions, the City is working with the U.S. Dept. of Transportation's Volpe National Transportation Systems Center (Volpe) to

1) develop strategies to decrease greenhouse gas emissions (GHG) from the municipal fleet;
2) establish a 2030 fleet GHG emissions reduction target from the 2016 baseline; and
3) create a fleet implementation plan to reach that target.[3]

This report addresses the first two priorities; an implementation plan will be developed subsequently.

Volpe modeled the GHG emission impacts of incorporating various advanced technologies in new City vehicles, such as electrification or hybridization, as well as of certain aftermarket technologies. In consultation with City staff, Volpe also modeled eight combinations of external and internal input assumptions. From the 2016 baseline year, Volpe's analysis projects that achievable 2030 GHG reductions due to advanced technologies and operational efficiencies could range from 55.7 percent to 64.5 percent; and that the net present value could range from $6,956,597 to $(5,392,612), with the wide NPV range due largely to uncertainty in future fuel prices.

2030 outcome name	Target GHG reduction	Modeled GHG reduction that supports target value	Modeled annual GHG reduction (tons)	Modeled savings (net present value)
Achievable Target	55%	55.9%	1,435	$1,159,195
Stretch Target	60%	60.5%	1,555	$568,817
Stretch Plus Target	65%	64.5	1,656	$568,817

Based on the analysis using average input assumptions and an annual incremental capital cost limit of $300,000, **it is feasible for the City to select 55% as a GHG reduction base target and 60% as a stretch target for its fleet** of 353 vehicles. The Stretch Target assumes additional capital investment and additional operational efficiency strategies. The addition of 100% renewable electricity supply, under separate consideration by the City, subsequently supports a **"stretch plus" target of 65% reduction**.

In the Achievable Target outcome, **336 of the 353 fleet vehicles** are equipped with advanced GHG reducing technologies or are replaced by vehicles other than conventional gasoline or diesel vehicles. Achieving this target will **reduce GHG emissions by 1,435 tons per year from the City's fleet** and significantly lower criteria pollutants, while maintaining a **positive net present value of $1.15 million**.

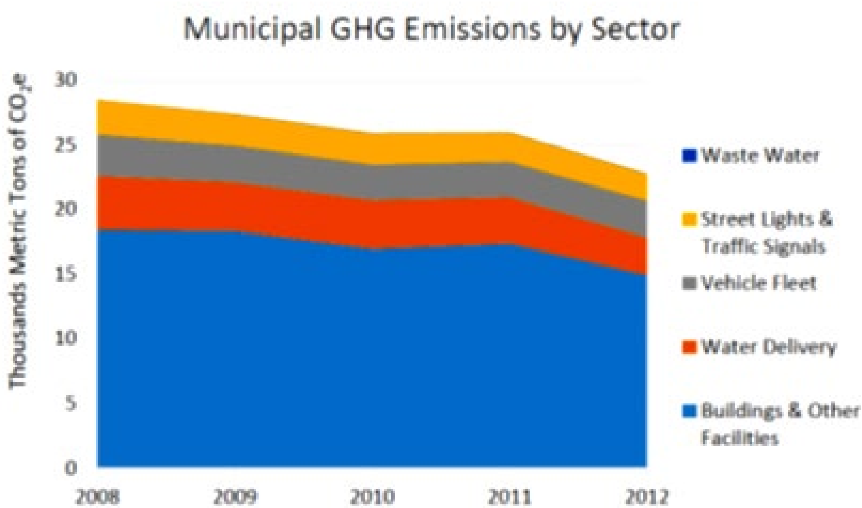
[1] http://www.cambridgema.gov/CDD/News/2016/11/metromayorsclimatecommitment.aspx
[2] http://www.cambridgema.gov/~/media/Images/CDD/Climate/NetZero/netzero_20150408_infographic.jpg
[3] https://www.cambridgema.gov/theworks/energyefficiency/cleanfleetinitiative

Analysis assumptions were based on best available information on technology availability, costs, projections for electric grid emissions, vehicle fuel economy and GHG emissions, vehicle performance, fuel prices, maintenance costs, and other parameters taken from the Energy Information Administration, U.S. Department of Energy, U.S. DOT, and the U.S. EPA.

2 Introduction

2.1 Clean Fleet Initiative

Working with the U.S. Dept. of Transportation's Volpe National Transportation Systems Center (Volpe), the City is developing strategies to significantly decrease the greenhouse gas emissions (GHG) of the municipal fleet, develop a 2030 fleet GHG reduction target, and chart an implementation plan to reach that target.[4] This Clean Fleet Initiative is being performed in alignment with the City's ongoing portfolio of sustainability initiatives,[5] including the Net Zero Action Plan for the built environment, citywide GHG emission reductions, decarbonization of the fuel supply, the Zero Waste Master Plan, and climate change resilience programs.



Total Scopes 1 and 2 (tons)	28,486	27,380	25,905	25,977	22,762
Percent reduction from 2008		-3.9%	-9.1%	-8.8%	-20.1%

Figure 1. Overall municipal GHG emissions have been decreasing.

Significant gains in building energy efficiency and other municipal operations have led to a downward trajectory of total overall municipal GHG emissions[6] in the 2008-2012 period, as shown in Figure 1. The

[4] City of Cambridge Department of Public Works, Clean Fleet Initiative, 2016. https://www.cambridgema.gov/theworks/energyefficiency/cleanfleetinitiative

[5] https://www.cambridgema.gov/Departments/publicworks/Initiatives/Sustainability

[6] City of Cambridge Environmental and Transportation Planning Division, *Municipal Greenhouse Gas Inventory: 2008-2012,* 2016. http://www.cambridgema.gov/~/media/Files/CDD/Climate/municipalghg/Municipal-GHG-Emissions-and-Energy-Use-3282016.pdf?la=en; City of Cambridge Department of Public Works, *Municipal*

GHG emissions of the municipal vehicle fleet have decreased less rapidly since 2009, as can be seen in Figure 4 in section 3.2. As the fleet's relative contribution to municipal GHG emissions has grown, so has the opportunity to reduce total municipal emissions. Furthermore, as the transportation sector has become the single largest source of Massachusetts GHG emissions, Cambridge's Clean Fleet Initiative can potentially serve as a model for municipal fleet vehicle GHG reductions across the State that would support the goals of the Massachusetts Global Warming Solutions Act.[7]

2.2 Current Fleet

The City of Cambridge fleet consists of 353 vehicles, ranging from motorcycles and sedans to refuse and fire trucks, distributed among 14 departments as shown in Figure 2. Labels are omitted for categories with less than 10 vehicles.

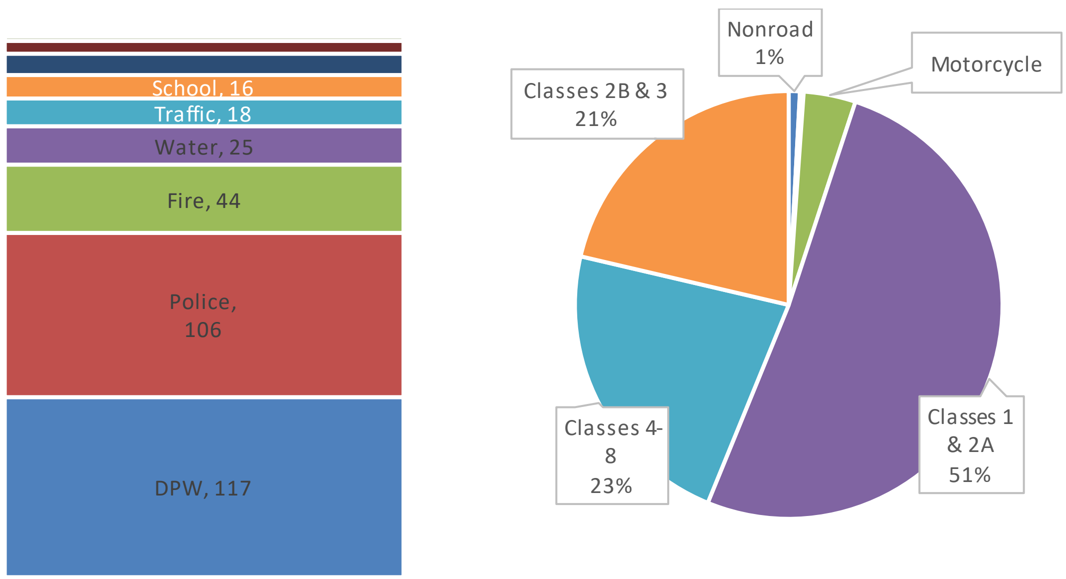


Figure 2. Left: Vehicles in Each City Department. Right: Fleet Breakdown by Vehicle Type (2016)

EPA Vehicle Classification System

- Class 1: Passenger cars, small pick-ups, small SUVs
- Class 2: Large pick-up trucks and vans
- Classes 3 through 6: Trucks, vans, buses, and other medium-duty vehicles weighing 10,000-33,000 lbs.
- Classes 7-8: Trucks, buses and other heavy-duty vehicles weighing >33,000 lbs.

The EPA classifies cars and trucks according to a system shown in Figure 3.

Vehicles in all classes of the U.S. EPA rating system can be found in the City of Cambridge fleet. For example, Ford Taurus and other passenger vehicles are in Class 1, while light- and medium-duty pick-up trucks such as the F150, F250, and F350 are examples of Class 2 and 3 trucks. Large vans and pick-up trucks such as the E450

Greenhouse Gas Reductions. https://www.cambridgema.gov/theworks/energyefficiency/municipalgreenhousegasreductions

[7] Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs, Progress Towards Reducing Greenhouse Gas Emissions. http://www.mass.gov/eea/air-water-climate-change/climate-change/massachusetts-global-warming-solutions-act/ma-ghg-emission-trends/ and https://www.mass.gov/service-details/ma-ghg-emission-trends

and F550 are examples of Class 4 and 5 vehicles. Large dump, water, fire, refuse, school buses, and other vehicles are classified as Class 6 - 8.

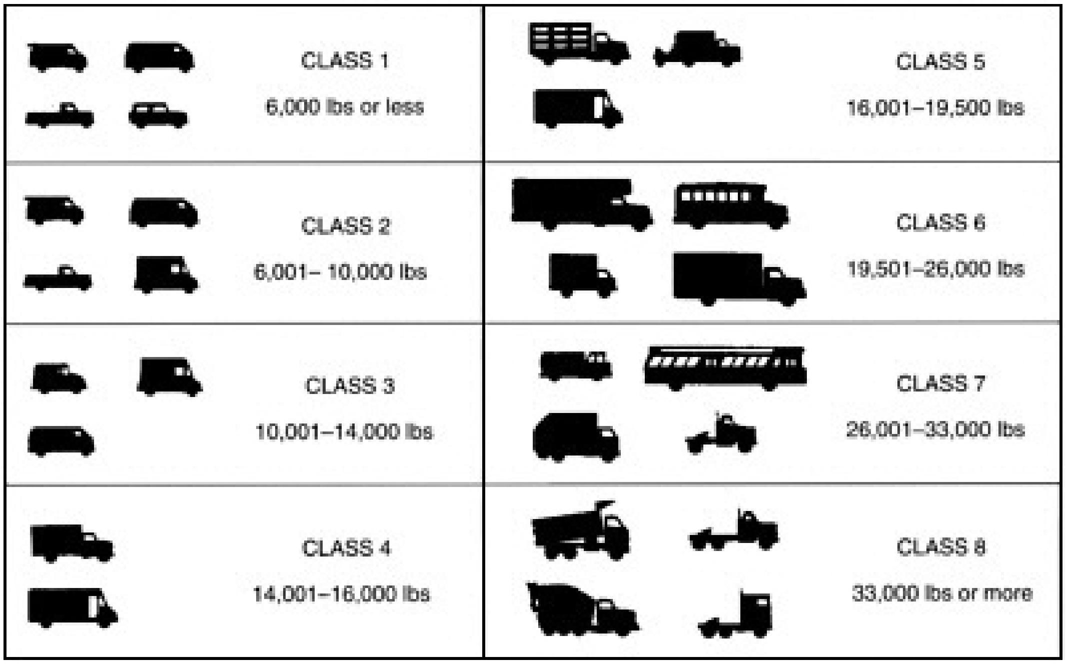


Figure 3: US EPA Vehicle Weight Classification System

The vehicles in the Cambridge fleet perform diverse tasks, requiring a range of vehicle types, weights, and performance capabilities that Volpe needed to consider in the GHG emissions reduction target setting analysis.

3 Approach and Baselining

3.1 Method and Constraints

Volpe's analysis of future GHG emissions and net savings or costs outcomes is based on modeled runs using the Department of Energy (DOE) Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool (AFLEET) tool. The model, with key inputs and assumptions such as vehicle drive cycles, idling times, and vehicle retirement ages that are based on the Cambridge fleet and on New England regional values, predicts the fuel consumption and emission impacts of incorporating advanced technologies in new as well as existing vehicles. Accordingly, Volpe customized these aspects of the AFLEET tool for the analysis. Additionally, Volpe developed an Excel Solver-based optimization tool to translate vehicle-level AFLEET outputs to the municipal fleet level, yielding different possible outcomes for the Clean Fleet Initiative.

The evaluated technologies in the model initially included a wide range of alternative fuels. However, the final model focuses on hybridization, electrification, idle reduction, and other feasible, effective GHG reduction technologies for vehicles based on:

1. challenges associated with siting natural gas or hydrogen fueling stations in Cambridge,
2. the relatively limited GHG reduction benefits of natural gas and propane vehicles, and
3. the limited availability of natural gas, propane, and fuel cell vehicle models.

The model maximizes the fleet-wide GHG reduction subject to a number of constraints, including incremental capital costs (additional purchase price of a vehicle or technology) and operational constraints (e.g., snowplowing) reflected in how many vehicles of a given type are allowed to receive advanced technologies.

Both external and internal factors determine the magnitude of GHG reduction that can be achieved in 2030 and at what cost or savings compared to the business-as-usual baseline. All of the model's GHG reduction outputs account for both regulatory baseline technologies (required by EPA and DOT regulations) and the advanced technologies (such as electrification or hybridization) that Cambridge can choose to implement for the Clean Fleet Initiative.

