Problem, research strategy, and findings: Reliable information on trash disposal is crucial but becomes difficult as waste removal chains grow increasingly complex. Lack of firm data on the spatial behavior of waste hampers effective recycling strategy design. In particular, the environmental impact of electronic and household hazardous waste is poorly understood. Our study investigates waste processing in an environmental, economic, and geographic context, using novel methods to track municipal solid waste in the city of Seattle (WA). We observed the movement of 2,000 discarded items using attached active GPS sensors, recording an unprecedented spatial dataset of waste trajectories. We both qualitatively identified facilities visited along each item’s trajectory, then statistical modeled characteristic transportation distance and the likelihood of ending up at a specific type of facility by product categories, place of disposal, and collection mechanism. We show that a) electronic and household hazardous waste items travel significantly longer and have more arbitrary trajectories than other types of waste and b) that existing models for waste emissions may underestimate the environmental impact of transportation by not accounting for very long trajectories.

Takeaway for practice: Transportation costs and emissions may diminish the value of recycling. Collection strategies deserve closer attention given the long distances over which they operate. Electronic tracking could provide data for evaluating waste management systems.

Keywords: waste management, environmental impact, pervasive sensing, recycling, transportation emissions

Measuring Tradeoffs in Waste Disposal and Recycling

Dietmar Offenhuber, David Lee, Malima I. Wolf, Santi Phithakkitnukoon, Assaf Biderman, and Carlo Ratti

The anthropologist Mary Douglas described dirt as “matter out of place” (Douglas, 1966). If we extend this metaphor to cities, the fundamental problem of urban waste management would be one of location. A complex set of social, legal, and physical constraints define which places are appropriate for trash, but these places are distinct and distant from the homes and businesses where trash is generated. Yet, as waste travels further from consumers, disposal practices become harder to scrutinize, confounding our ability to put trash “in its place” (Clapp, 2002). Until now, data on waste movement were not available; existing information is limited to the aggregated volumes processed at specific facilities. When we cannot reliably see where waste goes, how can we conclusively evaluate different waste policies?

Our study highlights a dilemma inherent in most recycling strategies: a tradeoff between distance and best treatment. How does transportation affect the overall environmental impact of different types of waste materials? Do these additional costs neutralize the potential benefits of recycling? Are waste materials from urban, suburban, and rural communities more or less likely to receive appropriate treatment?

The Trash Track project aimed to fill a substantive gap in our knowledge about waste removal systems. By electronically tracking the location of individual items from point of disposal, we could investigate how and to what extent waste distance depends on type of material, form of collection, and the area where discarded. Our results indicated that household hazardous and...
Background and Literature

Until the late 1970s, most cities operated their own landfills and removal distances were short. As cities grew, their perimeters moved outward and engulfed these local dumps, which were gradually shut down. The Resource Conservation and Recovery Act, in its amendment of 1984 (Resource Conservation and Recovery Act, 1984), imposed stricter regulations on the construction and management of landfills, which led to higher operating costs. As a result, there are fewer landfills today, most of which are privately owned and large, as economies of scale apply. They are typically located distant from densely populated areas because they benefit from a low land value, require special constructive measures, and are generally perceived as a nuisance by adjacent communities.

As waste transportation distances grow, complex environmental and sociopolitical issues emerge. The environmental costs of transportation, such as emissions, energy consumption, or the risk of accidents involving hazardous substances, offset the benefits of recycling. Long-distance waste transfer also raises questions of environmental justice on both the regional and international level. Historically, the location choice of waste facilities has followed the path of least resistance, often leading to underprivileged communities (Bullard, 2000). In the United States, the interstate transfer of waste remains a contested issue, with 8% of the nation’s municipal solid waste (MSW) disposed out of state (Abraham, 2000; Kinnaman & Fullerton, 2001). Finally, it has been suggested that increasing waste distance aggravates system opacity, and therefore promotes even more waste generation, as consumers’ awareness of the complex costs of production and disposal diminishes (Clapp, 2002).

The Uncertainty of Waste Distance

Poor transparency due to increasingly complex waste removal chains is also one of the central problems waste management currently faces. With increasing waste quantities, a substantial amount of waste goes unreported in national MSW totals, partly due to a lack of commonly shared definitions, a lack of clarity about the roles of federal and local governments, and a lack of even enforcement standards (Kreith & Tchobanoglous, 2002).

Currently, the available data would not be sufficient for calculating waste miles. While some states do collect some facility data concerning transportation,1 the U.S. Environmental Protection Agency (EPA) does not require tracking of nonhazardous municipal waste, and does not report any transportation-related statistics in its annual MSW reports.2 This is especially true for household hazardous wastes (HHW), that is, hazardous wastes generated in small quantities by households, including paint solvent, batteries, and CRT monitors. While HHWs are exempt from the definition of hazardous wastes on the federal level, regulations differ on the state level. As of 2010, California bans all batteries and other universal wastes from regular trash (California Departement of Toxic Substances Control, 2009), while Washington allows alkaline batteries in the MSW stream (State of Washington, 1994). For comparison, the European Waste Electrical and Electronic Equipment directive classifies electronic waste as a hazardous waste that is generally banned from household trash (European Parliament, the Council and the Commission, 2003).

While there are various collection mechanisms for solid waste and recyclables, no single strategy exists for HHWs, including electronic waste (Office of Solid Waste, 2008). Currently, different policies and collection mechanisms are discussed under the name of Extended Producer Responsibility (EPR), including mail-back or take-back programs operated by retailers, local collection at transfer stations, or special collection events (Atasu, Van Wassenhove, & Sarvary, 2009). However, their consequences for waste distance are not clear at this point. As can be seen in Table 1, these different mechanisms can be expected to have implications for transportation distance (Conn, Scott, Birch, Novak, & Forcella, 1989; Kang & Schoenung, 2005; Michaelis, 1995).
The Economic Costs of Waste Transportation

While transportation is only one of many economic factors shaping waste removal, its costs are significant. Studies estimate the total cost of transportation using a full garbage truck, including externalities such as pollution or road wear, to $5.33 per mile (Porter, 2002). The cost of disposal at a landfill depends on a number of different parameters, such as land value, capacity, construction and maintenance costs, and compensation to adjacent communities (Jenkins, Maguire, & Morgan, 2004). Most landfills have lower tipping fees for trash from local municipalities. Consequently, landfilling could be either the cheapest or the most expensive form of disposal; a review of operating costs of waste facilities reveals that among disposal methods, landfilling has the greatest cost variance, with a typical range of $10 to $120 per ton. Recent data from Washington State show a similar spread, with tipping fees ranging from $22 per ton up to $102 per ton in 2008–2009 (Washington State Department of Ecology, n.d.). It is reasonable to expect this range being large enough to motivate trips to a more remote facility.

