Transforming waste management systems through location tracking and data sharing

By

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ABSTRACT

This dissertation investigates how location tracking technologies can transform municipal solid waste management in smart cities. While waste is often tracked in aggregate as it flows between and through handling facilities, there have been few attempts to follow individual trash items geographically using GPS and web-based mapping. Such data change the interaction between citizens, local government, and service providers, by revealing inefficiencies or fraud in disposal practices, or building trust between stakeholders and enabling alternative approaches for contracting waste services.

Five essays demonstrate various designs and evaluations of real-time waste tracking systems, identify challenges and opportunities for incorporating these tools, and show how developed and developing cities can learn from each other.

The first essay presents a system where individuals electronically tag a trash item, and view its movements in real-time. By surveying volunteers who participated in this experiment, it shows how this feedback can significantly improve their knowledge of how waste systems operate and where different types end up. The second essay extends this method for tracking hazardous electronic waste, such as CRT monitors, when illegally exported from high- to low-income countries. This information allows activist groups to investigate smuggling routes and support public agencies in enforcing international law.

The third and fourth essays implement waste tracking in Brazil and Kenya, where many cities rely on informal workers to collect and recycle trash. By carrying smartphones tracking their location, waste pickers can map their own movements, waste generation, and material flow across the city. This allows them to organize more efficient routes, coordinate actions in real-time, and negotiate more favorable partnerships with government and private clients. Planners also benefit from crowdsourced data in informal areas.

Looking to the future, the fifth essay considers how formal waste collection services could be made transparent, and how this supports crowdsourcing efforts to improve their efficiency and better meet resident needs. Doing so requires design of both real-time urban dashboards and citizen feedback mobile applications. The result transforms how cities benchmark effective municipal services and strive for high quality urban environments.

Thesis Supervisor: Carlo Ratti

Title: Associate Professor of the Practice
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Introduction

Removing solid waste from our living environments is one of the oldest challenges for city planners, who must find both the space to receive such waste, and the technology to transport and reprocess or dispose of it. Municipal solid waste management (MSWM) today focuses on using mechanized labor to efficiently move waste out of the city to minimize its impact on its citizens. However, such systems continue to face problems of high volumes of household waste (with low levels of recycling), little control over the export of hazardous electronic waste, and incompatibility with informal waste collection practices in developing countries (UN-Habitat, 2010).

Should all these trends continue, we face a future where cities generate increasing amounts of solid waste, shipped further away at great cost to the environment and energy stocks, and exposing the most vulnerable populations to health risks and economic deprivation.

An alternative vision for future cities is that of the “smart city,” where information and communication technologies (ICTs) are applied directly to urban problems to enable safer, healthier, more sustainable cities capable of supporting their growing populations (Harrison et al., 2010). Such a city could host a “smart waste system” that knows where solid waste is being generated, collected, transported, and disposed of, using ICTs to track the location of discarded items in real-time. The combination of location-sensing technologies like GPS and wireless data transfer through mobile phone networks make it possible to sense this at the scale of the city, while interface tools like interactive web mapping can make these data accessible to a broader audience. The resulting data would reveal fundamental flaws in the handling of waste, raise public awareness around waste issues, or engage many stakeholders in the design of solutions appropriate for their local contexts.

The goal of this dissertation is to understand how waste tracking technologies can be used to design smart waste systems. What unique datasets can smart waste systems generate and utilize using location tracking? What do they tell us about the effectiveness of existing waste systems in both developed and developing economies? How can cities apply these data internally to improve waste collection, reduction, and disposal operations, achieving their goals more efficiently? How can they engage more stakeholders to participate in waste planning and help determine what those goals are?

To answer these questions, I present five smart waste projects designed and developed by myself in concert with colleagues at the MIT Senseable City Lab. Each considers a different context and application for location tracking in...
addressing modern problems associated with urban waste handling. The articles cover different types of waste, levels of formality, technological complexity in collection services, ways of engaging local residents, and geographical contexts around the world. By prototyping and deploying these systems, we can make recommendations for possible future smart waste systems, the technical challenges faced in their design and scaling, and the more fundamental changes they could spark in our planning and behavior toward solid waste in cities.

This dissertation and its component papers contribute to an alternate vision of smart waste systems in future cities. The papers demonstrate that waste tracking greatly aids planning sustainable waste systems, can be done without extensive new top-down infrastructure, and can be wielded by individual citizens or interest groups to influence public policy. They show how technology can preserve functioning forms of informal waste management, and allow governments to partner with and learn from them. This is a vision where smart cities choose to engage with their residents on the tough choices posed by solid waste generation, and data empowers them to shape the system as they desire.
How Technology and Place Shape Waste Systems
This section reviews the literature on municipal solid waste management (MSWM), smart cities, and ICT applications in solid waste. It outlines:

- The relationship between technology, place, and waste in cities, the state of solid waste systems today, and their many challenges. This helps contextualize the problems in MSWM, and their consequences to the form and experience of cities.
- Two common but not exclusive technological approaches to smart cities in relation to waste management: centralized systems meant to optimize the efficient operation of urban infrastructure and services, and pluralistic models meant to engage residents and employ their knowledge. While current waste systems are more aligned with the former, smart waste systems could employ and support both.
- Proposed frameworks and systems by smart cities researchers to improve MSWM through ICTs. This shows where efforts have focused so far, while highlighting the gaps in the literature that this dissertation seeks to address.

Technological causes and solutions for municipal solid waste

*Waste, place, and technology in history*
Solid waste is one of the oldest problems faced in cities. How much and which kinds of solid waste households generate, where it is sent, and how quickly it is removed from the living environment greatly impacted public health and the form of cities. Organic waste, including food remains and human excrement, was thrown from houses directly into the streets of ancient cities (Ben-Joseph, 2005). While such practices posed less of a risk in rural settings, in the tight quarters of urbanizing communities unchecked dumping could bring devastating waves of pests and disease. Such problems persist today in cities with rapid in-migration from rural areas and insufficient infrastructure to match (Watkins, 2006).

Inorganic waste, though less prevalent in ancient cities, also accumulated in the streets, gradually forcing residents to build the city in ever rising layers rather than remove the waste (Mumford, 1961). However, the impact of this material has steadily grown as our reliance on and demand for more durable goods has increased. The industrial revolution introduced a wide range of consumer products, produced cheaply enough to mass-market, and containing slow-composing or even toxic materials with which societies had little familiarity or capacity to handle (Strasser, 1999). Efficient raw material extraction and booming post World War I and II economies meant that there was relatively little value from recycling old materials (Melosi, 2004).
A city’s ability to handle both human and solid waste streams was closely linked with the development of technology to handle their removal, but these technologies in turn would influence how cities were designed and operated. Underground sewer systems could flush out the most problematic human wastes, preventing it from ending up on streets; having invested heavily into this form of infrastructure, cities must continue to upgrade it at the expense of other uses of land and capital (Ben-Joseph, 2005). Trucks and street sweepers could clear solid waste from the streets more quickly, but all required good paving and streets wide enough for vehicle traffic. Sanitary engineering and labor management practices at the turn of the 20th century enabled cities to handle waste at a large scale, aided by growing belief in the health and aesthetic values of cleanliness, along with expectations for the efficiency and professionalization of municipal services (Melosi, 2004).

Technology has also historically dictated how and where we disposed of solid waste. In pre-modern times, when overland freight was costly and slow, waste had to be burned, left in open dumps, or dropped into bodies of water. This kept the consequences of excess solid waste generation close to home, so that city residents needed to deal with the sights, smells, and handling costs of their own consumption (Engler, 2004). However, with the rise of cheap long-distance shipping via rail, road, and sea, waste disposal industrialized, with materials moved swiftly out of cities to large scale dumps, recyclers, or incinerators, often in poorer neighborhoods or rural locations (Bullard, 2000). Even source-separation at the home became inefficient within these systems, since it was cheaper to funnel all materials out for disposal rather than send multiple trucks for different materials along the same route (Melosi, 2004). Trash became decoupled from our daily lives, and this waste distancing may have contributed to even more consumer waste generation (Clapp, 2002).

As cities expanded to abut these open dumps, and our ability to trace water, air, and soil pollution back to disposal practices improved, solid waste returned to the public consciousness (Engler, 2004). Technological innovation shifted to making these centralized processes more efficient and minimizing their environmental impact, resulting in the sanitary landfill and waste-to-energy incinerators (Melosi, 2004). Policy shifts moved these facilities away from communities unwilling to host them, and outlawed burying of certain types of waste, such as electronic waste and hazardous chemicals. The cost of making waste “disappear” rose accordingly, as cities faced fewer options for disposal (Melosi, 2004). Recycling, take-back programs, and waste reduction found their way into common practice as ways to divert solid waste from landfill, also aided by technological improvements in industrial processes, product and packaging design, reverse-supply chain logistics, and mass media campaigns for such programs (Lehmann & Crocker, 2013).
Table 1: Selected MSW generation rates by country

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Urban population</th>
<th>Generation rate (kg/capita/day)</th>
<th>Total waste (tons/day)</th>
<th>Projected 2025 total waste (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>2006</td>
<td>241,972,393</td>
<td>2.58</td>
<td>624,600</td>
<td>701,709</td>
</tr>
<tr>
<td>China</td>
<td>2004</td>
<td>511,722,970</td>
<td>1.02</td>
<td>520,548</td>
<td>1,397,755</td>
</tr>
<tr>
<td>Brazil</td>
<td>2001</td>
<td>144,507,175</td>
<td>1.03</td>
<td>149,096</td>
<td>330,960</td>
</tr>
<tr>
<td>India</td>
<td>2006</td>
<td>321,623,271</td>
<td>0.34</td>
<td>109,589</td>
<td>376,639</td>
</tr>
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</table>

As societies urbanize and develop consumption-based economies, per capita solid waste generation rates increase. While OECD countries like the United States generate almost half the world’s MSW, low and middle income countries will soon dwarf those amounts. Data excerpted from (Hoornweg & Bhada-Tata, 2012).

**Municipal solid waste systems today**

Most cities in “developed” economies have centralized, mechanized systems for handling solid waste generated within their boundaries. These systems vary widely in terms of degree of mechanization (and thus, need for skilled or unskilled labor), consolidation amongst one or several agencies, privatization, and range of disposal outcomes. However, some common attributes of these systems include a reliance on trucks, full and regular service to homes within city limits, formalized labor relations, public regulation (if not direct operation) of waste businesses, centralized transfer and handling facilities, and use of national and international trade routes to move some materials out of the city (UN-Habitat, 2010). Recycling services are often integrated into centralized services, with separation happening at the household level or further downstream, but rarely reach recovery rates of over 60% (Lehmann & Crocker, 2013). Programs for disposing of electronic and hazardous waste are more fragmented, with rules less consistent across municipalities (Kahhat et al., 2008). Geographic Information Systems (GIS) are often used to identify service areas and plot collection routes, but generally a mix of heuristics, data analysis, and trial-and-error decide the actual routes (Kreith & Tchobanoglous, 2002).

In "developing" economies, both rural and urban areas, waste systems show considerably more diversity. The wealthiest, most globally connected cities may feature systems quite similar to those of developed economies, adopting the same technologies and concepts to serve their growing middle-class populations (Hoornweg & Bhada-Tata, 2012). However, many cities still rely on decentralized, informal systems of waste collection, recycling, and disposal. Solid waste is a more visible part of their lives, with junk dealers and waste pickers providing crucial services in areas unserved by public works. These areas feature many...

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1 I use the terms "developed" and "developing" as a designation of convenience, based on respective United Nations Human Development Indices. Their meanings are not exact and should be understood as a way to group common aspects of their waste systems in the context of this essay.
more informal actors collecting, sorting, transacting, and/or transporting waste; they use both manual and mechanized methods, are self-financed from material sales or collection fees, operate independently with ad-hoc labor arrangements, and are sometimes at odds with local governments (Wilson, Velis, & Cheeseman, 2006).

These actors may be the sole provider of recycling services across the city, and can divert high amounts of material away from landfill; the Zabbaleen achieve up to 80% recovery rates in Cairo (Iskandar, 2003), while micro-enterprises in Bamako, Mali divert 85% of waste (mostly food scraps and sweeping) to composting material for local agriculture (UN-Habitat, 2010). Cottage industries may also recover materials from or refresh electronic devices for resale. However, burying, submerging, and burning waste are less restricted by governments (Nnorom & Osibanjo, 2008), and the informal workers themselves may suffer in poor working conditions and exploitative labor arrangements (Medina, 2008). To address these issues, many cities may try to upgrade their waste services to match systems in developed countries, but risk crowding out the working aspects of their existing informal networks (Wilson, Araba, Chinwah, & Cheeseman, 2009), particularly where these networks can potentially reach high levels of recycling performance.

Figure 1 illustrates the different ways formal and informal collection systems operate in developed and developing cities. The first diagram depicts the basic flow of solid waste through a typical developed city. Recyclables are separated from other waste at the home, and both are hauled separately by collection trucks to transfer stations. There, they are loaded onto larger trucks (or trains or barges), and carried to disposal points or recycling plants.

The second diagram depicts informal recycling taking place at nearly every stage, as waste pickers recover materials from streets, public bins, transfer stations, open dumps, and landfills. They sell the recyclables to middlemen (themselves informal junk dealers) who then bundle and sell them to recycling industries. The waste pickers face the toughest working conditions and lowest profits, and are vulnerable to exploitation from those further up the value chain. This activity is ubiquitous in developing world cities such as Bangalore and Sao Paulo, and exists in developed cities to a lesser extent.

The third diagram depicts a situation where informal waste workers form cooperatives. In areas without door-to-door municipal waste collection, the coops can provide such services, earning money from user fees and recyclable sales while cutting out the middlemen. They are less vulnerable when self-organized. In some developing cities, such as Dhaka and Delhi, this may be the only organized waste service available to entire neighborhoods (UN-Habitat, 2010).
These are just some of many variations on waste systems today. The second and third systems can even co-exist in different parts of the same city, as they do in Sao Paulo (D. Offenhuber & Lee, 2012) and Pune metropolitan area (D. Lee, Vanky, & Felix, 2014).

**Developed Scenario**

**Developing Scenario 1**

**Developing Scenario 2**

Figure 1 Waste management scenarios in developing and developed world.

Diagrams courtesy of Youjin Shin and Eugene Lee.
Informal waste workers exist in nearly every city, handling trash directly to recover valuable materials. Those who work alone require hand-carts to transport material, and must manually sort waste close to the source (public bins, landfills). They earn meager incomes and can be perceived as public nuisances, but they provide public good by diverting material away from dumpsites, and reducing raw material usage through recycling.

Finally, the flow of waste between wealthy and poor regions, whether within or between nations, has grown dramatically. Solid waste from cities often ends up in landfills located in poorer outskirts of cities, or in rural communities well outside the urbanized zone. Such communities may offer little political resistance to accepting this waste and the attendant risks (Bullard, 2000). These issues are magnified when studying the global export of electronic and hazardous wastes, such as old computers or car batteries (Rosenthal, 2011; Urbina, 2013). These items, costly to dispose of due to domestic restrictions on disposal methods and labor protections, sometimes end up illegally sold to buyers in countries with less regulation. The environmental and health consequences of improper dumping can affect entire regions of poorer countries (Robinson, 2009), though there are local economic benefits as well as global environmental benefits from increased recycling. Illegal dumping is also an ever-present threat, one which is hard to detect in rural or ocean areas with little human presence (Massari & Monzini, 2004).

Current challenges in municipal solid waste management
1. Growing amounts of consumer solid waste: We continue to produce and dispose of huge amounts of solid waste in developed countries. In the US, MSW
per capita increased from 1.2 kg in 1960 to 1.9 kg in 1986, to 2.1 kg in 2000 (Kreith & Tchobanoglous, 2002). Growth is slowing but still net positive, even with recycling. Developing economies are also rapidly increasing their waste generation as their populations urbanize; city dwellers generate twice as much solid waste as rural, on average (Hoornweg & Bhada-Tata, 2012). Collecting, sorting, transporting, and disposing of all that waste imposes both direct and social costs. For example, the transportation cost alone for New York City’s waste averages $2/mile (in 1997 dollars) for a full truck, with a quarter of that cost stemming from pollution, accidents, and infrastructure wear (Porter, 2010).

2. Rising costs for disposal: While much of the Earth's surface has yet to be urbanized, there are still relatively few places where we can safely bury all of this waste. Sanitary landfills are often located far away from the cities they serve, raising the cost of collection and transport which can exceed 70% of waste management budgets, along with the subsequent vehicle emissions (Tavares, Zsigraiova, Semiao, & Carvalho, 2009). Even in developing economies, awareness of the long-term risks from poorly designed landfills and unregulated dumping is growing, causing public controversies and political actions against existing waste policies (Leao, Bishop, & Evans, 2001).

<table>
<thead>
<tr>
<th>Country income group</th>
<th>Income (GNI/capita)</th>
<th>Percent collected</th>
<th>2010 cost</th>
<th>Projected 2025 cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low income</td>
<td>&lt;$876</td>
<td>43%</td>
<td>$1.5 billion</td>
<td>$7.7 billion (+ 413%)</td>
</tr>
<tr>
<td>Lower middle income</td>
<td>$876-3,465</td>
<td>68%</td>
<td>$20.1 billion</td>
<td>$84.1 billion (+ 318%)</td>
</tr>
<tr>
<td>Upper middle income</td>
<td>$3,466-10,725</td>
<td>85%</td>
<td>$24.5 billion</td>
<td>$63.5 billion (+ 159%)</td>
</tr>
<tr>
<td>High income</td>
<td>&gt;$10,725</td>
<td>98%</td>
<td>$159.3 billion</td>
<td>$220.2 billion (+ 38%)</td>
</tr>
</tbody>
</table>

Table 2: Estimated solid waste management costs by country income group

The total cost of solid waste management, including collection, transport, and disposal, will increase significantly, with the most dramatic jumps for lower middle income countries. Low collection rates in lower income countries reflects the informal sector’s diversion of some materials, as well as cases of unregulated dumping. Data excerpted from (Hoornweg & Bhada-Tata, 2012).

3. Growing amounts of electronic waste (e-waste): The amount of e-waste generated in all countries is increasing, as we gain access to new, more diverse, and cheaper electronic devices. More common products like refrigerators now include computational components, becoming “smart” but also adding to the flow of e-waste (Hilty, Som, & Kühler, 2004). Some older devices, like cathode ray tube computer monitors, are no longer in demand for recycling in the US, which has led to the closure of facilities necessary to recover their value (Urbina, 2013). Safer
disposal technologies are available, such as glass-to-glass or glass-to-lead recycling (Kang & Schoenung, 2005), or even plasma gasification, which breaks down waste to its atomic elements (Wolman, 2012), but have yet to be implemented at large scale.

4. Awareness and behavior: All of these problems are not well-known to large sections of the population, whether for lack of exposure to solid waste practices (as in many developed economies) or the novelty of having a lot of waste to dispose of (as in developing economies) (Wilson, 2007). As a result, officials and planners tend to prioritize building more capacity rather than reduce waste or change behavior. This emphasis on engineering infrastructure leads to path-dependence on certain technologies, such as our reliance on aging and expensive sewer systems (Ben-Joseph, 2005).

5. Lack of data: We need to know how much waste is generated, where it is sent, trends in growth or decline, and the opportunities and risks in alternative treatments. Waste is not well-defined, some types are not counted, and high quality data on waste generation and environment, health, and safety impacts are not well known (Kreith & Tchobanoglous, 2002). This hampers planning and public dialogue on the choices between potential policies.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Sources</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste generation rates</td>
<td>Weight scales at transfer and disposal sites.</td>
<td>Coarse data (by truckload, not household), standards differ by city, state, and country.</td>
</tr>
<tr>
<td>Waste transport routes</td>
<td>Transaction records, vehicle GPS, operations data.</td>
<td>Unable to track individual items, nor across multiple transactions. Expense of data entry and errors.</td>
</tr>
<tr>
<td>Waste export activity</td>
<td>Shipping manifests, regulatory public audits.</td>
<td>Fraud, smuggling networks, weak enforcement.</td>
</tr>
<tr>
<td>Societal impacts</td>
<td>Scientific study of economic and environmental costs.</td>
<td>Lack of comprehensive data on waste flows, distances travelled, modes of transport and disposal, local economic and health impacts.</td>
</tr>
</tbody>
</table>

Table 3: List of needed waste management data types and limitations

6. Regulation and enforcement: The long distances and many boundaries (local, state, and national) increasingly crossed by waste today make it difficult to regulate its handling, with overlapping regulatory regimes and responsibilities (Kinnaman & Fullerton, 1999). Even where clear rules exists, enforcement by government agencies is difficult when the waste itself is hard to track, and reporting on cargo manifests can be doctored or ignored (Belenky, 1999).
Smart cities
The past decade has seen increased public and private interest in the concept of smart cities. Smart cities have been long theorized by architects and futurists, and debated and tested sporadically through the second half of the 20th century. They have since attracted mainstream attention, through the marketing efforts of major technology and real estate firms, profiles in industry trade publications, and academic research across a variety of fields (Greenfield & Kim, 2013).

Uses of this term are so numerous and broad as to defy easy definition (Chourabi et al., 2012; Hollands, 2008). Anthony Townsend (2013) succinctly describes them as

"places where information technology is wielded to address problems old and new."

Batty et al. (2012) insist that cities

"can only be smart if there are intelligence functions that are able to integrate and synthesize this data to some purpose, ways of improving the efficiency, equity, sustainability and quality of life in cities."

Both researchers cite the global influence of industry giant IBM, which has pushed the trademarked concept of "Smarter Cities," (Harrison et al., 2010) where

"the traditional concept of a physical city infrastructure is extended to a virtual city infrastructure, an integrated framework that will allow cities to gather, integrate, analyze, optimize, and make decisions based on detailed operational data."

In presenting this vision, Harrison et al. also point out the existential crises faced by both developing world cities (massive in-migration stretching infrastructure and services to their breaking point) and developed world cities (economic reinvention amidst globalization and deindustrialization), with ICTs serving as panacea for both (Harrison et al., 2010).

All three of these viewpoints define smart cities as deliberately using ICTs to solve problems traditionally ascribed to cities. Such traditional problems could range from traffic congestion to exposure to pollutants (Hall, 2007). This dissertation is primarily concerned with applications for solid waste. However, the way ICTs are designed, deployed, and controlled to address urban problems can vary dramatically depending on which smart city model we employ.
Cities as real-time control systems

Real-time control system, or RCS, is an architecture for systems that must understand and intelligently respond to uncertain environments in real-time. Inspired by the cerebellum, the part of the brain that coordinates motor activity across the human body, RCS models systems as hierarchies of feedback loops (Albus & Rippey, 1994). Each level of the hierarchy uses information from the environment and commands from higher levels to decide what to do next. For example, at a high level, a robot vacuum cleaner might use infrared sensors to understand a room’s shape and plot out the best route to clean the whole floor; at a lower level, it would use those same sensors to track its own position, and turn each of its wheels to follow that route.

One common narrative of smart cities is the idea that cities can be modeled, built, and operated as real-time control systems (Calabrese, Kloeckl, & Ratti, 2008). In this narrative, automated digital systems or trained operators can track the real-time state of a city through data generated by individuals, institutions, and sensors. They can then respond to disturbances at any level of the hierarchy with the appropriate action or policy, maximizing the performance of the city’s infrastructure. For example, by monitoring the localized phone activity in a city (provided by a mobile operator) and the movement of buses (provided by a transit agency), a system could identify mismatches and re-route more buses to lines serving higher-demand areas of the city (Calabrese, Colonna, Lovisolo, Parata, & Ratti, 2011). Such systems, when comprehensive, objective, and sufficiently responsive, could make cities more efficient, safe, and healthy.

An early formulation of this cybernetic model came from Jay Forrester, a systems engineer famous for applying RCS theory to industrial organizations. His Urban Dynamics modeled cities as overlapping feedback loops of population, housing, and industries, claiming that the interactions between these quantities could explain the growth and decline of cities, while predicting the success or failure of urban policies (Forrester, 1969). Fundamental to this model was the assertion that cities gravitate towards an equilibrium, such that improving a city’s attractiveness (such as new affordable housing or transportation networks) introduces negative consequences, primarily as a result of influx of poor residents (Mass, 1974).

Forrester’s findings, which depended heavily on state-of-the-art computational techniques, sparked great interest among academics but skepticism from urban planners, due to his omission of urban social theory or attendant data, such as built form, land use, and culture as variables affecting urban success (Alfeld, 1995). Furthermore, while claiming to achieve his “counterintuitive” results from impartial analysis, his models relied heavily on normative assumptions that turned out to be oversimplifications (e.g. that area, culture, physical organization, and land uses of the city are static, with no interactions with suburbs or beyond) or
incorrect altogether (e.g. that tastes, income, and technology don't appreciably change over hundreds of years) (Ingram, 1970). The model only responded to the variables he suspected would matter from the start (housing, jobs, and population), leaving it unsuitable for policy analysis of alternative outcomes (D. B. Lee, 1973).

Other attempts to streamline cities through operations research, such as the RAND Institute’s reorganization of New York City’s firefighting system, failed spectacularly; in that example, the model erroneously recommended closing critical fire stations, leaving entire neighborhoods to burn when capacity failed to meet demand (Townsend, 2013; Wallace & Wallace, 1990). Nonetheless, engineered logistics and control systems are at the heart of most urban infrastructure and services that move physical materials around the city, such as fresh water delivery, transportation, and sewage and waste removal (Larson & Odoni, 1981).

**GIS and big urban data**

Urban dynamics did not become a dominant paradigm, but computer modeling of urban growth developed steadily over the following decades, helped by the spread of desktop computing (Starr, 1994). The advent of geographic information systems (GIS) allowed planners to address the crucial gap in Forrester’s analysis: space. Armed with data from digitized maps, geological surveys, economic reports, and the census, GIS specialists could test increasingly sophisticated theories of how spatial factors affected the macro behavior of cities (Coppock & Rhind, 1991). GIS saw wide adoption for studying, recording, and planning any sort of urban operations, including law enforcement, urban design, route management, and many other diverse uses.
Part of IBM's smart city vision is the use of trained operators in "urban control rooms" who can monitor the city remotely with real-time data, perform advanced simulations of emergencies like flooding, and direct operations to relieve traffic congestion. Note that most of the screens show some form of GIS interface for observing data layered on a map. Source: ("Smarter cities software," 2015)

GIS has been used in many ways for urban maintenance, from decoding addresses into location information (Goodchild, 2007; Schwester, Carrizales, & Holzer, 2009), to visualizing and analyzing reports and inventories, to serving as the backbone for infrastructure data across agencies and contractors (Naphade, Banavar, Harrison, Paraszczak, & Morris, 2011). Asset management systems, such as those used to manage and maintain roads, are a specialized form of GIS used to both streamline operational, day-to-day work and to assign key performance indicators (KPIs) that measure agency performance overall (Horak, Emery, & Agaienz, 2001).