The analysis also shows how the financial decision to limit annual incremental capital investment in advanced vehicle technologies changes the achievable GHG reduction under different external factors such as fuel price. The model conservatively assigns an additional five percent reduction in fuel consumption and GHG emissions associated with management and behavioral strategies, which will be further examined in a follow-on task.[8]

In consultation with Cambridge, Volpe modeled a set of Average Cases based on intermediate assumptions, one of which will be used to develop the Implementation Plan, the final module of the model. The Implementation Plan will detail the phase-in of advanced technologies and vehicles year-by-year, with their associated annual incremental capital and operational costs and savings.

<u>Increased Resources/Efficiency Scenario</u>

- Favors electric vehicles
  - Largest reduction in fuel consumption

<u>Fixed Budget Scenario</u>

- Caps incremental annual capital costs at $300,000
- Fewer electric vehicles
- Favors:
  - Hybrid-electric
  - Plug-in hybrid
  - Idle reduction tech.

Detailed discussion of the fleet decarbonization model, including AFLEET modules, the Solver module, inputs, and assumptions can be found in Appendix sections 6.2 through 6.6.

[8] **Note:** Five percent may be considered a conservative figure since the fuel consumption reduction due to eco-driving alone may range from five to 40 percent. **See:** Alam, M.S. & McNabola, A., *A Critical Review and Assessment of Eco-Driving Policy & Technology: Benefits and Limitations*, Transport Policy 35: 42-49 (2014). https://www.sciencedirect.com/science/article/abs/pii/S0967070X14001152; Killian, R., *Ecodriving: The Science and Art of Smarter Driving,* TR News 281: 34-39 (2012). http://onlinepubs.trb.org/onlinepubs/trnews/trnews281ecodriving.pdf

3.2 Initial and Business-as-Usual Baselines

As the first analysis step, Volpe conducted an inventory of GHG emissions of City-owned vehicles for the years 2009 through 2016. The inventory was based on fuel usage records provided by the City of Cambridge for all departments. The results provided an estimate of total emissions for each calendar year (see Figure 4), as well as their distribution at a departmental level.

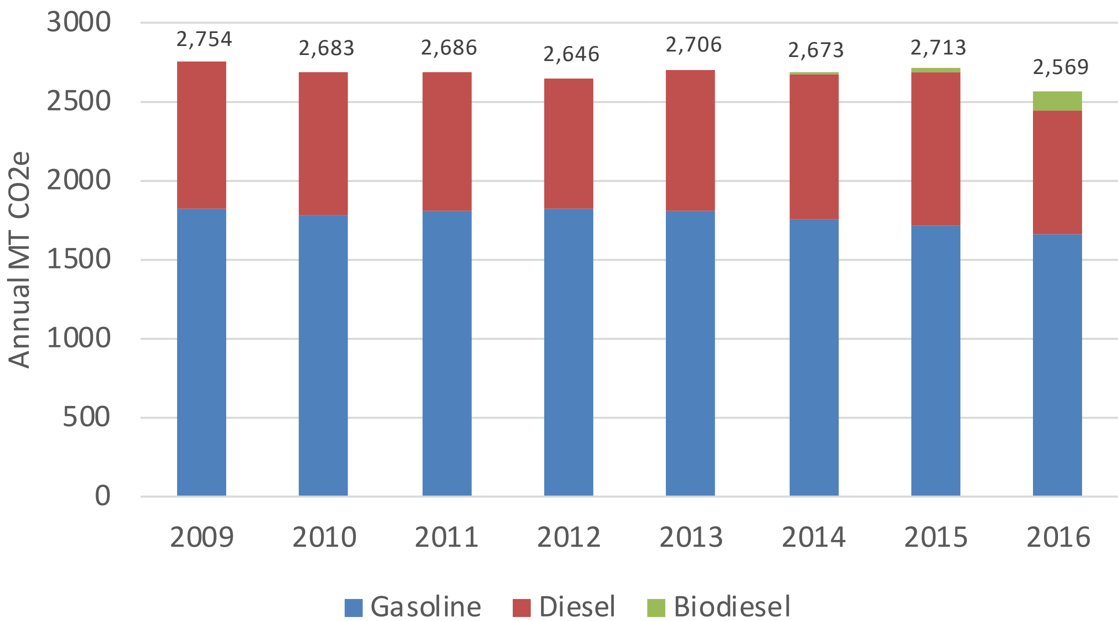


Figure 4. Annual GHG Emissions for the City of Cambridge Fleet (2009-2016)

Volpe next performed an assessment of available GHG-reducing strategies and technologies, including availability, benefit, and cost. The selection of technologies was based on an evaluation of City of Cambridge vehicle function, fuel consumption, mileage, idling information, staff interviews, and site visits to the Department of Public Works and Police Department garages.[9] In addition, the analysis evaluated what technologies might be introduced in the business as usual case by manufacturers in order to meet recent federal GHG and fuel economy regulations for all vehicles. These technologies, such as improved tires and auxiliaries, transmissions with greater numbers of gears,

GHG Reduction Strategies/Technologies

- Idle reduction
- Improved tires and auxiliaries
- Hybridization
- Electrification
- Vehicle substitution
- Engine right-sizing
- Transmission changes
- Management and Behavior Strategies
  - Anti-idle operator training
  - Eco-driving
  - Vehicle Sharing

[9] **Note:** A site visit of the Fire Department garage, the City's third fleet facility, could not be arranged during this period.

and other technologies were incorporated into the business as usual case for 2030. [10,11]

For the year 2030, Volpe calculated a business-as-usual (BAU) baseline in which only the GHG reductions required by U.S. EPA and DOT regulations that exist at the time of writing are implemented on the City of Cambridge fleet. Investment in advanced technologies and operational efficiencies under the Clean Fleet Initiative adds to this BAU baseline and results in significantly greater GHG reduction.

4 Results

This section describes the Case-Scenario combinations that Volpe evaluated and their estimated GHG reduction and NPV results.

4.1 Baselines

4.1.1 2016 Baseline

Volpe analysis of fleet fuel consumption data provided by City staff showed that 2,569 tons of CO_2 were emitted by City of Cambridge fleet vehicles in 2016. This is the baseline emissions value.

4.1.2 2030 Business-as-Usual Baseline

Volpe calculated a business as usual baseline for fleet-wide GHG emissions reduction in 2030. The analysis projects that a **17 percent** reduction in GHGs would result from reductions required by U.S. EPA and DOT fuel consumption and GHG regulations that exist at the time of writing for light-, medium-, and heavy-duty vehicles. [12] The fuel and maintenance savings would come from medium- and heavy-duty vehicles, with a slight cost resulting from introduction of technologies for passenger cars and light trucks.

4.2 Cases and Scenarios

With both the 2016 initial baseline and the BAU 2030 baseline in place, Volpe analyzed how a range of external and internal factors would affect the attainable GHG reduction in 2030.

4.2.1 Approach

Volpe developed multiple Cases and Scenarios, beginning with Cases that model the effect of external variables (i.e., factors outside of the City's control) on NPV and GHG emissions, and then exploring

[10] U.S. Environmental Protection Agency & National Highway Traffic Safety Administration, 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards, Office of the Federal Register, 2012. *https*://www.federalregister.gov/documents/2012/10/15/2012-21972/2017-and-later-model-year-light-duty-vehicle-greenhouse-gas-emissions-and-corporate-average-fuel

[11] U.S. Environmental Protection Agency, *Final Rule for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles- Phase 2,* 2016. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-and-fuel-efficiency

[12] **Note:** The BAU assumes all GHG and fuel consumption regulations that have been finalized by EPA and DOT are implemented as finalized.

additional Scenarios to illustrate the impact of factors generally under the City's control.[13] Table 1 shows the external variables, values, and sources that correspond to different Cases and Scenarios.

Volpe began by assessing a Best Case and a Worst Case for all factors outside of the City's control. This framed the analysis by setting upper and lower bounds for what the City might expect:

- The Best Case represents the most favorable condition for large GHG reduction with minimal incremental capital costs. It assumes the highest price of gasoline and diesel, lowest price of electricity, lowest amount of emissions from electricity generation, below-average electric and high efficiency vehicle costs, and highest internal combustion engine (ICE) cost.
- The Worst Case represents the least favorable condition for large GHG reduction, since the potential gains are offset by comparatively low gasoline prices and high electricity prices. It assumes the lowest price of gasoline and diesel, highest price of electricity, highest amount of emissions from electricity generation, above-average electric and high efficiency vehicle costs, and lowest internal combustion engine cost.

Since this initial bounding exercise focused on external factors, both "Best" and "Worst" Cases are fiscally unconstrained, that is, they do not assume a limit on the incremental additional capital cost that the City could invest each year.

Forecast values for fuel prices were obtained from the Energy Information Administration (EIA) Annual Energy Outlook, with high and low fuel and electricity prices each averaged between 2018 and 2030. As the City of Cambridge pays 17 cents per kilowatt-hour for electricity at the time of writing, Volpe used this current price and escalated it by the U.S. EIA 2005-2017 Massachusetts annual escalation rate, yielding 21 cents for the Worst Case electricity price value in 2030.

The Electricity Emissions Factor (EEF) reflects the amount of emissions produced as a result of electricity generation. The EEF used in the Best Case is consistent with 100% renewable energy (0 pounds of CO_{2e} per MWh). The Worst Case EEF reflects a 2030 emissions forecast of 485 pounds CO_{2e} per MWh for the New England grid.[14]

Table 1. Summary of Best Case and Worst Case assumptions for 2030 Clean Fleet outcomes.

Input	Best Case	Average Cases	Worst Case
Gasoline	\$5.59	\$3.82	\$2.05
Diesel	\$5.38	\$3.58	\$1.77
Electricity	\$0.18	\$0.195	\$0.21
Electricity Emissions Factor	0 pounds/MWh	0 or 485 pounds/MWh	485 pounds/MWh
Discount Factor	1.4%	2.21%	3.0%

[13] **Note:** Generally, the external factors were identified by Volpe and agreed upon with City of Cambridge as important variables to examine. Internal fiscal choices were set forth by the City of Cambridge based on expected funding availability.

[14] Consistent with ARUP analysis for the City of Cambridge and with projections by the Regional Greenhouse Gas Initiative (RGGI) for the New England independent system operator (ISO).

Input	Best Case	Average Cases	Worst Case
Electric Vehicle Cost	96.5% of forecast average	100.7% of forecast average	104.9% of forecast average
High Efficiency Vehicle Cost	94.7% of forecast average	102.4% of forecast average	110.0% of forecast average
Internal Combustion Engine Cost	106.0% of forecast average	99.7% of forecast average	93.3% of forecast average

The analysis predicts 64.5 percent attainable GHG emissions reduction for the Best Case, with a slightly lower attainable reduction of 60.5 percent for the Worst Case. This observed difference is due to the different assumed EEF. The NPV for these two bounding cases varied considerably, from a positive value of $6,956,597 in the Best Case to a negative value of ($5,392,612) in the Worst Case.

Given their wide NPV range, Volpe set aside these bounding Cases and developed an Average Case using intermediate input values, as shown in the middle column of Table 1. In consultation with the City, Volpe further segmented the Average Case into two fiscal Scenarios to represent the effect of budget factors under the City's control. The Scenarios were defined as follows:

- *Average Case, Increased resources and efficiency*: No limit on the incremental additional capital cost that the city could invest each year.
- *Average Case, Fixed Budget*: Fiscally constrained to $300,000 incremental capital cost per year.

Finally, Volpe further segmented the "Fixed Budget" Scenario to include one version with an EEF consistent with the RGGI projection for 2030, as in the Worst Case, and one version with 100% Renewable electricity, as in the Best Case. As shown in Figure 5, these last two segmentation steps resulted in three Average Cases and five possible outcomes overall.

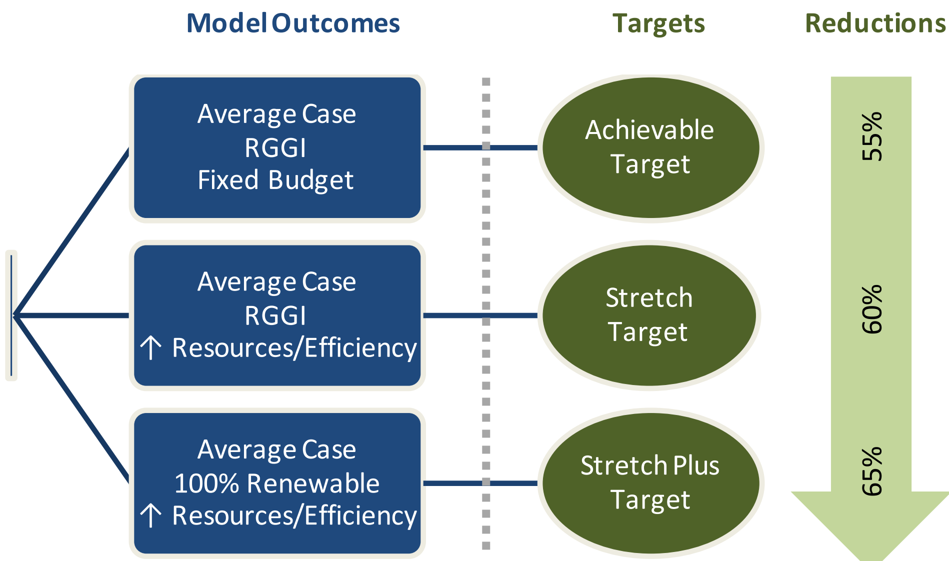


Figure 5. Segmentation of of Cases and Scenarios, leading to the Target and the Stretch Target, as well as a Stretch Plus Target when 100% renewable electricity is added.

4.2.2 Findings

The business-as-usual baseline is a fleet-level GHG reduction of 17 percent in 2030 from the starting year of 2016, based on normal turnover of the Cambridge fleet and the introduction of low-hanging-fruit technologies needed to meet federal fuel economy regulations. This approach avoids double-counting fuel economy benefits.

