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Radio-Frequency Identification: Environmental Applications

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Four Scenarios: Outcomes of Radio-Frequency Identification (RFID) Environmental Applications

1. *Traffic Congestion is Reduced*. Within the next decade, many U.S. cities could adopt congestion pricing, charging drivers a toll for access to congested areas. Implemented with RFID transponders, London's system has reduced congestion by 26%, reduced petroleum consumption by 20%, and reduced nitrogen oxides and particulate matter (PM-10) by 15%. Similar results throughout U.S. cities could reduce traffic, reduce petroleum consumption, and improve air quality.

2. *Basic Recycling Increases*. Within the next decade, RFID transponders on curbside recycling and waste bins could become widespread in the U.S. In Germany, where a third of waste collection uses RFID systems, these systems have reduced municipal waste disposal by 35% and increased recycling by 17%. RFID-mediated collection throughout the U.S. could significantly reduce waste and increase recycling.

3. *Consumers shop using RFID tags*. Using RFID readers on cell phones, consumers could compare the environmental, health, and social attributes of

products before they buy. Using assessments provided by independent environmental and consumer organizations, consumers could access detailed information on individual items.

4. *More Types of Products are Recycled*. RFID tags can provide a foundation for recycling many more kinds of products than are recycled today. By storing basic product information throughout the lifetime of the product, recycling operations could become efficient. RFID tags on products could support the development of new approaches to reuse, refurbishment and recycling of products. Smart trash cans could become the new home appliance, acting as 24/7 brokers for used materials and products. Material recovery facilities could use RFID tags on products to recover electronics, batteries, and small appliances, resulting in increased recovery of cadmium, nickel, mercury, gold, silver, copper, and reusable components.

Figure 1. A selection of RFID tags and transponders (penny to scale). (Alex Parlini, 2008)

EXECUTIVE SUMMARY

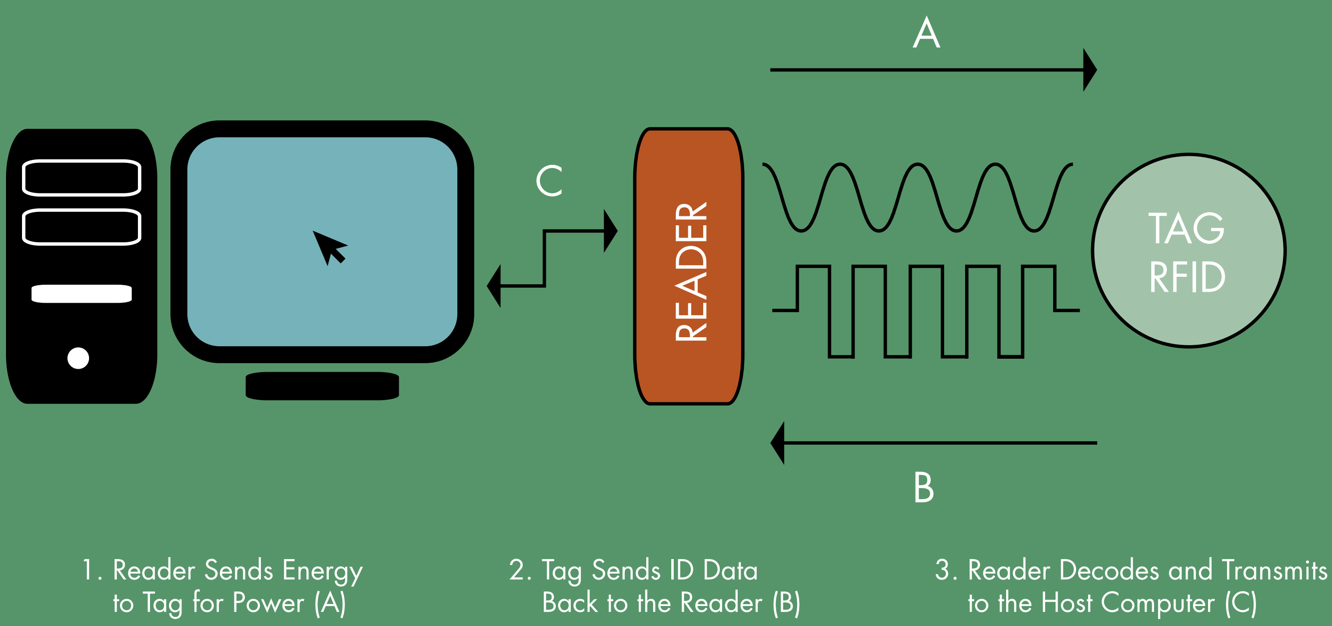
Radio-frequency identification (RFID) tags use a radio signal to transmit an identification code. They can be thought of as an advanced barcode, with the additional capability to transmit through objects for short distances. RFID tags are increasingly used on cartons and pallets of products shipped from manufacturer to warehouse to retail outlet, and are already widely used for automatic toll collection in cars. Within a few years, it is possible that RFID will be used on many products, perhaps even replacing the universal product code (UPC).