However, GIS was originally ill-suited to handle real-time behavior data generated from electronic sensors or from our growing activity on digital information networks (Resch, Mittlboeck, Girardin, Britter, & Ratti, 2009). New tools such as participatory web mapping, data dashboards, and urban application program
interfaces (APIs) have stepped into this void, forming a new generation of GIS tools for visually understanding and applying real-time knowledge of the city (Kitchin, 2014b).

The rise of “big data” also opened new opportunities for planners. In defining big data, Rob Kitchin (2014a) refers to the commonly cited 3 V’s: huge volume (order of terabytes or petabytes), high velocity (near real-time), and diverse varieties in type. Such big datasets are being generated from sensor networks, telecommunications infrastructure, social media, and many other sources as byproducts of urban life, and can be reapplied to understanding urban function or dysfunction when made available by companies and institutions. For example, combining GIS mapping with big data analysis of waste collection in Stockholm revealed inefficiencies in vehicle routing, and suggested interventions like a shared vehicle fleet (Shahrokni, van der Heijde, Lazarevic, & Brandt, 2014).

Machine learning, network science, and other computational techniques have also opened up urban data analysis to fields outside of planning and systems design (Batty et al., 2012). This open, flexible approach could lead to a more comprehensive model of how cities work, by incorporating orders of magnitude more data mined from human behavior, as well as contemporary behavioral theories from related fields (Batty, 2013).

Ultimately, advances in GIS, big data, computational power, and analytical techniques have helped revive the notion of modeling the city in order to optimize its functions (Townsend, 2013). Major firms like IBM and Cisco now seek to apply their expertise with technology and business consulting to urban problems in three ways:

- **instrumenting** the city with sensors gathering real-world data;
- **interconnecting** these data stores to make them accessible in a structured format; and
- using **intelligent** software to yield new insights or activate responses in real-time or the future (Harrison et al., 2010).

This approach to smart cities is predicated on capturing all available data generated by the city and its citizens, and providing administrators with seamless control over urban systems (Greenfield & Kim, 2013).

**Pluralistic models**

Meanwhile, a movement of researchers, activists, and entrepreneurs have been reshaping urban space from the bottom up (outside formal government channels), using the Internet to connect and mobilize communities, and applying digital technologies directly to enable new forms of urbanism. This “do-it-yourself (DIY)
urbanism” broadly encompasses such diverse and colorfully named activities as citizen science, timebanking, flash mobs, guerilla gardening, and open data hacking (Iveson, 2013). What these activities have in common is the use of interfaces to engage citizens directly about unseen processes in the city, such as emerging subcultures, new mediums of exchange and sharing, new practices in sensing and surveillance, or changes to urban form (Foth, Forlano, Satchell, & Gibbs, 2011).

While many of these projects manifest in temporary, small-scale experiments or installations, some have the potential to transform how cities operate at large. Howard Rheingold authored an early glimpse of how “smart mobs,” empowered by mobile, location-aware technology, could self-organize to perform logistically complex tasks in cities, such as surveillance, demonstrations, and sharing public goods (Rheingold, 2003). Clay Shirky has written about organizing without organizations, and how groups can spontaneously achieve certain kinds of production without an institution coordinating their efforts, such as in the early formation of Wikipedia (Shirky, 2009). Researchers in computer science, cognitive science, management studies, and the social sciences have converged on the study of “collective intelligence,” the ability of crowds of independently acting people to solve problems of cognition, coordination, and cooperation (Surowiecki, 2005). "Crowdsourcing" is the art of marshalling the collective intelligence of crowds using information technology, and urban planners are grappling with how to crowdsourced public participation in the planning and design of cities (Brabham, 2009).

Rise of urban crowdsourcing
Several high-profile successes of crowdsourcing, including Amazon’s Mechanical Turk\(^2\) service and the protein folding game Foldit\(^3\), have shown that the natural ability for humans to recognize patterns outpaces computers, and how incentive structures can guide large disconnected groups to cumulatively perform high-level tasks. Mechanical Turk allows users to distribute a large number of cognitive tasks to the browser screens of a global temporary workforce; by paying small amounts for short, discrete user tasks, the system can quickly scale up efforts like transcription, editing, image categorization, and surveying (Kittur, Chi, & Suh, 2008). With Foldit, thousands of video gamers solved puzzles that predicted the actual structure of proteins; its successor, EteRNA\(^4\), used such solutions to develop rules for RNA folding that were then tested in real-world biochemistry labs (J. Lee et al., 2014).

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\(^2\) [https://www.mturk.com](https://www.mturk.com)  
\(^3\) [https://fold.it/](https://fold.it/)  
\(^4\) [http://eterna.cmu.edu/](http://eterna.cmu.edu/)
Another high-profile success is OpenStreetMap\textsuperscript{5}, an online, publicly accessible, digital world map built solely through the efforts of volunteers. Each volunteer can contribute or edit road segments, points of interest, and other geographic features on a web-based map using digital image overlays or GPS traces as a guide (Haklay \& Weber, 2008). Their cumulative work rivals the detail and accuracy of proprietary, professionally generated datasets, though this quality varies by location (Barron, Neis, \& Zipf, 2014; Haklay, 2010). Volunteers are motivated by intrinsic rewards, such as those related to community, learning, and a recognition of the value on freely available mapping data (Budhathoki \& Haythornthwaite, 2013). Outside communities can also organize around an immediate humanitarian need, such as the crowdsourced effort to rapidly build out the network of streets and refugee camps in Haiti following the 2010 earthquake (Palen, Soden, Anderson, \& Barrenechea, 2015).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Growth in detail of OpenStreetMaps in Paris and Washington, D.C.}
\end{figure}

These screenshots contrast the state of the OpenStreetMap dataset for Paris (top) and Washington D.C. (bottom) in 2007 and 2014. All geographic features, such as walking paths, place names, and building footprints, were crowdsourced by many independent volunteers. Source: (Clarke, 2014).

\textsuperscript{5}https://www.openstreetmap.org
These examples are highly relevant to urban sensing systems, which also operate under tight constraints of data complexity and spatial dispersion, incomplete information and emergent behavior. In the urban context crowdsourcing has been used to good effect in detecting certain types of problems. SeeClickFix\(^6\) provides a global portal for citizens to report on broken sidewalks, graffiti, and other non-emergency issues that cities must nonetheless respond to (Mergel, 2012). Ushahidi\(^7\) is a platform for rapidly receiving localized crisis information, such as violent crimes or natural disasters (Okolloh, 2009). LocalData\(^8\) is a smartphone app that allows community-based organizations and municipal employees to gather data useful to urban planning, such as abandoned buildings or environmental violations, more quickly than centralized census or surveying (Rouault, 2013). Each platform uses smartphone and web interfaces to remotely gather information on the city's state, while cleaning and mapping these data for those with the resources and mandate to respond.

Open311 and open data

One area that combines the top-down management of the city with participatory, crowdsourced urban sensing is 311 systems, which began as dedicated phone lines for citizens to access non-emergency public services. In the early 2000s, cities began to consolidate their various department call centers into 311-phone systems, unlocking two benefits: collecting more and better reports on urban maintenance issues, and aggregating data to map and predict patterns of those issues (D. Offenhuber, 2014). With the advent of smartphone 311 apps, they could collect richer data such as location coordinates, timestamps, service categories, and photographs, making web map mash-ups a common interface for publicizing these data online. Many US cities adopted the "Open311" protocol to standardize the data formats they collect from phone, web, and mobile (Desouza & Bhagwatwar, 2012). In New York City, analyzing 311 data helped the city identify the source of a mysterious, neighborhood engulfing odor, crack down on public drinking stemming from illegal social clubs, and prepare seasonal air conditioner recycling programs (Johnson, 2010).

In parallel, local governments are increasingly adopting "open data" policies that make information held by government agencies, such as crime statistics, restaurant inspections, and mass transit data, accessible to the public in digital format (Goldsmith & Crawford, 2014). These data, generated both from within the agencies through their primary activities and from Open311 systems, make it possible for citizens to build their own practical applications (such as tracking the arrival of a bus at their stop) or perform their own analyses of urban service

\(^6\) http://en.seeclickfix.com/
\(^7\) http://www.ushahidi.com/
\(^8\) http://localdata.com/
performance (Davies & Bawa, 2012). However, open data policies also risk empowering some groups over others, particularly those with the technical and social knowledge to utilize these datasets over the poor and isolated; Gurstein (2011) argues for an “effective data use” model that considers the infrastructure, training, and advocacy needed to cross this “data divide”.

Smart cities and solid waste systems

In summary, this recent wave of smart city projects, proposals, and research seek to use sensing technologies, data analytics, and digital interfaces to understand and solve urban problems. Many of these purport to improve the efficiency and quality of urban services and infrastructure, such as mass transit, emergency response, air and water quality, etc (Harrison et al., 2010). Improved systems for solid waste are commonly included in smart city definitions, because of both the potential cost savings from optimizing operations, and sustainability outcomes in emissions and disposal impact (Lazaroiu & Roscia, 2012). Which aspects of waste management are addressed, such as collection or disposal, vary by city and are path-dependent (Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014).

ISO 37120, a set of city indicators for quality of life and sustainability, measures solid waste outcomes based on per capita generation, recycling diversion rates, and hazardous material handling (Karayannis, 2014). Such goals also align with the concept of zero-waste cities, for which the main benefits are less energy, water, and emissions used in processing virgin materials by recycling (Zaman & Lehmann, 2013). Yet, in the smart cities literature there are few examples or proposals for collecting spatial data on the generation and transport of waste. A recent Accenture report touts improved waste-to-energy plants as a key smart waste technology (Accenture, 2011), and disposal techniques tend to get more attention than collection systems or behavior change.

Waste tracking approaches and technologies

While operating municipal solid waste systems, local governments and service providers must constantly track the amounts of material they collect; national waste management laws often mandate this data collection for long-term planning (Beigl, Lebersorger, & Salhofer, 2008). However, with the exception of a few Pay-As-You-Throw cities where garbage is weighed at the household level, collected waste is weighed by the truck-load at transfer stations and within sorting, recycling, and disposal facilities, with paper or electronic manifests documenting the flows. The collection trucks themselves may be tracked using GPS sensors, for operations management purposes (Nguyen & Wilson, 2010). Planners must rely on life-cycle assessment models that project the generation of waste at the household, city, and regional scales, in order to make spatial and environmental decisions (Cleary, 2009). Thus, the primary technologies developed
to track waste focus on data input at waste handling facilities, vehicle GPS tracking, and decision-support tools.

One avenue for improving collections is better route planning to minimize fuel, labor hours, and emissions costs while maintaining level of service. Improved models of the city, such as going from two-dimensional representations of space to 3D GIS models, can help in calculating more optimized routes (Tavares et al., 2009). Advanced predictive models can allow services to anticipate daily household waste generation, allowing for dynamic collections (Tan, Huang, & Cai, 2010), and specifically use large, fine-grained datasets on current behavior (essentially, "big data" on trash) that municipal governments have struggled to utilize effectively (Song & He, 2014). Simulations that incorporate urban growth models can also plan for waste systems that effectively respond to changing populations and material flows (Fujii et al., 2014).

Another avenue for improving collections is in smart infrastructure, primarily focusing on sensors on trash bins and collection vehicles to track their state. This allows cities to optimize their collection of waste by preventing overflowing bins with their subsequent hygiene and aesthetic problems, while minimizing unneeded collection trips to empty bins. Strain sensors and cameras inside trash bins allow us to estimate the weight, volume, and type of material remotely (Vicentini et al., 2009); this information could be collected at pickup over RFID by receivers in the truck (Arebey, Hannan, Basri, Begum, & Abdullah, 2010) or transmitted over mobile networks for real-time awareness of fill levels (Longhi et al., 2012). Such smart bins are increasingly common in developed world cities, and have been shown to significantly reduce operating costs, collection and hauling distances, and labor hours, when paired with dynamic routing (Johansson, 2006).
Figure 5 Screenshot of animated visualization of smart trash can fill level in Boston.

This visualization uses data generated by Big Belly trash cans, which can wirelessly notify a server when they are half and nearly full. The city of Boston uses these real-time data to dynamically route its collection teams, and has recently made some of the data publicly available through their open data portal. The animation was generated using CartoDB, a web-based GIS software. Source: (D. Lee, 2015)

Source separation is another area of engineering focus. The growing prevalence of electronic identifiers, such as RFID tags on packaging or wireless capabilities in Internet of Things (IoT) objects, could aid in the automatic separation and recycling of mixed waste streams (Abdoli, 2009). These could allow us to track objects as they travel through various transfer points and recycling facilities, provided that there are RFID readers installed at all possible endpoints of the system (Humeres, 2012). Permanent identifiers also allow us to track the entire lifecycle of products, enabling deposit-rebate programs that would incentivize product return (Kahhat et al., 2008). However, there is a small but quantifiable risk of contamination when these electronic tags enter the disposal or recycling phase for papers, plastics, and other materials (Wäger, Eugster, Hilty, & Som, 2005).

Another area of focus is in driving more "sustainable" behavior among citizens, such as recycling, waste reduction, and reuse. Technology may provide feedback to citizens on how much material they throw away, incentivizing less waste generation or more recycling. For example, residents of Seoul have been required for years to dispose of waste in special plastic bags purchased within their district, tying a cost to the volume of waste generated (S. Lee & Paik, 2011). New intelligent
garbage bins there now require the owner to self-identify with an RFID card, measure the waste by mass, and charge proportionally. This also allows the information to be fed back immediately to the resident via web interface, and provides the city with behavioral data at the individual level; the bins have demonstrated a 33% reduction in food waste (Hong et al., 2014).

Finally, cities in developing countries have the option of adopting the technologies they see fit, as they attempt to upgrade their capacity to manage waste. As concerns over public health and environmental impact become internalized in policymaking, officials increasingly employ tools like GIS to site landfills and protect local air and water resources (Leao et al., 2001; Sumathi, Natesan, & Sarkar, 2008). However, because of the importance and prevalence of the informal sector in these cities, researchers also develop technologies unique from those seen in developed countries, aimed at supporting the work of informal waste workers. These tools, such as automated data entry for mass balance records (Fergutz, Dias, & Mitlin, 2011) could be seen as an alternate path for smart waste systems in rapidly growing cities around the world.

Summary and intended contribution
Solid waste management is a long-standing and important problem for urban planners, one that depends on available technology and environmental design. Cities face rising amounts of waste generated, but limited resources and space to manage this flow. ICTs could have a big impact on solid waste management, which has long been an opaque, but essential urban service, by visualizing its operations and spurring improvements. Smart cities may choose to optimize their existing systems or engage stakeholders in rethinking those systems completely, with different implications for technology development, interface design, and urban services model. However, there are few real-world smart waste system proposals that would generate more detailed or unique data than currently exists.

Waste tracking technology is still in infancy, but fine-grained location data could serve many applications and form the foundation for smart waste systems. Beyond the Trash Track project in 2009, which used GPS trackers to remotely follow waste through the Seattle waste network (Boustani et al., 2011; Phithakkitnukoon et al., 2013), there have been few attempts to track solid waste movement with this specificity. This thesis and its papers seek to define what knowledge can be gleaned from waste tracking, what value it holds to different stakeholders, how it could be made accessible using maps and visualization, and what a smart waste system could look like in a variety of contexts.
Five Essays on Waste Tracking Systems

This dissertation consists of five research papers, each presenting a separate project or experiment, but all using location tracking to enable smart waste systems. Each project builds off a novel technology developed to close the loop between sensing how cities operate and engaging stakeholders with this knowledge to take action.

Research questions

As stated earlier, the overall goal of this dissertation is to understand how waste tracking technologies enable smart waste systems in cities. Through these five projects, I explore the following questions about the development of these systems:

- What unique datasets can smart waste systems generate and utilize using location tracking?
  - How do these data relate to current problems in MSWM?
  - What specific technologies can be used today, and what are their limitations?
- How can cities apply these data internally to operational improvements in waste collection, reduction, and disposal services, achieving their goals more efficiently?
- How can cities apply these data to engage individual stakeholders in the general public to participate in waste planning and help determine what those goals are?
- How should cities in developed and developing countries proceed in designing smart waste systems?
  - What are some future research directions that could support these recommendations?

Background research covered in each essay

Listed here are topics specific to the questions and technologies explored in detail in each paper:

<table>
<thead>
<tr>
<th>Paper title</th>
<th>Topics reviewed</th>
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<tbody>
<tr>
<td>1 Learning From Tracking Waste: How Transparent Trash Networks Affect Sustainable Attitudes and Behavior</td>
<td>Behavior change through information feedback, Recycling behavior factors, Knowledge deficit theory</td>
</tr>
<tr>
<td>2 Monitor: Tracking the global flow of e-waste exports using GPS and smartphones</td>
<td>Electronic waste definitions and disposal risks, International export of e-waste and regulations, Cathode ray tube smuggling and black markets, Waste tracking technologies</td>
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| 3 | Designing Location-Aware Applications for Informal Waste Recyclers in Brazil | Location based services in logistics, shipping  
Informal waste collection and tech in Brazil  
Information and communications technologies for development (ICT4D) (appendix)  
Informal waste systems worldwide (appendix) |
| 4 | Mapping the Waste Handling Dynamics in Mombasa Using Mobile Phone GPS  | Waste management issues in Mombasa, Kenya  
Integrating informal work into municipal systems  
Waste tracking technologies |
| 5 | CityEye: Real-time Visual Dashboard for Managing Urban Services and Citizen Feedback Loops | Open311, GIS, and urban maintenance  
Urban data dashboards  
Smart city infrastructure in Spain |

Table 4: List of literature topics reviewed in each paper.
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<tr>
<td><strong>Title</strong></td>
<td>Learning From Tracking Waste: How Transparent Trash Networks Affect Sustainable Attitudes and Behavior</td>
<td>Monitour: Tracking the global flow of e-waste exports using GPS and smartphones</td>
<td>Designing Location-Aware Applications for Informal Waste Recyclers in Brazil</td>
<td>Mapping the Waste Handling Dynamics in Mombasa Using Mobile Phone GPS</td>
</tr>
<tr>
<td><strong>Paper completed</strong></td>
<td>2010</td>
<td>2015</td>
<td>2014</td>
<td>2015</td>
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<tr>
<td><strong>Where</strong></td>
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<td>California, USA and various countries in Asia</td>
<td>Recife, PE, Brazil</td>
<td>Mombasa, Kenya</td>
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<td><strong>Partner</strong></td>
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<td>Basel Action Network</td>
<td>Informal recycling cooperatives</td>
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<td>Smartphones, GPS sensors, online mapping</td>
<td>Smartphones, online mapping</td>
<td>Smartphone and web applications, GIS, open data</td>
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<td><strong>Technology created</strong></td>
<td>System for tracking trash movement and displaying in real-time</td>
<td>System for tracking e-waste movement worldwide</td>
<td>System for tracking real-time locations of waste-picking trucks</td>
<td>Interface for viewing urban service operations in real-time</td>
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<tr>
<td>My technical contribution</td>
<td>Research questions</td>
<td>Published?</td>
<td>Methods</td>
<td></td>
</tr>
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<td>---------------------------</td>
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</tr>
<tr>
<td>Backend programming, data cleanup, real-time website, survey design and execution</td>
<td>Can we make waste systems transparent by participatory sensing? How does this affect sustainable attitudes and behavior?</td>
<td>Yes, 2014</td>
<td>Design and implementation of technology, survey and quantitative analysis</td>
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<td>Design and implementation of technology, field observation, interview</td>
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<td>App development, survey design and execution</td>
<td>How can we design real-time logistics systems for informal groups of workers?</td>
<td>Yes, 2015</td>
<td>Design and implementation of technology, field observation, interview</td>
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<td>Backend and web development, data cleanup</td>
<td>How can informal waste collectors record and retain tacit knowledge about the informal settlements where they operate?</td>
<td>Yes, 2015</td>
<td>Design and implementation of technology, user testing, unstructured survey</td>
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<td>Project management, data analysis and cleanup</td>
<td>How can cities with contracted, formalized urban services engage citizens in operations decisions and issues reporting?</td>
<td>Yes, 2015</td>
<td>Design of technology, user interface prototyping, document analysis</td>
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Table 5: Matrix of essays, technical contribution, research questions, and methodologies.
Paper Summaries and Findings

Paper 1

*Learning From Tracking Waste: How Transparent Trash Networks Affect Sustainable Attitudes and Behavior*

In 2009, as a member of MIT Senseable City Lab, I helped execute Trash Track, a project to map out the movement of over two thousand discarded objects in the Seattle waste stream. With the help of hundreds of volunteers, we tagged the waste items with GPS location sensors that could report back over mobile phone networks and deployed them into recycling, trash, and takeback bins across the city. The results of this crowdsourced research effort revealed the characteristic distances traveled by different types of waste, the relative benefits of recycling when accounting for transport, and the unpredictability of movement for electronic and hazardous waste (Dietmar Offenhuber et al., 2012).

![Process diagram for Trash Track experiment.](image)

For my first paper, I ran an experiment concurrent with the Trash Track project on how making the movement of waste visible to the public might affect people’s attitudes or behaviors towards sustainability. For this purpose, I designed and launched a real-time mapping website that visualized the locations of items in the Trash Track project. Using this application, both the volunteers and members of the public could view the latest positions of over a thousand tagged trash items, filter by type or ownership, and zoom in to see the full path of any individual item. I ran surveys with website users before and after they viewed the visualization, asking questions about recycling, e-waste handling, and other aspects of waste disposal. My regression models showed significant changes in their knowledge but not in sustainable attitudes nor behavior.

This project, as a follow up to the original Trash Track experiment, was a revealing exercise in the challenges and limitations of using information feedback to
transform waste practices. Smart city systems that aim to shift citizen behavior towards sustainable practice must go beyond informing and educating citizens. Even with a completely novel dataset that reveals the consequences of one’s actions, deeper and persistent engagement may be needed to achieve lasting behavior change. Redesigning the interface according to advanced theories on behavioral nudging could increase the effectiveness of this data feedback. Scaling up the technology could in turn spread its reach to a much larger population, whether through a top-down effort to track waste at the city scale, or through a crowdsourcing project spurring independent deployments of sensors from communities across the world.

Paper 2

**Monitour: Tracking the global flow of e-waste exports using GPS and smartphones**

Our subsequent work showed that GPS-based remote location sensing could allow individuals and NGOs to track e-waste and uncover fraud and abuses in the waste stream, without the full cooperation of public authorities, nor direct access to the logistical infrastructure linking the countries.

The original Trash Track project data had suggested that some e-waste components were shipped overseas. Expanding our investigation to international flows of waste presented an opportunity to investigate the export of hazardous electronic waste, whose trade is strictly regulated by many countries because of its health and environmental risks. In the US, there are various state and local laws restricting export of cathode-ray tube (CRT) monitors, a potential source of lead and heavy metal pollution, but companies can secretly resell these to recyclers in developing countries while appearing to comply. With federal agencies unable to enforce all of these rules universally, non-governmental organizations (NGOs) are stepping in to track this e-waste trade and block it wherever possible.

In this project we deployed phone and GPS-based location trackers inside CRT monitors that were dropped off with electronics recyclers in Southern California. The trackers allowed us to follow some of these monitors to port facilities, where they disappeared only to reemerge across the Pacific in Vietnam, Malaysia, and China. The records sent back by the trackers showed the ports of entry and potential endpoints for this smuggled waste. Photographs taken by the sensors showed the warehouses and storage piles where these monitors ended up. Further field investigations determined where the handoffs occurred along the smuggling routes, possible end uses for the waste, and other possible ports of entry.
Such results have led to official enforcement action by the customs and environmental protection agencies in both exporting and receiving countries. They also allow us to fully map completely unknown smuggling routes and markets that bring hazardous waste overseas to often poorer, less protected communities. Ultimately, these could contribute to a broader awareness campaign that encourages public debate on our generation and handling of electronic waste.

Figure 7 Photograph of e-waste smuggling activity on Vietnam-China border.

Paper 3

*Designing Location-Aware Applications for Informal Waste Recyclers in Brazil*

The third paper looks at the issues faced by informal waste systems, and how to design technology to enhance these systems while remaining appropriate to their context. Overall, the project demonstrates how cooperatives can use location tracking and digital interfaces to make their operations transparent to themselves and their institutional partners. Such systems allow smaller informal groups to operate more efficiently while meeting modern government needs for waste oversight and responsive service.

In many developing cities recycling activity is dominated by informal, fragmented layers of waste pickers, middlemen, and industrial plants. They are no less effective than centralized systems at recovering a large portion of discarded recyclable materials, but their history, culture, and organizational structure defy efforts to formalize and unify these activities into a centralized, controllable system. Improving the performance and sustainability of these systems requires a
different set of assumptions and values from designing technology for formalized urban services.

Forage Tracking is an ongoing research effort initiated in Sao Paulo, Brazil, where my colleague Dietmar Offenhuber and I tested GPS technologies for supporting informal waste picking activities (D. Offenhuber & Lee, 2012). We partnered with recycling cooperatives in Recife, Brazil, to deploy a tracking system for their trucks that let them remotely manage collection routes in real-time, while streamlining documentation of their collection activities per government regulation. It consisted of a smartphone-based tracker installed inside the cab of the recyclers’ trucks, and a web application accessible from any Internet browser.

The web interface allowed cooperative members to view their trucks’ progress from their office, and identify possible opportunities, delays, and alternate routes. The tracker itself was an application installed on a mid-range smartphone with a data subscription, passively collecting location data on the truck’s whereabouts. It also allowed the collection team to document any special waste they receive for disposal, such as electronic waste, with a photograph, timestamp, location, and client information.

Figure 8 Photograph of waste truck tracking application in Recife, Brazil.

This project used a smartphone carried inside the collection truck, with a mobile application delivering stop information and real-time location to the cloud-based server. A web mapping application allows the cooperative to observe the truck’s routes and share these data with public and private stakeholders.
From our fieldwork in both Recife and Sao Paulo, we learned several of the design constraints facing waste pickers, such as widely variable literacy and technical skills, perceived risk at carrying around phones while out on foot, and repetitive data entry for reports to industry and government. We incorporated this work from previous software prototypes with the cooperatives in Recife and learned from their feedback, making this an iterative design process that could be classified as participatory design.

Paper 4

*Mapping the Waste Handling Dynamics in Mombasa Using Mobile Phone GPS*

The fourth paper shows how location data collected by the informal sector can inform municipal planning for waste and land use. It is an exploratory work on introducing tracking technology to areas where waste collection is even further fragmented into many small informal groups and collection services.

