Putting matter in place: tradeoffs between recycling and distance in planning for waste disposal

Citation: Offenhuber, Dietmar, David Lee, Malima I. Wolf, Santi Phithakkitnukoon, Assaf Biderman, and Carlo Ratti. “Putting Matter in Place.” Journal of the American Planning Association 78, no. 2 (April 2012): 173–196.

As Published: http://dx.doi.org/10.1080/01944363.2012.677120

Publisher: Taylor & Francis

Persistent URL: http://hdl.handle.net/1721.1/101625

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Putting matter in place: tradeoffs between recycling and distance in planning for waste disposal

Abstract

Problem, research strategy, and findings: As waste removal chains grow increasingly complex, obtaining reliable information on the movement of trash becomes crucial but difficult. Lack of empirical knowledge about the spatial behavior of waste hampers design of effective recycling strategies. In particular, the movement and environmental impact of electronic and household hazardous waste are poorly understood.

Our study investigates waste distances in an environmental, economic and geographic context, using novel methods to track municipal solid waste discarded in the city of Seattle. We observed the movement of 2000 discarded items using attached active GPS sensors, recording an unprecedented spatial dataset of waste trajectories. We qualitatively identified facilities visited along each item's trajectory, used regression analysis to model characteristic transportation distance, and multinomial logistic regression to model the likelihood of ending up at a specific type of facility. We compared across product categories, place of disposal, and collection mechanism. Our results show that electronic and household hazardous waste items travel significantly longer and more arbitrary trajectories than other types. We show how existing models for waste emissions, such as the Environmental Protection Agency's Waste Reduction Model, may underestimate the environmental impact of transportation by not accounting for very long trajectories that include multiple transport modalities.

Takeaway for practice: Planners must carefully scrutinize recycling strategies to minimize the environmental burden of waste movement, since transportation costs and emissions may significantly diminish the value of recycling. Collection strategies such as mail-back programs deserve closer attention due to the long distances over which they operate. We further demonstrated how electronic tracking could provide crucial, previously missing data for evaluating waste management systems.

Research support: Waste Management, Qualcomm, Sprint, and the New York Architectural League provided material support for this study.

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

This is a preprint of an article whose final and definitive form has been published in the Journal of the American Planning Association © 2012 APA; JAPA is available online at: http://www.informaworld.com/smpp/

About the authors:

Dietmar Offenhuber*
Research Fellow & PhD Student, Senseable City Lab
Dietmar@mit.edu

David Lee*
Research Fellow & PhD Student, Senseable City Lab
David733@mit.edu

Malima I. Wolf*
Postdoctoral Researcher and
Rocca Fellow, Politecnico di Milano
Research Affiliate, Senseable City Lab
miwolf@mit.edu

Santi Phithakkitnukoon**
Research Associate, Culture Lab
Research Affiliate, Senseable City Lab
santi@mit.edu

Assaf Biderman*
Associate Director, Senseable City Lab
abider@mit.edu

Carlo Ratti*
Director, Senseable City Lab
ratti@mit.edu

Mailing addresses:
*Senseable City Lab, MIT
77 Massachusetts Av. 10-400
02139 Cambridge, MA

**Newcastle University
Culture Lab, Space 2
King's Walk, Newcastle upon Tyne
NE1 7RU, United Kingdom

1. Introduction

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 was 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 do transportation affect the overall environmental impact of different types of waste materials? Do these additional costs neutralize the potential benefits of recycling? And 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 electronic waste travel significantly farther than other types, often by inappropriate means of transport, suggesting that the environmental costs of take-back programs should be re-examined. The study further demonstrates that long-distance, multimodal transportation of electronic waste can neutralize the overall benefit of recycling it. Where we live also affects how likely our waste ends up in recycling or landfill.

The objective of this paper is to investigate waste distances in an environmental, economic, and geographic context, based on empirical data describing the trajectories of individual garbage items discarded in the city of Seattle. Tracking waste opens up new possibilities both for officials, who must design waste management and land use policies around incomplete performance audits, and for city residents, who depend on services that operate beyond their influence and scrutiny. It also shows how inadequate our current knowledge is for making informed decisions about waste management and recycling strategies, particularly as we seek broader goals of addressing climate change and sustainability.

2. Background & 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 (*RCRA*, 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 US, 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, 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 EPA does not require tracking of non-hazardous municipal waste, and does not report any transportation-related statistics in their annual MSW reports.[2] This is especially true for household hazardous wastes (HHW) – hazardous wastes generated in small quantities by households, including paint solvent, batteries, or 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 WEEE Directive classifies electronic waste as a hazardous waste that is generally banned from household trash (European Parliament, the Council and the Commission, 2003).

---

[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

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. 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).

Table 1 Collection options for Electronic Waste (Kang & Schoenung, 2005).

Summary of collection options and transportation responsibilities

Collection options	Responsible for transportation		Advantages	Disadvantages
	To collection site	To recycling site		
Curb side	–	Local government or recycler	Convenient. Resident participation	Potential theft and abandonment. Need extra sorting. High transportation cost
Special drop-off event	Consumer	Local government or recycler	Increase recycling awareness. Good for rural area	Irregular collection amount. Need storage space
Permanent drop-off	Consumer	Local government or recycler	High sorting rate. Low transportation cost. Most cost-effective	Need regular checking. Not effective for all communities
Take-back	–	OEMs or recycler contract with OEMs	No collection site needed	High shipment cost. Need special packaging. Consumers visit shipping location
Point-of-purchase	Consumer	Retailer	Low cost. High visibility if promoted by retailer	Retailer commitment. Need storage space

OEM: original equipment manufacturer.

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 $5.3[3] 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

---

[3] Converted to 2009 Dollars, counting both directions and assuming the truck has to drive back empty at the same cost.

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 – 120/t (Table 2). Recent data from Washington State show a similar spread, with tipping fees ranging from $22/t to up to $102/t in 2008/09 (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.

Table 2 – Waste Facility Operation and Maintenance Costs as of 2002. Reproduced from (Kreith and Tchobanoglous 2002)

Typical Operation and Maintenance Costs for Composting Facilities, Combustion Facilities, and Landfills

System	Major system components	Cost basis	Cost*, dollars
Composting			
Low- end system	Source separated yard waste feedstock only; cleared, level ground with equipment to turn windrows	$/ton	20-40
high end system	Feedstock derived from processing of commingled wastes; enclosed building with concrete floors, MRF processing equipment, and in-vessel composting; enclosed building for curing compost product	$/ton	30-50
Waste to Energy			
mass burned, field erected	Integrated system of a receiving pit, furnace, boiler, energy recovery unit, and air discharge cleanup	$/ton	40-80
mass burned, modular	Integrated system of a receiving pit, furnace, boiler, energy recovery unit, and air discharge cleanup	$/ton	40-80
RDF production	Production of fluff and densified refuse-derived fuel (RDF from processed MSW)	$/ton	20-40
Landfilling			
Comingled Waste	Disposal of commingled waste in a modern landfill with double liner and gas recovery system	$/ton	10-120
Monofill	Disposal of commingled waste in a modern landfill with double liner and gas recovery system, if required	$/ton	10-80

All cost data have been adjusted to as Engineering News Record Construction Cost index of 6500

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 found that the benefits of recycling in terms of energy conservation easily compensate for the losses generated by the collection and transportation, processing and re-manufacturing of household recyclable materials (Morris, 2005). The Waste Reduction Model (WARM) developed by the Environmental Protection Agency (EPA) 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 (U.S. Environmental Protection Agency, 2006). 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, 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, 2011).

