Characterization of Municipal Solid Waste Collection Operations

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Abstract

Solid waste collection contributes to the cost, emissions, and fossil fuel required to manage municipal solid waste. Mechanistic models to estimate these parameters are necessary to perform integrated assessments of solid waste management alternatives using a life-cycle approach; however, models are only as good as their parameterization. This study presents operational waste collection data that can be used in life-cycle models for areas with similar collection systems, and provides illustrative results from a collection process model using

operational data. Fuel use and times associated with various aspects of waste collection were obtained for vehicles collecting mixed residential (residual) waste, recyclables, and yard waste from single-family residences in selected municipalities. The total average fuel economy for similarly-sized diesel collection vehicles was 0.6-1.4 km/L (1.4-3.3 miles per gallon (mpg)) for residual waste and 0.8-1 km/L (1.9-2.4 mpg) for recyclables. For residual waste and recyclables collection stops, the average time to collect at each residence using automated collection was 11-12 seconds and 13-17 seconds, respectively. The average time between stops was 11-12 seconds and 10-13 for residuals and recyclables, respectively. A single yard waste route was observed, and all collection times were longer than those measured for either recycling or residual waste. Unload or tip times were obtained or measured at a landfill, transfer station, and material recovery facility (MRF). Average time to unload was 7-9 minutes at a MRF, 14-22 minutes at a landfill, and 11 minutes at a transfer station. Commercial and multi-family collection vehicles tend to have longer stops and spend more time between stops than single-family collection, and a larger portion of fuel is used while driving relative to single-family collection. Roll-off vehicles, which collect more waste per stop, spend longer at each stop and drive longer distances between stops than front-loader vehicles. Diesel roll-offs averaged 2.4 km/L (5.7 mpg) and front-loaders averaged 1.4 km/L (3.3 mpg).

Keywords

collection; municipal solid waste; collection time; collection distance; collection fuel efficiency

1 Introduction

Waste collection is an integral component of solid waste management (SWM) systems that contributes to both the costs and environmental emissions associated with managing solid waste. Although collection costs vary depending on population, population density, location,

labor costs, and many other factors, waste collection has been reported to contribute over 40% of the total cost of municipal solid waste (MSW) management (Chalkias and Lasaridi 2009). Emissions from collection vehicles vary based on factors such as truck type, fuel type, efficiency, and route characteristics, but collection has consistently been found to be the most fuel-intensive process in SWM systems (NREL 1995). Therefore, a systematic characterization of the collection process is critical for developing and evaluating MSW management programs that cost-effectively minimize environmental emissions and energy use.

Limited collection process data have been previously reported. Agar et al. (2007) presented collection operation times and fuel use obtained by examining global positioning system (GPS) records of refuse collection vehicles, but this did not include stop duration or time between stops, which are necessary to mechanistically estimate both truck and fuel requirements. Farzaneh et al. (2009) presented data on truck and fuel requirements, as well as durations and distances for all collection activities (e.g., transit to landfill, unloading) for three truck-days of collection. Measurements have been reported on refuse collection vehicles to better characterize emissions (Farzaneh et al. 2009) and engine performance (Ivani 2007) during different operation, including urban driving, highway driving, refuse collection, and disposal activities. More recently, emissions and fuel use rates were measured for diesel and natural gas automated side loaders (Sandhu et al. 2016), diesel front loaders (Sandhu et al. 2014), and diesel roll-off collection vehicles (Sandhu et al. 2015). Heavy-duty diesel vehicles (HDDVs), a class that includes collection vehicles, have an estimated fuel efficiency of 2.8 to 3.2 km/L (6.6 to 7.5 mpg) (US EPA 2006). Since refuse trucks stop and start much more frequently than other HDDVs, they are expected to have lower fuel efficiency. A 2008 model year Autocar refuse collection truck with a Cummins diesel interact system model L (ISL) engine, for example, was

reported to average 1.15 km/L (2.94 mpg) (WIH Resource Group 2010). Values published in the literature for refuse vehicles vary significantly due to many factors including differences in collection vehicle fleet, housing density, and route characteristics. Additionally, fuel efficiencies per distance travelled do not consistently account for the fuel used during loading and unloading of waste, which can also vary significantly.

The objectives of this study were to 1) develop a set of empirical collection data to characterize MSW collection, 2) develop a set of default input parameters for use in mechanistic life-cycle collection models, and 3) illustrate how model parameters can be employed in a specific collection model.

The next section describes the acquisition and analysis of waste collection data. This is followed by presentation and discussion of measured collection data as well as data obtained from collection vehicle fleet operators and waste facility operators. Finally, a default data set for single-family residential collection is described. This data set is employed in the collection process model (Jaunich et al., forthcoming 2016) of the Solid Waste Optimization Life-cycle Framework (SWOLF) (Levis et al. 2013) and illustrative results are discussed.

2 Methods

Waste collection data were assembled for several cities in the U.S. (Table 1). A number of route parameters for single-family collection of recyclables, yard waste, and residual waste were directly measured for City A. In the U.S., recyclables collection typically includes aluminum and steel cans, glass containers, paper, cardboard, and several types of plastic containers. In addition, data were provided by several municipalities and private collection companies (Cities B - E). Collection activity data obtained during a recent collection vehicle emissions study for City F were also incorporated (Sandhu et al. 2014, 2015).

Table 1. Characteristics of Organizations Providing Waste Collection Data

Location or organization providing data ^a	Population density (pp/km ²)	% Multi-family units (MF) ^b	People/household	Data Provided or Measured ^{c, d}
City A	1080	27%	2.7	Obtained monthly fuel consumption and associated tonnage; observed four collection routes (one yard waste, one recyclables, two residual) and recorded distances, times, tonnages [calendar year (CY) 2012]
City B	1180	32%	2.8	Obtained GPS tracking data for 2 diesel and 2 CNG trucks over 4 collection days, for both residual and recyclables collection (route distances, times, tonnages) [CY 2012]
City C	4250	62%	2.2	Obtained monthly fuel use and tonnage for 68-77 residual waste vehicle routes and 45-62 recyclables collection routes [CY 2011]
City D	1160	32%	2.8	Obtained engine control module (ECM) records for residual and recyclables collection vehicles (e.g. fuel efficiency, total distance travelled) [CY 2010]
City E	1110	39%	2.4	Observed unload (tip) times (one day) at a material recovery facility (MRF); obtained tip times for City E tips for several days of operation [CY 2012]
City E	1110	39%	2.4	Obtained tip times for landfill and transfer station for several days of operation [CY 2012]
City F	1110	39%	2.4	Collection vehicle emissions study provided fuel use, mileage, tons per trip, tons per stop and collection activity times and distances for single- and multi-family residential and commercial collection [CY 2013]

^a All cities are located in the U.S.