Our experiment took place in a neighborhood of Mombasa, Kenya, where municipal services only cover a fraction of households, and local informal workers with hand-carts collect waste door-to-door for monthly subscription fees. The city’s design greatly impacts the structure of the system; collection routes overlap in the densest gathering points of the city, temporary dumps occupy unused land as makeshift transfer stations, and public dumpsters handled by the government are concentrated along arterial roads that can fit the large trucks.

Here, we deployed a system similar to Forage Tracking, using GPS loggers and phone-based trackers to map the collection activities of the informal groups. Since these collectors operated using hand-carts, data collection was more passive with the results mapped and viewed through a web application in a follow-up meeting. Through interviews and field observations we further studied how the waste collectors operated and adapted to each community they served. Finally, we shared these data with the municipal government to understand what value it might provide for their waste management efforts across the city.
The left image plots the raw GPS data from our smartphone application, taken at regular intervals and shifting from blue to red hues. Areas of dense markers indicate collection stops. The base map was generated from OpenStreetMap, and the lack of geographic details is typical for an informal settlement area. The right photograph shows a workshop held with an informal collection group, where members used maps to debate operational improvements.

Our findings revealed some insights on how the municipal government could act to better integrate informal collection into the waste system of the city. For example, there were commercial areas where collectors visited frequently to haul away waste; a municipal transfer point could be relocated closer to these hotspots to reduce the time and labor spent by the various groups and ensure the waste would not be dumped elsewhere. Other areas of cooperation would benefit from an understanding of how the collectors selectively visit spatially dispersed customers in order to maximize profit. The data provided common ground for learning and dialogue in a subsequent participatory design exercise between the waste groups and local officials.

One additional finding was that spatially mapping the waste collection dynamics (path taken through neighborhoods and amount of time spent at each stop) allowed us to infer characteristics of the built environment, such as building density, land use, and road hierarchy. Such observations, coupled with further crowdsourcing efforts, could help planners update their spatial information on informal areas that are poorly surveyed or rapidly changing.

Paper 5

CityEye: Real-time Visual Dashboard for Managing Urban Services and Citizen Feedback Loops
In partnership with Ferrovial, an urban services company most active in European cities, we designed a platform that not only connects citizens to services like trash collection through issue-reporting, but visualizes their real-time operations for those citizens to see. CityEye addresses a common application of crowdsourcing in cities: gathering place-based information on needed public repairs or services. Such applications rely on citizens to submit eyewitness accounts of non-emergency problems, such as broken sidewalks or uncleaned streets, to guide or pressure local governments to resolve them. However, despite the growing use of citizen feedback applications, local governments continue to base waste collection contracts on a regular schedule of collection activities, rather than evaluating whether the service met the demands of the city's residents in a timely manner.

We designed CityEye primarily as a web-based visualization dashboard and a smartphone application that serves as both dashboard and feedback tool. The application would allow users to view the real-time locations of vehicles and service teams operated by Ferrovial in a city, as they operate routes collecting waste. It presents historical data on the service level of units, routes, and areas of the city through place and graph-based visualizations. Further layered on this are real-time urban datasets such as traffic congestion and noise pollution, as well as feedback from other citizens on the need for or quality of service. The trash trucks themselves could further act as a mobile sensing platform measuring pollution and light levels throughout the city.
Ultimately such a system would allow citizens to scrutinize the efficiency and effectiveness of the waste system, well beyond their own personal experience. Unequal levels of service in different parts of the city would become transparent, as shown through the performance indicators for those routes and public complaints from residents. The relationship between waste service, human activity, and the environmental quality of place could be explored through the visualization of these data in layers. Furthermore, with equal access to this information across citizen, service provider, and government, the relationship could alter to one where each stakeholder communicates directly to the other two, reducing the abstraction of urban services and rewarding service providers for maintaining a high quality urban environment.
Conclusion

This chapter concludes with a brief discussion of the results of the five papers as they relate to the research questions, general recommendations for planners that follow from these results, and future research directions that would apply this approach to new contexts.

Discussion on research questions

What unique datasets can smart waste systems generate and utilize using location tracking? How do these data relate to current problems in MSWM? What specific technologies can be used today, and what are their limitations?

Location tracking enables us to follow individual waste items from the consumer to the trash bin to the disposal site, detailing the businesses, facilities, and routes taken along the way. It reveals the distances travelled by different kinds of waste, and how household decisions around waste generation and source separation affect how much material ends up in landfills. It also can reveal flaws or abuses, such as illegal e-waste export, and detail the means by which these problems occur. Such information is unknowable to planners relying on voluntary surveys and audits to understand where waste is sent, let alone the general public who might reconsider their actions with full knowledge of waste outcomes. Durable, long-lasting, concealable GPS trackers communicating over wireless networks are the key technologies to tracking waste without the cooperation of every member of the removal chain, but their widespread use is limited by cost, size, lifespan, area of operation, and environmental impact.

Location tracking also allows us to map the movement, effective service area, and service demand met by informal waste collectors and cooperatives, in a relatively inexpensive way. These data illustrate the scale and geographic reach of informal recycling, crucial for understanding whether this activity can continue as an equal or superior method of waste management in developing cities. They are also a prerequisite for smoother cooperation between informal waste workers and public and private institutions seeking to utilize their services. The important technologies here are smartphones with location sensing via GPS and wi-fi triangulation, and software apps to enable waste pickers to collect and manage these data. However, we are currently limited by hardware and data service costs, perceived security risk, incomplete wireless network coverage, and lack of user interface research in these contexts.

How can cities apply these data internally to operational improvements in waste collection, reduction, and disposal services, achieving their goals more efficiently?
Real-time awareness of waste movement allows swifter response to problems that may emerge. Such data can prompt authorities to investigate and shut down illegal dumping or smuggling activities, as demonstrated in the Monitour project. NGOs also can mount their own investigations of these violations, keeping pace with rapidly shifting trade networks, while relieving the burden on government agencies who lack the resources or political will to apply location tracking technology themselves. On a more mundane level, residents reporting waste service problems using 311-type mobile applications can generate up-to-date, rich, actionable information on waste system performance more quickly and cheaply than direct government monitoring, saving time and money while maintaining a high quality of service.

For informal waste cooperatives in Recife, affordable real-time vehicle tracking could greatly improve their ability to react to problems or opportunities, plan efficient routes, and reduce the costs of data reporting to regulators. By reducing miscommunications with clients, time lost to congestion, and unnecessary trips, the cooperative also reduces fuel use, maintenance costs, labor hours, and conflicts within and without. In informal areas such as the study area in Mombasa, tracking also allows planners to account for informal workers and dumpsites when planning new infrastructure that would complement, rather than duplicate, these functioning systems in place. In both cases, the tracking data mediate between the formal and informal stakeholders, and define the issues and space within which they can cooperate.

How can cities apply these data to engage individual stakeholders in the general public to participate in waste planning and help determine what those goals are?

First, the data generated from waste tracking can be returned to the resident as feedback on their personal actions, as we demonstrated in the Trash Track project. This information could initiate reflection and change in behavior, such as greater care taken in separating recyclables or disposing of hazardous waste, though such outcomes might require engagement beyond the feedback of data.

Second, data that reveal illegal waste handling may also influence public opinion, either raising awareness of the issue or changing opinions on its severity. With this knowledge in hand, citizens can better decide their political positions on such problems. Activists too can incorporate these data into efforts to pressure officials who are responsible for legislating and enforcing preventative laws.

Third, an issue reporting application like CityEye can elevate the opinions of individual citizens on the waste collection and street cleaning service above traditional metrics, such as adherence to predetermined schedules. Given the
means to rate satisfaction with the cleanliness of an urban area, citizens could
determine when a service provider is seen by the city as successful. Visualizing
data on the actual movement and activity of service crews can provide the context
necessary for citizens to suggest alternative criteria and improvements of their
own.

Recommendations

_How should cities proceed in developing smart waste systems?_

Here are six general recommendations to city officials, planners, and service
operators that follow from our findings:

1. _Generate unique datasets not being gathered through existing
means or technology._

Much of the data that waste systems generate currently is underutilized. The
barriers to integrating the electronic databases of waste handlers, disposal sites,
producers, recyclers, and governments are organizational; Waste Management,
Inc and SAP’s attempt to implement a company-wide “enterprise resource
planning” system failed because of poor cooperation between the companies,
rather than any technical constraints (Kanaracus, 2008). Cities and companies
that sustain interest in their waste removal chains will eventually overcome these
barriers, and integrate these data into their regular understanding of waste
management.

However, the types of data they will be gathering will still not cover the entirety of
waste outcomes, such as the alternative collection systems run by informal or
unlicensed operators, reuse and recycling by private individuals, illegal dumping
and export, and the sometimes roundabout paths taken by individual items of
waste. These outcomes can be detected and understood better with new
methods, enabled by technology developed on the margins. Cities and waste
operators should invest in developing these technologies, and the means to
evaluate their results, to capture the successes and failures hidden behind the
limited view that formal operations data provide.

2. _Generate data in places where little exists._

Waste tracking using location sensors like GPS is particularly important for
generating data where it has traditionally been sparse. For solid waste systems in
general, that means the long stretches of distance between cities and the landfills
or other destinations where they send their trash. For much of the world, it means
the vast informal settlements within and on the margins of cities that lack detailed
maps, let alone any operational data on the myriad services and systems that
make these places habitable. In the case of illegal dumping and export, it’s the rural areas and open sea expanses through which materials are transported and left temporarily or permanently.

The uneven quality of geographic data across time and space is a fundamental problem for planners seeking to improve waste system efficiency, exert quality control in problematic areas, and counteract illegal activities. Crowdsourcing offers some ability to engage large voluntary groups willing to lend their time, expertise, or local knowledge to filling in information for less-well-documented areas, and we can piggyback on informal activities to capture even more of the full picture.

3. Use waste movement as a proxy for other urban activity.

In Recife, we saw how location data from the hand-cart waste pickers could reveal accessibility issues for pedestrians in parts of the city. For example, in Sao Paulo the hand-cart picker would avoid crossing certain streets and districts, because of high automobile traffic or steep inclines. Such issues are not well documented everywhere, and the data could be useful to planners. Similarly, the waste pickers are keenly aware of the relative security of their areas.

In Mombasa, we also saw that the traces could hint at land use characteristics of their working areas, such as residential buildings of varying density and commercial hubs. Such data are especially valuable in places where up-to-date geographic data, even that from crowdsourced efforts like OpenStreetMap, are not as detailed or available.

In Monitour, though we did not explicitly explore this possibility, the smuggling routes used to carry valuable e-waste across borders are also possible routes for other types of contraband, such as human slaves, drugs, and counterfeit goods. We know that this was the case for Mong Cai, which was infamous as an entry point for all of these trafficking activities; the same infrastructure and corruption that enabled the free flow of one type of contraband would allow for the others as well (Bland, 2012). Thus e-waste tracking could become a valuable tool for other efforts to secure borders and track down illegal smuggling rings.

4. Bring waste “closer” to us, in visibility if not in physical space.

While it’s not clear whether the increasing distances waste travels away from us has caused a change in our attitudes towards its generation and management, these have certainly coincided. Engler (2004) argues that this distance, both in physical terms and in mental awareness, has encouraged a culture of consumption and waste. At the least, it has made the average citizen less aware of where their waste goes and what resources and planning are required to make it
disappear. This hampers efforts to broaden the public debate on what the desirable outcomes are and how to achieve them, as people are less knowledgeable and less interested in the topic.

One way is to bring waste closer is to open waste management data to public, in raw and visualized forms. For example, cities can include waste generation and recycling benchmarks on their public websites, and release daily statistics as open data. The positions and routes of collection and hauling trucks can be shared and mapped in real-time, as we proposed in CityEye. Boston released data generated by their Big Belly smart trash cans, which reveal the uneven landscape of waste generation in public space (see Figure 5). All of these datasets, in the hands of individual residents and NGOs, could be further analyzed, visualized, and used to further public debate on the performance and desired outcomes of municipal waste systems.

5. Seek both operational efficiencies but also participation and public satisfaction.

Often smart cities technologies are marketed to the public sector and public audiences in purely economic arguments. These improvements to operational efficiency, such as reducing fuel costs through better collection vehicle routing or profiting from diverting organic waste from landfill to composting, are certainly important and easier to achieve through big data analysis (Shahrokni et al., 2014). The short term gains from these often justify the costs of investing in technology in typically risk-adverse local governments, and ultimately drive upgrades to systems and rising standards.

However, public participation is another possible dimension for smart cities technologies to advance, and can be both a means and an end. Broad participation in projects such as Trash Track, or crowdsourcing systems like CityEye and 311 apps, enable much more effective data gathering in geographic area and scope. Citizens may also offer tacit knowledge about what problems exist with waste collection and disposal in their vicinity, or could provide out-of-the-box thinking on solutions to these problems. Their preferences ultimately matter in a democratic culture, and early engagement on the siting of transfer and disposal points in a city could avoid costly lawsuits and cancellations of these projects. To the extent that technology can enable participation to stakeholders that would otherwise be excluded from decision-making, it offers implicit value to societies where such participation is encouraged.

6. Smart waste systems should account for local tacit knowledge and preferences.
The tacit knowledge held by city residents, informal waste pickers, and urban services staff should not be ignored when evaluating the intelligence of the city’s waste system. Measuring only certain statistics on overall waste and recycling capture rates through the municipal collection system, as suggested by the ISO 37120 standard, leaves out many unmeasured activities by individuals that result in a cleaner, more sustainable city. Likewise, by those standards, small-scale cooperatives that provide waste services might not be as efficient compared to large, private, mechanized operators, but in some places residents may prefer the former because they provide needed jobs, produce less noise or air pollution, and are more reliable than government-managed services.

In our rush to modernize waste systems by applying technological solutions, we should not inadvertently push out the many informal, unseen processes that meet the local needs of communities. For that reason, it is impossible to recommend a single model as ideal for cities as diverse as Boston, Massachusetts and Sao Paulo, Brazil. Each city must make an effort to understand these processes, applying technology to measuring their impact as we have demonstrated in Brazil and Kenya. From a smart cities perspective, this aligns with both approaches described earlier; optimizing the waste system requires getting more complete data on how waste flows through these alternate pathways, while engaging stakeholders reveals new ways of defining success of the system.

Future research directions

What are some future research directions that could support these recommendations?

RFID citywide tracking project

The projects in this thesis that directly track the movement of waste are limited to only following a small sample of objects out of the many tons flowing through the city. GPS trackers are constrained by high cost per device, relatively large size, and finite battery life. To scale up and track larger volumes of waste within a city, we could consider using RFID as a base technology for identifying and sensing waste.

In this scenario, cheap passive RFID tags are attached to a batch of products or packaging, such as plastic detergent bottles. The tags are thin and light, using the induced current from RFID readers to bounce back a unique identifying code without need for a battery. In this way, thousands of disposable items could be made machine-readable from a distance, and identified even when bundled with other trash items without line-of-sight to the RFID reader.
Passive RFID tags are typically thin, light, inexpensive, and lack batteries, making them ideal for tracking items along an accessible supply chain. Image courtesy of Wikimedia, Creative Commons 2.5. Source: https://upload.wikimedia.org/wikipedia/commons/e/e8/RFID_Tags.jpg

When a tagged item is discarded, it can be scanned at multiple points along the waste stream: within the waste bins themselves, by the waste trucks at the point of collection (also giving us a full geographic path of the item if the trucks are themselves GPS-tracked), and at the entry points of transfer and disposal stations. Because the cost of RFID readers is higher and requires more infrastructure, installing them at transfer and disposal points is easiest and most cost-effective.

Residents participating in this project could also scan the tags themselves, using either the near-field communication (NFC) features of their smartphone or the phone's camera to read an accompanying bar code. This would provide a way to record a point of disposal, as an alternative to a reader-equipped waste bin, using the phone's location sensing and timestamp. As in Trash Track, the user could then follow the object in real-time as it is scanned at later points in the removal chain, just as they might follow a packaged shipped via UPS or FedEx.

This approach has been suggested in previous research, and proposed in a couple of student projects from the Digital City Design Workshop course at MIT. In the first, the tracking system would be applied to encourage source separation in public and household waste bins; residents who successfully send their tagged recyclables to the correct destination earn points for cash rebates. Such a system would generate a large sample of individual item traces to measure the success with which the city diverts and captures the value in these materials. The student
saw this working best in a city like Madrid with relatively centralized, formal waste collection (Humeres, 2012).

A second student proposed a similar system for Pune, India, as a way to track waste from personal hygiene products, such as sanitary pads and diapers. Such products present a health risk to the informal workers who touch waste directly, and local cooperatives encourage households to wrap these in special envelopes to be safely handled and diverted to incinerators. By tagging these envelopes, these items could be followed from user to waste picker to transfer and disposal points, with compliance earning the user points for discounts or donations to local causes. Over time, the data on where these products are discarded and transported could help the city expand its own biomedical waste collection services to absorb this waste stream (Rawoot, 2014).

In both examples, researchers need the full cooperation of city government, service operators, and producers to track this waste, as deploying the tags and reader infrastructure requires access to many facilities normally inaccessible to the public. The costs would also be significant, though still much more affordable than a similarly-scaled GPS-based tracking experiment. However, the information gleaned from even a single city would be truly unique, giving us a reliable and precise understanding of how large volumes of waste move through the city, and where the waste system is succeeding at diverting and properly handling different types of waste.

Informal waste systems in high-income cities
While informal waste workers are more visible and acknowledged in lower-income cities of the developing world, such activities remain common even in high-income countries like the United States. Homeless individuals can be seen in many cities sorting aluminum cans from public and residential waste bins, to be traded in for their deposit values. Junk dealers grab furniture, appliances, and other discarded items left outside the home to be scrapped or resold. Unused items can be sold or given away using online message boards such as Craigslist and Freecycle, or social networks like Facebook hosting local reuse groups.

This last phenomena is interesting because these are often spontaneous, peer-to-peer exchanges mediated through Internet communications. They are natural evolutions of similar “classified ads” in local newspapers, but more immediate and low cost. Understanding how these communities function, how much material is reused, what motivates participants, and the spatial reach of these networks could help cities encourage similar activities with minimal direct intervention. A research effort could focus on surveys and text analysis of particularly active online communities, such as the “reuse” mailing lists popular at MIT, or could involve building and testing a new digital platform where one doesn’t exist.
Elderly waste collectors in Asian cities

Rural-to-urban migration in China has led to explosive growth in urban populations, with all the attendant pressures on urban services such as waste management. Despite the lack of official recycling services offered by municipal governments, a significant amount of material is collected and recycled by informal workers, often elderly retirees seeking to augment meager pensions (Duggan, 2015; Griffiths, 2014). Even in Seoul, Korea, where municipal solid waste collection is strictly regimented and technologically advanced, there remain many elderly workers roaming their neighborhoods with hand-carts collecting scrap metal and corrugated cardboard for recycling (Koo, 2014).

Such workers face similar risks as informal collectors in developing world cities, such as unsafe working conditions, exploitation by organized crime, or lack of access to social services, while still delivering societal benefits by diverting material away from overburdened waste systems. The full extent of these networks remains unknown, and there is little academic research on these phenomena; a concerted research effort to map and document their activities could reveal to what degree they enable these relatively young Asian cities to grow rapidly. A future research project could focus on cooperating with these elderly groups, tracking their movements, measuring the scale of their activities and area of the city covered, and calculating the overall value they provide to the city in saved resources.

Extending location tracking technology

The GPS location sensors used in Trash Track and Monitour faced a number of technical limitations that prevented us from collecting complete and accurate traces. Further research and development of tracking systems could help overcome these limitations, and make it easier to track waste as it travels long distances from the city.

Power consumption, battery life – The finite battery life of the tracking devices compromises their function in two ways. The less time a tracker can remain active, the less likely we can detect its final resting point before it is destroyed, buried, or out of energy. Additionally, attempts to extend battery life add bulk and visibility to the tracker, making it difficult to conceal on smaller waste items. Optimizing the power consumption, testing new battery types, and exploring self-powering technologies like piezoelectric materials could help improve the functional lifetime of tracking devices.

Incomplete communication networks – Real-time trackers require some form of wireless communication channel back to servers. Unfortunately, mobile phone networks capable of carrying this information do not serve the entire globe, and are particular sparse in rural areas and non-existent over the ocean. This leaves us
with few options for transmitting data remotely from these areas, limiting our ability to track waste in the very places they are most likely to be smuggled or dumped. Experimenting with satellite-based communication networks could extend our reach to all points on the globe. Alternatively, ad-hoc communications infrastructures such as automatic packet reporting systems (APRS) could allow us to temporarily set up wireless communications in rural locations at less cost, but require us to anticipate the general areas we want to monitor in advance.

Occlusion from metal and other materials – Signal blocking from layers of debris or the walls of buildings and shipping containers also limit our ability to consistently receive data from the trackers. Beyond better power consumption (which could free space for a larger antenna and/or more powerful signal), we can experiment with different wavelengths of wireless communication, if we have some control over the spectrum available to us (as in the previous APRS example).

Size, form factor, durability – Most of these issues tie back to the size and shape of the tracking devices, which we want to make as inconspicuous as possible. Smaller components, more efficient power management, and lighter and thinner materials could further reduce the size of the trackers, allowing us to deploy them on smaller items such as discarded mobile phones and batteries. Durability is also a constraint, as methods to protect and pad trackers also increase their bulk; further experimentation with different materials would add to our knowledge of best practices.

Device contents posing a contamination risk – Tracking devices constitute a form of e-waste, and large numbers of them pose an environmental risk if not disposed of properly. Although in the long run, the benefits from knowledge gleaned from these experiments could outweigh the risks, we should still minimize these risks by reducing the amount of hazardous materials contained within each device. Miniaturizing the devices and reducing components and solder containing such materials would help, but the greatest improvement would come from developing self-powered trackers and eliminating batteries altogether.

Final thoughts
Some might look at the way solid waste is handled in developing world cities, and see them as primitive echoes of the past, stops along the path to today’s mechanized, centralized systems. I look at these cities and see the future of smart waste systems. The intelligence of a waste system, like that of any urban service, policy, or infrastructure, should depend on how well it responds to its city’s specific needs and leverages its unique advantages. In that sense, it is important to consider technology as lenses on the actual dynamics of waste, not just the machines that move it around.
The important common threads across the five papers presented are that location sensing technologies can give us a unique understanding of waste processes and outcomes normally unseen and unmeasured today, and that the data generated can engage more stakeholders in the planning of waste systems, rather than exclude them. To achieve these requires careful design of both the tracking devices and the interfaces by which we control and observe the resulting traces.

Smart waste systems can also change the interaction between citizen, service provider, and local government. Waste tracking data can reveal inefficiencies and fraud in waste disposal, allowing citizens to take personal or political action in response. Conversely, tracking data can build trust between stakeholders, allowing for new ways of sharing waste management duties between informal and formal sectors. Developing cities can thus strive for modern standards of waste service and sustainability, without strictly following the models of developed cities, especially when abruptly doing so would disrupt the jobs and high performance of their recycling sectors.

Finally, these examples show that even developed cities that have long invested in formalized, centralized waste services can still learn from hybrid systems in developing cities around the world. The practices of informal recycling cooperatives in Sao Paulo are relevant to local cooperatives like CERO in Boston, which serves underemployed communities and diverts recyclable and food waste to profitable use. The work of door-to-door collectors in Mombasa may inform Pedal People, a cooperative of waste-hauling bicycle couriers in Northampton, MA. Each of these groups can benefit from the visibility and organizational efficiencies offered by digital technologies.

Even cities with highly centralized, technically advanced municipal waste collection systems host some independent, decentralized waste activities, whether they are enterprising junk dealers, recycling and composting cooperatives, or communities engaged in local sharing and reuse activities. Thus, every urban waste system is a patchwork of institutions, companies, and independent actors; every system is a hybrid of formal-informal elements. If we recognize informal systems as legitimate, and use technology to mediate between the many independent actors and larger institutions, we can better integrate this patchwork into a smart, comprehensive waste system that is visible and responsive to the city’s needs. It is up to all cities to apply technology in creative, constructive ways that meet the many challenges solid waste presents.

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9 Dietmar Offenhuber and I organized a workshop at MIT on August 8, 2013 titled Technologies for Self-Organized Waste Systems, bringing together Brazilian waste researchers and representatives from CERO and Pedal People to exchange such ideas and experiences.
Citations


Greenfield, A., & Kim, N. (2013). *Against the smart city (The city is here for you to use)* (1.3 edition). Do projects.


Learning From Tracking Waste
How Transparent Trash Networks Affect Sustainable Attitudes and Behavior

Preface
This essay is adapted from my first-year PhD paper, originally written in 2010. A condensed version was presented at the 2014 IEEE World Forum on Internet of Things, and published in the proceedings under the citation:


Abstract
Building on top of an experiment in tracking the movement of trash, we tested whether viewing this sensor data would change peoples’ sustainability attitudes and behaviors. We showed subjects real-time maps of trash tagged with networked GPS sensors, and surveyed them before and after seeing this information. Our results show that subjects did not significantly change their behavior in the long run, but they reported better understanding of where their trash went and how tracking technologies worked. Those who participated in deploying sensors reacted differently on some questions from those who had not volunteered. This study illustrates both limits and new opportunities for urban sensing to improve sustainability outreach and action at the grassroots level.
Introduction

One of the most promising applications of urban sensing is the presentation of data to citizens in a way that reveals normally unseen processes in the city. These could be short-term ephemeral processes like air quality or traffic congestion on nearby roads, or long-term processes like growing crime incidence and climate change. Each application is an opportunity to improve awareness of a particular problem and evoke some sort of response from citizens, either through a change of opinion or a shift in behavior, which could then spark larger debate and positive action.

The cost of building a new, ubiquitous infrastructure of electronic sensors remains a substantial barrier for most cities hoping to implement wide-scale urban sensing. A cost-effective alternative to this is participatory sensing, where many volunteers perform sensing tasks independently and contribute their data to the whole picture (Paulos, Honicky, & Hooker, 2008). For example, citizens blogging photos of sick street trees could cost the city less than installing sensors to monitor every tree in real-time.

Such approaches engage the greater community, and make sensing more transparent and perhaps less threatening (Burke et al., 2006). Additionally, while data collected from non-experts might be less robust for science or policy research, they could be more appropriate for feedback to citizens (Dutta et al., 2009). For instance, if we want to report air pollution to pedestrians, we should measure it at street level where they are densest, rather than atop streetlights and buildings.

Past studies have shown how users perceive information from friends differently from those of the general public (Abbassi, Aperjis, & Huberman, n.d.). Crowdsourced knowledge repositories like Quora augment adoption by highlighting data from socially closer, more familiar people (Wang, Gill, Mohanlal, Zheng, & Zhao, 2013). However, how might we perceive information differently when collected by more familiar sensors? Having citizens help deploy sensors could “prime” them to trust the results more than if it were simply broadcast by experts. Citizens who have already invested time in revealing a problem might be more likely to change their behavior as well. However, proximity might also make us less confident in data, perhaps by showing firsthand the practical limits or flaws of the process.