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 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 is 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 & Thomas have conceptualized the possibility of waste tracking using active GPS location sensors (Lee & V. M. Thomas, 2004). 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 & V. 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.

3. 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:

1. What is the environmental cost of waste transportation associated with different collection mechanisms and waste materials?
2. Are there geographic differences in terms of waste distance between urban, suburban or rural settings?
3. 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 does 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 TVs for which the city of Seattle suggests alternative collection through take-back programs or recycling centers (Seattle Public Utilities, 2010a). 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, it should not expected 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 was 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[4] to record the trajectories of 2000 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 2000 tags relative to the total volume of waste processed daily citywide is miniscule, 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 ID, 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

---

[4] Using Qualcomm inGeo technology. http://www.qualcomm.com/innovation/stories/ingeo.html

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 EPA's Facility Registry System, a database of sites and facilities subject to environmental reviews (U.S. Environmental Protection Agency, 2009). 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, 2010b). Finally, in order to estimate the value of tracked materials, we acquired commodity spot market prices for various recyclable materials as presented in Table 10 (RecycleNet Corporation, 2010).

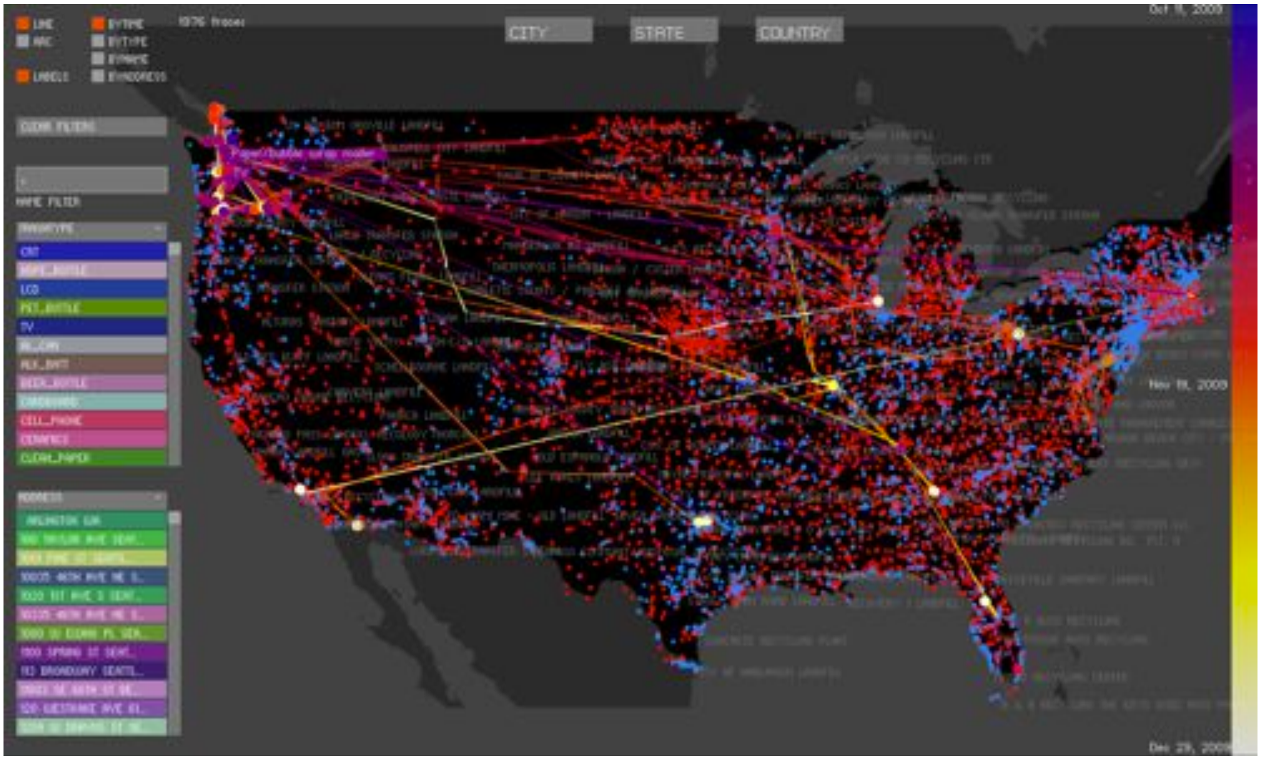

Figure 1 The collected traces overlaid with the locations of waste processing facilities from the EPA FRS database. Landfills are drawn in red, recycling facilities in blue.

Methodology

We analyzed the collected data using both qualitative visual inspection 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:

$$Y = \beta_0 + \beta\mathbf{T} + \gamma\mathbf{P} + \varepsilon,$$

where Y is the transportation distance, **T** is a vector of 36 waste types coded as dummy variables, **P** denotes a vector of eleven municipalities coded as dummy variables, and ε representing 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 (Table 9a and 9b). The place of disposal is coded as the municipality where the item was thrown away. Waste items were deployed in a total number of eleven 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 – is 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:

$$\mathrm{logit}(p_i) = \beta_0 + \beta\mathbf{C} + \gamma\mathbf{P} + \varepsilon,$$

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 3.

Table 3 List of variables used

Variable Category	Name	Type	Description
Properties of the sensor			
	id	Categorical	Unique ID of 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 (km)
	Euclidean dist.	Continuous	Euclidean distance of waste movement (km)

Km per day	Continuous	Speed of waste movement in km/day
Directness ratio	Continuous	Directness of waste movement (euclidDist/distanceKm)
Ln distance	Continuous	Natural log 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

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.

4. Analysis and Findings

A first visual analysis[5] of the dataset reveals that most traces remain within a 300km 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 via in Chicago. While the tracking devices were not able to send reports from overseas, a number 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[6]. Most traces allow an estimation of transport modalities used, including airfreight (Figure 4). In many cases, also the collection mechanism could be inferred from the trace, for example curbside collection, if the item reported from a 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 have ended up at a facility that not traditionally intended for waste treatment.

---

[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.

