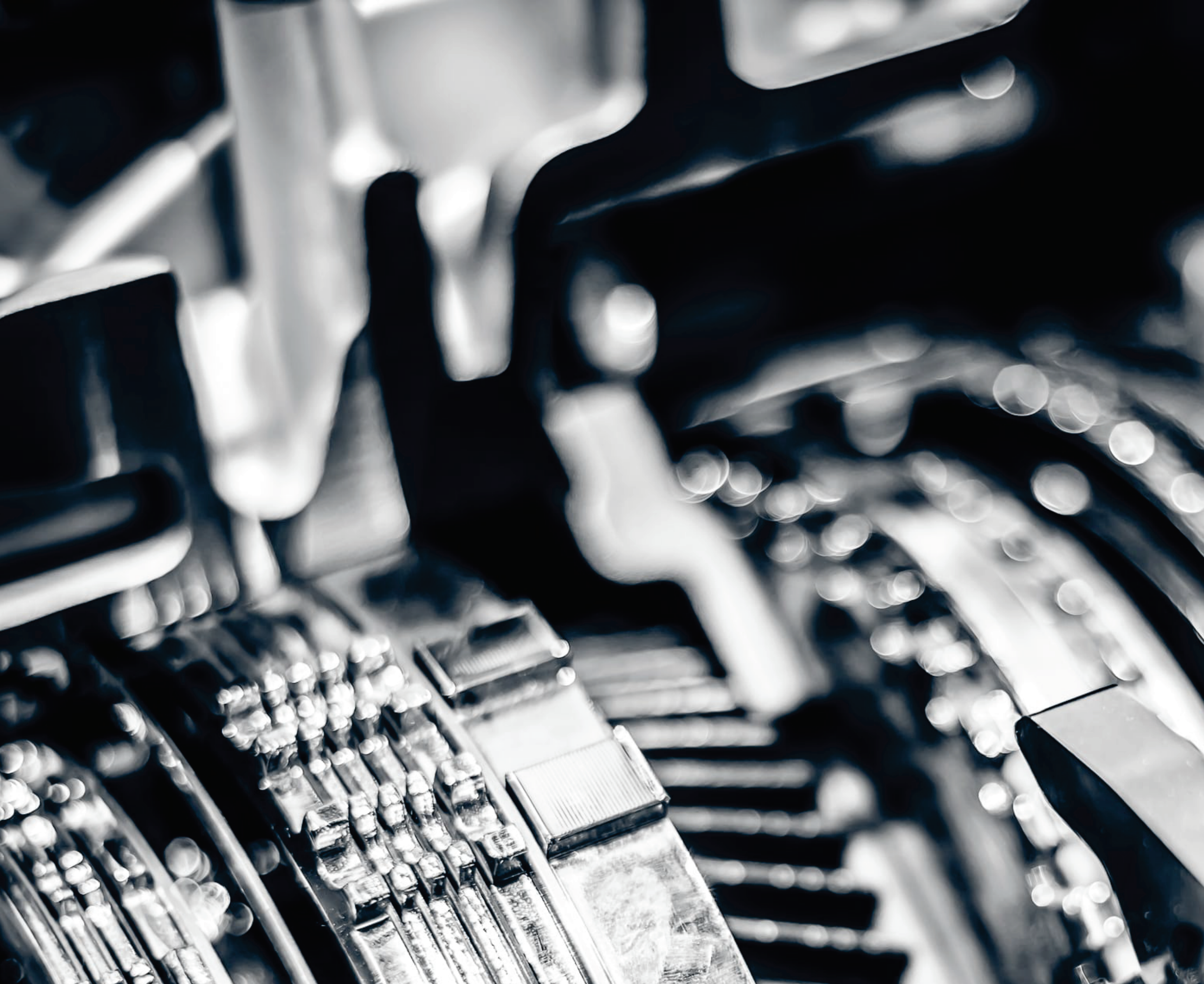

Developing a Tailpipe Emissions Inventory for Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) from the City's Fleet

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Executive Summary

As part of its endeavour to safeguard its current achievements in meeting the Clean Air Goal in the Greenest City Action Plan, the City of Vancouver (hereinafter referred to as "CoV" or "the City"), in partnership with the University of British Columbia, initiated this project to construct an inventory of tailpipe particulate matter (PM) (later replaced by carbon monoxide, or CO) and nitrogen oxides (NO_x) (represented by (NMHC + NO_x), where NMHC is short for non-methane hydrocarbon) emissions from its fleet (hereinafter referred to as "the Fleet") based on applicable emission standards from the United States Environmental Protection Agency (hereinafter referred to as "U.S. EPA") and fuel usage data of the Fleet from 2015 to 2017. Among the City's organizations, the majority of CO and (NMHC + NO_x) emissions from the Fleet source from Engineering Services and Parks & Recreation Services; per-vehicle-wise, Engineering Services is still the highest-emitting organization for both pollutants, with Fire & Rescue Services being the second highest-emitting. Overall, emissions per vehicle are lower for newer vehicles in the fleet, which is not entirely true when viewing specific vehicle classes. Freightliner, Ford, and Sterling are found to be among the highest-emitting makes for CO and (NMHC + NO_x) in the three years studied. If old vehicles matching the 30 highest-emitting vehicle class descriptions were to be replaced by their counterparts fabricated in 2018, CO emission from the Fleet is anticipated to decrease by 4.71% (37 tonnes annually) and (NMHC + NO_x) emission from the Fleet is expected to fall by 27.33% (44 tonnes annually). If funding for the replacement scheme is limited, the top-emitting models under the 30 class descriptions ought to receive priority, including Ford F450, E450, and F350 for CO, as well as Caterpillar D8T and 836H, Ford F450 and E450 (gasoline-powered).

Project Background

To maintain its leading position on urban sustainability worldwide, the City has proposed its Greenest City Action Plan, where 10 goals and targets to be achieved in miscellaneous fields by the year of 2020 are identified. Amongst these goals and targets, the Clean Air Goal aims at fulfilling or surpassing "the most stringent air quality guidelines from Metro Vancouver, British Columbia, Canada, and the World Health Organization", which was already achieved in 2013, 2014, and 2016, given the zero instances of non-compliance with the foregoing air quality standards observed in the three years (City of Vancouver, 2018). As a pioneer in the efforts to maintain these successes, CoV seeks to reduce the emission of select atmospheric pollutants (*i.e.*, CO and NO_x) from its own fleet through replacements of high-emitting vehicles therein.

Pollutant Definitions and Impacts

NMHC: non-methane hydrocarbon

NMHCs refer to all organic compounds that consist of solely carbon and hydrogen except methane (CH_4), which is commonly excluded in the context of air pollution due to its lack of significant health impacts.

Depending on chemical composition and dose and duration of exposure, similar to other volatile organic compounds (VOCs), NMHC may cause:

- Irritations to the eyes, nose, and throat;
- Headaches, coordination loss, and nausea;
- Partial damages to the liver, kidneys, and the central nervous system;
- Increased risk of developing cancer(s).

NO_x: nitrogen oxides

In atmospheric chemistry, NO_x commonly include NO (nitrogen oxide) and NO_2 (nitrogen dioxide) (Environment and Climate Change Canada, 2013). When exposed to O_2 (oxygen) in the air, NO is spontaneously converted to NO_2 by the following reaction:

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

Exposure to NO_2 can result in airway irritations, induce or exacerbate asthma, and increase susceptibility to respiratory infections. Along with CO and VOCs, NO_x (including NO_2) contribute to the formation of tropospheric O_3 in the presence of sunlight (U.S. EPA, 2016).

PM: particulate matter

Consisting of airborne solid and liquid particles, PM is generally classified by particle size (mass median diameter, usually in µm (micrometres)), which is an indicator of the extent to which the particles are capable of penetrating into the human respiratory system (Environment and Climate Change Canada, 2013):

- TPM (total particulate matter): PM with an aerodynamic equivalent diameter up to approximately 100 µm;
- PM_{10}: PM with a mass median diameter up to 10 µm;
- $PM_{2.5}$: PM with a mass median diameter up to 2.5 µm.

As outlined by the U.S. EPA (2018), exposure to PM can yield problematic impacts on lung and heart functions, including:

- Premature death (given pre-existing heart or lung conditions);
- Nonfatal myocardial infarctions (*i.e.*, heart attacks);
- Irregularities in heartbeat patterns;
- Asthma aggravation;
- Reduced lung function;
- Exacerbation of pre-existing respiratory symptoms.

Aside from health impacts, PM can also cause reduced visibility, environmental damages, and damages to materials, depending on its chemical composition. Examples include:

- Acidification of water bodies;
- Disruptions of aquatic nutrient balance;
- Soil nutrient depletion;
- Damages to sensitive plants;
- Reduced ecosystem diversity;
- Facilitated acid rain formation.

CO: carbon monoxide

CO is a potent toxic gas that is typically carried in the exhaust of incomplete combustion. Its toxicity mainly roots from its particularly strong affinity with hemoglobin (approximately 250 times stronger than O_2), which can severely disrupt O_2 transport in the bloodstream and yield headaches, dizziness, nausea, confusion and drowsiness, breathing difficulties, vision impairment, seizures, or death from respiratory failure (HealthLinkBC, 2017). Over the long term, CO can bring lasting neurological complications, ranging from "mild personality changes to severe intellectual impairment, blindness and deafness" (Harvard Health Publishing, 2013).

O_3: ozone (tropospheric)

Troposphere is the closest layer of the atmosphere to the earth's surface (up to 11 km in altitude), and thus tropospheric O_3 has direct impacts on human beings exposed to it (Stull, 2017). When inhaled, O_3 is capable of triggering (U.S. EPA, 2017):

- Shortness of breath and breathing difficulties and/or pain;
- Coughing and sore throat;
- Airway inflammation and/or damages;
- Aggravation of lung diseases;
- Increased susceptibility to lung infections;
- Chronic obstructive pulmonary disease (COPD).