If participation in distributed sensing does have a significant positive effect on how the resulting data is perceived by the participants, this has profound implications for urban sensing. If our goal is to spur action, the act of participating in identifying problems could prime citizens to seek solutions as well. Conversely, participating
could have the opposite effect of reducing confidence in the data and making the best course of action more ambiguous.

**Trash Track**

In October 2009, the MIT Senseable City Lab studied the movement of trash through the Seattle waste removal system using remote tracking sensors. Researchers from the Lab traveled to Seattle to deploy 2000 GPS tracking "tags"; each tag was attached to a separate trash item, then thrown away at some location in the city (Phithakkitnukoon et al., 2013). We asked Seattle residents to volunteer through the Trash Track website; selected volunteers provided trash items, helped catalog and attach tags, and deployed trash into the removal stream. Photographs in Figure 12 show how we worked with volunteers at their homes to prepare the trash items.

![Figure 12 Photographs of GPS tag deployment.](image)

Volunteers help with distributed sensing by identifying trackable trash items, attaching the tags using protective quick-setting foam adhesive, and throwing these items away.

Over the subsequent two months, we remotely tracked the location of each tagged piece of trash. We then visualized these paths in maps, animations, and videos, presenting them in public exhibitions and websites. This allowed both volunteers and the general public to see the "second life of trash" in real-time, after it was
thrown away. From such maps it was clear that trash could end up traveling far beyond city limits, and across state and country borders, especially electronic and hazardous waste. The method and direction of transport could thus mean a great difference in the energy and emissions impact of that waste (Offenhuber et al., 2012).

One of the main goals of Trash Track was to reveal the unseen processes of waste removal, increase awareness of the environmental impact of individual waste generation, and encourage citizens to act more sustainably. This approach of encouraging sustainable behavior through information feedback drew inspiration from attempts to moderate energy consumption in the home through feedback loops. Such approaches, when combining tailored information with goal-setting, can produce significant improvements in sustainable behavior (Abrahamse, Steg, Vlek, & Rothengatter, 2007). However, the question of how and why this works, and the causal relationship between knowledge and behavior, remains a vague and contested issue (He & Greenberg, 2008).

During our study, we surveyed volunteers from this experiment to measure how they understood and reacted to the real-time maps of their trash’s movement. We also surveyed non-volunteers to determine if they reacted differently. We wanted to know: did the experience of deploying the sensors alter how the volunteers viewed the results? If we want to use urban sensing to change attitudes or behavior at a large scale, does it help to have citizens participate in deployment?

Literature review
Recycling behavior
Many researchers have worked to understand what conditions encourage or discourage recycling behavior. There is a long history of debate about whether social pressure, personal attitudes, knowledge, and convenience influence recycling behavior. Three theories that predict such influences are the theory of reasoned action, theory of planned behavior, and theory of altruistic behavior. Another common concern is the direction of causality; do these factors induce behavior, or vice versa?

The theory of reasoned action states that behavioral intention is the product of both attitudes and subjective norms (Ajzen & Fishbein, 1980). If I see a certain behavior as positive (attitude), and feel that people whose opinions I care about want me to perform that behavior (subjective norms), I am more motivated to do so (behavioral intent). The higher my behavioral intent is, the more likely I am to perform that behavior. Empirical tests in the context of recycling behavior lend strong support to this theory (Jones, 1989).
Building on the theory of reasoned action, the theory of planned behavior is a stronger predictor of behavioral intention and action (Madden, Ellen, & Ajzen, 1992). It introduces "perceived behavioral control" as an additional factor in determining behavioral achievement; if I perceive that I am actually able to perform the behavior (self-efficacy), and that the behavior will produce the results I expect (outcome expectancy), then I am more likely to do so. Perceived behavioral control directly influences behavioral intent and its other factors (attitude and subjective norms), but it can also directly influence behavioral achievement if it accurately reflects actual behavioral controls (Ajzen, 1991).

Schwartz (1977) presents a theory of altruistic behavior that could be applied to recycling. The theory posits that the intensity of moral obligation influences altruistic behavior. I feel moral obligation when my cognitive structure of norms and values is activated, but defenses against relevance or appropriateness can neutralize this feeling. If I see recycling as an altruistic behavior, in that I understand that it benefits others, then personal norms that make me feel morally obligated to recycle must already be in place before I would consider performing such an altruistic behavior. This implies that social norms only affect my willingness to recycle once I have adopted them into my personal cognitive framework (Schwartz, 1977).

Modeling recycling as a form of altruistic behavior, Hopper and Nielsen (1991) found that social norms to recycle do influence behavior, but only when there is an intervening personal norm to recycle. In addition, personal norms only translated into behavior when subjects were well aware of the consequences of their actions. They also found that instituting "block-leader programs" strongly affected these social and personal norms more than simple reminders and informational brochures, implying that direct social interactions (like those that took place between Trash Track researchers and volunteers) have a positive effect on these norms to recycle (Hopper & Nielsen, 1991). Further studies confirmed the indirect effect of social norms, but found that awareness of consequences had no impact when translating personal norms to behavior (Bratt, 1999). This would appear to conflict with the theory of planned behavior, which posits that high awareness of consequences amplifies the translation from personal norms to behavioral achievement.

Effort plays a major role in the attitude-behavior relationship and may explain previous discrepancies in empirical tests of the above theories. Schultz and Oskamp (1996), in a series of studies, showed that attitude is a stronger predictor of behavior when the amount of effort required to act is high. Furthermore, higher environmental concern was positively correlated with the amount of effort subjects were willing to expend on recycling, absent any other incentives (Schultz & Oskamp, 1996). For the Trash Track survey, this impact might appear within an
individual’s survey responses, whose attitude towards sustainable behavior might translate differently into actual behavior for high-effort tasks (dropping off e-waste) and low-effort tasks (curbside recycling).

Finally, meta-analysis of many empirical studies of recycling behavior shows that it is highly dependent on intrinsic and extrinsic motivators of recycling and facilitators of recycling. Operationally, knowledge and social influence are the most effective predictors of recycling, (Hornik, Cherian, & Madansky, 1995) which agrees with the theory of planned behavior. The meta-analysis also discounts additional incentives and demographic variables as effective predictors of recycling; from a theoretical standpoint, however, these might factor into some of the other predictors of recycling behavior. For example, monetary incentives could improve recycling behavior, but more so for people with less positive environmental attitudes (Schultz & Oskamp, 1996), while children and the elderly might be less mobile and face greater perceived behavioral controls to action.

Knowledge-deficit theory and sustainable behavior
Knowledge-deficit theory states that increasing knowledge translates into change in behavior. Knowledge can be distinguished as procedural knowledge (understanding of the where, when, and how of recycling), normative knowledge (beliefs about the behavior of others) and impact knowledge (beliefs about the impact of one’s actions) (Schultz, 2002). Of these, Trash Track was best positioned to increase impact knowledge, as it showed the direct consequences of actions such as disposing of e-waste through “proper” procedures or neglecting to sort out recyclables.

Knowledge-deficit suggests three hypotheses: that recycling knowledge correlates with recycling behavior, that distributing educational materials increases knowledge, and that this increased knowledge produces more recycling behavior. Synthesizing the results of multiple studies, Schulz concludes that the third hypothesis fails when increasing procedural knowledge, mainly because this only removes a barrier to action but does not provide a motive. In contrast, normative knowledge about others’ actions motivates behavior change, but this works best when one’s own actions are transparent to others, which is rarely the case for waste disposal.

Trash Track lets us test all three hypotheses for impact knowledge. First, we may survey citizens with varying levels of knowledge about the impact of recycling and correlate this with their recycling behavior. Next, we can measure whether viewing the Trash Track traces website produced a change in their levels of knowledge. Finally, we can also look for a change in behavior after viewing the website. This study refines the last of these hypotheses by varying the degree to which subjects can relate to this impact knowledge, since volunteers who had their trash tracked
get direct feedback on their own actions, as opposed to non-volunteers who can only view the impact of others' actions.

Hypothesis and Variables
The unit of analysis is the individual. Members of the general public who visited the Trash Track website comprised the control group. The experimental group consisted of residents of Seattle who helped with the Trash Track project.

Hypotheses
1. Both before and after viewing the Trash Track data traces, volunteers and non-volunteers held different attitudes and reported different behaviors related to trash disposal.
2. Viewing the Trash Track data led to a change in attitudes and behaviors. The nature of this change differed for volunteers and non-volunteers.

Dependent variable
For hypothesis 1, the dependent variables were how frequently subjects engaged in sustainable behaviors, how effective they felt these behaviors to be, and how knowledgeable they felt about waste disposal.

For hypothesis 2, the dependent variables were changes in behavior or attitude after viewing the Trash Track data traces website. I measured behavior and attitude separately, as the causal link between these is not well established and beyond the scope of this experiment.

Independent (explanatory) variable
The independent variables separating the control and experimental groups were whether subjects volunteered and participated in the Trash Track tag deployment. Everyone belonging to the experimental group experienced the following things in common:

- learned about the Trash Track experiment, visited the website, filled out a volunteer form,
- communicated with the Trash Track team over the phone and in person, when the team visited volunteers' homes during the October tag deployment,
- provided trash items to tag and track, working from a list of "most wanted" items,
- witnessed or helped with the tagging process,
- disposed of tagged items in a matter of their choosing, and
- viewed their own trash items among the larger dataset of trash traces released on the Trash Track website.
Methodology

A total of 84 volunteers participated in the Trash Track project, over two weekends in the month of October 2009. We remained in contact with each volunteer after the Seattle deployment; they constituted group A of the study.

Group B comprised of members of the general public who visited the Trash Track website. Because they did not participate in Trash Track in any way prior to viewing the data, they act as the control group. They were recruited through e-mail announcements of the website launch through the same social networks used to recruit the original volunteers. Volunteers from Group A also were asked to spread the word about the Trash Track website through their own networks; some wrote articles and blog posts directing people to the site and survey. The purpose of this was to capture a population similar in interests and motivation to the Trash Track volunteers.

![Diagram](image)

Figure 13 The experience of each group, as controlled by the researcher.

Tag deployment

We used commercially available location sensors, the CMA8119BK by PCD, for the Seattle deployment. The tags were 71x41x16mm in size, small enough to avoid easy visual detection. We used a quick-setting foam adhesive to attach and protect the devices from moisture and shock, while still allowing wireless communication.

The tags used GPS and cellular triangulation to locate themselves, and the CDMA network to communicate with Qualcomm’s inGeo platform. Battery capacity was 700mAh; we maximized battery life by programming devices to report on a 3, 4, or 6-hour cycle. We received location reports from the devices directly to our servers via HTTP POST requests from inGeo. More technical details on hardware, deployment, and data results are in (Offenhuber et al., 2012; Phithakkitnukoon et al., 2013).

Tracking results website interface

We collected the trajectories of each trash tag in real-time over three months, in the form of timestamped geographic coordinates. We overlaid these raw trajectories on a web mapping application, using Google Maps API v2, Javascript,
PHP, and MySQL. Custom icons showed the first and last known locations and a polyline traced out the path in between.

Users could view the paths of each trash item individually, or see the latest known locations of many tags in aggregated view. In the latter, the user could filter by trash type, or isolate their own trash (for volunteers who provided items). Figure 14 illustrates the two basic views of the web interface. Since the data were updated in real-time, the actual map shown would change throughout the months following deployment.

![Figure 14 Screenshots of the Trash Track web interface.](image)

These real-time maps presented the data results of Trash Track to the public. On left is the view of a single item's trajectory, on the right is an aggregated view of where many tags have ended up. White markers represent transfer stations and disposal sites local to Seattle.

**Survey procedure**

Using an online survey tool, we polled over 200 visitors to the Trash Track website before they were able to view the tag maps. We achieved this by restricting access to those who took the pre-survey and received a password. For instance, group A subjects was able to view traces of their own tagged trash in addition to the large set of public data, while group B only saw the public data.10

A month later, we contacted every participant with a request to take the post-survey, with 70 of the original participants completing this follow-up questionnaire. From these 70 responses, 32 were volunteers from the Seattle deployment, and the remaining 38 were website visitors who had not volunteered.

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10 By default, the trash contributed and tagged by group A members was kept private and separate from the public dataset. Group A was given the option to release their trash data to the public, and many volunteered to do so, creating a large common dataset viewable to both groups that greatly standardized the experience.
Both the "pre-survey" and "post-survey" asked Likert-scaled questions on the subject’s current attitudes and beliefs in the impact of their decisions on the environment. Subjects were asked about their attitude toward waste generation and disposal, as well as how often they took certain sustainable actions like recycling and bringing e-waste to designated disposal sites. Each Likert item was a statement about the subject’s attitude toward waste generation and disposal, to which the subject could indicate their level of agreement on a five-point scale (ranging from "strongly disagree" to "strongly agree"). The difference in their answers between the pre-surveys and post-surveys helped quantify the effect of viewing the data traces.

Likewise, the surveys presented certain sustainable actions like recycling and bringing e-waste to designated disposal sites. The subject could indicate how often they acted in these ways, using a five-point scale ranging from "never" to "always." Both this rating scale and the Likert scale had the benefit of forcing subjects to choose a quantifiable answer, making it easier to compare and analyze their responses. However, both are subject to potential biases: central tendency bias (avoiding extreme categories), acquiescence bias (agreeing with statements as presented), and social desirability bias (portraying themselves positively).

Self-selection
The question of how to create a valid control group remains a vexing one. In order to gauge the impact of volunteerism on one’s behavior or opinions, we need to compare a group of volunteers with a group that did not participate. However, these two groups may reflect fundamentally different types of people, separated by much more than whether they were available on the particular weekend the Trash Track researchers were in Seattle. On average, those who volunteered for Trash Track might have been more passionate about environmental issues, more knowledgeable about global trends, or more educated and connected to academic networks. If factual, these trends would make it difficult to directly compare the survey responses from volunteers with those from the general public. For the behaviors and opinions we are trying to study, the two groups might diverge significantly regardless of the independent variable (participation in the deployment).

One approach would be to populate both experimental and control groups with people who had responded to our call for volunteers, placing those who wanted to help but ended up not actually participating into the control group. This would make the groups more homogeneous in initial outlook and behavior. Unfortunately, for this experiment at least, very few people who contacted us were unable to participate.
An alternate approach, then, is to try and control for this by asking survey takers from the general public whether they would volunteer to help with a Trash Track deployment, if one were to take place in their area. A follow-up question, asking them to choose the ways they would assist with deployment (such as donating trash items or driving researchers around), further details what volunteering entails, and helps capture their level of commitment within the same range as the actual volunteers.

Additionally, by surveying everyone with questions about their current state of opinions both before and after the website launch, I hoped to capture any preexisting differences between the two study groups. Using likert-scale questions to measure state helped standardize the measure of change between subjects, so that the above hypothetical biases could be detected and taken to account.

Thus, there were ways to mitigate selection biases that might distort the different outcomes for the experimental and control groups. However, this attempt to preserve internal validity could have undermined external validity, by focusing the study tightly on a group of like-minded would-be volunteers who do not reflect a diverse general populace. Despite this, the power of the experiment came from isolating the feedback effects, so I played to this strength and prioritized internal validity.

Results

Hypothesis 1 test
Recoding each question’s response to a 1-5 ordinal scale, I calculated average responses to each behavior survey question for each group, with higher values indicating higher frequency. Likewise, I calculated mean values for attitude questions, with 1 indicating “strongly disagree,” 3 as “neutral,” and 5 as “strongly agree.”

Table 6 shows the resulting means and standard deviations for selected survey questions. For behavior questions (1-9), higher values indicated higher frequency of that action. For attitude questions (13-23), values higher than 3 indicated agreement; lower than 3 indicated disagreement. The table omits several questions from the original surveys due to lack of relevance or detected collinearity with other variables.

<table>
<thead>
<tr>
<th>Question</th>
<th>Volunteer</th>
<th>Non-volunteer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>1. Inspect products before buying them to see if they can be easily reused or recycled.</td>
<td>3.69</td>
<td>3.84</td>
</tr>
<tr>
<td></td>
<td>(0.69)</td>
<td>(0.88)</td>
</tr>
<tr>
<td>2. Consider the amount of packaging that must be thrown away when purchasing products.</td>
<td>3.97</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>(0.82)</td>
<td>(0.84)</td>
</tr>
</tbody>
</table>
Look for information online on ways to reuse packaging like glass and plastic bottles.

Dispose of recyclables into recycling bins when outside the home.

Dispose of hazardous materials at special disposal sites or through arranged pickup.

The trash removal system in my area functions efficiently.

Curbside recycling is an effective way of reducing waste disposed of in landfills.

The amount of trash I generate has a significant effect on the environment.

How I choose to dispose of my trash has a significant effect on the environment.

I have a good understanding of where my trash goes.

I know the location of local hazardous waste disposal sites.

I understand how the Trash Track system works.

<table>
<thead>
<tr>
<th>Question</th>
<th>Survey 1</th>
<th>Survey 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inspect products before buying them to see if they can be easily reused or recycled.</td>
<td>-2.55*</td>
</tr>
<tr>
<td>2</td>
<td>Consider the amount of packaging that must be thrown away when purchasing products.</td>
<td>-1.90</td>
</tr>
<tr>
<td>4</td>
<td>Look for information online on ways to reuse packaging like glass and plastic bottles.</td>
<td>-0.72</td>
</tr>
<tr>
<td>7</td>
<td>Dispose of recyclables into recycling bins when outside the home.</td>
<td>-0.69</td>
</tr>
</tbody>
</table>

Table 6: Average responses to survey questions.

Means and standard deviations (S.D.) are shown for both survey rounds.

As hinted by the high mean values for many questions, subjects answered "always" and "strongly agree" on many questions, introducing possible ceiling effects. This is one sign of a self-selection bias, as only subjects motivated enough to help a sustainability-related study would donate their time to take a second survey and be included in the dataset. These ceiling effects would factor into measuring change between the two surveys, since for some subjects there was no room to answer more positively on the second than on the first.

We then ran two-group t-tests to compare the means of these distributions. These tests compared the mean responses and variances from two independent groups, to see if one group responded significantly differently on average from the other.
<table>
<thead>
<tr>
<th>Question</th>
<th>Pre-survey t-value</th>
<th>Post-survey t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispose of hazardous materials at special disposal sites or through arranged pickup.</td>
<td>-1.52</td>
<td>-0.39</td>
</tr>
<tr>
<td>The trash removal system in my area functions efficiently.</td>
<td>-3.97***</td>
<td>-2.43*</td>
</tr>
<tr>
<td>Curbside recycling is an effective way of reducing waste disposed of in landfills.</td>
<td>-2.13*</td>
<td>-2.88**</td>
</tr>
<tr>
<td>The amount of trash I generate has a significant effect on the environment.</td>
<td>0.00</td>
<td>0.21</td>
</tr>
<tr>
<td>How I choose to dispose of my trash has a significant effect on the environment.</td>
<td>-0.65</td>
<td>0.82</td>
</tr>
<tr>
<td>I have a good understanding of where my trash goes.</td>
<td>-2.57*</td>
<td>-3.17**</td>
</tr>
<tr>
<td>I know the location of local hazardous waste disposal sites.</td>
<td>-3.92***</td>
<td>-0.79</td>
</tr>
<tr>
<td>I understand how the Trash Track system works.</td>
<td>-2.87**</td>
<td>-1.05</td>
</tr>
</tbody>
</table>

Table 7: Results of two-group t-tests.

This table compares the means of volunteer and non-volunteer groups. Negative t-values indicate that volunteers scored higher on those questions than non-volunteers. (*P<.05; **P<.01; ***P<.001)

In every statistically significant category (questions 1, 2, 4, 7, 13, 14, 19, 22, and 23) volunteers responded higher than non-volunteers on average. Questions 1, 2, 4, and 7 showed that volunteers sought to reduce their waste footprint and recycle more after viewing the Trash Track data, significantly more so than non-volunteers. Questions 13, 14, and 19 showed that volunteers, both before and after viewing the Trash Track traces, placed higher faith in local disposal and recycling systems, and understood where their trash went after disposal. In contrast, questions 22 and 23 showed that volunteers better understood where hazardous waste disposal sites were and how Trash Track worked, but this statistical gap disappeared after everyone viewed the data traces.

We followed this up with an ordinal logistic regression to see if being a volunteer significantly increased the likelihood of answering more positively to each question. This type of regression models the probability of a subject choosing a higher value response (more frequent behavior or more likely to agree) as a function of other independent variables.

In this case, we used dummy variables that indicated if the subject was a volunteer, whether they were answering the pre-survey or post-survey, and how they answered an additional survey question (about which aspects of the Trash Track data they remembered to be particularly interesting). The last question, which allowed for multiple choices, improved the fit and statistical significance of each model. The resulting models with notable overall chi-square statistics are shown in Table 8. We focus on the coefficients for the "volunteer" and "post-survey" variables.
<table>
<thead>
<tr>
<th></th>
<th>Q02 Coef./S.E.</th>
<th>Q13 Coef./S.E.</th>
<th>Q14 Coef./S.E.</th>
<th>Q19 Coef./S.E.</th>
<th>Q22 Coef./S.E.</th>
<th>Q23 Coef./S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volunteer</td>
<td>1.299***</td>
<td>1.291***</td>
<td>1.217**</td>
<td>1.273***</td>
<td>1.173***</td>
<td>1.038**</td>
</tr>
<tr>
<td></td>
<td>(0.36)</td>
<td>(0.39)</td>
<td>(0.37)</td>
<td>(0.34)</td>
<td>(0.35)</td>
<td>(0.37)</td>
</tr>
<tr>
<td>Post-survey</td>
<td>0.435</td>
<td>0.231</td>
<td>-0.246</td>
<td>1.053***</td>
<td>0.157</td>
<td>0.708*</td>
</tr>
<tr>
<td></td>
<td>(0.32)</td>
<td>(0.34)</td>
<td>(0.34)</td>
<td>(0.32)</td>
<td>(0.31)</td>
<td>(0.34)</td>
</tr>
<tr>
<td>Final destination of</td>
<td>-0.423</td>
<td>-0.250</td>
<td>-0.487</td>
<td>-0.335</td>
<td>-0.417</td>
<td>-0.826*</td>
</tr>
<tr>
<td>trash items</td>
<td>(0.36)</td>
<td>(0.38)</td>
<td>(0.37)</td>
<td>(0.35)</td>
<td>(0.35)</td>
<td>(0.38)</td>
</tr>
<tr>
<td>Path taken by trash</td>
<td>-0.021</td>
<td>-0.338</td>
<td>-0.667</td>
<td>-0.364</td>
<td>0.632</td>
<td>0.529</td>
</tr>
<tr>
<td>items</td>
<td>(0.37)</td>
<td>(0.41)</td>
<td>(0.42)</td>
<td>(0.37)</td>
<td>(0.37)</td>
<td>(0.41)</td>
</tr>
<tr>
<td>Distance traveled by</td>
<td>0.828*</td>
<td>0.057</td>
<td>0.403</td>
<td>0.184</td>
<td>0.381</td>
<td>0.339</td>
</tr>
<tr>
<td>trash items</td>
<td>(0.35)</td>
<td>(0.36)</td>
<td>(0.37)</td>
<td>(0.34)</td>
<td>(0.34)</td>
<td>(0.37)</td>
</tr>
<tr>
<td>Variety of trash</td>
<td>0.543</td>
<td>-1.124**</td>
<td>-0.818*</td>
<td>0.050</td>
<td>0.141</td>
<td>-0.160</td>
</tr>
<tr>
<td>tracked</td>
<td>(0.37)</td>
<td>(0.41)</td>
<td>(0.39)</td>
<td>(0.36)</td>
<td>(0.35)</td>
<td>(0.39)</td>
</tr>
<tr>
<td>How different types</td>
<td>-0.722**</td>
<td>-0.086</td>
<td>0.084</td>
<td>0.324</td>
<td>0.100</td>
<td>0.320</td>
</tr>
<tr>
<td>of trash moved</td>
<td>(0.34)</td>
<td>(0.36)</td>
<td>(0.36)</td>
<td>(0.33)</td>
<td>(0.33)</td>
<td>(0.36)</td>
</tr>
<tr>
<td>differently</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cutpoint 1</td>
<td>-4.456***</td>
<td>-4.739***</td>
<td>-4.535***</td>
<td>-1.826**</td>
<td>-2.185***</td>
<td>-2.208***</td>
</tr>
<tr>
<td></td>
<td>(1.10)</td>
<td>(0.89)</td>
<td>(0.80)</td>
<td>(0.56)</td>
<td>(0.62)</td>
<td>(0.63)</td>
</tr>
<tr>
<td>cutpoint 2</td>
<td>-1.908***</td>
<td>-3.278***</td>
<td>-4.234***</td>
<td>0.208</td>
<td>-0.212</td>
<td>-0.564</td>
</tr>
<tr>
<td></td>
<td>(0.56)</td>
<td>(0.65)</td>
<td>(0.74)</td>
<td>(0.51)</td>
<td>(0.52)</td>
<td>(0.55)</td>
</tr>
<tr>
<td>cutpoint 3</td>
<td>0.070</td>
<td>-1.709**</td>
<td>-2.482***</td>
<td>1.210*</td>
<td>0.498</td>
<td>2.415***</td>
</tr>
<tr>
<td></td>
<td>(0.52)</td>
<td>(0.58)</td>
<td>(0.59)</td>
<td>(0.51)</td>
<td>(0.52)</td>
<td>(0.59)</td>
</tr>
<tr>
<td>cutpoint 4</td>
<td>1.939***</td>
<td>1.261*</td>
<td>0.060</td>
<td>3.133***</td>
<td>2.137***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.54)</td>
<td>(0.56)</td>
<td>(0.54)</td>
<td>(0.57)</td>
<td>(0.55)</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>139</td>
<td>137</td>
<td>139</td>
<td>140</td>
<td>139</td>
<td>140</td>
</tr>
<tr>
<td>McFadden's Pseudo-R2</td>
<td>0.066</td>
<td>0.094</td>
<td>0.081</td>
<td>0.066</td>
<td>0.041</td>
<td>0.065</td>
</tr>
</tbody>
</table>

Table 8: Ordinal logit model regression results.

Questions 2, 13, 14, 19, 22, and 23 are each tested as dependent variables. Positive coefficients indicate subjects were more likely to report higher frequency behaviors, or to agree with the presented statements. Subjects indicated which aspects of the sensor data they focused on when browsing the site; we controlled for this with dummy variables. (*P<.05; **P<.01; ***P<.001)

These models show that, for certain questions, volunteers answered significantly differently from non-volunteers across both survey periods, as indicated by positive coefficients with statistical significance at the 99% and 99.9% level. Volunteers were more likely to consider the amount of packaging waste that came with purchased products (Q02). They were more confident in knowing where their trash went (Q19) and where hazardous waste disposal points were (Q22), as well as understanding how Trash Track worked (Q23).
Also notable is that for two of these questions (Q19 and Q23), post-survey responses differed significantly from the pre-survey responses. This implied that, when controlling for the different aspects of the Trash Track traces that they investigated, both volunteers and non-volunteers felt an improved understanding of where their trash went and how the Trash Track system worked.