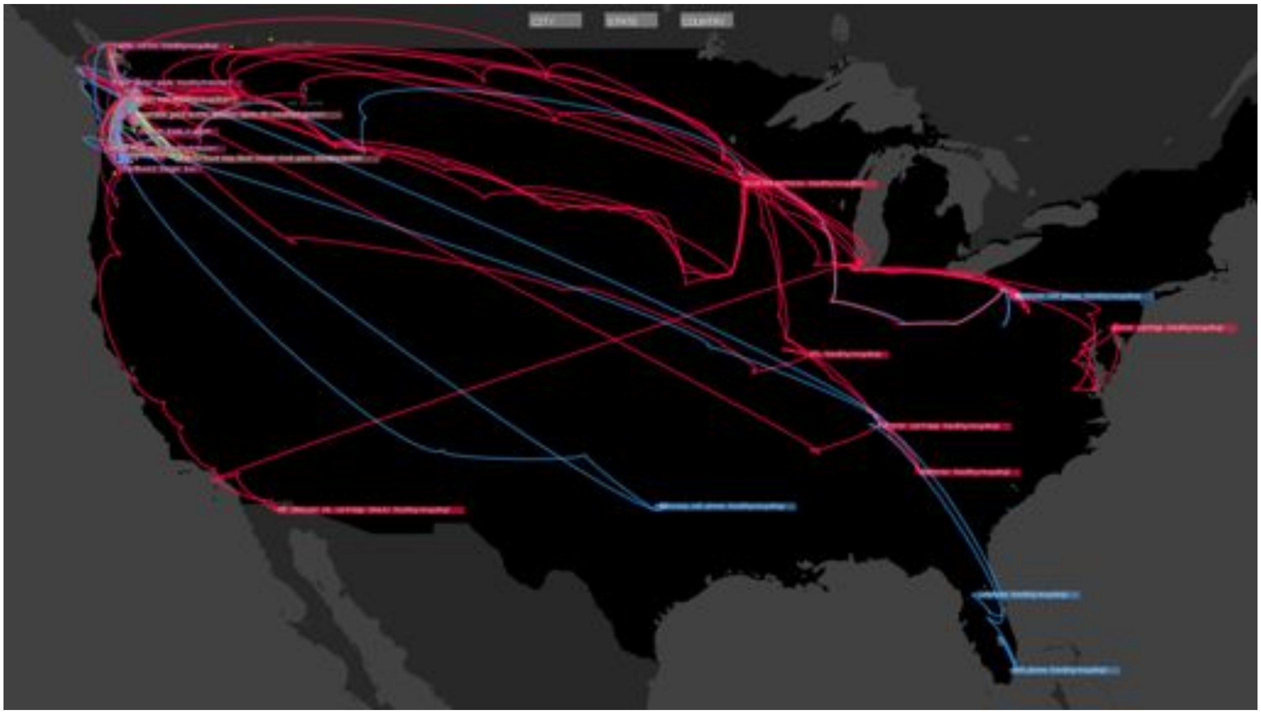

Figure 2 Screenshot of the developed visualization system showing the cleaned dataset, blue traces represent Electronic Waste, those in red Household Hazardous Waste items.

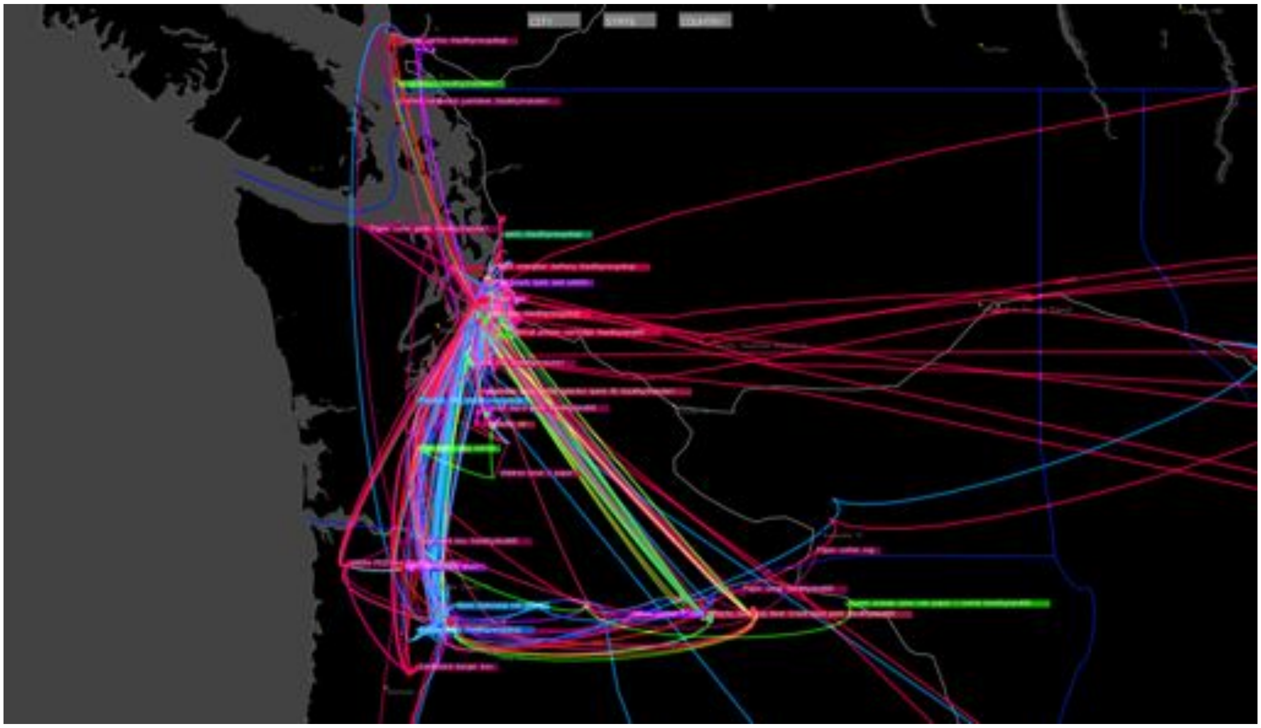

Figure 3 Closeup on the Washington / Oregon area. The transfer-stations in Portland, OR and the landfill "Columbia Ridge" in northeast Oregon are clearly visible. Some items traveled across the Puget Sound to Vancouver, Canada.

Figure 4 a Printer Cartridge at the Seattle-Tacoma International Airport.

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 4). The tracked items reported from up to four individual facilities. The most frequently visited facility was the Material Recovery Facility operated by Allied Waste (Table 4).

Figure 4 representation of the facility network based on facilities visited by the tracked items.

Table 4 Frequencies of visits to identified facilities

Destination Facility Types	Freq.	Percent
Landfill	110	9.55
Recycling	619	53.73
Special	97	8.42
Transfer	11	0.95

Top Recycling Facilities	Freq.	Percent
Allied Waste Recycling Center & Transfer St.	424	68.5
North Recycling and Disposal Station	35	5.65
Cascade Recycling Center	33	5.33
South Recycling and Disposal Station	30	4.85

Transit	150	13.02
Unknown	165	14.32
Total	1,152	100

Top Waste Facilities	**Freq.**	**Percent**
Cedar Hills Regional Landfill	34	28.1
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

Shoreline recycling and transfer station	21	3.39
IMS Electronics Recycling Inc	16	2.58
Seattle Iron & Metals Corporation	12	1.94
Smurfit-Stone Recycling Co	10	1.62
SP RECYCLING CORP TACOMA	9	1.45
Eastmont Transfer and Recycle Station	7	1.13
Seadrunar Recycling	5	0.81
SP Newsprint Depot	5	0.81
E-Cycle Environmental	3	0.48
Newberg Garbage & Recycling	2	0.32
Mercer Island Recycling Center	1	0.16
Pacific Disposal Recycling	1	0.16
Rabanco Eastside Disposal and Recycling	1	0.16
Savers Recycling Distribution Center	1	0.16
Wastech in Portland (plastics)	1	0.16
West Seattle Recycling Inc	1	0.16
WM Recycle America Kirkland	1	0.16
Total	619	100

Descriptive Statistics

The set of 1152 valid traces reported an average length of 114 km with the longest trace, created by a printer cartridge, reporting a length of over 6000 kilometers (Table 5). 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 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 5). HHW and electronic waste reported also the longest traces in terms of temporal duration (Figure 6).