RFID has some environmental drawbacks. RFID tags contain an electronic chip and small amounts of metal in the antenna, and these could interfere with recycling of products such as glass, steel, aluminum and plastic bottles (see Appendix). Also, RFID can raise privacy concerns.

RFID could have a number of environmental applications. RFID is already helping to reduce traffic congestion, with automated road pricing systems in London, Singapore, and Stockholm. RFID is also providing incentives for recycling, through transponders (low-cost passive RFID identifiers are typically called "tags"; higher cost battery-powered RFID identifiers are typically called "transponders") on garbage and recycling bins in the European Union and in some U.S. cities. RFID could make reuse, refurbishment, and recycling easier and cheaper. RFID could also make it easier for consumers to find out detailed environmental information about products.

Because the environmental benefits are largely public goods, realizing the environmental potential of RFID will require initiative from the public sector and from environmental advocates, as well as cross-industry coordination and cooperation.

Figure 2. How RFID works. (www.rollsoft.ro/RFIDe.htm)



> “RFID could make reuse, refurbishment, and recycling easier and cheaper.”

"Radio-frequency identification (RFID) uses radio waves to identify items at short distances."

I. WHAT IS RFID?

Radio-frequency identification uses radio waves to identify items at short distances. An RFID tag holds an electronic chip and an antenna. The tags in Figure 1 with loops, lines, and squiggles are passive (no battery) RFID tags. The loops, often made of copper, are the antenna. They also have a small electronic chip near the center.

These kinds of tags are increasingly used on cartons and pallets for managing the movement of products from the factory to the store. Wal-Mart has strongly encouraged its suppliers to use RFID, as has the U.S. Department of Defense. Several different radio frequencies are used: low frequency tags of about 100 kHz, high frequency tags of about 13.6 MHz, and very high frequency tags of about 900 MHz. RFID tags are not yet widely used on individual products, but some industry observers have suggested that RFID will increasingly be used on everyday consumer products (Meyer 2007).

RFID technology has been receiving increasing interest since the early 1990s. There has been some concern that if passive RFID tags were widely used on consumer products and packaging, they could interfere with recycling operations; these issues are discussed in the Appendix. There has also been the suggestion that RFID could have environmental benefits, especially for product reuse and recycling (Saar and Thomas 2003; Thomas 2003). To reap these benefits, environmental applications should be explored and thought through early, before the RFID infrastructure is completely fixed. This paper is written as a starting point for discussion and development of the potential environmental applications of RFID.

As shown in Figure 2, when a reader antenna is near the tag—typically within one meter—(A) the reader sends a radio signal to the tag, (B) the tag reflects its identification number back to the reader antenna, and (C) the reader then decodes and transmits the signal to the host computer.

Figure 3 shows an EPC (Electronic Product Code). Like the universal product code (UPC), part of the code (the EPC Manager) indicates the manufacturer and another part (the Object Class) indicates the product. In addition, there is a serial number that can uniquely identify the item.

