Monitour: Tracking global routes of electronic waste

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ABSTRACT

Many nations seek to control or prevent the inflow of waste electronic and electrical equipment, but such flows are difficult to track due to undocumented, often illegal global trade in e-waste. We apply wireless GPS location trackers to this problem, detecting potential cases of non-compliant recycling operations in the United States as well as the global trajectories of exported e-waste. By planting hidden trackers inside discarded computer monitors and printers, we tracked dozens of devices being sent overseas to various ports in Asia, flows likely unreported in official trade data. We discuss how location tracking enables new ways to monitor, regulate, and enforce rules on the international movement of hazardous electronic waste materials, and the limitations of such methods.

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1. Introduction

The impacts of waste electronic and electrical equipment (waste EEE, also known as WEEE or e-waste) on public health and the environment are a growing global concern. Due to lack of global monitoring infrastructure, we can at best estimate its magnitude from national data on the sales and usage characteristics of EEE products, which take several years to compile. From the most recent comprehensive study in 2014, the United Nations University estimated global WEEE generation to be 41.8 million metric tons (Mt), and forecasted an increase to 50 Mt by 2018 (Baldé et al., 2015). Although Europe and the United States were once responsible for most of this waste, China, Latin America, and other growing economies now generate more e-waste in aggregate, and their per capita rates are rising as their populations become wealthier (Robinson, 2009).

The growing tide of WEEE presents both environmental and health risks. WEEE commonly contain toxic substances, such as lead, mercury, arsenic, and other heavy metals which may leach into soil and groundwater; in U.S. landfills, 70% of heavy metals come from e-waste (Widmer et al., 2005).

These risks are not shared evenly across the world; some countries and even cities bear a greater burden than others. China and India, which produce and export many of the world’s electronic devices, import even more discarded devices from other countries, thanks both to robust secondary markets and lacking regulations. Yet, these factors have also made it difficult to manage the massive flow of e-waste with efficient and healthy practices (Lu et al., 2015).

The generation of WEEE in India is growing at a compounded annual rate of 25%, totaling 1.5 Mt in 2015, along with substantial amounts of imported waste (estimated at 0.97 Mt in 2010) (Garlapati, 2016). Due to ambiguities about how to dispose electronic waste, and a common view of e-waste as a commodity, it is estimated that 75% of obsolete WEEE in India are stored at home, rather than returning them to producers, which limits recycling programs (Borthakur & Govind, 2017).

In 2014, China generated an estimated 6.0 Mt of WEEE (Baldé et al., 2015), much of which is treated within the country along with imported waste. Within China, the towns of Guiyu, Qingyuan, and Taizhou alone were estimated to receive ~4 million tons in 2005, or 11.5% of WEEE generated worldwide at the time, and employed nearly 200,000 informal workers in processing this waste (Breivik et al., 2014).

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 et al., 2011; Streicher-Porte et al.,...
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 predominance of the informal sector, lack of knowledge of the risks, or lack of capital to invest in safer methods, both workers and local residents are exposed to hazardous compounds (Wang et al., 2013). In Guiyu, a host of studies have documented dangerous levels of pollutants in air (Li et al., 2007), soil (Leung et al., 2007), and water (Wong et al., 2007), all well beyond the initial work area.

To combat the flow from high- to low-income countries, 184 countries have signed the Basel Convention (UNEP, 1989) on the control of transboundary movements of hazardous wastes and their disposal. Despite the international agreement’s positive impact on regulating e-waste flows, enforcement of the export ban remains a central challenge, and it is unclear whether the convention accurately addresses the bulk of flows amidst changing trade patterns (Lepawsky, 2015). For their part, China has banned the import of e-waste in 2002 and added further restrictions since, but import continues through illegal smuggling channels, as well as through Hong Kong due to legal loopholes (Lu et al., 2015). India has likewise enacted rules banning unauthorized WEEE import since 2011, but also faces loopholes for used EEE, illegal smuggling, and a thriving informal recycling sector (Ghosh et al., 2016).

Though the United States did not ratify the Basel Convention, some of its states have similar export agreements with party nations, and host 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 Environmental Protection Agency (EPA) has the power to enforce existing laws, but is hampered by lack of monitoring programs and the ease with which exporters can operate undetected (USGAO, 2008).