Hypothesis 2 test
To see if viewing the Trash Track traces had a significant impact on subjects' attitudes and behavior, we began with a combined analysis of responses to each survey. The pairwise t-test for all 70 subjects calculates the differences between their answers pre-survey and post-survey, and tests if the average change is significantly non-zero; this is appropriate when the observations are not independent of each other. It showed significant average changes in responses to questions 2, 7, 19, and 23.

<table>
<thead>
<tr>
<th>Question</th>
<th>Combined dataset</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Survey 1 mean</td>
<td>Survey 2 mean</td>
</tr>
<tr>
<td>1  Inspect products before buying them to see if they can be easily</td>
<td>3.43</td>
<td>3.53</td>
</tr>
<tr>
<td>reused or recycled.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2  Consider the amount of packaging that must be thrown away when</td>
<td>3.74</td>
<td>3.93</td>
</tr>
<tr>
<td>purchasing products.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4  Look for information online on ways to reuse packaging like glass</td>
<td>2.49</td>
<td>2.70</td>
</tr>
<tr>
<td>and plastic bottles.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7  Dispose of recyclables into recycling bins when outside the home.</td>
<td>4.41</td>
<td>4.27</td>
</tr>
<tr>
<td>9  Dispose of hazardous materials at special disposal sites or through</td>
<td>4.57</td>
<td>4.46</td>
</tr>
<tr>
<td>arranged pickup.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 The trash removal system in my area functions efficiently.</td>
<td>3.93</td>
<td>4.01</td>
</tr>
<tr>
<td>14 Curbside recycling is an effective way of reducing waste disposed of</td>
<td>4.23</td>
<td>4.20</td>
</tr>
<tr>
<td>in landfills.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 The amount of trash I generate has a significant effect on the</td>
<td>4.29</td>
<td>4.24</td>
</tr>
<tr>
<td>environment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 How I choose to dispose of my trash has a significant effect on the</td>
<td>4.39</td>
<td>4.51</td>
</tr>
<tr>
<td>environment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 I have a good understanding of where my trash goes.</td>
<td>2.81</td>
<td>3.44</td>
</tr>
<tr>
<td>22 I know the location of local hazardous waste disposal sites.</td>
<td>3.60</td>
<td>3.71</td>
</tr>
<tr>
<td>23 I understand how the Trash Track system works.</td>
<td>3.83</td>
<td>4.10</td>
</tr>
</tbody>
</table>

Table 9: Average responses to surveys 1 and 2 across both groups.

A paired two-sided t-test determines if there is a significant change in average response between the pre- and post-surveys. (*P<.05; **P<.01; ***P<.001)
We used another ordinal logistic regression to test whether volunteers changed their responses between surveys differently from how non-volunteers changed. To our previous regression, we added a new dummy variable, the logical intersection of the "volunteer" and "post-survey" variables. This would isolate any difference between the two groups' transitions. Table 10 shows how this additional variable adjusted the models. Again, we focus on the first three rows of coefficients.

<table>
<thead>
<tr>
<th>Question 2</th>
<th>Question 19</th>
<th>Question 22</th>
<th>Question 23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coef.</td>
<td>S.E.</td>
<td>Coef.</td>
<td>S.E.</td>
</tr>
<tr>
<td>Volunteer</td>
<td>0.995*</td>
<td>0.466</td>
<td>1.206*</td>
</tr>
<tr>
<td>Post-survey</td>
<td>0.144</td>
<td>0.430</td>
<td>0.991*</td>
</tr>
<tr>
<td>Volunteer post-survey</td>
<td>0.636</td>
<td>0.637</td>
<td>0.129</td>
</tr>
<tr>
<td>Final destination of trash items</td>
<td>-0.430</td>
<td>0.356</td>
<td>-0.334</td>
</tr>
<tr>
<td>Path taken by trash items</td>
<td>-0.026</td>
<td>0.376</td>
<td>-0.364</td>
</tr>
<tr>
<td>Distance traveled by trash items</td>
<td>0.841*</td>
<td>0.353</td>
<td>0.181</td>
</tr>
<tr>
<td>Variety of trash tracked</td>
<td>0.549</td>
<td>0.377</td>
<td>0.05</td>
</tr>
<tr>
<td>How different types of trash moved differently</td>
<td>-0.721*</td>
<td>0.344</td>
<td>0.321</td>
</tr>
<tr>
<td>cutpoint 1</td>
<td>-4.600***</td>
<td>1.114</td>
<td>-1.858**</td>
</tr>
<tr>
<td>cutpoint 2</td>
<td>-2.062***</td>
<td>0.586</td>
<td>0.172</td>
</tr>
<tr>
<td>cutpoint 3</td>
<td>-0.082</td>
<td>0.543</td>
<td>1.175*</td>
</tr>
<tr>
<td>cutpoint 4</td>
<td>1.801**</td>
<td>0.563</td>
<td>3.102***</td>
</tr>
<tr>
<td>Observations</td>
<td>139</td>
<td>140</td>
<td>139</td>
</tr>
<tr>
<td>McFadden's Pseudo R-Square</td>
<td>0.069</td>
<td>0.066</td>
<td>0.053</td>
</tr>
<tr>
<td>Chi-square statistic</td>
<td>24.757**</td>
<td>27.756***</td>
<td>21.139**</td>
</tr>
</tbody>
</table>

Table 10: Ordinal logit model regressions for selected Likert-scale questions.

Positive coefficients for questions 2 and 7 indicate that subjects were more likely to report higher frequency behaviors, while positive coefficients for questions 19 and 23 indicate that they were more likely to agree with the presented statements. (*P<.05; **P<.01; ***P<.001)

The ordinal logistic regression for question 7 did not produce a statistically significant model. The other models show that volunteers more frequently considered the amount of packaging when purchasing items, but that this did not change significantly for them, nor for the non-volunteers, after viewing the data.
Volunteers felt they had a stronger understanding of where their trash went, and that viewing Trash Track data improved everyone's awareness of this issue, but volunteers did not advance this awareness any further than non-volunteers did (Q19). Question 23 shows that both groups improved their understanding of how Trash Track worked after seeing the traces. Again, volunteers did not experience this change any differently than non-volunteers.

However, the model for question 22 produced statistically significant coefficients for the key independent variables "volunteer" and "volunteer post-survey"; the "post-survey" coefficient was also significant at the 95% confidence level, using a one-sided z-score. The coefficients imply three things:

- On the pre-survey, volunteers were more likely to indicate knowing the locations of hazardous disposal sites than non-volunteers.
- Non-volunteers were more likely to indicate knowing the locations of hazardous disposal sites after seeing the Trash Track traces, though this did not bring them up to par with the volunteer responses from the pre-survey.
- Volunteers experienced the opposite effect upon seeing the Trash Track traces. They were less likely to indicate knowing the locations of hazardous disposal sites on the post-survey. These results confirm what was hinted at in the average responses to question 22 shown in Table 6.

Concluding Remarks

In summary, the models show that, while the information feedback from Trash Track did significantly change some people's understanding of trash issues and sensing technologies, it did not significantly change their attitudes or behavior toward trash generation and disposal.

Volunteers involved in deployment reported engaging in more frequent sustainable behavior. On average, they tried to reduce their waste impact by reusing items, minimizing packaging, and recycling when outside the home more often than non-volunteers. They also expressed more confidence in the effectiveness of the waste disposal system and their own understanding of it. Yet, these effects did not completely linger in the long term. Past the "high" of participating in the experiment and seeing its results, volunteers lost or gained little in the following months. The memory of the event might have faded over time, without new information or ways to participate beyond that initial engagement.

Three significant changes between the pre-survey and post-survey were in knowledge-based questions. Both groups reported significant differences in how well they understood where their trash went, how the tracking experiment worked, and where hazardous waste disposal sites were located. As an experiment in
creating awareness, Trash Track achieved some success in explaining how the waste stream works and how tracking technology can be used to reveal its path.

At the same time, the opposite ways that volunteers with the project and non-volunteers changed their responses to the latter question (knowing where hazardous waste disposal sites were located) points to another, potentially positive outcome of viewing the traces. For some, the traces revealed previously unknown facts about where these materials are disposed. For others, the traces demonstrated that the system was more complex and unpredictable than they had previously thought, forcing them to reevaluate consequences of their own actions.

We must be careful about drawing broad conclusions from this study, considering the inherent problems of self-selection and ceiling effects in voluntary surveys. Likert-scale survey questions are subject to potential biases: central tendency bias (avoiding extreme categories), acquiescence bias (agreeing with statements as presented), and social desirability bias (portraying themselves positively).

In the context of waste disposal, we must study these effects further, in controlled settings with a larger sample population, to understand how distributed sensing supports city-wide behavioral change. From free-response questions on our survey we found anecdotes that indicated some discrete attitude and behavioral changes:

"[Trash Track] made me more aware of details on how to dispose of certain items. Before, I had been too lazy to look up where to take an old laptop or light bulbs. I didn't want to throw them away, so they just say around. Trash Track made me motivated to learn the proper disposal process for such items."

"Drawing the connection between my garbage and where it goes creates a sense of responsibility. Hopefully it will help me bridge the gap between my consumer choices and making the planet a little cleaner."

We believe such quotes reflect the potential impact of participatory sensing projects, and future projects should try to reliably effect lasting change. For instance, a focus on electronic waste items and their sometimes long, unpredictable trajectories could engage participants over a longer period of time. The risks presented by unsafe e-waste disposal are more immediate and severe, and citizens often have more options for disposal that can be tracked and compared. A crowdsourced e-waste tracking project, with independent deployments in homes across the world, could yield valuable data for the collective, while revealing best practices to the individual.
Fortunately, the technology behind sensing trash locations is advancing and becoming increasingly scalable, allowing for more accurate, real-time feedback to citizens. As more objects become integrated into the Internet of Things, we will gain the ability to track their movements through their entire lifecycle. How this feedback can encourage sustainable behavior, and transform social norms, is worth further careful study.

Acknowledgment
We thank the Trash Track team, City of Seattle (Office of Arts and Culture Affairs, Seattle Public Utilities, Seattle Public Library), and the many volunteers in Seattle who helped execute the original tracking experiment. We also thank JoAnn Carmin, Frank Levy, Karen Polenske, and Vlad Trifa for their thoughtful review and feedback. We thank Waste Management Inc., Qualcomm Inc., Sprint, and the Architectural League of New York for funding and supporting the research. Special thanks to Dietmar Offenhuber for leading the Trash Track deployment, E Roon Kang for assisting with website design, and our data cleanup team: Malima Wolf, Angela Wang, Eugene Lee, and Santi Phithakkitnukoon.

References


Monitour
Tracking the global flow of e-waste exports using GPS and smartphones

Preface
This paper covers work I completed in 2012 with Dietmar Offenhuber and the Basel Action Network on tracking electronic waste export from California. I am the sole author of the text below, but many team members from Senseable City Lab and beyond contributed to the execution of the project. I have not submitted this essay to any publications for review, but should it be accepted somewhere, the expected citation will be:


Abstract
The export of electronic waste from wealthy to less wealthy nations is a growing problem with potentially severe consequences to the environment and human health, but difficult to precisely track. Remote GPS tracking with location sensors allows us to identify previously unknown smuggling routes, waste endpoints, and violators of international law. We designed smartphone-based trackers that could relay back their location and photographs of their surroundings from anywhere in the world with GSM mobile networks. We embedded these along with off-the-shelf GPS trackers inside discarded cathode-ray tube monitors, then deployed them in several recycling businesses in Southern California. The resulting traces revealed illegal e-waste export and smuggling into China and Malaysia, via major ports and border crossings known for contraband exchange. Such data can bolster the efforts of enforcement agents to prevent the illegal shipping of e-waste, but individuals and NGOs can also utilize this technology to publicize known blind spots in regulation, raise awareness of the scale of the network, and mount independent investigations into the fluid structure of global e-waste trade.
Introduction
Electronic waste (e-waste) is a growing and serious global problem. The world’s countries discard an estimated 20-25 million tons of e-waste annually, primarily in Europe and the United States, but China, Latin America, and other growing economies will soon be producing just as much e-waste per capita (Robinson, 2009). Ironically, countries like China and India, which manufacture many of the electronics that are consumed around the world, also bear the brunt of processing the resulting piles of discarded devices, thanks both to robust secondary and scrap markets, and lax safety and environmental protections. A number of international agreements and conventions attempt to limit the amount of e-waste that flows between nations, but lack the means to effectively monitor and enforce this trade.

However, the growth of wireless networks and location-based technologies offers us the opportunity to directly follow our waste through normally opaque systems of transport and exchange. Furthermore, we can build our own devices from relatively inexpensive components to independently track objects without the full cooperation of large institutions. How can we use such technologies to improve our handling of e-waste? How does this information support research and activist efforts to understand and stem the international flow of hazardous materials? What are the technical challenges when using tracking devices for this purpose, and how can we validate and interpret the data we collect?

The purpose of this paper is to demonstrate one approach using GPS and smartphone-based trackers that can gather rich information on the movement of e-waste around the world, testing them with cathode ray tube (CRT) monitors. We describe the difficulties in tracking the flow of e-waste from wealthy to less wealthy regions of the world, the potential consequences of unregulated trade, and past efforts to track such contraband with electronic sensing. We developed a cheap smartphone-based location tracker, and deployed them along with commercial units on CRT monitors that were given to California-based e-waste collection and recycling companies. We found that the monitors could be tracked to several locations in Asia, sometimes in violation of laws in multiple states and countries, and discuss current and future field investigations, as well as potential future uses for this technology.

Background
E-waste encompasses a wide range of discarded electronic devices, including computers, televisions, and mobile phones, that tend to contain microprocessors and printed circuit boards. Waste Electrical and Electronic Equipment (WEEE), defined through the European Community directive 2012/12/EU, includes both e-waste and electrical appliances such as refrigerators and washing machines not
normally considered e-waste. However, through the growth of pervasive computing and the Internet of Things, these distinctions become blurred as microprocessors find their way into common objects (Hilty, Som, & Köhler, 2004). Even as computing miniaturizes, we still continue to generate more e-waste as new devices are invented and old devices become “smart” (Hilty, 2005).

As a mixture of metals, plastics, and more exotic materials, e-waste poses particular opportunities and challenges as part of global waste streams. The more common metals found, such as copper in wiring, aluminum and steel casings, and precious metals such as gold and platinum in electrical contacts, can easily be recycled for profit. Reusing these also substitutes for mining and refining new materials, which also risk significant environmental impacts. However, cheaper and primitive methods of extraction, such as burning away plastic casings and burying unused components, tend to inadvertently release toxic chemicals into the nearby air, soil, and water table. This poses both severe environmental and health risks, mainly to the workers and those living in close proximity, through direct exposure or at the end of the food chain (Robinson, 2009). Thus it is often profitable to recycle electronics outside of OECD countries, where safety regulations drive up the cost of business.

E-waste handling internationally
Repairing and refurbishing computers and monitors for resale is common practice in India and China, and prolongs the value of the product and materials (Chi, Streicher-Porte, Wang, & Reuter, 2011; Streicher-Porte et al., 2005). Along with disassembly for material recovery, this work provides much-needed jobs and income to impoverished communities, along with cheap access to technology on the second-hand market. However, because of the lack of regulation in the informal sector, lack of knowledge of the risks, or simply lack of capital to invest in safer methods, both workers and local residents are exposed to hazardous compounds, usually in geographically concentrated areas (Wang, Kuehr, Ahlquist, & Li, 2013). In the e-waste dismantling cluster in Guiyu, China, a host of studies have documented dangerous levels of pollutants in air (Li, Yu, Sheng, Fu, & Peng, 2007), soil (Leung, Luksemburg, Wong, & Wong, 2007), and water (Wong et al., 2007), all well beyond the initial work area. Further studies found heightened levels of PCBs, lead, and other compounds in the blood, hair, and breastmilk of Guiyu residents, as well as chromosomal aberrations amongst e-waste workers, though the causation is not clear (Robinson, 2009).

While debate continues on the ethical implications of wealthy countries exporting e-waste to less wealthy, non-OECD countries, international treaties like the Basel Convention already require participating countries to track all trans-boundary movement of hazardous wastes and reduce such transfers overall (Widmer, Oswald-Krapf, Sinha-Khetriwal, Schnellmann, & Böni, 2005). Though the USA is not
party to the Basel Convention, it has direct agreements with several party nations and hosts non-governmental organizations (NGOs) and private company-backed initiatives that promote similar obligations. At the state level, there are a variety of approaches to collect and manage e-waste, such as landfill bans, extended producer responsibility (EPR), and advanced recovery fee (ARF) systems (Gregory & Kirchain, 2007), though the overall country lags behind national EPR systems in Europe, Japan, and South Korea (Kahhat et al., 2008). In practice, the US Department of Homeland Security (DHS) and Environmental Protection Agency (EPA) have power to enforce existing laws, but are hampered by lack of actionable data and the ease with which shippers can submit fraudulent manifests (Puckett, 2015).

Cathode ray tubes and California
Cathode ray tubes (CRTs) exemplify these dilemmas and more. As the main display component of older television and personal computer monitors, they contain a toxic mixture of lead, glass, barium, and other circuitry materials, about 45% of which can be recycled profitably (Lee, Chang, Fan, & Chang, 2004). Promoting recycling through subsidies can reduce improper disposal through incineration or landfiling (Macauley, Palmer, & Shih, 2003). However, with consumer tastes shifting to flat-panel displays, there is little market left for recycled CRT glass in the USA, and recyclers without subsidies have no profitable use for their stockpiles (Urbina, 2013). As a result, there have been a growing number of illegal dumping incidents in remote parts of the USA.

A more accepted and legal action is to ship CRTs to a material recovery facility (MRF). These facilities recover lead and copper from the CRT glass through a smelting process, and protect workers from exposure (Kang & Schoenung, 2005). Building out the necessary infrastructure is expensive, with the State of California projected to need 60 MRFs at cost of $16 million (Kang & Schoenung, 2006); to make this financially sustainable, the state pays recyclers for the weight of electronic devices recycled, per the California Electronic Waste Recycling Act (EWRA) (California Electronic Waste Recycling Act. SB 20 (Sher, 2003) and SB 50 (Sher 2004), n.d.). However, there is still a market for recycled CRT glass in China and India, and it can be much cheaper to ship CRTs from the west coast to other countries by container ship, instead of by land to east coast MRFs (Kang & Schoenung, 2005). Unscrupulous recyclers in California can pocket the state subsidies, while shipping and selling the CRTs to dealers in Asia, in violation of the EWRA’s export restrictions. We explicitly sought to detect such behavior in the course of our experiment.

Known smuggling routes
This smuggling of e-waste in general and CRTs in particular requires some degree of secrecy on both shores of the Pacific Ocean. Container ships once brought
large amounts of e-waste to the port of Hong Kong, where loopholes allowed second-hand equipment to be then transferred to cities in the Chinese mainland. However, under increased scrutiny, Hong Kong customs officials have cracked down on illegal containers of hazardous waste (Wang et al., 2013), and Greenpeace activists blocked a vessel from the Port of Oakland, California, from offloading its e-waste (Ni & Zeng, 2009).

E-waste also arrives in China via ports in Vietnam, where they are transferred to border towns and brought to China by river boats (Wang et al., 2013). Through a series of six field studies, Shinkuma and Huong detailed the routes and loopholes by which CRTs enter Vietnam at the port of Haiphong, brought through the Mong Cai border town to Dongxin in China, rebuilt in Guangzhou, and resold locally or re-exported back to Vietnam by the same routes (Shinkuma & Huong, 2009). They also identify Sihanoukville, Cambodia, as a port of entry into that country and parts of southern Vietnam, with many sets refurbished and resold in Ho Chi Minh City. In both cases the e-waste tends to follow the paths of least resistance (in terms of customs control) and some pieces will “leak” out to towns along the way. The Mong Cai route is now well-known to officials and international press (Bland, 2012), and smugglers are shifting to new ports with less surveillance. Quickly identifying these new ports of entry is essential for launching new field studies to map out the routes.

Methodology

Tracking e-waste with technology

Efforts to control the flow of e-waste, both domestic and international, require accurate quantitative and qualitative data. Global quantitative data are difficult to collect directly, especially those for illicit trade, and many studies estimate flows based on production/purchase of new products, with certain assumptions made for device lifetime and prevailing export practices per country (Breivik, Armitage, Wania, & Jones, 2014; Widmer et al., 2005). These assumptions rely on qualitative investigation of the geographic routes and exchanges by which e-waste travels. Electronic tracking and “person in the port” studies, while requiring significant effort, offer the highest quality information in this area (Miller, Gregory, Duan, Kirchain, & Linnell, 2012).

The two technologies most frequently mentioned in the context of waste tracking are radio frequency identification (RFID) and geographic positioning systems (GPS). Proposed uses for RFID focus on its ability to store the contents and manifest of individual electronic devices; this information could then help recyclers easily sort and recover materials at the end-of-life (EOL) (Binder, Quirici, Domnitcheva, & Stäubli, 2008) or allow companies to track the entire lifecycle of the product, ensuring that ARF schemes eventually pay for their dismantling.
(Kahhat et al., 2008). However, this approach does not collect geographic data in absence of a world-spanning infrastructure of RFID readers, and requires the full knowledge and cooperation of the waste collectors, transporters, and recyclers, making it ill-suited for tracking illegal transboundary exchanges (Boustani et al., 2011).

GPS can be applied more flexibly to this challenge, by directly tracking the path of e-waste from suspected exporters along smuggling routes through their ports of exit and entry. When tracking containers abroad, this requires a lot of coordination between local and national law enforcement (Wang et al., 2013), but could conceivably be done as a private effort in domestic transfers without the help of government (Auld, Cashore, Balboa, Bozzi, & Renckens, 2010). For example, an independent investigation by news organizations and Greenpeace successfully used a satellite tracking device to follow an irreparable CRT television set from England to Lagos, Nigeria (Milmo & Reporter, n.d.). While satellite communications can be expensive to scale up, GPS trackers connected over mobile phone networks can operate at much less cost in most parts of the world. The Trash Track project followed 146 e-waste items across the United States this way, but was not able to track beyond national borders because of incompatible mobile infrastructure (Offenhuber, Wolf, & Ratti, 2013).

**Experimental procedure**

Our overall strategy to implement GPS tracking was as follows: develop our own experimental trackers, pair with robust off-the-shelf GPS units, install these within CRT computer monitors, drop these monitors off at several recyclers in California, track the units abroad, and follow up with on-the-ground field studies. Both our experimental trackers and the commercial GPS units would need to locate themselves using GPS, run on long-lasting batteries for several months, and report their stored traces when in range of a mobile data network.

We used unlocked Android smartphones (specifically LG Thrive models) as the basis for our experimental trackers, because of their ease in reprogramming, built-in camera and GPS module, compatibility with international SIM cards, and significantly cheaper cost than commercial global GPS trackers. A custom-built application on the phone would periodically detect its location, capture an image through the camera, and upload these data to our server. However, we faced a number of technical challenges, listed below along with our attempted solutions:

**Limited battery life**

We aimed for the phone trackers to last on a single battery charge for at least three months, but a standard smartphone lithium ion battery at the time carried around 1500 mAh, good for about one day of passive use. To address this, we
focused on reducing the average power consumption through software, and expanding battery capacity through external hardware.

When coupled with custom firmware allowing access to the phone’s power management functions, our application placed the phone in a low-powered “sleep mode” for four hours at a time. In this mode, we measured the average current draw of the phone at around 3 mA, with the current spiking up to 200-300 mA for brief periods when waking to capture and send data. Timeouts would prevent the phone from draining too much energy while out of signal range and repeatedly attempting to connect, and a 24-hour sleep cycle would activate if the phone could not reach a network for 16 or more hours (in this scenario we assumed that the device entered a storage or transport vessel and would not likely emerge for several days). If the phone ever awoke and had a signal, it would send off any backlogged reports and images.

Figure 15 Extending battery life of phone-based trackers.
Top: Soldering external battery leads to the contact points on the rear of the LG Thrive smartphone, and testing a Tenergy 18650 cell. Bottom: Comparing voltage over time as a measure of battery drain for two possible external battery alternatives.
To expand capacity, we replaced the standard battery with external batteries with higher energy density. We considered lithium ion rechargeable battery packs (Tenergy 18650 cells), lithium thionyl chloride cells (ER34615), and lithium polymer prismatic cells, all providing the necessary 3.7V. We found the Li-ion packs to be most efficient for their low internal resistance, per unit cost, and embedded protector circuits; we could easily solder the battery lead wires directly to the terminals on the back of the LG Thrive phones. Ultimately we attached 12 of these cells to each phone tracker, arranged in PVC-wrapped packs of 6 and connected in parallel pairs. This brought our total capacity up to 31200 mAh, and extended the life of our customized phone trackers to an estimated 100 days on full charge.

Our application code and battery testing findings are published in (Yen, 2012).

Signal strength and unit detection
During an initial test using global GPS trackers, we found that it was easiest to mount the bulky devices to the interior of the monitors' plastic casings. However, eventually these casings would be separated from the housed CRT, which would be sent elsewhere to be refurbished or disposed of. To understand where this dismantling occurs and where the CRT travels, we would need to embed the tracker on the glass itself. However, placing the tracker completely inside the glass tube would block its signal completely, given the high lead content in the glass absorbing radiation. Placing it completely outside the glass would leave it easily detectable and likely to be discarded completely.

To address this, we paired our experimental phone trackers with smaller model GPS trackers with external batteries connected by wire. While the phones would be attached to the interior of the plastic casing (aligned with a drilled hole allowing the camera to capture outside images), the dedicated tracker would be mounted on the outside of the CRT near the deflection coils, with the batteries mounted on the interior of the CRT. By cracking the tube at the point of attachment with the coils, we could run wire between the tracker components while still obscuring the object when the coils were re-attached\textsuperscript{11}. We used a hard-setting insulation foam to fuse the trackers to their surfaces, hide them visually while maintaining network signal, and reseal the tube underneath the coils.

\textsuperscript{11} Warning: this is a dangerous procedure that should only be attempted with the proper equipment and location. Cracking a CRT can release a cloud of toxic particles, including lead and cadmium, and the vacuum may implode the set. Safety goggles and respirators are essential, as is a well ventilated workspace. The glass itself will be sharp on its edges, so reaching into the tube also requires protective gloves and sleeves.
Figure 16 Process of embedding e-waste trackers.