The Uncertainty About the Environmental Cost of Waste Transportation

For evaluating the performance of recycling policies, it is crucial to understand the associated environmental costs of transportation. Transportation distance is only one of many contributing parameters besides the effects of end of life treatment or the potential of long-term hazards (Porter, 2002), and some literature suggests that transportation plays a minor role in the environmental impact of MSW and curbside recycling (Thorneloe, Weitz, Nishtala, Yarkosky, & Zannes, 2002). A comparative Life Cycle Assessment (LCA) by Morris (2005) found that the benefits of recycling in terms of energy conservation easily compensate for the losses generated by the collection and transportation, processing and remanufacturing of household recyclable materials. The Waste Reduction Model (WARM), developed by the U.S. EPA (2006) for estimating greenhouse gas emissions of waste systems, assumes truck transportation over a default 20-mile distance for the transportation of waste, which has generally little impact on the overall result. However, it has to be considered that the WARM model does not account for long-distance waste transport using multiple modes (Scharfenberg, Pederson, & Choate, 2004). In fact, an EPA study investigating the impact in variation of waste transportation energy considered only increasing the impact of transportation up to 400%, or the equivalent of increasing waste transportation distance to 80 miles (ICF International, 2004). Subsequently, the report was dismissive of the impacts of waste transportation. However, already preliminary findings of the Trash Track project have demonstrated that individual pieces of trash can travel across the United States (Boustani et al., 2010).

The impact of waste distance seems especially relevant in the context of recycling electronic waste, which
contributes 2% of the volume of the solid waste stream (Office of Solid Waste, 2008). Transportation is often the most costly step in the recycling process of electronic waste (e-waste) and can account for up to 80% of the total cost of its recycling process (Kang & Schoenung, 2005). However, choosing an appropriate mechanism for the collection of these devices can help to mitigate this issue. Waste transportation distances vary greatly depending on the collection strategy of recyclables (Lonn, Stuart, & Losada, 2002). The optimal transportation distance also depends on the recyclable material. In the example of milk containers, the traditional heavy glass containers have advantages for local reuse, but disadvantages when transportation distances grow. On the other hand, light recyclable plastic containers require a certain level of centralization (and, therefore, distance) in order to be recycled in an economically feasible way (Fairlie, 1992).

Methodologies for Tracking Waste

As data collected at the facility level are not sufficient to estimate overall waste distances, tracking the movement of individual waste items promises to fill this gap in the available data. Unfortunately, tracking garbage using pervasive sensing technologies is a challenging task: The physical conditions in the waste removal stream are hostile to the operation of electronic devices, and the sensors cannot practically be recovered once they enter the waste stream. For these reasons, very few examples of prior work related to garbage tracking using pervasive sensing technologies exist. Prior to our study, Lee and Thomas (2004) have conceptualized the possibility of waste tracking using active GPS location sensors. The authors proposed using radio transmitters to report back the locations acquired by a mobile GPS device and outlined potential applications, such as enforcing a hauler’s compliance or monitoring the movement of hazardous wastes in order to prevent environmental damage.

Supply chains are monitored mainly using radio frequency identification technology (RFID), a technology that could also be employed for monitoring the waste removal chain (Binder, Quirici, Domnitcheva, & Stäubli, 2008; Saar & Thomas, 2002). However, while RFID tags are much cheaper than active location sensors, they can only be detected at very short range and, therefore, require an expansive infrastructure of detectors that is currently not in place.

Research Questions and Methods

In order to evaluate the environmental impact and the geographical aspects of waste removal it is important to understand the relationship between the properties of the discarded objects and their end-of-life transportation distances, the collection mechanism, and the geography where the items have been discarded. Based on the uncertainties and gaps in the literature indicated above, this study aims to answer the following questions:

RQ1: What is the environmental cost of waste transportation associated with different collection mechanisms and waste materials?

RQ2: Are there geographic differences in terms of waste distance between urban, suburban, or rural settings?

RQ3: How do these environmental costs affect the overall benefits of recycling?

As presented above, the existing literature largely neglects waste distance as a factor in assessing environmental performance. At the same time, the existing data do not allow the reliable estimation of actually occurring waste distances. As explained earlier, waste distance depends on a variety of factors including material, collection mechanisms, as well as legal, geographic, and economic issues.

In the first question, we look at the relationship between material and waste distance in order to identify especially problematic materials. The collection mechanism is implicitly captured (and estimated through manual review of each recorded trace), as the waste removal system in Seattle provides multiple mechanisms for different types of waste. Recyclable materials such as glass, metal, and paper are collected from the curbside, excluding HHW and electronic waste items, such as computers, compact fluorescent light (CFL) bulbs, or televisions for which the city of Seattle suggests alternative collection through take-back programs or recycling centers (Seattle Public Utilities, 2010b). Based on this variety of collection options, one can expect to observe different transportation distances for different waste types.

The second question aims at differences in service quality between rural and urban settings. In a system that works as intended, we should not expect to find significant differences in this respect, although the size of our sample limits our ability to answer this question.

The third question is a crucial metric for the usefulness of any recycling program. According to the reviewed literature, the environmental impact of waste transportation should be expected to be negligible for most materials.

Data Sources

The data used to answer these questions were acquired through an experiment conducted in the area
around Seattle during October 2009. In the course of the Trash Track project, we used active GPS/GPRS (Global Positioning System/General Packet Radio Service) location sensors to record the trajectories of 2,000 waste items provided by volunteers. Each participating household was asked to prepare 15–20 different garbage items of different materials according to a prioritized list. After we visited these households and attached location sensors to the prepared items, we asked the volunteers to dispose of the items as they normally would. We avoided tagging items smaller than the tracking devices in order to preserve their original shape and prevent detection at material recovery facilities (MRFs), as well as organic waste to prevent contamination of compost. While the impact of 2,000 tags relative to the total volume of waste processed daily citywide is minuscule, a larger-scale deployment will require a separate assessment of negative environmental impacts, as it has been discussed with the example of RFID chips in MSW (Wäger, Eugster, Hilty, & Som, 2005).

The acquired dataset consists of location reports sent back from the deployed tracking devices, supplemented by additional information about the tracked waste item and its waste stream. A location report from a deployed tracking device included a device identification, the geographical coordinates, a timestamp and a sequential number of the report. To find the best compromise in the tradeoff between battery life of the sensors and the resolution of the acquired traces, approximately half of the tags were initially configured to report every six hours, with the rest configured to report every three or four hours. All incoming reports were compiled into a database and supplemented with descriptions of the item and its material composition, the time and location. Sensors that failed to produce useable traces as well as traces that indicate non-compliance, technical failure or tag removal were excluded from the data set.

In order to identify specific waste facilities from the recorded locations, we used data from the EPA’s (2009) Facility Registry System, a database of sites and facilities subject to environmental reviews. The results of a first automated matching process were subsequently verified and cleaned manually on a per trace basis. Additional data on waste streams, destinations, and collection mechanisms were drawn from the published contracts between the city of Seattle and various waste management companies (Seattle Public Utilities, 2010a). Finally, in order to estimate the value of tracked materials, we acquired commodity spot market prices for various recyclable materials as presented in Appendix Table A-3 (RecycleNet Corporation, 2010). See Figure 1.