In principal, information about each product could be contained in an RFID code. But the predominant approach, used for both the UPC bar codes and for RFID, is to store the information in a database, and let the RFID tag provide an identifying number for referencing the database. That is, in a grocery store, the UPC code on products is used to look up the price in a database at the checkout counter. When the price changes, the database changes but the code stays the same. Similarly, the EPC code can be used to look up information about the product including details about the supply chain history. Databases can also contain environmental information that can be updated over time.

Figure 4 shows an active RFID transponder used for automatic toll collection. (The term "transponder" is typically used for battery-powered RFID, and "tag" is often used for a non-powered, passive RFID. In Figure 1 the transponders are the solid, mostly black, discs and cylinders.) This kind of RFID tag has a battery to provide enough power to transmit from the car to the antenna in the toll booth, as shown in Figure 5. These active RFID tags are widely used for automatic toll collection in many U.S. cities and states, in Georgia, Massachusetts, New Jersey, New York, Baltimore, and many other places.

Another type of active RFID transponder, used on recycling bins, can be seen in Figure 1. These look like mostly black discs and cylinders and have a lower frequency than the transponders typically used for toll collection. For waste bin applications, the reader is located on the collection truck, and the information can be used to identify the owner of the bin and either charge for waste collection or to give rebates for recycling.

Widespread use of RFID tags on consumer products could interfere with recycling. Choice of tag material, and removability of tags in the recycling process, may be able to resolve this. The issue of environmental drawbacks from RFID is discussed in the Appendix.

Figure 3. The EPC product code.

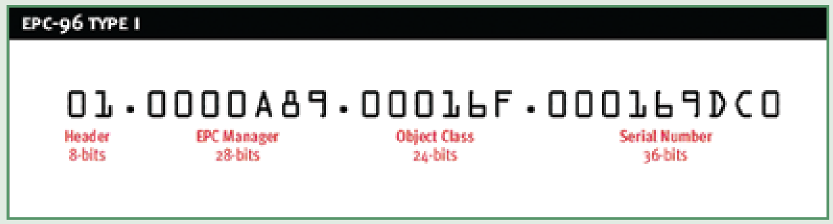


Figure 4. An active RFID transponder used for automatic toll collection. (Alex Parlini, 2008)

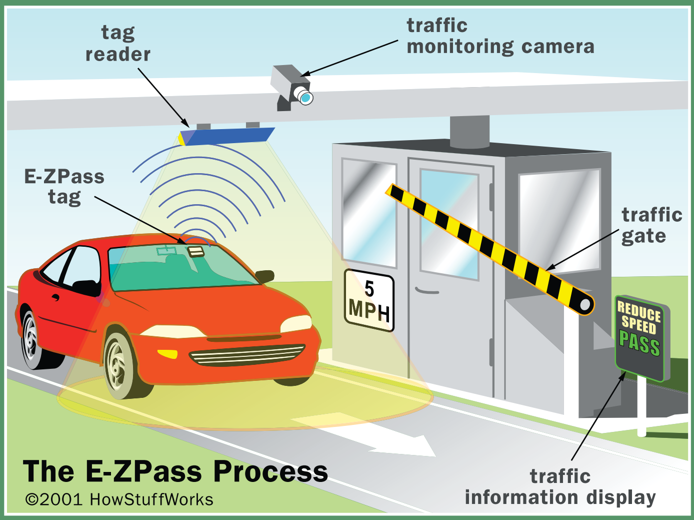


Figure 5. How E-ZPass works. (www.howstuffworks.com, 2001)