Top: Cracking open the CRT at the point of attachment with copper yoke, and attaching the tracker batteries within the tube. Quick-setting insulation foam cements the device and reseals the yoke over the hole. Bottom: Resealing the tube and mounting the tracker outside. The experimental phone tracker can also be seen mounted on inside wall of the plastic casing, with its external batteries attached to the monitor’s circuit board.

Deployment

We embedded sensors in 17 CRT computer monitors, with 7 containing only pTrac-5000 GPS trackers, 5 containing only phone trackers, and 5 containing both a phone tracker and an mTrac3 GPS tracker\textsuperscript{12}. The monitors were distributed to 15 e-waste collecting businesses in the Southern California area, mostly within Los Angeles County and nearby cities. We noted the status of each business under the CalRecycle program, behavior on site (including any data logging and equipment breakdown), and related e-waste handling certifications under the e-Steward and R2 Certified programs. Following the drop-offs, we tracked each monitor remotely from our servers, and mapped their full paths using QGIS and web mapping tools.

\textsuperscript{12} Both the pTrac-5000 and mTrac3 are products offered by 2-Track Solutions Inc. Technical specifications can be found on their website http://www.2-track.com/.
Results

Phone trackers
Of the ten experimental phone trackers, four reported for less than two weeks while remaining stationary at their drop-off points. However, because these trackers reported 100% battery level (derived from their voltage curves) up to their last report, we believe this was not due to a power failure, but rather a physical obstruction or manual removal that prevented the phones from sending any further reports. Two more phones remained stationary for one month and sent their last reports at ~25% battery life.

The remaining four phones produced readable traces that hinted at the fate of the CRT monitors. Two of these monitors traveled north along a highway to Stockton, CA, and last reported from within a kilometer from a CRT glass processing plant. The photographs from these phones captured the interiors of the warehouses. A third monitor was tracked from the drop-off in Gardena to a second e-waste recycling business 50 miles away in Ontario, CA. After another week it was tracked to the Port of Long Beach, CA, where it remained among shipping containers for a week before ending up on a container ship and running out of battery life.

However, the last phone tracker successfully followed its monitor on a complex path across Southern California, onto a container ship at the Port of Long Beach, and arriving at Hong Kong 4 months after its drop-off. It correctly transitioned from a 4-hour reporting cycle to a 24-hour cycle once it lost contact with mobile networks over its 23 days at sea, conserving battery life along the way. This allowed it to last weeks beyond the expected 100 days of battery life we predicted for the devices. It also produced photos that allowed us to confirm one of its intermediate locations in California, by cross-checking an outdoor photograph with the Google Street View image of the reported GPS coordinates.
Figure 17 Using photographic evidence collected from trackers.
Top: Photograph taken by the phone tracker mounted inside the CRT monitor casing. Bottom: Google Street View image from the reported GPS location of the phone tracker. We can identify the same fence pattern and plantings in both images, supporting the veracity of the location reporting.

Commercial trackers
The five mTrac3 devices coupled with phone-tracked CRTs failed to report any usable location data once deployed. However, the pTrac-5000 devices produced strong results, with five of the seven reporting from locations in Asia and a sixth traveling directly to the CRT processing plant in Stockton; the former lasted for three to four months.

International traces
The six monitors that we detected in Asia arrived through four points of entry: Malaysia through Pinang, and China through Hong Kong, Tianjin, and Dongxing, a border city with Vietnam. The gaps between reports indicate that the Pacific crossing took anywhere from 3 weeks to 3 months. One Tianjin monitor traveled further inland to Henan, while the other four monitors converged to Guangdong
province in southern China, a region known for electronics manufacturing and e-waste recycling. Two of these monitors had been deployed at California recyclers approved under the CalRecycle program as approved e-waste collectors; this export of CRTs was a breach of the rules set by the EWRA. Table 11 summarizes the path each monitor took to its final report location.

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Primary tracker</th>
<th>City deployed</th>
<th>Max days in Pacific</th>
<th>Asia port of entry</th>
<th>Asia final report location</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>GPS</td>
<td>Commerce, CA</td>
<td>60</td>
<td>Tianjin, China</td>
<td>Guangdong, China</td>
</tr>
<tr>
<td>5</td>
<td>GPS</td>
<td>City of Industry, CA</td>
<td>43</td>
<td>Pinang, Malaysia</td>
<td>Pinang, Malaysia</td>
</tr>
<tr>
<td>7</td>
<td>GPS</td>
<td>South El Monte, CA</td>
<td>21</td>
<td>Dongxing, China</td>
<td>Tengxian, China</td>
</tr>
<tr>
<td>9</td>
<td>GPS</td>
<td>Tujunga, CA</td>
<td>39</td>
<td>Tianjin, China</td>
<td>Henan, China</td>
</tr>
<tr>
<td>10</td>
<td>GPS</td>
<td>Los Angeles, CA</td>
<td>103</td>
<td>Dongxing, China</td>
<td>Foshan, China</td>
</tr>
<tr>
<td>99</td>
<td>Phone</td>
<td>Chino, CA</td>
<td>23</td>
<td>Hong Kong, China</td>
<td>Hong Kong, China</td>
</tr>
</tbody>
</table>

Table 11: Six monitors tracked to Asia, with estimated port of entry and final report location.

Satellite imagery at the final coordinates show both rural and urban areas, residential buildings and industrial warehouses, some secluded and others easily accessible. However, there were few clues as to the activities on site or whether these were where the monitors were finally dismantled.
Field investigations
Our partners from the Basel Action Network (BAN) used this information to conduct on-the-ground investigations of the transfer and disposal sites. They
spoke with local residents and captured photographic and video evidence of both smuggling activity and e-waste processing. Handheld GPS receivers allowed investigators to travel directly to the points from where the devices reported, sometimes stumbling onto structures and staging points unmarked on any existing maps or registries (Puckett, 2015).

In Dongxing, an inland town where two monitors had first reported from China, they learned that the containers had most likely arrived through the Vietnamese port of Haiphong. There, the CRTs were transferred to semi-trucks and driven to Mong Cai, the Vietnamese town opposite of the border from Dongxing, now well-known as a primary transfer point for illicit trade in e-waste, drugs, and human trafficking. Small boats carry CRTs down and across the river to a public park in Dongxing, where they are then sent off to buyers in the Guangdong province.

Other investigations into the end points of our location traces revealed trucking depots, temporary storage yards, and warehouses where local workers dismantle the CRTs. Thus, we could begin to reconstruct the series of exchanges that brought the monitors to their final resting points. Interviews with local residents also helped BAN uncover possible smuggling routes through Myanmar, routes which are becoming more important as Mong Cai and Dongxing continue to attract unwanted regulatory attention.
Figure 19 Tracking CRT monitor smuggling into Asia.

Top: Tracked CRT monitor paths from California recyclers to ports and cities in China, Vietnam, and Malaysia. Bottom: Photograph of smugglers carrying CRTs by boat across the Vietnam-China border in Dongxing.
Conclusions

Implications for tracking smuggling routes
E-waste travels long distances to places we don’t yet know. It cheaply crosses the Pacific Ocean on container ships returning from delivering manufactured goods to the United States. It can enter countries at multiple ports, or cross over in rural areas or loosely policed border towns. It is mixed in with other contraband entering and exiting nations, shepherded by experienced smugglers who are well aware of where local authorities are turning their attention. There are significant economic incentives to accept e-waste in a developing country, to ship waste out of a developed country, and to flout regulations meant to prevent exposure to hazardous materials.

Technology and field research must go hand in hand to map out e-waste movement. Location tracking tools let us surreptitiously follow e-waste as it passes between many hands, but the data require context to interpret correctly. The ability to capture photographs adds a useful dimension to investigations. Mobile network connectivity allows for real-time communication and limited location fixing while being more affordable than satellite based technology. Efficient battery use provides a longer window for capturing a complete picture of the path taken, especially when shipping times are uncertain. The overall independence of our trackers allows us to follow these items into rural areas without the infrastructure or partnerships we normally rely on for logistics tracking.

Ultimately, technology enables new approaches to managing the vast and nebulous movement of hazardous e-waste. Location tracking can be used to track violations of local, national, and international rules, with direct action against violators or broader efforts to improve the rules and enforcement practices. It can be used as a regular tool for making legal transactions transparent and optimizing the use of public and private waste processing facilities. Finally, it can educate the public about the realities and consequences of e-waste export, driving behavior changes such as reduced consumption of new products or greater scrutiny of the standards certifications held by private e-waste collection companies.

Future work and strategic actions
There remain many technical limitations to this approach, including limited battery life, visual identification and removal of the devices, and loss of signal from inside containers. While successful, the larger GPS trackers and phone-and-battery combinations cannot be deployed within smaller electronic devices of interest, such as flat screen monitors, laptops, and mobile phones. Future research should consider how to extend the life of the batteries while reducing the size and visibility of the devices overall. An immediate next step would be perfecting a motion-
activated wake cycle which conserves the tracker’s battery when remaining stationary; longer term research could consider power-harvesting technologies from light, heat, and vibration that could greatly extend the life and range of tracking sensors.

For the Basel Action Network, the challenge is to collect reliable, credible data that can support regulatory action. They can use the data strategically in several ways. In the short term, they can share findings with the US DHS and EPA, who can investigate, arrest, and charge violators of domestic and international law. In the medium term, the tracking data can confirm the existence of suspected smuggling routes, but also reveal new destinations for e-waste that were previously unknown. This can prompt new lines of inquiry in countries where the flow of e-waste is beginning to expand. Finally, in the long term they hope to reconstruct the full path of e-waste, from cities in the US to endpoints deep within developing countries, and present this information publicly through high-profile news and mass media. By showing the volumes and visceral effects of this material flow they hope to raise awareness, sway public opinion, and pressure policymakers to strengthen waste legislation and devote more resources to enforcement (Puckett, 2015). In these ways, NGOs can impact the global export of electronic waste through the strategic collection and sharing of remote sensing data.

Acknowledgments
This project was conducted with the financial and technical support of Qualcomm Inc., along with the Senseable City Lab Consortium. We thank Thien Lee and his engineering team at Qualcomm for initial help with designing the phone trackers, and Richard Howlett for his expert consultation on optimizing battery performance. Weng Hong Teh performed valuable battery testing experiments, and Mark Yen, David Perez, and Brandon Nadres helped prepare both the hardware and software on the phone trackers for deployment. Eugene Lee assisted with the California deployments along with Jim Puckett and his team from Basel Action Network. Youjin Shin helped design the website visualization of the monitor traces. We again thank Jim Puckett and BAN for their knowledge and recall of field research in Asia.

Sources


Designing Location-Aware Applications for Informal Waste Recyclers in Brazil

Preface
This paper is a continuation of work led by myself, Dietmar Offenhuber, and Lucia Helena Xavier on the Forage Tracking project in Sao Paulo and Recife, Brazil. I produced the majority of the text and analysis in this essay, with contributions from Dietmar. A condensed version has been accepted for presentation at the 4th International Workshop on Pervasive Urban Applications (PURBA 2015), with publication in the ACM Ubicomp 2015 adjunct proceedings as:


Abstract
Informal waste collectors can provide recycling services to developing cities, while cities seek better data collection and stewardship of their waste systems. Mobile applications can mediate this relationship, but must be accessible and adopted by informal workers. With recycling cooperatives in Brazil, we prototyped and tested two smartphone and web-based systems, both intended to improve coordination and visibility between cooperatives, their clients, and local government. We apply lessons learned to a third platform, Forager, which allows coops to track their own collection vehicles in real-time and share this information with partners. Through observations, workshops, and interviews, we identified simple, error-tolerant, unobtrusive interfaces as ideal for informal work environment. Finally, we discuss how security, workload, and user expectations present unique challenges in conducting HCI research in developing contexts.
Introduction

Informal economies, such as those based on waste picking and recycling, provide many needed goods, services, and jobs in cities in the global south. Waste pickers divert useful recyclable material away from general waste streams, reducing the burden on municipal landfills and waste management (Medina, 2007). Despite poor working conditions and financial vulnerability, waste pickers are able to subsist and sometimes thrive from the sale of recyclables to industry. A growing number of countries acknowledge their informal workers, support their integration with the formal economy, and encourage public and private institutions to contract services from waste cooperatives. This approach focuses on creating new opportunities for waste-pickers to modernize on their own terms (Scheinberg, 2012).

New federal legislation in Brazil recognizes them as a central part of the value chain, and offers them access to government and private contracts (Brazil, 2010). However, these opportunities come with challenges; the regulations also include strict requirements for tracking waste flows and product life-cycle information. To compete for lucrative contracts, cooperatives need to be able to plan and document their own processes amidst greater demands for transparency, service efficiency, and data quality (Fergutz, Dias, & Mitlin, 2011).

This demand for prompt, accurate data can be met by adopting new technologies, such as smartphones and location-based applications. Mobile phones are already well-used and valued by the poor as tools of economic survival (Galperin & Mariscal, 2007). However, designing digital tools for cooperatives can be a considerable challenge. As communities of practice based on tacit knowledge, they mostly rely on informal organization (Lave & Wenger, 1991). New technologies need to respect the unwritten rules within these vulnerable organizations.

The goal of this paper is to present new opportunities, experiments, and lessons for supporting informal waste management in modernizing cities using mobile applications. We review related work in building applications for logistics workers. We present two of our own studies that informed our design approach and objectives. Finally, we develop a system for a recycling cooperative to track the locations and activities of their collection trucks in real-time, called Forager, and test it in the wild. From these three examples we draw conclusions to our research questions and the implications for human-computer interaction for development (HCI4D) and sustainable waste management.

Our work contributes to the field by focusing on traditionally under-represented users: informal workers and cooperatives with low resources. It addresses two questions:
1. How can location-aware mobile technology support informal waste cooperatives, and integration into urban waste systems?
2. How should we design such technology to maximize adoption by and usefulness to its users?

Our studies reveal specific issues faced by informal waste collectors, but also general issues in designing applications for subsistence workers. We also raise challenges in conducting design research in such communities. We highlight the ethical challenges in disrupting existing work patterns, and the need for both immediate and long-term usefulness in driving adoption.

Related Work
Mature tracking systems are used in many logistics fields, such as package delivery and formalized waste management. Real-time tracking and routing technologies arose in response to "Just-In-Time" procurement practices and on-demand consumer delivery needs from electronic commerce (Roy, 2001); widely available GIS software and GPS hardware formed the foundation for such applications (Golden, Assad, & Wasil, 2002). The generated data are used in shorter feedback loops to guide vehicles efficiently within their shifting daily context, and in longer feedback loops to guide decisions on fleet and labor management, route planning, and infrastructure build-out (Hanebeck & Tracey, 2003). For instance, package delivery service U.P.S. claimed to reduce fuel use by three million gallons in one year, by identifying the relative inefficiency of making left-hand turns and eliminating them from truck routes (Lovell, 2007).

Urban and transportation planners are finding value in gathering such data across all logistics activities in cities, to understand the flow of urban freight and mitigate congestion or environmental impact. Methods for collecting these data have evolved from surveys, to traffic sensing at key nodes, and finally to sharing of GPS-generated location data between firms and governments (Patier & Routhier, 2009). GPS tracking of municipal solid waste trucks in Thailand allowed planners to detect population changes in dynamic immigrant neighborhoods, gaps in waste service that were filled by informal workers, and growing waste generation rates that would soon outpace their truck capacity (Hiramatsu, Hara, Sekiyama, Honda, & Chiemchaisri, 2009).

Many researchers and practitioners grapple with how to introduce these technologies to users unfamiliar with their capabilities. Location-based services, both those that inform the user of their location and those that inform others, have been broadly accepted by consumers for use in mobile applications, but only if the perceived individual benefit outweighs the loss of privacy (Junglas & Watson, 2008). Their use in tracking employee activities raises ethical questions of fair treatment (Michael, McNamee, & Michael, 2006), which we sought to understand.
in the context of informal cooperatives where there is less hierarchy between the workers.

As Johansson and Pettersson (2001) found, integrating new technology, such as real-time navigation assistance, into the practice of truck drivers who normally rely on their own knowledge, intuition, and analog tools, required close observation of their work. They saw how drivers used waybills, standardized paper forms with their destinations and cargo, as a central artifact in planning and execution of their routes. Their interaction design thus revolved around seamlessly scanning a barcode added to the paper waybill to activate the digital navigation screen, augmenting the drivers’ awareness of location without taking his attention from the road (Johansson & Pettersson, 2001). We adopted these methods of closely observing existing work practices and sought the same unobtrusive design for our interface as well.

In Brazil there are several ongoing efforts to develop technologies to aid small or informal waste handlers with logistical needs. One survey highlights the need for route planning support and better management of vehicles (Ramos, Castilhos Jr, Forcellini, & Graciolli, 2013). Researchers have also prototyped automatic data entry for electronic waste (Xavier et al., 2014) and RFID tagging for hazardous materials (Namen et al., 2014), both under increased scrutiny by the federal waste policy. The success of these systems may determine whether informal workers are trusted to handle certain types of waste, while meeting the monitoring and regulatory needs of the broader urban waste system.

Initial User Studies
We recount a series of projects conducted with recycling cooperatives in Brazil since 2011. These cases informed our problem statement and design approach to our subsequent Forager truck-tracking application. More comprehensive description of these projects can be found in (Offenhuber & Lee, 2012).

Study 1: Mapping informal collection routes in São Paulo

Context
Our initial project partner, COOPAMARE, was a long-established recycling cooperative collecting material in the Perdizes neighborhood of São Paulo, Brazil. Often cited as a model for other Brazilian coops to emulate, COOPAMARE selectively collects recyclables from apartments, supermarkets, and public partners, operating two trucks to collect these shipments and processing them in a central location. Some members also operate handcarts daily to collect material from the street.

Compared to a relative abundance of material, labor was the constraining factor for the cooperative at the time of the study. Being understaffed, the cooperative
had to evaluate which jobs they should accept. They also had difficulty coordinating their many activities. Due to traffic and limited means of communication during collection, drivers would miss shipments or make pointless trips. Handcart and truck routes rarely took account of each other. Knowledge tended to reside in the memories or notepads of a few senior members, without whom work could be delayed. In general, the coop sought more efficient operations, better communications, and visibility to maintain its strong relations with its neighbors and public partners.

**Experimental approach**

Before starting the experiment, we prepared two prototype systems. Our tracking system used off-the-shelf GPS loggers to record the movement of their waste collectors; the user could then view the traces on a digital map and record audio notes. Second, we created an online platform through which clients could request a material pick-up via website form, smartphone app, or text message; by entering their location and material amount and type, this request would be posted to a web-based map accessible to the coop. We made these prototypes to test whether they would function properly in the environment, and to demonstrate to the members what data could be collected using the underlying technology.

![Figure 20 Applying digital technology to informal recycling in Sao Paulo.](image-url)
On arrival, we immersed ourselves in COOPAMARE’s daily activities, observing them at work in their headquarters and joining them at hauling recyclables during truck collection. We interviewed coop leaders about the methods they use and the challenges they face, and documented their tools for record-keeping and client management. Several members agreed to carry GPS loggers for a week with them while collecting. Each day, we conducted semi-structured interviews with them, using these maps as guides to articulate their thought process. We shared the traces with the cooperative and held a workshop with all members where we asked them to comment on and annotate large printed maps of the data we collected. Coop members also tested the mobile and web interfaces of the pick-up request platform, and offered their opinions.

Results
From a research perspective, collecting traces using GPS loggers provided valuable insights about COOPAMARE’s spatial logic of collection. The value of such a map was also immediately recognized by the cooperative, leading to an engaged discussion between truck- and manual collectors. The visualized traces provided useful context for the waste pickers to explain knowledge that had never been codified, such as how handcart operators choose their routes. They also provided concrete evidence of the coop’s operational challenges, such as congestion and driving restrictions acting as greater obstacles than distance.

Our pick-up request platform also helped clarify the design preferences of the cooperative. By seeing the platform in action, they inferred that such a system would clash with their current practices. They noted that without a face-to-face or phone conversation, they would not be able to manage expectations for the timeliness of the pick-ups. They also preferred to encourage people to drop off material, to minimize their number of trips. Thus, the interfaces would be better off if reversed, with the cooperative able to broadcast their activities in real-time, and clients able to observe this information from the map.

Study 2: documenting e-waste in Recife

Context
In Recife, we addressed a different dilemma of modern waste management: the safe disposal of electronic waste. New national and state laws hold both companies and public agencies accountable for the full lifecycle of their electronics, demanding new practices for tracking their transport and disposal. While lawmakers intended for private companies to meet these obligations by applying data management and technology, we hypothesized that recycling
cooperatives would also need to adapt, since they receive e-waste from many areas of the city.

We worked with several small-scale cooperatives in the region that were adapting to these new requirements. Some, like COOCARES in Abreu e Lima, have developed partnerships with large firms like Coca-Cola and adopted strong accounting practices to maintain transparency with their partners. Others, like Pró Recife, deal with local institutions and receive equipment and contracts through cooperation with the government. In all cases, coops received e-waste from clients that could not earn them value, because of the stringent requirements for documenting these handoffs.

**Experimental approach**

Our prototype system paired a smartphone application with printed 2-dimensional barcode stickers, each with a unique value to be applied to each e-waste item received by the cooperative. The app prompted users to photograph the object, classify its type, and scan its code, thus creating a time-stamped record of where it was received. Subsequent barcode scans could then add more handoff records, or reveal the object’s full history. A web application mapped all of these handoffs for the cooperative or regulators to review.

We followed a similar pattern for each cooperative we visited: interview them on their coop’s practices and challenges, map their area of operations on paper, equip them with the phones and barcode labels, and witness them using the app at the coop or on the streets. Through this process we could see firsthand how the design of our system succeeded or failed in different contexts. We were able to incorporate these findings into new software versions for testing on return visits.
Results
Our interview partners largely confirmed our hypothesis on the indirect effects of the documentation requirement. Companies would pay higher prices for well-documented e-waste, and would provide better contracts for collectors who were
able to provide these data. This underlined the need for fast and simple waste tracking tools.

While testing the e-waste tagging system in the wild, however, we quickly learned limitations of our approach. Our smartphone application was too complex, visually and sequentially, to be used effectively while working to collect materials. For subsequent tests, we modified the app to minimize text labels (accommodating illiterate users), resized buttons to focus attention on critical steps, and provided bright color feedback on whether location tracking was activated. While these improved user comfort and accuracy with the app, the clumsiness of applying barcode labels while exposed outdoors remained a burden.

We also discovered practical limits on applying this system to hand-cart waste picking. When asked to carry and test the smartphones on their collection routes, manual pickers declined due to risk of theft. Waste pickers already operate in less policed, often informal areas, and carrying around advanced electronics could increase their vulnerability. While such technologies might work well from the cab of a truck, they offered more risks than benefits for some workers in contested areas.

Forager application
Context
Through our interviews with Pró Recife, we learned that real-time vehicle tracking, a minor feature of our previous e-waste handling app, was actually much more relevant to their operations. Because traffic congestion and road infrastructure in Recife are highly unpredictable, and because they pick up materials from clients all over the city, their truck is active through the whole day. Communication runs through mobile phone, but some information such as their current location and changes to routes are difficult to transmit while on the road. The coop felt it could benefit greatly from seeing the vehicle’s location in real-time on a map. Archiving these traces could also help them plan better routes, and document their collection activities in a form easily shared with their public and private partners.

Design challenges
We were faced with several challenges with designing the Forager system, gleaned from our previous studies:

Tracking technology – Cost and ease of procurement and maintenance are important factors for introducing any new technology, and coops lack the financial flexibility to invest in single-use technologies like dedicated location trackers. We needed hardware that would be easy to procure, easy to repair or replace, and relatively inexpensive to operate.
Financial uncertainty – What resources cooperatives have to test out new technologies often come from government initiatives, NGOs, or research grants. These are often restricted to a few years at the most, and subject to political or economic shocks that may reduce or eliminate their funding. Cooperatives benefit from technologies that are free or inexpensive to maintain, and can be adapted and improved despite changing personnel.

Technological infrastructure – As an extension of this, computing resources in a coop could range from banks of networked computer workstations down to an outdated single PC. Internet access might consist of a local wi-fi network with broadband paid for by an outside partner, or a jerry-rigged 3G modem relying on pre-paid mobile SIM cards. We had to account for a wide range of processing speeds, operating systems, internet bandwidth, and hardware set-ups in our potential user base.

Technical literacy – Because many informal waste pickers lack formal secondary education, we couldn’t count on all users being familiar with the jargon and norms of information technology. Older workers might also be unfamiliar with recent features of mobile and smartphones, such as touch interfaces and built-in cameras.

Field conditions – By limiting our tracking activity to the movement of collection vehicles, we addressed two earlier concerns of the collectors: keeping the phone out of view of would-be-thieves, and protecting it from exposure inherent to waste work. However, we were still faced with uncertain access to electrical power (thus limiting us to battery power range) and mobile data networks.

Design choices
Because of these design limitations, we devised a system that relied on two simple interfaces: one to track collection activity in the field, and the other to view these data away from the field. The former would be installed on an Android smartphone capable of tracking its own position using internal GPS and a standard geolocation API, while also allowing users to manually input metadata such as the material collected and the fill level of the truck. The latter interface would be accessible by web browser, allowing users to browse and map any of the location traces collected by the phone trackers in real time, and annotating the map to aid in route planning.
Figure 22 Truck-tracking mobile and web applications.

Top left: Smartphone with truck tracking app safely mounted to inside of truck cab. Right: Mobile app screens for toggling tracking and logging stops. Bottom left: Web interface for mapping truck routes in real-time.

We designed the smartphone application to be simple to operate, with only three interface screens: one for turning on location tracking, one for detailing a pickup stop, and one for identifying the worker and coop. Buttons were sized by importance, primary colors indicated whether tracking was turned on or off, and data input at pickups required only approximate observations (broad categories for types of waste, and a visual slider for amount of material filling the truck).
Behind the interface were more complex functions for caching this information when a data connection wasn’t available, and uploading it to a cloud server when in range of mobile or wi-fi networks. This was essential for ensuring that data would be saved despite unpredictable network access, while avoiding any complicated manual upload procedures and possible data loss or duplication, as we had encountered with using GPS loggers in COOPAMARE. An external 11200 mAh battery provided additional charge life for over a full day of use, while mobile connectivity required a pre-paid SIM card from a Brazilian-based operator. Finally, we installed a windshield-mounted smartphone grip to hold the phone in place while driving.

As for the real-time map, we chose to develop a web application that would work consistently on most browsers, while allowing us to remotely update it with feedback from the cooperative after our deployment. This application was also kept visually simple, devoting its single screen to an online map showing a selected trace and a set of points-of-interest (usually waste pickup and drop-off locations). It would serve dual purposes: as a real-time tracking application by showing the most recent in-progress trace as it developed, and as an analysis tool for groups of workers to review past traces and identify areas of opportunity or inefficiency. It could easily be shared with clients or public partners as evidence of past activities as well.