Exhaust Emission Control Technologies

Diesel Oxidation Catalyst [DOC]

A DOC is installed in the engine of a diesel-powered vehicle as a "flow-through honeycomb structure" coated with catalytic materials (commonly, precious metals) that facilitate certain oxidative chemical reactions through which detrimental pollutants (typically, HC, CO, and PM) carried in the exhaust gas are broken down into less harmful substances (U.S. EPA, 2010). Due to the simplicity of the installation process as well as the little need for maintenance, DOCs have been adopted as a retrofit technology by a wide range of manufacturers (*e.g.*, Caterpillar, John Deere, and Subaru) for a considerable number of years, although they do accelerate the conversion of NO to NO_2 and produce sulphates (SO_x) as by-products, which lead to new PM formation and acidification (U.S. EPA, 2010; Caterpillar, 2018; John Deere, 2017; Subaru, 2018). In Stage III B PowerTech engines by John Deere (2017), the DOC is combined with a diesel particulate filter (DPF) to create a joint exhaust filter. In Partial Zero Emission Vehicles (PZEVs) by Subaru (2018), the contact area of the catalytic converter is allegedly nearly twice that of a traditional one for a higher efficiency in converting pollutants.

Diesel Particulate Filter [DPF]

As its name suggests, a DPF is installed in the engine of a diesel-powered vehicle as a porous filter consisting of typically ceramic or cordierite that traps and removes PM from the exhaust, after which the PM collected is "reduced to ash during filter regeneration" (*i.e.*, combustion). As non-combustible materials and ash accumulate, the DPF needs to be properly inspected, cleaned, and replaced periodically to ensure optimal performance (U.S. EPA, 2010). The DPF is used by Caterpillar (2018) and John Deere (2017), and in Stage III B PowerTech engines by John Deere, the DPF is combined with a diesel oxidation catalyst (DOC) device to create a joint exhaust filter.

Selective Catalytic Reduction [SCR]

The SCR process utilizes a nitrogen-based reagent (*i.e.*, ammonia or urea) and a metal-based catalyst to selectively reduce NO_x into diatomic nitrogen (N_2) and water vapour (H_2O). Since the early 1970s, it has been applied in a wide range of industries that generate NO_x around the world, and it delivers a higher level of NO_x reduction than a three-way catalyst (TWC) (U.S. EPA, 2016). As a standardized practice, a diesel exhaust fluid (DEF), which comprises of 32.5% urea and 67.5% deionized water according to the globally recognized ISO 22241 standard, is commonly used as the aforementioned nitrogen-based reagent in the SCR process. Among the manufactures that adopt SCR in their engines, Caterpillar applies an ammonia oxidation catalyst (AMOX) in addition to the SCR catalyst to minimize ammonia that enters the atmosphere; Freightliner and Mercedes both source their Bluetec® SCR technologies from Detroit™ engines, which utilize a slightly different DEF formula (two-thirds of pure water and one-third of automotive-grade urea) (Caterpillar, 2018; Freightliner, *n.d.*; Schommers *et al.*, 2008).

Exhaust Gas Recirculation [EGR]

An EGR system dilutes fresh air in the engine intake with recycled non-reacting exhaust gas to lower peak combustion temperatures in the engine cylinder and displace oxygen, thereby reducing NO_x emissions. At the same time, however, engine efficiency is compromised due to slowed-down combustions and more HC and PM are generated in the process. The EGR technology is used in both gasoline and diesel engines, and the process is often controlled by an EGR control valve (Naresh *et al.*, 2015). When using EGR, John Deere (2017) pairs the technology with a variable geometry turbocharger (VGT) that delivers variable exhaust pressure based on load and speed to optimize engine performance by safeguarding a smooth EGR flow; EGR is also embedded as part of the Earth Dreams Technology by Honda (2013).

Research Methodology

Overview

In order to build an emission inventory for all the ~1,900 (1,906 in 2015; 1,870 in 2016; 1,918 in 2017) vehicles in the CoV fleet, efforts are made to derive emitted pollutant mass from individual vehicles from fuel usage (consumed volume) and regulatory tailpipe emission standards (pollutant mass emitted per unit volume), assuming general compliance therewith. For demonstration purposes, assuming that emitted pollutant mass is expressed in grams (g) and that fuel usage is expressed in litres (L), such derivation can be represented by the **Equation 1**:

$$g = (g/L) \times L \quad [\textbf{Equation 1}]$$

Change of Target Pollutants

As outlined in the project plan, PM and NO_x were the initial target pollutants. This had been subsequently modified for optimal adaptation to the progression of the project, as the following preliminary findings surfaced while the project unfolded in the beginning phase.

On one hand, the project was set to target CO in lieu of PM. This was primarily because every litre of fuel consumed emits 13 to 1,549 (336 on average) times more CO than PM by mass, based on vehicles in the Fleet of different ages using various types of fuel. Moreover, data on U.S. EPA tailpipe emission standards are noticeably more comprehensively available for CO than for PM.

On the other hand, (NMHC + NO_x) emissions were selected to serve as the sole indicator of NO_x emissions from the Fleet. As illustrated by Figure 1, the availability of U.S. EPA emission standard data for NO_x, NMHC, and (NMHC + NO_x) alone can be highly inconsistent over time, which creates the need for sufficient flexibility in the NO_x-representing variable in terms of its ability to be manually derived/inferred. Since (NMHC + NO_x) emissions can be derived by summing NMHC and NO_x emissions and/or inferred from NO_x or (HC + NO_x) emissions, the project was set to proceed using (NMHC + NO_x) as the NO_x-representing variable.

U.S. EPA Standard Data Availability																								
Year of Manufacture	Directly available in U.S. EPA standards?																		Available with manual derivations/inferences?					
	NO_x						**NMHC**						**NMHC + NO_x**						**NMHC + NO_x**					
	Heavy-duty		Light-duty		Nonroad		Heavy-duty		Light-duty		Nonroad		Heavy-duty		Light-duty		Nonroad		Heavy-duty		Light-duty		Nonroad	
	Gasoline	Diesel	Passenger Vehicles	Trucks	Gasoline	Diesel	Gasoline	Diesel	Passenger Vehicles	Trucks	Gasoline	Diesel	Gasoline	Diesel	Passenger Vehicles	Trucks	Gasoline	Diesel	Gasoline	Diesel	Passenger Vehicles	Trucks	Gasoline	Diesel
1998	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	Yes	Yes	No	Yes	Yes	No	No	No	Yes**	No	Yes	Yes*	Yes***	Yes***	Yes**	Yes***
1999	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	Yes	Yes	No	Yes	Yes	No	No	No	Yes**	Yes	Yes	Yes*	Yes***	Yes***	Yes**	Yes
2000	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	No	Yes*	No	Yes	Yes	No	No	No	Yes**	Yes	Yes	Yes*	Yes*****	Yes****	Yes**	Yes
2001	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	No	Yes*	No	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes*	Yes*****	Yes****	Yes	Yes
2002	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	No	Yes*	No	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes*	Yes*****	Yes****	Yes	Yes
2003	No	Yes	Yes	Yes	No	Yes	Yes*	Yes*	No	Yes*	No	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes*	Yes*****	Yes****	Yes	Yes
2004	No	No	Yes	Yes	No	Yes	Yes*	No	No	Yes*	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes*****	Yes****	Yes	Yes
2005	Yes	No	Yes	Yes	No	Yes	Yes*	No	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes****	Yes	Yes*****	Yes****	Yes	Yes
2006	Yes	No	Yes	Yes	No	No	Yes*	No	No	Yes*	No	No	No	Yes	No	No	Yes	Yes	Yes****	Yes	Yes*****	Yes****	Yes	Yes
2007	Yes	Yes	Yes	Yes	No	No	Yes*	Yes	No	Yes*	No	No	No	Yes	No	No	Yes	Yes	Yes****	Yes	Yes*****	Yes****	Yes	Yes
2008	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes*	No	No	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2009	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes*	No	No	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2010	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes*	No	No	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2011	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2012	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2013	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2014	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2015	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2016	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2017	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes
2018	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes*	No	Yes	No	Yes	No	No	Yes	Yes	Yes***	Yes	Yes*****	Yes****	Yes	Yes

Figure 1: Availability of U.S. EPA tailpipe emission standard data for NO_x, NMHC, and (NMHC + NO_x) and year of manufacture between 1998 and 2018.

Red cells: unavailable; yellow cells: available via indirect derivations/inferences; green cells: directly available

* given as HC; ** given as (HC + NO_x); *** derived by adding NMHC and NO_x; **** derived by adding HC and NO_x; ***** inferred from solely NO_x

Data Sourcing

By courtesy of the mentor (Evan Dacey), detailed fuel usage data (in litres) of every vehicle in the Fleet from 2015 to 2017 are obtained as a comprehensive spreadsheet by querying the City's fleet management system. In addition to fuel usage, other attributes supplied by the spreadsheet include but are not limited to: Unit ID ("UnitID"), organization ("Organization"), fuel type ("FuelGroup"), year of manufacture ("EHYear"), vehicle make ("EHMake"), vehicle model ("EHModel"), vehicle class description ("ClassDesc"), and vehicle class category ("Class Category").

As outlined in the *Federal Agenda on Cleaner Vehicles, Engines and Fuels* by David Anderson, former Minister of Environment of Canada in 2001, a number of policy measures are in place to align/harmonize federal on-road and off-road vehicle tailpipe emission standards in Canada with those of the U.S. EPA. On the grounds of such context, this project sources tailpipe emission standards of the concerned pollutants from the U.S. EPA, and data manipulation/transformation efforts below are hence introduced to ensure alignment of the data format with the needs of this project.