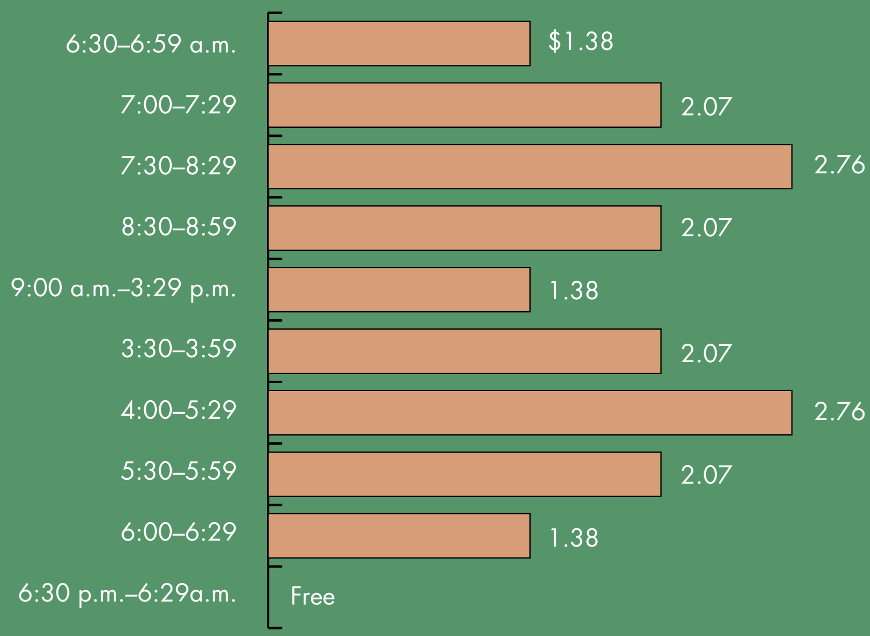


Figure 6. Congestion pricing in Stockholm, mediated by RFID transponders. Fees for travel within Stockhom vary according to peak driving times with higher tolls during rush hours.

Note: Converted from Swedish Krona at 2007 rate Source: Stockholm Trial Expert Group (Environmental Defense 2008)

II. ACTIVE RFID

Scenario 1. RFID to Reduce Traffic

RFID transportation applications, for paying tolls and for congestion pricing and area pricing, already offer significant environmental benefits. Battery-powered RFID transponders mounted in the car (Figure 4) register the passage of the car through the toll both and automatically charge the driver's account (Figure 5). Automatic toll collection is already widely used in a number of states. Automated toll collection reduces idle time and reduces the amount of braking and acceleration needed at toll booths. Use of the EZ-Pass RFID transponders for toll payment on the New Jersey Turnpike is reported to have saved 1.2 million gallons of fuel per year, with corresponding reductions in air pollutant emissions, and significant savings in travel time (New Jersey Turnpike 2001).

London, Singapore, and Stockholm all use congestion pricing (i.e., charging higher fees during peak travel times), managed with RFID transponders. For examples of this pricing and signage, see Figures 6 and 8. In London, this has resulted in an average congestion reduction of 26%, a drop in nitrogen oxides and particulate matter (PM-10) levels of 15%, and a 20% decrease in petroleum consumption within the congestion charging zone (Littman 2006). Singapore's area pricing system, in place since 1975, produced a 45% reduction in traffic. Stockholm's system, introduced in 2006, has produced a 10-14% reduction in carbon dioxide emissions (Environmental Defense 2008).

Although highly effective in reducing traffic, reducing air pollution, and reducing petroleum use, proposals for congestion pricing have not been popular. New York City proposed congestion pricing (New York City 2007). The proposal was approved by the New York City Council, was endorsed by New York Governor David Paterson, but, facing opposition, the State Assembly of New York decided in a closed-door session not to vote on the measure. The proposal remains under discussion and may be considered again in the future (Environmental Defense 2008).

Scenario 2. RFID Transponders on Curbside Waste and Recycling Bins

In a number of European cities, residential curbside waste bins are equipped with RFID transponders. The waste collection truck is equipped with an RFID reader system, which identifies the waste bin when the bin is picked up by the truck. In some cities, the household is charged for each bin of waste picked up by the truck. In other cities, the customer is not charged, and the RFID system simply increases waste collection efficiency through route planning and logistics management.

These waste collection systems typically use a 135 kHz RFID transponder (Figure 1). In some cases the transponder is placed under the rim of the bin, in the so-called "chip nest" made to hold the 135 kHz transponder.