^b Percent of housing units which are multi-family (U.S. Census City Data, 2014)

^c Collection activity and route data were for single-family residential collection except where noted

^d All collection vehicles were diesel except where noted

Total logged distance, waste collected, fuel use, and truck capacity were used to estimate the fuel efficiency (L/kg), fuel use per metric ton (Mg) waste, and effective in-truck density (i.e., Mg/m³). Because of the variety of data sources and formats, city-specific details are described below.

City A

Collection vehicles performing single-family residential collection of recyclables, yard waste, and residual waste were followed in a trailing passenger vehicle to record transit times, distances, time at each collection location, and unload (tip) time at the disposal facility using a handheld GPS. Trip logs provided fuel quantity and tonnage disposed. Recyclables and residual

waste routes used automated side-loaders (ASL) while the yard waste route was serviced by a rear-loader (RL).

City B

GPS logs were supplied for eight residual truck-days for diesel vehicles collecting residual waste, eight collection truck-days for compressed natural gas (CNG) vehicles also collecting residual waste, and seventeen collection truck-days for diesel vehicles collecting recyclables (28 yd³ (21 m³)). All vehicles were ASLs. Logs included truck number, date, speed, distance traveled, latitude and longitude, and address. Route times and distances were determined from the GPS logs and arm actuation.

City C

City C provided monthly records of tonnage unloaded at the disposal facility for a fleet of 68 to 77 vehicles that were used for both residual waste collection and recyclables collection. Because of the overlap in vehicle use, the calculated distance travelled per quantity of fuel consumed is an aggregate of residual waste and recycling collection. Average waste tonnage per trip was provided for 880 vehicle-days for residual waste collection and 641 vehicle-days for recyclables collection. Effective in-truck waste density was estimated for residual waste and recyclables using the nominal truck volume of 13.4 m³ (16 yd³).

City D

City D furnished fuel and cost data from its waste management provider. The city provided records from the engine control module (ECM) for 17 diesel collection vehicles, which were all 27 yd³ (21 m³) automated side-loaders. Data represented over 100,000 hr of collection vehicle operation. The ECMs recorded the volume of fuel consumed during driving (>2.8 km/hr, 1.2 mph) and idling (<2.8 km/hr). The fuel use data were provided for each vehicle over the

entire time span of operation, and the average idle fuel economy (L/hr of idling) and the overall average fuel economy (km/L) were calculated.

City E

Operators from a landfill, transfer station, and material recovery facility each supplied unload (tip) times for collection vehicles. Additionally, tip times were observed and recorded for one day of operation at a MRF. Tip time was measured from facility check-in to check out.

City F

Sandhu et al. (2014, 2015, 2016) performed a collection vehicle emissions study in Raleigh, NC. Engine control units and GPS devices tracked fuel use, distances, and times on refuse collection vehicles, in addition to using a portable emissions measurement system to track emissions, which was the primary study objective. Six diesel and three CNG truck-days were monitored for both ASL and front-loader (FL) vehicles, as well as six truck-days of diesel roll-off (RO) vehicles. Times at each stop, at the disposal facility, and other route times and distances were presented, as well as the fraction of fuel and time spent driving and idling.

3 Results

Single-family residential collection data are presented first (Section 3.1), followed by multi-family and commercial collection data (Section 3.2). Based on these results, a default set of collection inputs is presented, showing proposed low, middle, and high values for single-family collection input parameters (Section 3.3). Lastly, the SWOLF collection process model (Jaunich et al. 2015,) is summarized and used to predict collection fuel use, cost, and number of trucks for “better”, “medium”, and “worse”-case scenarios based on the range of default input values (Section 3.4).

3.1 Single-family Residential Collection Data

Single-family residential collection in the U.S. typically consists of waste containers brought to the curb of single-family houses, or in some cases duplex-style homes. Collection vehicles then empty the waste containers into the truck manually or with an automated arm. This section describes the quantity of waste collected, the density of the waste (in terms of waste per available truck volume), vehicle fuel use, and collection activity times and distances.

3.1.1 Mass of Waste Collected

Data on the quantity of waste collected per stop were collected from Cities A and B and are summarized in Table 2. City A collected less residual waste per stop than City B (16.2 vs. 22.6 kg), although both cities performed weekly collection. The mass of residual waste collected per stop will vary based on the collection services offered, the frequency of collection, the waste composition and generation rate, the average household size, and the number of households per stop. City A offered weekly collection of residual and yard waste, and bi-weekly recyclables collection. City B provided weekly residual and recycling collection, but offers only limited yard waste collection (twice annually, or upon request). Cities A and B are in the mid-Atlantic and Southwest, respectively. As such, considerably less yard waste is likely generated in City B.

198 **Table 2. Mass collected and fuel use for single-family collection**

City ^a , Service	A, RW ^b	A, Rec ^c	A ^d , Rec ^c	A, YW ^e	A ^f , R/Y ^f	B, RW ^b	B, Rec ^c	C, RW ^b	C, Rec ^c	D, RW ^b	F, RW ^b	F ^g , RW ^b
Effective density (kg/m ³)	464 [2T] ^h	160 [2T] ^h	-	94 [2T] ^h	-	353 [32T] ^h	195 [120T] ^h	344 [880D] ⁱ	275 [641D] ^j	-	-	-
Waste per stop (kg/stop)	16.2 [1269S] ⁱ	12.0 [590S] ⁱ	-	15.5 [270S] ⁱ	-	22.6 [15,400S] ⁱ	-	-	-	-	-	-
Fuel use (L/Mg)	11.0 [2D] ^j	18.2 [1D] ^j	20.2 [1Y] ^k	-	9.8 [1Y] ^k	9.2 [20D] ^j	22.3 [60D] ^j	-	-	-	-	-
Avg. eff. (km/L)	0.7 [2D] ^j	1.0 [1D] ^j	-	-	-	0.9 [20D] ^j	0.8 [20D] ^j	1.0 [1M] ^l	1.0 [1M] ^l	1.1 [10 ⁵ H] ^m	1.3 [6D] ^j	0.6 [3D] ^j
Idle eff. (L/hr)	-	-	-	-	-	-	-	-	-	7.8 [10 ⁵ H] ^m	-	-
^a Cities designated by A through F						^g RW collection routes in city F serviced by CNG vehicles						
^b RW – Residual waste collection						^h T – number of collection vehicle trips						
^c Rec – Recyclables collection						ⁱ S – number of collection vehicle stops						
^d Data are from the public works department for a 1-yr period						^j D – number of collection vehicle-days						
^e YW – Yard waste collection						^k Y – number of years of collection vehicle fleet operations						
^f R/Y – Data are from the combined collection data for residual waste and yard waste						^l M – number of months of collection vehicle fleet operations						
						^m H – number of hours of collection vehicle fleet operations						