One way to support these efforts is by improving enforcement options through better tracking of the movement of WEEE. By directly following the movement of individual items, we can uncover evidence of unreported e-waste flows. Such studies may also inform top-down estimates of WEEE flows, which must indirectly infer or ignore unreported or illegal WEEE trade. The purpose of this study was to advance the tools and methods of remote GPS tracking to better detect the global movement of electronic waste.

In a series of experiments conducted from 2011 to 2015, we developed and tested a methodology for covertly monitoring electronic waste transportation that might normally go unreported. Partnering with Basel Action Network (BAN), an NGO investigating illegal e-waste disposal, we deployed computer monitors, each tagged with wireless GPS devices, at California-based collection/recycling companies and remotely tracked their movements. We also analyzed a dataset from BAN’s subsequent, larger deployment of trackers from across the United States. Finally, we discuss the implications of these results, as well as potential future uses and risks for this technology.

1.1. The case of cathode ray tubes

The Basel Convention defines waste as “substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law,” while hazardous waste is defined through lists in Annexes of the convention (Kummer, 1999). Explicitly listed as hazardous waste is the leaded glass of cathode ray tubes (CRTs), which exemplify the dilemmas around e-waste 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 et al., 2004).

By the early 2010s, consumer tastes shifted decisively to flat-panel displays, and there was little market left for recycled CRT glass in the USA; recyclers without subsidies had no profitable use for their stockpiles (Urbina, 2013). However, there was demand for used CRTs in developing economies like China, where they could be cheaply recycled or refurbished. Companies in these countries actively sought out shipments of used CRTs from the US via e-commerce websites (USGAO, 2008).

The regulation on CRT disposal and trade are complex. While CRT glass is regulated as hazardous waste under RCRA (Resource Conservation and Recovery Act, Hazardous and Solid Wastes Amendments, 1984), it is, like other types of electronic wastes, exempt from this status if sent for recycling, and therefore legal to export. Some state regulations are more stringent. California, for example, treats CRT glass as hazardous waste. Other states including Maine, New Hampshire, and Rhode Island have classified CRTs as universal wastes, subject to regulations less stringent than those for hazardous wastes, but more stringent than exempt wastes. In all cases, federal rules require mandatory reporting and consent from the receiver.

The most accepted action is to ship CRTs to a material recovery facility (MRF) specially equipped for electronic waste materials. These facilities recover lead and copper from the CRT glass through a smelting process, and protect workers from exposure (Kang & Schoenung, 2005). In the US, there are very few remaining MRFs that handle CRT glass, forcing recyclers to ship them long distances with help from state subsidies. For instance, California pays recyclers for the weight of electronic devices they collect, to offset the costs of recycling, per the Electronic Waste Recycling Act (EWRA) (Sher, 2003, 2004). However, in the early 2010s it was much cheaper to ship CRTs from the west coast to other countries by container ship, instead of by land to MRFs on the east coast (Kang & Schoenung, 2005). Unscrupulous recyclers in California could 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 during our experiment.

1.2. Tracking the flow of e-waste

Researchers have been quantifying the export and import of e-waste (Kellenberg, 2009), and the existence of e-waste trafficking is well-known. Yet global quantitative data are difficult to collect directly, especially for illicit trade. E-waste may pass through multiple collectors, sub-contractors, and staging points before exiting the country. Though exporters may be required to notify state officials of pending e-waste shipments, they can self-report the amounts, conditions, and destinations. Detecting fraud amidst the vast scale of global shipping is impossible without costly audits and inspections.

Previous studies have estimated flows between countries based on global trade data such as from European Union’s Eurostat, United Nations COMTRADE, or the Harmonized Tariff Schedule of the United States (HTS), using information about the production or sales of new products, with certain assumptions made for device lifetime and prevailing export practices per country (Baldé et al., 2015; Breivik et al., 2014; Lepawsky, 2015; Widmer et al., 2005). These assumptions rely on qualitative investigation of the geographic routes and exchanges by which e-waste travels. Yet for illicit trade, shipping containers may bounce from port to port, making it impossible to know which of the thousands of global ports to monitor ahead of time (Indonesia alone has hundreds of
seaports) (USGAO, 2008). Land routes may be secret and closely guarded (while often used for other trafficking operations).

