Curbside Collection of Yard Waste: I. Estimating Route Time

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Abstract: Curbside collection of compostable material can be expensive because the inherent costs of curbside collection are high, but also because amounts collected per residence are small compared to the total waste stream, and time is wasted driving by residences at which no material is set out. In this paper, a model is presented capable of estimating route time based on the set-out rate and distribution, the amount of materials collected, and collection method characteristics. The model separately estimates travel time, collection time, and time spent waiting at stop signs and traffic lights. Model parameters are based on observation of compostables collection. Over six collection days for a collection route in Norman, Okla., the model estimated route time to within 4.8% of observed values.

INTRODUCTION

Municipal solid waste (MSW) collection costs are estimated to be approximately \$10 billion/yr in the United States (Tchobanoglous et al. 1993). A cost analysis conducted by Ludwig and Black (1968) revealed that 85% of the solid waste system cost was due to collection and only 15% to disposal. Though modern disposal costs are relatively higher, collection is still a large portion of solid waste costs. More communities are implementing programs to divert solid waste from landfills and incinerators. Thus, nontraditional waste collection systems are increasingly in use. One material that is now commonly diverted from disposal is yard waste, which can be composted to yield a valuable soil amendment (Glenn 1993).

Yard waste is defined as material containing not less than a specified percent by volume of plant debris, i.e., grass, leaves, prunings, and tree trunks and branches not exceeding a specified diameter. Exact definitions vary from community to community. Yard waste is the second most prevalent material in MSW, following paper (EPA 1989).

Collection cost plays an especially significant role in programs where compostable materials are collected from individual residences and transported to a central location for composting. First, the amount of material collected per residence is small compared to the total waste stream. Second, considerable time can be wasted in driving by non-participating residences. Route time (RT), i.e., the total time spent collecting compostables on a given collection vehicle route, may vary considerably depending on the amount, number, and distribution of residences at which yard waste is set out. Furthermore, the time spent per unit of compostable material collected will increase as materials are set out at fewer residences. Collection time may be further increased if it involves additional on-route tasks, such as debagging.

The goal of the present paper is to describe a new method for estimating yard waste collection route time. The objectives are:

1. To discuss literature on related topics in solid waste management and review previously developed methods for estimating collection needs.
2. To present a mathematical model capable of estimating the time required for curbside collection of yard waste, based on the set-out rate and distribution, amount of material collected, and collection method.
3. To use data gathered by observing the collection of compostables in a residential neighborhood in Norman, Okla., to estimate the parameters in the mathematical model.
4. To verify the accuracy of the model.
5. To present conclusions and suggest additional research.

The research presented here deals solely with the curbside collection of yard waste. The validation of the proposed model is based on data collected for six collection runs, during summer and early fall, in a residential neighborhood of Norman, consisting of 268 residences with a route length of approximately 6.9 km (4.3 mi). The model's applicability to other collection routes and collection methods is not tested.

BACKGROUND

Adequate solid waste management planning is an issue facing many communities in the United States. As the practice of solid waste management becomes more complicated, sophisticated analytical tools are used more frequently in the decision-making process. A number of models have been developed for the design and analysis of various components of solid waste management systems. Numerous solid waste management models can be found in general literature overviews given by Liebman (1975), Helms and Clark (1971), and Greenberg (1978). The common approaches to tackle solid waste management problems have been through heuristic, linear, and mixed integer programming. However, none of the models developed to date have dealt with the collection of compostables. Also, although models allow for sensitivity analysis, few allow for simulation analysis based on parameters which may be changed based on known or estimated distributions.

Only one example of a simulation of solid waste collection incorporating randomly distributed parameters has been identified in the literature. Truitt et al. (1970) simulated collection for a 6-d work week in an area of Baltimore, Md., to determine the effect of transfer station location and collection frequency on collection costs per ton. In their model, it is assumed that

$$T_c = \text{Wt Col/Col Rate} \tag{1}$$

where T_c = collection time, h; Wt Col = collection vehicle net load, kg (lb); and Col Rate = collection rate, kg/h (lb/hr). Histograms of Wt Col and Col Rate frequencies were developed from observations of solid waste collection in Baltimore for different vehicle sizes and neighborhood types. For each con-

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dition of transfer station location and collection frequency, multiple runs were made using the histograms to assign vehicle net weights and collection rates based on occurrence probability. However, this technique can be applied to the collection of compostable materials only if histograms are developed for each condition of set-out rate, and so forth. This does not appear to be feasible or desirable.

