Benchmarking the Impacts and Effectiveness of City of Vancouver Street Sweeping Operations

Prepared by: Timothy H. Luk, Greenest City Scholar, 2019

Prepared for: Dave Tolnai, Senior Engineer, Zero Waste and Resource Management, City of Vancouver

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Executive Summary

The City of Vancouver's Street Sweeping Benchmarking study is an effort by the City of Vancouver to better understand the environmental impacts of street sweeping and the operations of other municipal street sweeping programs, in order to provide additional information to city staff to maximise the benefits and impact of Vancouver's street sweeping efforts. This project aims to support the Greenest City Action Plan's clean water goals by reducing pollution of Vancouver and area waterways.

This research project is comprised of two phases; first a literature review of street dirt composition and second a benchmarking study of street sweeping fleets in various cities.

The street dirt literature review was conducted using street sweeping studies and reports published by other cities and regional authorities, and other academic works. The aim of this review was to improve our understanding of the composition of street dirt collected by sweepers and the health and environmental impacts of street dirt. This review identified several toxins of common concern and established potential ranges for these toxins within municipal street dirt. These toxins of interest are arsenic, cadmium, chromium, copper, lead, mercury, and zinc. While no national quality guidelines exist for street dirt, comparison to Canadian Soil Quality Guidelines indicate that the estimated ranges of cadmium, copper, lead, mercury, and zinc contained in street dirt may exceed a safe level, supporting the need for sweeping programs to address their build up.

The benchmarking study of street sweeping programs collected data through a survey of 9 cities as well as through previously reported statistics from various municipal authorities for a total of 14 municipalities. This study was designed to compare key indicators of performance and operations across municipal street sweeping programs focusing on the number of sweepers operated by municipalities and how much sweeping is being performed. The key indicators are; the size of street sweeper fleet, the annual distance of km swept, the annual hours spent sweeping, and the annual tonnage of street debris collected.

The benchmarking study revealed a number of key findings about the current City of Vancouver street sweeping program:

1. The City of Vancouver's fleet size is smaller than comparable cities, both in absolute and relative, per capita, terms. In comparison to the cities observed in this report, Vancouver was tied for operating the fewest street sweeper, and when compared to those cities that perform the majority of their sweeping in-house, it had the fewest per capita.

2. From an operational basis, Vancouver has average or above average performance measures. Vancouver collected the most street debris per sweeper of the cities in this report.

The benchmarking survey also revealed that the cities which operate the most extensive and comprehensive sweeping programs, including regular sweeping of residential streets, collected more street debris than those that operate more modest sweeping programs, suggesting that the most direct way to increase the total amount of street debris collected from roadways is to increase the amount of sweeping performed.

City of Vancouver Street Sweeper

Introduction

Historically street sweeping has been an activity designed to provide visually cleaner streets, but with improvements in technology and greater understanding of the composition of the dirt found on city streets, street sweeping is beginning to be understood as a tool to provide a cleaner environment and improve quality of life for urban residents[1]. In order to most effectively provide these benefits it is necessary for cities to understand not only what is being picked up, but also the operations involved in keeping streets clean. To this end, the City of Vancouver has embarked upon this benchmarking study into the impacts and effectiveness of municipal street sweeping.

The dirt and debris that gathers on streets comes from many different sources such as automotive activities, industrial and residential land uses, and natural sources, both regional and local, and is therefore composed of many different components from litter and leaves to fine particulate matter. This report will refer to the collective material that accumulates on city streets as street debris, while street dirt will refer to the finer grain material that excludes litter, larger material such as leaves, and anything that can be easily separated out through a visual inspection. Through chemical analysis researchers have found that a portion of the composition of street dirt consists of a multitude of toxic substances, such as heavy metals which originate from sources such as tire and brake wear, exhaust fumes, local industry, and residential waste[2]. In many ways, a multitude of toxins are slowly released through the daily tasks of living. These toxins settle on city streets and build over time, where they can eventually be kicked up by traffic and reduce air quality, or be washed away by rainfall and enter local waterways, endangering wildlife and human health.

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[1] Breault, R.F., Smith, K.P., and Sorenson, J.R., 2005, Residential street-dirt accumulation rates and chemical composition, and removal efficiencies by mechanical- and vacuum-type sweepers, New Bedford, Massachusetts, 2003–04: *U.S. Geological Survey Scientific Investigations Report 2005-5184*; Rochfort, Quintin, Kirsten Exall, Jonathan P'ng, Vicky Shi, Vesna Stevanovic-Briatico, Sandra Kok, and Jiri Marsalek. 2009. "Street Sweeping as a Method of Source Control for Urban Stormwater Pollution." *Water Quality Research Journal* 44 (1): 48-58.

[2] Thorpe, Alistair and Roy M. Harrison. 2008. "Sources and Properties of Non-Exhaust Particulate Matter from Road Traffic: A Review." *Science of the Total Environment* 400 (1): 270-282; Gunawardana, Chandima, Ashantha Goonetilleke, Prasanna Egodawatta, Les Dawes, and Serge Kokot. 2012. "Source Characterisation of Road Dust Based on Chemical and Mineralogical Composition." *Chemosphere* 87 (2): 163-170; Kalinosky, Paula M. 2015. "Quantifying Solids and Nutrient Recovered through Street Sweeping in a Suburban Watershed." *ProQuest Dissertations Publishing*; Lloyd, Lewis. "Characterization and Reuse of Residuals Collected from Street Sweeping Operations." University of Virginia, 2017. https://doi.org/10.18130/V35933.

In order to prevent these toxins from polluting the environment, and our urban spaces, cities utilise a number of different tools which can range from regulating the release of toxic matter to collecting it before it enters local systems. While these measures vary in their effectiveness and applicability, none seem to be completely effective at reducing pollution levels to zero, and as such it would seem advisable for municipalities to bring many different efforts to bear to increase their overall effectiveness. One such tool is street sweeping, which physically removes street debris from roadways using a variety of technologies, including mechanical brooms, vacuums, and regenerative air systems which using powerful blasts of air to lift debris from the streets and into large hoppers which contain the debris and dirt. This report will focus on the effectiveness and impacts of street sweeping technology generally at cleaning city streets.

This Benchmarking study has two phases. The first is a review of street sweeping literature and the second is a survey of municipal street sweeping operations from around North America and the World. The literature review will consist of studies performed by other cities and regions, and will focus on the chemical composition of street dirt. This literature review will allow for an identification of key chemical components of interest in street dirt and an estimate of ranges for those key components. The second phase is composed of a survey of street sweeping operations from various cities and data gathered from published municipal operational statistics. This data will then be used for a comparison of key operational factors which will provide an estimate of the effectiveness of Vancouver's operation, along with other operational findings.

Background

Literature Review

The purpose of this study is to develop a more comprehensive understanding of the origins and composition of street dirt along with its effects on human health and the environment. In order to develop and contribute to our understanding, this research has relied upon a literature review of similar studies performed by other municipal authorities and academic and trade literature on the subject of street sweeping and street dirt. While there are many similarities in the studies reviewed for this project, the width and breadth of this subject is extensive and there are no formal or uniform methodologies or approaches that have been adopted. As a result, each study has provided its own perspective on the issue and contributed in part to our greater understanding of street dirt. This has also meant that in order to compile and compare the results of these studies it has been necessary to make some estimations and assumptions of the source data. In performing this review we have strived to best represent the data as it has been presented and provide a meaningful analysis towards our own study.

Benchmarking Study

The purpose of the benchmarking study has been to compile data on the street sweeping programs of multiple cities such that comparisons can be made across several facets, and to allow for an estimation of how Vancouver's street sweeping program in particular compares to other cities.

Street sweeping programs in Canada do not have any overarching regulatory body or guidelines to which they must adhere, and while in the United States there are state level environmental requirements for storm water runoff, it is up to the individual municipality to determine how they will meet these requirements. As a result, there are no established standards which municipalities must adhere to in respect of how their street sweeping programs are operated. This research in part then seeks to answer whether despite a lack of official guidance, industry standards exist through informal networks or practices. This will be explored through a comparison of basic measures of fleet composition and operational statistics.

In addition to answering the question of whether informal standards exist in street sweeping operations, this benchmarking study can also provide a guide for cities to determine how their operations compare those of similar cities and whether and how improvement can be made to current street sweeping operations.

Research Approach

Literature Review

Research for this project took on two phases, corresponding with the two main sections; the street dirt study and the sweeper benchmarking. The initial street dirt phase was a review of academic and professional reports associated with street dirt composition, collection, and accumulation. Several of the studies were conducted with or by other municipalities. The articles for this review were gathered using academic databases[3] as well as online search engines[4], and an online street sweeper database[5].

[3] Academic databases were accessed through the University of British Columbia's Library website. https://www.library.ubc.ca/

[4] Online search engines utilized include Google.com, Bing.com, and Qwant.com.

[5] SweeperWorld.com, "Street and Municipal Sweeping: STUDIES" http://www.worldsweeper.com/Street/Studies/index.html (accessed 22 August 2019).

The purpose of this literature review was to establish the primary areas of focus with regard to street dirt analysis, such as the metrics used for analysis, chemicals of interest, established health and environmental concerns, and areas of further research. The review gave particular attention to the major chemical components of street dirt and their respective concentrations, focusing on which components where of the most concern to researchers, why that was, and how concentrations were reported. Information was also sought on the methods of collection and at which point in the sweeping process samples were taken. This was of concern to this research project as it has implications for potential follow up research and reproduction of analysis by the City of Vancouver.