Because of these difficulties, a 2011 EPA workshop favored electronic tracking as a method for characterizing transboundary e-waste flows (Miller et al., 2012). Though it requires significant effort, tracking was also seen to provide among the highest quality information.

1.3. Electronic tracking methods

The two technologies most frequently mentioned in the context of waste tracking are radio frequency identification (RFID) and global 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 (Binder et al., 2008; Saar & Thomas, 2002) 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 is a method of identification rather than localization, the latter of which would require 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 et al., 2010). Any use of remote GPS tracking raises ethical concerns of privacy, particularly if individual persons are being followed without their knowledge (Michael et al., 2008). There are many precedents of law enforcement using such technology in monitoring the movement of suspects, itself a controversial practice, and similar practices by employers have been challenged for violating privacy and risking abuse by those with power over others. Tracking waste objects directly, rather than people, provides some buffer from the risks of human-centric location monitoring; the ambiguity of location data prevents us from identifying who held the tracked item, when it passed in or out of their possession, and whether their actions had any bearing on where the item would end up.

In 2009, the Senseable City Lab, at the Massachusetts Institute of Technology, tagged 3000 trash objects in the Seattle metropolitan area, using GPS trackers connected via wireless phone network. Objects ranged from household items to standard recyclables to electronic waste. The trackers revealed how these objects travelled through transfer stations, processing plants, and landfills, sometimes ending up hundreds of km from their starting points. The electronic waste tended to travel further and visit more intermediate facilities than other types of waste (Offenhuber et al., 2013). However, despite tracking objects to harbor facilities along the US west coast, they were not able to track beyond national borders because of incompatibilities of global mobile infrastructure standards, as well as battery life limitations inadequate for the longer durations of international transport.

A UK-based NGO also piloted electronic tracking in 2010, embedding GPS trackers in two non-functioning CRT monitors and dropping them off at disposal sites in Greater London (Environmental Investigation Agency, 2011). These were tracked to Lagos, Nigeria and Tema Port, Ghana, respectively, implying that the monitors were illegally exported despite being WEEE. This investigation demonstrated the feasibility of electronic tracking in revealing global flows of e-waste.

2. Materials and methods

In partnership with investigators from Basel Action Network, we embedded sensors in 17 CRT monitors that were dropped off in 15 e-waste collecting business in Southern California, mostly within Los Angeles County. We noted the status of each business under the CalRecycle (California Department of Resources Recycling and Recovery, 2017) 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 GIS software and web mapping tools.

As described in section 1.1, we chose to track CRT monitors due to their large size (making it easier to embed and hide a tracking device within), explicit regulation under federal and California state laws, and likelihood to be left intact when exported.

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 mobile networks, 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. We also extended battery life by entering the trackers in sleep mode every four hours, and attaching external lithium-ion batteries. Our application code and battery testing findings are published in (Yen, 2012); ultimately we were able to extend the battery life of the phone trackers to an estimated 100 days.

We paired our experimental phone trackers with commercially available GPS asset trackers with GSM/GPRS modems to collect data in parallel: seven vehicle location trackers with high-capacity batteries (55 × 55 × 260 mm), and five asset trackers with a smaller form factor (68 × 37 × 20 mm), which were selected based on their battery capacity, energy efficiency, and compatibility with global wireless network standards. Table 1 shows how the phone and GPS trackers were distributed among the 17 monitors.

To attach the trackers, we applied a hard-setting insulation foam at the point of adhesion and around the devices themselves. This bonded the devices to the CRTs tightly and afforded some protection from moisture and shock. The foam also concealed the devices while allowing wireless signal to pass through. To ensure we could track the leaded glass tube itself, we cracked the tubes open near their deflection coils, mounted the bulky external batteries to the interior, and ran wires out to the exterior where the tracker would be attached (Fig. 1). Such methods were important for ensuring that the tracker stayed coupled with the CRT for as long as possible. They also ensured that the CRTs were unambiguously e-waste, rather than reusable electronics, and any proper inspection by the recycler prior to export should identify them as such.