Figure 7. Congestion on Garden State Parkway. (en.wikipedia.org, 2007)

Figure 8. Congestion pricing in London has reduced congestion. (Transport for London, 2008)

Figure 9. Recycling bin with RFID transponder (black disk) and recycling truck with RFID antenna (white rectangular prism). (RecycleBank)

Figure 10 shows a standard packer truck with arms for lifting and dumping waste bins. The white bars near the bottom edge contain RFID antennas.

Figure 11 shows a waste bin, with an RFID transponder in its chip nest, that the worker has placed on the rim of the waste truck. In this position, the RFID antennas on the truck can read the signal from the RFID transponder on the waste bin.

Figure 12 shows the computer screen inside the waste collection truck.

A 2001 survey of German municipal waste management companies that were using RFID-based systems reported an average increase in receipts of 2.85% from being able to find and assess previously unassessed bins, as well as from the implementation of more efficient waste collection routes using data provided by the RFID system. For those municipalities in which residents were charged by the number of bins disposed, the survey reported an average decrease of 35% in the amount of non-recycled waste disposed, and an average reduction of 17% in the total waste generated including both recycled and non-recycled materials (VKS 2001). That is, the 35% decrease in disposable waste is about half from decreasing overall waste and half from recycling more. These results are consistent with the results of pay-as-you-throw systems in the United States, which have produced reductions of 25-35% in municipal waste disposed (U.S. EPA 2005).

Variations of this system are possible. In the U.S., a company called RecycleBank uses RFID transponders on residential curbside recycling bins. When the recycling truck picks up the waste bin it weighs the amount of recycled material and sends the customer RecycleBank Points based on the amount of waste recycled. These Points can be redeemed (online or via toll free number) at hundreds of local and national Reward Partners such as Coca-Cola, Kraft, CVS/pharmacy, grocery stores, movie theaters and "mom and pop" shops throughout the U.S. In addition to these rewards, members learn how many trees and gallons of oil they have saved through their recycling efforts. This type of "positive nudge", providing customers with an incentive to recycle, could become a popular way to increase recycling rates (Figure 9).

Figure 10. Waste collection truck with RFID antennas indicated with arrows. (Photograph taken at Dresden, Germany waste management facility, July 2004.)

Figure 11. RFID-labeled waste bin being held by RFID-enabled waste collection truck. For this truck, the worker places the bin onto the truck. (Photograph taken at Dresden, Germany waste management facility, July 2004.)

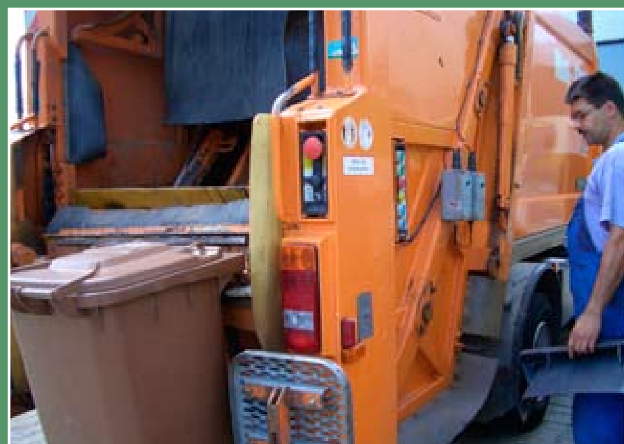


Figure 12. Computer panel inside waste collection truck. Blue buttons allow operator to register waste conditions, including spilled trash, inaccessible waste bins, etc. Yellow buttons allow operator to move from one household record to the next. (Photograph taken at Dresden, Germany waste management facility, July 2004.)

IV. PASSIVE RFID

Scenario 3. RFID for Consumer Environmental Information

Item-level RFID tagging could provide information not just about the product in general but about specific items; that is, not just about a specific brand of soup, but about the specific single can of soup. This type of information could be used to quickly trace tainted meat, poultry or other foods. This could be useful to regulators, the food service industry, and ordinary consumers. Consumers could also check how far an item had been transported, the net greenhouse gas emissions, the presence of allergens, and myriad of other details. Product information might be provided by the manufacturer, but a wide range of other organizations could establish independent product information services. Consumers could select these services based on their needs and interests.