Table 5 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 km	1152	114	11.48	508.07	0.02	6151.71
Euclidean dist. in km	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 lon	1152	-122.311'	-122.323’	0.069'	-122.408'	-121.995'

Start lat	1152	47.635'	47.639’	0.132'	46.864'	48.181'
End lon	1152	-121.665'	-122.331’	4.625'	-123.598'	-75.388'
End lat	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 hrs	1152	4.88	6	1.18	3	6
Number of reports	1152	13.85	5	24.86	1	216

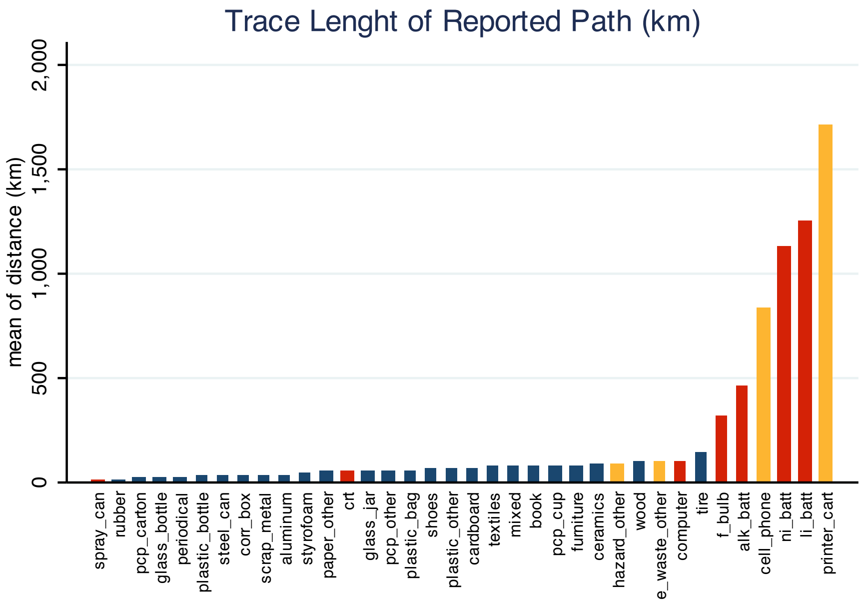

Figure 5 Transportation distance and duration by waste type, household hazardous (orange) and universal waste items (red) highlighted.

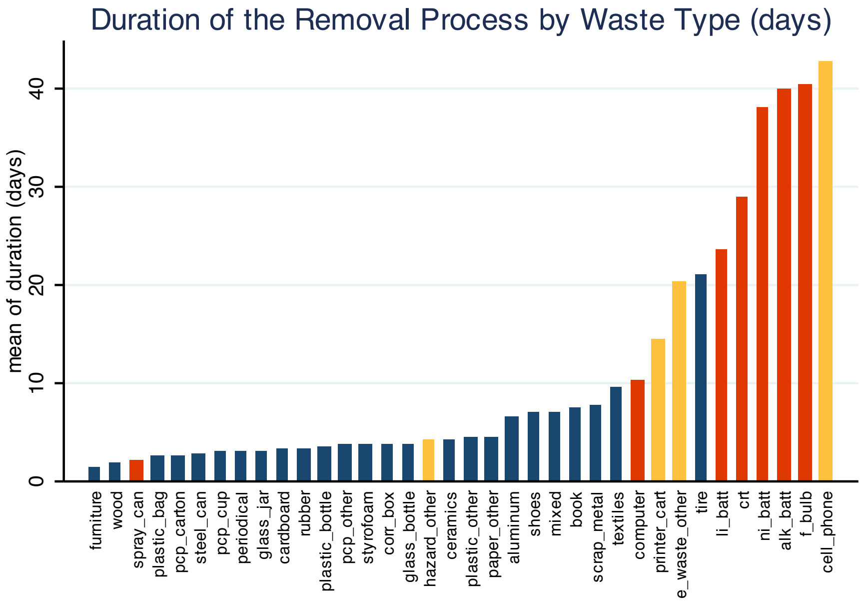

Figure 6 Duration of the waste removal process by waste type

A logarithmic scatter-plot of each individual item's transportation distance reveals three characteristic clusters (Figure 7): the majority of traces remained within in 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 1500 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 e-scrap and materials that represent a liability such as hazardous wastes (Figure 8). This similarity in the behavior of valuable and expensive-to-treat materials is discussed further in the conclusion.

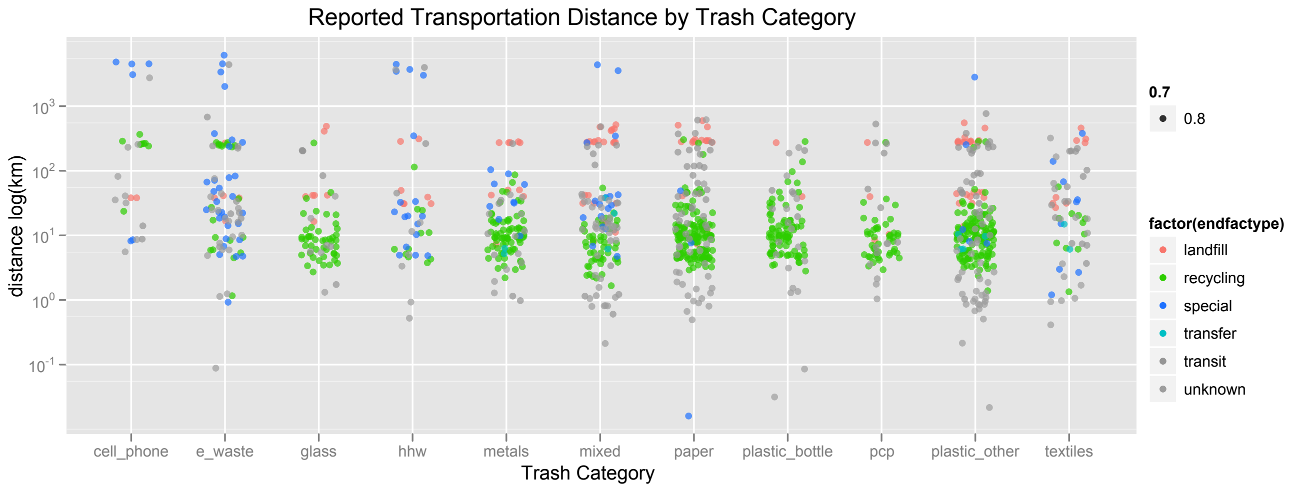

Figure 7 Logarithmic Scatter Plot of recorded transportation distance separated by waste category. On the vertical, logarithmic axis three distinct clusters associated with different waste streams become visible.

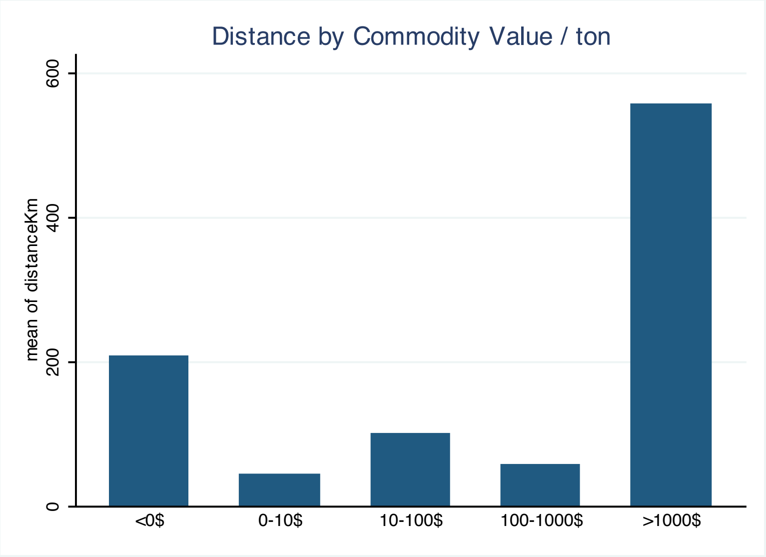

Figure 8 Distance by commodity value of scrap materials.