From this literature review seven major chemicals were identified as the most routinely tested and of environmental concern. These seven components are: arsenic, cadmium, chromium, copper, lead, mercury, and zinc. While other components of concern were noted in various studies, these were selected here for their consistency in the reviewed literature, which allowed for greater reliability within our own estimates. The primary sources for many of these toxins are anthropogenic, often related to the wearing down or consumption of automobile components or land use in properties near roadways[6]. Zinc has been linked to tire erosion and brake dust[7]. Similarly, copper has been linked to brake pad erosion[8]. Lead has provided an interesting case study as its levels have dropped significantly over the years since the 1970s, which has been associated with the phase out of lead in gasoline[9]. It does though persist as a result of various

[6] Thorpe, Alistair and Roy M. Harrison. 2008. "Sources and Properties of Non-Exhaust Particulate Matter from Road Traffic: A Review." *Science of the Total Environment* 400 (1): 270-282; Gunawardana, Chandima, Ashantha Goonetilleke, Prasanna Egodawatta, Les Dawes, and Serge Kokot. 2012. "Source Characterisation of Road Dust Based on Chemical and Mineralogical Composition." *Chemosphere* 87 (2): 163-170; Kalinosky, Paula M. 2015. "Quantifying Solids and Nutrient Recovered through Street Sweeping in a Suburban Watershed." *ProQuest Dissertations Publishing*; Lloyd, Lewis. "Characterization and Reuse of Residuals Collected from Street Sweeping Operations." University of Virginia, 2017. https://doi.org/10.18130/V35933.

[7] Thorpe, Alistair and Roy M. Harrison. 2008. "Sources and Properties of Non-Exhaust Particulate Matter from Road Traffic: A Review." *Science of the Total Environment* 400 (1): 270-282; Canadian Council of Ministers of the Environment. 2018. Canadian soil quality guidelines for the protection of environmental and human health: zinc (2018). *In:* Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg; Councell, Terry B., Kea U. Duckenfield, Edward R. Landa, and Edward Callender. 2004. "Tire-Wear Particles as a Source of Zinc to the Environment." *Environmental Science & Technology* 38 (15): 4206-4214.

[8] Hildemann, Lynn M., Gregory R. Markowski, and Glen R. Cass. 1991. "Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol." *Environmental Science & Technology* 25 (4): 744-759; Rosselot, K. Copper released from brake lining wear in the San Francisco Bay area. Prepared for the Brake Pad Partnership. February 2006.

[9] Breault, R.F., Smith, K.P., and Sorenson, J.R., 2005, Residential street-dirt accumulation rates and chemical composition, and removal efficiencies by mechanical- and vacuum-type sweepers, New Bedford, Massachusetts, 2003–04: *U.S. Geological Survey Scientific Investigations Report 2005-5184*.

industrial activities such as smelting and fossil fuel combustion. Mercury, while found naturally in the environment, has increased in environmental levels due to industrial activities such as smelting and coal burning[10]. It is able to travel significant distances in the atmosphere and can accumulate in the environment.

These chemicals are also of interest as they present significant concern to the environment and human health. Mercury is a neurotoxin associated with developmental and behavioural issues and can cause death[11]. It has been shown to be toxic to human and animal populations, with significant risk to lifeforms that exist higher on the food chain as it accumulates in tissue. Lead is also a well-recognized toxin as it can cause significant problems in the cardiovascular and renal systems in humans[12]. It has been observed to be especially toxic to young children as it can disrupt their development. Cadmium has been noted as a carcinogen to humans, and is toxic to the development of fish, causing deformities and reducing lifespan[13].

Review of sampling methods indicated that a regular point of sampling, and the most readily reproducible, was street dirt collected by street sweepers. Sweeper dirt had the added benefit of aggregated results as compared to samples gathered directly from the road surface, which could vary dramatically due to highly localised conditions and the timing of the last sweeper cleaning. As such, this research project focused on the chemical analysis of sweeper dirt sampled from debris collected by street sweepers when producing the estimated ranges of chemical concentrations.

The concentration ranges were established by recording reported concentrations from the reviewed studies and setting those concentrations as the reported high and low marks. The

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[10] Ocean Wise. *Pollution Tracker: Mercury*, http://pollutiontracker.org/contaminants/mercury/ (accessed 22 August 2019)

[11] Scheuhammer A, Braune B, Chan HM, Frouin H, Krey A, Letcher R, Loseto L, Noël M, Ostertag S, Ross P, Wayland M. 2015. Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic. *Science of the Total Environment* 509-510: 91-103.

[12] Ocean Wise. *Pollution Tracker: Lead*, http://pollutiontracker.org/contaminants/lead/ (accessed 22 August 2019); Bellinger, DC. 2011. The protean toxicities of lead: New chapters in a familiar story. International Journal of Environmental Research and Public Health 8: 2593-2628.

[13] Ocean Wise. *Pollution Tracker: Cadmium*, http://pollutiontracker.org/contaminants/cadmium/ (accessed 22 August 2019); Rani A, Kumar A, Lal A, Pant M. 2014. Cellular mechanisms of cadmium-induced toxicity: a review. International Journal of Environmental Health Research 24: 378-399; AMAP. 1998. Assessment report: Arctic pollution issues. Arctic Monitoring and Assessment Programme, Oslo.

ranges were then compared to environmental guidelines for soil and sediment contamination as established by the Canadian Council of Ministers of the Environment[14].

Benchmarking Study

The second phase of this research was the collection of street sweeper statistics from a variety of cities for analysis and comparison to Vancouver. In total 14 cities are represented in this report. They are Auckland, Burnaby, Calgary, Dublin, Edmonton, New York, Portland, San Diego, San Francisco, San Jose, Seattle, Surrey, Toronto, and Vancouver. Cities were chosen based on a number of factors including population size, area, geography, climate, accessibility of data, and the existence of some form of street sweeping program. The initial steps consisted of invitations to participate in the proposed survey made to fleet and operation staff in a number of prospective cities. Those that confirmed their desire to participate received a standard set of questions in survey form and were asked to provide as much detail as possible. As the survey progressed it was determined that the most important and relevant data could be refined to a set of 6 questions which were sent to participating and prospective cities. At the end of the survey only available data linked to those 6 questions was used in this report[15]. These questions related to the size of the street sweeper fleet, distance driven and swept, equipment hours, sweeping hours, and tonnage collected.

In addition to gathering data from survey questions sent directly to municipal employees, data was gathered on municipal street sweeping programs using published statistics found online in reports and studies. This additional data gathering process allowed for an expanded list of cities being included for examination. This was deemed as desirable as it had the potential to expand and deepen the analysis of comparable data. In every case, efforts were made to confirm the consistency and validity of the data collected, both from reports and survey answers. Where data could not be reasonably classified or verified it was removed from the analysis.

With regard to the municipal street sweeping data, due to variations in the way each municipality collects and records its data not all of the sought after information was available. The data that was most variable between cities was tonnage, distances swept, and time spent sweeping. In order to standardise as much of the data as possible, questions regarding sweeper statistics were restricted to large and medium sweepers intended for road usage only. This had the effect of

[14] Canadian Council of Ministers of the Environment, “Canadian Environmental Quality Guidelines”, https://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines/ (accessed 22 August 2019).

[15] See Appendix A Survey Questions

excluding sweeper data on bike path and pedestrian areas. Additionally, some cities which participated in this study contract their street sweeping services to private vendors and therefore do not collect the requested data. In cases where data was absent, and were reasonably possible, comparisons or estimates have been made[16], and where comparison was not reasonably possible the cities have been excluded.

While recording data from participant cities it was noted that some statistics being provided were estimations on the part of participant cities, often due to differences in recording methods. Wherever possible the presence of estimates has been noted in the analysis as it was determined by the researchers that inclusion of reasonable data was of greater benefit than exclusion and the assumption that reporting cities understood their operation best. Further, it has been noted in this report where municipal data was obtained from sources other than the survey questions[17].

Findings

Street Dirt Composition

The literature review of street dirt analysis identified seven chemicals of interest; arsenic, cadmium, chromium, copper, lead, mercury, and zinc. Table 1 sets out each component's concentration and the source study. These concentrations represent the mg/kg of street dirt collected by sweepers in each listed study. The concentrations are based on particle sizes less than 2mm, otherwise referred to in this study as street dirt. In the case of arsenic and mercury found in the Breault (2005) study, reported concentrations were found at these levels or lower and for the purposes of this report have been calculated as equaling the reported level in the source material.

[16] See Appendix B Municipal Data Estimate Calculations

[17] See Appendix C City Survey Data

Table 1. Chemical Concentrations

Chemical	Study	Total (mg/kg sweeper dirt)
Arsenic	Breault, (2005) Pg. 23	0.76*
	Contra Costa (2007) Pg. 10	3.08
Cadmium	Breault, (2005) Pg. 23	1.60
	Contra Costa (2007) Pg. 10	0.61
Chromium	Breault, (2005) Pg. 23	35.00
	Seattle (2012) Pg. 67	37.00
	Contra Costa (2007) Pg. 10	31.60
Copper	Breault, (2005) Pg. 23	56.00
	Seattle (2012) Pg. 67	85.00
	Contra Costa (2007) Pg. 10	133.79
Lead	Breault, (2005) Pg. 23	51.00
	Seattle (2012) Pg. 67	115.00
	Contra Costa (2007) Pg. 10	55.17
Mercury	Breault, (2005) Pg. 23	0.07*
	Contra Costa (2007) Pg. 10	0.18
Zinc	Breault, (2005) Pg. 23	120.00
	Seattle (2012) Pg. 67	250.00
	Contra Costa (2007) Pg. 10	335.88

*concentrations from Breault (2005) on arsenic and mercury were originally reported as <0.76mg/kg and <0.07mg/kg.

