Curbside Collection of Recyclable Material: Simulation of Collection Activities and Estimation of Vehicle and Labor Needs

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ABSTRACT
This paper presents a mathematical model that can be used to estimate the time required to collect recyclable material (route time) by simulating the activities of a collection vehicle driving over its route. Data obtained by observing the collection of recyclable material in The Village, OK, were used to determine parameters for the model. The validity and robustness of the model were tested by comparing model-predicted route time to observed route time. The model was able to predict route time within 8%.

Simulation procedures are presented that can be used to estimate route time under conditions not actually observed—for instance, very low or high rates of material being set out for collection. The simulation procedures, incorporating randomly assigned set-out distributions, indicate that set-out distribution (proximity of houses setting out materials) has little effect on route time. Vehicle and labor needs for the curbside collection of recyclable material in a hypothetical town are estimated to demonstrate a practical application of the simulation procedure. The results indicate that if set-out rate were to increase from 20% to 40%, labor needs would increase by 34% and an additional vehicle would be needed to serve the same number of households. Increasing set-out rate from 20% to 40% would result in a labor requirement increase of 68%. Calculations such as these are particularly significant if a program to increase participation is being considered.

INTRODUCTION
Many communities have implemented, or are in the process of implementing, programs to divert solid waste from landfills and incinerators. Such programs may involve source reduction or reuse, or, more commonly, recycling or composting. In many cases, recycling and composting programs involve the collection of materials at the curb. According to a recent estimate, over 7,000 curbside collection recycling programs are currently operating in the United States.

Collection costs per ton of material can be high when recyclable or compostable material is collected from individual residences and transported to a central location for processing. Collection is often the largest cost component in a curbside collection recycling program, with costs ranging from $90 to $150 per ton. Therefore, it is important to identify and use efficient collection methods.

The goal of this paper is threefold: to present the route time estimation model; to estimate route time for the collection of recyclable material in a residential neighborhood over a range of set-out rates wider than actually observed; and to estimate vehicle and labor needs over this range. Set-out rate (SOR) is the fraction of residences on a collection route that set out material for collection on a given collection day. The simulation was accomplished using a model capable of estimating route time for the collection of recyclable material for a given collection method, collection route, and set-out rate and distribution. Route time—the time spent driving by residences and collecting material—is used to estimate vehicle and labor requirements. Collection route time can vary by collection method or route, or from collection route to collection route.

IMPLICATIONS
Results from this paper are expected to assist solid waste planners and engineers in the development, design, and evaluation of programs for curbside collection of recyclable material. A mathematical model is presented that can be used to estimate the time required to collect recyclable material by simulating the activities of a collection vehicle driving over its route. Route time can in turn be used to estimate vehicle and labor needs for any set-out rate. The model allows the user to predict the effect of changes in set-out rate on vehicle and labor needs.
day to collection day—for example, by set-out rate. Unfortunately, route time is not easily measured or estimated. Direct measurement requires observing collection activities, which is time consuming. Furthermore, values so obtained are valid only for the observed collection method, route, and set-out rate. Fortunately, route time can be estimated for any set-out rate using the route time estimation model presented in this paper.

A collection method must be specified for the route time estimation model because route time will vary for different methods. For example, the size of the collection crew or the degree of sorting will affect the time required to collect a given amount of material and, thus, will affect route time. The characteristics of the specific collection route, such as route length and number of residences, can also affect route time. The set-out rate affects route time because it directly affects the number of stops, the average distance traveled between stops (and, thus, the vehicle speed), and the time spent collecting and loading materials. Finally, the set-out distribution describes the location of residences at which material is set out. Set-out distribution can have an effect on route time; it affects the distance traveled between stops and, thus, vehicle speed.

The route time estimation model can be used for a number of purposes. In addition to estimating route time, the model can also be used to investigate the effect of collection method or route parameters on route time, identify set-out rates at which collection methods become inefficient, compare different collection methods on the same route, compare different routes for the same collection method, and estimate vehicle and labor needs at any set-out rate. In this paper, it is used to investigate the effect of set-out rate and distribution on route time and to estimate route time and vehicle and labor needs at any set-out rate.