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

Table 6 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 ($p<0.05$). 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 ($p<0.001$), 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 eleven municipalities reported significantly shorter values. The variable controlling for the sensor's reporting interval configuration is significant ($p<0.01$), indicating that battery failure was an issue: shorter reporting intervals led to an overall shorter duration reported from the sensors.

Table 6 Regression results for Research Question 1

	(1)			(2)		
Variable	**distance km**		**se**	**duration days**		**se**
Alkaline battery	446.7	***	-113.1	35.6	***	-2.856
Aluminum	-46.95		-88.53	1.468		-2.235
Book	-28.17		-129.3	2.032		-3.266
Cardboard	-18.22		-54.49	-1.694		-1.376
Cell phone	842.4	***	-97.11	38.48	***	-2.452
Ceramics	20.13		-129	-0.285		-3.257
Computer	14.65		-162.6	4.811		-4.104
Corrugated box	-57.19		-88.01	-1.721		-2.222
CRT	-42.34		-126.6	23.64	***	-3.196
E-waste other	46.76		-71.96	16.52	***	-1.817
Flourescent bulb	301.8	*	-137.1	35.65	***	-3.461
Furniture	0.544		-230.5	-1.102		-5.819
Glass bottle	10.68		-105.5	-1.257		-2.665
Glass jar	-30.55		-76.51	-1.979		-1.932
Hazard other	41.67		-155.3	0.843		-3.92
Lithium battery	1242.2	***	-136.1	19.06	***	-3.437
Mixed waste	19.47		-77.84	3.006		-1.965
NiCd battery	1151	***	-229	35.22	***	-5.782
Paper waste other	-8.951		-85.66	-0.203		-2.163
PCP carton	-67.95		-83.15	-2.55		-2.099
PCP cup	3.571		-134.2	-2.249		-3.389
PCP other	-36.15		-114.1	-1.638		-2.882
Periodical	-28.38		-94.5	-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)	.		.	.		.
Printer cartridge	1692.3	***	-134.8	10.28	**	-3.404
Rubber	-38.01		-205.1	-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	1.555		-165.1	-1.957		-4.167
Steel can	-51.83		-87.44	-2.519		-2.208
Styrofoam	-39.6		-97.62	-1.665		-2.465
Textiles	-9.433		-66.72	4.395	**	-1.685
Tire	29		-227.6	14.51	*	-5.746
Wood	60.24		-154	-1.983		-3.888
Locations:						
Arlington	11.72		-133.6	3.182		-3.373
Eatonville	4.179		-107.4	1.218		-2.711
Graham-Thrift	1.95		-265.6	2.441		-6.707
Issaquah	-133.4		-76.89	-0.964		-1.941
Lake Forest Park	-129.1	*	-63.21	-5.363	***	-1.596
Mercer Island	-213.2		-138.1	-4.118		-3.488
Mountlake Terrace	-59		-114.7	-7.228	*	-2.896
Newcastle	-45.15		-146.6	3.643		-3.702
Redmond	-92.39		-118.7	-3.527		-2.997
Seattle (Base Cat.)	.		.	.		.
Woodinville	-42.97		-128.6	-6.025		-3.248
Control Variables:						
risk of tag removal	-92.36	*	-38.98	-0.974		-0.984
reporting interval (h)	3.051		-12.02	0.869	**	-0.303
number of reports						
_cons	88.39		-68.25	1.205		-1.723
sample size	1152			1152		
R-sq	0.25			0.426		

* p<0.05, ** p<0.01, *** p<0.001

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 item ending up at a specific facility type. Possible outcomes include a landfills or facilities related to landfilling, recycling centers, special facilities such as a facility remanufacturing batteries or cell phones, or a 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 ending up at a recycling facility rather than at a landfill (Table 7). These materials include glass, metals, paper, and plastic items, confirming that materials collected through curbside recycling are treated differently compared to waste. Interestingly, household hazardous 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 ending up at a special facility compared to a recycling facility or a landfill, although also not on a statistically significant level.

Perhaps more striking --- 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 Forrest Park, Mercer Island, and Issaquah reported significantly higher odds of the landfill outcome.

Table 7 Regression Results for Question 2. Note: 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 to end up at a landfill compared to recycling.

Relative Odds Ratios* for specified Destination Facility compared to Recycling as a Base Outcome

Landfill	Odds Ratio	Z - score	Special Facility	Odds Ratio	Z - score	Unknown Dest.	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							
AIC*	2356.4							

* Odds Ratio = $\dfrac{p_2 / (1 - p_2)}{p_1 / (1 - p_1)}$

Odds Ratio = 1 -> no effect
Odds Ratio < 1 -> lower odds than reference
Odds Ratio > 1 -> higher odds than reference

*Akaike Information Criterion

How do the environmental costs of waste distance 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 diesel produces 2.68 kg of CO2 when burned in a combustion engine (U.S. Environmental Protection Agency, n d). Since a fully loaded 22 US ton Garbage Truck has an average fuel efficiency of 6 miles/gallon[7] (Gaines, Vyas, & Anderson, 2006), it emits about 0.048 kg of CO2 Equivalent per kilometer per US ton[8].

Table 8 shows the recorded waste distances and the corresponding Green House Gas (GHG) Emissions, assuming a typical 22-ton, garbage truck with a fuel efficiency of 6 mpg used for transportation. For typical curbside recycling materials such as plastic and metal, the greenhouse gas emissions generated through the transportation impact seems in fact rather insignificant. Glass, however, is a borderline case. According to EPA WARM (Table 11), 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 8). 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 greenhouse gases, 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

---

[7] converting to 2.55 km/l

[8] The EPA uses a more optimistic value of 0.04kg CO2E/ton-mile in its WARM model (U.S. Environmental Protection Agency, 2006)

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.

Table 8 Recorded Distances by Waste Type and corresponding Green House Gas Emissions (assuming a fully loaded 22 ton garbage truck with 6 mpg fuel consumption, distance counting one direction)