Data Manipulation/Transformation

As an endeavour to conform to the U.S. EPA vehicle categorization methodology, vehicles of the Fleet are categorized into the following four classes:

- Heavy-duty vehicle
- Light-duty passenger vehicle
- Light-duty truck
- Nonroad vehicle

The foregoing categorization results are yielded by incorporating fragments of information from the “ClassDesc” and “Class Category” variables, as demonstrated in **Table 1**:

<table>
<tr><td rowspan="7">Class Category =</td><td rowspan="7">→</td><td>"Emergency Heavy Duty"</td><td rowspan="7">→</td><td colspan="7" rowspan="3">Heavy-Duty Vehicle</td></tr>
<tr><td>"Heavy Duty"</td></tr>
<tr><td>"Medium Duty"</td></tr>
<tr><td rowspan="2">"Light Duty"</td><td rowspan="2">Light-Duty Vehicle</td><td rowspan="2">→</td><td rowspan="2">ClassDesc contains "TRUCK"?</td><td>→</td><td>TRUE</td><td>→</td><td>Light-Duty Truck</td></tr>
<tr><td>→</td><td>FALSE</td><td>→</td><td>Light-Duty Passenger Vehicle</td></tr>
<tr><td>"Construction Equipment"</td><td colspan="7" rowspan="2">Nonroad Vehicle</td></tr>
<tr><td>"Other"</td></tr>
</table>

Table 1: Derivation of vehicle classes from the original data.

Given the limited availability of data on emission standards targeting vehicles manufactured prior to 1998, such vehicles are considered to have been manufactured in 1998 for the purpose of this project when citing applicable emission standards (as reflected in the variable “EHYear_e”, derived from “EHYear” by replacing all the values equal to or less than 1997 with 1998). In addition, for simplicity, the variable "FuelGroup_e" is created to unify the denotation formats of fuel types in the original variable "FuelGroup", as shown in Table 2:

FuelGroup	FuelGroup_e	Fuel Composition
Gasoline	E10	90% gasoline + 10% ethanol
B5	B5	95% diesel + 5% biodiesel
B20	B20	80% diesel + 20% biodiesel

Table 2: Comparison of values of FuelGroup and FuelGroup_e and fuel compositions.

Noticeably, the U.S. EPA publishes emission standards for different vehicle class in different sets of units: standards for heavy-duty vehicles are presented in grams of pollutant per brake horsepower-hour (g/bhp-hr); light-duty vehicles are regulated by standards in grams of pollutant per mile (g/mi); nonroad vehicles are subject to standards expressed in grams of pollutant per kilowatt-hour (g/kW-hr). Therefore, targeted efforts are made for different vehicle classes to unify the units of the standards to grams of pollutant per litre (g/L) so as to facilitate subsequent calculations.

For standards targeting heavy-duty vehicles (in g/bhp-hr), fuel energy contents for all three fuel types (in bhp-hr/L) are applied:

$$\text{g/L} = (\text{g/bhp-hr}) \times (\text{bhp-hr/L}) \quad [\textbf{Equation 2}],$$

where fuel energy contents in bhp-hr/L are derived from energy conversion factors for stationery fuel combustion (in gigajoules per litre, or GJ/L) from Table 1 in the 2016 B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions by the B.C. Ministry of Environment (2016):

$$\text{bhp-hr/L} = (\text{GJ/L}) \times (372.5\ \text{bhp-hr/GJ}) \quad [\textbf{Equation 3}].$$

For standards targeting light-duty vehicles (in g/mi), the annual average fuel economies of all light-duty vehicles permitted for sale in Canada from 1998 to 2018 (given as fuel consumption ratings in L/(100 km), courtesy of Natural Resources Canada, 2018) are applied:

g/L = (g/mi) × (mi/gal*) ÷ (3.785 L/gal*) [**Equation 4**], * U.S. gallons

where

mi/gal* = 235.21 ÷ [L/(100 km)] [**Equation 5**].

Notably, fuel consumption ratings differ for city and highway driving, and thus combined ratings are used, assuming the following driving pattern (Natural Resources Canada, 2018):

100% combined driving = 55% city driving + 45% highway driving [**Equation 6**].

For simplicity, both "regular gasoline" and "premium gasoline" are included under the fuel type "gasoline"; due to the lack of fuel consumption ratings for light-duty diesel trucks from 1999 to 2013, these ratings are interpolated using those from 1998 and 2014, assuming a constant, steady, and gradual change between every neighbouring two years over the period.

For standards targeting nonroad vehicles (in g/kW-hr), the following conversion formula is used:

g/bhp-hr = (g/kW-hr) ÷ 1.341 (California Air Resources Board, *n.d.*),

prior to applying **Equation 1** to yield (g/L).

Additionally, in extracting information from the published U.S. EPA tailpipe emission standards, the following assumptions apply:

- All gasoline (E10) vehicles in the Fleet are powered by spark-ignition (SI) engines;
- All diesel (B5/B20) vehicles in the Fleet are powered by compression-ignition (CI) engines;
- For heavy-duty vehicles, emission standards for gross vehicle weight ≤ 14,000 lbs and those for gross vehicle weight > 14,000 lbs are averaged;
- All light-duty vehicles in the Fleet have a vehicle useful life of 10 years / 100,000 miles;
- For light-duty vehicles:
    - Tier 1 standards apply to vehicles manufactured in or prior to 1999;
    - NLEV (National Low-Emission Vehicle) standards apply to those manufactured from 2000 to 2003; emission category = "LEV";
    - CFV (Clean Fuel Vehicle) standards apply to those manufactured in or after 2004; emission category = "LEV";

    - Standards for LDT1 (Light-Duty Truck 1) and LDT2 (Light-Duty Truck 2) are averaged;
- All nonroad gasoline vehicles in the Fleet have a rated power < 19 kW;
- All nonroad diesel vehicles in the Fleet have a rated power ≥ 19 kW;
    - Standards for all rated power classes ≥ 19 kW are averaged, where available;
- Manual derivations are performed where data are not directly available, as outlined in Figure 1;
- "<DUMMY>" and "NULL" are included with other vehicle makes in the annual total emissions graphs to reflect their important influence on the Fleets' total emissions;
- "<DUMMY>" and "NULL" are excluded from other graphs due to the lack of reliable background information on engine attributes associated with these makes.

Regression Analysis

In an attempt to establish a quantitative relationship between pollutant (*i.e.*, CO and (NMHC + NO_x)) mass emitted by a vehicle in the Fleet and select attributes of this vehicle (*i.e.*, organization, fuel type, year of manufacture, vehicle make, and vehicle class) so as to facilitate the identification of high-emitting vehicles in the Fleet, a multiple linear regression is performed for each pollutant, with the aforementioned set of attributes serving as the independent variables and emitted pollutant mass being the dependent variable, with statistics shown below:

Multiple linear model for CO emissions: **adjusted R^2** ≈ 0.3821; **p-value** $< 2.2 \times 10^{-16}$

Multiple linear model for (NMHC + NO_x) emissions: **adjusted R^2** ≈ 0.4829; **p-value** $< 2.2 \times 10^{-16}$

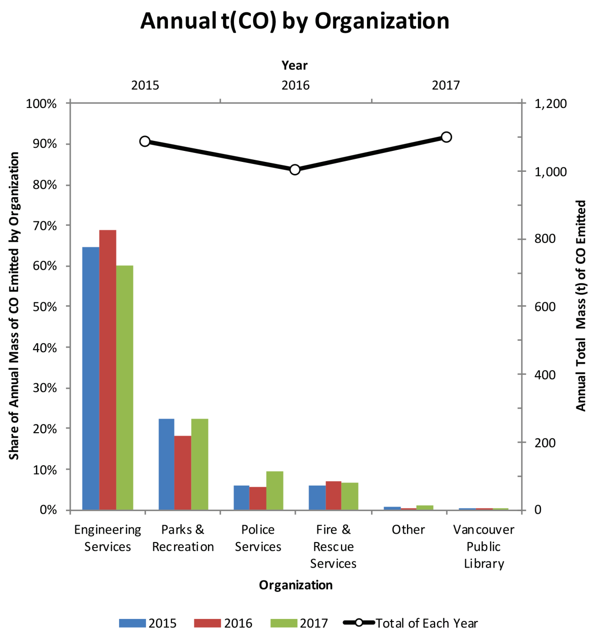
Since organization, fuel type, vehicle make, and vehicle class are all categorical variables, neither data transformation nor a polynomial regression would be a feasible option. Thus, although neither model has a coefficient of determination (R^2) that indicates a strong fit of the model with the actual data (despite the statistical significance among the variables demonstrated by the low **p-values**), the foregoing multiple linear regression models are, relatively, the most viable path to a quantitative relationship among CO/NO_x emissions and vehicle attributes. As a result, this project will proceed with efforts to examine the relationship between CO/NO_x emissions and individual vehicle attributes separately and to identify vehicles that fall into the highest-emitting vehicle classes, as opposed to continuing the pursuit of a numerical formula.

Findings

Annual Emissions by Organization

As **Figures 2a** and **2b** suggest, within the three years studied, the annual total CO emission of the Fleet fluctuates around 1,050 tonnes and the annual total (NMHC + NO_x) emission remains stable around 200 tonnes. For both pollutants, Engineering Services is responsible for the majority (over half) of the total annual emissions in all three years, followed by Parks & Recreation, Police Services, and Fire & Rescue Services. By contrast, Vancouver Public Library and other organizations account for less than 2% of the annual total emissions each. Overall for all organizations within the CoV, percentage shares of annual total emissions of both pollutants are fairly stable across the three years, with the most noticeable yearly change occurring to CO emissions from Engineering Services between 2016 and 2017 (a reduction of share by less than 10%).