However, this is a dangerous procedure that should only be attempted with the proper equipment, location, and training. Safety goggles and respirators are essential, as is a well-ventilated workspace. Cracking a CRT can release a cloud of toxic particles, including lead and cadmium, and the vacuum may implode the set. We worked with experienced recyclers who discharged the tubes and broke their vacuum seals safely. The glass itself was sharp on its edges, so reaching into a tube also required protective gloves and sleeves.

2.1. BAN deployment

After our initial experiments, BAN followed up with a larger scale investigation, deploying electronic trackers onto CRTs, LCDs,
and printers, totaling 205 pieces of e-waste (all devices were confirmed to be non-functional, and unambiguously e-waste instead of used devices). As with our use of CRTs in the first experiment, BAN chose these devices for their large size (allowing for the hidden installation of trackers), clear status as regulated WEEE, and likelihood of being transported intact; other devices like smartphones and computers were either harder to install with a concealed tracker, or more likely to be disassembled prior to export.

Of these, they delivered 152 pieces to companies claiming to be electronics recyclers, with the remainder going to thrift shops and

<table>
<thead>
<tr>
<th>Monitor ID</th>
<th>Tracker installed</th>
<th>Deployment location</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle tracker</td>
<td>Commerce</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>2</td>
<td>Vehicle tracker</td>
<td>City of Industry</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>3</td>
<td>Vehicle tracker</td>
<td>South El Monte</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>4</td>
<td>Vehicle tracker</td>
<td>South El Monte</td>
<td>Tracked to domestic disposal</td>
</tr>
<tr>
<td>5</td>
<td>Vehicle tracker</td>
<td>Tujunga</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>6</td>
<td>Vehicle tracker</td>
<td>Los Angeles</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>7</td>
<td>Vehicle tracker</td>
<td>Walnut</td>
<td>No movement</td>
</tr>
<tr>
<td>8</td>
<td>Phone tracker, asset tracker</td>
<td>City of Industry</td>
<td>No movement</td>
</tr>
<tr>
<td>9</td>
<td>Phone tracker, asset tracker</td>
<td>Tustin</td>
<td>Tracked to domestic disposal</td>
</tr>
<tr>
<td>10</td>
<td>Phone tracker</td>
<td>Ontario</td>
<td>No movement</td>
</tr>
<tr>
<td>11</td>
<td>Phone tracker</td>
<td>Chino</td>
<td>No movement</td>
</tr>
<tr>
<td>12</td>
<td>Phone tracker, asset tracker</td>
<td>Los Angeles</td>
<td>Tracked to domestic disposal</td>
</tr>
<tr>
<td>13</td>
<td>Phone tracker</td>
<td>Corona</td>
<td>No movement</td>
</tr>
<tr>
<td>14</td>
<td>Phone tracker, asset tracker</td>
<td>Commerce</td>
<td>No movement</td>
</tr>
<tr>
<td>15</td>
<td>Phone tracker</td>
<td>Chino</td>
<td>Tracked overseas</td>
</tr>
<tr>
<td>16</td>
<td>Phone tracker</td>
<td>Gardena</td>
<td>Tracked to domestic port</td>
</tr>
<tr>
<td>17</td>
<td>Phone tracker, asset tracker</td>
<td>Vista</td>
<td>No movement</td>
</tr>
</tbody>
</table>

Fig. 1. Process of embedding e-waste trackers on CRTs. 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.

For their work, BAN used off-the-shelf GSM/GPRS asset trackers, similar in size to the earlier mTrac3 small devices but with external batteries, that communicated over a separately purchased machine-to-machine (M2M) service. Each tracker was set up to run in “sleep mode”, turning on every 24 h to send off its GPS location to the back-end server via GSM networks, and storing data if a signal was not available. The trackers usually had at least a 9-month battery life, with some trackers still communicating after 12 months.

BAN deployed these sensors between July 2014 and December 2015, in highly populated regions of the United States. They applied the same methods that we used to attach the trackers, and shared their location data with us for further analysis. A detailed description of their deployments and resulting dataset is provided in (Hopson & Puckett, 2016). They selected publicly accessible recyclers listed on state ecology or environmental quality agency websites, as well as Google search results from the phrase “computer recycling [city of deployment]”; they claimed to not factor industry certification in their selections (a potential source of bias, as BAN administers and promotes one such certification program, e-Stewards). (Hopson & Puckett, 2016)

3. Results

3.1. Phone trackers

Of the ten experimental phone trackers, four produced readable traces that hinted at the fate of the CRT monitors. Two of these monitors (id:09, 12) travelled north along a highway to Stockton, CA, and last reported from within 1 km of a CRT glass processing plant. The photographs from these phones captured the interiors of the warehouses. A third monitor (id:16) was tracked from the drop-off in Gardena to a second e-waste recycling business 80 km 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 draining its battery.