The concentrations from Table 1 have been used to establish a range of possible concentration for street dirt in urban areas broadly. These ranges have been set out in table 2.

Table 2: Chemical Ranges of Street Dirt

Chemical	High Factor (mg/kg sweeper dirt)	Low Factor (mg/kg sweeper dirt)	Sediment Quality Guidelines for the Protection of Aquatic Life[18] [Marine] (mg/kg)	Soil Quality Guidelines for the Protection of Environmental and Human Health[19]^ (mg/kg)
Arsenic	3.08	0.76	7.24	12/12
Cadmium	1.60	0.61	0.70	1.4/10
Chromium	37.00	31.60	52.30	64/64
Copper	133.79	56.00	18.70	63/63
Lead	115.00	51.00	30.20	70/140
Mercury	0.18	0.07	0.13	6.6/6.6
Zinc	335.88	120.00	124.00	250/250

^concentrations displayed as: agricultural/residential

The chemical concentrations set out in table 2 represent the range of concentrations found in street dirt set out in table 1, and therefore are a representation of possible chemical concentration ranges in street dirt generally. No national quality guidelines exist in Canada for street dirt but sediment and soil quality guidelines have been published by the Canadian Council of Environment Ministers. As street dirt has the potential to enter local waterways it is reasonable to assume that any toxins contained in street dirt may also enter and pollute those waterways and their corresponding sediment. As such, while there is no direct correlation between sediment quality and street dirt contamination, comparison to sediment quality guidelines has some informational benefits as these toxins will build in the waterway sediment overtime, if not removed.

With respect to Canadian soil guidelines, while street dirt cannot be directly compared to these guidelines, like sediment quality guidelines, there is the potential for some informational

[18] Canadian Council of Ministers of the Environment, "Canadian Environmental Quality Guidelines", http://ceqg-rcqe.ccme.ca/en/index.html (accessed 22 August 2019).

[19] Canadian Council of Ministers of the Environment, "Canadian Environmental Quality Guidelines", http://ceqg-rcqe.ccme.ca/en/index.html (accessed 22 August 2019).

comparisons to be made. Canadian soil guidelines are based on exposure and the potential to harm human health[20]. Like soil, street dirt can be found in close proximity to humans in urban environments, and street dirt is composed of similar material as soil, such as organic matter, so it stands to reason that some meaningful comparisons can be made between soil guidelines and street dirt. Major points of divergence will like include the quantity of material being examined, which will affect the nature of the exposure.

Table 2 provides the sediment guidelines for marine waters and soil guidelines divided into land uses[21]. Comparison of the sediment guidelines to the possible street dirt chemical ranges indicate that cadmium, copper, lead, and zinc may exceed the recommended concentration. Comparison to the agricultural soil guidelines, which represent the highest standard given their use in producing food stuffs, finds that cadmium, copper, lead, and zinc levels in street dirt may exceed safe exposure levels. When compared to residential/parkland guidelines copper and zinc are the only chemicals that may exceed safe exposure levels.

City Street Sweeper Benchmarking

Through the collection of street sweeping data this report presents factors and analysis which allows for the comparison and benchmarking of street sweeper programs in multiple cities. This analysis will help build the collective knowledge of street sweeping operations and can lead to more complete understanding of efficiency and industry standards. The following are profiles of the cities involved in this report highlighting city statistics.

City Profiles[22]:

Vancouver, CA – A coastal city with a temperate climate characterised by wet winters and warm dry summers. The city has a population of 631,486 residents and approx. 1,416 km of roadway within 115 square km. Vancouver relies primarily on regenerative and vacuum sweepers. At the time of this report there were 6 sweepers within the fleet with an additional sweeper anticipated in the near future. The city's street sweeping program is focused on the downtown area as well as the primary arterials. Sweeping occurs throughout the year with reduced coverage during the

[20] Canadian Council of Ministers of the Environment. 1999. Canadian soil quality guidelines for the protection of environmental and human health: Introduction. In: *Canadian environmental quality guidelines*, 1999, Canadian Council of Ministers of the Environment, Winnipeg

[21] The Soil Quality Guidelines for the Protection of Environmental and Human Health are divided into 4 categories of land use; agricultural, residential/parkland, commercial, and industrial.

[22] See Appendix C City Survey Data

rainy winter months. A dedicated leaf cleanup program is operated in the fall, which often utilises contractors for a portion of the sweeping efforts.

Burnaby, CA – A neighbouring city to Vancouver, Burnaby shares Vancouver's mild climate and utilises similar regenerative air and vacuum technology. Burnaby has a population of 232,755 residents and 693 km of roadway, all within 91 square km. Burnaby does not currently record the same data as was requested in this study and therefore was restricted in analysis to questions of equipment hours and total number of street sweepers. Burnaby reported having 6 sweepers in their fleet.

Surrey, CA – Neighbour to Burnaby and Vancouver, Surrey has the same geography and climate as these two cities. Surrey has a population of 517,887 residents, 1,635 km of roadway, all within 316 square km. Surrey relies entirely on contractors to perform its street sweeping duties and does not record sweeping data. The total mileage swept was provided in this survey.

Edmonton, CA – Situated in Alberta, Edmonton differs in climate from Vancouver experiencing longer and colder winters. The cold winter conditions limit street cleaning operations during the winter and require the use of sand on city streets. The use of sand results in the need for a large spring cleanup initiatives. Edmonton reported having 20 street sweepers utilising mechanical broom technology rather than regenerative or vacuum technologies. Edmonton has a population of 932,546 residents, approx. 4,500 km of roadways, and is 685 square km in area. No data was provided regarding the use of contractors during the spring cleanup period. Edmonton was unable to provide data regarding the annual sweeping hours and annual km swept. Estimates were calculated using average ratios created through survey answers[23].

Calgary, CA – Also situated in Alberta, Calgary is similar in size, population, and geography to Edmonton, and has a population of 1,239,220, 5,258 km of roadway, and is 826 square km in area. Calgary also uses sand during the winter months and therefore relies heavily on mechanical sweepers, with a fleet of 8 street sweepers. Calgary reported that they retain contractors during the spring cleanup period to supplement their in-house fleet. These contractors represent a significant addition in total kilometers swept by the city over their municipally run fleet[24]. Calgary does not record the distance swept separately from total mileage

[23] See Appendix B Municipal Data Estimate Calculations

[24] Survey data indicates that Calgary sweeps approx. 26% of the annual km swept.

of their sweepers, and therefore an estimate was produced within this report using average sweeping rates of other cities[25].

Toronto, CA – Canada's most populous city, Toronto has a population of 2,731,571 residents, has 5,230 km of roadway, and is 630 square kilometers. Toronto is dissimilar to Vancouver as it experiences cold, snowy winters and hot humid summers. It is not near an ocean but is situated on the shores of Lake Ontario. Toronto has recently purchased regenerative air street sweepers as it works to improve its air quality along major roadways.

Seattle, US – Similar to Vancouver in terms of geography and climate, Seattle is situated south of Vancouver in the US State of Washington. Seattle has a population of 608,660 residents, 2,921 km of roadways, and is 217 square km in size. Seattle reported their sweeper fleet consisted of 10 sweepers, primarily utilising regenerative air technology with a smaller number of mechanical sweepers.

Portland, US – Situated south of Seattle along the US Western seaboard, Portland is in the US state of Oregon. It shares similarities to Vancouver in terms of geography and climate, and has a population of 583,776, with 3,318 km of roadways, and is 346 square km. Portland reported having 12 street sweepers that are a mix of mechanical and vacuum technologies. The total distance swept by Portland sweepers was recorded separately from survey answers through data published in a report by the City of San Francisco[26].

San Francisco, US – located in the US state of California along the US Western seaboard, San Francisco shares a similar climate to Vancouver, though drier throughout the year. San Francisco has a population of 805,235, with 1,578 km of roadways, and is 121 square km. This city shares significant similarities to Vancouver with respect to population, roadway length, and size. San Francisco relies almost entirely on mechanical sweepers, of which they report to have 48. San Francisco is unique in this study as one of only two municipalities which operates a residential sweeping program which aims to have most residential streets cleaned on a regular (weekly or

[25] See Appendix B Municipal Data Estimate Calculations

[26] City and County of San Francisco Board of Supervisors, Policy Analysis Report: *Comparative Street Cleaning Costs: San Francisco and 11 Other Cities*, San Francisco, CA, June 25,2018, https://sfbos.org/sites/default/files/BLA_Report_Street_Cleaning_Cost_Survey_062518.pdf (accessed 22 August 2019).

bi-weekly) basis[27]. The majority of cities included in this study either schedule no residential sweeping or have that scheduled less than once a month.

San Jose, US – Farther south along the Californian coastline is San Jose. This city has a population of 945,942 residents, has 3,862km of roadway, and is 457 square km in size. It is climactically drier and hotter than Vancouver. San Jose relies primarily on mechanical sweepers for its street sweeping program. Data for San Jose was gathered from an internal sweeping report using data from 2014[28]. San Jose also reports contracting out a significant portion of its sweeping operations in order to supplement its in-house operations[29]. At the time of this report it was noted that San Jose's sweeping program had been expanded and that some of the 2014 statistics had changed, but due to incomplete current data the 2014 data has been used in this report to provide a more complete picture. The author acknowledges that San Jose's performance has likely changed as of the publishing of this report, though the full extent of any change is not known.