199 Based on the average household size of each city (2.7 and 2.8 persons/household,
200 respectively), the collected residual waste per stop corresponds to 0.79 kg/person-day for City A
201 and 1.14 kg/person-day for City B. The U.S. EPA (2015) reported average MSW generation of 2
202 kg/person-day and a nationwide recycling rate (including composting) of 34.3% for 2013, which
203 would result in average residual waste generation of 1.31 kg/person-day. Because the EPA
204 definition of MSW includes waste not collected in a residential collection system (e.g.,
205 commercial and institutional waste), it is expected that residual collection mass observed would
206 be lower than EPA averages.

208 3.1.2 Waste Density

209 Jaunich et al. (forthcoming 2016) showed that the mass collected at each stop on a
210 collection route significantly affects the cost and fuel use because it influences the length of time
211 required to fill the truck and therefore the total number of trips to the disposal facility that a truck
212 can make in a given day. Estimating the mass collected during each route requires an estimate of

the mass required to fill a specified truck volume. An effective in-truck density was calculated by dividing the mass of waste in the truck when it unloads by the volume of the collection vehicle. Table 2 shows the effective in-truck density for recyclables and residual waste for Cities A, B, and C, and yard waste for City A. This effective density is less than the maximum potential density in the truck because it is based on the total mass of waste collected which is often lower than the maximum capacity of the truck by mass. In each city, residual waste had a higher effective density than recyclables or yard waste. The most likely explanation for this is that residual waste would be expected to contain more wet dense material such as food waste, as opposed to the relatively dry recyclables stream and the bulky yard waste stream.

3.1.3 Fuel Use

Available data on collection vehicle fuel consumption from Cities A and B are summarized in Table 2. For both cities, fuel consumption per metric ton of waste collected was higher for recyclables than residual collection. This is expected because the household generation rate of recyclables is lower (i.e., less waste is collected per stop), and the effective density of recyclables is lower than residual waste (i.e., a full truck has less mass in it). For City A, residual waste made up just over two thirds of total mass, with recyclables and yard waste making up 16% and 15%, respectively. Observed effective waste densities for recyclables ranged from 160 to 195 kg/m³, while residual waste was 353 to 464 kg/m³ (Table 2). Fuel consumption per metric ton of residual waste was 17% higher for City A relative to City B. This is likely explained by the lower fuel efficiency observed for City A (0.7 km/L) compared with city B (0.9 km/L). Differences in network distances (e.g., route to disposal facility) would also contribute.

3.1.4 Fuel Economy

Figure 1 shows the range of average fuel economies compared with results from two reports of fuel economy during collection vehicle operation. For observed routes where data were available, overall average fuel economy of diesel vehicles ranged from 0.7 to 1.4 km/L (1.7 to 3.3 mpg) for residual or recycling routes. The fuel efficiency in Figure 1 includes all modes of operation for each route (i.e., average fuel efficiency is the total distance traveled by a vehicle, divided by its total fuel consumption during all operations). There was not a consistent trend in fuel economy between residual or recycling routes. The values in Figure 1 are within the range for average collection vehicle fuel efficiency in two recent studies: 0.9 ± 0.44 km/L (2.1 ± 1.0 mpg) in the city of Hamilton, Ontario, Canada (Agar et al. 2007) and 1.5 to 1.7 km/L (3.5 to 4 mpg) in the City of El Paso, Texas (Farzaneh et al., 2009). The first study had sufficient data to include error bars (1 standard deviation), while the second was based on three collection-days.

Data acquired from City D included the distinction between fuel and time spent while idling and driving. Thus, it was possible to compare fuel consumption during the different operating modes for City D with those measured by Farzaneh and Agar, whose results included efficiency while idling as well as idling with trash lifting (not shown in Figure 1). Fuel use during idling for City D trucks was 7.8 L/hr (2.1 gal/hr), which included time spent picking up and compacting waste. This was between Agar et al. (2009), which reported an average of 3.1 L/hr (0.82 gal/hr) during all time spent idling, and Farzaneh et al. (2009) which reported 3.9 L/hr (1.03 gal/hr) while idling with no arm use and 10.2 L/hr (2.7 gal/hr) during idling while using the vehicle arm to lift and tip cans.

City D provided ECM records of over 100,000 hours of operation. Figure 2 shows that while 42% of collection time was spent idling, only 22% of total fuel use occurred during idling for City D vehicles. Collection activity and fuel consumption data for City F illustrated a similar

trend, where a larger fraction of time than fuel was spent idling, for both diesel and CNG vehicles (Figure 2). These values have a similar trend to that reported by Agar et al. (2007), where it was estimated that 52% of collection time was spent idling, but idling only accounted for 16% of fuel use. Similar data for multi-family and commercial collection activities are discussed in Section 3.3.

City F collection trucks spent a larger portion of the collection day idling than City D trucks, with CNG trucks in City F idling for two thirds of the collection day. Sources of variability include whether or not the truck was left idling during crew breaks, traffic conditions, distance between stops, and network distances (e.g., distances to garage and disposal site).

3.1.5 Collection Activity Times and Distances

Time, distance, and speed metrics for collection and transit activities are presented in Table 3. Transit distances are based on the location of the garage, route, and disposal facility and the typical routes used.