### Methodology

We analyzed the collected data using both qualitative visual inspections on a trace-by-trace basis, network analysis, as well as a quantitative regression analysis. Operationalizing the first question, we estimated the impact of waste type and location on waste transportation distance using an ordinary least squares (OLS) regression model with categorical predictors, a popular regression method for finding a function that best fits a set of data by minimizing the sum of its squared errors. The regression model is specified as:

\[ Y = \beta_0 + \beta T + \gamma P + \epsilon, \]

where \( Y \) is the transportation distance, \( T \) is a vector of 36 waste types coded as dummy variables, \( P \) denotes a vector of 11 municipalities coded as dummy variables, and \( \epsilon \) represents the error term. Additional control variables are used to correct for internal properties of the tag, including configured reporting interval, the risk of tag removal, and the total number of reports received.

The unit of analysis is the trajectory of a single garbage item, constituted by the sequence of location reports containing time-stamped geographical coordinates that were received from the tracking device attached to the specific waste item. The dependent variables are transportation distance and duration. Geographical distance is approximated as the sum of the geodesic distances between the individual location reports in the sequence they were recorded. Duration is expressed as the time span starting with the item leaving the volunteers’ home until the last report received from the device. The independent variables are the waste type and the broader waste category of the discarded item. The 36 different waste types are based on the taxonomy used in EPA reports and further grouped into 10 broader categories (Appendix Tables A-1 and A-2). The place of disposal is coded as the municipality where the item was thrown away. Waste items were deployed in a total number of 11 cities in the greater metropolitan area of Seattle in order to allow for the comparison of waste removal service in different areas.

The odds of an item ending up at a specific kind of facility (a landfill, a recycling facility, or a facility for special disposal) are estimated using a multinomial logistic regression. The logit approach is preferable in our regression model because it allows the estimation of the likelihood of a specific outcome for a categorical dependent variable, as in our case the facility type of the final destination. The independent variables are the municipality where the item entered the waste stream and the waste category. The specification for the second question is:
where $C$ is a vector describing the broader waste category of the item, $P$ is a vector describing the municipality where the item entered the waste stream, and both vectors are coded as dummy variables. A comprehensive list of variables used in the analysis can be found in Table 2.

**Limitations of the Dataset**

Given the exploratory nature of the experiment and the novel approach used for tracking garbage, the validity of the results is subject to some limitations. Due to the physical conditions in the waste stream, the sensors rarely report the whole trajectory of a waste item to its final destination. Intermediate treatment of recyclables, such as crushing and shredding would most likely destroy the sensor, obscuring further movement. The possibility of separation of the tag from the tagged item must also be taken into account. Furthermore, a sensor might not report accurately, either because the signal is physically shielded or the item is located in an area with little or no network reception. A third concern about internal validity is the compliance and self-selection bias of the volunteers participating in the study. Since almost all participants were interested in environmental issues, a higher than average recycling rate was expected. Finally, based on the small sample size and the availability of trackable waste items, the sample is not perfectly random. Since our data further violate the OLS assumption of normally distributed errors, the estimation of the standard errors will not be considered in the analysis.

These known limitations were considered in the framing of the research questions and addressed during the analysis through a manual review of the traces, appropriate coding and the introduction of several control variables.

**Analysis and Findings**

A first visual analysis (Figures 2 and 3) of the dataset reveals that most traces remain within a 300-km radius around Seattle, with the landfills in north Oregon being a frequent destination. The location of the Allied Waste Recycling center in South Seattle emerges as a prominent feature, visited by a large number of traces. A small group of very long traces stands out, most of them associated with cell phones, printer cartridges, and batteries. Two printer cartridges sent their last report from the same location at the Mexican border, which they reached via very different routes: one through California along the route of Interstate 5, the other one in Chicago.

While the tracking devices were not able to send reports from overseas, a number of reports were received from British Columbia region. A significant number of items reported from harbor facilities in Seattle and ports en
route to the Pacific Ocean. Most traces allowed an estimation of transport modalities used, including airfreight (Figure 4). In many cases, the collection mechanism could be inferred from the trace, for example, curbside collection, if the item reported from an MRF; or a take-back program, if it reported from a large retail store. Although the collected GPS traces cannot be regarded as evidence, our data showed that a portion of the object we tracked ended up at a facility not traditionally intended for waste treatment.

**Destination Facilities and the Topology of the Removal Chain**

Once all facilities visited by a tracked item were identified, we were able to construct a network graph showing the interactions between facilities, companies, and waste streams (Figure 5). The tracked items reported from up to four individual facilities. The most frequently visited facility was the MRF operated by Allied Waste (Table 3).

**Descriptive Statistics**

The set of 1,152 valid traces reported an average length of 114 km with the longest trace, created by a printer cartridge, reporting a length of over 6,000 km (Table 4). Our sample contains a large number of very short traces, reflected in the low median values compared to the mean. In most cases, these very short traces represent partial traces, where the sensor was not able to report the whole trace, usually indicated when the endpoint is a random location en route. Therefore, the very long traces should not be disregarded as outliers, rather as traces that

| Variable category                | Name             | Type           | Description                                      |
|----------------------------------|------------------|----------------|-------------------------------------------------|
| Properties of the sensor         | ID               | Categorical    | Unique identifier of the trash tag              |
|                                  | Risk of tag removal | Binary        | Risk of tag removal                             |
|                                  | Rep. num          | Ordinal        | Number of received location reports from the tag |
|                                  | Rep. cycle        | Continuous     | Location reporting cycle                        |
|                                  | Tox. level         | Categorical    | Toxin level                                     |
| Material properties of tagged object | Trash type          | Categorical    | Trash type                                      |
|                                  | Trash category    | Categorical    | Trash category                                  |
|                                  | Trash name        | Categorical    | Short description of trash item                 |
|                                  | Trash disposal    | Categorical    | Appropriate waste stream                        |
|                                  | Spotmarket Value  | Continuous     | Value of recyclables per ton                    |
| Deployment location              | Start lon         | Continuous     | Longitude of disposal location                  |
|                                  | Start lat          | Continuous     | Latitude disposal location                      |
|                                  | Start place        | Categorical    | Municipality of disposal location               |
|                                  | Start ZIP          | Categorical    | Zip code of disposal location                   |
|                                  | Start state        | Categorical    | State of disposal location                      |
| Reported movement                | Duration in days   | Continuous     | Time elapsed since disposal (days)             |
|                                  | Distance in km     | Continuous     | Distance traveled from disposal location (kilometers) |
|                                  | Euclidean dist.    | Continuous     | Euclidean distance of waste movement (kilometers) |
|                                  | Km per day         | Continuous     | Speed of waste movement in kilometers/day       |
|                                  | Directness ratio   | Continuous     | Directness of waste movement (Euclidean distance/total distance) |
|                                  | Ln distance        | Continuous     | Natural logarithm of distance                   |
|                                  | End lon            | Continuous     | Longitude of end location                       |
|                                  | End lat            | Continuous     | Longitude of end location                       |
|                                  | End place          | Categorical    | Municipality of end location                    |
|                                  | End ZIP            | Categorical    | Zip code of end location                        |
|                                  | End state          | Categorical    | State of end location                           |
|                                  | Endfac. name       | Categorical    | Name of final waste facility reached by trash item |
|                                  | Endfac.            | Categorical    | Type of final waste facility reached by trash item |
|                                  | Facilities count   | Ordinal        | Number of waste facilities visited by trash item |
Figure 2. Screenshot of the developed visualization system showing the cleaned dataset, blue traces represent electronic waste, those in red household hazardous waste items.