In the Increased Resources/Efficiency Scenarios, the model favors electric vehicles, as they provide the largest reduction in fuel consumption irrespective of cost. Operational constraints communicated to Volpe by the City departments, as well as technology maturity constraints, limited which vehicles could receive certain advanced technologies. Within these constraints, the maximum feasible reduction in 2030 was found to be approximately 64.5 percent from the 2016 baseline.

Compared to the Increased Resources/Efficiency Scenarios, the fixed budget Scenarios—which are constrained by annual incremental capital cost—result in fewer electric vehicles and more of the following: hybrid-electric vehicles combined with idle reduction (HEV + IR), idle reduction (IR), and plug-in hybrid-electric vehicles (PHEV). These types of technologies allow for reduction in fuel use and emissions while also keeping the total incremental capital costs below the specified threshold of $300,000 per year.

4.2.3 Reductions and Costs Summary

As shown in Table 2, the analysis projects GHG reductions in 2030 due to advanced technologies and operational efficiencies would range from 55.9 percent to 64.5 percent.

Table 2. Summary of scenarios considered and their GHG reduction and NPV results

Case	Financial Scenario	GHG reduction	Net Present Value
Best	Increased Resources/Efficiency	64.5%	$6,956,597
Worst	Increased Resources/Efficiency	60.5%	$(5,392,612)
Average, RGGI	Fixed	55.9%	$1,159,195
Average, RGGI	Increased Resources/Efficiency	60.5%	$568,817
Average, 100% Renewable	Increased Resources/Efficiency	64.5%	$568,817

The total program GHG reductions and NPVs, which account for both capital costs and operating savings, are summarized in Figure 6. These results combine BAU technologies, advanced technologies, and a five-percent conservative reduction estimate due to implementing behavioral and management strategies, such as eco-driving, anti-idle operator training, or vehicle sharing.

Figure 6. GHG Reduction and NPV summary of all Cases and Scenarios

Table **4** in Appendix 6.1 presents a detailed breakdown of the separate incremental capital and operating costs or savings for an expanded set of eight Case-Scenario combinations.

4.3 Achievable Target GHG Reduction Outcome

This section describes the results of the **Average Case, RGGI, Fixed Budget Scenario** for the municipal fleet GHG emissions in 2030. This scenario, with 60.5% or 1,555 tons reduced, serves as the basis for the Achievable Target GHG reduction outcome. This section provides the numbers and types of technologies assumed to be introduced into the City of Cambridge fleet between 2019 and 2030, as well as the overall net savings and costs of the program.

A total of **336** vehicles receive technology between 2018 and 2030. GHG emission reductions in this scenario are more than triple the emissions reduction that would be achieved through business as usual.

Achievable Target at a Glance

- Positive net present value of over **$1.15m**
- **1,435** tons GHG per year avoided in 2030
- **$300,000** maximum annual incremental capital investment over current levels

Table 3. Distribution of Technologies by Vehicle Category in the Achievable Target Outcome

vehicle category	HEV + IR	electric	transmission	mild HEV	HEV	PHEV	EREV	downsize to motorcycle	idle reduction	HHV	Total
Class 8	27	2	0	0	8	0	0	0	5	6	**48**
Passenger Car	0	35	0	0	0	23	0	0	0	0	**58**
Light truck (Tacoma/Colorado)	0	0	0	0	19	12	0	0	0	0	**31**
Light duty vans (Transit)	0	0	0	0	8	0	0	0	0	0	**8**
Vans (medium and heavy duty)	10	21	0	0	1	0	0	0	0	0	**32**
Police Interceptor	0	0	0	0	23	10	0	0	0	0	**33**
SUV Hybrid	0	21	0	0	0	0	0	0	0	0	**21**
Pickup (medium)	64	0	0	0	0	0	0	0	0	0	**64**
Pickup (Large)	0	0	0	0	0	0	0	0	9	0	**9**
Bus	0	0	0	0	1	0	0	0	0	0	**1**
Firetruck	0	0	0	0	0	0	0	0	17	0	**17**
Motorcycle	0	14	0	0	0	0	0	0	0	0	**14**
TOTALS	101	**93**	**0**	**0**	**60**	**45**	**0**	**0**	**31**	**6**	**336**

The table shows that 60 vehicles are hybrid electric, 45 are plug-in hybrid electric, 93 are battery electric, and 101 hybrid-electrics equipped with idle reduction technology. Six refuse trucks are equipped with hydraulic hybrid, and 31 vehicles, including 17 fire apparatus, are equipped with idle reduction, so as to reduce the load on the diesel engine while on a job or emergency response site. The data in Table 3 is graphically represented on the following page in Figure 7.

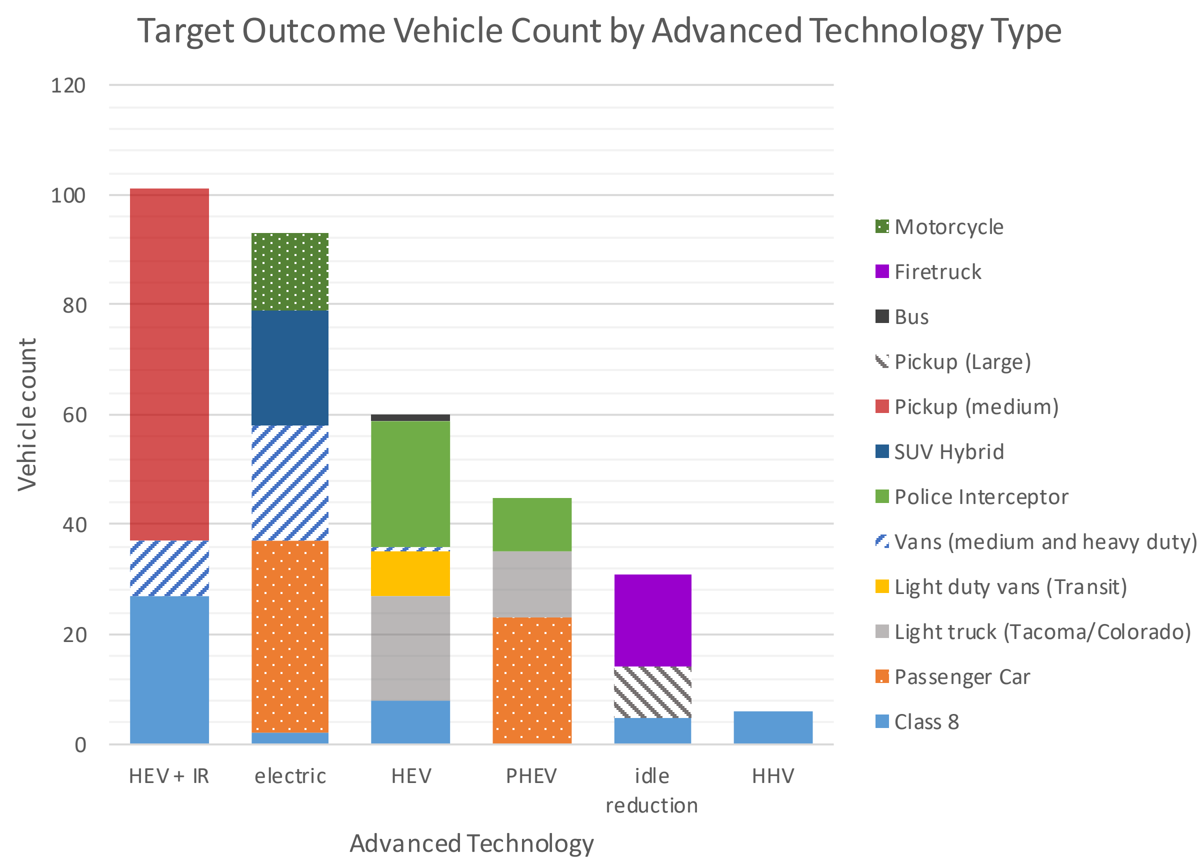


Figure 7 – Achievable Target Outcome Vehicles Receiving Advanced Technologies

Below, Figure 8 illustrates the GHG amounts reduced by each advanced technology. The blue bars indicate remaining emissions after each advanced vehicle technology is applied to the fleet. The BAU reduction of 17 percent is the difference between the first and second bars, followed by reductions resulting from the implementation of electric and hybrid vehicles, idle reduction technology, and so on.

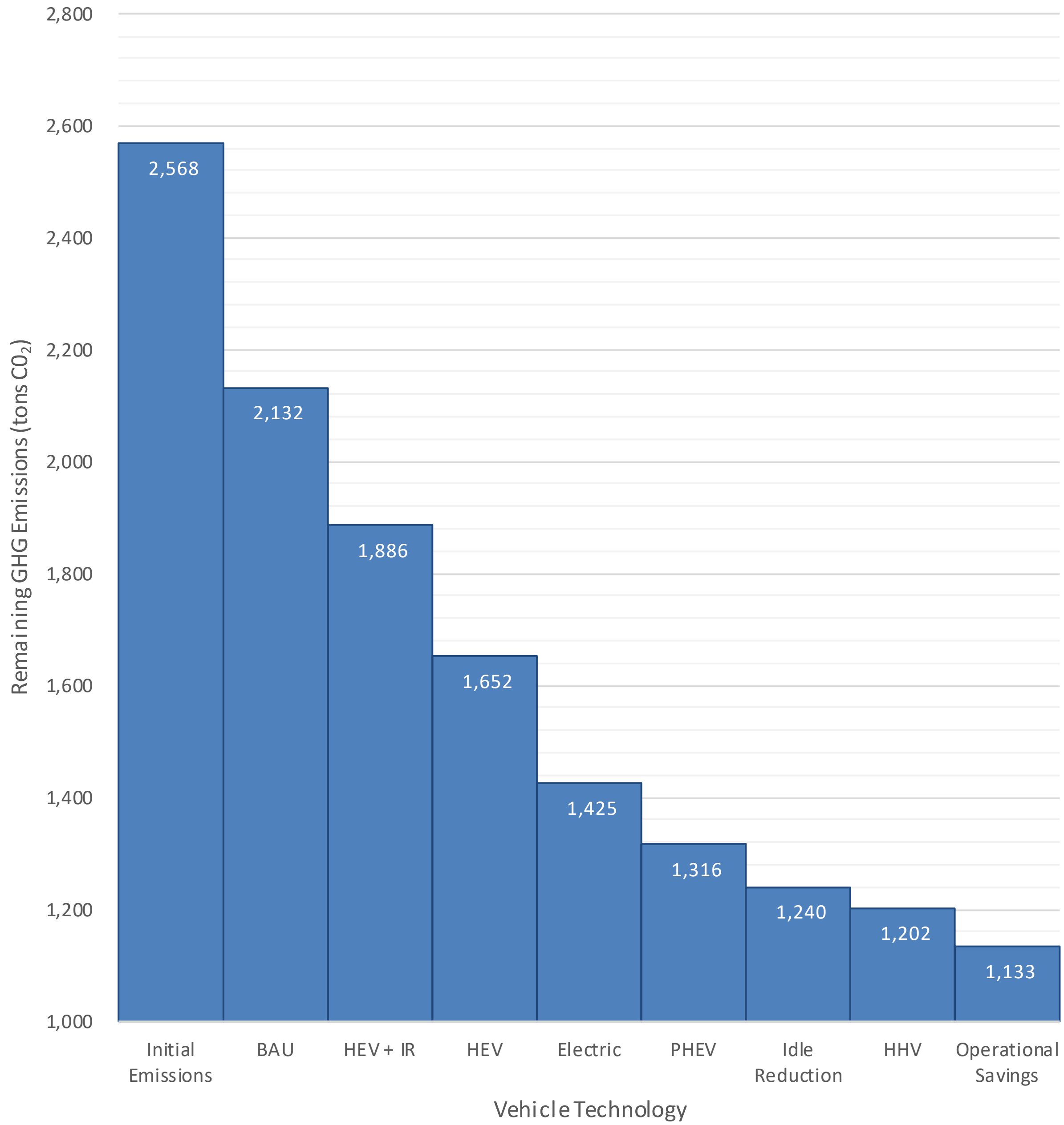


Figure 8. GHG annual emissions remaining in 2030 after implementing each Clean Fleet strategy

Whereas Figure 8 illustrated GHG reduction by technology type, Figure 9 shows GHG reduction in the Achievable Target outcome by vehicle type. Across the fleet, all vehicle types would contribute to the GHG reduction under the plan.