Table 3. Collection transit distances, times, and speeds

	City A RW	City A Rec	City A YW	City B RW	City B RW ^a	City B Rec	City F RW ^b
Observations (trips ^c)	3	2	1	16	23	16	10
Travel times (minutes):							
garage to route	7	6	6	- ^d	-	12	26.1
route to facility	25	18	23	18	23	26	16.9
facility to garage	-	19	-	25	15	23	11.7
Travel distances (km)							
garage to route	6.0	3.5	6.4	-	-	9.5	19.3
route to facility	20.0	34.6	28.0	15.9	15.0	20.9	20.0
facility to garage	-	40.7	-	19.0	12.9	22.5	12.9
Travel speeds (km/hour)							
garage to route	51.5	35.4	64.4	-	-	47.5	44.3
route to facility	48.3	111.0	72.4	54.7	38.6	48.2	50.8
facility to garage	-	128.7	-	46.7	53.1	58.7	54.2

^a CNG collection vehicles

^b Includes six diesel and three CNG collection vehicles

^c Trips are defined as filling a truck, unloading at a facility, and returning to the collection route

^d Distance/time data was unavailable for some routes

Two important parameters for characterizing refuse collection are the average stop duration at a service location and the transit time between collection stops (Appendix Table A2). Data from Cities A and B illustrate that the distribution of stop durations and transit times are both positively skewed (Figure 3) (i.e., there is more variability in the upper 50% of the data). This is because while most stops were approximately 10 seconds, the range for stop duration was large as some drivers or collectors provided additional service at certain houses (e.g., bringing trash bin from the house to the curb and back for households with elderly or disabled customers). Similarly, the majority of transit times were on the order of 10 seconds, but the range was large because inter-street and inter-neighborhood times were included. The stop times for yard waste were more widely distributed, which is attributable to the more varied nature of the waste set at curbside (e.g., bagged leaves, loose branches, bins of yard waste). Appendix Table T-A1

presents the values for each metric described here, as well as the mean and mode of each distribution.

When a truck enters a disposal, treatment, or transfer facility carrying residual waste or recyclables, it is typically weighed and the time of arrival is recorded. The term “tip time” is used to denote the duration between arrival and departure from the facility, which may include the vehicle driving to the unload location, waiting in queue, unloading the residual waste or recyclables, driving to the facility exit, getting weighed, and then departing. Tip times for observed collection routes were recorded, but there were relatively few instances for each city. As a result, only tip times from City E, which had a large number of tips, are shown in Figure 4. The average time required to unload at a landfill for observed collection routes in Cities A (Appendix T-A1), B (Appendix T-A1), and E ranged from 12 to 22 minutes. Longer tip times at landfills relative to MRFs and transfer stations could be expected as there is generally a longer distance between the weigh station and the disposal area and more truck maneuvering is typically required at landfills. Average tip times by City B (Appendix T-A1) and City E at transfer stations ranged from 11-12 minutes, and tips at the City E area MRF ranged from 7-9 minutes. In addition to variation in tip times between different types of facilities, facility-specific factors also play a role in the time needed to unload at facilities of the same type.

In general, the distributions illustrated in Figure 4 are positively skewed, with a few instances of longer tip times influencing the mean. Since life-cycle collection process models are not intended for detailed route planning, average tip times are useful. However, it is preferable to have a large dataset for a given disposal, treatment or transfer facility so that outliers during a particular hour or day do not have a disproportionate impact on the mean. Knowing the distribution of input parameters is also valuable for sensitivity and uncertainty analysis.

3.2 Multi-family Residential and Commercial Collection Data

Fuel consumption and collection activity data for commercial and multi-family sector collection are presented in this section. These data were derived from Sandhu et al. (2014, 2015), who made measurements on front-end loading and roll-off vehicles serving the multi-family and commercial sectors. Six diesel front-loaders collecting a mix of multi-family residential MSW, commercial waste, and cardboard (recyclables) were observed in the study, along with three CNG front-loaders collecting multi-family residential MSW. Six diesel roll-off vehicles collecting commercial waste and cardboard (recyclables) were also observed. As described in Section 2, vehicle instrumentation provided fuel use and collection activity data.

3.2.1 Fuel Consumption

Front-loaders and roll-off vehicles used a larger fraction of fuel (Figure 5) while driving than was observed for side-loaders (Figure 2), and also spent more time driving. Front-loaders and roll-offs spent just over half of collection vehicles' operational time driving. Roll-off vehicles used 88% of fuel while driving, while front-loader diesel and CNG vehicles consumed 83% and 81%, respectively. CNG fuel consumption was tracked in DEL. The observed front-loader vehicles (diesel and CNG) made 15 to 62 stops prior to unloading, and therefore had more stop-and-go driving than diesel roll-off vehicles which made four or fewer stops. The average fuel efficiency for these roll-off vehicles was 2.4 km/L (5.7 mpg), while diesel front-loaders were lower at 1.4 km/L (3.3 mpg), which is consistent with roll-off vehicles making fewer stops. CNG front-loaders had approximately 35% lower fuel efficiency than diesel front-loaders, performing at 0.9 km/DEL (2.1 miles per DEL). This difference is higher than findings in studies comparing CNG and diesel buses (NREL 1995) which reported 10-30% lower fuel efficiency for CNG vs. diesel.

3.2.2 Multi-family and Commercial Collection: Characterization of Collection Activities

Figures 6 and 7 show the average collection activity times and distances for front-loader and roll-off vehicles. Minimum and maximum values for each measurement were taken from the average for each truck-day. Front-loaders and roll-off vehicles spend similar time driving to and unloading at the facility (Figure 6). Front-loaders make more stops prior to emptying, and therefore the time at each stop and the distance and time between stops are shorter than for roll-off vehicles. For most observed routes, the garage was co-located with the disposal facility, so “garage to route” and “route to facility” travel segments are approximately equivalent (Figure 7). This is not the case for all collection systems, so it is important to identify these distances for the collection system being analyzed. More details about each measurement are presented in Appendix T-A1.