ROUTE TIME ESTIMATION MODEL
The model presented in this section can be used to determine route time for a known collection route by simulating the activity of a collection vehicle traveling over a collection route. The information the model requires includes collection method characteristics, collection route characteristics, and the set-out rate and distribution. Collection method characteristics include stop-point selection rules, relationships between travel time and travel distance, and relationships between collection time and collection activity. Collection route characteristics include the distances to all 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 likely 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 requires rules or equations to compute stop point, travel time between each pair of stops, collection time, and wait times at stop signs and traffic lights. Field data were collected to develop these relationships for a single collection method.

Data Collection
The collection of recyclable material was observed in a residential neighborhood in The Village, OK. Residents place commingled recyclable material, including newspaper, aluminum, three colors of glass, tin cans, High-Density Polyethylene (HDPE), and Polyethylene Terephthalate (PET) in rigid plastic bins. The bins are placed at the curb for collection once per week. The material is sorted by a one-person collection crew and placed in one of nine compartments in a dedicated International recycling truck.

Data were collected by observing collection on eleven collection days. On six collection days, detailed observations were made of the collection process. The data collected included set-out rate and distribution, travel time between all stops, identification of all stop points, collection time and activity at each collection stop, and wait time at each stop sign (observed routes did not include traffic lights). The distance from the beginning of the route to all residences and stop signs was measured using a walking wheel and recorded to the nearest foot. Data were used to develop stop rules, travel time relationships, collection time relationships, and average wait times. On the remaining five collection days, only set-out rate and distribution and total route time were recorded. Data from these collection days were used to verify the model.

Conceptual Model Description
The route time estimation model works by simulating the activities of a collection vehicle as it is driven over a collection route. First, the model computes the distance from the beginning of the route to the first stop. From this, the travel time between the two locations is computed, based on the distance and travel equation for the given collection vehicle. The vehicle stops at residences with material, based on stopping rules developed from observation of route activities, stop signs, and traffic lights. The time spent at each stop is computed based on the collection activity performed 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 until the end of the route is reached.

A flow chart for the model is shown in Figure 1. Travel, collection, and wait times are totaled for the entire route. Unproductive time, such as breaks or time spent talking to residents, is not computed by the route time estimation
However, the vehicle and labor estimation method described in the next section incorporates unproductive time. In the next four sub-sections, methods for estimating stop point, travel time, collection time and wait time are presented. For a more detailed explanation, see Riley and Everett.

**Stop Point**
The rules used by the collection vehicle operator to select where the vehicle will stop to collect material may depend on many things, including set-out locations, material collected, crew preferences, crew size, and sorting requirements. The driver may stop the vehicle to collect material from one residence, then drive on to collect the next set-out. Alternatively, if set-outs are at adjacent residences, the collection crew may collect two or three set-outs during one stop. In cases such as this, the stop location of the truck is assumed to be midway between the first and last set-outs.

Based on observation of The Village routes, a number of multiple set-out collection rules were developed. For example, when two set-outs were located directly across the street from each other, the driver always stopped the collection vehicle midway between the two and collected both during one stop 71% of the time. Three set-outs were collected at one stop 78% of the time—when two set-outs were located next to each other with the third directly across the street from one of them. For all other situations, only one set-out was collected per stop.

The route time estimation model, as developed for the observed collection method, includes a code that is used to identify the set-out configuration. An additional code, including a random number generator, is used to determine whether the vehicle will stop to collect one, two, or three set-outs, depending on set-out location. Once the set-outs to be collected have been identified, the appropriate stop point is calculated as the mid-point between the first and last set-outs collected.

**Travel Equation**
To estimate the travel equation, average velocities between stops were plotted against the run distance for the one person collection method. These average velocities were calculated by dividing each run's travel time by the run's distance. A run is defined as traveling between two stops; for example, two setting-out residences or a setting-out residence and a stop sign. The raw data were scattered. Smoothed data were created by taking the mean of nine adjacent average speed points (four on either side and the central data point). Because similar setting-out distances occurred repeatedly over a collection route, smoothed 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, because proportionately less run length is devoted to acceleration and deceleration. As run length increases, a maximum average value is approached. The relationship can be modeled as

\[
\frac{\Delta T}{D} = \frac{D}{[1-e^{-kD}]C} \tag{1}
\]

where:
- \(\Delta T\) = travel time between two consecutive stops, sec;
- \(D\) = distance between two consecutive stops, m (ft);
- \(L\) = an empirical coefficient, Km/hr (miles/hr);
- \(k\) = an empirical coefficient, m\(^1\) (ft\(^1\)); and
- \(C\) = conversion factor, 1.467 for English units, 0.278 for Metric units.