Traces begin and end wherever the user starts and stops the tracking function, respectively, and from the web application side, the traces appear as polyline segments overlaid on a draggable, zoomable map. Markers indicate the stops made by the truck during its route, as well as the latest known position; mouse-over events show the timestamp of each stop, and click events display the waste types and fill as input by the workers. Additional markers show the various points-of-interest that the cooperative had previously annotated on the map. The street layer of the map is sourced from collaborative OpenStreetMap data, visually styled using Mapbox.\(^\text{13}\)

Experimental procedure
Our visit to Pró Recife focused on how to incorporate this technology into their workflow. This meant demonstrating the system with their workers, mounting the phone in their vehicle, setting up their office computer to access the web application, and sending their truck out for collection to observe their reaction to the interface. We monitored their use of the system remotely, through access to

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\(^{13}\) The web application front-end was written in Javascript, using the Mapbox API and Bootstrap template to present the interactive map interface. The smartphone and web apps used a common backend: Parse, a cloud-based model-view-controller application platform. Both apps benefited from a shared data object structure, shorter technology stack, and automatic data caching and upload in the Android SDK.
the web console and continued hardware troubleshooting. After several months of use, we followed up with a series of semi-structured interviews with the cooperative members to understand how the tool had affected their working practices thus far, and how they planned to use it going forward. Although the cooperative comprised of 29 members, they chose to only have two members participate in our interview: their truck driver and manager.

Results
From our database, we observed the cooperative running the tracking mobile application sporadically from May through October of 2014. Rather than incorporate the application into their daily practice, they chose to use it occasionally for specific purposes.

The driver indicated little experience with using web-based applications or maps, and neither he nor the manager owned smartphones. However, while training them to use our application, we did not observe any difficulty in running the app or navigating its interface. During our subsequent interviews, neither mentioned the interface as a challenge.

The driver said that he had begun using the phone’s navigation app for locating addresses, indicating an improved familiarity with the smartphone overall. Additionally, the driver said the navigation app improved his ability to collect material. This was not a function we had intended when installing the smartphone in the truck, but the driver clearly valued it and justified having the system in place.

The manager also felt the system helped his work, citing “credibility, reliability, and transparency” as ways the system improved his relationship with the government. He also noted that they could negotiate more lucrative contracts with clients now. In his words, being a “pioneer” in this field and an “academic reference” provides them a great advantage in gaining “support for the cooperative.”

However, they did encounter problems with maintaining credit on the pre-paid mobile account. Knowing when the account was near zero and topping it up in advance proved difficult for the manager, and may have contributed to some of the gaps in usage we observed. The manager explained that he intended to use the system on a daily basis, but in conjunction with new contracts with clients who would help fund its running costs.

He also reiterated his fears of theft or robbery of the phone, even when placed inside of the truck, and that this “third party might make personal use of the device.” His request was to add password protection to the application, indicating that they wished to protect not only the physical hardware, but also the collected data.
Conclusion

How can location-aware mobile technology support informal waste cooperatives, and integration into urban waste systems? New technologies enable cooperatives to apply real-time tracking and route optimization to their work, without having to adopt the strict command structures of formal businesses. They can choose tools that do not interfere with their current evolved practices, while collecting information that can be used to stabilize or improve their situation. This information requires less formal training, infrastructure, and commitment to obtain than with commercial logistics technologies. Such tools can be scaled down to their needs, minimizing costs so that they can compete on equal footing with private companies for contracts.

However, cooperatives can also scale up to provide municipal solid waste services across the city through partnerships with local governments, by using those tools to make their operations transparent and easy to monitor for public officials. This transparency helps companies and governments hold the cooperatives accountable for their operations, at the same standards by which private waste operators are tracked. Having cooperatives take on the tasks at which they excel, such as recovering valuable materials and collecting in poorly mapped, informal communities, allows governments to focus on other problems, such as enforcing health and safety regulations.

Such hybrid formal-informal waste collection systems could offer the best of both approaches: efficient localized collection with minimal added infrastructure, employment for the most in need, transparency and accountability, and the preservation of tacit knowledge in communities.

How should we design such technology to maximize adoption by and usefulness to its users? Basic ergonomic, technical, and environmental factors make it difficult to deploy technologies in environments such as waste cooperatives. These include glare from sunlight, exposure to dust or moisture, battery drain, signal coverage, and lack of charging infrastructure. These represent classic HCI problems that are not unique for informal environments. Limiting the system to use inside vehicles and offices, as we did with Forager, helped minimize these problems without sacrificing much in functionality. External batteries, protective casing, and data caching can improve the system's resilience in uncertain conditions.

Interface design techniques that reduce cognitive load on the user are all welcome. Simple interfaces with only a few sequential steps greatly improve user comfort and success with these systems. Minimal use of text and hierarchy in color and size also help workers quickly navigate the applications and devote more
attention to their manual work. Data transfer between devices should be automatic and invisible. However, over time these features may become less critical as workers become more familiar with smartphone interaction.

Lessons for design research in informal settings
Social challenges constituted the largest part of our work, due to the complex nature of how technology and the social practices in the cooperative affect each other. For example, fear of robbery strongly deterred manual collectors in Recife from carrying phones with them. This drove our decision to only track motorized vehicles using the smartphone application.

Social realities may also limit participation and our capacity to conduct HCI research and training. Workshops had to be as non-intrusive as possible, since any time spent with us would delay their tasks at hand. Cooperatives also preferred to limit interviews and surveys to those workers who would use the technology directly, rather than all members. Such constraints prevented us from testing across a large sample population, and forced us to focus on how the group as a whole might respond to the technology.

We frequently discussed the expectation of an immediate benefit versus long-term infrastructural payoffs; many cooperatives quickly dismissed tools that did not meet their needs or expectations. In this sense, mobile phones offered many flexible benefits, such as navigational tools, that help drive adoption and enable us to test other systems.

In general, taking an iterative and participatory approach to HCI4D research afforded us the time and flexibility to immerse ourselves in the cooperatives’ work environment, and adapt our research methods and design goals to best fit within their practices. Our experience is reflected in those of many others working in HCI4D and grappling with similar ethical, methodological, and operational dilemmas (Ho, Smyth, Kam, & Dearden, 2009).

How do the data generated by these applications close the feedback loop in modern urban waste systems? We see three types of feedback loops that can be closed using the information generated by tracking systems like the Forager application:
In the short run, real-time vehicle tracking can mitigate disturbances like cancelled or rescheduled pick-ups. A change in the itinerary or traffic accident can be communicated rapidly between the cooperative, collection crews, and clients. They can then alter the planned route of the collection vehicle, and monitor its progress for any further changes. Thus they can avoid wasted trips or missed opportunities that might result from a miscommunication or ambiguity.

In the medium run, the cooperative can use its data on material flows and client locations to plan better routes for its collection. New clients can be folded into existing routes or rejected based on the relative cost of picking up the material. The system as a whole can ensure the best use of limited vehicles and man hours, while retaining a steady and profitable flow of recyclable materials.

In the long run, the cooperative can comply with the demand for transparency from both public officials and private partners. The steady flow of operations data holds both sides accountable to their commitments; cooperatives can demonstrate their impact on waste management for the city, while their partners can identify where additional operational support is needed (such as vehicles, infrastructure access, or specialized training). This build trust and visibility for the cooperative, and stabilizes their contracts and political support.

Summary
In this paper, we explored how technology can transform waste systems in developing cities, through the inclusion of informal recycling activities. We referred to the literature on ICT4D, informal waste picking, and logistics systems to guide our design approach. We also applied lessons learned from two prior projects using waste tracking technology to support recycling cooperative operations. This culminated in development of the Forager system for tracking collection vehicles in real-time. We concluded that location-based mobile technology can enable new ways of managing waste in developing cities, though there are many challenges to
designing such systems in a participatory way. Finally, we discussed several unique challenges in conducting HCI research in informal work settings.

Yet, the work of understanding informal waste pickers, their tacit knowledge, and importance to developing cities remains unfinished. Many cooperatives and individual pickers remain in precarious situations, and further technological innovations can help solidify their position in the formal waste chain. Future research should continue to take an action-based, participatory approach to building solutions that respect the independence and expertise of the informal sector.

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References


Appendices
Appendix 1: Additional literature review

Information and communications technology for development

ICT4D is an interdisciplinary research field concerned with applying ICTs to problems of economic and social development. In research and in practice, these studies and experiments have focused on the "developing world," a blanket term for countries, regions, and cities with lower living standards and Human Development Index than areas with post-industrial economies. ICT4D proponents argue that ICTs can accelerate or enable programs for improving the well-being of the most vulnerable populations, especially on problems that resist traditional development solutions like an influx of capital or labor. One famous example is Ushahidi, an online platform for collecting and disseminating crowdsourced information, first used to rapidly map post-election violence in Kenya more quickly than mainstream media could report (Goldstein & Rotich, 2008).

ICT4D has evolved several times in its history, from a general adoption of ICTs by governments and firms to improve on existing processes, to the optimistic rollout of computer-filled telecenters intended to link poor communities to the Internet, to a current generation of projects applying a diverse set of tools to an equally diverse set of problems (Heeks, 2008). Many early projects failed to improve quality of life, as they were more expensive to build and maintain than expected, did not offer specific useful applications, or would not or could not be adopted because of language or other barriers. On an operational level, critics attribute these failures to the top-down, supply led approaches common to such initiatives as telecenter construction or One Laptop Per Child (Kleine & Unwin, 2009). On a research level, ICT4D critics point out that many authors are not multidisciplinary (Raiti, 2006), but are biased toward computer science or information systems (leading to projects that are technically sound but unsuited for the context) or development studies (the reverse problem).

Technological innovation has also driven the evolution of ICT4D. Many far-flung regions, once too expensive to link with wired Internet infrastructure, are now within reach of mobile phone networks. Poor communities have naturally adopted mobile phones for a variety of uses, from simple communications to cashless payments and information lookup. Mobile phones are also cheaper to obtain, connect to service, charge, and transport. Their value shows in their widespread uptake and increased economic activities in communities with high mobile phone adoption, and ICT4D projects can build on and strengthen these platforms (Zuckerman, 2010).

We internalized several lessons from this literature. First, projects must be sustainable in the long run, scalable to wider areas and sections of the population,
and open to evaluation and improvement, in order to achieve meaningful improvements in their target communities (Heeks, 2008). Second, low-cost, decentralized systems for sharing knowledge are more sustainable for poor communities, and are a more effective use of Internet and networked technologies (Kleine & Unwin, 2009). Third, tools that enhance the capabilities of individuals to share and act on knowledge are more successful in human development (Hamel, 2010); mobile phones are a leading platform for expanding human capabilities (Smith, Spence, & Rashid, 2011). Finally, ICTs alone cannot improve well-being; they have to be paired with broader strategies to make the most of their potential impact.

Informal waste picking and recycling in the world
Informal waste collection and recycling are nearly ubiquitous in developing world cities (and persist in many developed cities), stemming from a need for income among poor and marginalized social groups and inadequate formal municipal solid waste (MSW) collection services. Waste picking takes many forms, from the sorting of usable material from community bins and MSW trucks, to foraging for material from streets and open landfills, to door-to-door collections for negotiated fees (Wilson, Velis, & Cheeseman, 2006). Recyclables are traded up a hierarchy to cooperatives, middlemen, wholesalers, and manufacturing industries, gaining value as they are better sorted, cleaned, and bundled in larger amounts. Because individual waste pickers earn the least from this trade and suffer the harshest working environments, they benefit from joining or aligning with cooperatives to move up the hierarchy and improve their bargaining position with authorities and middlemen (Medina, 2000).

In developing cities, informal waste picking provides many economic and environmental benefits. They are efficient at identifying, separating, and adding value to recyclable materials with minimal capital expenditure (Scheinberg, 2001). This reduces the amount of waste that must be transported and buried in municipal landfills (reducing costs and energy use), and ensures a steady supply of material for local industries. Because MSW service only collects between 50 and 80% of waste in these cities, the informal sector is crucial to filling this gap and preventing waste from overwhelming streets and waterways (Moreno-Sanchez & Maldonado, 2006). Waste picking also provides work for those with the fewest opportunities, often women, children, and certain minority groups, reducing the burden on some welfare programs (but possibly exacerbating other social costs) (Huysman, 1994). For example, the Zabbaleen, a minority community of primarily Coptic Christians in Cairo, collect 30-40% of Cairo’s waste, and recycle up to 80% of what they collect (Aziz, 2004).

Despite these benefits, waste picking is fraught with risks and conflict. The work itself is physically strenuous, and exposes the worker to environmental dangers
such as extreme heat, pollution, toxic materials, and fast-moving vehicles (Wilson et al., 2006). Waste pickers may be discriminated against or actively preyed upon, because of the social standing of the groups that often do this work or the perceived nature of the work itself, which may be seen as unclean, backwards, or criminal (Sembiring & Nitivattananon, 2010). On an institutional level, municipal governments may be hostile to waste pickers and other informal markets for recycling, seeing them as antithetical to their drive for modernization, or may simply ignore them in the process of partnering with private companies to provide MSW services (Wilson et al., 2006). These governments may not recognize that the labor-intensive model of informal recycling might be more cost-effective than capital-intensive models from the developed world, and thus a better target for investment (Ahmed & Ali, 2004).

Past development approaches tend to miss the point by only focusing on worker welfare, education, or rights, without understanding their place as legitimate stakeholders in the solid waste system (Scheinberg & Anschutz, 2006). Actively engaging all stakeholders, formal and informal, waste generating and waste collecting, is key to improving cleanliness and sustainable waste management in developing world cities (Joseph, 2006). Cooperation between informal and formal sectors can protect the livelihoods of workers, improve their earning potential and working conditions, and retain the benefits they bring, but is often hampered by mistrust between governments and informal workers (United Nations Environment Programme, 2011). For example, the Kagad Kach Patra Kashtakari Panchayat (KKPKP) union has operated a successful door-to-door waste collection and recycling service in Pune, India for many years, but tension around unpaid subsidies from the Pune Municipal Corporation have prevented KKPKP from scaling up this business model (Chikarmane, 2012).

So far, we have not seen ICT4D applied to improving trust between formal and informal stakeholders in the MSW system, nor to leveraging the unique skills and knowledge waste pickers have toward waste challenges at the urban scale.
Appendix 2: Semi-structured interview guide

**Personal work background**
- How long have you worked with this cooperative?
- Which tasks do you participate in at the cooperative?
  - e.g. driving, hauling, sorting, data entry, management, etc.
- Are you being trained for any other tasks at the cooperative?
- Do you communicate directly with any of the clients of the cooperative?

**Technical background**
- Do you own a mobile phone?
  - Is it a smartphone? Does it have access to the Internet?
- How comfortable are you with the following technologies:
  - Mobile phone calling, mobile phone text messaging, smartphone applications, Internet browsing, Internet mapping applications, e.g. Google Maps

**Mobile and web applications**
- Did you use the mobile app at any point in the last two weeks? For what purpose?
  - How did this affect your collection routine while collecting by truck?
  - [ask for general improvements to the application interface, language, etc.]
- Did you use the mapping app at any point in the last two weeks, while trash collection was underway? For what purpose?
- Did you use the mapping app at any point in the last two weeks, after collection was complete for the day? For what purpose?
- Did you use the mapping app at any point in the last two weeks, in meetings with collection staff and other workers? For what purpose?
  - [ask for general improvements to the application interface, language, etc.]

**System**
- How was your experience with using the system? Did it enhance or hinder your work?
- Are there ways to improve the platform?
  - Technical problems with the installed features
  - Need for new or different features
  - Readability, attractiveness, other interface issues
  - Cost and safety issues

**Information feedback**
- Do you plan to continue to use this system? How often? (daily, weekly, occasionally?)
- Would you be willing to share this information with your clients? In real-time or afterwards?
How would this information affect your relationship with your clients?

- Would you be willing to share this information with the government? In real-time or afterwards?
  - How would this information affect your relationship with the government?

- What do you think is the greatest advantage of having this system?

What do you think is the greatest danger in having this system?
Mapping the Waste Handling Dynamics in Mombasa Using Mobile Phone GPS

Preface
This paper covers work I completed in 2013 with a team of MIT-based researchers: Kevin Kung, Maria Davydenko, Ali Kamil, Julian Contreras, Mohit Kansal, and Dietmar Offenhuber. Kevin and I co-wrote this paper, contributing equally to the text and analysis. It was accepted to the 14th International Conference on Computers in Urban Planning and Urban Management (CUPUM 2015), and published in its proceedings under the citation:


Abstract
In many Sub-Saharan African cities, informal collectors, waste pickers, and middlemen provide the bulk of waste management and recycling services. These workers also retain useful tacit knowledge about urban form and activities. However, such knowledge is often poorly understood and rarely documented from a geographic perspective. We designed and deployed an application to map informal waste management in Mombasa, Kenya. The phone application provided easy location tracking with the collectors’ existing Android phones, and mapped the traces in real-time through a simple web interface. We selected three neighborhoods and worked with local waste cooperatives to map their collection routes. From the generated datasets, we observed how they operate and adapt to each community. Such data not only delineates the areas serviced by the waste collectors, but could also improve operating efficiency of informal waste handling services. The platform also gives planners useful contextual knowledge for areas lacking official geographic data.
Introduction
In many cities in Sub-Saharan Africa, informal collectors, waste pickers, and middlemen provide the bulk of waste management and recycling services. Even where municipal services exist, informal players often complete the first-mile collection from households, as well as primary segregation to extract recyclable materials, critically extending the reach and efficiency of the formal waste service. These workers also retain useful tacit knowledge about urban form and activities in the areas they serve. However, such knowledge is often poorly understood and rarely documented from a geographic perspective.

In this study, we designed and deployed a phone and web-based application to map informal waste management in the city of Mombasa, Kenya. Based on prior work tracking individual waste objects in the United States and informal collection routes in São Paulo, Brazil with GPS-based devices, this work extends the capability of collectors to track themselves. The phone application provides easy location tracking with the collectors' existing Android phones, and maps the traces in real-time through a simple web interface.

With the help of the Mombasa municipal council, we first built a detailed map of the primary garbage collection points, as well as a limited number of informal recycling points in the city. We then selected three particular neighborhoods of Mombasa and worked with local waste cooperatives to map their collection routes. From the datasets generated by the phone application, we could observe how the cooperatives operate and adapt to each community.

Such data not only specifically delineates the areas serviced by the waste collectors, but could also lead to improvements in the operating efficiency of informal waste handling services in a given neighborhood. The platform enables a more powerful city-wide waste mapping endeavor that would improve communication and coordination amongst the various informal waste handling groups, by allowing them to share the generated maps with each other and with city managers. This also gives planners useful contextual knowledge for areas of the city lacking official geographic data.

Waste Management Status in Mombasa
With 0.9 million residents, Mombasa is the major port of Kenya and its second largest city, compared with 3.1 million in Nairobi, the country's capital (Kenya National Bureau of Statistics, 2014). Due to rapid population growth, the urban waste management system—first designed in the colonial era for a much sparser population density—has faced many challenges in recent years, such as open dumping and insufficient landfill space (Okot-Okumu, 2012). For example, much of Mombasa's municipal waste currently goes to the Kibarani dumpsite, which was unlicensed in 2000. However, the lack of a replacement landfill meant that the
city's only choice was to continue to use Kibarani, which currently operates under a special permission from the National Environmental Management Authority (NEMA). Today, Mombasa generates about 660-750 tons of household waste per day (Mugaza, 2013).

In 2007, funded by the French Agency for Development (AFD), several international corporations collaborated on two urban waste management projects (AFD, 2014). The first project set up a community-run comprehensive recycling facility that includes composting, briquetting, plastic recycling, and other processes in Jomvu Kuu, about 10 km outside of Mombasa. The second project was the establishment of the Mwakirunge sanitary landfill, located about 17 km northwest of Mombasa proper. The authors visited the Jomvu Kuu plant in 2013, which had not yet started running (Fadhil, 2013). According to the local reports, the facility may be slated to be in operation in the near future. However, due to disputes, NEMA has not licensed the Mwakirunge landfill to date (Hanga, 2013). Thus, both Kibarani and Mwakirunge operate as unlicensed dumpsites, though private waste collection companies are forbidden to make use of Kibarani.

As illustrated in Figure 24, municipal household waste collection typically follows a three-stage process (Davydenko, 2013). First, the waste is collected from households or the nearby neighborhood. In more affluent neighborhoods (such as the Old Town), municipal services collect from public dumpsters, though only about 13% of the households are served by this formal network. Larger institutions such as schools and restaurants must hire private companies to collect their waste, a service which we also consider to be part of the formal network. Such private companies also collect waste directly from about one-third of Mombasa households (Tan, 2012). However, the remaining households are not within reach of these formal services, and the role of informal waste collectors becomes important in such neighborhoods. For a monthly subscription fee, these groups go door-to-door twice a week on foot to collect trash from unserved areas.

Second, collectors bring waste to an intermediate transfer point (illustrated in Figure 25), typically located within or near the neighborhood. Valuable recyclable materials such as plastics and metals are sorted out first-pass, either by the waste collection groups themselves, or by itinerant waste-pickers. Finally, about every two to seven days, trucks transport the remaining waste from the transfer point to the large dumpsites. In some cases, the municipal council provides this pick-up service, but informal waste collection groups often need to arrange and pay for their own pick-ups from private entities.

Thus, waste management throughout all levels in Mombasa is an intricate mixture of government services, private enterprises, and informal groups. Increasingly, the distinction between the latter two has blurred given the emergence of 'youth
groups" in Kenya, which is a way for the government to facilitate formal registration of otherwise informal groups or enterprises. In fact, a few successful youth groups in waste management eventually become incorporated entities, effectively becoming part of the formal private sector. However, since many youth groups in waste management in Kenya play similar roles as waste collector groups in other countries (which are often informal or semi-formalized), for simplicity we will treat them as informal players in this study.

Figure 24 Schematic of Mombasa’s waste collection, transport, and value chains.
Figure reproduced from (Davydenko, 2013).

Figure 25 Photographs illustrating waste systems in Mombasa.
A formal waste collection dumpster at the Old Ports (left) and an informal transfer point within the Kisauni community (right) in Mombasa, Kenya. Photographs taken by Maria Davydenko.
Integrating Informal Waste Collection

Historically, waste management interventions and reforms in developing urban centers have been modelled after the formalized systems commonly found in North America and Europe (Medina, 2007). Such practices are often perceived as incompatible with existing informal waste collection networks, given that many formalized systems call for exclusive collection and recycling of the entire waste stream, displacing the work of any informal and community-based waste collectors and waste-pickers. However, centralized waste management services, whether through public or private monopoly, have a long history of failure in developing cities, whether due to exogenous political and economic instability, explosive informal settlement growth, or lack of timely investment (Oosterveer & Spaargaren, 2010). Scholars have sought a “modernized mixtures” approach that combines the best features of both centralized and decentralized systems (Tukahirwa, Mol, & Oosterveer, 2013).

Recent works have increasingly identified the pivotal roles of the informal sector in waste management. For example, the waste recovery and recycling rates by informal systems in many cities may actually be on par with those of more formalized systems found in North America and Europe (Wilson, Velis, & Cheeseman, 2006). In Brazil, there are more than 50,000 self-organized catadores, who recover enough recyclable material to reduce waste in landfills by 20%; an estimated 90% of material recycled by industry is collected by waste pickers (Fergutz, Dias, & Mitlin, 2011). In many places, the labor-intensive model of informal recycling might be more cost-effective than capital-intensive models from the developed world, and thus a better target for investment (Ahmed & Ali, 2004).

Scheinberg and Anschutz (2006) and Joseph (2006) have argued that engaging the informal sector is essential to any sustainable, participatory waste management approach, since waste collectors and pickers already engage with the local communities. However, such integration presents many challenges from the perspective of urban planning. Offenhuber and Lee (2012) noted that it is often difficult to codify informal operations and local knowledge, given the relatively high cost (in labor hours, training, and infrastructure) to capital-poor subsistence workers. Information about collection routes, timing, and open trash transfer points may be unavailable outside the group and the immediate vicinity of the community. Therefore, developing a method to easily collect and quantify such tacit knowledge is crucial for city-wide planning and integration of informal waste management in the future.

Yet as Gutberlet (2008) notes, informal workers and cooperatives are often excluded because of their lack of visibility and representation, despite the valuable knowledge they retain about their communities and best practices. Activists and academics have often employed action research to make the recyclers’ voices
heard, and media tools such as video documenting help facilitate dialogue in both directions. However, while these tools can periodically illuminate the personal plight of informal workers, they do not capture how they work as a system. In order to close the information loop and build a sustainable partnership between stakeholders, we need to make their operations visible on a regular basis (Fergutz et al., 2011).

**Waste Tracking Technology**

In this paper, we explore the role of sensing technology to provide details about waste management activities in the informal sector. This work builds upon prior attempts to quantify municipal waste handling dynamics since 2010. For example, the Trash Track project, described previously in (Phithakkitnukoon et al., 2013) and (Offenhuber et al., 2012), placed self-reporting GPS tags within sample waste items of different types. Traces collected in Seattle show the temporal dynamics of the waste transport and recovery chain for different types of waste within the United States.

In São Paulo, Brazil, the Forage Tracking project used off-the-shelf GPS loggers (HOLUX Technology, Hsinchu, Taiwan) to track the collectors themselves (Offenhuber & Lee, 2012). We spatially mapped the waste collection activities of recycling cooperative COOPAMARE over a period of one week, resulting in detailed resolution of the trash collection routes. However, in these cases, the GPS signal devices were either highly specialized, expensive equipment unavailable to city planners and the informal sector, or standalone devices unwieldy for regular data transfer and sharing. Single-purpose GPS hardware is also difficult to repair, replace, or upgrade as needed.

**Methodology**

We designed a GPS tracking application for smartphones that addresses the challenges described above. While many Kenyans currently possess basic feature phones without GPS capabilities, smartphone ownership is steadily increasing. From our experience in Mombasa working with several waste collector groups, it was not difficult for a given waste group to locate at least two or three smartphones amongst themselves for use on the project. Because our tracking platform has the potential to be freely downloaded and used on the phones of the local stakeholders, it drastically eliminates the cost and complications associated with employing exotic hardware.

The application runs on Android operating systems, and uses the Parse application platform to handle phone-to-server communication. During waste collection, the user presses an on-screen button to begin recording their route; in the background, the application records its GPS coordinates on a fixed time interval of one minute, and uploads these logs to the Parse backend when in reach.
of a mobile phone connection. A separate web interface allows any remote user to view the trace overlaid on a digital map (generated from OpenStreetMap data and styled in Mapbox), and observe the route develop in real-time.