4 Single-family Collection: Sample Inputs and Illustrative Results

4.1 Operationally-based Collection Model Default Inputs for Single-Family Collection

The objective of this section is to present a set of default values based on the operational data for single-family collection. This data set can be used to estimate costs and emissions associated with MSW collection using a life-cycle process model in the absence of site-specific data (e.g., Jaunich et al., forthcoming 2016). Table 4 aggregates the values reported in this study and provides a low, middle, and high value for each parameter for use in a collection process model. For analyzing different collection systems, these values should be used selectively to best represent the system of interest. The middle value may be a reasonable starting point, and could be adjusted based on the specifics of the collection area being analyzed.

Collection process models typically use the average value of a parameter’s distribution as input to represent an average collection system. In this study, some parameters had a large

number of data points, while others did not. In general, for those parameters with few observed data points, the low values represent the lowest observed value, with the middle and high values representing the median and highest of observed data, respectively.

Table 4. Input parameter set for single-family residential collection

Collection model input parameter	Units	Low	Middle	High	Notes
Effective density, Residual waste	kg/m ³	344	353	464	Low – City A, Middle – City B, High – City C
Effective density, Yard waste	kg/m ³	76	85	94	Low – Harrison et al. (2001), midpoint of Low and High, High – City A
Effective density, recyclables	kg/m ³	160	195	295	Low – City A, Middle – City B, High – City C
Average diesel refuse truck efficiency	km/L	0.6	1.0	1.4	Lowest, median, and highest observed values
Idle diesel refuse truck efficiency	L/hr	-	7.8	-	One observation
Stop duration, Residual waste	sec	4	12	20	Low – lowest observed mean for any city minus one standard deviation, Middle – median of the means for all cities, High – highest mean for any city plus one standard deviation
Stop duration, Yard waste	sec	3	25	48	
Stop duration, Recyclables	sec	4	15	26	
Time between stops, Residual waste	sec	3	12	25	
Time between stops, Yard waste	sec	3	25	47	
Time between stops, Recyclables	sec	3	12	25	
Tip time, Landfill	min	6	17	32	For observed truck-days at landfill, two medians were observed (11 and 22 minutes). The middle value is the average of these.
Tip time, MRF	min	5	9	21	
Tip time, Transfer station	min	9	17	25	

4.2 Default Inputs: Illustrative Results

In this section, data from this study were employed in a collection process model (Jaunich et al., forthcoming 2016) to estimate fuel consumption, cost, and emissions associated with different collection systems. The referenced model is a spreadsheet-based representation of MSW collection that includes three sector types (single-family residential, multi-family residential, and commercial) and 10 separate collection services (e.g., residual waste, recyclables, yard waste collection). The model allows the user to change over 50 input parameters based on the details of the analyzed system. This includes inputs such as vehicle type (diesel vs. CNG), labor costs, and collection services offered, as well as fuel efficiency, waste density, and collection activity parameters as discussed in this study. The data in Table 4 were used to create a “better case”, “moderate case”, and “worse case” and perform illustrative analyses of residential residual waste collection. For some parameters, lower values are more favorable (e.g., lower times and distances means fewer trucks required, less fuel used, and lower cost), while for others, higher values are more favorable (e.g., higher in-truck density results in more waste collected per trip to the landfill).

Using the collection process model, fuel consumption, cost, and number of trucks for each of the “better”, “moderate”, and “worse” case data sets were estimated to illustrate the range of results possible for a representative city. These values are estimated for each collection type (residual waste, yard waste, and recyclables), and then the weighted average is computed to find the cost and fuel use per metric ton of waste for the city. In Jaunich et al. (forthcoming 2016), costs, fuel consumption, and number of trucks for City A were compared with model-predicted values for two sample cases. The results for the better, moderate, and worse cases, using the values in Table 4, are compared with empirical and model-predicted results from

Jaunich et al. (forthcoming 2016) in Table 5 (all model inputs are presented in Appendix Table T-A5). The “moderate case” predicts less than 1% higher fuel use, and 14% higher cost, than the City A model results (Jaunich et al., forthcoming 2016). Compared with the empirical fuel consumption, the moderate case is 22% higher and the favorable case is 29% lower.

Table 5. Illustrative results for better-, moderate-, and worse-case inputs

	Fuel (L/Mg)	Number Collection Vehicles	Cost (\$/Mg) ^a
Better case ^b	16.6	15.9	76.8
Moderate case ^b	28.7	28.0	142.5
Worse case ^b	64.9	43.8	231.4
City A, Model ^c	28.6	25.8	124.9
City A, Operational ^d	23.5	24.0	102.2

^a Cost includes estimated diesel fuel price of \$0.66/L (\$2.50/gallon)

^b All parameters except those listed in Table 4 take the same values as Jaunich et al. (forthcoming 2016) (see Appendix T-A5)

^c Jaunich et al. (2016). Model results are from the referenced paper.

^d Jaunich et al. (2016). Operational results are from referenced paper.

This analysis illustrates the importance of model parameterization when modeling a collection area. It also shows the value of using mechanistic models to explore how collection costs and emissions change based on changes in truck performance and type and route efficiency.

5 Conclusions

In practice, collection is a non-uniform task that cannot be simplistically characterized due to the many interrelated factors that must be considered. For example, the level of automation of a collection vehicle will influence the time required to collect waste at each stop, as will the skill of the driver or collection workers. While this was not explicitly considered in this study, the data presented here provide insights into valid ranges for several parameters that are critical to the analysis of a collection system.

This research contributes to the available data related to MSW collection and may be applicable to areas with formal, organized residential or commercial collection in the U.S. and abroad. Field observations of collection vehicle activities as well as data provided by municipalities and disposal facilities were used to determine values for parameters that describe MSW collection. The results illustrate that MSW collection activity parameters can vary substantially with implications for cost, fuel use and truck requirements (Table 5). In the illustrative analysis, fuel consumption was a factor of four higher for the worst-case scenario relative to the best-case scenario, illustrating the importance of site-specific data in estimating collection system performance.

Collection vehicles' fuel use was characterized using thousands of hours of recorded collection operations for City D. Comparing this to previous studies, field observations, and other municipality-provided data showed good agreement. Although the collection areas, services offered, and collection vehicles differed, all areas studied had an average fuel economy ranging from 0.6 to 1.4 km/L (1.4 to 3.3 mpg) for all single-family collection routes. Front-loaders servicing multi-family and commercial collection averaged 1.4 km/L (3.3 mpg), and roll-off vehicles averaged 2.3 km/L (5.4 mpg). For single-family collection, times and distances were fairly consistent between a large metropolitan area (City B) and a smaller suburban center (City A), but both cases illustrate that outliers are common. City B's mean stop duration for residual waste was 8% higher than City A, but 20% lower for recyclables collection. The mean time between stops for recyclables and residual waste routes ranged from 10.1 to 13.3 seconds for both cities. Because multi-family and commercial collection activities are more difficult to generalize, it is important to measure or estimate the collection distances and times from operational data to develop a representative set of inputs for modeling efforts.