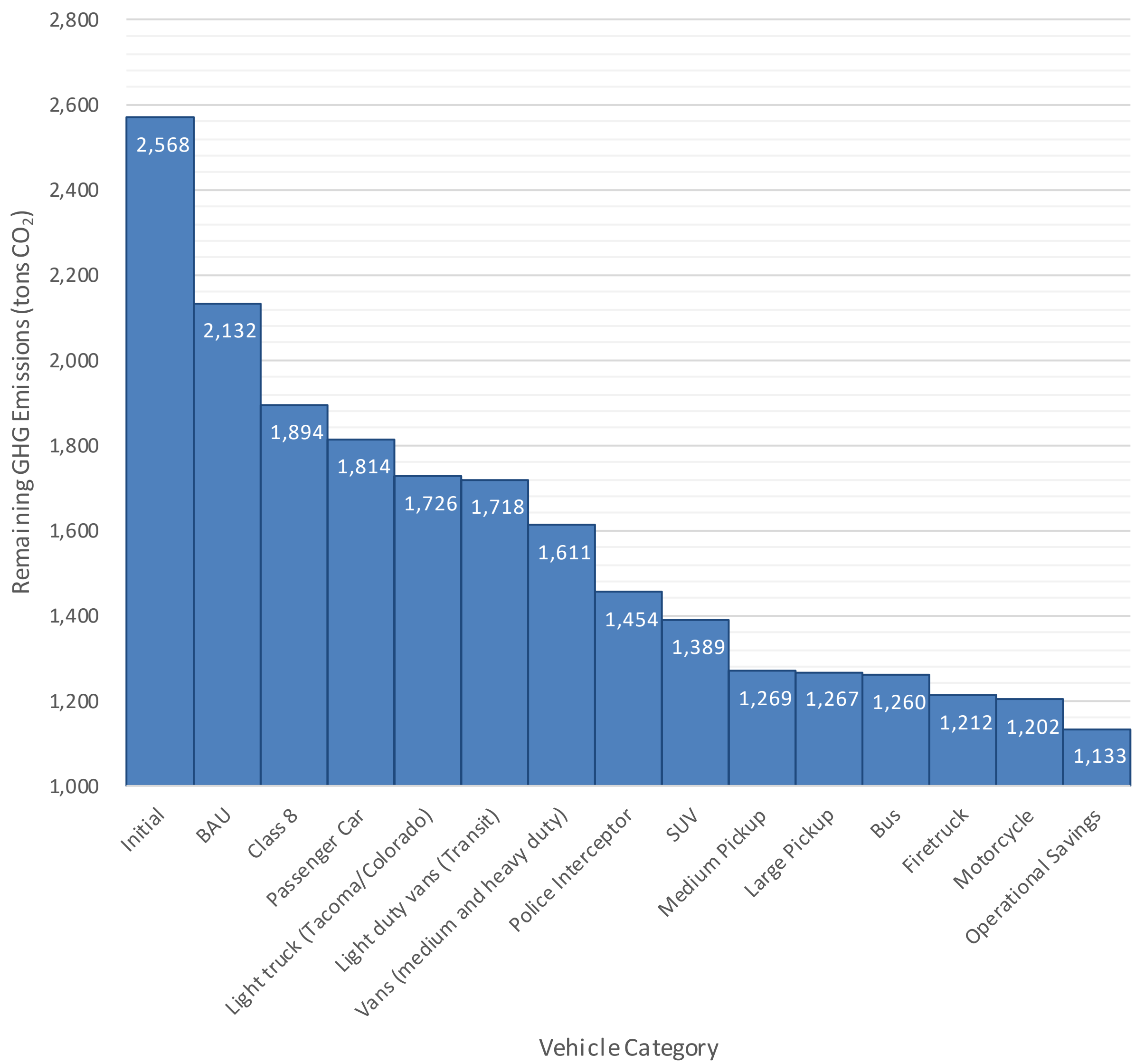


Figure 9. GHG annual emissions remaining in 2030 after implementing Clean Fleet strategies on each vehicle category

Class 8 trucks such as refuse, tree and sewer, and large dump trucks provide the greatest reductions. Passenger cars are next given the ability to purchase plug-in and electrified versions of these vehicles in early years. In the next section, the Stretch Target for GHG reduction is described.

4.4 Stretch Target and Potential Strategies

The **Average Case, RGGI, increased resources and efficiency Scenario**, which only differs from the above in that it assumes additional capital investment and additional operational efficiencies, is the basis for the Stretch Target. Under this set of assumptions, the modeled GHG reduction would be 60.5 percent, or 1,555 tons. The Stretch Target is achieved by yielding more operational savings from behavioral, training, ride-sharing, or other practices, beyond the conservative estimate of five percent used throughout this analysis, and with more capital investment in low or zero-emissions vehicles, either through current capital funding streams or by outside grants. Future vehicle technology breakthroughs may allow more types of City vehicles to receive advanced technologies. Given these multiple paths to greater-than-modeled reduction levels, the City could choose to set a Stretch Target of 60 percent GHG emissions reduction in 2030 in addition to the Achievable Target reduction of 55 percent.

Paramedic Motorcycles

- Improve response times by arriving at scenes quicker than large vehicles
- Used in: Fort Walton Beach, Daytona Beach, and Miami, FL; Los Angeles, CA; Austin, TX

Miami documented average response times of less than three minutes for paramedic motorcycles versus seven for ambulances

Additional operational savings could result from even greater implementation of already-identified operational efficiencies such as idle reduction and eco-driving training, combined with telematics implementation and driver coaching across departments. One approach not included in the conservative five percent operational efficiency assumption is using smaller fire vehicles for medical calls. A percentage of these emergency response trips could be diverted to paramedic motorcycles, bicycles, or other low-or-no-emissions vehicles instead of full size apparatus.[15] The existing 17 fire apparatus would still be maintained. This strategy has been implemented in a growing number of jurisdictions—primarily for decreased response times and reduced equipment wear and tear—and can be examined further in the operational strategies task.

The City is separately considering the procurement of 100% renewable electricity supply. The **Average Case, 100% Renewable, Increased Resources/Efficiency** outcome indicates that implementing 100% renewable electricity can further reduce emissions by four percent for a potential "Stretch Plus" Target of 65%, after additional capital investment and operational efficiencies are achieved.

5 Conclusions

5.1 Achievable Target and Stretch Target

Based on Volpe's analysis and as shown in Figure 10, **it is achievable for the City to select 55% as a GHG reduction target and 60% as a stretch goal target for its fleet** of 353 vehicles. The *Average, RGGI, Fixed Budget* outcome is the basis for the proposed target, as it uses average assumptions for future fuel price, electricity price, and hybrid/electric vehicle technology costs; assumes high electricity emissions; and is financially constrained to $300,000 incremental capital cost per year.

[15] https://www.firerescue1.com/fire-products/specialty-vehicles/articles/a-case-for-firefighting-motorcycles-q0zH39QgzcBATM4s/

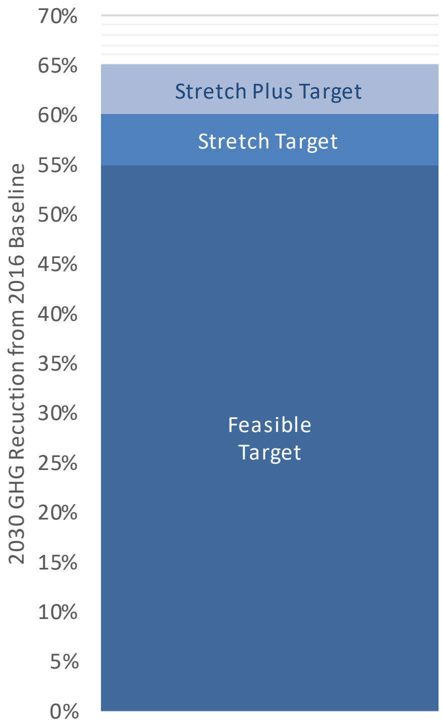


Figure 10. Achievable, Stretch, and Stretch Plus Target GHG reductions

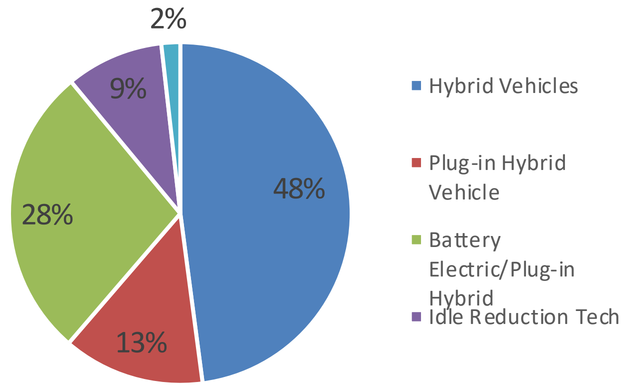


Figure 11. Achievable Target Fleet Technology Mix

In the Achievable Target, 336 of the 353 fleet vehicles are equipped with advanced GHG reducing technologies or are replaced by vehicles other than conventional gasoline or diesel vehicles. Figure 11 shows graphically the vehicle technology mix. Achieving this target will reduce GHG emissions by 1,435 tons per year from the City's fleet, equivalent to eliminating the use of about 147,000 gallons of fuel annually, and will significantly lower criteria pollutant emissions. The program is projected to provide these benefits while maintaining a positive net present value of $1.15 million.

The *Average, RGGI, Increased Resources/Efficiency* outcome, which differs in that it assumes more capital investment (potentially including external grants) and implementing more operational efficiency strategies, forms the basis for a possible **60% reduction Stretch Target**.

Building on the Stretch Target, rapid advancement in the electric vehicle market and procuring 100% renewable electricity supply could ultimately support a **65% reduction Stretch Plus Target**.

5.2 Next Steps

In the follow-on tasks, Volpe will expand the Target outcome analysis to help support the implementation of the Clean Fleet Initiative in partnership with the City. The elements of this effort are described below.

5.2.1 Evaluate behavioral, management, and policy strategies

Volpe anticipates analyzing operational strategies for reducing GHG emissions that complement the advanced technology strategies analyzed in the present report. These may include:

- The feasibility and effect on GHG-reduction of a “buy-electric policy” for sedans and SUV’s
- Expected benefits and risks of right-sizing/down-sizing strategies.

- Management or behavioral strategies, including anti-idling policy, driver training and education; and vehicle consolidation or sharing strategies for improved EV economics[16]

Longer term, Volpe can develop more detailed analysis of the potential benefits and feasibility of fire apparatus trip substitution for non-fire emergencies by low-or-no-emission vehicles.

5.2.2 Technical assistance for selected special applications of Clean Fleet technologies

Advanced technology solutions underpin the 2030 Target for the Clean Fleet Initiative, based on Volpe and Cambridge's projection that these technologies will be implementable in a wide range of City vehicles. In consultation with Cambridge, Volpe will determine and provide technical assistance related to a number of special applications that are important to address in the course of attaining the 2030 Target or Stretch Target reduction levels. Technical assistance tasks may be specifically helpful for:

- Plow, water, and other pick-up truck requirements in terms of power and payload, and whether or not lower power and torque can fulfill those requirements
- Idling activity: What idle reduction device can provide air conditioning, heat and power radio and possibly other power needs? What idle reduction technologies can address various departments' specific operational needs?
- Power Take-Off – what technologies can address PTO loads and how significant are the loads?

Volpe technical assistance will likely rely on fleet stakeholder input, access to telematics data such as AAT/Samsara idling data, literature review, and targeted outreach to fleet managers with experience in the identified special applications, as available funding permits.

In a later phase, Volpe may develop an Implementation Plan that will annualize incremental capital and operating costs and savings to meet the financial constraints of the selected outcome. Initially, the Implementation Plan may use a default EV-to-head charging infrastructure ratio. In a future analysis, the best ratio for each vehicle category and operation can be assessed to refine the EVSE component of the Implementation Plan, potentially including refined costing for different EVSE types and locations.

6 Appendices

6.1 Detailed Case-Scenario Results

A detailed summary of results for the full 4x2 matrix of Cases and Scenarios that Volpe analyzed is provided in Table **4**.

Table 4. Detailed Case-Scenario Results

[16] **See** for example Indianapolis "Freedom Fleet" deck for fleet segmentation by TCO/mile.

Case/Scenario		Best/ ↑ Resources & Efficiency	Best/ Fixed Budget	Worst/ ↑ Resources & Efficiency	Worst/ Fixed Budget
Fleet Total	**Net Present Value vs. Business-As-Usual**	**$ 6,956,597**	**$ 6,181,268**	**$ (5,392,612)**	**$ (3,576,136)**
	Total Operational (Cost)/Savings	$ 12,686,067	$ 9,480,910	$ 3,877,090	$ (277,387)
	Total Capital (Cost)/Savings	$ (5,729,470)	$ (3,299,642)	$ (9,269,701)	$ (3,298,748)
	2030 Gallons Reduced	122,567	108,499	112,077	99,844
	2030 GHG Reduced (tons)	1,656	1,518	1,555	1,435
	2030 GHG Reduction (percent)	61.4%	56.3%	57.7%	53.2%
	2030 GHG Reduction (percent) with addition of Operating Efficiencies	**64.5%**	**59.1%**	**60.5%**	**55.9%**
(Cost) or Savings per Ton Reduced	**Net Present Value vs. BAU**	**$ 4,201**	**$ 4,072**	**$ (3,467)**	**$ (2,492)**
	Operational	$ 7,661	$ 6,246	$ 2,493	$ (193)
	Capital	$ (3,460)	$ (2,174)	$ (5,960)	$ (2,299)

Case/Scenario		Average/ ↑ Resources & Efficiency/ 100% Renewable	Average/ ↑ Resources & Efficiency/ RGGI	Average/ Fixed Budget/ RGGI	Average/ Fixed Budget/ 100% Renewable
Fleet Total	**Net Present Value vs. Business-As-Usual**	**$ 568,817**	**$568,817**	**$1,159,195**	**$ 1,150,264**
	Total Operational (Cost)/Savings	$ 6,298,287	$ 6,298,287	$ 4,457,943	$ 4,449,906
	Total Capital (Cost)/Savings	$ (5,729,470)	$ (5,729,470)	$ (3,298,748)	$ (3,299,642)
	2030 Gallons Reduced	122,567	112,077	99,844	108,499
	2030 GHG Reduced (tons)	1,656	1,555	1,435	1,518
	2030 GHG Reduction (percent)	61.4%	57.7%	53.2%	56.3%
	2030 GHG Reduction (percent) with addition of Operating Efficiencies	**64.5%**	**60.5%**	**55.9%**	**59.1%**
(Cost) or Savings per Ton Reduced	**Net Present Value vs. BAU**	**$ 343**	**$ 366**	**$ 808**	**$ 758**
	Operational	$ 3,803	$ 4,050	$ 3,107	$ 2,932
	Capital	$ (3,460)	$ (3,684)	$ (2,299)	$ (2,174)

6.2 Method

This section provides an overview of the method Volpe used to estimate the GHG reductions that could be achieved by introducing advanced technologies into the City of Cambridge fleet between 2018 and 2030. The core of the analysis consists of a series of modeled runs using the Department of Energy (DOE) Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool (AFLEET) tool to predict the emission impacts of incorporating various technologies in new vehicles. AFLEET is an Excel-based tool that provides detailed information on GHG and criteria emissions, fuel consumption, and costs for different motor vehicles. AFLEET allows the user to evaluate a range of technologies including hybridization, electrification, fuel cell, and other technologies in motorcycles, trucks, buses, refuse, and other vehicles in the light-, medium-, and heavy-duty vehicle categories. This enables the user to investigate – on a vehicle-level basis – how modifying the technologies affects vehicle emissions and fuel consumption, assuming standardized driving cycles.