A deterministic approach to estimating MSW collection costs, adopted from Tchobanoglous et al. (1993), is presented next. The method can be used to estimate the available time per route, the required vehicle capacity, and the number of routes and vehicles required. From this information capital, operating, maintenance, and labor costs can be estimated. Given that the objective of an activity is to collect materials from residences, the time available for each route is

$$P_{scs} = \frac{H(1 - W) - (t_1 + t_2)}{N_d} - (s + h) \tag{2}$$

where P_{scs} = time spent collecting materials from residences on each route, from the first residence to the last, h/route; H = hours vehicle is on the road each working day, h/working day; W = off-route time factor, consisting of the fraction of the day spent in nonproductive activities such as breaks; t_1 = time spent at beginning of the day driving vehicle from dispatch area to first residence, h/working day; t_2 = time spent at end of day driving vehicle from last residence to dispatch point, h/working day; N_d = number of routes each vehicle can complete in a working day, routes/working day; s = time spent at the unloading site per route, h/route; and h = round trip haul time from end of typical route to unloading site and back to beginning of next route, h/route. In this method it is assumed that vehicles unload only when full. Thus, at the end of the working day vehicles with partial loads return to the parking facility. A route consists of the path through a neighborhood taken while loading a collection vehicle. The maximum allowable number of residences per route is

$$N_p = [(60 \text{ min/h})P_{scs}n]/t_p \tag{3}$$

where N_p = number of residences/route, residences/route; n = number of collectors riding on the vehicle, collectors; and t_p = collector-time per residence (a function of set-out rate and distribution, the number of collectors, the average number of containers set out, the equipment used, the distances between pick-up points, the set-out point, e.g., curbside or backyard, etc.), collector-min/residence. The volume of material set out at each residence can be estimated as

$$V_R = (MP_RC_p)/\text{SW} \tag{4}$$

where V_R = volume of waste collected at each residence during each collection period, volume/residence; M = waste set out per person per day, mass/person/d; P_R = persons per residence, persons/residence; C_p = time between collections; days; and SW = density of waste as set out, mass/volume. Therefore, the required volume of the collection vehicle is

$$R_v = (V_RN_p\text{SOR})/r \tag{5}$$

where R_v = required volume of vehicle, volume/route; SOR = setting-out rate as a fraction; and r = compaction ratio. The number of routes that must be driven during each collection period is

$$R_{cp} = \text{NOR}/N_p \tag{6}$$

where R_{cp} = number of routes that must be driven each collection period, routes; and NOR = the number of residences that must be served each collection period, residences.

Based on the parameters estimated using (2)–(6), vehicle and labor requirements can be estimated. The number of vehicles required is

$$\text{NOV} = R_{cp}/N_dC_p^W \tag{7}$$

where NOV = number of vehicles required to operate the collection program, unitless; and C_p^W = number of working days in each collection period, working days. The labor requirements are

$$\text{LR} = \frac{n[R_{cp}P_{scs} + R_{cp}^{\prime\uparrow}(s + h) + C_p^W(t_1 + t_2)]7 \text{ d/week}}{(1 - W)HC_p} \tag{8}$$

where LR = labor requirements, collector-days/week; and $R_{cp}^{\prime\uparrow}$ = the integer number of routes in a collection period, i.e., the smallest integer larger than R_{cp}, routes.

Eqs. (2)–(8) can be used to estimate the number of vehicles, the required vehicle volume, and the amount of labor required to collect materials on a given route. However, the equations require estimates of a number of parameters. Most of the parameters are dependent on the collection method used and/or the type of waste collected, or can be specified by the program operator. Only M, P_R, and t_p are expected to depend, at least in part, on route characteristics. Waste set out per day, M, can be determined from waste characterization study data; P_R values will be available from census data; t_p is difficult to measure.

The parameter t_p can be measured by observing the collection process; it is the total time required to collect materials on a given route divided by the number of houses on the route and the number of collectors. On a typical collection route, MSW is set out at each house each collection day. Thus, t_p for MSW collection is not affected by variance in set-out rate or the distribution of residences at which materials are set out.

Truitt et al. (1970) report t_p values for MSW collection as a function of the percentage of houses receiving rear-of-house (ROH) service for a two-person collection crew. Thus, t_p is assumed to depend on the collection method (the two-person crew) and neighborhood characteristics. The relationship between average t_p and ROH presented by Truitt et al. (1970) is linear, though the range of possible t_p values increases as ROH increases. The mean t_p values range from approximately 1 collector min to approximately 2.4 collector min, for 0 and 100% ROH, respectively.

For once-per-week curbside collection and one-person crews, Tchobanoglous (1993) reports t_p values of 0.50–0.60 and 0.92 collector-min/residence, when the average number of containers per location is 1 to 2 and 3 or more, respectively. Again, t_p depends on collection method (curbside once-per-week collection by one-person crews) and neighborhood characteristics (the average number of containers that are set out).

Unfortunately, t_p is not as easily estimated when the materials to be collected are compostables. While t_p is still expected to be a function of collection method and neighborhood characteristics, important neighborhood characteristics include set-out rate and distribution.