The term in the denominator on the right side of eq 1 is an estimate of the average velocity attained on a run of length D. The coefficient \(k\) determines the rate at which
the average speed approaches the maximum average speed with distance. The higher the value of \( k \), the closer the denominator is to the product of \( L \) and \( C \) for a given distance. The variable \( L \) represents the maximum average speed attainable by the vehicle (i.e., the average speed attainable between stops that are separated by an infinite distance). \( L \) and \( k \) may vary for different vehicle types, driver ability, and road conditions. The parameters used in eq 1, \( k \) and \( L \), were estimated, using the Thomas method, as 0.002 m\(^{-1}\) and 19.8 km/hr (0.0066 ft\(^{-1}\) and 11.7 miles/hr), respectively.

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

\[
TT = a + bD
\]  

(2)

where \( a \) and \( b \) are empirical constants. This method was used by Truitt et al. to relate average haul speed (i.e., average speed of the collection vehicle as it travels from the collection route to the unloading location) to round-trip distance.\(^4\) The constant \( b \) represents the inverse of the maximum speed. If necessary, several equations with the same form as eq 2 can be used to predict \( TT \), each applicable for a specific range of distances. The constant \( a \) is expected to be zero if the range of applicable \( D \) values includes zero, because \( TT \) should be zero if no distance is traveled.

In the research presented here, eq 1 was used to predict \( TT \) based on \( D \) 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 for the observed route because run distances ranged from under 24 ft to over 2400 ft. At these distances, truck acceleration may have a significant effect on average speed. Use of eq 2 does not allow the user to describe both vehicle acceleration and set \( TT \) to zero when \( D \) equals zero, unless, as mentioned previously, multiple equations are used.

Eq 1 will not accurately predict the travel time for a single run, or even a small number of runs. However, over an entire collection route many runs are made. An accurate prediction of the total travel time over a route can be determined by totaling values of \( TT \) for an entire route. For a more detailed discussion of travel time estimation, see Riley and Everett, Everett, or Everett and Shahi.\(^5,6\)

**Collection Time**

The time required to sort and load recyclable material into the vehicle at each setting-out residence was measured by observing collection in The Village. Set-outs from one, two, and three residences were collected per vehicle stop, depending on the location of the set-outs, as described above. The set-outs from a single residence almost always consisted of a single recycling container, which contained variable amounts and types of material.

The raw data for each collection method were, as expected, scattered. The mean values for collecting one, two, and three set-outs at one stop were 53, 98, and 158 seconds, respectively. These values are not expected to accurately predict the time spent collecting material at a single location. They can, however, be used to predict collection time for a large number of collection events, as is the case when predicting collection time over a route.

**Stop Sign and Traffic Light Equation**

The equation for computing wait time (i.e., time spent at stop signs and traffic lights) involves multiplying average wait times by the number of stop signs or traffic lights on a given route. Because of the limited number of stops signs and traffic lights on most routes, wait time usually represents a minor component of route time. The average wait time observed at stop signs on the routes observed in The Village was 14 seconds. The route had four stop signs. This number includes only those stop signs that the driver obeyed by bringing the collection vehicle to a complete stop. The route had no traffic lights.

**Route Time Simulation without Specifying a Set-out Distribution**

In some cases, it is desirable to estimate route time for a given set-out rate without specifying a particular distribution. In this case, for each set-out rate the route time estimation model is run 500 times. At the beginning of each model run, houses are randomly assigned set-out status, enough to attain the appropriate set-out rate. The model is then used to estimate route time for the given set-out rate and specific set-out distribution. After 500 model runs at a given set-out rate, the minimum, maximum, and mean route time for that set-out rate are determined. Because set-out status was randomly assigned at the beginning of each model run, the distribution of set-outs was different each time, resulting in slightly different route times. The minimum and maximum values indicate the possible effect of set-out distribution on route time. In this case, the model flowchart given in Figure 1 must be modified slightly to include specification of SOR, multiple model runs at each SOR, random assignment of set-out status for each model run, and determination of minimum, maximum, and mean route times for each SOR.