The leading shares of CO and (NMHC + NO_x) emissions of Engineering Services and Parks & Recreation, who jointly account for about 90% of the total emission of either pollutant, can be rationalized by the numbers of vehicles under their administration and the most prevalent vehicle classes within them. According to **Table 3a**, Engineering Services, Police Services, and Parks & Recreation own the most, second most, and third most vehicles within the Fleet, with their most prevalent vehicle classes being heavy-duty vehicles, light-duty passenger vehicles, and nonroad vehicles, respectively. Nonetheless, as demonstrated in **Table 3b**, on a per-vehicle basis, heavy-duty vehicles and nonroad vehicles produce the most CO and (NMHC + NO_x) emissions, while light-duty passenger vehicles are associated with the least tailpipe emissions. Therefore, although Police Services own slightly more vehicles than Parks & Recreation, the latter emits markedly more pollutants per vehicle, justifying the interorganizational patterns observed in **Figures 2a** and **2b**.



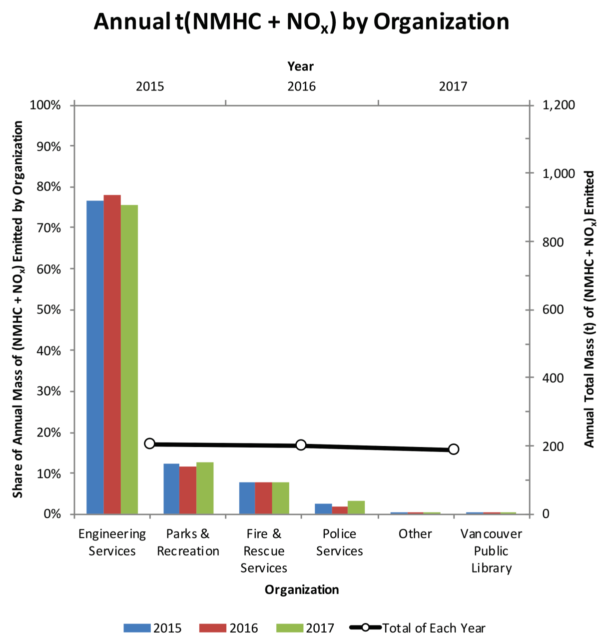


Figure 2a (left): Percentage shares of annual tonnes of CO emitted by CoV organizations from 2015 to 2017.

Figure 2b (right): Percentage shares of annual tonnes of ($NMHC + NO_x$) emitted by CoV organizations from 2015 to 2017.

Primary axes (bottom, left): percentage shares of emitted pollutant mass by organization;

Secondary axes (top, right): annual total tonnes of pollutant emitted by the Fleet.

% relative to sum of all organizations	2015	2016	2017	Overall
Engineering Services	**48.22%**	**45.78%**	**44.63%**	**46.21%**
Heavy-Duty Vehicle	21.67%	16.90%	14.70%	17.76%
Light-Duty Passenger Vehicle	9.44%	9.68%	9.91%	9.68%
Light-Duty Truck	6.56%	8.50%	8.34%	7.80%
Nonroad Vehicle	10.55%	10.70%	11.68%	10.98%
Fire & Rescue Services	**5.77%**	**6.52%**	**8.45%**	**6.92%**
Heavy-Duty Vehicle	3.15%	3.69%	4.43%	3.76%
Light-Duty Passenger Vehicle	1.78%	1.93%	1.93%	1.88%
Light-Duty Truck	0.58%	0.64%	0.63%	0.61%
Nonroad Vehicle	0.26%	0.27%	1.46%	0.67%
Other	**1.31%**	**1.28%**	**1.36%**	**1.32%**
Heavy-Duty Vehicle	0.10%	0.11%	0.16%	0.12%
Light-Duty Passenger Vehicle	0.84%	0.86%	0.89%	0.86%
Light-Duty Truck	0.16%	0.16%	0.16%	0.16%
Nonroad Vehicle	0.21%	0.16%	0.16%	0.18%
Parks & Recreation	**20.83%**	**21.60%**	**20.91%**	**21.11%**
Heavy-Duty Vehicle	3.04%	2.46%	2.97%	2.83%
Light-Duty Passenger Vehicle	3.73%	4.33%	4.28%	4.11%
Light-Duty Truck	4.83%	5.72%	5.16%	5.23%
Nonroad Vehicle	9.23%	9.09%	8.50%	8.94%
Police Services	**23.61%**	**24.55%**	**24.35%**	**24.17%**
Heavy-Duty Vehicle	0.31%	0.32%	0.31%	0.32%
Light-Duty Passenger Vehicle	20.88%	20.75%	20.33%	20.65%
Light-Duty Truck	2.10%	3.26%	3.49%	2.95%
Nonroad Vehicle	0.31%	0.21%	0.21%	0.25%
Vancouver Public Library	**0.26%**	**0.27%**	**0.31%**	**0.28%**
Heavy-Duty Vehicle	0.05%	0.05%	0.10%	0.07%
Light-Duty Passenger Vehicle	0.21%	0.21%	0.21%	0.21%

Colour scheme:

Most vehicles

- Engineering Services
- Police Services
- Parks & Recreation
- Fire & Rescue Services
- Other
- Vancouver Public Library

Fewest vehicles

	kg CO per vehicle	**kg (NMHC + NO_x) per vehicle**
Heavy-Duty Vehicle	1,224	213
Light-Duty Passenger Vehicle	46	3
Light-Duty Truck	52	13
Nonroad Vehicle	564	158

Highest kg per vehicle

- Heavy-Duty Vehicle
- Nonroad Vehicle
- Light-Duty Truck
- Light-Duty Passenger Vehicle

Lowest kg per vehicle

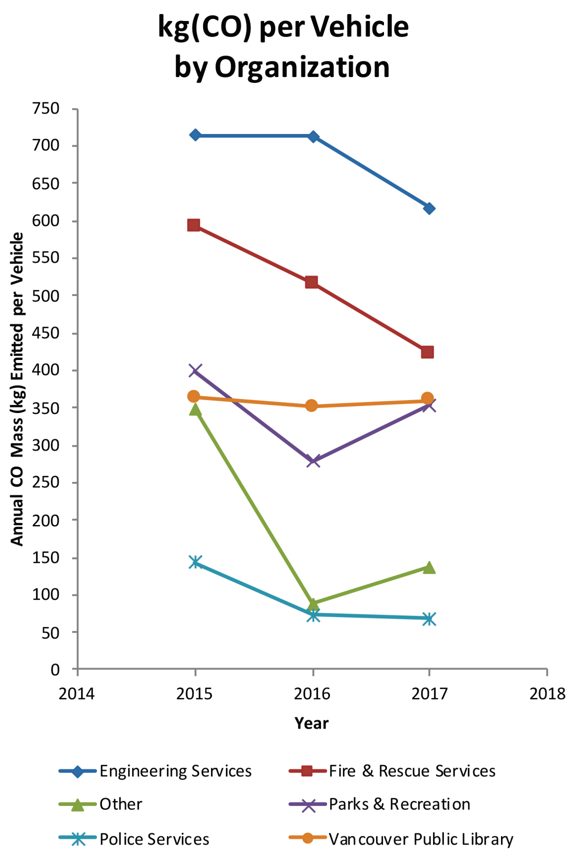
Most prevalent vehicle class within organization:

Table 3a (green): Percentage share of number of vehicles under each organization versus the total number of vehicles in the Fleet.

Table 3b (purple): Kilograms of CO and (NMHC + NO_x) emitted per vehicle by vehicle class.

Annual Emissions per Vehicle by Organization

As shown in **Figures 3a** and **3b**, in all CoV organizations, every vehicle emits approximately 4 times more CO than (NMHC + NO_x) by mass, which is likely because U.S. EPA emission standards are generally (10 times, on average) more lenient for CO than for (NMHC + NO_x). On a per-vehicle basis, Engineering Services has the highest CO and (NMHC + NO_x) emissions, followed by Fire & Rescue Services, Vancouver Public Library, Parks & Recreation, other organizations, and Police Services, in approximate descending order. In spite of fluctuations, all organizations see an overall decline in their emissions of both pollutants to varying extents over the three years, which is attributable to the trend that U.S. EPA emission standards become increasingly stringent over time.



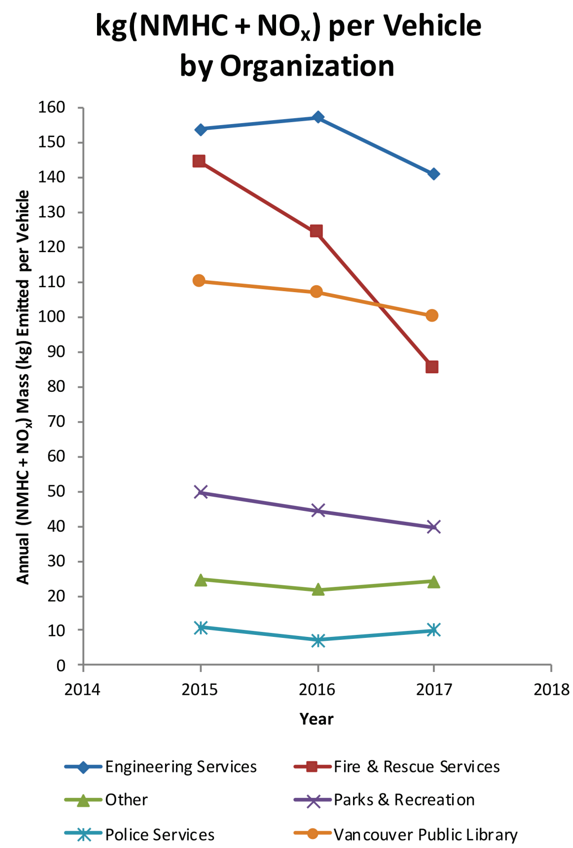


Figure 3a (left): Kilograms of CO emitted per vehicle by CoV organizations from 2015 to 2017.