(Color figure available online.)

Figure 3. Closeup on the Washington/Oregon area. The transfer-stations in Portland (OR) and the landfill, Columbia Ridge, in northeast Oregon are clearly visible. Some items traveled across the Puget Sound to Vancouver, Canada.

(Color figure available online.)
are more complete. To accommodate for these long traces, we use the mean values rather than the medians in our further analysis. Comparing different waste categories revealed that electronic and household hazardous waste generally produced the longest traces, whereas glass and metal items reported the shortest traces (Figure 6). HHW and electronic waste reported also the longest traces in terms of temporal duration (Figure 7).

A logarithmic scatter-plot of each individual item’s transportation distance reveals three characteristic clusters (Figure 8). The majority of traces remained within the city, sending their last report from recycling facilities in Seattle. A second, smaller cluster can be identified at a distance of approximately 300 km, corresponding to the distance to Seattle’s main landfills. The third cluster, finally, combines 21 traces longer than 1,500 km, all of them from the electronic and hazardous waste categories.

The distribution of waste distances can be also expressed in terms of the monetary value of the recovered recyclables. Interestingly, the longest traces are associated with materials that are either highly valuable or worthless. This result could be explained with the specialized treatment that is necessary for both potentially valuable materials such as electronic waste and materials that represent a liability such as hazardous wastes (Figure 9). This similarity in the behavior of valuable and expensive-to-treat materials is discussed further in the conclusion.

What is the environmental cost of waste transportation associated with different collection mechanisms and waste materials? Table 5 shows the results of the OLS estimation of geographical distance and temporal duration as dependent variables. While transportation distance varies across all trash types and locations, only five waste types reported statistically significant longer traces. All of them were from the electronic and hazardous waste category: alkaline and lithium batteries, cell phones, printer cartridges, and fluorescent light bulbs. The geographic location seems to have less influence on transportation
distance; only a single location reported significantly shorter transport distances ($p < .05$). The dummy variable controlling for the risk of tag removal is also significant, indicating that the sturdiness of the tag attachment was important for the outcome.

The second model uses the total duration reported by the sensors as the dependent variable. Compared to the first model, the results are slightly nuanced: as previously, electronic waste and hazardous waste items report the highest significant coefficients ($p < .001$), including CRT monitors, handheld electronic devices, and other types of electronic waste.

In this model, the geographic location has significant influence on the reported duration of waste removal. Two of the 11 municipalities reported significantly shorter values. The variable controlling for the sensor’s reporting
interval configuration is significant \( p < .01 \), indicating that battery failure was an issue: shorter reporting intervals led to an overall shorter duration reported from the sensors.

| Destination facility types | Freq. | %  | Top recycling facilities | Freq. | %  |
|-----------------------------|-------|----|--------------------------|-------|----|
| Landfill                    | 110   | 9.55 | Allied Waste Recycling Center & Transfer St. | 424   | 68.50 |
| Recycling                   | 619   | 53.73 | North Recycling and Disposal Station | 35    | 5.65 |
| Special                     | 97    | 8.42 | Cascade Recycling Center | 33    | 5.33 |
| Transfer                    | 11    | 0.95 | South Recycling and Disposal Station | 30    | 4.85 |
| Transit                     | 150   | 13.02 | Shoreline recycling and transfer station | 21    | 3.39 |
| Unknown                     | 165   | 14.32 | IMS Electronics Recycling Inc. | 16    | 2.58 |

| Total                        | 1,152 | 100 |

| Top waste facilities | Freq. | %  |
|----------------------|-------|----|
| Cedar Hills Regional Landfill | 34    | 28.10 |
| Columbia Ridge LF    | 31    | 25.62 |
| Finley Buttes Regional LF | 20    | 16.53 |
| Milton, WA Landfill  | 16    | 13.22 |
| WM Transfer Station across from SRDS | 9     | 7.44 |
| Roosevelt Regional Landfill | 5     | 4.13 |
| 304th Street Landfill (near Eatonville) | 4     | 3.31 |
| Bow Lake transfer station | 1     | 0.83 |
| Houghton Transfer Station and Recycling | 1     | 0.83 |

| Total | 121 | 100 |

Table 3. Frequencies of visits to identified facilities.

Table 4. Summary statistics.

| Variable                     | Observations | Mean | Median | Std. dev. | Min   | Max  |
|------------------------------|--------------|------|--------|-----------|-------|------|
| Duration in days             | 1152         | 7.79 | 2.01   | 14.66     | 0.06  | 100.07 |
| Distance in kilometers       | 1152         | 114.00 | 11.48 | 508.07    | 0.02  | 6151.71 |
| Euclidean distance in kilometers | 1152     | 91.10 | 9.28   | 409.63    | 0.02  | 4373.55 |
| Km per day                   | 1152         | 17.17 | 6.14   | 37.98     | 0.02  | 683.11 |
| Directness ratio             | 1152         | 0.84  | 0.96   | 0.24      | 0.004 | 1    |
| Start longitude              | 1152         | −122.311° | −122.323° | 0.069° | −122.408° | −121.995° |
| Start latitude               | 1152         | 47.635° | 47.639° | 0.132°   | 46.864° | 48.181° |
| End longitude                | 1152         | −121.665° | −121.331° | 4.625° | −123.598° | −75.388° |
| End latitude                 | 1152         | 47.208° | 47.578° | 1.603°   | 25.989° | 49.288° |
| Spotmarket value USD         | 1152         | 249.7 | 140    | 392       | 0     | 1900 |
| Risk of tag removal          | 1152         | 24.22% | | | |
| Facilities count             | 1151         | 1.21  | 1      | 0.45      | 1     | 4    |
| Reporting cycle in hours     | 1152         | 4.88  | 6      | 1.18      | 3     | 6    |
| Number of reports            | 1152         | 13.85 | 5      | 24.86     | 1     | 216 |

Are There Geographic Differences in Terms of Waste Distance Between Urban, Suburban, or Rural Settings? For answering the second question, a multinomial logistic regression was used to estimate the likelihood of a waste
Figure 6. Transportation distance and duration by waste type, household hazardous (orange) and universal waste items (red) highlighted.