However, the last phone tracker (id:15) successfully followed its monitor on a complex path across Southern California, onto a container ship at the Port of Long Beach, and arrived at Hong Kong 4 months after its drop-off. It correctly transitioned from a 4-h reporting cycle to a 24-h 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 (Fig. 2).

3.2. Commercial trackers

The five asset trackers failed to report any movement from their drop-off point once deployed. However, the vehicle trackers produced strong results, with five (id:01, 02, 03, 05, 06) reporting from locations in Asia and a sixth (id:04) travelling directly to the CRT processing plant in Stockton; the former lasted for three to four months.

3.3. International traces

Of the 17 monitors we deployed, we detected 6 that travelled overseas to Asia (Table 2). Each arrived through one of four points of entry: Malaysia through Pinang, and China through Hong Kong, Tianjin, and Dongxing, a border city with Vietnam (Fig. 3). The gaps between reports indicate that the Pacific crossing took anywhere from 3 weeks to 3 months. One Tianjin monitor (id:05) travelled further inland to Henan, while four other monitors (id:01, 03, 06, 15) 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 e-waste collectors; this export of CRTs was a breach of the rules set by the EWRA.

Satellite imagery at the final coordinates showed both rural and urban areas, residential buildings and industrial warehouses, some

![Fig. 2. Left: Photograph taken by the phone tracker mounted inside the CRT monitor casing, depicting the temporary holding area where the monitor was stashed between the recycling facility and point of export. Right: Google Street View image (©2015 Google) from the reported GPS location of the phone tracker.](image_url)

| Table 2
<table>
<thead>
<tr>
<th>Monitor ID</th>
<th>City deployed in California</th>
<th>Max days in Pacific</th>
<th>Asia port of entry</th>
<th>Asia final report location</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Commerce</td>
<td>60</td>
<td>Tianjin, China</td>
<td>Guangdong, China</td>
</tr>
<tr>
<td>02</td>
<td>City of Industry</td>
<td>43</td>
<td>Pinang, Malaysia</td>
<td>Pinang, Malaysia</td>
</tr>
<tr>
<td>03</td>
<td>South El Monte</td>
<td>21</td>
<td>Dongxing, China</td>
<td>Tengxian, China</td>
</tr>
<tr>
<td>05</td>
<td>Tujunga</td>
<td>39</td>
<td>Tianjin, China</td>
<td>Henan, China</td>
</tr>
<tr>
<td>06</td>
<td>Los Angeles</td>
<td>103</td>
<td>Dongxing, China</td>
<td>Foshan, China</td>
</tr>
<tr>
<td>15</td>
<td>Chino</td>
<td>23</td>
<td>Hong Kong, China</td>
<td>Hong Kong, China</td>
</tr>
</tbody>
</table>

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.

3.4. BAN deployment traces

BAN’s deployment of 205 trackers included CRT monitors (76 tagged), as well as LCD monitors (72) and printers (57). These travelled for a median 72 days and 908 km between the drop-off point and their final stop (highly skewed right with a mean distance of 4220 km).

69 trackers (34%) crossed over to other countries (Table 3). The majority of devices were shipped to Asia, especially Hong Kong, China, and Taiwan. However, we also detected e-waste travelling to Pakistan, Thailand, and other emerging destinations (Fig. 4). Pakistan, in particular, was recently highlighted as a significant importer of e-waste (Iqbal et al., 2015).

Some devices were immediately sent abroad, as the case of an LCD dropped off in Lakewood, NJ, which travelled 13,044 km to Hong Kong in two months.

Other devices took longer, with more stops, and along uncommon routes. One CRT tagged in Chicago in November 2014 took two months by land to arrive in New York. From there it was shipped east across the Atlantic Ocean and Mediterranean Sea, passing by Sharjah in the United Arab Emirates, entering Asia via Muhammad Bin Qasim port in Karachi, and arriving in Faisalabad, 11,480 km from the drop-off location.