Trash Type	Mean Dist. (km)	mean GHG (MTCE / US ton)	Min Dist. (km)	Max Dist. (km)	max GHG (MTCE / US ton)	Median Dist. (km)
Rubber	11.67	0.001	3.24	34.92	0.002	7.56
Spray can	10.94	0.001	0.93	45.1	0.002	5.59
Glass bottle	18.4	0.001	2.71	84.07	0.004	9.59
PCP carton	16.39	0.001	1.04	187.6	0.010	7.43
Periodical	21.95	0.001	0.9	224.03	0.012	7.02
CRT	49.75	0.003	5.04	239.59	0.013	26.04
Furniture	79.46	0.004	4.25	248.54	0.013	32.53
Computer	101.24	0.005	0.92	269.4	0.014	17.26
Tire	135.7	0.007	2.48	271.68	0.014	134.32
Scrap metal	31.98	0.002	0.98	272.49	0.014	12.23
Aluminum	32.86	0.002	1.29	274.39	0.015	10.75
PCP other	54.62	0.003	4.13	275.36	0.015	10.11
Steel can	28.67	0.002	1.15	281.08	0.015	9.4
Plastic bottle	27.15	0.001	0.03	283.54	0.015	10.02
Corrugated box	29.49	0.002	0.8	291.05	0.015	10.78
Styrofoam	46.33	0.002	0.79	294.96	0.016	8.3
Paper other	49.35	0.003	1.16	306.94	0.016	14.02
Hazard other	90.14	0.005	0.52	347.29	0.018	30.93
Plastic bag	58.01	0.003	0.21	380.35	0.020	10.03
Shoes	58.96	0.003	0.21	431.88	0.023	12.8
Ceramics	84.49	0.004	0.82	447.13	0.024	12.09
Textiles	70.48	0.004	0.41	459.17	0.024	19.7
Mixed	71.5	0.004	0.6	481.59	0.025	14.82
Glass jar	50.89	0.003	1.32	488.63	0.026	8.57
Wood	92.36	0.005	1.22	515.89	0.027	6.36
PCP cup	76.78	0.004	1.76	529.46	0.028	10.15
Cardboard	67.31	0.004	0.02	608.02	0.032	10
Book	75.09	0.004	0.49	616.85	0.033	13.63
E-waste other	97.91	0.005	0.09	678.07	0.036	25.32
Plastic other	61.11	0.003	0.02	2814.8	0.149	10.74
Flourescent bulb	313.64	0.017	3.34	3454.86	0.183	21.55
Lithium battery	1246.15	0.066	4.84	3975.58	0.210	141.76
Alkaline battery	458.64	0.024	3.97	4374.11	0.231	18.11
NiCd battery	1128.47	0.060	6.62	4443.76	0.235	31.74
Cell phone	831.14	0.044	5.56	4825.22	0.255	230.72
Printer cartridge	1713.57	0.091	1.16	6151.71	0.325	28.2
Total	113.95	0.006	0.02	6151.71	0.325	11.48

5. Conclusion

Our data indicates 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 provides 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 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 shows 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 a 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 has can have high value, but also of high toxicity; a material that is costly to recycle, but also offers much room for future recycling innovations.

Acknowledgements

Special thanks to Angela Wang, Eugene Lee, Dr. Rex Britter and Jennifer Dunnam

6. References

Abraham, G. (2000). Concepts of Community in Environmental Disputes: Farmersville and Western New York's Garbage Wars. *Buffalo Environmental Law Journal*, *7*, 51.

Atasu, A., Van Wassenhove, L.K., Sarvary, M. (2009). Efficient Take-Back Legislation. Production and Operations Management, 18 (3), 243-258.

Binder, C. R., Quirici, R., Domnitcheva, S., & Stäubli, B. (2008). Smart Labels for Waste and Resource Management. *Journal of Industrial Ecology*, *12*(2), 207-228.

Bullard, R. D. (2000). *Dumping In Dixie: Race, Class, And Environmental Quality, Third Edition* (3rd ed.). Westview Press.

Boustani, A., Girod, L., Offenhuber, D., Britter, R., Wolf, M. I., Lee, D., Miles, S. B., Biderman, A., Ratti, C. (2010). Investigation of the waste-removal chain through pervasive computing, IBM Journal of Research and Development, 55(1&2), 119-129.

California Departement of Toxic Substances Control. (2009). Consolidated Universal Waste Regulations and Authorized Treatment of Electronic Hazardous Waste. DTSC Ref. Nr.: R-2006-02. California Departement of Toxic Substances Control.

Clapp, J. (2002). The Distancing of Waste: Overconsumption in a Global Economy. *Confronting Consumption* (p. 155–176). Cambridge, Mass. The MIT Press.

Conn, W. D., Scott, D. W., Birch, V., Novak, J. T., & Forcella, D. (1989). Managing Household Hazardous Waste. *Journal of the American Planning Association*, *55*(2), 192.

Douglas, M. (1966). *Purity and danger: an analysis of concepts of pollution and taboo*. New York, Praeger.

European Parliament, the Council and the Commission. (2003). *Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment*

(WEEE) - Joint declaration of the European Parliament, the Council and the Commission relating to Article 9. Official Journal L 037 (pp. 0024 - 0039).

Fairlie, S. (1992). Long Distance, Short Life: Why Big Business Favours Recycling. *Ecologist*, *22*(6), 276–276.

Gaines, L., Vyas, A., & Anderson, J. (2006). Estimation of Fuel Use by Idling Commercial Trucks. *Transportation Research Record: Journal of the Transportation Research Board*, *1983*(-1), 91-98.

ICF. (2004). "WARM Model Transportation Research - Draft." Memorandum from ICF Consulting to United States Environmental Protection Agency. September 7, 2004. Retrieved March 7, 2012 from http://epa.gov/climatechange/wycd/waste/downloads/BackgroundDocumentA.pdf

Jenkins, R. R., Maguire, K. B., & Morgan, C. L. (2004). Host Community Compensation and Municipal Solid Waste Landfills. *Land Economics*, *80*(4), 513-528.

Kang, H.-Y., & Schoenung, J. M. (2005). Electronic waste recycling: A review of U.S. infrastructure and technology options. *Resources, Conservation and Recycling*, *45*(4), 368-400.

Kinnaman, T. C., & Fullerton, D. (2001). The economics of residential solid waste management. In T. Tietenberg (Ed.), *The International Yearbook of Environmental and Resource Economics 2000/2001: A Survey of Current Issues*. Edward Elgar Publishing.

Kreith, F., & Tchobanoglous, G. (2002). *Handbook of solid waste management*. McGraw-Hill Professional.

Lee, J. A., & Thomas, V. M. (2004). GPS and radio tracking of end-of-life products [recycling and waste disposal applications]. *Proceedings of the International Symposium on Electronics and the Environment* (pp. 309-312). IEEE Computer Society.

Lonn, S. A., Stuart, J. A., & Losada, A. (2002). How collection methods and E-commerce impact product arrival rates to electronics return, reuse, and recycling centers. *2002 IEEE International Symposium on Electronics and the Environment* (p. 228–233).

Michaelis, P. (1995). Product Stewardship, Waste Minimization and Economic Efficiency: Lessons from Germany. *Journal of Environmental Planning and Management*, *38*(2), 231.

Morris, J. (2005). Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery (12 pp). *The International Journal of Life Cycle Assessment*, *10*(4), 273-284.

Office of Solid Waste. (2008). *Electronics Waste Management in the United States: Approach 1, Final* (No. EPA530-R-08-009). United States Environmental Protection Agency.

Porter, R. C. (2002). *The Economics of Waste*. Resources for the Future.

RecycleNet Corporation. (2010, August). ScrapIndex.com. Retrieved August 10, 2010, from http://www.scrapindex.com/spotmarket/

Resource Conservation and Recovery Act, Hazardous and Solid Wastes Amendments. (1984). *42 U.S.C. 6901, P.L. 98-616, 98 Stat. 3221*.

Saar, S., & Thomas, V. (2002). Toward trash that thinks: product tags for environmental management. *Journal of Industrial Ecology*, *6*(2), 133–146.