Solid waste collection systems are rapidly changing, and effectively parameterized models are necessary for estimating how collection system performance will respond to these changes. Site-specific physical, demographic, and operational aspects of the collection area of interest should be considered where such information is available. The collection data presented here are a starting point for the selection of values for the many required input parameters in a collection process model.

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7 References

- Chalkias C., Lasaridi K. Optimizing municipal solid waste collection using GIS. Athens; AG Loannou Theologu 17-23, 15773. World Sci and Eng Acad and Soc; 2009.
- Chatzouridis C., Komilis D. A methodology to optimally site and design municipal solid waste transfer stations using binary programming. *Resour Conserv Recycl* 2012; 60:89-98.
- Curtis E. M., Dumas R. D. A Spreadsheet Process Model for Analysis of Cost and Life-Cycle Inventory Parameters Associated with the Collection of Municipal Solid Waste. 2000. Accessed Dec. 12 2015 from https://mswdst.rti.org/docs/Collection_Model_OCR.pdf
- Environmental Protection Agency. Advancing Sustainable Materials Management: Facts and Figures. Accessed Dec 2, 2015. http://www2.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf
- Everett J., Shahi S. Vehicle and Labor Requirements for Yard Waste Collection. *Waste Manage Res* 1997; 15:627-40.
- Everett J., Maratha S., Dorairaj R., Riley P. Curbside collection of recyclables I: route time estimation model. *Resour Conserv Recycl* 1998; 22:177-92.
- Everett J., Riley P. Curbside collection of recyclable material: Simulation of collection activities and estimation of vehicle and labor needs. *J Air Waste Manage Assoc* 1997; 47:1061-9.
- Farzaneh M., Zietsman J., Lee D. Evaluation of In-Use Emissions from Refuse Trucks. *Transp Res Rec* 2009:38-45.
- Fontaras G., Martini G., Manfredi U., Marotta A., Krasenbrink A., Maffioletti F. Assessment of on-road emissions of four Euro V diesel and CNG waste collection trucks for supporting air-quality improvement initiatives in the city of Milan. *Sci Total Environ* 2012; 426:65-72.

Harrison K., Dumas R., Solano E., Barlaz M., Brill E., Ranjithan S. Decision support tool for life-cycle-based solid waste management. J Comput Civ Eng 2001; 15:44-58.

Ivani Z. Data Collection and Development of New York City Refuse Truck Duty Cycle. SAE Technical Paper Series, SAE International, Powertrain and Fluid Systems Conference and Exhibition, Rosemont, IL October 29-November 1 2007 2007; 01.

Jaunich M. K., Levis J. W., Barlaz M. A., DeCarolis J. F. Municipal Solid Waste Collection Using Life-Cycle Methodology. Journ of Env Eng. Forthcoming, 2016.

Jovicic N. M., Boskovic G. B., Vujic G. V., Jovicic G. R., Despotovic M. Z., Milovanovic D. M. Route Optimization to Increase Energy Efficiency and Reduce Fuel Consumption of Communal Vehicles. Therm Sci 2010; 14:S67-78.

Komilis D. P. Conceptual modeling to optimize the haul and transfer of municipal solid waste. Waste Manage 2008; 28:2355-65.

Larsen A. W., Vrgoc M., Christensen T. H., Lieberknecht P. Diesel consumption in waste collection and transport and its environmental significance. Waste Manage Res 2009; 27:652-9.

Lee D., Zietsman J., Farzaneh M., Johnson J. Characterization of On-Road Emissions of Compressed Natural Gas and Diesel Refuse Trucks. Transp Res Rec 2011:80-9.

Levis J. W., Barlaz M. A., DeCarolis J. F., Ranjithan S. R. A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management. Environmental Modelling Software, 2013.

Lopez J. M., Gomez A., Aparicio F., Sanchez F. J. Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid. Appl Energy 2009; 86:610-5.

Maimoun M. A., Reinhart D. R., Gammoh F. T., Bush P.M. Emissions from US waste collection vehicles. *Waste Manage* 2013; 33:1079-89.

National Renewable Energy Laboratory (NREL). Integrated Municipal Solid Waste Management: Six Case Studies of System Cost and Energy Use. A Summary Report. Nov. 1995 NREL/TP-430-20471

North Carolina State University and Research Triangle Institute. Default Data and Data Input Requirements for the Municipal Solid Waste Management Decision Support Tool. 2000. Accessed Dec. 12 2015 from https://mswdst.rti.org/docs/Inputs_Document_OCR.pdf

Rose L., Hussain M., Ahmed S., Malek K., Costanzo R., Kjeang E. A comparative life cycle assessment of diesel and compressed natural gas powered refuse collection vehicles in a Canadian city. *Energy Policy* 2013; 52:453-61.

Sandhu G. S., Frey H. C., Bartelt-Hunt S., Jones E. In-use measurement of the activity, fuel use, and emissions of front-loader refuse trucks. *Atmos Environ* 2014; 92:557-65.

Sandhu G. S., Frey H. C., Bartelt-Hunt S., Jones E. In-use activity, fuel use, and emissions of heavy-duty diesel roll-off refuse trucks. *Jour Air & Waste Manage. Assoc.* 2015; Vol. 65, 3:306-323

Sandhu G. S., Frey H.C., Bartelt-Hunt, S., Jones E. Real-World Activity, Fuel Use, and Emissions of Diesel Side-Loader Refuse Trucks. *Atmos Environ* 2016; DOI:10.1016/j.atmosenv.2016.01.014

Solano E., Dumas R., Harrison K., Ranjithan S., Barlaz M., Brill E. Life-cycle-based solid waste management. II: Illustrative applications. *Jour Env Eng-ASCE* 2002a; 128:993-1005.

Solano E., Ranjithan S., Barlaz M., Brill E. Life-cycle-based solid waste management. I: Model development. *Jour Env Eng-ASCE* 2002b; 128:981-92.