While the set-out rate is the fraction or percent of residences on a route at which materials are set out on a given collection day, the participation rate is the fraction or percent of residences on a given route at which materials are set out at least once in a given period. The average set-out rate is not the participation rate, it is the arithmetic mean of the set-out rates for a number collection days. The set-out rate describes participation on a single collection day; the participation rate describes participation over a longer period, often 4–8 weeks and is often 1.2 to 2 or more times higher than the set-out rate. It is important to note that a route or program with a high participation rate will not always have a high set-out rate.

Thus, a program with a high participation rate can have a low set-out rate.

The average set-out rate for compostable materials can vary greatly between community programs and between routes within a program. The set-out rate can also vary from collection to collection, even on a single route. Average set-out rates between programs may vary, for example, because of promotional factors. In a community where the collection program has received little publicity, many residents may not set out materials because they do not understand the benefits of participation or they are not sure how to participate. In a community with superior publicity more people may set out materials because they better understand the ''why and how'' of participation. Climatic factors may also be used to explain variation between communities. In areas where climate results in high yard waste generation, set-out rates may be high because many residents have significant amounts of yard waste requiring processing.

Economic factors can be used to explain variations between communities or routes within a community. For example, high-income families may tend to reside on large lots, and thus may produce large amounts of yard waste. This could result in higher set-out rates in areas with a high proportion of high-income families. Alternatively, high-income families may be more likely to pay for yard services, including yard waste hauling, which could result in lower set-out rates.

Unit pricing programs may also increase average set-out rates. When unit pricing is used, residents pay for the amount of MSW they set out for collection. Thus, they pay more for solid waste collection if they set out more MSW. This encourages residents to reduce the amount of MSW set out; this can be achieved through source reduction, recycling, and composting (Miranda et al. 1994). If curbside collection of compostables is available, unit pricing may result in higher average set-out rates of compostable material.

Even on a single route, the set-out rate can vary from collection to collection and/or seasonally. Some residents place materials out on every or almost every collection day; some rarely or never set out compostables, either because they have no yard waste, they compost or otherwise process their yard waste on-site, or they contract with a yard service that hauls the waste material away. These two groups contribute little to set-out variation. Others, however, participate occasionally or seasonally, only when they generate materials that they do not wish to process on-site or for which they have no contracted service. For example, some occasionally set out bush and tree trimmings. Others only set out leaves, thus participating in the fall. In many communities very little yard waste is generated in the winter. Programs that continue collecting materials do so with very low set-out rates. For this reason, many yard waste collection programs discontinue collection in the winter.

Finally, some occupants may generate material regularly, but at intervals that are longer then the collection period. For example, a resident may mow his or her lawn every 10 days. If collection is every 7 days the resident might set out grass for compostable collection on a somewhat irregular basis. The combined effect of all the above mentioned factors causes set-out rates to vary from collection to collection.

It is clear that set-out rates can vary for compostables curbside collection. For a given collection method and route, the average time spent per residence is expected to be a function of set-out rate and distribution. The lower the set-out rate, the lower the route time because (1) the truck spends less time stopped in front of residences as compostables are collected and loaded, and (2) the truck travels longer distances between stops and thus is able to maintain a higher speed. Because the number of residences served—i.e., provided the opportunity to have compostable materials collected—stays the same, t_p will be lower for lower set-out rates.

The distribution of material set-outs may also effect route time. Two hypothetical neighborhoods are shown in Fig. 1, identical in every way except set-out distribution. Black boxes represent houses at which compostable material has been set out; boxes with white interiors represent houses at which compostables have not been set out. In each neighborhood, the number of residences that have set out material is the same, thus the set-out rates are identical. In Fig. 1, each set-out rate is 50%. The set-out distribution of neighborhood A is uniform, i.e., the number of non–setting-out residences between each consecutive pair of setting-out residences is the same. Because the set-out rate is 50%, materials are set-out at every other house. The set-out distribution of neighborhood B is extremely nonuniform. In this case, all of the residences at which materials have been set-out are found in one contiguous group at the beginning of the route, called a ''clump'' of setting-out residences.

Collection vehicles are expected to attain higher speeds when traveling longer distances between stops, up to a maximum speed dependent on the speed limit, vehicle characteristics, and driving conditions. Thus, it is expected that vehicle average speed will be lowest in the clump of setting-out houses, highest in the clump of non–setting-out houses, and somewhere in between for neighborhood A. Depending on the actual velocities, the route time in neighborhood A can be higher, lower, or the same as the route time in neighborhood B. An example will suffice to demonstrate the potential effect of set-out distribution on route time.

The example is based on the neighborhoods shown in Fig. 1. The time spent collecting compostables—i.e., the time spent stopped in front of setting-out houses—is assumed to be the same for each neighborhood. Thus, any variation in route time is solely a function of variation in travel time, i.e., the time the vehicle is in motion as it covers the route. In order to calculate travel time it is necessary to know distance and velocity. The total route distance in each neighborhood is assumed to be 600 m (1,968 ft). The travel distance through the clump of setting-out houses in neighborhood B is assumed to be 300 m (984 ft). The average speed through neighborhood A is assumed to be 230 m/min (750 ft/min), while the average speed through the clump of non–setting-out houses in neighborhood B is assumed to be 300 m/min (984 ft/min).