San Diego, US – the farthest south of any North American city included in this survey, San Diego lies within the southern portion of California and has a hotter and drier climate compared to Vancouver. San Diego has a population of 1,307,402, has 4,828 km of roadways, and is 842 square km in area making it larger in each respect to Vancouver. Data for San Diego was gathered through a published street sweeper report which consisted of km swept and annual debris collected[30]. Its street sweeping fleet consists of 29 mechanical sweepers.

New York, US – The most populous city in this report, New York City has a population of 8,175,133 residents, 9,656 km of roadway, and is 784 square km. It is the most populous city included in this report and is intended to represent cities which are significantly larger than Vancouver. Data for New York City was gathered through media and municipal reports, which indicate it has approx. 450 sweepers using primarily mechanical broom technology[31]. Additional

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[27] San Francisco Public Works, "Mechanical Street Sweeping and Street Cleaning Schedule", https://www.sfpublicworks.org/services/mechanical-street-sweeping-and-street-cleaning-schedule (accessed 22 August 2019).

[28] Office of the City Auditor, *Street Sweeping: Significant Investment And Re-Tooling Are Needed To Achieve Cleaner Streets*, Sharon Erikson, February 26, 2016. San Jose, CA, 2016. https://www.sanjoseca.gov/DocumentCenter/View/54619 (accessed 22 August 2019).

[29] The data available for 2014 indicates that approx. 36% of total km swept were completed by San Jose's in-house fleet.

[30] Clem Brown and Bryn Evans, "Street Sweeping Pilot Study" January/February 2013, https://www.sandiego.gov/sites/default/files/legacy/thinkblue/pdf/swdsweeparticle.pdf (accessed 22 August 2019).

[31] The Council of the City of New York, *Report of the Finance Division on the Fiscal 2019 Preliminary Budget and the Fiscal 2018 Preliminary Mayor's Management Report for the Department of Sanitation*, March 14, 2018. New York

data includes estimates of the total km swept and the annual street debris collected[32]. Like San Francisco, New York City is the only other municipality in this report to complete regularly residential street sweeping.

Dublin, IE – The only city in this report in Europe, Dublin is the capital of Ireland and shares many similarities to Vancouver with regard to population, length of roadways, and climate. It has 525,383 residents, 1,142 km of roadways, and is 318 square km in area. Due to a lack of available and appropriate data only the number of sweepers was able to be included in this study. Its fleet consists of 14 street sweepers utilizing mechanical or vacuum technologies.

Auckland, NZ – The only city from Oceania, Auckland is located on the northern New Zealand main island and contains 1,438,446 residents, 4,949 km of roadways, and is 784 square km. Similarities to Vancouver include Auckland's situation near mountains and the ocean, while differences include a wetter climate. Auckland relies entirely on contracted labour for its street sweeping program and similar to Surrey was only able to provide data regarding the total km swept.

Benchmarking Analysis

The collection and analysis of street sweeping data focused on two primary concepts, the number of sweepers and the amount of sweeping being performed. The amount of sweeping performed was divided into three subgroups of measurement; distance swept, time spent sweeping, and tonnage collected. Through these metrics this report has establish the following base comparisons for the cities in this study.

I. Number of Sweepers:
   a. Number of sweepers per 100,000 residents
   b. Number of sweepers per 100 km of roadway
II. Distance swept:
   a. Number of km swept annually per km of roadway
   b. Number of km swept annually per 1,000 residents
   c. Number of km swept annually per sweeper

City, NY, 2018, https://council.nyc.gov/budget/wp-content/uploads/sites/54/2018/03/FY19-Department-of-Sanitation.pdf (accessed 22 August 2019), p. 6.

[32] Clarke, Roger. "A Day in the Life of a New York City Street Sweeper" *Spectrum News NY1,* February 14, 2019. https://www.ny1.com/nyc/all-boroughs/news/2019/02/14/a-day-in-the-life-of-a-new-york-city-street-sweeper (Accessed 22 August 2019).

III. Time Spent Sweeping
   a. Number of annual equipment hours per sweeper
IV. Tonnage Collected:
   a. Number of tonnes collected annually per sweeper
   b. Number of tonnes collected annually per km swept
   c. Number of tonnes collected annually per km of road
   d. Number of tonnes collected annually per 1,000 residents

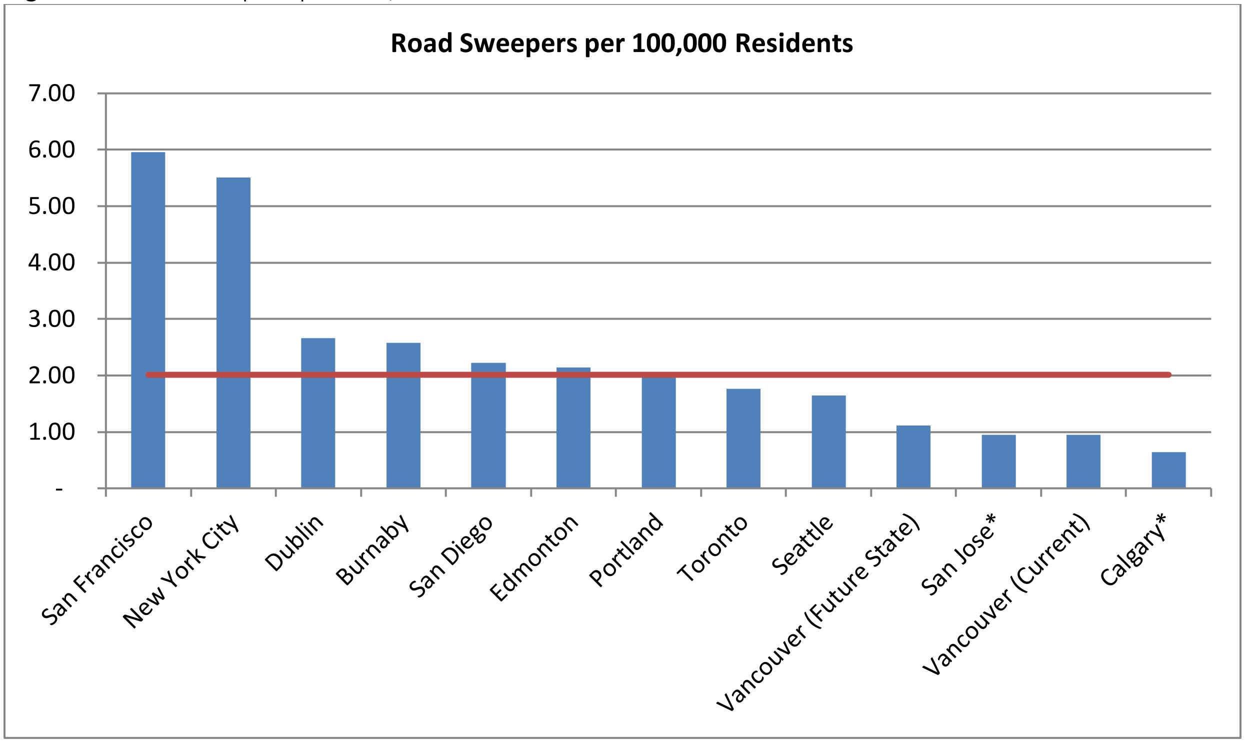
NUMBER OF SWEEPERS

The number of sweepers operated by a city or municipal region provides a base statistic of comparison between cities. The mean number of sweepers operated by a municipality is 44 and the median number is 10. New York City is an outlier with 450 reported sweepers and as such skews the mean significantly. Vancouver currently operates 6 sweepers which places it below both averages. It is even with Burnaby as having the fewest sweepers operated by any city in this report.

When the number of sweepers is presented as a factor of sweepers per 1,000 residents or 100 km of roadway it facilitates a more even comparison of cities by allowing for a base factor of comparison. It also provides a means of comparing cities by a factor of potential street dirt generated through human activity and the area requiring cleaning. This is meaningful as it provides an analysis based on variables that are anticipated to affect how much street dirt is being generated and the area being cleaned. Within this report, the mean number of sweepers operated per 100,000 residents is 1.97, with the median 1.91 (figure 1). Vancouver has 0.95 sweepers per 100,000 residents, meaning it has fewer sweepers than most other cities on this survey, both in an absolute term and per resident. Of note, the only cities in this report with similar sweeper to resident ratios made significant use of contractors to supplement their in-house sweeping program.