**ESTIMATING VEHICLE AND LABOR REQUIREMENTS**

The vehicle and labor estimation process incorporates a number of variables and equations based on vehicle
activity. Given that the objective of an activity is to collect material from residences and deliver that material to a processing or disposal facility, the daily activities of a typical collection vehicle can be described as follows (see Figure 2). The vehicle is stored overnight in a parking facility. The first activity each day involves driving to the beginning of the first route. The vehicle is then driven through its first route, collecting material. When the first route is completed, the vehicle is driven to a processing facility (a material recovery facility or composting facility) and unloaded. The truck is then driven to the next route (if more than one route is completed per day). Similar activities are again repeated, until the truck has been again unloaded at the processing facility and driven back into the collection area. At this point, a third route can be completed, or the vehicle can be driven back to the parking facility.

Based on these activities, a number of formulas have been developed to estimate vehicle (number and volume) and labor needs, based on the time spent completing the daily activities. A method for estimating municipal solid waste (MSW) collection vehicle and labor requirements has been presented by Tchobanoglous et al. This method requires slight modification if it is to be used to estimate vehicle and labor requirements for collecting recyclable material: SOR must be incorporated in the method. The appropriate equations are presented in Figure 3.

Most of the variables described in Figure 3 have relatively constant values, or average values can also be used, whether recyclable material or MSW are collected. The values taken by these variables depend on the collection method used, the size of the community, the location of the processing facility, the type of waste collected, and the program operator (e.g., length of working day). The primary modification required when estimating collection vehicle and labor needs for recyclable material instead of MSW involves the variable $t_p$—the time expended per house during the collection portion of the daily activities. All else being equal, as SOR increases, $t_p$ will also increase because the collection vehicle will stop more frequently and collect more material, resulting in a higher route time and higher $t_p$. SOR is relatively constant for MSW collection; thus, $t_p$ is also relatively constant. However, SOR can vary significantly for recycling programs, resulting in $t_p$ variability.

The variable $t_p$ can be estimated as route time divided by the number of residences on the route. Thus, the route time estimation model can be used to estimate $t_p$ for any SOR.

**RESULTS AND DISCUSSION**

In this section, the results of the route time estimation model verification process are presented. The model is then used to estimate route time for a wide range of SORs. Finally, equipment and labor needs are estimated for a hypothetical community for a range of SORs.

**Verification**

The route time estimation model, executed in FORTRAN, is capable of estimating route time for the curbside collection of recyclable and compostable material for collection route. In other papers, the ability of the model to accurately estimate route time has been demonstrated by
Table 1. Comparison of observed vs. predicted route time.

(a) collection days used for parameter estimation and verification

<table>
<thead>
<tr>
<th>Collection day SOR</th>
<th>Predicted Time (seconds)</th>
<th>Adjusted Observed Route Time (seconds)</th>
<th>%Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>4520</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>5475</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>5233</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>5654</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>5173</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>5918</td>
<td>9</td>
</tr>
</tbody>
</table>

(b) collection days used for verification only

<table>
<thead>
<tr>
<th>Collection day SOR</th>
<th>Predicted Time (seconds)</th>
<th>Observed Route Time (seconds)</th>
<th>Unadjusted % Error</th>
<th>Adjusted % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>22</td>
<td>5166</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
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<td>5263</td>
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<td>3</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>4128</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>6018</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>36</td>
<td>7777</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: Adjusted observed route time is the observed route time minus unproductive time, which includes breaks, talking to residents, etc. Observed route time is reported for collection days 7–11, because collection activity throughout the route was not observed. Unadjusted and adjusted errors are reported for collection days 7–11. Unadjusted % error is the percent difference between the predicted route time and the observed route time. Adjusted % error is the difference between predicted time and observed time multiplied by 0.94. The 0.94 factor is used because unproductive time for collection days 1–6 averaged 8%. Comparing model results to observed route times (Everett and Shahi and Riley and Everett). For the collection method observed in The Village, the model was able to predict route time within 8%. Model results for a number of collection events are presented in Table 1. Model parameters were based on data obtained during collection days 1–6. The model performed well when used to predict route time on collection days 7–11, even for an SOR of 36%, higher than observed during the collection days used for model parameter estimation.