Scharfenberg, J., Pederson, L., & Choate, A. (2004). *WARM Model Transportation Research - Draft* (No. Methane Contract 009, Task 06). Memorandum. ICF International. Retrieved from http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html

Seattle Public Utilities. (2009). Seattle Public Utilities -- Where Does It Go? - Flyer. Retrieved May 20, 2010, from http://www.seattle.gov/util/Services/Recycling/Recycle_at_Your_House/WhereDoesItGoFlyer/index.htm

Seattle Public Utilities. (2010a). Seattle Public Utilities -- Special Items. Retrieved August 21, 2010, from http://www.seattle.gov/util/Services/Garbage/SpecialorHazardousItems/SpecialItems

Seattle Public Utilities. (2010b). Seattle Public Utilities -- Contracts. Retrieved August 10, 2010, from http://www.seattle.gov/util/About_SPU/Garbage_System/Contracts

State of Washington. (1994). Washington Dangerous Waste Regulation WAC 173-303-071 (3)(c). Retrieved from http://apps.leg.wa.gov/WAC/default.aspx?cite=173-303-071

Thorneloe, S., Weitz, K., Nishtala, S., Yarkosky, S., & Zannes, M. (2002). The impact of municipal solid waste management on greenhouse gas emissions in the United States. *Journal of the Air & Waste Management Association*, *52*, 1000–1011.

U.S. Environmental Protection Agency. (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Retrieved from http://epa.gov/climatechange/wycd/waste/SWMGHGreport.html

U.S. Environmental Protection Agency. (2009, December 7). EPA Facility Registry System (FRS). Retrieved August 10, 2010, from http://www.epa.gov/enviro/html/fii/index.html

U.S. Environmental Protection Agency. (n.d.). Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel. Retrieved August 12, 2010, from http://www.epa.gov/oms/climate/420f05001.htm

Wäger, P. A., Eugster, M., Hilty, L. M., & Som, C. (2005). Smart labels in municipal solid waste—a case for the Precautionary Principle? *Environmental Impact Assessment Review*, *25*(5), 567–586.

Washington State Department of Ecology. (n.d.). Generation, Recycling and Per Capita data (1986-2008). Retrieved August 11, 2010, from http://www.ecy.wa.gov/programs/swfa/solidwastedata/recyclin.asp

7. Appendix

Table 9a 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 9b 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 & accessories and other household electronics.
Glass	65	single material glass items, such as bottles, jars, and glass tableware.
Plastic-coated paper	64	milk cartons, coasted 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 phone	27	only cell phones
Total	**1,152**	

Table 10 Spot Market Value of Scrap Materials (Source: Spotindex.com)

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
Flourescent 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

Table 11 Greenhouse gas emission factors used by the EPA WARM model, assuming average transportation distances (Zhao et al. 2009)

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

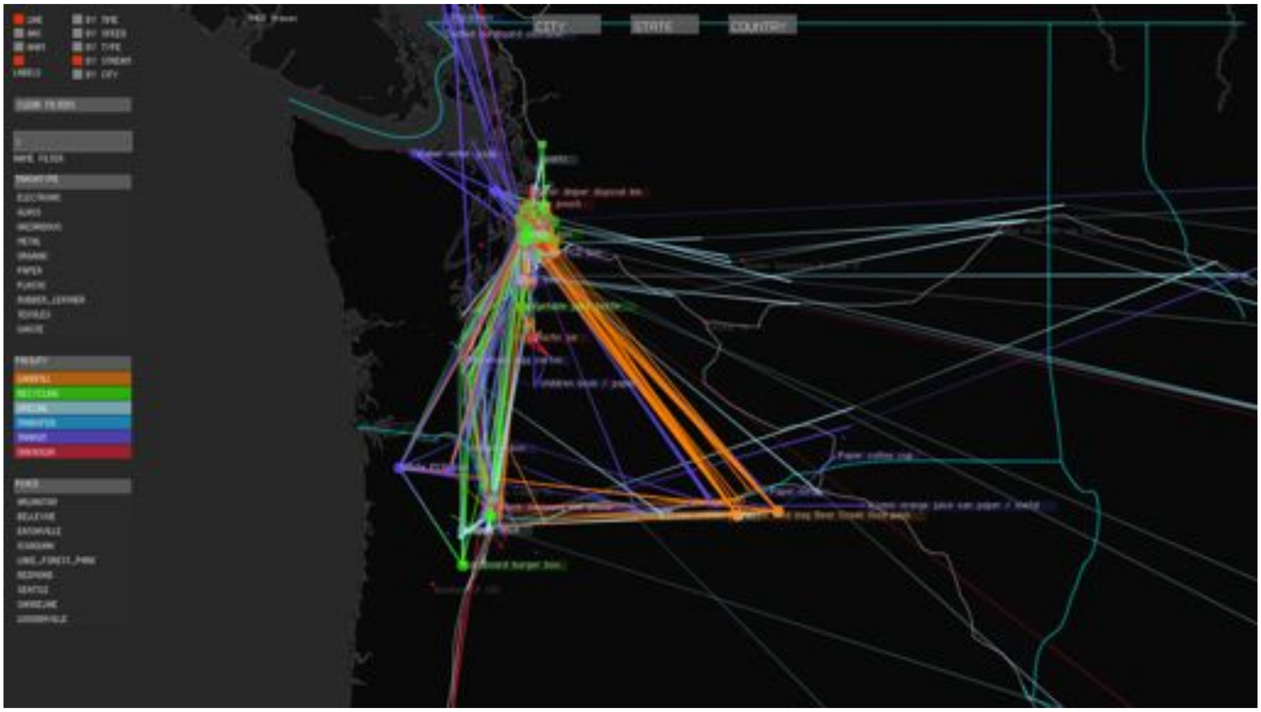

Figure 10 Geographical structure of different waste streams: most prominently orange trajectories lead to landfills, green ones to recycling facilities and light blue ones to special facilities.

Figure 11 the color represents the average velocity of trajectory segments – sections using airfreight can be made out.