The effect of varying the average speed through the clump of setting-out houses is shown in Fig. 2. The travel time in neighborhood A is indicated in Fig. 2 as a horizontal line at 2.6 min. If the speed through the clump of setting-out houses in neighborhood B is below 186 m/min (612 ft/min), the travel

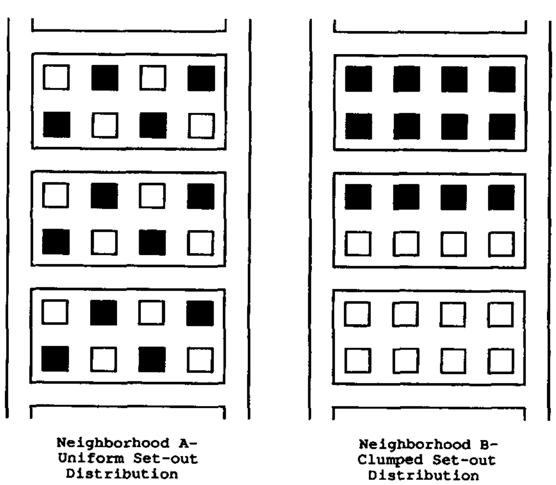

FIG. 1. Set-Out Distribution in Hypothetical Neighborhood: (a) Neighborhood A—Uniform Set-Out Distribution; (b) Neighborhood B—Clumped Set-Out Distribution

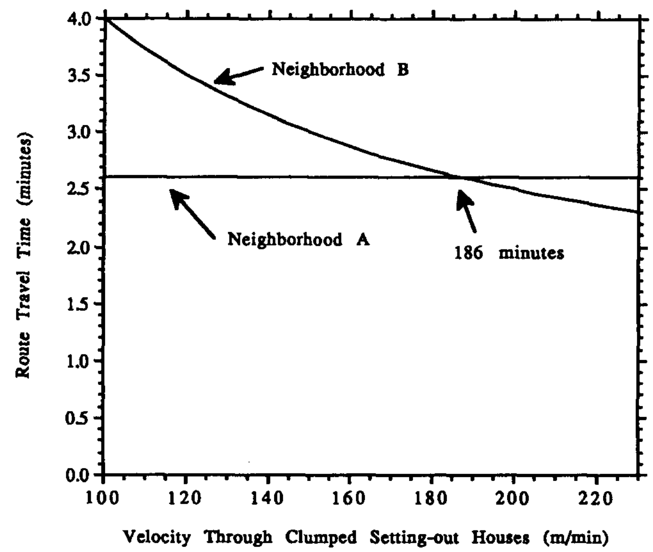

FIG. 2. Effect of Set-Out Distribution on Travel Time for Different Vehicle Velocities

time through neighborhood A is less than the travel time through neighborhood B. The reverse is true above 186 m/min (612 ft/min). This example demonstrates that travel time, and thus route time, can be a function of set-out distribution, and that the effect relative to a uniform distribution (i.e., lower or higher route time) will depend on vehicle average velocity under specific route conditions. Many other distributions of set-out distribution can be envisioned, each with a unique route time.

The parameter t_p can be measured for compostables collection for a given route and one set-out rate by observation of collection activities on a single collection route and collection day. However, it is very difficult to conduct controlled experiments, i.e., experiments in which set-out rates are preselected and varied under controlled, but not biased, conditions. Thus, the observer is constrained to the set-out rates that occur on the observed collection days. The observer is also constrained to measuring t_p for operating collection routes. Finally, it will be difficult, and often impossible, to observe different collection methods on the same collection route. Thus, a method that can be used to predict t_p for a given collection method under changing route characteristics—such as distance between houses, set-out rate, and set-out distribution—will be very useful to the solid waste researcher and engineer. Such a method can be used to

- Compare the efficiency of different collection methods for identical actual or hypothetical collection routes.
- Predict the effect of changing route characteristics, such as set-out rate or distribution, on route time.
- Estimate vehicle and labor requirements for new routes.

In subsequent sections a method for estimating t_p for the curbside collection of compostable material is presented.

COMPOSTABLES CURBSIDE COLLECTION MODEL

The model presented here can be used to determine t_p by simulating a collection vehicle traveling through a collection route. The required input information includes collection method characteristics; collection route characteristics; and the set-out rate, distribution and amount. The set-out amount describes how much material is set out. Collection method characteristics include relationships between travel time and travel distance, and collection time and amount of compostables loaded. Collection route characteristics include the distances between all adjacent potential stops, including residences, stop signs, and traffic lights, and the average time spent at stop signs and traffic lights. The time spent at stop signs and traffic lights is probably a function of both vehicle and route characteristics, but is considered here to be only a function of route characteristics. Left turns also represent potential stops, but are generally kept to a minimum on collection routes and are ignored here.