(Color figure available online.)

Figure 7. Duration of the waste removal process by waste type.

(Color figure available online.)
item ending up at a specific facility type. Possible outcomes include landfills or facilities related to landfilling, recycling centers, special facilities such as a facility remanufacturing batteries or cell phones, or an unknown destination including final reports sent during transit. The waste category and municipality where the item was disposed were used as predictor variables coded as a set of dummy variables.

As could be expected from the exploratory analysis, certain waste categories had significantly higher odds for ending up at a recycling facility rather than at a landfill (Table 6). These materials include glass, metals, paper, and plastic items, confirming that materials collected through curbside recycling are treated differently compared to waste. Interestingly, HHW have higher odds for ending up either at a special facility or at a landfill compared to the reference outcome, the recycling facility; however, these coefficients are not significant. Electronic waste has higher odds for ending up at a special facility compared to a recycling facility.
Table 5. Regression results for Research Question 1.

| Variable            | (1) Distance (kilometers) | Standard error | (2) Duration (days) | Standard error |
|---------------------|----------------------------|----------------|---------------------|----------------|
| Alkaline battery    | 446.70***                  | −113.10        | 35.600***           | −2.856         |
| Aluminum            | −46.95                     | −88.53         | 1.468               | −2.355         |
| Book                | −28.17                     | −129.30        | 2.032               | −3.266         |
| Cardboard           | −18.22                     | −54.49         | −1.694              | −1.376         |
| Cell phone          | 842.40***                  | −97.11         | 38.480***           | −2.452         |
| Ceramics            | 20.13                      | −129.00        | −0.285              | −3.257         |
| Computer            | 14.65                      | −162.60        | 4.811               | −4.104         |
| Corrugated box      | −57.19                     | −88.01         | −1.721              | −2.222         |
| CRT                 | −42.34                     | −126.60        | 23.640***           | −3.196         |
| E-waste other       | 46.76                      | −71.96         | 16.520***           | −1.817         |
| Florecesnt bulb     | 301.80*                    | −137.10        | 35.650***           | −3.461         |
| Furniture           | 0.54                       | −230.50        | −1.102              | −5.819         |
| Glass bottle        | 10.68                      | −105.50        | −1.257              | −2.665         |
| Glass jar           | −30.55                     | −76.51         | −1.979              | −1.932         |
| Hazard other        | 41.67                      | −155.30        | 0.843               | −3.920         |
| Lithium battery     | 1242.20***                 | −136.10        | 19.060***           | −3.437         |
| Mixed waste         | 19.47                      | −77.84         | 3.006               | −1.965         |
| NiCd battery        | 1151.00***                 | −229.00        | 35.220***           | −5.782         |
| Paper waste other   | −8.95                      | −85.66         | −0.203              | −2.163         |
| PCP carton          | −67.95                     | −83.15         | −2.550              | −2.099         |
| PCP cup             | 3.57                       | −134.20        | −2.249              | −3.389         |
| PCP other           | −36.15                     | −114.10        | −1.638              | −2.882         |
| Periodical          | −28.38                     | −94.50         | −2.345              | −2.386         |
| Plastic bag         | −14.84                     | −83.78         | −2.717              | −2.115         |
| Plastic bottle      | −50.19                     | −54.57         | −1.323              | −1.378         |
| Plastic other (Base category) | na                      | na             | na                  | na             |
| Printer cartridge   | 1692.30***                 | −134.80        | 10.280**            | −3.404         |
| Rubber              | −38.01                     | −205.10        | −2.111              | −5.177         |
| Scrap metal         | −37.94                     | −71.62         | 1.904               | −1.808         |
| Shoes               | −26.74                     | −99.96         | 2.126               | −2.524         |
| Spray can           | 1.56                       | −165.10        | −1.957              | −4.167         |
| Steel can           | −51.83                     | −87.44         | −2.519              | −2.208         |
| Styrofoam           | −39.60                     | −97.62         | −1.665              | −2.465         |
| Textiles            | −9.43                      | −66.72         | 4.395**             | −1.685         |
| Tire                | 29.00                      | −227.60        | 14.510*             | −5.746         |
| Wood                | 60.24                      | −154.00        | −1.983              | −3.888         |

**Locations:**

| Location            | (1) Distance (kilometers) | Standard error | (2) Duration (days) | Standard error |
|---------------------|----------------------------|----------------|---------------------|----------------|
| Arlington           | 11.72                      | −133.60        | 3.182               | −3.373         |
| Eatonville          | 4.18                       | −107.40        | 1.218               | −2.711         |
| Graham-Thrift       | 1.95                       | −265.60        | 2.441               | −6.707         |
| Issaquah            | −133.40                    | −76.89         | −0.964              | −1.941         |
| Lake Forest Park    | −129.10*                   | −63.21         | −5.363***           | −1.596         |
| Mercer Island       | −213.20                    | −138.10        | −4.118              | −3.488         |
| Mountlake Terrace   | −59.00                     | −114.70        | −7.228*             | −2.896         |
| Newcastle           | −45.15                     | −146.60        | 3.643               | −3.702         |
| Redmond             | −92.39                     | −118.70        | −3.527              | −2.997         |
| Seattle (Base category) | na                       | na             | na                  | na             |
| Woodinville         | −42.97                     | −128.60        | −6.025              | −3.248         |

**Control variables:**

| Variable            | (1) Distance (kilometers) | Standard error | (2) Duration (days) | Standard error |
|---------------------|----------------------------|----------------|---------------------|----------------|
| Risk of tag removal | −92.36*                    | −38.98         | −0.974              | −0.984         |
| Reporting interval (h) | 3.05                     | −12.02         | 0.869**             | −0.303         |

Sample size 1152.00

R² 0.25
or a landfill, although also not on a statistically significant level.

Perhaps more striking is that the geographic setting seems to be relevant for whether an item ends up at a recycling center or a landfill. Based on the estimation, rural and suburban areas that are more distant from Seattle have higher odds of disposed items ending up at a landfill rather than a recycling center or special facility. Specifically, the surrounding municipalities of Woodinville, Eatonville, Lake Forest Park, Mercer Island, and Issaquah reported significantly higher odds of the landfill outcome.