Adjusted observed and predicted route time for collection days 1–6 differ by 9% on average. On collection days 3 and 4, adjusted observed route times were 13% and 17% longer than the predicted time. On day 3, the driver was working after sustaining a back injury and was observed to work at a noticeably slower pace. On day 4, the driver distributed promotional information about the recycling program by placing a pamphlet in each recycling bin after emptying it. To do this the driver had to replace the bins carefully to make sure they would remain upright and the information would not blow away. This was slower than replacing the bins by sliding them along

the ground, or tossing them to the curb. Average error is only 5.6% for collection days 1–6 if days 3 and 4 are ignored.

Route Time Simulations

Route time was estimated over a wide range of set-out rates, a range wider than actually observed. The set-out rate on the observed collection days in The Village ranged from 19% to 36%. To estimate route time for all possible set-out rates on the route, as well as the effect of set-out distribution on route time, a simulation model was used to simulate collection of recyclable material for the collection method and route characteristics of the observed collection route, from 0% to 100% SOR, as described earlier.

The main determinants of route time are collection time and travel time, shown in Figures 4 and 5. Collection time (Figure 4) appears to be an approximately linear function of set-out rate. This is a result of the nearly linear relationship between collection time and the number of set-outs collected at a single stop. Research presented elsewhere indicates that multi-person crews use less time per set-out when multiple set-outs are collected, as compared to the collection of single set-outs, resulting in a non-linear relationship.41 Travel time versus set-out rate is shown in Figure 5. The relationship is non-linear because of the distribution of distances between houses, the stop point rules, and the travel time-run distance relationship.

A plot of high and low route time, versus set-out rate, is shown in Figure 6. From the plot it can be seen that set-out distribution has little effect on route time. The relationship of route time versus SOR shown in Figure 6 is approximately linear for several reasons. First, wait time is small and does not vary with SOR for a given

![Figure 4. Collection time vs. set-out rate.](image-url)
route. Second, collection time linearly increases with SOR for the collection method analyzed. Finally, travel time increases in a nearly linear manner with SOR. It is therefore unsurprising that the sum of these relationships (i.e., route time) also varies in a nearly linear manner with SOR.

The accuracy of the plots in Figures 4, 5, and 6, however, is not assured over the entire SOR range. It may not be reasonable to assume that the equations derived from collection days during which SOR ranged from 19% to 25% can be applied to SORs from 0% to 100%. For example, the maximum speed used by the model based on observation, is only 19.8 km/hr (12.2 miles/hr). The collection vehicle was observed to rarely reach the speed limit; perhaps the driver was continually looking ahead to the next setting-out residence, ready to stop. However, if SOR is routinely very low, the driver might expect to drive long distances between stops and might attempt to attain higher speeds. Alternatively, very high SORs might result in modification of collection procedures. For example, high set-out rates might cause the collection crew to work at a faster pace or modify the decision rules used to identify the stopping point and/or number of set-outs collected during each stop. However, the plots provided in Figures 4, 5, and 6 do provide an accurate prediction of route times at various SORs if the collection crew continues to behave as it did on the collection days observed.

The relationship between route time per number of set-outs collected and SOR is shown in Figure 7. While the time spent on the route increases as SOR increases, the time spent per set-out collected decreases. Interestingly, Everett and Shahi discovered that simulations of a yard waste compost collection program, somewhat different from the recyclable material collection program presented here, indicated that route time per yard waste unit collected increased dramatically at approximately 15% SOR. For example, if the set-out rate is 20%, about 74 seconds are spent per set-out collected. At 10% SOR, almost 1.3 times as much time is used—approximately 93 seconds. At low SOR, the program will become prohibitively expensive per unit diverted to recycling. This demonstrates how the model can be used to assess collection efficiency (measured as route time per set-out collected) as a function of SOR.

The shape of the plot shown in Figure 7 is the result of the requirement that the collection vehicle be driven over the entire route, no matter what the SOR. The collection vehicle must be driven past every house, to determine whether or not material has been set out for collection. As can be seen in Figure 6, it takes approximately 1500 seconds to drive through the route when SOR equals zero. Thus, for very low SOR, time is still expended driving by houses with no set-outs, resulting in a very high route time per set-out.

The monetary benefits achieved by operating a curbside collection recycling program are material diversion from disposal and revenue from sale to market. Costs are incurred for collecting recyclable

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Figure 5. Travel time vs. set-out rate.

Figure 6. Route time vs. set-out rate.