Figure 3b (right): Kilograms of (NMHC + NO_x) emitted per vehicle by CoV organizations from 2015 to 2017.

Annual Emissions per Vehicle by Year of Manufacture

Resembling **Table 3b** above, the vertical axes of **Figures 4a**, **4b**, **4c**, and **4d** reveal how CoV organizations compare with one another in terms of kilograms of CO and (NMHC + NO_x) emitted per vehicle (*i.e.*, kg/veh). For heavy-duty vehicles (**Figure 4a**), pollutant mass emitted per vehicle has steadily declined over the two decades between 1998 and 2018 for both CO and (NMHC + NO_x), which is also the case for the Fleet in general in **Figure 4e**, within reasonable expectations: U.S. EPA emission standards for heavy-duty vehicles and vehicles in general become increasingly stringent over time. However, trends observed in **Figure 4b** and **4c** for light-duty vehicles appear to align less with expectations: emissions per vehicle exhibit gradual increases during the period between 1998 and 2015 before drastically plummeting in the last several years within the observed temporal domain. As for nonroad vehicles, no clear temporal pattern of changes in kg(CO)/veh or kg(NMHC + NO_x)/veh is observed over the 20 years.

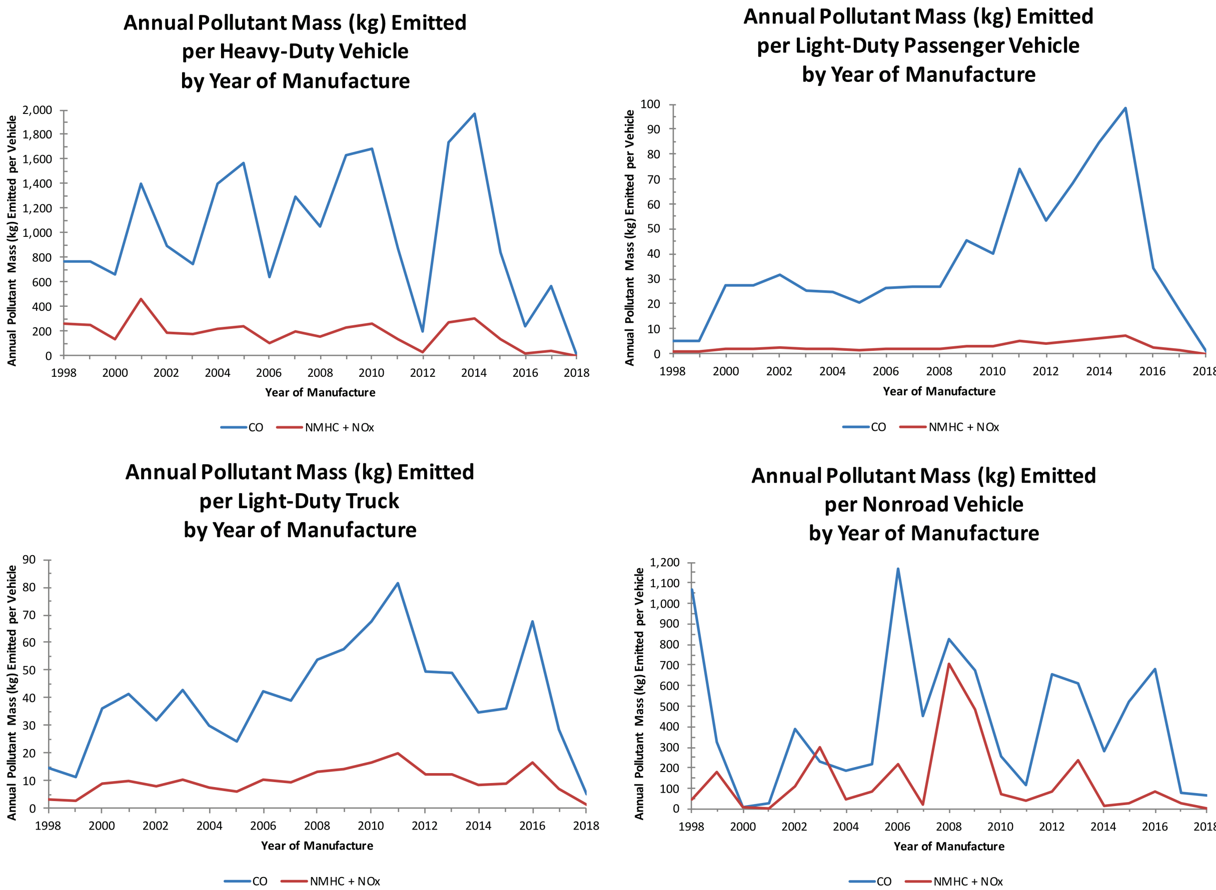


Figure 4a (upper-left): Kilograms of pollutants emitted per heavy-duty vehicle.

Figure 4b (upper-right): Kilograms of pollutants emitted per light-duty passenger vehicle.

Figure 4c (lower-left): Kilograms of pollutants emitted per light-duty truck.

Figure 4d (lower-right): Kilograms of pollutants emitted per nonroad vehicle.

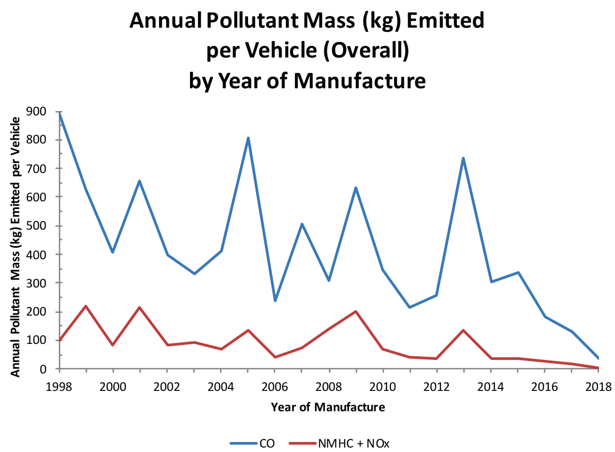
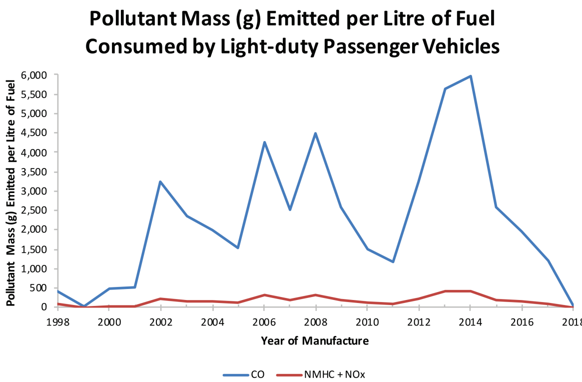


Figure 4e: Kilograms of pollutants emitted per vehicle in general.

The unexpected patterns in per-vehicle emissions from light-duty vehicles are likely justifiable by similar trends exhibited by pollutant emission per unit volume of fuel (*e.g.*, g/L, see **Figures 5a** and **5b**) and fuel consumption per vehicle (*e.g.*, L/veh, see **Figures 6a and 6b**), since the product thereof is (kg/veh) (upon unit conversion, see **Equation 7**):

kg/veh = (g/L) × (L/veh) ÷ 1,000 g/kg [**Equation 7**].

As per **Figures 5a** and **5b**, CO and (NMHC + NO_x) emissions per unit volume of fuel (g/L) rise between 1998 and 2014 (CO) / 2016 (NMHC + NO_x), which directly results from the escalation of average fuel economy (in mi/gal) during the period (see **Equation 4**), despite the fact that U.S. EPA standards for light-duty vehicles (in g/mi) have remained stable.



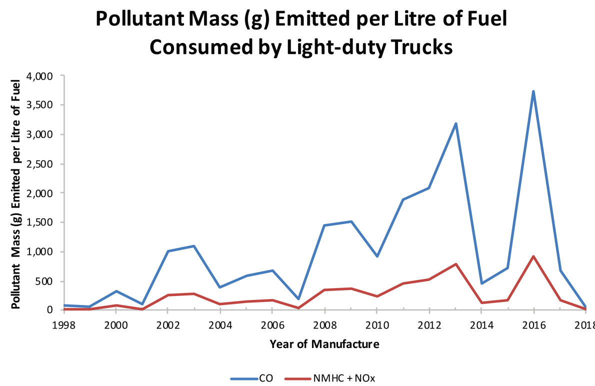
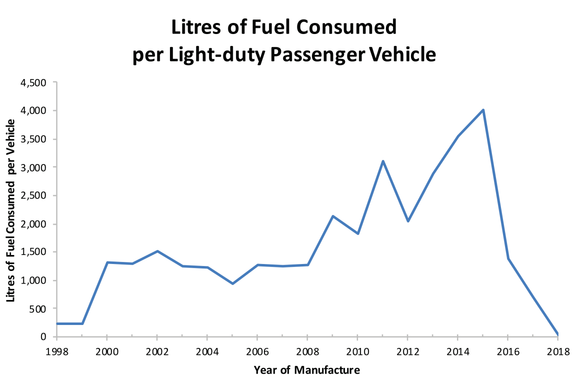


Figure 5a (left): Grams of pollutant emitted per litre of fuel consumed by light-duty passenger vehicles.