How Do These Environmental Costs Affect the Overall Benefits of Recycling? We approximate the environmental cost of waste transportation through the emissions generated from energy consumption using a specific mode of transportation. Because of its chemical composition, 1 liter of diesel produces 2.68 kg of CO2 when burned in a combustion engine (U.S. EPA, n.d.). Since a fully loaded 22 U.S. ton garbage truck has an average fuel efficiency of 6 miles/gallon7 (Gaines, Vyas, & Anderson, 2006), it emits about 0.048 kg of CO2 equivalent per kilometer per U.S. ton.8

Table 7 shows the recorded waste distances and the corresponding greenhouse gas (GHG) emissions, assuming a typical 22-ton garbage truck with a fuel efficiency of 6 mpg used for transportation. For typical curbside recycling

| Landfill         | Odds ratio | Z score | Special facility | Odds ratio | Z score | Unknown destination | Odds ratio | Z score |
|------------------|------------|---------|------------------|------------|---------|---------------------|------------|---------|
| E-waste          | 0.42       | −1.24   | E-waste          | 1.99       | −1.27   | E-waste             | 0.51       | −1.45   |
| Glass            | 0.26*      | −2.10   | Glass            | 0.00       | −0.01   | Glass               | 0.09***    | −4.99   |
| Cell phone       | 0.41       | −0.94   | Cell phone       | 0.97       | −0.05   | Cell phone          | 0.46       | −1.34   |
| HHW              | 1.25       | −0.32   | HHW              | 1.90       | −1.08   | HHW                 | 0.33*      | −1.97   |
| Metal            | 0.23*      | −2.44   | Metal            | 0.14***    | −3.39   | Metal               | 0.10***    | −5.42   |
| Mixed            | 0.76       | −0.50   | Mixed            | 0.42       | −1.62   | Mixed               | 0.38*      | −2.40   |
| Paper            | 0.23**     | −2.65   | Paper            | 0.03***    | −4.87   | Paper               | 0.14***    | −5.07   |
| Plastic bottle   | 0.03***    | −3.96   | Plastic bottle   | 0.00       | −0.02   | Plastic bottle      | 0.09***    | −5.72   |
| Plastic coated P.| 0.15**     | −2.62   | Plastic coated P.| 0.00       | −0.01   | Plastic coated P.   | 0.11***    | −4.69   |
| Plastic other    | 0.26*      | −2.49   | Plastic other    | 0.04***    | −4.83   | Plastic other       | 0.16***    | −4.74   |
| Arlington        | 0.00       | −0.01   | Arlington        | 0.00       | −0.01   | Arlington           | 0.58       | −0.70   |
| Eatonville       | 8.88**     | −2.92   | Eatonville       | 5.06       | −1.35   | Eatonville          | 5.66**     | −2.83   |
| Graham Thrift    | 0.00       | 0.00    | Graham Thrift    | 3.42       | −0.72   | Graham Thrift       | 1.39       | −0.22   |
| Issaquah         | 4.03**     | −2.83   | Issaquah         | 1.60       | −0.65   | Issaquah            | 1.57       | −1.09   |
| Lake Forest P.   | 2.83**     | −2.62   | Lake Forest P.   | 0.75       | −0.42   | Lake Forest P.      | 0.98       | −0.07   |
| Mercer Island    | 5.45*      | −2.29   | Mercer Island    | 0.88       | −0.10   | Mercer Island       | 0.34       | −0.96   |
| Mountlake T.     | 0.00       | −0.01   | Mountlake T.     | 1.05       | −0.07   | Mountlake T.        | 0.11*      | −2.06   |
| Newcastle        | 2.78       | −1.17   | Newcastle        | 3.10       | −1.25   | Newcastle           | 0.44       | −0.73   |
| Redmond          | 0.00       | −0.01   | Redmond          | 0.00       | −0.01   | Redmond             | 1.40       | −0.60   |
| Woodinville      | 18.05***   | −3.70   | Woodinville      | 0.00       | 0.00    | Woodinville         | 1.65       | −0.58   |
| constants        | 0.49       | −1.46   | constants        | 0.80       | −0.49   | constants           | 2.88**     | −3.01   |

Observations: 1152
Akaike Information Criterion: 2356.4

Notes:
An odds ratio >1 indicates an increased probability for the specified outcome compared to the reference outcome (in this case, an item ending up in a recycling facility). For example, an odds ratio of 1.2 in the landfill column translates to a 20% higher probability of the specified waste type ending up at a landfill compared to recycling.

a. Odds ratio = \( \frac{p_2}{1 - p_2} \frac{p_1}{1 - p_1} \)
Odds ratio = 1 ➔ no effect
Odds ratio < 1 ➔ lower odds than reference
Odds ratio > 1 ➔ higher odds than reference
* \( p < .05 \) ** \( p < .01 \) *** \( p < .001 \)
materials such as plastic and metal, the GHG emissions generated through the transportation impact seem in fact rather insignificant. Glass, however, is a borderline case. According to the EPA WARM (Appendix Table A-4), the recycling of glass yields only a small amount of saved energy. The traces collected from tracked glass items have a maximum length of 488 km (Table 7). This distance would translate to 0.023 tons GHG generated per ton of material, which is substantial compared to the 0.076 tons of GHG saved in its recycling process.

The impact of transportation becomes more substantial for long traces. The longest trace reported by a printer cartridge would generate 0.3–0.8 metric tons of GHG emissions, depending on the mode of transportation. This amount is substantial enough to neutralize the expected benefit of recycling; according to WARM, the recycling of 1 ton of scrap computers yields a recycling benefit in terms of greenhouse gas reduction of 0.618 metric tons. While this is only a rough estimate based on the values provided by the EPA, it shows that long transportation distances...
involving multiple modes of transportation can in fact neutralize the environmental benefit of recycling. As these modes of transportation are not covered in EPA’s WARM model, these cases deserve further attention.

Conclusion

Our data indicate that, when it comes to curbside recycling and landfilling, the environmental impact of transportation distance seems to play a minor role, consistent with literature. Furthermore, the expected transportation distances do not significantly differ whether the item was discarded in an urban, suburban, or rural setting (although the setting seems to have some influence on the duration of the waste removal process). What stands out are the reported transportation distances of electronic and household hazardous wastes, which are significantly longer by orders of magnitude. This finding has a seemingly paradoxical implication:

1. Toxic Waste Items Are Associated With the Longest Transportation Distances

   This observation can be attributed to two different reasons, the collection mechanism and the geographic distribution of specialized treatment facilities. Seattle recommends electronic and household hazardous waste to be brought to transfer stations or back to retailers; the disposal through curbside recycling is banned (Seattle Public Utilities, 2009). As a result, these items have to be sent to highly specialized, and often remote, facilities where recycling or remanufacturing takes place. While centralized curbside collection of metal, paper, and glass is streamlined and efficient, the best collection mechanism for household hazardous and electronic wastes has not yet been found. Mail-back and take-back programs present similar advantages and drawbacks: They are convenient for consumers, but have the disadvantage of externalizing a part of waste removal to mail services not optimized for handling waste.