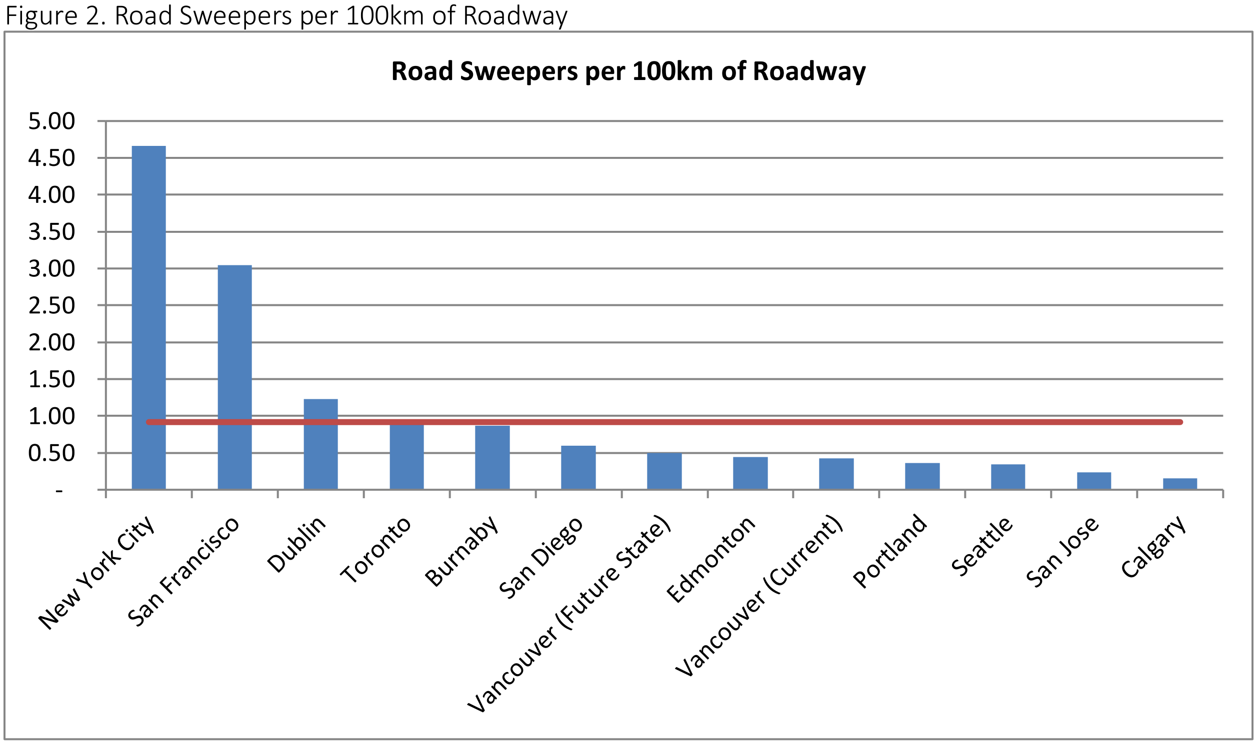
The mean number of sweepers per 100 km of roadway is 1.04 (figure 2). Vancouver (Current) has 0.42 sweepers per 100 km of roadway, which is below the mean of 1.04, but is situated closer to the middle of the listed cities than in figure 1. In both measures, New York and San Francisco have significantly more sweepers than the other cities, which likely results from those cities operating more comprehensive residential sweeping programs. When San Francisco and New York are excluded from the equation the mean drops to 0.47 resulting in Vancouver, both currently and after the anticipated additional sweeper, being situated on the mean.

Figure 1. Road Sweepers per 100,000 Residents



*San Jose and Calgary utilise contractors to complete a significant portion of their annual km swept. 2014 data indicates approx. 64% of San Jose's total km swept was completed by contractors and survey data indicates approx. 74% of Calgary's total km swept were completed by contractors.

Figure 2. Road Sweepers per 100km of Roadway



Distance Swept

The mean number of km swept per 1,000 residents is 96km, with approximately half of cities below this mean (figure 3). Vancouver recorded the second fewest number of km swept per 1,000 residents with only 39 km. Of the six cities that are close to or above the mean two operate regular residential sweeping programs, and three either operate significant seasonal clean-up programs or contract out sweeping services in order to supplement their in-house programs.

With regard to the number of km swept per km of roadway (figure 4), San Francisco and New York recorded exceptionally high numbers compared to the other cities in this report. As noted previously, this is most likely due to those cities' regular residential sweeping programs which require more sweeping be performed. At 17.3 km swept per 100km of roadway Vancouver registered in the lower half of the total number of cities included in this analysis.

Figure 3. Km per 1,000 Residents

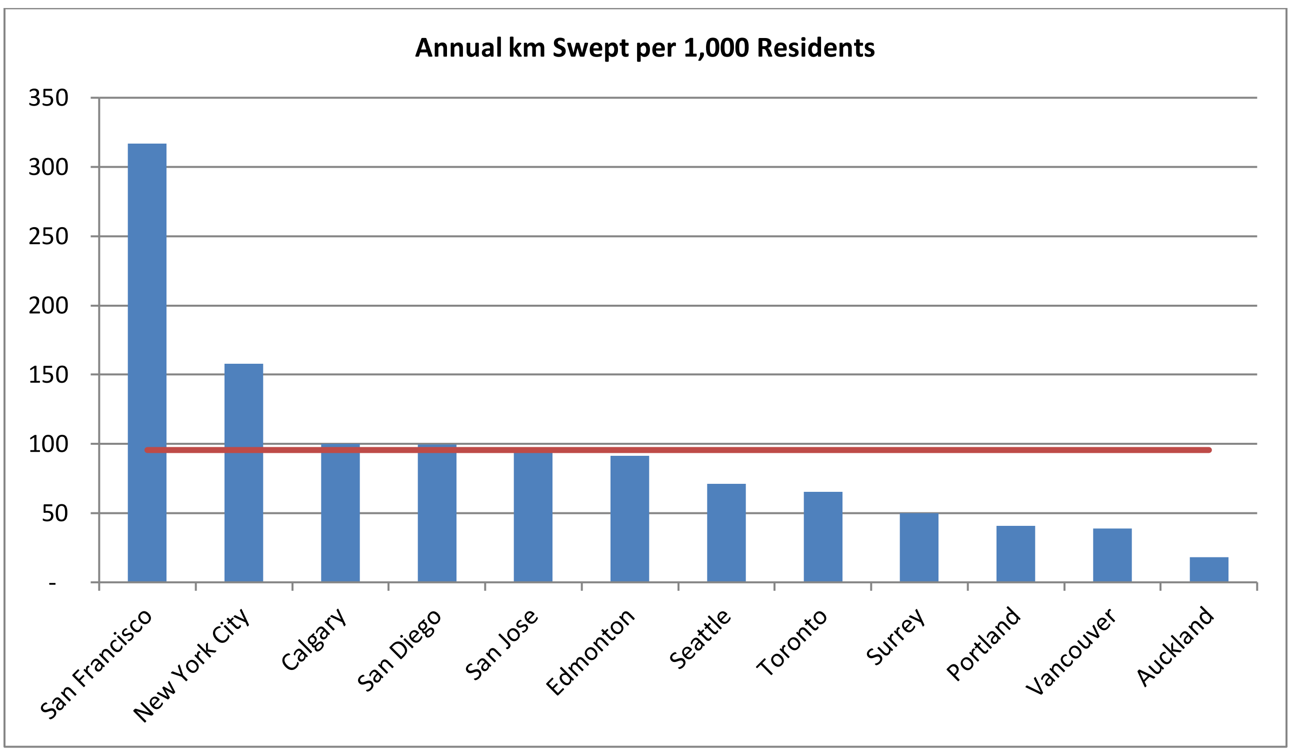
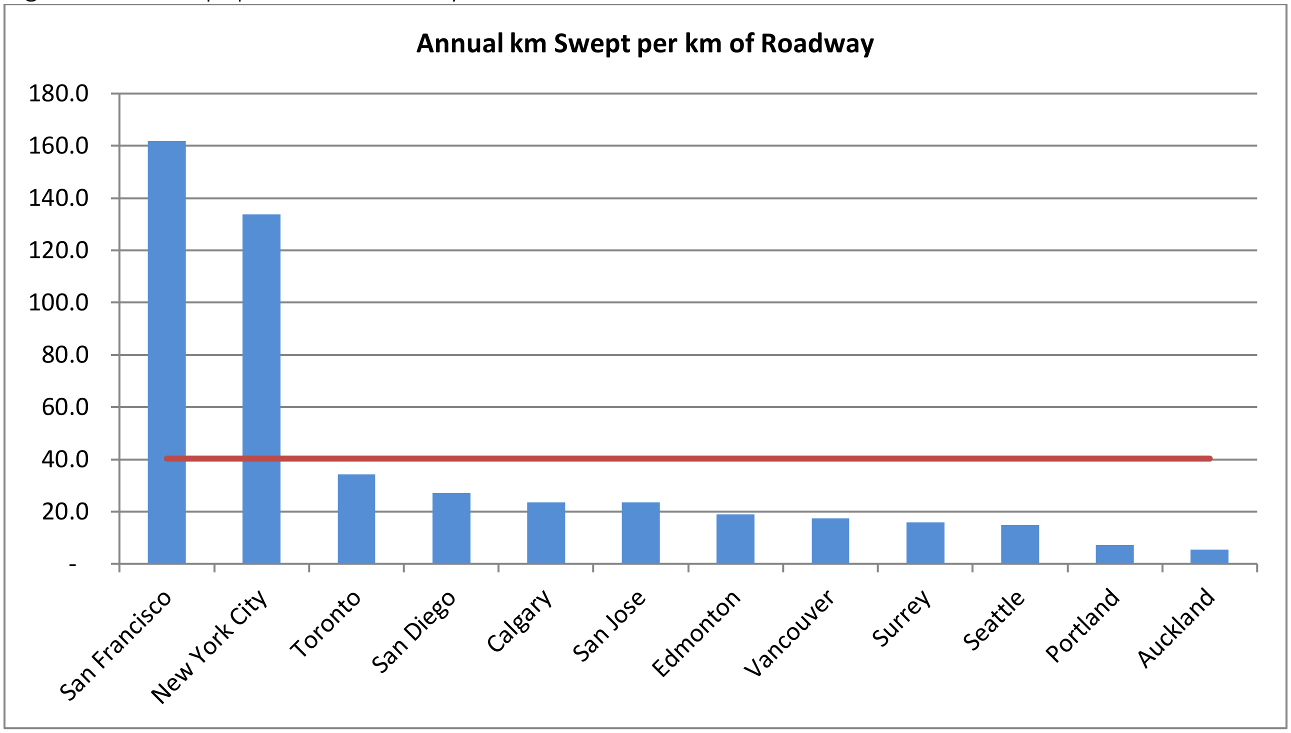
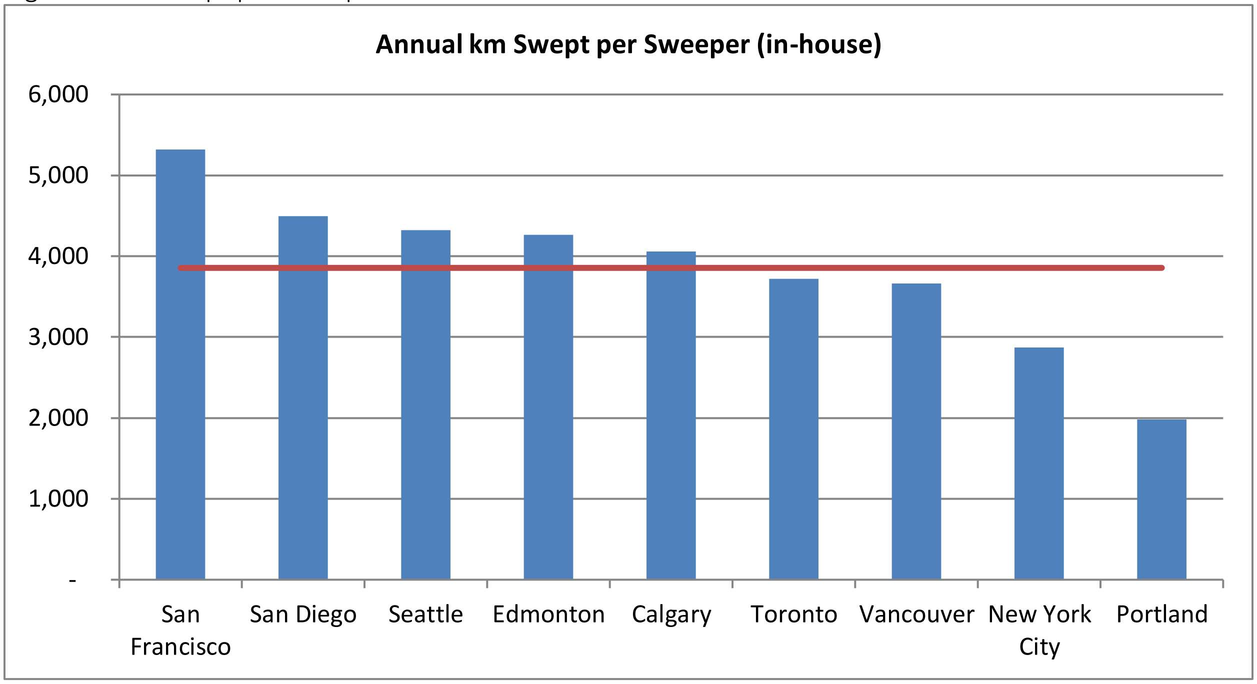