The model works by computing the distance from the current vehicle stop to the next stop point. A "stop" is considered to be any setting-out residence, stop sign, or traffic light. From this, the travel time between the two stops is computed based on the distance and characteristics of the collection vehicle. The next stop becomes the new current stop. The time spent at the new current stop is computed based on the amount of material set out (collection time) or, in the case of stop signs and traffic lights, the average wait time. A new stop point is identified and the process repeats itself. Travel, collection, and wait times are summed over the entire route. Unproductive time such as breaks or time spent writing instructions to residents failing to meet program requirements is not computed.

Fig. 3 is used to demonstrate conceptually how the collection of compostables is simulated in the model. A small portion of a collection route is shown in the figure. Large squares represent houses, while small darkened squares are set-out compostables. Time is spent collecting materials (CT_1 and CT_2), traveling between setting-out houses (TT_1 and TT_2), and waiting at a stop sign (W_{ss}).

The model requires equations to compute travel time between each pair of stops, collection time for compostable units at each setting-out residence, and wait times at stop signs and traffic lights. Field data were collected to develop these relationships for one route and collection method.

Data were gathered by observing the collection of compostables in a residential neighborhood in Norman. Alleys constitute less than 10% of the route and the area is flat. Compostable materials, grass, leaves, and brush with stems under 5 cm (2 in.) in diameter, are set out at the curb in bags, cans, or bundles (referred to as a units) once a week by residents. Tree branches and shrubs are tied in a bundle or placed in cans. Units are collected in 15.3 m^3 (20 cu yd) compaction vehicles by three-person crews, including a driver who rarely engages in loading activity. Materials are debagged as necessary during the manual loading process. Collection personnel operate under a work completion incentive system. If they complete their assigned task they are free to leave work.

Data were collected for one route over six collection days in March through August, 1993. Observations were made while riding in the collection vehicle. The data include: travel time between stops at residences; collection time at each residence; and total number of units collected (compostables in cans, bags, and bundles) at each setting-out residence. The distance from the beginning of the route to all residences, stop signs, and traffic lights was measured using a walking wheel and recorded to the nearest foot (1 ft ≈ 0.3 m). A summary

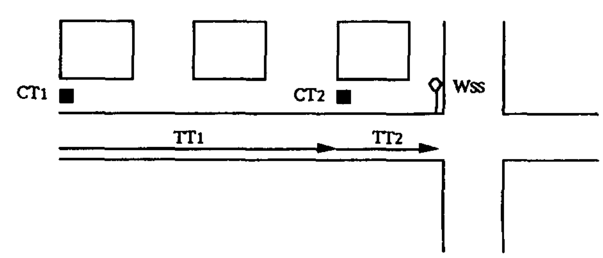

FIG. 3. Conceptual Model

of the route data collected over the six collection days is presented in Table 1.

Travel Equation

To estimate a travel equation, average velocities between setting-out residences, calculated by dividing each run's travel time by the run's interresidence distance, were plotted versus the distance between each setting-out residence (Fig. 4). A run is defined as traveling between two stops, for example two setting-out residences or a setting-out residence and a stop sign. Only runs that did not include stop signs or traffic lights were used. As expected, the raw data are scattered. The data are smoothed by taking the mean of nine adjacent average speed points (four on either side of the central data point). Because similar setting-out distances occurred repeatedly over collection routes, the smooth data represent an estimated mean average speed for a given travel distance.

It is reasonable to assume that the collection vehicle will attain a higher average speed on longer runs, but that as run length increases a maximum value will be approached. The relationship can be modeled as

$$v = L[1 - e^{-k(D)}] \tag{9}$$

where v = average speed over a run, km/h (mi/hr); L = maximum speed achieved by the collection vehicle, km/h (mi/hr); k = a coefficient, m^{-1} (ft^{-1}); and D = distance traveled, m (ft). The coefficient k determines how the average speed approaches the maximum speed with distance. The higher the value of k the closer v is to L for a given distance. The parameter L represents the maximum speed attainable by the vehicle, i.e., the average speed attainable between stops that are separated by an infinite distance. Values of L and k may vary for different vehicle types, driver ability, and road conditions.

Eq. (9) is of the same form as the biochemical oxygen demand (BOD) curve found in wastewater treatment literature, thus, techniques developed for estimating BOD curve parameters can also be used to calculate L and k. One of the simplest is the Thomas method (Vesilind and Peirce 1982). For the smoothed data shown in Fig. 4, the Thomas method estimates k and L as 0.003 m^{-1} and 17.1 km/h (0.01 ft^{-1} and 10.7 mi/hr), respectively. The coefficient of determination, R^2, is 0.74. The method is described in Appendix I.