We conducted a pilot of the platform in Mombasa, Kenya for a period of three weeks. First, by working with the Mombasa Municipal Council, we mapped the prominent formal and informal waste collection points within the city. Second, through informal networking, we approached four waste collection groups in different neighborhoods of Mombasa, and observed their work activities. The groups agreed to use the application to track their own collection routes over a one-week period. Finally, we shared the visualized data with the groups and municipal government to understand what value it might provide for their operations and analyses.

Results

Locations of Collection Sites

We first met with the Mombasa Municipal Council to obtain information on the city's formal waste management practices, as well as the status of formal and informal waste transfer points. The distinction between formal and informal, in this case, was also nuanced: formal waste transfer points typically have one or more dumpsters in place (though these are often unmanaged and overflowing), and may be regularly collected by the municipal waste trucks to be transferred to one of the two dumpsites. Informal waste transfer points are open dumping sites which may or may not be managed. When too much waste accumulates in informal points between shipments to landfill, the waste may simply be set on fire.

We visited many of these transfer points both on the Mombasa Island and in the surrounding neighborhoods, and interviewed the waste-pickers at some of these transfer points. A map showing the locations of these waste transfer points is plotted in Figure 26 below, with red concentric circles marking formal community transfer points and smaller orange circles representing informal transfer points.
Figure 26 Mapping the waste infrastructure of Mombasa.

Locations of informal dumps (orange circles) and community transfer points (red concentric circles) on Mombasa Island. The base map was generated using Google Maps.

Overall, there are more informal waste transfer points (38 recorded) than formal waste transfer points (18 recorded), and the formal points tend to be located near or on trunk routes. This makes sense, as these points need to be accessible to large vehicles such as garbage collection trucks. The distribution of the informal transfer points is also spatially uneven. Qualitatively, we noted that they are more concentrated near the Old Town area, which is frequented by tourists. The informal sector here appeared to be capitalizing on higher value materials in an area less well-served by municipal collection.

Dynamics of Waste Collection
We proceeded to characterize the detailed dynamics of the waste collection from the perspective of informal waste collectors. Figure 27 below illustrates the sample GPS traces of three collection groups in different neighborhoods as preliminary results from our pilot. In particular, panels (d) and (e) illustrate the same waste collection group with different pushcarts/collection routes being tracked on the same day.
The first distinction we note is that the dynamics of waste collection vary greatly from community to community. Given that each consecutive point in the track reflects equal time intervals, the differing densities of points within a given track reflect on the activities occurring along the way. Along tracks where the individual points are sparsely spaced, this indicates a higher speed of travel, which typically corresponds to waste transport with little collection activity. Segments where the individual points are densely spaced indicate more stopping for collection from clients.

In panel (b), the collection was done primarily for institutional customers (e.g. restaurants) in a dense neighborhood, and we generally see consistent movement rates from place to place. Panel (c) presents a different waste collection dynamic for a different community geography. There are numerous byways that branch off from a long service road, which in turn leads to the main trunk road about 800 m to the southwest. As their main transfer point was located next to the trunk road,
the waste collectors needed to shuttle back and forth between the network of byways and the trunk road. This particular pushcart covered about 40% of the byway network shown on the top-right portion of panel (c), while another pushcart (not being tracked) covered the byway system shown towards the middle part of panel (c). This is a residential neighborhood primarily served by the informal sector, in contrast with that shown in panel (b).

Finally, panels (d) and (e) show two independent tracks on the same day, from two different pushcarts of the same waste collection group. We make two observations here. First, we note that the density of points is much more clustered at certain places, which reflects fewer but longer stops. This corresponds well to this specific neighborhood, which comprises of blocks of multi-story apartment buildings. As the waste collectors travel through the different floors to reach households, the stop becomes longer, and the load per stop also increases.

Second, we can see that while the two tracks primarily follow different but complementary collection routes, there are sections of apparent redundancies, especially in the area closest to Magongo Road. This area actually corresponds to a dense network of roadside restaurants and markets, where large quantities of waste—especially organic waste—is generated in bulk. Given the limited capacity of a single pushcart, several trips are often needed in order to completely transport all the waste from this area to the community's transfer point.

Conclusions and Discussion
In this study, we discussed the context and stakeholders within Mombasa's municipal waste management system. We identified the informal waste management sector as one which warrants further understanding, and described our deployment of mobile-phone-based GPS tracking to help us track and map the waste collection dynamics. We worked with several informal groups in Mombasa to pilot our platform, and obtained promising results.

We also presented a preliminary tracking dataset as a proof of functionality. Despite its limitations, visualizing the dataset already yields some interesting insights. For example, in panels (d) and (e) of Figure 27, we noted that this particular group needed to make repeated trips to a cluster of restaurants and markets. This presents an opportunity from the logistical point of view; currently, the closest waste transfer point is located about 500 m away from this cluster of restaurants at the center of the community along a narrow road. One testable hypothesis that could potentially benefit the group would be to have the municipality relocate its community transfer point closer to the restaurant cluster and main road, such that the multiple pushcart pick-ups from the restaurants become less time- and labor-consuming.
This also echoes earlier experiments in São Paulo, Brazil, where the collected data showed that the waste collectors tend to selectively service spatially dispersed customers in order to maximize profit, but risked unpredictable logistical costs (Offenhuber & Lee, 2012). Such mapping data, when shared and communicated between the waste collectors, municipal authorities, and communities, can initiate a participatory dialogue about current practices and challenges, and how these relate to the future visions of the urban waste management system. While not described in this study in detail, we were subsequently able to carry out such a human-centered design session with a waste collector group in Mombasa and public officials, with both parties successfully learning from each other.

As a side benefit, we also could infer characteristics of the communities from their collection dynamics, such as building density, building use (e.g. residential, commercial), and road hierarchy. These observations, coupled with other crowdsourcing efforts, could help planners update their spatial information on informal areas that are poorly surveyed or rapidly changing.

Ultimately, we see such spatial mapping, when used in the appropriate context, as a powerful tool towards integrated municipal waste management. The Mombasa Municipal Council has expressed interest in the GPS tracking platform, for the purpose of ensuring its trucks follow set routes and schedules; their participation could help groups to coordinate pickups from informal transfer points as well. Given increasing government and private interest in many urban areas of Sub-Saharan Africa to improve waste management, a clearer perspective of the informal waste network’s geographic reach and tacit knowledge will be critical to planning efficient, inclusive waste handling strategies.

References


CityEye
Real-time Visual Dashboard for Managing Urban Services and Citizen Feedback Loops

Preface
This paper covers work I completed in 2014 as a member of Senseable City Lab along with Jesus Ricardo Alvarez Felix, Shan He, and Dietmar Offenhuber. I produced the majority of the text and analysis in this essay, with contributions from Ricardo, Shan, and Dietmar. It was accepted to the 14th International Conference on Computers in Urban Planning and Urban Management (CUPUM 2015), and published in its proceedings under the citation:


Abstract
Digital platforms such as smartphones can enable a richer dialogue between the general population and urban maintenance services in real time. Data dashboards may help officials and companies manage urban operations, but often lack relevance, accessibility, or actionability when presented publicly. We review the history of urban dashboards and 311 platforms, and the context of two Spanish cities where these could be combined to engage citizens in monitoring the state of the city. We describe CityEye, a platform that brings together operations, sensor, and citizen feedback data through a web-based dashboard and a service-based mobile application. Greater participation by citizens could allow cities to base maintenance goals on results rather than process, but will require new interfaces and policies for contracting services.
Introduction
Urban infrastructures and services are often described as invisible, not only because they are hidden from plain view, but also because we have learned to take them for granted and rarely notice them daily. However, digital platforms such as smartphones can enable a richer dialogue between the general population and various urban infrastructures and services in real time. For example, social media provides a channel for urban managers to communicate critical service information directly to citizens, while feedback hotlines like 311 and related applications allow citizens to contribute their observations and opinions.

In this paper, we present the technical, informational, and visual design of CityEye, a platform to reduce the distance between citizens and urban service providers, by making the processes of urban maintenance more legible through real-time information dashboards, and by integrating user activated feedback loops through their mobile devices. CityEye aggregates both real-time and asynchronous data generated by service operations, environmental sensors, and citizen feedback, and visualizes these through two interfaces, a “Dashboard” and a “Lens”. We assess the opportunities and challenges in deploying CityEye in two Spanish cities based on data availability, existing sensor infrastructure, and relationship between service providers and local government.

Methodology
We begin by discussing the history of participatory systems for urban maintenance like Open311, and several case studies of data dashboards specifically designed to present real-time information about city operations. For each dashboard we identify its target audience, information content, and unique aspects of its visual design. We also discuss to what degree these dashboards engage the user in the running of the city.

Following this, we describe the context of Barcelona and Santander in Spain, where we collaborated with public and private officials on ways to engage residents in urban maintenance operations. Each city presented distinct opportunities, challenges, and relationships around the types of and access to real-time data.

We then present a system called CityEye that synthesizes our lessons from the case studies and responds to the contexts of the two cities. We describe its graphical user interface and potential use cases, as well as its underlying technological infrastructure. Finally, we analyze the institutional changes a system like CityEye would require if implemented in one of the cities.
Related Work

Open311

Offenhuber (2014) reviewed the history of 311-phone systems, which began as dedicated phone lines for citizens to access non-emergency public services. In the early 2000s, cities began to consolidate their various department call centers into 311-phone systems, unlocking two benefits: collecting more and better reports on urban maintenance issues, and aggregating data to map and predict patterns of those issues. When private firms are contracted to perform urban maintenance services, the 311 systems also provide key performance indicators (KPIs) on their responsiveness, as an alternative to direct public inspections.

In parallel, web-based platforms also emerged to collect public requests for urban maintenance, starting with simple citizen-created mash-ups that map pothole photographs, independent websites like “FixMyStreet” and “SeeClickFix”, and city-based portals like Boston’s “Citizens Connect”. These platforms added mobile app interfaces as smartphones grew more popular. The data collected would include location coordinates, timestamps, service categories, and often photographs, making web map mash-ups a common interface for viewing these data online.

Many US cities adopted the “Open311” protocol to standardize the data formats they collect from phone, web, and mobile, making it easier to open, share, and build applications using these data (Desouza & Bhagwatwar, 2012). Open data movements in many cities also offer the opportunity for the public to observe how local governments operate and build innovative applications to visualize, analyze, and apply these Open311 data (Goldsmith & Crawford, 2014).

GIS, urban maintenance, and public engagement

This strong reliance on mapping and standardized data has brought the Open311 movement closer to the development of geographic information systems (GIS). GIS has been used in many ways for urban maintenance, from decoding addresses into location information (Schwester, Carrizales, & Holzer, 2009), to visualizing and analyzing reports and inventories, to serving as the backbone for infrastructure data across agencies and contractors (Naphade, Banavar, Harrison, Paraszczak, & Morris, 2011). Asset management systems, such as those used to manage and maintain roads, are a specialized form of GIS used to both streamline operational, day-to-day work and to assign KPIs that measure agency performance overall (Horak, Emery, & Agaienz, 2001).

These tools were traditionally designed for and sold to urban managers, and lacked public-facing interfaces to the information. However, there are examples of urban maintenance operations going public in real-time through maps. For example, major US cities such as Boston, New York, Pittsburgh, and Chicago have
released single-issue websites tracking the locations of snow plows and plowed status of streets.\textsuperscript{14}

GIS is also used to engage the public in bridging their experiences and knowledge with the actions of planners, through the development of softGIS methods (Kahila & Kytta, 2009). More broadly, public participation GIS (PPGIS) seeks to empower non-expert users to achieve their own goals using GIS tools through user-centered design (Haklay & Tobón, 2003; Schlossberg & Shuford, 2005). These are examples of how geodesign, the use of geospatial analysis and simulation tools to design environments (Goodchild, 2010), can be wielded by those outside of planning professions.

Urban dashboards
The rise in availability of urban data has encouraged city governments, academia and private companies to invest in ways to analyze, operationalize and communicate the vast amounts of information being created by urban services and operations. To this extent, there’s been a growing trend of cities adopting online urban dashboards as instruments in which both public officials and the general public can interact with city data in order to have a better understanding of the operating dynamics of cities (Kitchin, 2014). These dashboards often coexist with a larger information ecosystem that includes service oriented apps for mobile devices and online platforms for e-government, among others.

Preceding the rise of urban dashboards are the concept of cybernetic “control centers,” where operators could monitor the behavior of social systems (such as a city or national economy) in real-time and react to stabilize the system accordingly. Cybersyn was one such control center manifested in a physical room in the 1970s, designed to allow technocrats to observe data on all aspects of Chile’s economy (then under left-wing Allende government rule) from a single chair (Medina, 2006). Many modern cities maintain traffic control centers filled with closed-circuit television screens and data visualizations, through which staff can detect road congestion and accidents; IBM has extended this logic to its massive control room in Rio de Janeiro from which the city can command and control all emergency services (Batty, 2015).

Urban dashboards take this concept out of physical space and make them available from anywhere using personal computer or mobile device screens. This makes it more convenient to share the same information view among a dispersed population, whether they be an expanded group of public officials and technicians, or all residents of the city. These virtual dashboards can help make complex and

\textsuperscript{14} \url{http://snowstats.boston.gov/}, \url{http://maps.nyc.gov/snow/}, \\
\url{http://pittsburghpa.gov/snow/snow-plow-tracker}, \\
\url{http://www.cityofchicago.org/city/en/depts/mayor/iframe/plow_tracker.html}
diverse urban phenomena seem digestible, using raw data visualizations or simplified indicators/benchmarks, but there is an inherent danger of obfuscating or reducing the importance of causes that are not easily sensed or modeled (Kitchin, Lauriault, & McArdle, 2015).

Figure 28 Dashboard examples.
Clockwise from top left: CityDashboard, Edmonton Citizen Dashboard, IBM IOS citizen feedback applications, IBM IOS executive dashboard ("Smarter cities software," 2015).

CityDashboard is an early, influential project with the goal of "summarizing quantitative data (both officially provided and crowd-sourced) for the major UK cities, in a single screen" (O’Brien, 2012). It shows primarily weather, environmental, transportation, and energy demand in a single screen website, with numerical values in color coded boxes for ease of view. Other data such as camera feeds, news, and OpenStreetMap updates are shown in small screenshots; the dashboard also graphs bike share availability over time, but aggregated across the whole city. It also has a secondary Map view which gives access to specific traffic camera views and sensor readings, but requires users to click each marker to see any information.

While the project attempts to give the user a birds-eye view of what is happening in the city, we see three areas to be improved. First, the overall selection and

15 http://www.citydashboard.org
representation of real-time data is inconsistent, where it is unclear what different colors mean in diverse contexts. Second, the information displayed is in many cases not translated from raw numerical values to a format that might be easier to digest for non-technical users. It is hard for the user to tell if the city is actually performing well, without this context. Third, due to its focus on the most recent reports, it misses the opportunity to give users additional context by visualizing data over recent hours, days, and months. The map view also functions only as a selector, when visualizing data over space could have provided a quicker understanding of traffic patterns overall. Thus, it’s not clear if the dashboard is intended for residents or for experts.

Another interesting example is the Edmonton Citizen Dashboard\textsuperscript{16}, which is part of that city’s open data program. The project seeks to "Enable Edmontonians to review and use City data for multiple purposes" (Edmonton, 2015). The citizen is the dashboard’s intended user, which is reflected by the way in which integrates data from various official sources and in which it simplifies key performance indicators (KPIs), interaction design, and information selection criteria. The dashboard is structured over six key topics: transportation, livability, environment, urban form, economy, and finance. Each one has additional subtopics; for example, the environmental topic shows KPIs for activities such as sewage cleaning, missed waste collection spots, lot grading inspections, and number of eco-stations user. For transportation the site shows transit ridership, potholes filled, disabled adults transit services levels, and street sweeping.

The Edmonton Citizen Dashboard does a good job of both organizing the data in a hierarchical structured manner, and in representing the data in an easy to understand form. It uses a combination of simplified KPIs, a clear explanation of what each one represents, and displays them in a clear graphical form that uses consistent color-coding, iconography and fonts. It also shows each KPI in contrast to the city’s desired goal to provide performance context. Furthermore, the Dashboard allows users to do a more thorough analysis of the data with a series of interactive tools that graph historical data. Users can then filter the data and access it in raw form. Its main shortcomings are a lack of any real-time operational data; even when it links to social media services, these feedback loops are unrelated to what the user might be observing in the data.

Finally the IBM Intelligent Operations Center for Smart Cities (IOS) allows for citywide monitoring for operations from diverse city agencies, such as emergency response, transportation services, public safety, water, etc ("Smarter cities software," 2015). The platform is geared towards city managers, and as such it

\textsuperscript{16}https://dashboard.edmonton.ca
aims to be a comprehensive tool that allows for multiple levels and tools for data analysis, along with its integration with urban operations. Although its implementation is dependent on the particularities of each city, its best known instance is the Centro de Operacoes Rio de Janeiro.

The IOS follows a dashboard design that in many ways reflects other solutions derived from the business intelligence and analytics expertise of the company. As such its visual language is primarily integrated graphics and ranking tables, which it complements with spatial mapping of services, GIS analysis, and real-time video feeds. The information is then linked to order processing flows for actionable tickets management. The solution also provides a historical data analysis engine for decision making and planning purposes.

However, the IBM IOS is not an easy-to-access tool; it has a complex interface that still shows many dashboard design principles from the early 2000’s which require a steep learning curve from users. It is therefore not suited for general population consumption, who usually interact with the city through service specific applications on mobile phones, call centers, or dedicated city attention points.

System Context
In partnership with the company Ferrovial Servicios, we analyzed the Spanish cities of Barcelona and Santander for their potential to open up urban maintenance services information to the public in real-time. For each city, we worked with public officials, researchers, and Ferrovial technicians to identify datasets they could provide through contracted operations with the city, data-sharing partnerships between public and private institutions, and infrastructural advantages or opportunities.

<table>
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<tr>
<th>Waste service information</th>
<th>Barcelona</th>
<th>Santander</th>
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<tr>
<td>Dumpster pick-ups (RFID scan), collection vehicle locations, routes with updated itineraries.</td>
<td>Public inspections of KPIs for outdoor trash bins, such as fill level; routes with itineraries.</td>
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<tr>
<th>Road information</th>
<th>Street cleaning vehicle locations, routes with updated itineraries, traffic congestion.</th>
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<th>Environmental sensor information</th>
<th>Environmental sensor data gathered through Sentilo platform.</th>
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<th>Data Source</th>
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<td>Santander</td>
<td>Public inspections of KPIs for outdoor trash bins, such as fill level; routes with itineraries.</td>
</tr>
</tbody>
</table>
| Environmental sensor data gathered through Sentilo platform. | Environmental sensor data gathered through SmartSantander program.
Citizen feedback apps

“Citizens Postbox” app launched and monitored by City Council, Open311 app implemented by Code for Europe.

Service areas

Fragmented into districts and service types, served by competing companies.

Table 12: Comparison of Barcelona and Santander urban operations contexts.

Both Barcelona and Santander are self-proclaimed testbeds for “smart city technologies”, but with different emphases (Zygisaris, 2013). As a larger city with some power devolved to districts and lieutenant-mayors, Barcelona’s efforts have been more fragmented but agile. Waste collection and road maintenance contracts are split between various companies to encourage competition; the companies can experiment with technologies like service vehicle GPS-tracking and waste-bin fill sensors within dense districts like Les Corts. Thus, the available data varies greatly in availability and detail across the city, and the city has had to invest in data standardization projects, like their Sentilo sensor-mapping platform. They have repeatedly redeveloped citizen feedback apps to adhere to new standards and backends, and the challenge is to unify all of the overlapping programs and private technologies into a “city operating system”.

By contrast, Santander has invested many resources into deploying fixed environmental sensors throughout the central city, and seeks ways to generate value from these data. All data are collected and handled jointly by the city council and the University of Cantabria, who also developed the citizen feedback application in-house. Contracted urban services are also awarded for the whole city, rather than piecemeal, allowing companies to develop citywide information systems. While this approach has produced more uniform sensor networks and consolidated data collection, the resulting applications have failed to generate much interest from citizens or companies operating there. For example, its citizen feedback mobile application shows relatively few users and incident reports.

System Design

To address these diverse issues, we propose a data visualization platform called “CityEye” with two main components: the “Dashboard” and the “Lens”. The dashboard gives an overview of all incoming real-time data generated by the city – data from urban sensors and other sources such as traffic condition, urban maintenance activities, and incoming citizen reports. It is designed as a data-rich visualization of the whole city, allowing managers to identify and prioritize cross-cutting problems. By contrast, the lens provides a local view, showing a specific set of sensor feeds proximate to the user’s location and time. We implement the lens as a smartphone application, designed to provide citizens with more immediate, useful information.
Dashboard
The data sources included in CityEye can be divided into three categories: (1) data generated by and inferred from environmental sensors, (2) data generated during the provision of services (KPIs), and (3) data generated by citizens. Each dataset either describes the state of the urban environment, or primarily represents human activity.

Environmental sensors, like those deployed in Santander and other smart city projects, can provide us an impartial real-time view of the state of the city. Measurable weather conditions like temperature, humidity, wind, and visibility all affect the hygiene of the city, making prompt trash collection and street cleaning more important at times. Other phenomena like air pollution (such as particulate concentration and NOx level), parking usage, and noise serve as indirect indicators of traffic congestion or crowd gatherings. When collected across many sensors across the city, these data can be visualized to detect patterns and infer service needs or bottlenecks well before they are directly reported. They are also useful to citizens planning events and walking or cycling routes through the city.

Service providers themselves can provide valuable information to this platform. The positions of service vehicles, as measured by GPS and wireless network triangulation, reflect their performance and daily progress. They also help predict the cleanliness of certain parts of the city, as well as when to expect noise and congestion. The itineraries and actions of service workers can be scrutinized for their relative efficiency, and their own observations can augment the city’s ability to keep streets safe. Statistics on trash collected and fuel usage allow both citizens and cities to determine sustainable behavior, and which neighborhoods could stand to improve. When incorporated into the dashboard, these data expose the operational challenges and opportunities of maintaining the streets, parks, waste bins, and other public spaces of the city.

Finally, citizen feedback forms a crucial part of the CityEye dashboard. Complaints, questions, and requests are central to understanding where urban services must go in the short and long term. These can be collected through direct channels, via phone banks, email, and web and mobile applications, but also through social media such as Twitter and Facebook. Social media also allows indirect sentiment analysis, gauging citizen satisfaction with public spaces, which can also guide near and long-term decisions on where to send services and how to incorporate such feedback.

Combining these three data categories into a high-resolution visualization platform can provide a more reliable birds-eye view of the city. By showing citizen reports side-by-side with operations and sensing data, it elevates these concerns to the level of other KPIs.
The smartphone app acts as the "lens" of CityEye, and is an important innovation for the transition to smarter urban services. The app will allow citizens to view data from Ferrovial’s cleaning and maintenance services in a useful and relevant way, and empower them to communicate their needs or satisfaction with services back to the city and Ferrovial. Our goal is to demonstrate how real-time data, direct actuation by citizens, and urban sensing can help us rethink the possibilities of a core set of urban services, while making them more accessible and human.

The app visualizes both historic and real-time operations data from internal systems for managing service routes and schedules. The user will be able to follow the service routes and service levels related to them, including time of arrival, pick-up, and information on the driver/vehicle/service in progress; garbage weight and recycling composition; as well as historic and future service requests. The app will also show the citizens real-time environmental information from sensors (e.g. environmental noise, CO, CO2, air particles, light levels, cameras) mounted on Ferrovial’s service trucks, transforming them into a flexible and dynamic sensing platform for the city. Rather than show visualizations overlaid on the entire city as in the dashboard, the lens focuses on graphs and predictions for service in the user’s vicinity.

Figure 29 Interaction mock-up screens for Lens application
Each highlights operations data most relevant to user in place, over time.

Most important, the platform will have tools to integrate citizens’ feedback into the service. In this way, the app closes and humanizes an interaction loop between users and what is often perceived as an anonymous service. Users could use the app to directly report a problem (such as an overflowing bin or a messy area),
request a future service, or even post satisfaction comments with the service; these interactions will be publicly visible through the interface in order to foster social interaction around topics like recycling and street safety. The proposed interactions would take full advantage of the smartphone's capabilities, and will integrate geo-location and multimedia data captured from the devices. Finally, the app would also have a push notification module that will keep citizens informed in real time on service level conditions and relevant information to the users.

**Operational Deployment**

![Data flow diagram for CityEye](image)

Interaction between "lens" mobile application, servers, and operations data in Barcelona implementation.

Ultimately, the citizen can use the app for a variety of purposes, including:

- Monitor the processes of urban maintenance in their neighborhoods.
- Check environmental conditions and urban activity for personal decisions; for example, the choice of public transportation depends on factors such as traffic condition, heat, or pollution levels.
- Deploy incident reports or requests, which become publicly visible.

Individuals working for the city and the service provider can use the system to:

- Estimate the demand for a specific urban service depending on human activity or environmental factors.
- Monitor citizen-submitted incident reports to inform decisions regarding service provision or urban repair.
- Engage the public in the processes of urban maintenance, creating appreciation of these often-invisible services.
Through the smartphone app, CityEye brings the power of the city dashboard down to the ground level of the city, where data can be directly applied to improving quality of life. In this way, the lens becomes a two-way communication channel, linking individual citizens, workers, and officials to the larger task of maintaining the city. Over time, the depth of this interaction will yield more valuable insights, and the benefits in reduced cost and improved service will be shared by all.

Discussion and Conclusion

Additional data sources
One possible shortcoming of the three proposed data streams is that they do not capture all human activity in the city. Such data, however, are highly important to inform and support citizens and service providers. We therefore suggest including additional data sources, such as:

- Real-time traffic information
- Real-time public transportation schedules and usage
- Additional sensors that capture pedestrian activity in public space – these could include Bluetooth radios that count the number of active mobile devices carried by pedestrians, a proven proxy for overall pedestrian flow
- Sensors that capture information relevant for urban maintenance – for example, sensors capturing the amount of material inside waste bins
- Local wind sensors and local amount of traffic
- Water quality testing in drains, sewers, and public waterways

However, since such information is not usually included in urban operations dashboards, developing an adequate visual language is an important next step for CityEye.

Conclusion
For urban service providers, CityEye could allow for more agile operation of urban services, making it possible to quickly react to real-time events and demands rather than static performance targets. Local governments will be able to track the progress of services and needs of citizens, spending fewer resources to maintain a clean, responsive public realm. Citizens will also be able to witness this improved transparency, and may come to demand it in the same way that public transportation and traffic data have become ubiquitous; real-time awareness may also drive more useful feedback to the city.

However, those outcomes depend on several prerequisites: governments and service providers must share data in real-time; these shared data must be standardized in breadth and depth, if not format; visualizations must be readable and useful to non-experts; and service providers must be swiftly responsive to
citizen reports, in order to close the feedback loop and encourage further public participation.

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