Figure 4. Km Swept per km of Roadway



The last comparison using distance swept is the number of km swept per sweeper (figure 5). For this measure only in-house sweepers and in-house km swept were utilized, as this provides the most reliable comparable data and allows for a perspective focused on the actual municipalities sweeping program. The results of this comparison displayed a smaller difference between San Francisco and other cities, though Vancouver was again below the mean.

Figure 5. Km Swept per Sweeper



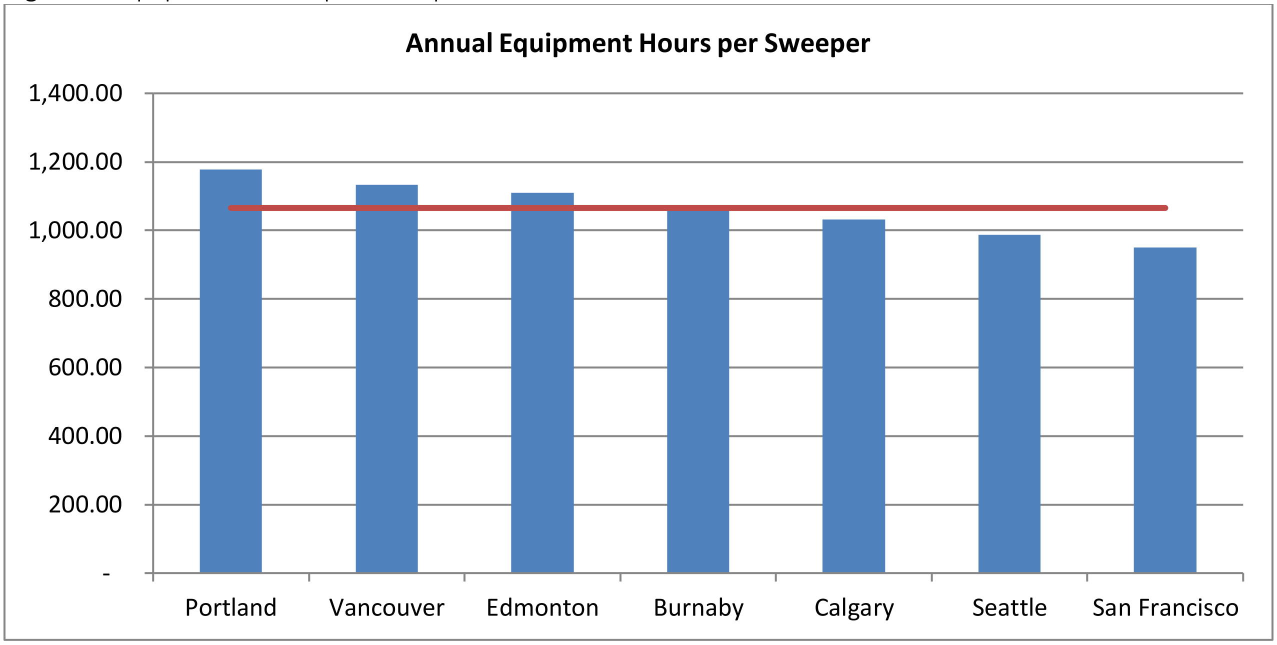
Time Spent Sweeping

A unique piece of comparable data, the time cities spent sweeping was only report by about half of surveyed cities and provides one of the few comparable figures for Burnaby. The most reliable and broadly applicable data collected for this report was equipment hours, which represent the travel time plus sweeping time accrued by each sweeper (figure 6). This factor revealed a relatively small variation between the cities that provided equipment hours, suggesting that regardless of the extent of a city's street sweeping program there is a relatively narrow band of time that can or will be spent operating these vehicles. This may be influenced by operator availability and required maintenance which would limit the amount of time a sweeper can operate. This suggests that there are operational limits to how many hours a sweeper may be reasonably operated, beyond that of available hours in a day. It also suggests that despite the seasonal and scheduled variations in sweeping programs most municipalities continue to operate their sweepers for similar amounts of time each year.

When this data is compared with the number of km swept per sweeper an estimate of which cities are spending more of their operating time sweeping as opposed to travelling can be revealed. This is because a low operating time coupled with a large number of km swept implies that more time is being spent sweeping, and vice versa. The largest differencing is between Portland and San Francisco, with Portland seemingly spending more time driving than San

Francisco, as Portland has a low number of km swept per sweeper but the largest amount of equipment hours per sweeper, whereas as Francisco is the opposite. This may be the result of the geography of these cities, with a fleet yard being located far from the assigned sweeping areas, or sweepers being required to travel to a dumping area repeatedly throughout a shift.

Figure 6. Equipment Hours per Sweeper



Tonnage Collected

Tonnage is not a regularly collected or disseminated piece of data for several municipalities in this report and therefore the available comparisons are limited to often only 8 cities. Tonnage can also be recorded through different methods, but in Vancouver it is recorded by sweepers being weighed as they enter the transfer station where their hoppers are unloaded. This method records total street debris collected as opposed to street dirt and it is assumed that all data collected for the report reflects that as well. The factors of comparison were the number of tonnes collected per 1,000 residents, the number of tonnes collected per km of roadway, the number of tonnes collected per km swept, and the number of tonnes collected per sweeper. While these are related factors, each provides a unique outlook on the efficiency and effectiveness of the street sweeping program. The number of tonnes collected per 1,000 residents reflects the efficiency of collecting street debris generated by the city as a whole[33],

[33] Population acts as a rough stand-in for total activity of the city as this representation does not take into account external factors such as commuting population and pollution entering from outside city limits.

whereas the number of tonnes collected per km of roadway and km of roadway swept reflect the ability of the sweepers to collected street debris from the perspective of total roadway and the actual roadway swept respectively. Lastly, the tonnage collected per sweeper presents a rough estimate of the effectiveness of the street sweeping program as a whole, where each sweeper's contribution is set out within the overall effort.

With respect to number of tonnes collected per 1,000 residents (figure 7) , San Francisco again is found to collect significantly more than the other cities, registering almost double that of the next highest city, San Jose. As with the other instances of San Francisco's recorded statistics being higher than the other cities, it is likely due to the more robust residential sweeping program which requires a greater amount of sweeping be performed and necessitates more sweepers to perform that task. Interestingly though, this higher rate of collection is not reflected in New York's numbers, despite New York sweeping a similar number of km per 1,000 residents to San Francisco. The reason for this is not clear from the data, though it could be related to New York's substantial population density as New York collected above the mean for tonnes per km swept.