Remaining sections of this chapter describe each basic step of the analysis methodology. In brief, these steps consisted of:

(1) Developing a GHG baseline and business-as-usual case for the City of Cambridge fleet.
(2) Defining representative vehicle types, i.e., passenger cars, pick-up trucks, refuse trucks, class 8 trucks, motorcycles, and others.
(3) Developing a list of technology options for each of the vehicle types.
(4) Performing AFLEET model runs to assess the cost and GHG reductions resulting from the introduction of technologies.
(5) Using Excel Solver to develop fleet-wide costs and GHG reductions for three GHG reduction scenarios (i.e., 30 percent, 40 percent, and 50 percent GHG reduction).
(6) Developing a fleet-level implementation plan for technology phase-in.

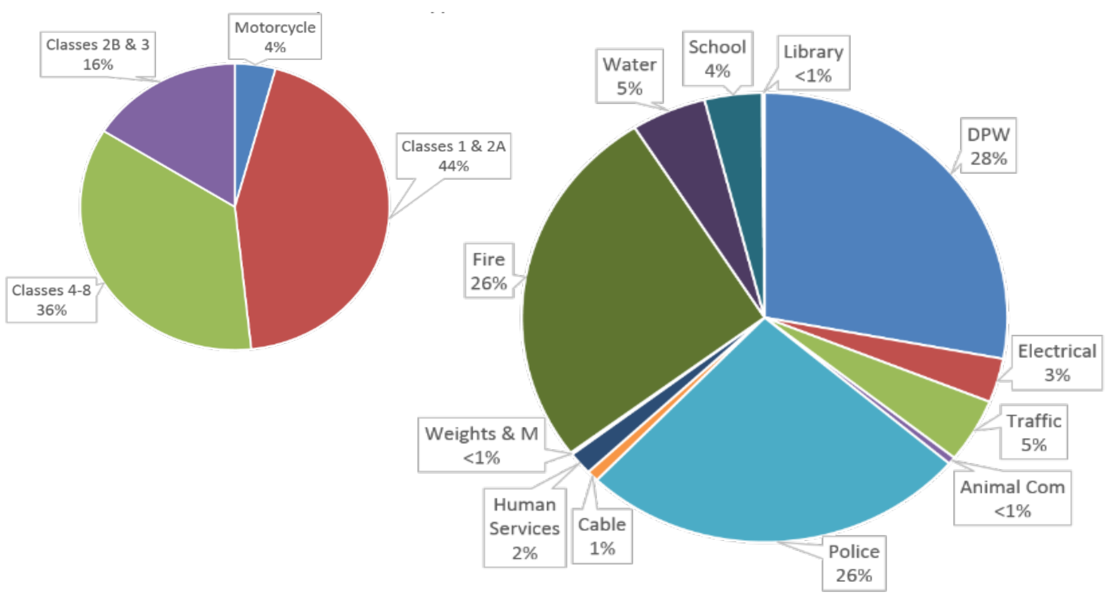


Figure 12. GHG Distribution by Vehicle Class (left) and Department (right)

6.2.1 Developing a GHG Baseline and Business as Usual Case

Fuel consumption records for each of the vehicles in the City of Cambridge fleet for calendar year 2016 were used to calculate carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions in 2016. The City of Cambridge provided emission factors for the pollutants and global warming potentials for CH_4 and N_2O for the analysis. GHG emissions were expressed as carbon dioxide equivalent (CO_{2e})[17]. The

[17] **Note:** A metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon

emissions distribution by vehicle type and department are shown in Figure 12.

Once the baseline GHG inventory for each vehicle had been calculated for calendar year 2016, Volpe projected a 2030 business as usual case (BAU) for each vehicle and for the fleet as a whole. This was done by calculating the percent change in GHG emissions that would occur if the City purchased a replacement vehicle of the same technology type (e.g. gas, diesel, gas plug-in hybrid electric (PHEV), electric, hybrid, other) and class (e.g. passenger car, light-truck, other) in the year the vehicle would normally be replaced. The replacement year was determined by creating an age distribution by class of vehicle in the City of Cambridge fleet. The assumed retirement age for each vehicle class, summarized in Table 5, was determined by selecting the age at which 30 percent of the vehicles remain in the fleet.[18] The retirement age ranged from 12 years for light duty vehicles to 16 for heavy trucks. In the DPW fleet, passenger cars were assumed to retire after 12 years; ¾ ton pick-ups at 15 years old; and heavier trucks, such as the largest dump trucks at 16 years of age.

Table 5. Estimated scrappage (retirement) age by vehicle class

Vehicle class	Assumed scrappage (retirement) age
Passenger car/SUV/light-duty truck (Class 1-2a)	12
Medium trucks/vans (Class 2b-3)	15
Heavy trucks (Class 4-8)	16

Figure 13 shows a histogram of the age of vehicles in the City fleet, in one year increments. While the histogram shows vehicle age for the entire fleet, the replacement year calculation analyzed age by vehicle class.

dioxide equivalents ($MMTCO_2Eq$)." The carbon dioxide equivalent for a gas is derived by multiplying the tons of the gas by the associated GWP. $MMTCO_2Eq$ = (million metric tons of a gas) * (GWP of the gas) **Source:** U.S. Environmental Protection Agency, *Climate Change Glossary*. https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html

[18] **Note:** Based on internal consultation with Corporate Average Fuel Economy Program Office staff.

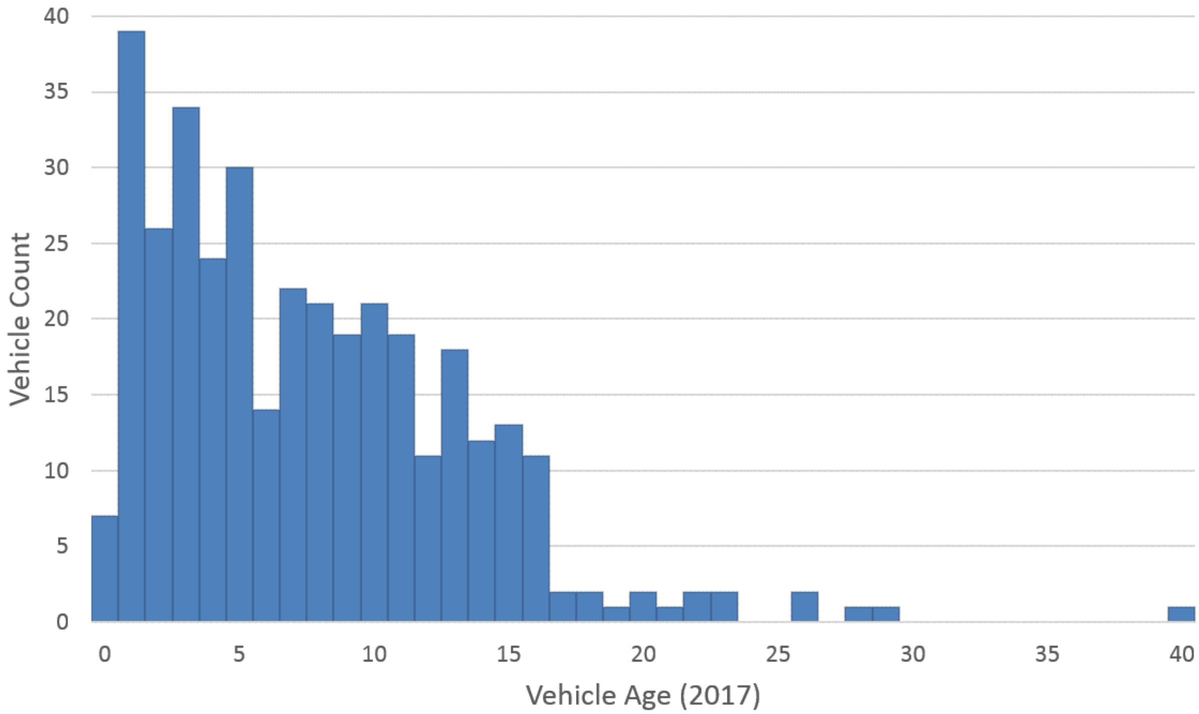


Figure 13. Fleet Vehicle Age Distribution

Using each vehicle's year of manufacture and projected retirement year, Volpe calculated the percent GHG reduction that would be realized in the BAU case. For example, a model year 2009 gasoline-powered passenger car replaced with the same type of vehicle in 2021 would consume about 45 percent less fuel and emit about 45 percent less CO_2. A model year 2017 truck retired in 2030 and replaced with the same gasoline technology would reduce GHG emissions by approximately 15 percent. These reduction percentages were based on U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) GHG and fuel consumption regulatory requirements for light-duty, medium-duty, and heavy-duty vehicles.[19] The GHG reduction percentages assume the introduction of technologies such as 10-speed automatic transmissions, electrified accessories, gasoline direct injection, turbocharging and downsizing, and aerodynamic and other improvements. Once individual vehicle GHG BAU reductions were calculated for each of the vehicles in the Cambridge fleet, the GHG savings were summed across the fleet and calculated as a percentage of 2016 GHG emissions. The 2030 fleet BAU GHG emissions were estimated to be 83 percent of fleet GHGs in 2016, or a 17 percent reduction from 2016 emissions. This percentage improvement assumes full implementation of the regulatory requirements for light-, medium-, and heavy-duty vehicles with no changes to the current regulations. Should any of these regulations change between now and 2030, projected BAU emissions

[19] "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule," 77 FR 62623, October 2012. "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," 76 FR 57106, September 2011. "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles-Phase 2"; Final Rule, 81 FR 73478, October 2016.

would also be affected.[20]

6.2.2 Defining Representative Vehicles in the City Fleet

In order to understand opportunities for and limitations to the introduction of additional technologies in City vehicles (above and beyond what is expected in the BAU case), the City of Cambridge organized discussions between Volpe and City fleet managers. Participants included representatives from the Department of Public Works, Fire Department, Police Department, Water Department, and others. In addition, garage visits were also arranged so Volpe staff could see vehicles and learn from maintenance and repair staff about the operation of individual vehicles. During these meetings, vehicle functions and attributes such as towing, payload, snow plowing, four-wheel drive (4wd), storage needs, idling time, heating and cooling requirements, and driving distances were discussed. For example, Police Department cruisers indicated a need for maintaining cargo storage volume (a 2018 Ford Interceptor Utility provides 133.2 cubic feet[21]), and DPW indicated a need for snow plowing capability (e.g., F-350 range of horsepower). The City also made GPS records available for a limited portion of the subset of vehicles that had been outfitted with GPS technology, which provided information on idling times, fuel consumption, and vehicle speeds. Based on the information from these meetings and data sources, Volpe segmented the City fleet into 11 vehicle categories as shown in Table 6.

Table 6: Vehicle Segmentation of Cambridge Fleet

Vehicle type	Vehicle class	Example model
heavy truck	class 8	International Harvester
refuse truck	class 8	Freightliner M106
passenger car	class 1	Ford Taurus
light-duty pick up	class 2a	Ford F-150
light-duty van	class 2a	Ford Transit Connect
medium-duty pick up	class 2b, 3, 4, 5	Ford F-250/350/450/550
medium-duty van	class 2b, 3, 4, 5	Mercedes-Benz Sprinter
SUV	class 2a	Ford Explorer
School bus	class 8	Thomas Saf-T-Liner HDX
Fire apparatus	class 8	Pierce Arrow-XT
Motorcycle	Motorcycle	Yamaha YZF-R1

Additional segmentation was made, but is not shown in the table, to reflect different baseline characteristics. For example, passenger cars were further segmented into gasoline engine, hybrid, and plug-in hybrid (PHEV) for the purposes of identifying technologies and to properly account for vehicle GHG reductions in the GHG reduction scenarios.

SUVs were segmented into several categories to reflect different functions: One category required

[20] **Note:** EPA has determined that its post-2021 light-duty GHG standards are inappropriate, and NHTSA and EPA are working jointly on an NPRM regarding future fuel economy and GHG standards.

[21] Ford Motor Company, *Police Interceptor Utility*. https://www.ford.com/police-vehicles/police-interceptor/utility/

maximum storage area, another was already hybridized, and a third did not have specific constraints on storage. Heavy trucks were segmented based on the amount of idling, snow plowing, or other characteristics. Once these subcategories had been selected, a total of 26 vehicle categories were established for the City of Cambridge fleet.

6.2.3 Defining Technology Options for Each Vehicle Type

Volpe then researched technologies that could be expected to be available between 2018 and 2030 and that could be applied to the 26 vehicle categories. Significant information is available in published regulatory documents. In addition, Volpe conducted internet research, reviewed trade publications, and held conversations with suppliers and vehicle conversion companies. Conversations were also held with fleet managers and maintenance staff from fleets that have introduced advanced technology vehicles to learn how the vehicles have performed in service. Based on this research and fleet stakeholder engagement, Volpe selected technologies to be evaluated using the DOE AFLEET tool for each of the 26 vehicle categories and subcategories. Table 7 provides an overview of the technologies and approaches evaluated in this study.

Table 7: Vehicle Technologies Evaluated for GHG Scenarios

Engine/fuel Technologies	**Transmission Technologies**
Cylinder deactivation	Infinitely variable shift/neutral at stop
Engine downsizing	Pack at idle
Compressed natural gas engine	**Operational Approaches**
Biodiesel	Vehicle accelerated retirement
E85	Substitution of VMT with smaller vehicles
Idle Reduction Technologies	**Vehicle Technologies**
Fuel operated air heater	Mild hybrid (48 volt)
Fuel operated coolant heater	Hybrid electric
Battery Management (Start/Stop)	Hydraulic hybrid
APU (battery)	Plug-in hybrid electric
APU (diesel)	Electric (conversion or OEM)
APU (Battery) & Battery Management Start/Stop	Fuel cell

Some of the technologies in the table are already commercialized in light-duty vehicles, such as cylinder deactivation, engine downsizing, hybridization and plug-in electric vehicles. A subset of these, including cylinder deactivation, downsizing, mild hybrids and full hybrids are expected to be available from original equipment manufacturers (OEMs) in heavier vehicles between 2017 and 2030.[22] Other technologies (i.e. extended range electric vehicles) may be available from OEMs or can be obtained through aftermarket conversion. Examples of currently available aftermarket

Heavy Vehicle Hybridization

Orlando, FL

- Pilot of 9 HHV refuse trucks (2013)
- Significant fuel/emissions reductions and productivity gains
- Expanded to 18 vehicles (2016)

[22] **See** Heavy-Duty regulatory documents cited in footnote XX

conversion for medium- and heavy-duty vehicles are gasoline electric hybrids, hydraulic hybrids (HHV), and plug-in hybrids.