510 Sonesson U. Modelling of waste collection - a general approach to calculate fuel
511 consumption and time. Waste Manage Res 2000; 18:115-23.

512 Tavares G., Zsigraiova Z., Semiao V., Carvalho M. G. Optimisation of MSW collection
513 routes for minimum fuel consumption using 3D GIS modelling. Waste Manage 2009; 29:1176-
514 85.

515 WIH Resource Group. City of Tucson, AZ: Alternative Fuel Study for Refuse Collection
516 Vehicles – Final Report. 2010. Available
517 http://www.tucsonaz.gov/files/es/City_of_Tucson_Alt_Fuel_Study_-_Final_Report1.pdf.
518 Accessed 3/23/15.

519 Zsigraiova Z., Semiao V., Beijoco F. Operation costs and pollutant emissions reduction
520 by definition of new collection scheduling and optimization of MSW collection routes using
521 GIS. The case study of Barreiro, Portugal. Waste Manage 2013; 33:793-806.

8 Appendix

T-A1. Time to unload (tip time) at various disposal facilities from check-in through check-out

Location and facility information			Tip time (minutes)		
			Number of observations	Average	Standard Deviation
City A	Residual Waste, Diesel	City E landfill	2	12	-
	Recycling, Diesel	Private Recycling Facility	2	15	-
	Yard Waste, Diesel	City E landfill	1	14	-
City B	Residual Waste, Diesel	Private Landfill	16	22	10
	Residual Waste, CNG	Private Transfer Station	22	12	7
	Recycling, Diesel	Material Recovery Facility	26	14	7
City E	One day of disposals observed	Material Recovery Facility	23	7	2
	Residential Loads	City E Transfer Station	153	17	8
	Residential Loads	City E Landfill	410	11	5
	City E disposals	Material Recovery Facility	657	9	4

528 **T-A2. Collection - Time at Stop and Time between Stops**

	# Routes	Stop Duration (sec)						Transit Times (sec)					
		Mean	Mode	SD	Q1	Med	Q3	Mean	Mode	SD	Q1	Med	Q3
City A RW ^a	2	11.4	7.7	7.2	7.5	9.8	12.0	12.5	7.4	13.6	5.5	9.3	13.1
City A Rec ^b	1	16.9	11.3	15.2	10.5	12.8	15.2	13.1	7.6	12.4	5.3	9.4	13.5
City A YW ^c	1	25.2	15.1	22.9	4.9	16.6	28.2	24.7	15.1	22.2	4.3	15.8	27.3
City B RW	16	12.3	9.0	10.8	8.0	10.0	12.0	11.2	6.0	12.6	5.0	8.0	11.0
City B Rec	17	13.0	4.0	16.0	5.5	9.0	12.5	10.3	3.0	13.2	4.0	8.0	12.0

^a RW – Residual waste

^b Rec – Recyclables

^c YW – Yard waste

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530 **T-A3. Average Fuel Economy while Driving (km/L) (Figure 1)**

	A, RW ^a	A, Rec ^b	B, RW	B, Rec	C, RW	C, Rec	D, RW	F, RW	F, RW [^]	Agar, 2007	Farz., 2009
Average fuel economy, km/L	0.7	1.0	0.9	0.8	1.0	1.0	1.1	1.3	0.6	0.9	1.6

^a RW – Residual waste

^b Rec – Recyclables

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532 **T-A4. Effective in-truck density for City C residual waste and recyclables (kg/m³)**

	Truck- days	Mean	SD	Q1	Med	Q3	Max	Min
City C, RW	880	344.5	114.3	301.6	376.6	417.6	780.5	2.0
City C, Rec	641	275.1	79.3	234.6	273.8	320.0	652.3	8.8

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534 **T-A5. All Model Inputs**

Parameter description	Units	Name	Res	Rec	YW
Collection schedule					
Number of households at one stop	households/stop	HS	1	1	1
Participation rate	fraction of stops	Prtcp	1 ^a	0.75 ^a	0.5 ^a
Collection frequency	1 / week	Fr	1	1	1
Number of working days a week	days/week	CD	4	4	4
Actual working hours a day	hours/vehicle-day	WV	9	9	9
Working hours a day for wage	hours/person-day	WP	9	9	9
Collection Rules					
Is the route or truck subject to a weight limit?		Yes or No	No	No	No
If subject to a weight limit, max collected weight before unload	Mg/vehicle	max_weight	-	-	-
Collection operation times					
Loading time at one service stop	min/stop	TL	Table 4		
Travel time between service stops (based on 100% Participation)	min/stop	Tbtw			
Travel time between route and disposal facility	min/trip	Trf			
Time to unload at disposal facility (tip time)	min/trip	S			
Lunch time	min/day-vehicle	F1	30 ^a	30 ^a	30 ^a
Is truck left idling during lunch?	Yes or No	F1_idle	Yes	Yes	Yes
Break time	min/day-vehicle	F2	30 ^a	30 ^a	30 ^a
Is truck left idling during break?	Yes or No	F2_idle	Yes	Yes	Yes
Time from garage to collection route	min/day-vehicle	Tgr	Table 4		
Time from disposal facility to garage	min/day-vehicle	Tfg			
Labor					
Does a driver work as a collector?	Yes or No		Yes	Yes	Yes
Number of additional collectors per vehicle	persons/vehicle	Nw	0	0	0
Worker backup rate	backup workers/ collection workers	bw	0.1 ^a	0.1 ^a	0.1 ^a
Economic data					
Fringe benefit rate	fringe benefit pay/wage pay	a	0.46 ^a	0.46 ^a	0.46 ^a
Other expenses rate	\$/worker-year	d	12114 ^a	12114 ^a	12114 ^a
Administrative rate	administrative cost/ (capital+operating cost)	e	0.12 ^a	0.12 ^a	0.12 ^a
Hourly wage for a collector	\$/hour-person	Wa	12.96 ^a	12.96 ^a	12.96 ^a
Hourly wage for a driver	\$/hour-person	Wd	15 ^a	15 ^a	15 ^a