Figure 5b (right): Grams of pollutant emitted per litre of fuel consumed by light-duty trucks.

As per **Figures 6a and 6b**, litres of fuel consumed per vehicle (L/veh) surged between 1998 and 2015 (light-duty passenger vehicles) / 2016 (light-duty trucks) as well, which can also be attributed to the increase in fuel economy, leading to reductions in the volume of fuel needed to run a certain distance.



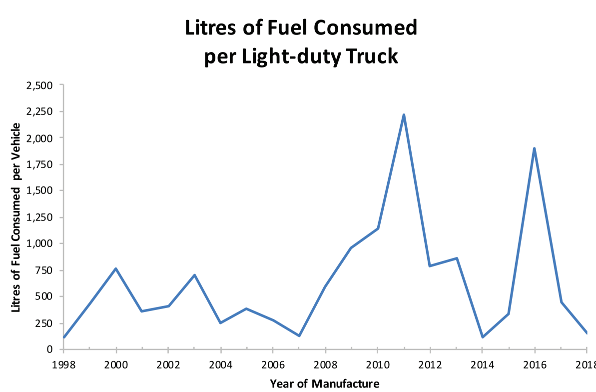


Figure 6a (left): Litres of fuel consumed per light-duty passenger vehicle.

Figure 6b (right): Litres of fuel consumed per light-duty truck.

Share of Annual Emissions by Vehicle Make

Figures 7a and **7b** demonstrate that for either CO or (NMHC + NO_x) in any year, the four highest-emitting vehicle makes account for approximately 60% of the annual total emissions, and they are identified as follows:

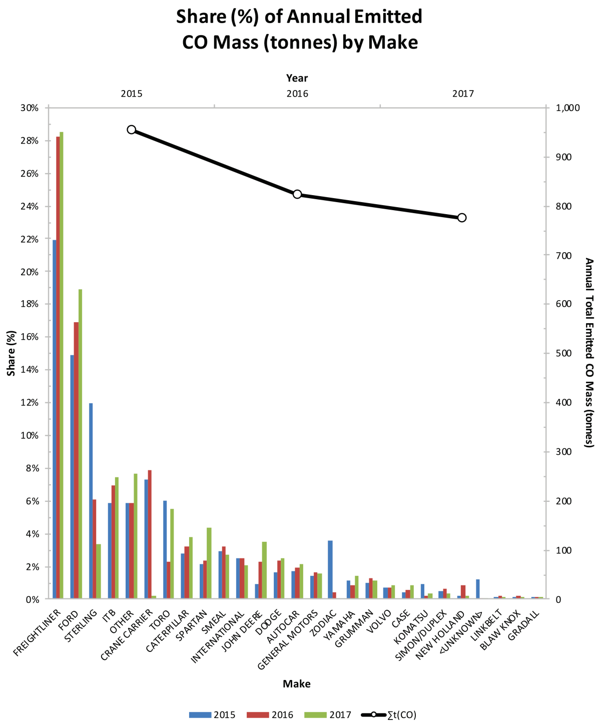
CO: Freightliner > Ford > Sterling > ITB

(NMHC + NO_x): Freightliner > Caterpillar > Ford > Sterling

Note that other than Ford, all other highest-emitting vehicle makes identified above are associated with heavy-duty or nonroad vehicles in the Fleet, as shown in **Table 4**. Despite variations in emission changes of individual makes over the three years, both CO and (NMHC + NO_x) emissions of the Fleet continuously decrease overall from 2015 to 2017 (see **Figures 8a** and **8b**).

Make	Composition
Freightliner	All heavy-duty vehicles; mostly trucks
Ford	Mostly light-duty vehicles
Caterpillar	All nonroad diesel heavy equipment
Sterling	All heavy-duty diesel trucks
ITB	All nonroad trailers; 75% gasoline, 25% diesel

Table 4: Composition of vehicle makes that emit the most CO or (NMHC+NO_x) in the Fleet.



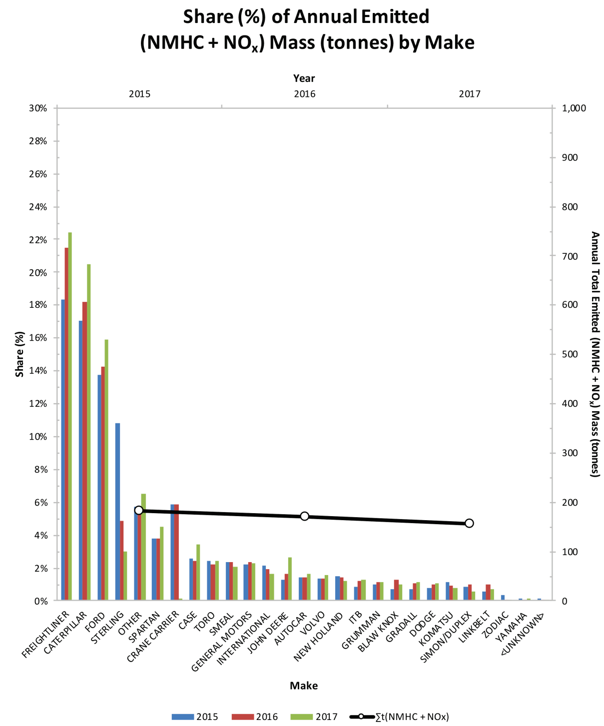


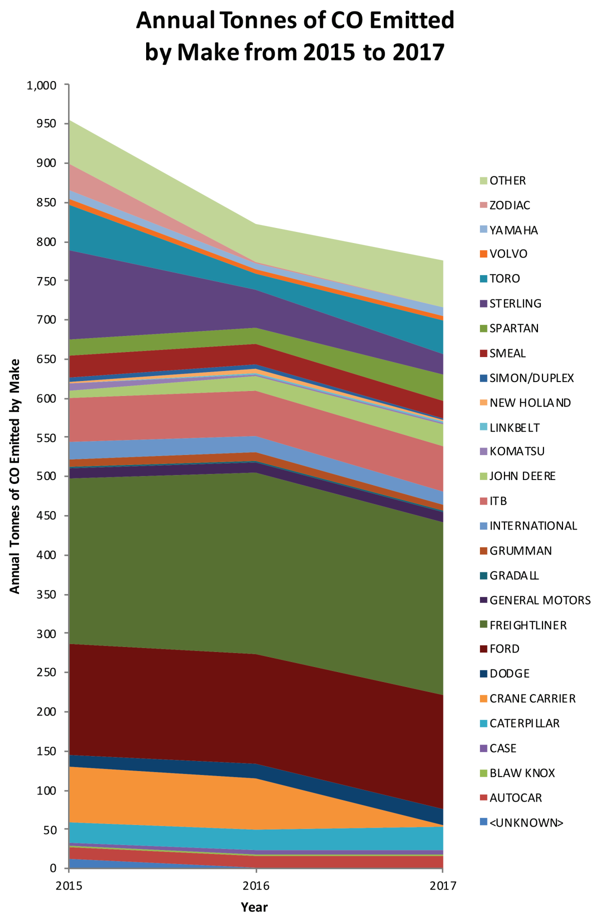
Figure 7a (left): Percentage shares of annual tonnes of CO emitted by make from 2015 to 2017.

Figure 7b (right): Percentage shares of annual tonnes of (NMHC + NO_x) emitted by make from 2015 to 2017.

Primary axes (bottom, left): Percentage shares of emitted pollutant mass by make;

Secondary axes (top, right): Annual total tonnes of pollutant emitted.

Note: Makes on the primary horizontal axes are sorted by their 3-year average emissions.



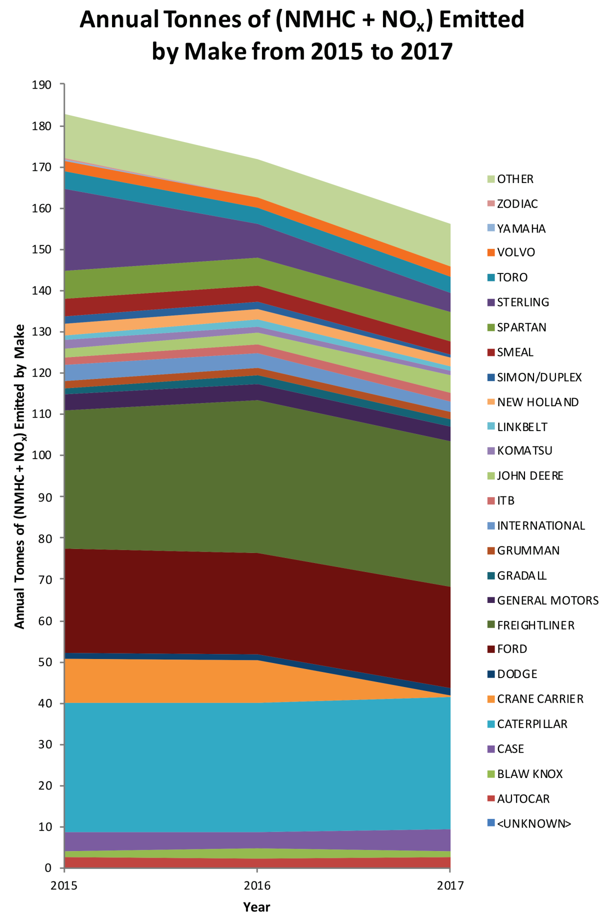


Figure 8a (left): Annual tonnes of CO emitted by make from 2015 to 2017.

Figure 8b (right): Annual tonnes of ($NMHC + NO_x$) emitted by make from 2015 to 2017.