Hybridization for the heaviest vehicles are not yet widely available. However, based on the experience of several cities, Volpe included the technology in the analysis. For example, Orlando, Florida conducted a pilot of nine HHV refuse trucks in 2013, and based on the results doubled their HHV fleet to 18 vehicles in 2016. Orlando documented significant reductions in fuel use and emissions, and also identified productivity gains (completing scheduled routes earlier). On a life-cycle basis, Orlando found the HHVs to be more cost effective than conventional trucks, with reduced maintenance and lower fuel consumption offsetting the initially higher cost within a few years.[23] Other success stories include, but are not limited to: Miami-Dade, Florida; UPS;[24] Loveland, Colorado; and Detroit, Michigan.[25] In cases where fleet managers indicated advanced technologies were too new to draw conclusions on performance and costs, Volpe excluded the technologies from the analysis.
To identify vehicle types that could be replaced with electric versions, Volpe researched manufacturer product announcements, OEM electric vehicles currently offered for sale, and availability of aftermarket conversion kits. Table 8 provides examples of currently, or soon to be, available electric light-, medium-, and heavy-duty PHEV or electric vehicles. Both OEM and aftermarket conversion kits are listed.

Table 8. Examples of Currently Available Light-, Medium-, and Heavy-Duty Electric Vehicles

Vehicle name	Manufacturer	OEM/conversion	Vehicle type	Technology
Bolt	GM	OEM	Passenger car	All-electric
Leaf	Nissan	OEM	Passenger car	All-electric
Volt	GM	OEM	Passenger car	PHEV
W-15	Workhorse	OEM	Pick-up truck	PHEV
R1T	Rivian	OEM	Pick-up truck	All-electric
Transit	Ford/Lightning	conversion	Heavy-duty van	All-electric
eCanter	Fuso	OEM	Heavy-duty van	All-electric
Cargo Van	Zenith	OEM	Heavy-duty van	All-electric
F450	Ford/Odyne	conversion	Heavy-duty pick up	PHEV

[23] GreenFleet, City of Orlando Gains Nine Hybrid Refuse Trucks, 2015. www.greenfleetmagazine.com/channel/hybrids/news/story/2015/04/city-of-orlando-gains-nine-hybrid-refuse-trucks.aspx
[24] U.S. Department of Energy National Renewable Energy Laboratory, *Hydraulic Hybrid Fleet Vehicle Evaluations*. https://www.nrel.gov/transportation/fleettest-hydraulic.html
[25] www.government-fleet.com/list/tag/hydraulic-hybrid.aspx

Vehicle name	Manufacturer	OEM/conversion	Vehicle type	Technology
Micro Bird G5	Blue Bird	OEM	School bus	All-electric
eM2 106	Freightliner	OEM	Medium-duty truck	All-electric
Electric LR	Mack	OEM	Refuse truck	All-electric
Electric 520	Peterbilt	OEM	Refuse truck	All-electric

Examples in Table 8 show that plug in vehicles are available either as conversions or from original equipment manufacturers for a range of vehicle weights and classes. The majority of electric vehicles and PHEVs are available in the passenger vehicle category,[26] but product announcements have been made for vans, light- and medium- pick-up trucks, school buses, refuse, and other heavy trucks as well. In some cases, Volpe contacted fleet managers mentioned in articles to ask how electric vehicle performance compared with that of conventional vehicles.

6.2.4 Technologies Assumed to Be in the BAU Case

As mentioned earlier, a number of technologies anticipated to be used by manufacturers to comply with GHG regulatory requirements were assumed to be in the business as usual case. For light-duty vehicles, these included weight reduction, aerodynamic improvements, engine friction reduction, electrified accessories, transmission technologies (continuously variable (CVT), dual-clutch (DCT), 8 or 10-speed automatic transmissions), turbocharging and downsizing of gasoline engines, cylinder deactivation, gasoline direct injection, mild hybridization (48 volt technology), and high compression ratio engines. For medium-duty vehicles, most of the same technologies were included in the BAU case, with the exception of mild hybridization and cylinder deactivation. For heavy-duty vehicles, weight reduction, aerodynamic improvements, automated manual transmissions, conventional automatic transmissions, combustion improvements, low rolling resistance tires, automatic engine shut off, and automatic tire inflation or tire pressure monitoring systems were assumed to be in the BAU case.

6.2.5 Restricted Technologies

In addition to the excluded technologies described above, some technologies were restricted due to vehicle performance requirements. As mentioned earlier, vehicle performance requirements were identified by City of Cambridge fleet managers during meetings on the GHG analysis. Examples of requirements are: Department of Public Works vehicles that plow snow in the winter must be able to operate around the clock during a storm without interruption. For this reason, some technologies, such as electrification that currently require significant down-time for charging were not applied to trucks that plow. Fire trucks are used for both fire-fighting and for emergency medical response and need to be able to respond immediately from the scene of a medical emergency to a fire and vice versa. Further,

[26] **Note:** Department of Energy reports 53 light-duty electric vehicle models available in 2018. **Source:** U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, *Find Electric Vehicle Models*. https://www.energy.gov/eere/electricvehicles/find-electric-vehicle-models

space constraints in fire stations limit options for technology introduction. For these reasons, a very low technology adoption rate was assumed for fire trucks. Certain Police vehicles require storage space for equipment and for these vehicles there is limited opportunity for hybridization given the smaller trunk space in current hybrids.[27] These and other considerations were taken into account in matching technologies with vehicles. Restriction of technologies was accomplished in one of two ways in the analysis. In some cases, technologies were excluded altogether from use in certain vehicles. In other cases, the introduction of a technology was delayed, under the assumption that some technology limitations may be resolved by manufacturers over time. The latter approach will be described in more detail in the implementation section of this report.

Once Volpe had evaluated the fleet vehicle operating constraints, potential GHG reduction technologies, and the availability of technologies, the costs, GHG, and criteria emission changes resulting from introduction of the technologies into the Cambridge fleet vehicles were then evaluated. This process is described in the next section.

6.2.6 Assess Vehicle GHG Reductions and Costs

GHG emissions changes, criteria emissions changes, and costs for individual vehicles and technologies were evaluated in the AFLEET model. AFLEET has a number of modules that allow the user to specify vehicle type, using the Environmental Protection Agency (EPA) MOVES[28] model vehicle classification system; vehicle baseline fuel (gasoline, diesel, or other); vehicle idling time (hours per year); purchase price of the vehicle; mileage (mpg) of the vehicle; and other parameters. AFLEET also allows the user to specify the mix of fuels used to generate electricity in the county, either by specifying the EPA eGRID region or by inputting the specific mix of fuels for the locality.[29] AFLEET provides default values for maintenance costs (labor rates and parts costs), tailpipe GHG and criteria emissions reductions. The model also provides costs and savings over the life of a vehicle with and without technologies, as well as on an annual basis. Costs or savings are provided for fuel, maintenance, depreciation, insurance, registration and licensing, electric vehicle charging infrastructure, and other categories. Savings are discounted using a default 1.2 percent discount rate. Monetized savings associated with GHG and criteria emissions reductions are also provided for each vehicle and technology in AFLEET. **Error! Reference source not found.** provides an overview of the assumptions used by Volpe for the AFLEET modeling of the Cambridge fleet.

[27] **Note:** As battery energy density increases, battery size is expected to decrease, potentially allowing future hybrid and electric vehicle models to increase available storage volume for police applications.

[28] **Note:** MOtor Vehicle Emission Simulator

[29] **Note:** EPA's eGRID stands for "Emissions and Generation Resource Integrated Database" and is a comprehensive source of data on the environmental characteristics of electric power generated in the United States.

Table 9. Summary of Default and Customized Information Used for AFLEET Runs

Technology	Technology Purchase Price	Vehicle mpg	Maint-enance costs	Fuel costs	Electric grid emissions[30]	Vehicle activity
Baseline vehicles (gas, diesel, hybrid, PHEV, biodiesel)	AFLEET default	Adjusted for BAU case to account for regulatory requirements	AFLEET default	AFLEET default	RGGI 2030 target assumed to be achieved	VMT based on City data
PHEV, EV, HEV, biodiesel	Used DOE ANL costs	EPA mpg rating	AFLEET default	AFLEET default	Massachusetts grid mix specified	VMT based on City data
Hydraulic hybrid, fuel cell, CNG, biodiesel	AFLEET default	AFLEET default	AFLEET default	AFLEET default	N/A	N/A
Transmission and engine improvements	Supplier or OEM information	EPA/ NHTSA rulemaking documents	AFLEET default	AFLEET default	N/A	VMT based on City data
Idle reduction	AFLEET default	N/A	AFLEET default	AFLEET default	N/A	Idling hours based on GPS data
Vehicle or engine downsizing	Supplier or OEM information	Published data	AFLEET default	AFLEET default	N/A	VMT based on City data

Monetized savings for GHGs and criteria emissions were estimated in the AFLEET model. AFLEET monetizes the following criteria pollutants: oxides of nitrogen (NOx), fine particulate ($PM_{2.5}$), particulate (PM_{10}), carbon monoxide (CO), and volatile organic compounds (VOC). Emission factors for the pollutants as well as other assumptions, such as emissions deterioration, come from EPA's MOVES 2014a model. In addition, a cost is assigned to the value of CO_2 reduced. Monetization of pollutants reduced assumes the following:

- Social cost of carbon $46/ton – DOT guidance[24];
- Criteria emissions damages – EPA AP2[31]

In addition to the information provided in Table 9, cost estimates specific to the City of Cambridge for

[30] **Note:** The Regional Greenhouse Gas Initiative has adopted a 30 percent reduction target between 2020 and 2030, which will result in approximately 500 pounds CO_2/MWh in 2030. Volpe's analysis is consistent with RGGI targets.

[31] **AFLEET documentation source:** U.S. Department of Energy Office of Science. https://greet.es.anl.gov/afleet_tool

electric vehicle charging infrastructure were used by Volpe for the analysis, based on information provided by the City.

For each vehicle category, a number of technologies were evaluated in AFLEET. As an example, the City's hybrid passenger cars were run as a category, and Volpe used for inputs an average of the hybrids' annual vehicle miles travelled and an average fuel economy for the hybrids. In addition, the run separately evaluated a move to plug-in hybrid, full electrification, or fuel cell. For some vehicle categories additional analysis was needed if a technology was not available in AFLEET. Mild hybridization and pack-at-idle[32] are examples. In these cases, the purchase price of the vehicle was adjusted to reflect the increased cost of the technology in AFLEET. Fuel economy was also adjusted to reflect improved fuel economy, based on the assumptions and data sources shown in **Error! Reference source not found.**.

The outputs of AFLEET include the total cost of ownership for each technology. The total cost of ownership is the sum of the costs and discounted benefits for each vehicle and technology over the life of the vehicle. Volpe subtracted the baseline total cost of ownership from the technology case to arrive at an incremental total cost of ownership. Other outputs of the AFLEET model are mass of criteria pollutants and GHGs reduced, societal benefits resulting from lower criteria emissions, and fuel savings.

Results from AFLEET for the technology runs were then entered into Excel for the next step in the analysis. The incremental total cost of ownership for the technology and the annual gallons saved for each technology were entered into Excel for each vehicle type.

6.2.7 Assess Fleet-Wide GHG Reductions and Costs

To assess the lowest cost approach to achieve a specified fleet-wide GHG reduction target, Volpe entered the AFLEET results into Microsoft Excel's Solver module. Solver is an add-in program that produces an optimized solution for a parameter (such as fleet GHGs), subject to constraints set by formulas in other cells. For example, for one of the scenarios in this analysis Volpe specified a maximum fuel savings with a constraint that the overall net present value (NPV) for the fleet vehicles had to be positive, and then used Solver to find the combination of vehicle categories and selected technologies that maximizes fuel savings while maintaining a positive NPV. Solver was used to optimize for GHG reduction scenarios as described in the next section. Solver outputs included the following for each scenario:

- Fleet NPV in the GHG reduction case as compared to the baseline;
- Cumulative fuel saved (gallons) which was converted to GHGs; and
- Number of vehicles (overall and in each category) receiving each technology option.

The Solver analysis provides the number of vehicle-technology combinations that result in the lowest cost for vehicles in the City's fleet between 2018 and 2030: for example 15 electric passenger cars, 30 medium pick-up trucks with idle reduction technology, seven refuse trucks with pack at idle technology,

[32] **Note:** Reduces rubbish packer cycling noise and increases fuel economy during the pack cycle. Pack at idle normally packs with the engine at approximately 1,200 rpm.

and so forth. Not all vehicles are assigned a technology: some vehicles remain in their BAU gasoline or diesel configuration.

Additionally, Volpe wrote a Visual Basic macro to automate Solver to run iteratively on a range of GHG reduction targets, calculating the maximum achievable NPV with the selected technologies at each GHG reduction level.