   Beyond the issue of shipping, the collection of electronics products and HHW collection requires additional consideration. Despite their longer travel distance, their treatment in specialized facilities captures toxic materials that would otherwise be released into the environment, providing a benefit beyond just energy savings. In the case of cell phones, computers, and print cartridges, refurbishing allows for energy savings that are much greater than that of recycling, possibly justifying the transportation impact. Therefore, the balance between end-of-life treatment and transportation impacts must be carefully scrutinized when making policy decisions regarding collection and take-back programs. Still, our data provide a cautionary tale:

2. Long Transportation Distances Involving Multiple Modes of Transportation Can Neutralize the Benefits of Recycling

   Especially in the case of the sometimes erratic trajectories of electronic and hazardous waste items, the environmental cost of transportation likely outweighs energy and emission savings of recycling these items. Since current models such as the EPA’s WARM do not account for long distances with mixed mode of transport, this is a significant finding that calls for future refinement of life cycle assessment models.

3. Whether a Recyclable Item Is Actually Recycled or Ends Up at a Landfill Also Depends on the Location Where It Was Thrown Away

   The collected data show that the quality of waste collection and processing shows geographic differences. Among the few municipalities included in the experiment, especially items discarded in the more rural areas had higher odds of ending at a landfill rather than in a recycling process. While the small sample size did not allow for the comparison of a large number of cities, this indicates an important area for future studies. In this respect, we have shown that the methodology employed in the Trash Track project can be successfully applied for comparing the quality of municipal collection and removal systems.

   In conclusion, the Trash Track study provides empirical data and a methodology for evaluating the efficiency of removal systems and waste stewardship models. The study provides previously unavailable data about long waste removal distances involving multiple modes of transportation. In combination with cost factors of waste disposal the data reflects the relationship between tipping fees, transportation costs, and commodity value of recyclable materials. The study also points out important directions for future inquiries into a proportionally small but steadily growing part of municipal solid waste: electronic waste, which can have high value, but also high toxicity; it is a material that is costly to recycle, but also offers much room for future recycling innovations.

Acknowledgments

Special thanks to Angela Wang, Eugene Lee, Dr. Rex Britter, and Jennifer Dunnam.
Notes
1. See http://www.ecy.wa.gov/programs/swfa/facilities/forms.html
2. See http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_
   Tables_and_Figures_508.pdf
3. Converted to 2009 dollars, counting both directions and assuming
   the truck has to drive back empty at the same cost.
4. Using Qualcomm inGeo technology. http://www.qualcomm.com/
   innovation/stories/ingeo.html
5. We developed a real-time visualization application that would allow
   the fast and interactive exploration of the data set.
6. Further examples of visualized traces can be found in the Appendix.
7. Converting to 2.55 km/l.
8. The U.S. EPA (2006) uses a more optimistic value of 0.04 kg
   CO2E/ton-mile in its WARM model.

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### Table A-1. Waste types, sorted by number of valid traces received.

| Trash type       | Frequency | Trash type       | Frequency |
|------------------|-----------|------------------|-----------|
| Plastic other    | 198       | Glass bottle     | 22        |
| Cardboard        | 109       | Alkaline battery | 18        |
| Plastic bottle   | 108       | PCP other        | 17        |
| Textiles         | 60        | CRT              | 14        |
| Scrap metal      | 52        | Book             | 13        |
| E-waste other    | 50        | Ceramics         | 13        |
| Glass jar        | 43        | Fluorescent bulb | 12        |
| Mixed            | 41        | Lithium battery  | 12        |
| PCP carton       | 35        | PCP cup          | 12        |
| Plastic bag      | 34        | Printer cartridge| 12        |
| Paper other      | 33        | Hazard other     | 9         |
| Corrugated box   | 31        | Wood             | 9         |
| Steel can        | 31        | Computer         | 8         |
| Aluminum         | 30        | Spray can        | 8         |
| Cell phone       | 27        | Rubber           | 5         |
| Periodical       | 27        | Furniture        | 4         |
| Styrofoam        | 24        | NiCd battery     | 4         |
| Shoes            | 23        | Tire             | 4         |

**Total** 1,152

### Table A-2. Waste categories and their contents, sorted by number of valid traces received.

| Trash category      | Frequency | Description                                                                                                           |
|---------------------|-----------|-----------------------------------------------------------------------------------------------------------------------|
| Plastic other       | 232       | polypropylene, polystyrene, PVC, and other non-PET, non-HDPE plastic products                                        |
| Paper               | 213       | plain paper, card, cardboard, corrugated cardboard, periodicals, books and other plain paper products                |
| Mixed               | 141       | all types of materials that are suggested for regular household waste disposal, either because there is no other recycling or collection mechanism, or because the product mixes several materials that are not separable using current strategies |
| Metal               | 113       | aluminum and steel cans and small scrap metal pieces                                                                   |
| Plastic bottle      | 108       | HDPE and PET plastic bottles                                                                                        |
| E-waste             | 84        | CRTs, peripherals, and accessories and other household electronics                                                    |
| Glass               | 65        | single material glass items, such as bottles, jars, and glass tableware                                               |
| Plastic-coated paper| 64        | milk cartons, coated paper cups, tetra paks, and other coated paper products                                          |
| Textiles            | 60        | clothing and textile home goods                                                                                      |
| HHW                 | 45        | both universal waste items, such as fluorescent bulbs and certain types of rechargeable batteries, and other waste items not suggested for regular household disposal including spray cans and some household cleaners |
| Cell phones         | 27        | only cell phones                                                                                                      |

**Total** 1,152
Table A-3. Spot market value of scrap materials.

| Trash type           | Trash disposal | Toxine level     | Spot value |
|----------------------|----------------|------------------|------------|
| Alkaline battery     | special disposal | universal waste | 40 $/ton   |
| Aluminum             | single stream recycling | inert | 1420 $/ton |
| Appliance             | special disposal | hhw              | 175 $/ton  |
| Book                 | single stream recycling | inert | 85 $/ton   |
| Candles              | waste           | inert            | <0 $/ton   |
| Cardboard            | single stream recycling | inert | 126 $/ton  |
| Cell phone           | special disposal | hhw              | 1900 $/ton |
| Ceramics             | waste           | inert            | <0 $/ton   |
| Corrugated BOX       | single stream recycling | inert | 126 $/ton  |
| CRT                  | special disposal | universal waste | 43 $/ton  |
| Computer             | special disposal | hhw              | 175 $/ton  |
| E-waste other        | special disposal | hhw              | 31 $/ton   |
| Fluorescent bulb     | special disposal | universal waste | <0 $/ton  |
| Furniture            | waste           | inert            | <0 $/ton   |
| Glass bottle         | single stream recycling | inert | 3 $/ton   |
| Glass jar            | single stream recycling | inert | 3 $/ton   |
| E-waste other        | single stream recycling | inert | 3 $/ton   |
| Handheld device      | special disposal | hhw              | 1500 $/ton |
| Hazard other         | special disposal | hhw              | <0 $/ton   |
| Incandescent bulb    | waste           | inert            | 3 $/ton   |
| Laptop               | special disposal | universal waste | 175 $/ton |
| Lithium battery      | special disposal | universal waste | 1300 $/ton|
| Mixed waste          | waste           | inert            | <0 $/ton   |
| NiCd battery         | special disposal | universal waste | 154 $/ton |
| Organic waste other  | compost         | inert            | 5 $/ton   |
| Paper waste other    | single stream recycling | inert | 61 $/ton  |
| PCP carton           | single stream recycling | inert | 49 $/ton  |
| PCP cup              | single stream recycling | inert | 102 $/ton |
| PCP other            | single stream recycling | inert | 49 $/ton  |
| Periodical           | single stream recycling | inert | 104 $/ton |
| Plastic bag          | single stream recycling | inert | 0 $/ton   |
| Plastic bottle       | single stream recycling | inert | 460 $/ton |
| Plastic other (Base category) | single stream recycling | inert | 140 $/ton |
| Printer cartridge    | special disposal | hhw              | 0 $/ton   |
| Rubber               | single stream recycling | inert | 5 $/ton   |
| Scrap metal          | single stream recycling | inert | 161 $/ton |
| Shoes                | waste           | inert            | 900 $/ton |
| Spray can            | special disposal | universal waste | <0 $/ton  |
| Steel can            | single stream recycling | inert | 161 $/ton |
| Styrofoam            | waste           | inert            | <0 $/ton   |
| Textiles             | waste           | inert            | 570 $/ton  |
| Tire                 | single stream recycling | inert | <0 $/ton  |
| Wood                 | waste           | inert            | 5 $/ton   |