Vehicles in the Fleet with the Highest Potential for Reductions in CO and ($NMHC + NO_x$) Emissions through Replacements

Since the attempted regression models to forecast CO and ($NMHC + NO_x$) emissions based on vehicle attributes do not provide strong predictability, efforts are alternatively focused on determining key sections of the Fleet with the potential to yield the highest CO and ($NMHC + NO_x$) emissions reductions through replacements with current technologies. Among the 294 vehicle class descriptions (*i.e.*, ClassDesc) within the Fleet from 2015 to 2017, units that fall under the 30 most CO-emission-intensive (see **Table 5**) and the 30 most ($NMHC + NO_x$)-emission-intensive (see **Table 6**) ClassDesc's are identified, after which they are filtered by year of manufacture (*i.e.*, yom) to old vehicles manufactured before applicable U.S. EPA emission standards (in g/L) become significantly more stringent, thereby distinguishing vehicles that emit significantly more CO and/or (NMHC + NO_x) than their counterparts manufactured in 2018. Subsequently, the tables are collapsed to the level of vehicle model, and relative (in %) as well as absolute (in tonnes) reductions through replacements with corresponding new models manufactured in 2018 are calculated, as shown in Tables 7a, 7b, 7c, 7d, 7e, and 7f.

ClassDesc	kg(CO)	Number of Units
TRUCK, DUMP, 1 YARD	159,183	175
TRUCK, REFUSE, SIDE LOADER, AUTOMATED, 20 YARD	137,880	66
TRUCK, TRACTOR, TANDEM AXLE	134,085	33
TRUCK, RECYCLING, RIGHT PICKUP	126,741	64
TRUCK, DUMP, TANDEM AXLE	101,146	65
TRUCK, CLASS 7, REG CAB, DUMP BODY, SNOW EQUIPPED	83,320	76
TRAILER, OFFICE	78,632	12
VAN, 1.5TON, CUBE BODY	78,116	65
TRUCK, CLASS 8, REG CAB, DUMP BODY, SNOW EQUIPPED	72,098	39
TRUCK, FIRE, PUMPER, 2000 GPM	67,639	39
TRAILER, WORK, 3-5 MAN, WITH TOOLS, TANDEM AXLE	59,025	58
TRUCK, CLASS 8, REG CAB, DUMP BODY	47,134	25
TRUCK, REFUSE, SIDE LOADER, 10 YARD	46,355	14
TRUCK, FIRE, QUINT, 75 FT LADDER	44,803	40
TRUCK, CLASS 8, REG CAB, DUMP BODY, TOW EQUIPPED	44,063	18
SWEEPER, AIR, 4 WHEEL, 8 CU.YD.	43,672	14
TRUCK, SEWER CLEANER, HYDRAULIC & EDUCTOR	41,336	20
TRUCK, REFUSE, REAR LOADER, 20 YARD	40,816	25
CONSTRUCTION, BULLDOZER, 300 HP	40,320	17
TRUCK, AERIAL, 34 FT BOOM	39,682	47
BOAT, POLICE, GAS	37,332	3
TURF, MOWER, ROTARY, 60-72", RIDE-ON	33,310	59
AUTO, POLICE, MARKED	31,228	348
TRUCK, SERVICE, WITH TOOLS, 3 TON	30,883	27
TURF, RAKE, SANDTRAP, RIDE-ON	30,353	11
TRUCK, CLASS 7, CREW CAB, DUMP BODY, HYDRAULIC BRAKES	29,074	43
TURF, GAS, CART GOLF COURSE	28,991	17
COMPACTOR, LARGE, LANDFILL	27,268	6
TRUCK, REFUSE, REAR LOADER, 25 YARD	26,581	10
TURF, MOWER, FAIRWAY, RIDE-ON	26,227	18

Table 5: Kilograms of CO emitted and number of units falling under the 30 highest-CO-emitting vehicle class descriptions in the Fleet from 2015 to 2017.

ClassDesc	kg($NMHC + NO_x$)	Number of Units
CONSTRUCTION, BULLDOZER, 300 HP	46,968	17
COMPACTOR, LARGE, LANDFILL	32,795	6
TRUCK, DUMP, 1 YARD	29,111	175
TRUCK, REFUSE, SIDE LOADER, AUTOMATED, 20 YARD	21,349	66
TRUCK, TRACTOR, TANDEM AXLE	20,824	33
TRUCK, RECYCLING, RIGHT PICKUP	19,624	64
TRUCK, DUMP, TANDEM AXLE	16,441	65
TRUCK, FIRE, QUINT, 75 FT LADDER	15,320	40
VAN, 1.5TON, CUBE BODY	14,204	65
CONSTRUCTION, LOADER, RUBBER, >250 HP	12,951	12
TRUCK, CLASS 7, REG CAB, DUMP BODY, SNOW EQUIPPED	12,901	76
TRUCK, CLASS 8, REG CAB, DUMP BODY, SNOW EQUIPPED	11,163	39
TRUCK, FIRE, PUMPER, 2000 GPM	10,473	39
TRUCK, REFUSE, REAR LOADER, 25 YARD	9,089	10
CONSTRUCTION, LOADER BACKHOE, HEAVY	8,852	40
TRUCK, CLASS 8, REG CAB, DUMP BODY	7,298	25
TURF, MOWER, ROTARY, 16 FT, RIDE-ON	7,240	28
TRUCK, REFUSE, SIDE LOADER, 10 YARD	7,178	14
TRUCK, CLASS 8, REG CAB, DUMP BODY, TOW EQUIPPED	6,823	18
SWEEPER, AIR, 4 WHEEL, 8 CU.YD.	6,762	14
TRUCK, SEWER CLEANER, HYDRAULIC & EDUCTOR	6,400	20
TRUCK, REFUSE, REAR LOADER, 20 YARD	6,320	25
TRUCK, SERVICE, WITH TOOLS, 3 TON	5,913	27
TRUCK, FIRE, LIFE SUPPORT UNIT	5,094	26
PAVING, PAVER, RUBBER	5,091	6
CONSTRUCTION, LOADER, EXCAVATOR, TRUCK MOUNTED, LARGE	5,053	6
TRUCK, CLASS 7, CREW CAB, DUMP BODY, HYDRAULIC BRAKES	4,888	43
CONSTRUCTION, LOADER, RUBBER, 100-150 HP	4,551	11
TURF, TRACTOR, LAWN, MEDIUM	4,366	43
TRUCK, AERIAL, 34 FT BOOM	4,347	47

Table 6: Kilograms of ($NMHC + NO_x$) emitted and number of units falling under the 30 highest-($NMHC + NO_x$)-emitting vehicle class descriptions in the Fleet from 2015 to 2017.

Heavy-duty Gasoline Vehicles Manufactured before 2008									
make	model	yom	fuel	g(CO)	g(CO)/L	[g(CO)/L]_2018	Reduction (%)	Reduction [t(CO)]	Number of Units
FORD	E450	2001	E10	3,294,442	325	182	44.08%	1.45	17
		2002	E10	9,224,055	325	182	44.08%	4.07	
		2003	E10	42,375,847	325	182	44.08%	18.68	
		2004	E10	15,895,851	325	182	44.08%	7.01	
	F350	2000	E10	32,160,775	325	182	44.08%	14.18	18
		2002	E10	6,431,401	325	182	44.08%	2.83	
		2004	E10	5,002,018	325	182	44.08%	2.20	
	F450	1999	E10	2,056,773	325	182	44.08%	0.91	35
		2002	E10	61,866,147	325	182	44.08%	27.27	
		2003	E10	26,885,664	325	182	44.08%	11.85	
		2004	E10	7,201,706	325	182	44.08%	3.17	
GRUMMAN	TP31042	2002	E10	3,809,862	325	182	44.08%	1.68	1
	TP31442	2002	E10	18,316,561	325	182	44.08%	8.07	5
	WP31442	2002	E10	6,635,135	325	182	44.08%	2.92	2

Table 7a: Reduction potential (in % and tonnes) of CO emissions from replacements of heavy-duty gasoline vehicles manufactured before 2008 that fall under the 30 highest-CO-emitting ClassDesc's.

Nonroad Diesel Vehicles Manufactured before 2006									
make	model	yom	fuel	g(CO)	g(CO)/L	[g(CO)/L]_2018	Reduction (%)	Reduction [t(CO)]	Number of Units
ITB	SMCREW	1998	B5	7,005,695	121	45	62.96%	4.41	4

Table 7b: Reduction potential (in % and tonnes) of CO emissions from replacements of nonroad diesel vehicles manufactured before 2006 that fall under the 30 highest-CO-emitting ClassDesc's.

Heavy-duty Gasoline Vehicles Manufactured before 2008									
make	model	yom	fuel	g(NMHC + NO_x)	g(NMHC + NO_x)/L	g(NMHC + NO_x)/L] _2018	Reduction (%)	Reduction [t(NMHC + NO_x)]	Number of Units
FORD	E450	2001	E10	639,698	63	4	93.20%	0.60	17
		2002	E10	1,791,079	63	4	93.20%	1.67	
		2003	E10	8,228,320	63	4	93.20%	7.67	
		2004	E10	2,469,258	50	4	91.50%	2.26	
	F350	2000	E10	6,244,811	63	4	93.20%	5.82	18
		2002	E10	1,248,816	63	4	93.20%	1.16	
		2004	E10	777,013	50	4	91.50%	0.71	
	F450	1999	E10	319,499	50	4	91.50%	0.29	35
		2002	E10	12,012,844	63	4	93.20%	11.20	
		2003	E10	5,220,517	63	4	93.20%	4.87	
		2004	E10	1,118,712	50	4	91.50%	1.02	
GRUMMAN	TP31042	2002	E10	739,779	63	4	93.20%	0.69	1
	TP31442	2002	E10	3,556,614	63	4	93.20%	3.31	5
	WP31442	2002	E10	1,288,376	63	4	93.20%	1.20	2

Table 7c: Reduction potential (in % and tonnes) of (NMHC + NO_x) emissions from replacements of heavy-duty gasoline vehicles manufactured before 2008 that fall under the 30 highest-(NMHC + NO_x)-emitting ClassDesc's.