6.3 Model overview

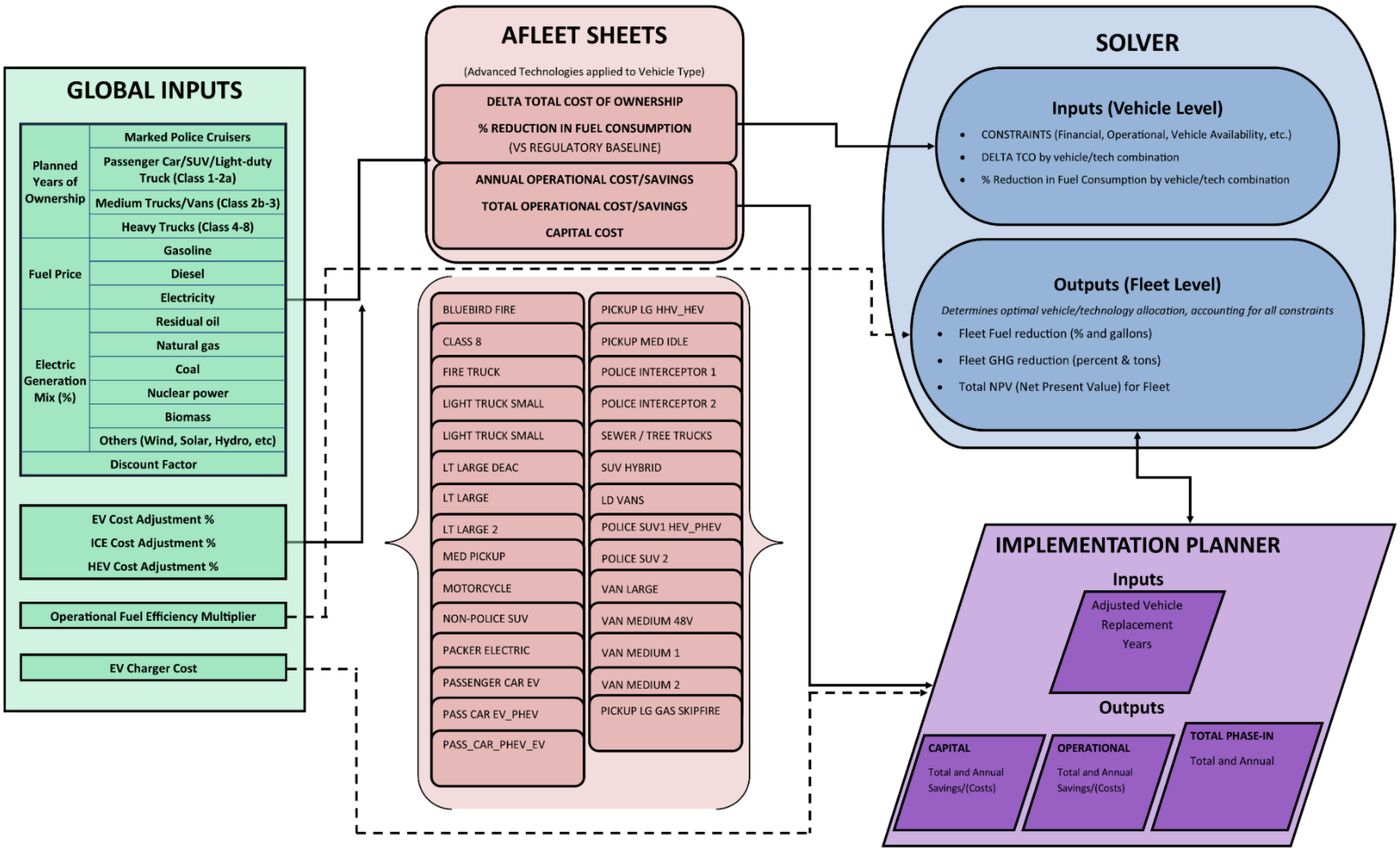


Figure 14 – Clean Fleet modeling analysis process flowchart

6.3.1 Global Inputs and Refresh macro

The Global Inputs spreadsheet is the tool by which users can enter and edit variables and values that propagate through the rest of the modules in the analysis process. Global inputs are both internally controlled values such as planned years of ownership for different vehicle categories, or operational and behavioral savings; or external factors that are quantified by groups such as Volpe, Arup, or the Argonne National Laboratory. External factors that can be input at this stage of the analysis process include gasoline and diesel price, electricity generation mix, and vehicle costs (internal combustion, hybrid, and electric). These external factors have an estimated range of forecast values, and the bounds of these forecasts are used as values in the Best Case and Worst Case scenarios.

6.3.2 Vehicle category AFLEETs

The Department of Energy's Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool estimates petroleum use, greenhouse gas emissions, air pollutant emissions, and cost of ownership of light-duty and heavy-duty vehicles using spreadsheet inputs. The tool uses data from Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) fuel-cycle model to generate necessary well-to-wheels petroleum use and GHG emission coefficients for key fuel production pathways and vehicle types. In addition, the Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) and certification data are used to estimate tailpipe air pollutant emissions. Various sources are used to provide default cost data, including the Clean Cities Alternative Fuel Price Report and American Recovery and Reinvestment Act awards.[33]

The first processing step of the decarbonization analysis involves using 25+ AFLEET spreadsheets, one for each defined vehicle type category. AFLEET is designed to handle only one specific vehicle type at a time, with particular inputs relating to purchase price, fuel efficiency, and annual idling hours that cannot be aggregated to the Global Inputs level. Within the spreadsheet tool, selected advanced vehicle technologies (chosen by Volpe in consultation with City of Cambridge) are applied to the base vehicle, and costs or savings for operations, fuel consumption, and GHG emissions are calculated. In addition, the total cost of ownership, or TCO, is calculated using the operational costs/savings coupled with the incremental capital cost associated with each advanced technology.

6.3.3 Solver

The Solver module aggregates the relevant individual outputs from each AFLEET run into a single analysis table. These variables are multiplied according to the total number of available vehicles per category in the fleet and summed together, moving the level of analysis from the vehicle level to the fleet level. The fleet-level outputs are used as targeted variables for the "Solver" optimization tool in

[33] https://greet.es.anl.gov/afleet_tool

Microsoft Excel. With the Solver tool, Volpe is able to select the variables for optimization such as Fleet fuel reduction, Fleet GHG reduction, and total net present value (NPV); the Solver tool will determine the best possible application of vehicle technologies to produce the best possible output values. The Solver module accepts constraints inputs for any values that affect the targeted output. In this case, such constraints include the number of vehicles per category available for technology implementation, the types of technologies available for specific vehicle categories, and the maximum fleet-level incremental capital cost. All of these constraints have been determined in consultation with the City of Cambridge and can be changed at any point in the analysis process.

6.3.4 Implementation Planner

The Implementation Planner module sequences the phase-in of technologies across specific vehicles in the fleet through 2030 and tabulates the per-year incremental changes to TCO, capital costs, and operational costs or savings. The fleet-level solution of Solver is translated back to a vehicle-level solution in the Implementation Planner. The Implementation Planner includes one input: an adjusted replacement year schedule for all vehicles, in which the category-level replacement years is the default value but can be overridden for specific vehicles. Adjusted replacement years are based either on information from the City of Cambridge or are based on inference for those vehicles in the inventory that have already exceeded their category-level replacement cycle. The current assumption is that those vehicles have been replaced according to their replacement cycle and that the following replacement year (if it falls in 2030 or sooner) falls under the Clean Fleet plan. In addition to incremental costs and savings associated with vehicle technologies, the Implementation Planner also accounts for electric vehicle charging station costs and shows the number of stations implemented per year based on an assumed ratio of vehicles to stations.

6.4 Input Variables and Constraints

Volpe developed a bounding matrix of inputs, based on external factors and internal fiscal choices. Generally, the external factors were identified by Volpe and agreed upon with City of Cambridge as important variables to examine. The internal fiscal choices were set forth by the City of Cambridge based on expected funding availability. The analysis model is designed to handle changes in both the external and internal factors as new or updated information becomes available.

Table 10 shows the external variables, values, and sources, with the combination of forecast values that would be most favorable for large GHG reduction and for small incremental cost forming the "Best Case," and the least favorable values forming the "Worst Case." The "Average Cases" use intermediate assumptions, with the exception of electricity grid mix. Forecast values for fuel prices were obtained from the Energy Information Administration Annual Energy Outlook 2018 (accessed December 10, 2018), with high and low fuel and electricity prices each averaged across all forecast years between 2018 and 2030 for consistency. As the City of Cambridge pays 17 cents per kilowatt-hour for electricity at the time of writing, Volpe used this current price and escalated it by the U.S. Energy Information Administration (EIA) 2005-2017 Massachusetts annual escalation rate of 3.32%, yielding 21 cents for the Worst Case electricity price value in 2030. The electric generation mix values used in the Best and Worst Cases are respectively consistent with 100% renewable energy (0 pounds of CO_{2e} per MWh) and the ARUP Regional Greenhouse Gas Initiative (RGGI) 2030 emissions factor forecast of 485 pounds of CO_{2e} per MWh. At Cambridge's request, Volpe analyzed both a 100% renewable electricity variation and a high EEF variation for the Average Case rather than one based on an intermediate EEF assumption.

Table 10. Input variables, values, and sources for the Cases.

Parameter	Units	Worst Case	Average Case RGGI	Average Case 100% Renewable	Best Case	*Sources*
Gasoline price	$/Gallon	2.05	3.82	3.82	5.59	*EIA*
Diesel price	$/Gallon	1.77	3.58	3.58	5.38	*EIA*
Electricity price	$/kWh	0.21	0.195	0.195	0.18	*EIA and Cambridge contract w/ 3% escalation*
Discount rate	Percent	3.00%	2.21%	2.21%	1.42%	*AFLEET and Volpe/OMB (based on treasury yields)*
Electricity-related GHGs	Lbs./MWh	485	485	0	0	*Arup RGGI scenario and Cambridge*
EV costs	% of default value	104.9%	100.7%	100.7%	96.5%	*Argonne National Lab*
ICE costs	% of default value	93.3%	99.7%	99.7%	106.0%	*Argonne National Lab*
HEV costs	% of default value	110.0%	102.4%	102.4%	94.7%	*Argonne National Lab*

Each of the four Cases was analyzed for an Increased Resources/Efficiency and a Fixed Budget Scenario of investment. These two Scenarios, related to fiscal constraints, were defined as follows:

- *Increased Resources/Efficiency Reduction*: fiscally unconstrained
- *Fixed Budget Reduction*: fiscally constrained to $300,000 incremental capital cost per year

Based on consultation with the City, Volpe assumed that in the Best Case, RGGI emissions cap reductions will occur through 2022, followed by 100% renewable electricity with zero emissions in years 2023-2030. Volpe currently assumes no change in electricity price associated with switching to 100% renewable energy.

The inputs to the Solver module are a series of three columns with gallon reductions for each of up to three technologies per vehicle category row, TCO change for the same, and the number of vehicles available for Solver to assign to each respective vehicle category. The numbers of vehicles in each category that are available for Solver to assign an advanced technology are shown in the third column in Table 11. The advanced technologies available to select among for each vehicle category are in the "technology 1" through "technology 3" columns. As can be seen, every vehicle in the fleet with the exception of the eight SUV hybrids was made available for advanced technologies in the sensitivity analyses.

Table 11. Selected Solver module inputs

category name	description	Number of these vehicles for Solver	technology 1	technology 2	technology 3	total number in fleet
packer	International, Freightliner, Peterbilt rubbish trucks	16	diesel HEV	diesel HHV	electric	16
class8tree/sewer	either Int'l Harvester or Peterbilt, class 8 truck, dedicated route - high idle	5	HEV + IR	idle reduction	PHEV	5
class8	miscellaneous large trucks	29	electric	HEV + IR	idle reduction	29
pass car	gasoline passenger car, does not include police cruisers	23	PHEV	electric	hybrid	23
pass car hybrid	gasoline electric hybrid	35	PHEV	electric		35
pass car PHEV	plug in hybrid vehicle such as the Volt	2	electric			2
Ltsmall	Toyota Tacoma size truck	19	HEV	electric	48 volt	19
Ldvan	transit connect, other LD vans under 8,500 GVWR	8	electric	HEV	48 volt	8
VanMedium2	8500-14,000 GVWR school or human services MD van	10	electric (Lightning upfit)	HEV + IR	cylinder deac/skip	10
VanMedium1	8,500 - 14,000 GVWR, police or fire MD van	21	electric (Lightning upfit)		HEV + IR	21
policeinterceptor1	only mild hybrid considered due to space constraints	0	48 volt		idle reduction	0
policeinterceptor2	hybrid and electric considered	33	HEV	PHEV	electric	33

category name	description	Number of these vehicles for Solver	technology 1	technology 2	technology 3	total number in fleet
SUVhybrid	Ford escape and other SUV hybrids	0	electric	PHEV		8
Ltlarge	Chevy Colorado, F150	12	electric	hybrid	PHEV	12
PickupMedium1	F250, F350	64	HEV + IR	idle reduction	PHEV	64
PickupMedium2	F250, F350	0	48 volt	idle reduction		
PickupLargegas	F450, F550	9	HEV + IR	deac with skip fire	idle reduction	9
PickupLargediesel	F450, F550	0	HHV	HHV + IR		
VanLarge	Int'l CF600, Gruman Olsen	6	hybrid			6
Bus	Fire S1701,	1	electric	diesel HEV	diesel HHV	1
SUV1	SUV and minivan: expedition, tahoe, explorer, Sienna	21	electric	HEV	PHEV	21
SUV2	same as above but Police Dept	0	HEV	idle reduction		0
firetruck	Pierce, Saber	17	downsize to motorcycle	idle reduction		17
motorcycle	motorcycle	14	electric			14

In addition to inputs in the Solver module, the actual Solver add-in is programmed with a number of adjustable constraints for the optimization. These include the maximum annual incremental capital cost (not to exceed $3.3 million per year, as shown in the first constraint in Table 12 and in Figure 15, as well as a number of validation constraints, e.g., ensuring non-negative integer numbers of vehicles assigned to a technology. Other constraints in this list are adjusted to restrict the number of vehicles that receive one of the advanced technology options available for its vehicle category, e.g., limiting the number of Class 8 vehicles that can be electrified. These specific technology constraints reflect operational constraint inputs provided to Volpe by fleet stakeholders, and they can be adjusted if those inputs change in the future.