Figure 7. Route time per set-out vs. set-out rate.
material, processing it for sale to the market, and transporting it to market. All benefits and costs increase as more material is collected. It has been suggested here, however, that on a per-amount-collected basis, collection costs will decrease as more material is collected. On the same basis, processing and transportation costs are also expected to decrease, due to economies of scale. Similarly, benefits from revenue will at least remain stable, and will probably increase if there is a market. Buyers of processed recyclable material prefer dealing in large quantities.

Finally, benefits from diversion from disposal could decrease or remain stable, depending on ownership of the disposal option. For example, if a private landfill is used for disposal and a long-term contract is in place, the benefits of diversion will remain stable on a per-amount-collected basis. If the same entity owns the landfill and operates the recycling program, the benefits of diversion may decrease as more materials are collected because of fixed costs associated with landfilling. However, the above discussion indicates that unless the benefits of diversion decrease dramatically, net benefit will increase as more recyclable material is collected.

**Labor and Equipment Requirements**

Route time results from the simulation program were used to estimate $t_p$ and labor and truck requirements for a hypothetical community, using the equations presented in Figure 3. The results of the labor and equipment calculations are shown in Table 2. The simulation assumes that the hypothetical town consists of 10,000 residences on routes with characteristics similar to those of the route studied in The Village, OK. Typical values were used for variables such as hours per working day, off route time, travel to and from the processing facility, and unloading time. These are listed in the notes of Table 2. Collection vehicles were assumed to have sufficient volume and time to complete two routes per day.

The results of the simulation demonstrate how changes in set-out rate will change vehicle and labor requirements. The results also demonstrate the value of simulation modeling to program planners and decisionmakers responsible for collection routes for recyclable material. For example, the simulation indicates that if set-out rate were to increase from 20% to 30%, labor needs would increase by 34% and an additional vehicle would be needed to serve the same number of households. Increasing set-out rate from 20% to 40% would result in a labor requirement increase of 68%. Calculations such as these are particularly significant if a program to increase participation is being considered.

Figure 8 is used to demonstrate the relationship between equipment and labor needs and SOR, on a per set-out collected basis. A precipitous drop in labor needs is observed as SOR increases from 0% to 30%; a similar drop is observed for equipment needs (i.e., vehicles) as SOR increases from 0% to 10%. As also shown in Figure 7, this indicates the importance of avoiding low SORs. The vehicle curve is not smooth: a “jump” is observed at each point that an additional vehicle is required. This indicates that the vehicle, though required, is used inefficiently for specific SORs. As SOR increases, the size of the “jump” decreases because the collection fleet is larger and the addition of one additional vehicle has less effect.

**CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH**

A mathematical model was presented that can be used to estimate route time by simulating the activity of a collection vehicle driving over a collection route. The model separately estimates stop point and travel, collection, and

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**Table 2. Labor and vehicle requirements calculated for a hypothetical city of 10,000 residences.**

<table>
<thead>
<tr>
<th>SOR (%)</th>
<th>mean RT (minutes)</th>
<th>$t_p$ (minutes/residence)</th>
<th>$N_p$ (residences/route)</th>
<th>$R_{cp}$ (routes)</th>
<th>$R_{tp}$ (integer)</th>
<th>LR (collector-days/week)</th>
<th>NDVI (integer)</th>
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Note:

- $t_p$ = 8 hrs/working day; $W = 0.15; t_1 = 0.3$ hours; $t_2 = 0.3$ hours; $s = 0.2$ hours; $h = 0.25$ hours;
- $r = 2$ routes; $n = 1$ collector;
- $C_p = 7$ days/collection period; NOR = 10,000 residences; and $C_{tp} = 5$ working days/collection period.

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wait times. Inputs to the model include collection method parameters and route characteristics, based on observation of operating collection programs. The validity of the model has been tested for a commonly observed range of set-out rates by comparing model estimates to observed route times.

Results of simulations of route activity for the complete range of possible set-out rates indicate that set-out distribution has little effect on route time. Of the main components of route time—collection time and travel time—collection time is approximately linearly related to set-out rate, resulting in an approximately linear relationship between route time and set-out rate.

The simulation model was used to provide input to a series of equations that can be used to estimate labor and equipment needs for any set-out rate. The results of this analysis indicate that labor and equipment needs are sensitive to changes in set-out rate, even within the small range commonly observed.