Vancouver, at 4.43 tonnes, is situated well below the mean of 6.79 tonnes per 1,000 residents. The reason for this could be related to the fact Vancouver has fewer sweepers than the other cities in this comparison. San Francisco is also the largest collector of tonnes per km of roadway (figure 8), though in this case New York is well above the mean of 2.93, at 5.37 tonnes per km of roadway.

Figure 7. Tonnes Collected per 1,000 Residents

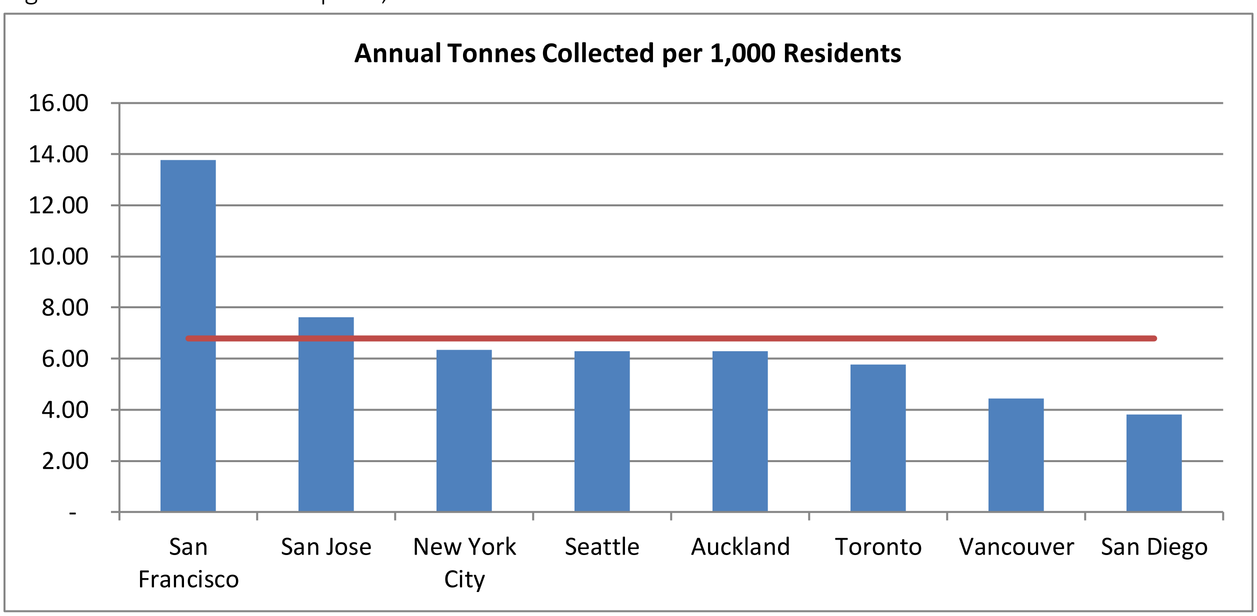
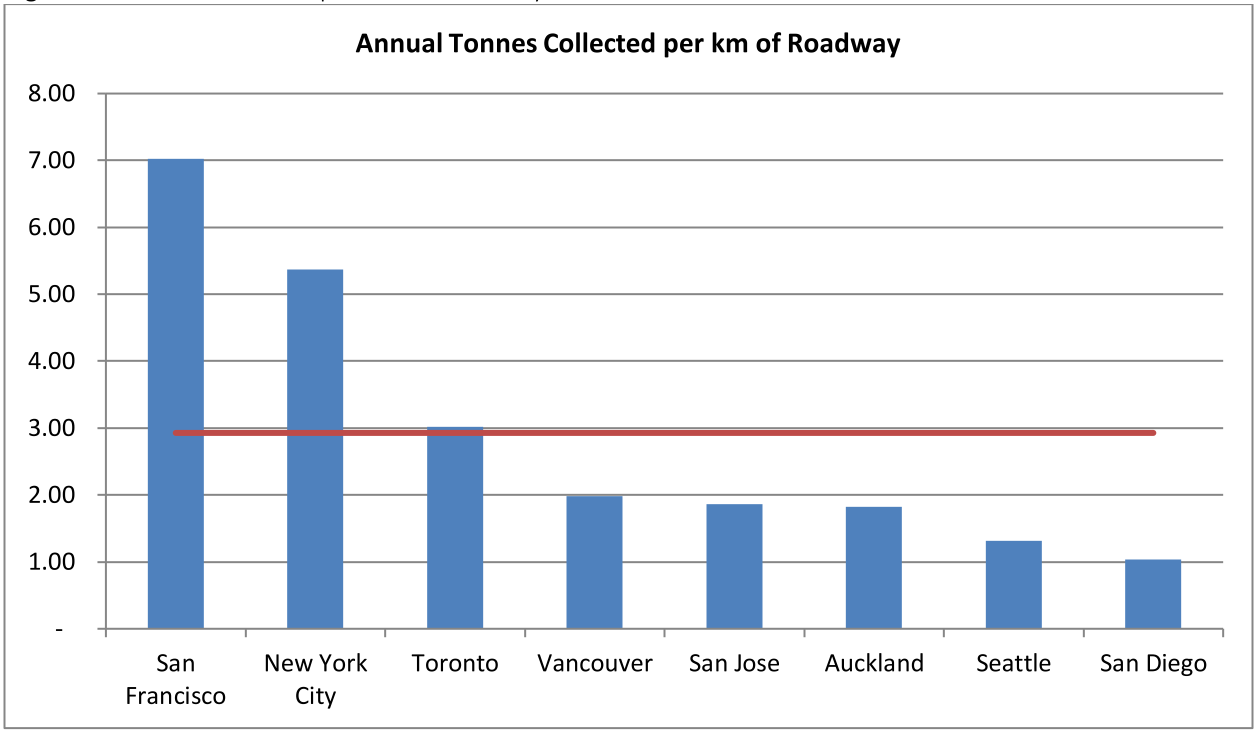


Figure 8. Tonnes Collected per km of Roadway



The order of these cities undergoes a significant reordering when the number of tonnes per km swept (figure 9) and tonnes per sweeper (figure 10) are compared. Here Vancouver collects the largest amount of street debris in both cases with major sweeping cities New York and San Francisco collecting relatively little. As noted previously, these factors are a reflection of the efficiency of the individual city's sweeping program, as opposed to the sheer extent of the sweeping program. Vancouver collects more per km swept and per sweeper than any other city in this report, where tonnage was comparable. While other cities collect more in absolute tonnes, this figure along with the conclusion that cities such as San Francisco sweep more km per sweeper than Vancouver, suggests that there are diminishing returns for the amount of street debris collected as more sweepers are put into service, though at this point the data does not suggest why this may occur. It should also be noted that despite the observation that cities with larger sweeping fleets collect less street debris per sweeper than cities with smaller fleets, cities with larger sweeper fleets still collect more street debris in total than those with smaller fleets. These diminishing returns may be related to less demand on individual sweepers as more are put into service, or may be related to less street dirt accumulating on streets between scheduled sweeping.