Table 12. Solver parameter constraints

VARIABLE	CONSTRAINT	TOTAL IN FLEET	BASIS FOR CONSTRAINT
Annual incremental capital (cost) or savings	($3,300,000)	N/A	Cambridge input
Class8/electric	<=6	29	Market availability, snow plowing
Fire truck/downsize to motorcycle	<=2	17	Fire station space constraints
Light truck large/electric	0	12	Snow plowing
Packer/diesel HEV	8	16	Market availability, anticipated procurement plans

VARIABLE	CONSTRAINT	TOTAL IN FLEET	BASIS FOR CONSTRAINT
Packer/electric	2	16	Market availability, technology maturity
Packer/HHV	6	16	Market availability, anticipated procurement plans
Police interceptor/electric	0	33	Market availability, Cambridge input
Police interceptor/PHEV	<=10	33	Market availability, Cambridge input

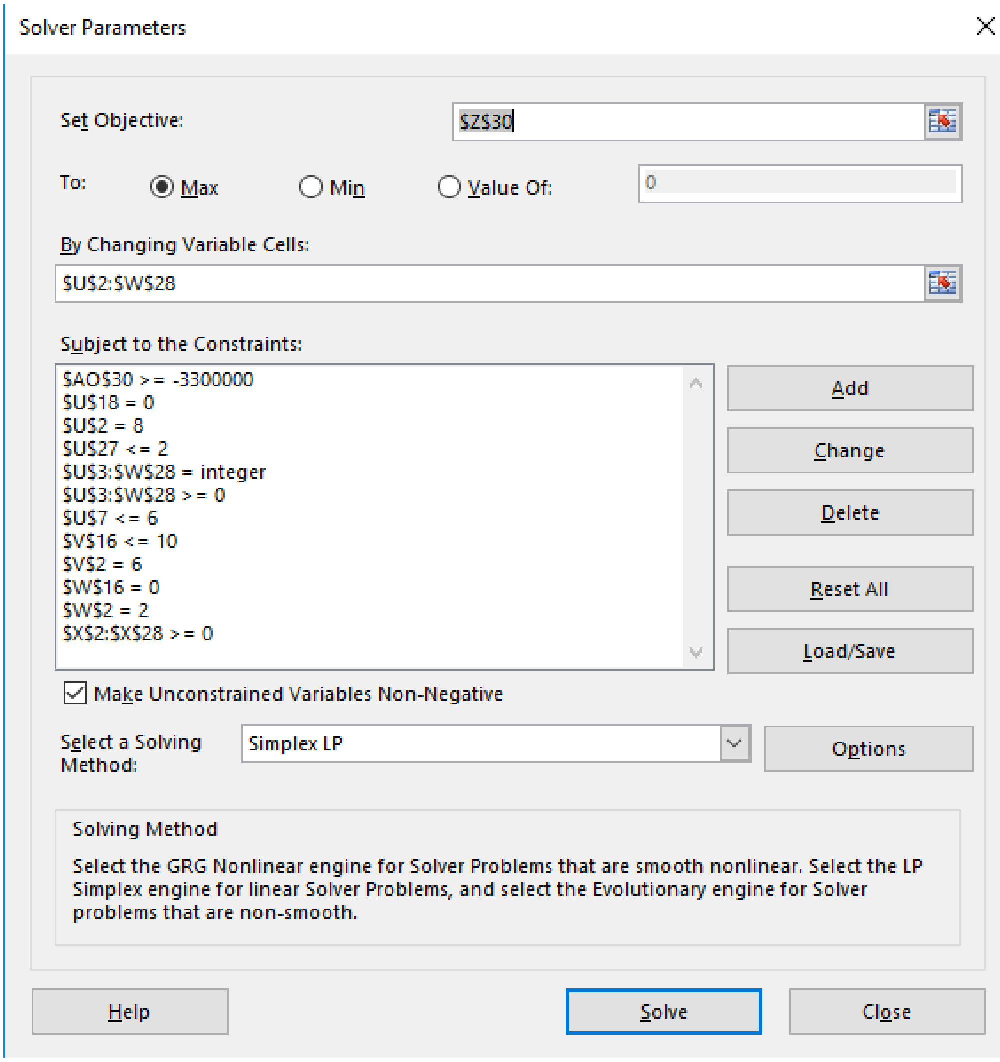


Figure 15. Solver constraints dialog box.

6.4.1 Electricity emissions factors

The electricity emissions factor for the New England Independent System Operator in 2030 under the Regional Greenhouse Gas Initiative model rule policy scenario (assuming no national clean power program) was determined to consist of the grid mix shown in Table 13 based on RGGI program documentation.[34] This electricity generation mix is consistent with the ARUP forecast for 2030 of 485 pounds of CO_{2e} per MWh. By comparison, the 2017 emissions factor for the New England Independent System Operator (ISO) is 682 pounds of CO_{2e} per MWh.

Table 13. RGGI 2030 New England ISO electricity generation mix used as inputs to the Worst Case.

	2030 net generation (GWh)	Percentage
Biomass	9,694	9%
Coal (Without CCS)	0	0%
Combined Cycle (Gas)	41,014	39%
Combustion Turbine (Gas)	1,916	2%
Nuclear	24,989	24%
Oil/Gas Steam	0	0%
New Combined Cycle (Gas)	1,994	2%
New Combustion Turbine (Gas)	0	0%
Other	21	0%
Conventional Generation Total	*79,629*	*75%*
Hydro	8,971	8%
Solar	533	1%
Wind	4,527	4%
New Solar	7,081	7%
New Wind	4,142	4%
Other Renewable	1,267	1%
Renewable Generation Total	*26,522*	*25%*
Total	**106,150**	**100%**

6.4.2 Idling input data

Volpe collected idling data using the AAT telematics system for the calendar year 2018 and summed total annual idling for medium pickups, large pickups, and Class 8s, the vehicle categories for which Volpe identified high potential benefit of idle reduction technology based on these vehicle categories' baseline fuel consumption and common usage (e.g., at worksites, snowplow rest periods, etc.). The only available Large Pickup data point available on AAT for 2018, Vehicle 91, recorded 341 idling hours.

[34] https://www.rggi.org/sites/default/files/Uploads/Program-Review/9-25-2017/Draft_IPM_Results_Model_Rule.xlsx

Table 14. 2018 idling hours on Class 8 vehicles based on AAT data

Make	Model	DPW Vehicle #	Total idle hours for 2018
International Harvestor	7400	82	335
International Harvestor	7300	145	653
International Harvestor	7400	76	387
Peterbilt	348	83	384
Freightliner	M2-106V	71	368
International Harvestor	4900	148	345
		Average annual hours	**412**

Table 15. 2018 idling hours on Medium Pickup vehicles based on AAT data

DPW Vehicle #	Total idle hours for 2018
49	389
54	437
69	924
88	261
89	793
129	577
204	819
205	484
Average annual hours	**586**

6.5 AFLEET model assumptions

Table 16. Assumptions used for AFLEET inputs

Input Variable	Assumption/Entry	Values	Modules Using Input
Primary vehicle location (state and county)	Middlesex County, MA	See column at left	All
Vehicle type	Used closest match in AFLEET	Varied by vehicle type	All
Vehicle fuel type	Varied based on technology options	See column at left	All
Annual vehicle mileage	Estimated based on 2016 average fuel	Varied by vehicle type	All

Input Variable	Assumption/Entry	Values	Modules Using Input
	consumption and fuel economy		
Fuel economy	Used default	Varied by vehicle type	All
Vehicle/technology purchase price	Used default and/or market research	Varied by vehicle type	All
Public or private fuel station pricing	Private	See column at left	All
Fuel price	Used default values	• Gasoline: $2.10 per gallon • Diesel: $2.43 per gallon • Electricity: $0.20 per kWh	All
Diesel Emission Fluid Use (% of fuel consumption)	Used default values	2% for all vehicles fueled at least in part by diesel	Total cost of ownership
Diesel Emission Fluid Price	Used default values	Base price is $2.80 per gallon, and assumes a 1.9% price escalation rate per year	Total cost of ownership
Planned years of ownership	Used values provided by Cambridge	15 years for all categories, except for the following: • Passenger cars: 12 years • Vans with GVWR < 14,000 lbs.: 13 years • Vans with GVWR > 14,000 lbs.: 17 years	Total cost of ownership
Whether purchase is financed by a loan	No	See column at left	Total cost of ownership
Loan term (if applicable	N/A	N/A	Total cost of ownership
Loan interest rate (if applicable)	N/A	N/A	Total cost of ownership
Discount factor	Default value	1.42%	Total cost of ownership
Source of electricity	Default based on geographic location		Total cost of ownership
Fuel price sensitivity (high/low values)	No	See column at left	Total cost of ownership
Insurance	Default values	• Light-duty: $993 per vehicle per year • Heavy-duty: $5,127 per vehicle per year	Total cost of ownership

Input Variable	Assumption/Entry	Values	Modules Using Input
		• Adjusted for inflation for future years.	
Maintenance	Default values	See Table 17 below	Total cost of ownership
Depreciation	Default values	• First year of vehicle ownership: 23% • Subsequent years: 15%	Total cost of ownership
License and Registration	Default values	• Light-duty: $107.50 per vehicle per year • Heavy-duty: $540 per vehicle per year • Adjusted for inflation for future years.	Total cost of ownership
Taxes	Default values	Not included	Total cost of ownership
Vehicle model year	Average of Cambridge fleet	Varied by vehicle type	Total cost of ownership
Annual idling hours	GPS data	Varied by vehicle type	Idle reduction
Percent of idling hours by service (vehicle heating, engine heating, cooling, electrical)	GPS data	Varied by vehicle type	Idle reduction
Baseline Fuel consumption	City fleet records and GPS	Varied by vehicle type	Idle reduction
Electrical power demand for idle reduction equipment	Default values	Light-duty: 250 watts Heavy-duty: 704 watts	Idle reduction
Idle reduction equipment price	Market research	Varied by vehicle/technology type. • Light-duty: $900-$5,800 per vehicle • Heavy-duty: $1,700 - $10,500 per vehicle	Idle reduction

Table 17. Maintenance Costs per Mile (Default Values from AFLEET)

	Gasoline	Diesel	Gasoline Hybrid Electric Vehicle (HEV)	Gasoline Plug-in Hybrid Electric Vehicle (PHEV)	Gasoline Extended Range Electric Vehicle (EREV)	All-Electric Vehicle (EV)	Diesel Hybrid Electric Vehicle (HEV)	Diesel Hydraulic Hybrid (HHV)
Long Haul Freight Truck		$0.19				$0.17	$0.18	$0.18
Regional Haul Freight Truck		$0.19				$0.17	$0.18	$0.18
Delivery Straight Truck	$0.20	$0.20				$0.16	$0.18	$0.18
Delivery Step Van	$0.20	$0.20				$0.14	$0.16	$0.16
Dump Truck		$0.20				$0.14	$0.16	$0.16
Bucket/Aerial Truck		$0.20				$0.14	$0.16	$0.16
Snow Plow/Sander		$0.20				$0.14	$0.16	$0.16
Sewer Cleaner		$0.20				$0.14	$0.16	$0.16
Street Sweeper		$0.20				$0.14	$0.16	$0.16
Fire Truck		$1.50				$1.44	$1.46	$1.46
Refuse Truck		$2.89				$2.83	$2.85	$2.85
Transit Bus		$1.00				$0.94	$0.96	$0.96
School Bus	$0.93	$0.93				$0.87	$0.89	$0.89
Shuttle/Paratransit Bus	$1.00	$1.00				$0.94	$0.96	$0.96
Medium-Duty Pickup Truck	$0.18	$0.29	$0.18	$0.18	$0.18	$0.17		
Utility Cargo Van	$0.23	$0.31	$0.23	$0.22	$0.22	$0.21		
Shuttle/Paratransit Van	$0.21	$0.28	$0.21	$0.20	$0.20	$0.19		
Ambulance	$0.95	$1.03	$0.94	$0.94	$0.94	$0.93		
Tow Truck	$0.18	$0.29	$0.18	$0.18	$0.18	$0.17		
Light-Duty Pickup Truck	$0.16	$0.22	$0.16	$0.15	$0.15	$0.14		
SUV	$0.15	$0.20	$0.14	$0.14	$0.14	$0.13		
Taxi SUV	$0.15	$0.20	$0.14	$0.14	$0.14	$0.13		
Police SUV	$0.15	$0.20	$0.14	$0.14	$0.14	$0.13		
Car	$0.14	$0.19	$0.14	$0.13	$0.13	$0.13		
Taxi Car	$0.14	$0.19	$0.14	$0.13	$0.13	$0.13		
Police Car	$0.14	$0.19	$0.14	$0.13	$0.13	$0.13		

6.6 Technologies Considered in the Analysis

Table 18. GHG Reduction Strategies Considered in the Analysis

Low rolling resistance tires
Tire pressure monitoring systems (TPMS)/automatic tire inflation systems (ATIS)/ central tire inflation system (CTI)
Auxiliary power systems
Coolant heaters ("fuel-fired heaters")
Improved air conditioning (low leakage)
Neutral idle/ neutral at stop
AESS (automatic engine stop-start)
Electronic engine parameters (e.g. automatic engine shut down after idling for a certain period)
Stop start (<11 liters only)
Improved transmissions
Fully electric
Plug-in electric hybrid (new or conversion from regular hybrid)
Plug-in electric hybrid (conversion from conventional ICE)
Hybrid electric (new or conversion from conventional ICE)
Hydraulic hybrid
Gasoline to diesel fuel switching for some 4 wheel drive vehicles
In-cab monitoring of fuel economy
Cylinder deactivation
Right-sizing, for engine
Right-sizing, for overall vehicle (e.g. for fire truck)
Engine downspeeding
Multi-torque engines
8-speed automatic transmission
Automated manual transmission
Continuously variable transmission
Dual clutch transmission
Low RPM pack at idle
Allison “Fuel Sense 2.0”
Electric power steering
Electric water pump
Electric air conditioner compressor
Clutched air compressor (for brakes)
Electric oil pump
Electric power take-off (ePTO)
Electric alternator
High efficiency alternator
Weight reduction
Drop-in biodiesel
Drop-in hydro treated vegetable oil
Variable displacement hydraulic pump
Variable speed water pump (engine coolant)

Pursuit-rated hybrid police car
Lean-burn gasoline direct injection
Early replacement
Cargo E-bike (replacement for passenger car)
Waste heat recovery system (to keep cab warm for a period of time after turning off engine)
Automatic Power Management Systems
Air heaters

6.7 Accelerated Retirement

The results of the accelerated retirement analysis showed that by advancing vehicle retirement by 1-3 years for vehicles – e.g. by taking vehicles out of service and purchasing a new vehicle earlier than would normally be the case – GHG emissions could be reduced by 1-4 percent, depending on the type of vehicle replaced and how many vehicles are replaced early. The greatest benefit would be realized by accelerating retirement for the heaviest trucks, since these vehicles use the most fuel in the Cambridge fleet. This approach could result in additional costs to the City, which were not analyzed as part of this study.

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