The travel time equation for a single run, relating travel time to run distance, is

$$\mathrm{TT} = \frac{D}{10.7[1 - e^{-0.01(D)}]C} \tag{10}$$

where TT = travel time between two consecutive stops, s; and C = conversion factor, 1.467 for English units, 0.278 for Metric units. Eq. (10) will not accurately predict the travel time for a single run, or even a small number of runs. Examination of Fig. 4 indicates that the raw data deviate significantly from (9). However, over an entire collection route many runs are made. An accurate prediction of the total travel time over a route can be determined as

$$\mathrm{TTT} = \sum_{i=1}^{N} \left\{ \frac{D_i}{10.7[1 - e^{-0.01(D_i)}]C} \right\} \tag{11}$$

where TTT = total travel time over the route, seconds; N = the total number of runs over the route; and D_i = length of run i, m (ft).

Because the observed route contains some alleyways and turns, separate analyses were conducted to calculate k and L for runs on alley ways and runs with turns. The comparison of straight runs (runs between two consecutive participating residences not on alley ways and without turns) and runs on alleyways and runs with turns yielded comparable results. However, this may not be true for all routes.

TABLE 1. Route Data Collected Over Six Collection Days

Parameter (1)	Value (various units) (2)
Number of residences in neighborhood	268
Average distance between residences	26 m (85 ft)
Total Route Distance	6.9 km (4.3 mi)
Overall participation rate[a] (PR)	70%
Average set-out rate (SOR) over six runs	26%
Multiplier (PR/SOR)	3
Average number of units at setting-out residence	3.2
Average time to collect from setting-out residence	47.2
Average collector time per setting-out residence (three person crew)	141.6
Average time per unit collected	15.3
Average collector time per unit collected	45.9
Average time spent per route writing tags	5 min
Number of stop signs	16
Average time spent at stop sign	7.1
Number of traffic lights	7
Average time spent at traffic light	11.9

[a]Participation rate is defined as the percent of residences on the route at which compostable units were set out at least once during the six collection days.

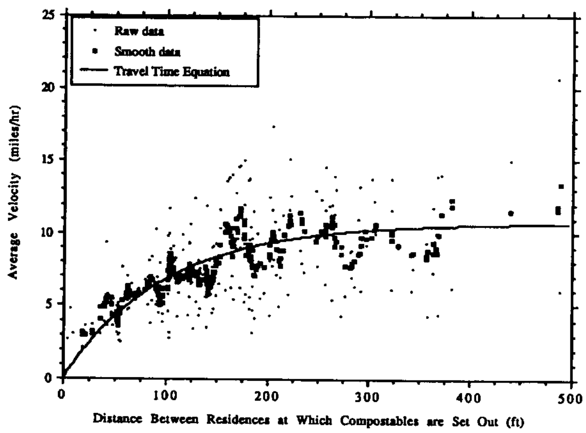

FIG. 4. Average Speed versus Interresidence Distance

There are other methods that can be used to relate TT to distance traveled. For example, it can be hypothesized that TT is linearly related to distance traveled. This can be modeled as

$$\mathrm{TT} = a + bD \tag{12}$$

where a and b = empirical constants. This method was used by Truitt et al. (1970) to relate average haul speed (i.e., average speed of the collection vehicle as it travels from the collection route to the unloading locations) to round-trip distance. The constant b represents the inverse of the maximum speed. If necessary, several equations with the same form as (12) can be used to predict TT, each applicable for a specific range of distances. The constant c is expected to be zero if the range of applicable D values includes zero, because TT should be zero if no distance is traveled. Alternatively, one can assign different constant values to TT for different ranges of distance.

In the research presented here, (9) was used to predict TT based on D. Eq. (9) was chosen because: it represented the data well; it can represent both vehicle maximum speed and acceleration capabilities; and its use automatically ensures that the predicted TT equals zero when D equals zero. Vehicle acceleration capabilities are especially important because run distances range from under 3 m to over 152 m. At these distances, truck acceleration may have a significant effect on average speed. Use of (12) does not allow the user to describe both vehicle acceleration and set TT to zero at D equal to zero, unless, as mentioned previously, multiple equations are used.

Collection Equation

The time required to load compostables into the vehicle and the number of units at each setting-out residence was measured by observation of the Norman route. Collection time includes time to pick up bags, cans, and bundles at the curb; open bags (debagging); load compostables into the vehicle; return cans to the curb; and start vehicle moving. Time spent issuing tag notices at residences where materials were set out incorrectly was not included. Break time was also not recorded.