In future research, the effect of varying collection method parameters and route characteristics, such as inter-residence distance, and vehicle characteristics should be examined, and the rules used for stop point determination varied. This would allow identification of those factors which most directly influence route time. Once such factors are identified, it may be possible to identify more cost efficient methods of collecting recyclable material from curbside. Relationships between resident characteristics and the volume and types of material they set out could be determined and used to estimate the volume of recyclable material that would be set out on a given route. This would allow estimation of required vehicle size. This information could also be used to size specific truck compartments for the different types of materials collected. Equation parameters can be determined for other collection methods. A database of equation parameters could be developed for a universe of collection methods and route characteristics. This database could then be used in the comparison and design of collection programs for compostable or recyclable materials. Finally, the simulation model could be used to determine program trade-offs by looking, for example at the effect of set-out rate on equipment and labor costs, revenues, fuel consumption, and pollution generation.

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REFERENCES

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Analysis of PM$_{10}$ Trends in the United States from 1988 through 1995

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ABSTRACT
Because the U. S. Environmental Protection Agency (EPA) has changed the National Ambient Air Quality Standards (NAAQS) for ambient particulate matter (PM), there is a great deal of interest in determining recent PM trends. This paper examines trends in PM$_{10}$ (i.e., particulate matter less than 10 micrometers in diameter) for areas of the United States based on their attainment status—PM$_{10}$ and ozone nonattainment and attainment areas. The analysis also focuses on urban, suburban, and rural areas, and eastern and western areas. The time period of evaluation is from 1988 through 1995. To shed further light on the ambient PM$_{10}$ trends, trends in ambient SO$_x$, NO$_x$, and volatile organic compounds (VOCs) are also analyzed. Finally, trends in emission inventories of SO$_x$, NO$_x$, VOCs, and PM$_{10}$ are evaluated. Results of the analysis show that widespread and similar reductions in PM$_{10}$ levels have occurred over the last seven years. Annual reductions range from 3.0% to 3.8%, with the greatest reductions coming in PM$_{10}$ nonattainment areas, but with very significant reductions also in PM$_{10}$ attainment areas, ozone attainment areas, and rural areas. The widespread reductions appear to be due to a set of controls or common factors that are having a fairly uniform effect in all of the areas. The consistency of the reductions in different areas suggests that the reductions may also be primarily in the fine particles (i.e., those less than 2.5 micrometers in diameter, or PM$_{2.5}$), which are more readily transported than coarse particles.

INTRODUCTION
The U.S. Environmental Protection Agency (EPA) recently adopted changes to the primary and secondary National Ambient Air Quality Standards (NAAQS) for particulate matter. EPA revised the current primary (health-based) PM standards by adding a new annual PM$_{2.5}$ standard of 15 $\mu$g/m$^3$, and a new 24-hour PM$_{2.5}$ standard of 65 $\mu$g/m$^3$. The annual PM$_{2.5}$ standard is met when the 3-year average of the annual arithmetic mean PM$_{2.5}$ concentrations—spatially averaged across designated air quality monitors in an area—is less than or equal to the standard. For the 24-hour PM$_{2.5}$ standard, the form is based on the 98th percentile of 24-hour PM$_{2.5}$ concentrations in a year (averaged over three years), based on the single population-oriented monitoring site with the highest measured values in an area. EPA further retained the current annual PM$_{10}$ 24-hour standard of 50$\mu$g/m$^3$, and changed the current form of the 24-hour PM$_{10}$ standard of 150 $\mu$g/m$^3$, replacing the 1-expected-exceedance form with a 99th percentile form, averaged over three years. The secondary standards are set to the primary standards in conjunction with a regional haze program.

EPA’s recent Air Quality Criteria Document for Particulate Matter included an analysis of PM$_{10}$ trends from its Aerometric Information Retrieval System (AIRS) database. EPA divided the U.S. into seven different geographical regions, and analyzed trends in PM$_{10}$ from 1988 to 1994. For the entire U.S., ambient PM$_{10}$ levels were 20% lower in 1994 than in 1988. The percent reduction from 1988 to 1994 for the various regions ranged from 17% in the Southeast to 33% in the Southwest. A summary of this information is shown in Table 1.

Also shown in Table 1 is EPA’s estimate of the average fraction of fine particles to PM$_{10}$ in the various regions.