Figure 9. Tonnes Collected per km Swept

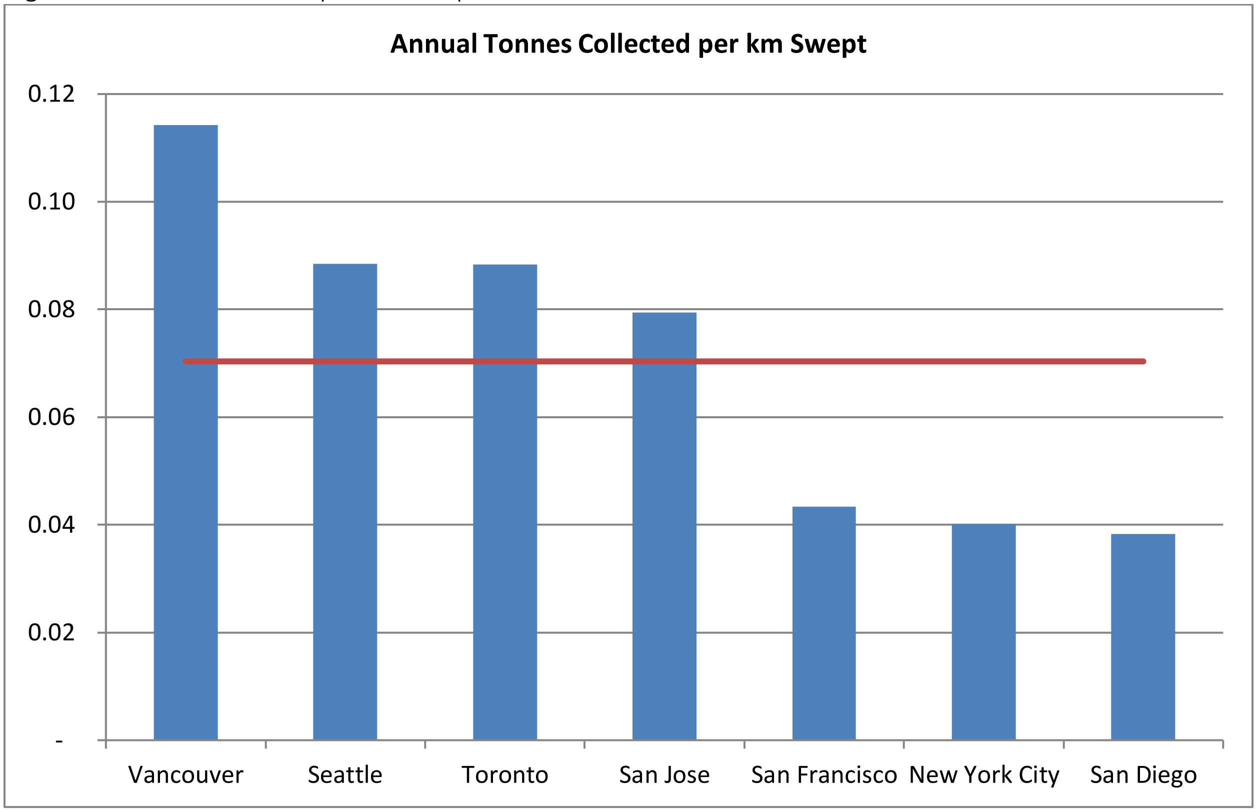
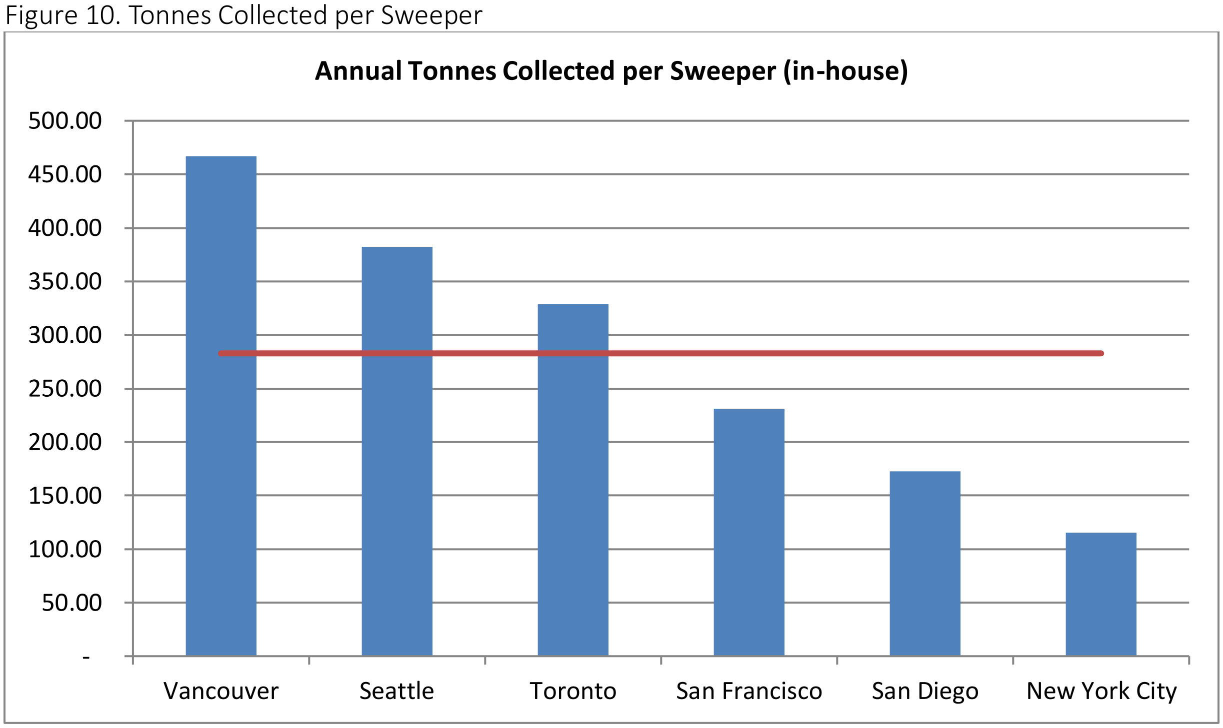


Figure 10. Tonnes Collected per Sweeper



Summary

Street dirt which contains a myriad of toxic chemicals settles on to streets from various sources associated with urban activities, such as driving and industry, as well as natural sources. As these chemicals build on streets they have the potential to pose health concerns for humans and the larger environment and therefore are a growing concern to municipal authorities. Focused research on street sweepers has shown that they can be used as an effective tool for removing street dirt and therefore also removing toxins from the urban environment before they enter local waterways.

As the focus of this benchmarking survey, some observations regarding Vancouver's street sweeping program were made. Vancouver has a smaller fleet in both absolute and relative terms than most comparable cities. On an operational and efficiency basis, Vancouver can be considered average or surpassing other cities of comparable size with average km swept per sweeper and more tonnage collected per sweeper than any other city in this report.

From the perspective of municipal street sweeping programs generally, it was observed that cities that operate regular residential sweeping programs swept more km of roadway, operated more sweepers to fulfil those residential sweeping schedules, and collected an absolute larger quantity of street debris than those cities that focused on arterial roadways. This had the effect of reduced tonnage collected on a per sweeper basis, meaning that some diminishing returns appear to occur with a greater number of sweepers operating, but this does not appear to lead to less street debris being collected in total.

Next Steps

The projected chemical concentrations of street dirt provided in this report have been compiled using reports studying street dirt in areas outside of Vancouver. While they represent findings from various parts of North America, and therefore potential findings from any urban area in North America, how those results compare specifically to Vancouver is unknown. As a next step in increasing and improving our understanding of the impacts of street sweeping, it is recommended that a dedicated analysis of street dirt collected from Vancouver streets be completed.

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Appendices

Appendix A Survey Questions

After initial research the following survey questions were provided to participating cities.

1. How many sweepers does your city operate and how many does it contract (excluding sidewalk/small sweepers)? Do they use mechanical brooms or vacuum/regenerative air technology, or what is their make and model?

2. What is the total annual tonnage/kg of debris collected by your city sweepers?

3. What is the annual length of roadway swept (brooms down)?

4. What is the annual mileage of city sweepers (owned and contracted, separated if you have it)?

5. How many hours does your city operate its sweepers annually (a.k.a. equipment hours)?

Appendix B Municipal Data Estimate Calculations

While most data sets were completed using a combination of survey answers and data published by the cities or by other researchers, some data was estimated with reference to trends within the data. The proportion of time spent sweeping versus the total equipment time was estimated for Edmonton and San Francisco. In this case the total equipment hours were supplied in the survey answers but the sweeping time was not available. During analysis it was noted that three cities, which reported their annual hours spent sweeping (Vancouver, Calgary, and Seattle), spent approximately 54%, 58%, and 57% respectively of their total equipment hours actually sweeping streets. Given the researchers confidence in these numbers it was concluded that by applying the average of these three times to Edmonton and San Francisco's reported equipment hours their sweeping hours could be estimated.

In-house km swept were estimated for Calgary and Edmonton using the average sweeper speed (6.835km/hr), as calculated from the estimated sweeping speed of Vancouver and Seattle, and hours spent sweeping. This was then multiplied by the number of hours spend sweeping (brooms down) to calculate an estimated number of km swept annually.

Appendix C City Survey Data

	Vancouver	Auckland	Burnaby	Calgary	Dublin	Edmonton	New York City	Portland	San Diego	San Francisco	San Jose	Seattle	Surrey	Toronto
City Statistics														
Population	631,486	1,438,446	232,755	1,239,220	525,383	932,546	8,175,133	583,776	1,307,402	805,235	945,942	608,660	517,887	2,731,571
Area (square km)	115	1,103	91	826	318	685	784	346	842	121	457	217	316	630
Length of Roadways (km)	1,416	4,949	693	5,258	1,142	4,500	9,656	3,318	4,828	1,578	3,862	2,921	1,635	5,230
Equipment														
Total Large Sweepers	4	0	6	8	14	20	450	12	29	41	9	10	0	48
Total Medium Sweepers	2	0	0	0	0	0	-	-	-	7	-	0	0	0
Total Sweepers	6	0	6	8	14	20	450	12	29	48	9	10	0	48

	Vancouver	Auckland	Burnaby	Calgary	Dublin	Edmonton	New York City	Portland	San Diego	San Francisco	San Jose	Seattle	Surrey	Toronto
Operational														
Total Owned Equipment Hours	6,800	0	6,400	8,250	-	22,188	-	14,140	-	45,650	-	9,875	0	-
Total Owned Sweeping Hours	3,700	0	-	4,750	-	12,477	-	-	-	25,670	-	5,600	0	-
Total Owned Sweeper Mileage (km)	81,000	0	-	96,000	-	195,107	-	123,475	-	482,803	-	82,962	0	-
Total Owned km swept (km)	22,000	0	-	32,466	-	85,279	1,292,027	23,786	130,357	255,284	32,700	43,244	0	178,692
Total Contractor km swept (km)	2,500	26,320	-	91,788	-	0	-	-	-	0	57,940	0	25,849	-
Total km swept (km)	24,500	26,320	-	124,254	-	85,279	1,292,027	23,786	130,357	255,284	90,640	43,244	25,849	178,692
Annual Debris Collected (tonnes)	2,800	-	-	-	-	-	51,830	-	5,000	11,079	7,200	3,825	-	15,791

City Survey Data Sources

All City Statistics sources are listed below. All City Equipment and City Operational data was obtained through survey responses, unless otherwise noted. Square colour denotes alternative sources of data as indicated below. All City of Vancouver equipment and operational data was obtained from city staff. City data that was not provided in surveys, obtained through published data, or otherwise unusable in this report is denoted by "-".

Data obtained from a separate report.

Data calculated using survey averages for other cities.

Auckland:

- Statistics New Zealand. 2013. *2013 Census QuickStats about a place: Auckland*. http://archive.stats.govt.nz/Census/2013-census/profile-and-summary-reports/quickstats-about-a-place.aspx?request_value=13171&parent_id=13170&tabname=#13171 (accessed 28 August 2019).

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