The plot of collection time versus the number of units, for all six collection runs, is presented in Fig. 5. Small dots represent the raw data. As the plot indicates, a line can be fit to the means, represented by large dots. In a few instances more than nine units were set out as a given residence. However, such events were relatively rare and are not shown on the graph. The high R^2 value of 0.98 indicates a good fit. The best-fit line is

$$\mathrm{CT} = 9.23 + 11.6 \cdot (U) \tag{13}$$

where CT = collection time, s; and U = number of units collected. The intercept and slope values are dependent on collection method and materials collected.

Eq. (13) is not expected to predict accurately the time spent collecting materials at a single location. Inspection of Fig. 5 indicates that the equation poorly predicts individual collection events. However, the equation accurately predicts average times to collect a given number of units. Thus, it can be used to predict collection time for a large number of collection events, as is the case when predicting collection time over a collection route. Given the set-out rate and average number of

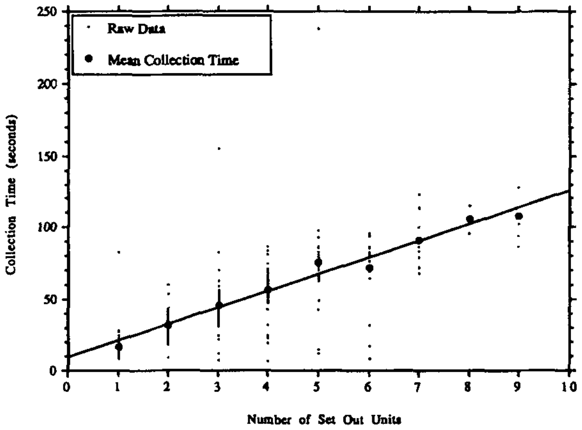

FIG. 5. Collection Time versus Number of Units Set Out

TABLE 2. Comparison of Predicted and Observed Route Time

Collection event (1)	Set-out rate (%) (2)	Predicted time (s) (3)	Observed time (s) (4)	Percent error (5)
1	26	5,245	5,092	3.0
2	25	5,033	4,832	4.1
3	28	5,641	5,437	3.7
4	23	4,523	4,312	4.8
5	30	5,812	5,636	3.1
6	25	5,354	5,192	3.2

units at setting-out residences, the estimated time required for collection over an entire route is

$$\mathrm{TCT} = \mathrm{SOR} \cdot \mathrm{NOR}[9.23 + 11.6 \cdot (AU)] \tag{14}$$

where TCT = total collection time over entire route, seconds; and AU = average number of units collected at setting-out residences. Eq. (14) is not expected to predict accurately collection times for programs using different collection methods or collecting different materials.

Stop Sign and Traffic Light Equation

The equation for computing wait time, i.e., time spent at stop signs and traffic lights is based on the means of wait times measured during one collection run. The measured means were 7.1 s at stop signs and 11.9 s at traffic lights. The equation for estimating total wait time is

$$\mathrm{TWT} = (M_{ss} \cdot N_{ss}) + (M_{tl} \cdot N_{tl}) \tag{15}$$

where TWT = total time at stop signs and traffic lights over the route, s; M_{ss} = mean time spent at stop sign, 7.1 s; N_{ss} = number of stop signs; M_{tl} = mean time spent at traffic lights, 11.9 s; and N_{tl} = number of traffic lights.

Verification

The model is capable of estimating route time, i.e., the sum of the total travel, collection, and wait times—using (11), (14), and (15)—for the collection of compostables from residential neighborhoods. The final equation is

$$\mathrm{RT} = \sum_{i=1}^{N} \left\{ \frac{D_i}{L[1 - e^{-k(D_i)}]C} \right\} + \mathrm{SOR} \cdot \mathrm{NOR}(a + bAU)$$
$$+ M_{ss} \cdot N_{ss} + M_{tl} \cdot N_{tl} \tag{16}$$

where RT = time to collect compostables on a route, s. The model is executed using a computer program written in FORTRAN and was used to estimate route time for the six observed collection runs based on the observed route characteristics, set-out amounts, and set-out distributions. Inputs to the computer model are the sequential order of residences, stop signs, and traffic lights for the route, along with the associated distance from the beginning of the route and the number of units at each setting-out residence. Observed and predicted times are reported in Table 2. Results differ by only 3.6% on an average. The largest error is only 4.8%. Thus, it appears that the model is able to estimate route time accurately.

The high accuracy of the model concerning the observed collection route does not mean that it can be applied directly to other collection methods or collection routes. Such application may require parameter reestimation for the total travel, collection, and wait time equations. The model may not be applicable to the same route for collection days other than the six observed. For example the weather, the driver, or the season might affect the required parameters. However, the model predicted accurate route times for the six observed collection days, which varied according to weather and driver. In addition, k and L values estimated using data from single collection days were very similar to the values estimated from the combined data from all six collection days.

Though not presented here, the model can be used to investigate the effect of varying collection method and route characteristics. Parameters that can be changed include interresidence distance, set-out rate, set-out distribution, and vehicle characteristics. Set-out distribution can be varied based on probability distributions to explore the range of possible route times for a given set-out rate on a given route.