An LCD monitor dropped in Amesbury, Massachusetts in August 2015 stayed in the area for four months. In December it was sent to Colón, Panama, and travelled to Asia via Nakhodka, a Russian port city in the Sea of Japan. It continued the trip through the port of Ningbo-Zhoushan, in China, one of the busiest ports in the world. Finally, it travelled by land to Ha Tsuen, Hong Kong, totaling 20,116 km in 171 days.

All the mapped location data and routes can be explored through our interactive web application, Monitour (http://senseable.mit.edu/monitour-app/).

![Fig. 3. Mapped CRT monitor paths from California recyclers to ports and cities in China and Malaysia.](image)

<table>
<thead>
<tr>
<th>Destination</th>
<th>Count</th>
<th>Percentage of all abroad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong Kong</td>
<td>37</td>
<td>54%</td>
</tr>
<tr>
<td>Mainland China</td>
<td>11</td>
<td>16%</td>
</tr>
<tr>
<td>Taiwan</td>
<td>5</td>
<td>7%</td>
</tr>
<tr>
<td>Pakistan</td>
<td>4</td>
<td>6%</td>
</tr>
<tr>
<td>Mexico</td>
<td>3</td>
<td>4%</td>
</tr>
<tr>
<td>Canada</td>
<td>2</td>
<td>3%</td>
</tr>
<tr>
<td>Thailand</td>
<td>2</td>
<td>3%</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Kenya</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Cambodia</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Togo</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>69</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Final destinations of devices that left the United States.

Overall, of the devices tracked, LCDs were most likely to be detected leaving the country (53% of the 72 tagged devices) (Table 4). Of the three types, CRTs are subject to federal laws requiring prior approval to export, and perhaps as a result had the lowest export rate at 18%. Nonetheless, none of the 13 unique companies involved in exporting CRTs appeared on EPA’s list of approved exporters (Hopson & Puckett, 2016), so such flows were likely secret and thus undercounted by official trade statistics.

Members of BAN investigated certain location traces in person. Noticing that most of the trackers no longer went to mainland China like in our first deployment, they followed the trail to a large cluster of junkyards in Hong Kong’s New Territories region. There they documented 48 unique sites where the trackers had been, and gathered evidence of the scrap workers’ unprotected working conditions; these are detailed in their final report: (Hopson & Puckett, 2016).

4. Discussion

We detected 6 of 17 CRT monitors, or 35%, exported in our first experiment. The subsequent BAN deployment detected 18% of CRT monitors exported, and 34% overall export rate for WEEE items. By comparison, past studies of the US using material flow analysis estimated a 6–29% export rate for used computers in 2010 (Kalhat & Williams, 2012) and overall 10–16% export rate for WEEE from 2003-05 (Breivik et al., 2014).

The above results come with many caveats. The sample size was very small relative to the massive scale of e-waste management. The selected drop-off locations were not randomly sampled, but chosen by BAN, an NGO that prioritizes detecting and exposing rule-breaking. BAN itself is not a neutral organization, as it has staked out clear positions on the incidence and nature of international e-waste flows, and we should not consider its selected recyclers to be representative of the United States nor its entire e-waste recycling industry.

Trackers could fail to produce accurate or complete location data, or stop reporting midway along their journeys for any number of reasons. When inside buildings, containers, vehicles, or dense piles of waste, the trackers could fail to wirelessly connect with cell towers; GPS location data also become less precise with such obstructions. Batteries could fail, or become dislodged or disconnected from the trackers. If the monitor or printer were dismantled, either in the home country or abroad, any trackers within could easily be discovered and deactivated.

For these reasons, we cannot easily extrapolate the prevalence of unreported, possibly illegal export flows of e-waste from the data above.

Our results still show that e-waste can be tracked as it travels abroad, despite international, national, and even voluntary regulations designed to detect and prevent transboundary movement of e-waste. Some of this activity may indeed be illegal; none of the companies involved in CRT export were listed by the EPA as having provided the necessary notification. Many of the receiving countries are party to the Basel Convention, thus making the import of such materials from the United States illegal. Whatever the amount of WEEE flow that goes undetected, those involved have great incentive to keep it so.