Heavy-duty Diesel Vehicles Manufactured before 2004									
make	model	yom	fuel	g(NMHC + NO_x)	g(NMHC + NO_x)/L	g(NMHC + NO_x)/L] _2018	Reduction (%)	Reduction [t(NMHC + NO_x)]	Number of Units
FORD	E450	2003	B5	227,967	75	34	54.72%	0.12	1
	F750	2000	B5	284,380	75	34	54.72%	0.16	5
		2003	B5	421,394	75	34	54.72%	0.23	
FREIGHTLINER	FL50	1999	B5	5,065,271	75	34	54.72%	2.77	8
GENERAL MOTORS	TF7B064	2001	B5	9,088,889	75	34	54.72%	4.97	4
INTERNATIONAL	9400I	2002	B5	113,298	75	34	54.72%	0.06	1
SPARTAN	GLADIATOR	1998	B5	12,145,668	75	34	54.72%	6.65	14
		1999	B5	3,174,036	75	34	54.72%	1.74	
STERLING	LT7501	2003	B5	1,327,932	75	34	54.72%	0.73	18
			B20	97,057	75	34	54.72%	0.05	

Table 7d: Reduction potential (in % and tonnes) of (NMHC + NO_x) emissions from replacements of heavy-duty diesel vehicles manufactured before 2004 that fall under the 30 highest-(NMHC + NO_x)-emitting ClassDesc's.

Nonroad Diesel Vehicles Manufactured before 2014									
make	model	yom	fuel	g(NMHC + NO_x)	g(NMHC + NO_x)/L	g(NMHC + NO_x)/L]_2018	Reduction (%)	Reduction [t(NMHC + NO_x)]	Number of Units
BLAW KNOX	PF3172	2003	B5	5,091,099	86	23	72.84%	3.71	2
CASE	590SM-2	2008	B5	1,534,160	54	23	56.83%	0.87	3
	590SM3+	2009	B5	716,002	54	23	56.83%	0.41	1
	590SN	2013	B5	5,779,161	45	23	47.95%	2.77	9
			B20	641,751	44	23	47.95%	0.31	
CATERPILLAR	836H	2009	B5	32,795,157	54	23	56.83%	18.64	2
	924G	2002	B5	389,127	95	23	75.55%	0.29	1
	924K	2013	B5	296,760	45	23	47.95%	0.14	1
	980K	2013	B5	7,595,283	45	23	47.95%	3.64	2
	D8T	2008	B5	35,587,013	54	23	56.83%	20.23	5
		2009	B5	10,223,105	54	23	56.83%	5.81	
GRADALL	XL4100	2002	B5	1,977,454	95	23	75.55%	1.49	2
		2006	B5	3,075,895	63	23	63.40%	1.95	
JOHN DEERE	5220	2002	B5	216,478	95	23	75.55%	0.16	2
		2003	B5	341,513	86	23	72.84%	0.25	
	444K	2010	B5	3,555,221	54	23	56.83%	2.02	2
KOMATSU	WA480-6	2009	B5	1,518,033	54	23	56.83%	0.86	1
NEW HOLLAND	T4020	2009	B5	2,473,269	54	23	56.83%	1.41	13
		2010	B5	1,063,985	54	23	56.83%	0.60	
		2011	B5	271,037	48	23	51.53%	0.14	
TORO	5910	2012	B5	3,555,213	48	23	51.53%	1.83	8
		2013	B5	3,216,150	45	23	47.95%	1.54	
VOLVO	L220F	2009	B5	3,837,731	54	23	56.83%	2.18	1

Table 7e: Reduction potential (in % and tonnes) of (NMHC + NO_x) emissions from replacements of nonroad diesel vehicles manufactured before 2014 that fall under the 30 highest-(NMHC + NO_x)-emitting ClassDesc's.

Total CO Reduction (t)	Total (NMHC + NO_x) Reduction (t)	Overall CO Reduction (%)	Overall (NMHC + NO_x) Reduction (%)
111	131		
Annual Average CO Reduction (t)	Annual Average (NMHC + NO_x) Reduction (t)	4.71%	27.33%
37	44		

Table 7f: Total and annual average reduction potential (in % and tonnes) of CO (NMHC + NO_x) emissions from replacements of vehicles manufactured before significant changes in applicable U.S. EPA emission standards that fall under the 30 highest-emitting ClassDesc's.

As showcased in Tables 7a, 7b, 7c, 7d and 7e, the replacement of old top-(NMHC + NO_x)-emitting heavy-duty gasoline vehicle models is expected to yield a reduction in their (NMHC + NO_x) emissions by over 90%, and replacing old vehicles in other vehicle classes is also anticipated to lead to reductions in their CO or (NMHC + NO_x) emissions by at least 40%. Overall, replacements of old vehicles of all vehicle classes under the 340 highest-emitting ClassDesc's are estimated to result in a reduction in overall CO tailpipe emissions from the Fleet by less than 5% (37 tonnes annually) and (NMHC + NO_x) emissions by over 27% (44 tonnes annually) (see Table 7f).

Conclusions

Engineering Services and Parks & Recreation are responsible for the majority of CO and (NMHC + NO_x) emissions from the Fleet; annual total emissions of the two pollutants have remained stable between 2015 and 2017, with annual total CO emissions outnumbering (NMHC + NO_x) emissions by a factor of 4. On a per-vehicle basis, Engineering Services still takes the lead in both CO and (NMHC + NOx) emissions, followed by Fire & Rescue Services. Across the 20 years of manufacture studied, emissions of both pollutants per vehicle have declined for heavy-duty vehicles and the entire Fleet, while having increased for light-duty vehicles and displaying no clear pattern for nonroad vehicles. The highest-emitting makes across the 3 years for CO are Freightliner, Ford, Sterling, and ITB; the highest-emitting makes for (NMHC + NO_x) are Freightliner, Caterpillar, Ford, and Sterling. Under the 30 highest-CO-emitting and the 30 highest-(NMHC + NO_x)-emitting vehicle class descriptions, replacing old vehicle models of different vehicle classes with models manufactured in 2018 is projected to reduce CO or (NMHC + NO_x) emissions by 44-93% individually; the forecast overall reduction in CO emission from the Fleet is 4.71% (37 tonnes annually) and the forecast overall reduction in the Fleet's (NMHC + NO_x) emission is 27.33% (44 tonnes annually).

Recommendations

In order to continue to meet the Clean Air Goal outlined in the Greenest City Action Plan, the City needs to actively pursue the replacements of its high-CO-emitting and high-(NMHC + NO_x)-emitting vehicles. On the occasion that the City has sufficient funds to replace the 30 highest-emitting vehicle class descriptions of either pollutant, prioritization should be given to the highest-(NMHC + NO_x)-emitting vehicles, since (NMHC + NO_x) is estimated to be more sensitive to such replacements than CO percentage-wise; in case that the City has limit funds to commit to such replacements, prioritization should be given to the vehicle models with the highest potential of absolute reductions (in tonnes) in CO and (NMHC + NO_x) emissions: Ford F450, E450, and F350 should be the first targets for CO reductions (see Table 8), while Caterpillar D8T and 836H, Ford F450 and E450 (gasoline-powered) should be the first targets for (NMHC + NO_x) reductions (see Table 9).

Make	Model	Number of Units	Reduction [t(CO)]
FORD	F450	35	43.20
FORD	E450	17	31.20
FORD	F350	18	19.22
GRUMMAN	TP31442	5	8.07
ITB	SMCREW	4	4.41
GRUMMAN	WP31442	5	2.92
GRUMMAN	TP31042	1	1.68

Table 8: Highest absolute CO reduction potentials (in tonnes) of old vehicle models under the highest-CO-emitting ClassDesc's in the Fleet from 2015 to 2017.

Make	Model	Number of Units	Reduction [t(NMHC + NO_x)]
CATERPILLAR	D8T	5	26.04
CATERPILLAR	836H	2	18.64
FORD	F450	35	17.38
FORD	E450	17	12.19
SPARTAN	GLADIATOR	14	8.38
FORD	F350	18	7.70
GENERAL MOTORS	TF7B064	4	4.97
BLAW KNOX	PF3172	2	3.71
CATERPILLAR	980K	2	3.64
GRADALL	XL4100	2	3.44
TORO	5910	8	3.37
GRUMMAN	TP31442	5	3.31
CASE	590SN	9	3.08
FREIGHTLINER	FL50	8	2.77
VOLVO	L220F	1	2.18
NEW HOLLAND	T4020	13	2.15
JOHN DEERE	444K	2	2.02
GRUMMAN	WP31442	2	1.20
CASE	590SM-2	3	0.87
KOMATSU	WA480-6	1	0.86
STERLING	LT7501	18	0.78
GRUMMAN	TP31042	1	0.69
JOHN DEERE	5220	2	0.41
CASE	590SM3+	1	0.41
FORD	F750	5	0.39
CATERPILLAR	924G	1	0.29
CATERPILLAR	924K	1	0.14
FORD	E450 (diesel)	1	0.12
INTERNATIONAL	9400I	1	0.06

Table 9: Highest absolute (NMHC + NO_x) reduction potentials (in tonnes) of old vehicle models under the highest-(NMHC + NO_x)-emitting ClassDesc's in the Fleet from 2015 to 2017.

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