CONCLUSIONS

Conclusions and recommendations for future research are as follows:

1. The literature review revealed no methods or models that could be used to estimate the time required to collect compostable materials.
2. A mathematical model was presented that can be used to estimate the time required to collect compostable materials by simulating a collection vehicle driving over its route. Travel, collection, and wait times are estimated separately in the model. Input to the model include collection method and route characteristics.
3. Data obtained by observing the collection of compostable material on a residential route in Norman, Okla. were used to determine parameters for travel, collection, and wait equations. The resulting model estimates of route times were within 4.8% of observed values.
4. In future research, the effect of varying collection method and route characteristics, such as interresidence distance, set-out rate, set-out rate distribution, and vehicle characteristics, should be examined. The robustness of the simulation model should also be investigated. For example, (16) should be used to estimate times for the observed collection routes on new collection days, i.e., route collection days not used in the determination of the model parameters. Finally, the equations should be applied to other routes that use the same collection method.
5. In future research, the equation parameters should be determined for other collection methods and materials, such as recyclables. A database of equation parameters should be developed for a universe of collection methods and route characteristics. This database can then be used in the design and comparison of collection programs for compostable or recyclable materials.

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APPENDIX I. ESTIMATION OF *k* AND *L* BY THOMAS METHOD

According to the Thomas method, (9) can be arranged as

$$(D/v)^{1/3} = (2.3kL)^{-1/3} + \frac{(k/2.3)^{2/3}}{3.43L^{1/3}} D \tag{17}$$

This equation is in the form of a straight line

$$x = a + bD \tag{18}$$

where $x = (D/v)^{1/3}$; $a = (kL)^{-1/3}$; and $b = (k/2.3)^{2/3}/3.43L^{1/3}$. Thus, plotting $(D/v)^{1/3}$ versus D, the slope b and intercept a can be obtained, and used to determine k and L using (19) and (20)

$$k = 6(b/a) \tag{19}$$

$$L = 1/ka^3 \tag{20}$$

APPENDIX II. REFERENCES

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APPENDIX III. NOTATION

The following symbols are used in this paper:

- a = empirical constant used in collection equation;
- AU = average number of units collected at setting-out residences;
- b = empirical constant used in collection equation;
- C = conversion factor, 1.467 for English units, 0.278 for metric units;
- Col Rate = collection rate, mass/h;
- CT = collection time, length;
- C_p = time between collections, days;
- C_p^W = number of working days in each collection period, working days;
- D = distance traveled, length;
- D_i = length of run i, length;
- e = 2.718281828;
- H = hours vehicle is in use, h/working day;
- h = round trip haul time from end of route to unloading site and back to next route, h/route;
- k = a coefficient, length^{-1};
- L = maximum speed achieved by collection vehicle, length/time;
- LR = labor requirements, collector-days/week;
- M = waste set out per person per day, mass/person/d;
- M_{ss} = mean time spent at stop sign, 7.1 s;
- M_{tl} = mean time spent at traffic lights, 11.9 s;
- N = total number of runs over route;
- n = number of collectors riding on vehicle, collectors;
- NOR = number of residences that must be served each collection period, residences;
- NOV = number of vehicles required to operate collection program, unitless;
- N_d = number of routes each vehicle can complete in a working day, routes/working day;
- N_p = number of residences/route, residences/route;
- N_{ss} = number of stop signs;
- N_{tl} = number of traffic lights;
- PR = participation rate as a fraction or percent;
- P_R = persons per residence, persons/residence;
- P_{scs} = time spent collecting materials from residences on each route, h/route;
- RD = route distance, length;
- RT = route time, s;
- R_{cp} = number of routes that must be completed each collection period, routes;
- $R_{cp}^{i\uparrow}$ = integer number of routes in a collection period, routes;
- R_v = required volume of vehicle, volume/route;

RT_{sep} = route time estimated by simple estimation procedure, s;
r = compaction ratio;
SOR = set-out rate as fraction or percent;
SW = density of waste as set out, mass/volume;
s = time spent at the unloading site per route, h/route;
T_c = collection time, h;
TCT = total collection time over entire route, s;
TT = travel time between two consecutive stops, s;
TTT = total travel time over the route, s;
TWT = total wait time, s;
t_p = collector-time per residence, collector-min/residence;
TTT_{sep} = total travel time estimated by simple estimation procedure, seconds;
t_1 = time spent at beginning of day driving vehicle from dispatch area to first residence, h/working day;
t_2 = time spent at end of day driving vehicle from last residence to dispatch point, h/working day;
V_R = volume of waste collected at each residence during each collection period, volume/residence;
v = average speed of collection vehicle, length/time;
U = number of units collected;
W = off-route time factor, fraction; and
Wt Col = collection vehicle net load, mass.