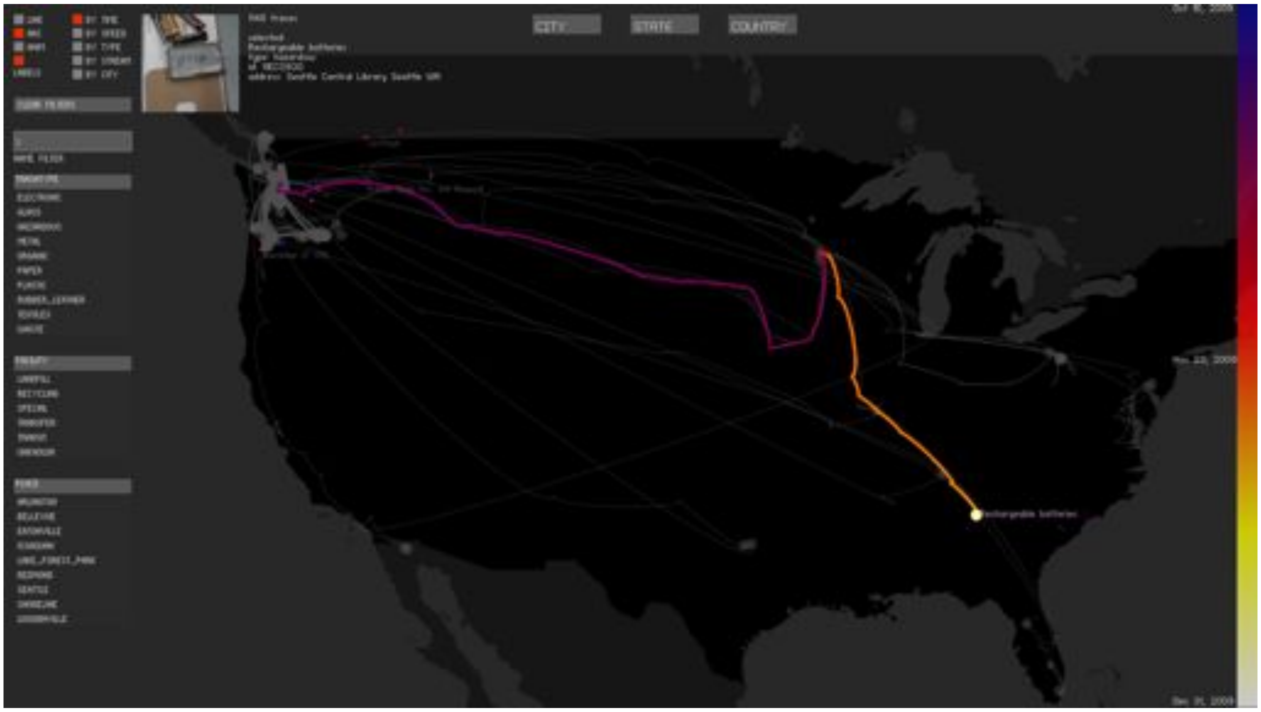

Figure 12 The trajectory of an assortment of small rechargeable batteries, the color represents the date of individual travel segments.

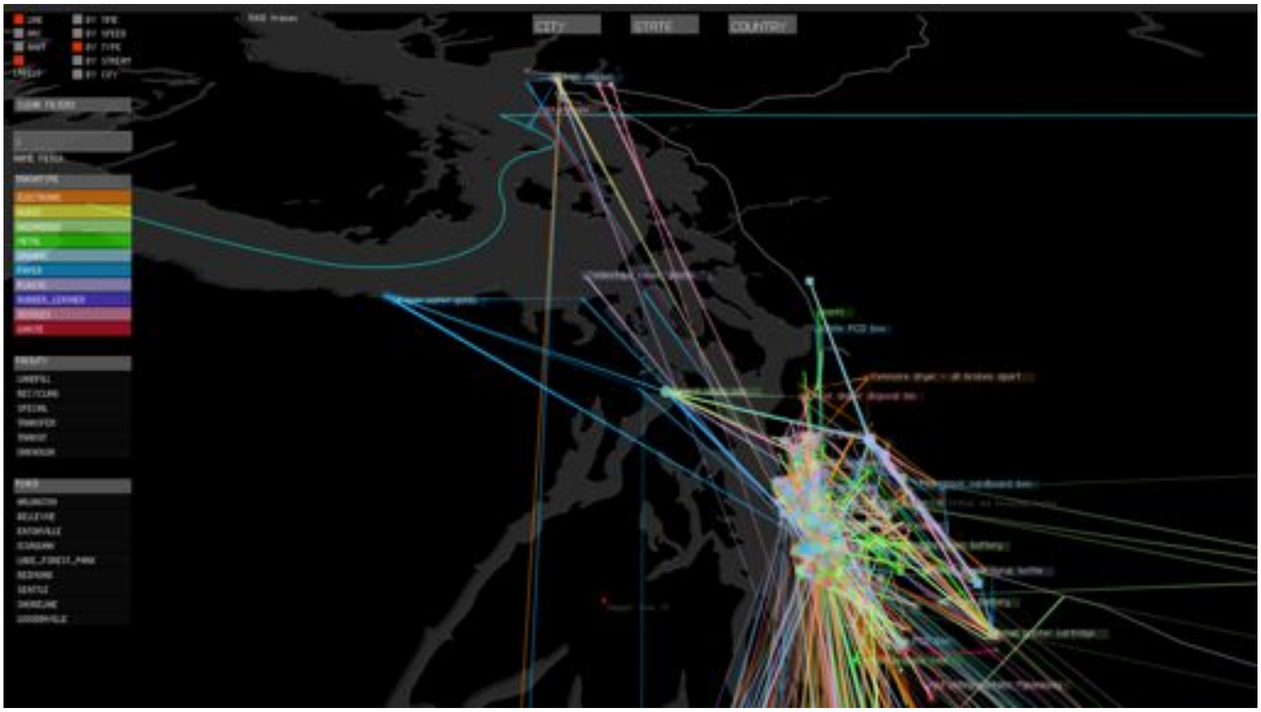

Figure 13 Sensors reporting from waterways in the Puget Sound and Vancouver, CA. Note that localization only works where cell phone infrastructure is available, therefore very few sensors report from within the Sound or Ocean.

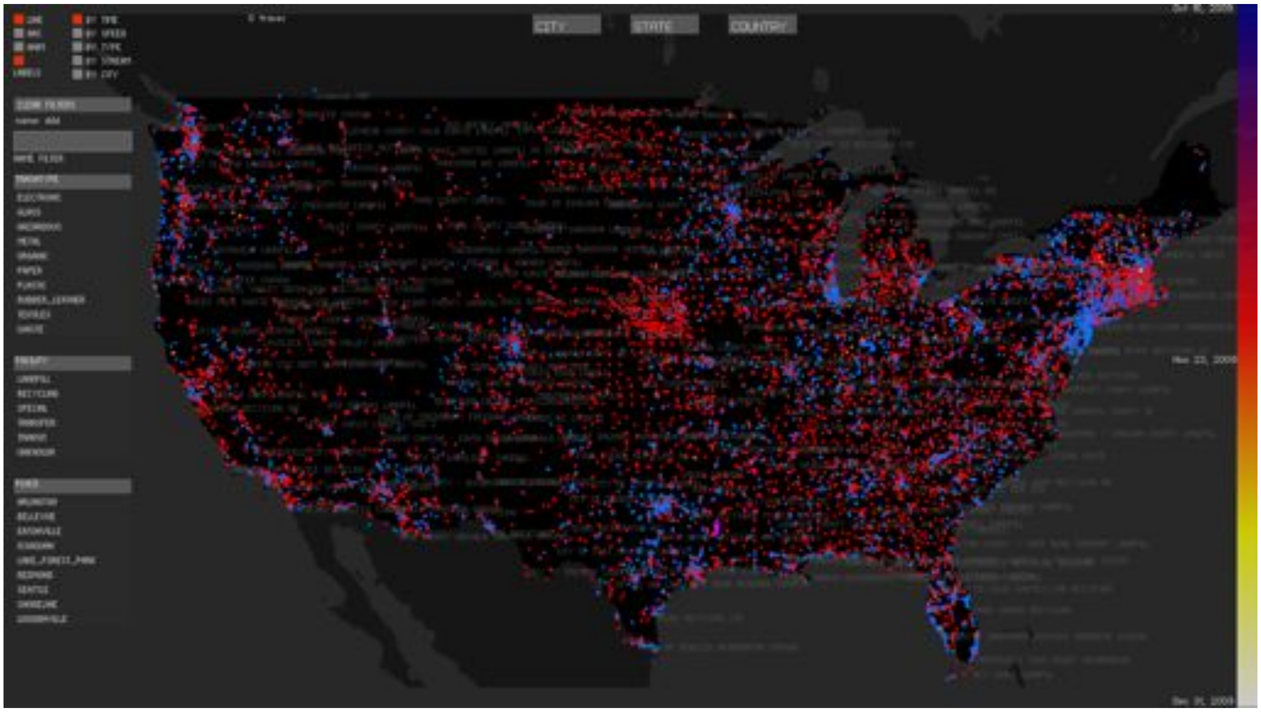

Figure 14 The distribution of landfills and recycling facilities across the U.S. Note how densely populated areas have a higher density of recycling facilities (blue) compared to landfills (red)