Parameter description	Units	Name	Res	Rec	YW
Vehicle operational parameters					
Backup rate for vehicles	backup vehicle/ collection vehicle	bv	0.1 ^a	0.1 ^a	0.1 ^a
Utilization factor	max occupied yd ³ / usable yd ³	Ut	0.8 ^a	0.8 ^a	0.8 ^a
Usable vehicle capacity	m ³	v	31 ^a	31 ^a	31 ^a
Economic life of a vehicle	year	Lt	7 ^a	7 ^a	7 ^a
Vehicle type			ASL	ASL	ASL
Unit price of a vehicle	\$/vehicle	Pt	240000 ^c	240000 ^c	240000 ^c
Vehicle operation and maintenance cost	\$/vehicle	c	40000 ^c	40000 ^c	30000 ^c
Assumed compartment compaction density	kg/m ³	d	Table 4		
Travel speeds					
Between collection stops	km/hour	Vbet	Calculated based on times in Table 4 ^d and distances, below		
From collection route to facility	km/hour	Vrf			
From garage to route in the morning	km/hour	Vgr			
From facility to garage	km/hour	Vfg			
Distances					
Distance between collection route and destination	km	Drf	20.0 ^b	34.6 ^b	28.0 ^b
Fraction of route to destination which is highway	km	fDrf	0.5	0.5	0.5
Distance between destination and garage	km	Dfg	28.0 ^b	40.2 ^b	36.1 ^b
Fraction of destination to garage which is highway	km	fDfg	0.5	0.5	0.5
Distance between service stops (regardless of non-participation)	km	D100	0.05 ^b	0.05 ^b	0.05 ^b
Distance between garage and collection route	km	Dgr	5.95 ^b	3.54 ^b	6.44 ^b
Fraction of distance between garage and collection route which is highway	km	fDgr	0	0	0

Parameter description	Units	Name	Res	Rec	YW
Fuel usage rates					
Fuel split: fraction of stops serviced by CNG vehicles	%	Fract_CNG	0	0	0
Fuel split: fraction of stops serviced by diesel vehicles	%	Fract_Dies	1	1	1
CNG average fuel usage	km/diesel equiv. L	ef _{avg} _CNG ^{e,f}	-	-	-
CNG during urban driving	km/diesel equiv. L	ef _u _CNG	-	-	-
CNG during highway driving	km/diesel equiv. L	ef _h _CNG	-	-	-
CNG during collection	km/diesel equiv. L	ef _b _CNG	-	-	-
CNG while idling/dropping off waste	diesel equivalent L/hr	ef _i _CNG	-	-	-
Diesel average fuel usage	km/L	ef _{avg} ^e	Table 4		
Diesel during urban driving	km/L	ef _u	-	-	-
Diesel during highway driving	km/L	ef _h ^f	-	-	-
Diesel during collection	km/L	ef _c	-	-	-
Diesel while idling/dropping off waste	L/hour	Efi	-	-	-
Garage and office parameters					
Maintenance area per collection vehicle	m ² /vehicle	grg_area	37.2 ^a	37.2 ^a	37.2 ^a
Office area per collection vehicle	m ² /vehicle	off_area	1.86 ^a	1.86 ^a	1.86 ^a
Maintenance area electricity consumption rate	kWh/day-m ²	grg_enrg	0.00001 ^a	0.00001 ^a	0.00001 ^a
Office area electricity consumption rate	kWh/day-m ²	off_enrg	0.00002 ^a	0.00002 ^a	0.00002 ^a
Mixed waste and recyclables storage					
Unit price of a bin	\$/bin	Pb	7.59 ^a	7.59 ^a	7.59 ^a
Number of bins for each house	bins/house	Rb	1 ^a	1 ^a	1 ^a
Economic life of a bin	year	Lb	10 ^a	10 ^a	10 ^a

^a Values adapted from Curtis and Dumas (2007), Harrison et al. (2001), Solano et al. (2002a and 2002b), Curtis and Dumas (2000), NCSU and RTI (2000)

^b Data from observation of City A collection routes

^c Truck and operations and maintenance costs from personal communications with waste collectors and truck manufacturer (2013-2014).

^d Speed calculated based on distance and time for each segment (distances are representative of those used for City A (Jaunich et al. 2016), and times based on ranges of operational data reported in Table 4).

^e Average fuel efficiency is used instead of modal fuel efficiencies for illustrative cases

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figures for Jaunich et al. “Characterization of Municipal Solid Waste Collection Operations”

Figure 1. Single or 1.5 column width

Figure 2. Single column width

Figure 3. Single column width

Figure 4. Single column width

Figure 5. Single column width

Figure 6. Single or 1.5 column width

Figure 7. Single or 1.5 column width

Figure 1. Overall Average Fuel Economy while Driving (km/L)

City designated by A through F (Table 1); Collection Type: RW – Residual waste, Rec – Recyclables, YW – Yard waste. City F, RW^ represents CNG routes, efficiency presented as km per diesel equivalent liter (km/DEL) [1 DEL contains the energy equivalent of one liter of diesel fuel (approximately 35.8 GJ/L)]. Data in Appendix Table A-T3.

* Agar et al. 2007, Farzaneh et al. 2009

Figure 2. Portion of total fuel and time used while driving and idling for automated side loader (ASL) vehicles by city (D and F) and fuel type (Diesel and CNG)

Figure 3. Stop duration and transit time between stops. The center line is the median, and the bottom and top of the boxes are the 25th and 75th percentiles, respectively (the inter quartile range, or IQR). The top bar is the 75th percentile plus 1.5·IQR, and the bottom bar is the 25th percentile minus 1.5·IQR. (The dashed lines and bars encompass approximately 95% of the data.)

Figure 4. Frequency of tip times observed for City E, including one day of tips measured at single-stream MRF (MRF - measured), and facility-reported tip times for a single-stream MRF (MRF), transfer station (Transfer), and a landfill (Landfill). The center line is the median, and the bottom and top of the boxes are the 25th and 75th percentiles, respectively. The top bar is the 75th percentile plus 1.5·IQR, and the bottom bar is the 25th percentile minus 1.5·IQR.

Figure 5. Portion of total fuel and time used while driving and idling for roll-off (RO) and front-loader (FL) for City F

Figure 6. Average collection times for front-loader (FL) and roll-off (RO) vehicles. FLs make more frequent, shorter stops but have comparable tip times.

Figure 7. Average collection distances for front-loader (FL) roll-off (RO) vehicles.