Source: Based on data from Spotindex.com.
### Table A-4. Greenhouse gas emission factors used by the EPA WARM model, assuming average transportation distances.

| Material                          | GHG Emissions per ton of material source reduced (MTCE) | GHG Emissions per ton of material recycled (MTCE) | GHG Emissions per ton of material landfilled (MTCE) | GHG emissions per ton of material combusted (MTCE) | GHG emissions per ton of material composted (MTCE) |
|----------------------------------|-------------------------------------------------------|--------------------------------------------------|----------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Aluminum cans                    | -2.256                                                | -3.717                                           | 0.010                                              | 0.016                                             | NA                                                |
| Steel cans                       | -0.870                                                | -0.490                                           | 0.010                                              | -0.419                                            | NA                                                |
| Copper wire                      | -2.016                                                | -1.352                                           | 0.010                                              | 0.014                                             | NA                                                |
| Glass                            | -0.145                                                | -0.076                                           | 0.010                                              | 0.014                                             | NA                                                |
| HDPE                             | -0.493                                                | -0.383                                           | 0.010                                              | 0.284                                             | NA                                                |
| LDPE                             | -0.625                                                | -0.466                                           | 0.010                                              | 0.284                                             | NA                                                |
| PET                              | -0.577                                                | -0.423                                           | 0.010                                              | 0.311                                             | NA                                                |
| Corrugated cardboard             | -1.527                                                | -0.846                                           | 0.105                                              | -0.165                                            | NA                                                |
| Magazines/third-class mail       | -2.362                                                | -0.837                                           | -0.084                                             | -0.119                                            | NA                                                |
| Newspaper                        | -1.333                                                | -0.763                                           | -0.238                                             | -0.189                                            | NA                                                |
| Office paper                     | -2.183                                                | -0.778                                           | 0.505                                              | -0.159                                            | NA                                                |
| Phonebooks                       | -1.719                                                | -0.725                                           | -0.238                                             | -0.189                                            | NA                                                |
| Textbooks                        | -2.494                                                | -0.848                                           | 0.505                                              | -0.159                                            | NA                                                |
| Dimensional lumber               | -0.551                                                | -0.670                                           | -0.135                                             | -0.198                                            | NA                                                |
| Medium density fiberboard        | -0.607                                                | -0.674                                           | -0.135                                             | -0.198                                            | NA                                                |
| Food scraps                       | 0.000                                                 | NA                                               | 0.195                                              | -0.044                                            | -0.054                                            |
| Yard trimmings                   | 0.000                                                 | NA                                               | -0.050                                             | -0.055                                            | -0.054                                            |
| Grass                            | 0.000                                                 | NA                                               | 0.046                                              | -0.055                                            | -0.054                                            |
| Leaves                           | 0.000                                                 | NA                                               | -0.155                                             | -0.055                                            | -0.054                                            |
| Branches                         | 0.000                                                 | NA                                               | -0.135                                             | -0.055                                            | -0.054                                            |
| Mixed paper, broad               | NA                                                    | -0.956                                           | 0.087                                              | -0.166                                            | NA                                                |
| Mixed paper, resid.              | NA                                                    | -0.956                                           | 0.063                                              | -0.165                                            | NA                                                |
| Mixed paper, office              | NA                                                    | -0.932                                           | 0.117                                              | -0.151                                            | NA                                                |
| Mixed metals                     | NA                                                    | -1.475                                           | 0.010                                              | -0.286                                            | NA                                                |
| Mixed plastics                   | NA                                                    | -0.417                                           | 0.010                                              | 0.296                                             | NA                                                |
| Mixed recyclables                | NA                                                    | -0.784                                           | 0.048                                              | -0.145                                            | NA                                                |
| Mixed organics                   | NA                                                    | NA                                               | 0.071                                              | -0.050                                            | -0.054                                            |
| Mixed MSW                        | NA                                                    | NA                                               | 0.411                                              | -0.038                                            | NA                                                |
| Carpet                           | -1.096                                                | -1.969                                           | 0.010                                              | 0.128                                             | NA                                                |
| Personal computers               | -15.208                                               | -0.618                                           | 0.010                                              | -0.052                                            | NA                                                |
| Clay bricks                      | -0.078                                                | NA                                               | 0.010                                              | NA                                                | NA                                                |
| Concrete                         | NA                                                    | -0.002                                           | 0.010                                              | NA                                                | NA                                                |
| Fly ash                          | NA                                                    | -0.237                                           | 0.010                                              | NA                                                | NA                                                |
| Tires                            | -1.094                                                | -0.501                                           | 0.010                                              | 0.024                                             | NA                                                |

Source: U.S. Environmental Protection Agency (2006).
Figure A-1. Geographical structure of different waste streams: Most prominently, yellow trajectories lead to landfills, blue to recycling facilities, and light blue to special facilities.

(Color figure available online.)

Figure A-2. Colors represent the average velocity of trajectory segments; sections using airfreight can be made out.

(Color figure available online.)
Figure A-3. The trajectory of an assortment of small rechargeable batteries; colors represent the date of individual travel segments.

(Color figure available online.)

Figure A-4. Sensors reporting from waterways in the Puget Sound and Vancouver, Canada. Note that localization only works where cell phone infrastructure is available, therefore, very few sensors report from within the sound or ocean.

(Color figure available online.)
Figure A-5. The distribution of landfills and recycling facilities across the U.S. Note how densely populated areas have a higher density of recycling facilities (blue) compared to landfills (yellow).

(Color figure available online.)