Even as international regulations evolve and governments step up enforcement, the underlying incentives to smuggle e-waste remain powerful. Thus, while China has apparently suppressed the import of e-waste to its mainland cities, the physical paths and networks for e-waste have become more dispersed and harder to track over time. As the results show, exported WEEE items can travel for months and thousands of miles, stretching the capabilities of GPS trackers to reliably report throughout the trip. While

### Table 4

<table>
<thead>
<tr>
<th>Device type</th>
<th>Tagged</th>
<th>Exported</th>
<th>Percent exported</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRT</td>
<td>76</td>
<td>14</td>
<td>18%</td>
</tr>
<tr>
<td>Printer</td>
<td>57</td>
<td>17</td>
<td>30%</td>
</tr>
<tr>
<td>LCD</td>
<td>72</td>
<td>38</td>
<td>53%</td>
</tr>
</tbody>
</table>

### Table 5

<table>
<thead>
<tr>
<th>Tracker type</th>
<th>Benefits</th>
<th>Risks</th>
<th>Cost</th>
</tr>
</thead>
</table>
| Commercial vehicle asset tracker
  Commercial item asset tracker
  Modified smartphone with attached external batteries | Long battery life (>1 year); durable, waterproof Small, easier to conceal Small, easier to conceal; lower cost; hackable; built-in camera | Bulky, difficult to conceal; expensive Wide range of cost and performance; more fragile Battery management hard to control directly; fragile; requires time and skill to modify hardware and software | $400 USD
  175 USD ~ 500 USD
  ~ 160 USD |

Fig. 4. Trajectories of devices that left the United States.
most of our experimental phone trackers did not last the entire journey, many of the commercial trackers were able to survive the shipment process and report from overseas. Table 5 compares the different approaches we tested.

Long battery life appeared to be crucial for trackers to successfully last the entire trip overseas. Unfortunately, this makes electronic tracking difficult to implement for smaller WEEE like mobile phones or laptop computers, as the trackers and additional batteries are difficult or impossible to hide while attached to the device. To remotely track such devices, we will need to develop smaller, more energy-efficient location sensors, and novel methods for concealing them. For instance, a miniaturized asset tracker could be custom-designed to appear like a modern smartphone, and discarded along with other phones in a targeted deployment.

5. Conclusions

Location tracking technology has advanced enough to make it feasible to study these dynamic networks directly. Mobile network connectivity allows for real-time communication and limited location fixing, and is becoming ubiquitous even in rural and low-income regions. Efficient battery use provides a longer window for capturing a complete picture of the path taken, especially when trajectories span many months. The overall independence of GPS trackers allows us to follow these items without the infrastructure or partnerships we normally rely on for logistics tracking.

Ultimately, this technology enables new approaches to managing the vast and nebulous movement of hazardous e-waste today. Location tracking can be used to track violations of local, national, and international rules, providing evidence of fraud or ineffective management, and spurring closer audits and investigation. Government regulators and certification programs can implement randomized tracking to proactively detect violations. Watchdog groups can monitor suspected violators directly and share their findings with authorities or the public.

However, because of the imperfect nature of the technology and plausible deniability of firms, these efforts still need follow-up investigations with transparent oversight. Location tracking technology could easily be abused to harass individuals and private firms, or to present skewed or falsified information. The tracking devices themselves also add to the e-waste stream, and their contents present the risk of contamination or fire if disposed of incorrectly. Finally, the cost of the devices and data service remain relatively high, limiting the reach of such deployments.

From a more positive perspective, location tracking can become a regular tool for making legal transactions transparent, and build trust between recycling partners. It can also educate the public about the realities and consequences of e-waste export. This could drive more awareness of best practices in disposing of e-waste, greater demand for more reusable, less toxic devices, or greater scrutiny of the laws and enforcement actions of public regulators.

However, location data alone are rarely sufficient to force change; contextual evidence, on-the-ground investigation, and due process are necessary to legitimize enforcement. Even as GPS tracking makes the waste system more transparent, agencies will need more resources to confirm and act on this information. Clearer policies and responsibilities across firms, institutions, and states are necessary to maximize the usefulness of such technology.

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Conflict of interest

The authors declare that there is no conflict of interest.

References