> **"Consumers could also check how far an item had been transported, the net greenhouse gas emissions, the presence of allergens, and myriad other details."**

Some manufacturers and retailers are beginning to provide carbon labels for products. The British supermarket chain Tesco will assign a carbon label to every product it sells, quantifying the amount of greenhouse gases emitted during production, transportation and consumption of each product (Financial Times 2007). Walkers' Crisps, Boots Plc, and Innocent are companies that have developed carbon footprint metrics for their products and have committed to carbon-labeling their products in 2008; Cadbury Schweppes, Coca-Cola, Kimberly-Clark and other companies currently have pilot projects on carbon labeling (Carbon Trust 2007). These carbon footprint labels include the greenhouse gas emissions associated with the product throughout its lifecycle. Wal-Mart has announced that it is developing an environmental scorecard for electronics and will make that information available to its customers. RFID-accessed information extends the amount and type of environmental information that could be available to consumers.

RFID tags can provide an individualized environmental footprint for retail products that would differ based on where the product is sold. As a product travels from the factory to the distribution center to the store it will pass a range of RFID sensors. A database can collect the transportation history of the product as well as information on the transportation mode (Figure 13 and 14), and automated environmental lifecycle assessment software can calculate the associated environmental impact. This individualized record can be particularly useful for fruits, vegetables, baked goods, meats, and other food products that can have widely varying impacts by season and by location. With tracking of individual animals with RFID tags (Figure 14), environmental and consumer information can draw on the complete supply chain, back to the specific animal.

Much of this information can be provided through today's UPC barcodes. Development of a barcode-based system would be a low-cost way to develop the infrastructure that an RFID-based system could build upon.

Figure 13. An RFID equipped truck can identify individual cartons. An RFID equipped supply chain can allow specific environmental information about products to be available to the consumer. (www.tri-mex.com, 2007)

Figure 14. White RFID tag and yellow herd management tag. (commons.wikimedia.org, 2008)

Figure 15. RFID tags on products could be used by consumers to access product information. (Alex Parlini, 2008)

There are already a few services that let consumers access product information by using their cell phone camera to read a barcode on the product (Wired 2004). Some of these applications use a two-dimensional barcode developed especially for cell phone cameras, called QR codes (Story 2007). In Japan, McDonald's customers can point their cell phone at a barcode on a cheeseburger wrapper to download nutritional information (Hamani 2006).

Scenario 4. RFID for Refurbishment and Reuse

RFID tags could increase recycling efficiency in the same ways that UPC codes increase efficiency at the beginning of the supply chain. Tags on batteries, for example, could make the sorting of battery types for recycling cheaper and more efficient. Tags on electronic equipment could link to Web sites showing how to dismantle the product. Tags on hazardous products, such as household chemicals, could identify the contents and how and where to dispose of them. Tags on consumer products could make it easier to resell items on the Internet.

RFID would be an extension of the way UPC is used in today's one-way supply chains. Almost every item that is sold today has a UPC code: clothes, books, groceries, computers, toys. Product codes are used not only at the point of sale, but also to manage inventory, for shipping, for reordering, and for returns management. Today the bar code is what links the physical world of commerce to the world of information.

UPC bar codes were developed by the grocery industry in the United States in the 1970s, without government intervention, and have spread throughout retailing and around the globe. A European numbering system, EAN, a superset of the UPC, was also established, and is now the international standard. The UPC now serves as an economy-wide standard for communication; it has enabled innovative forms of coordination within and between organizations (Dunlop and Rivkin 1997).

RFID could allow product codes to stay on the product rather than being thrown away with the packaging. Product codes could make possible many kinds of incentives for recycling. By knowing when a recyclable (or hazardous or valuable) item is put in a recycling bin (or trash can or dumpster), it becomes possible to design programs to reward recycling, or to punish improper disposal. Although recycling incentives, such as deposits on bottles, are not new, an automated, product-mediated approach can reduce costs and support innovation. RFID systems could provide small incentives for low-value recyclables or big incentives for hazardous products or high-value items. A single curbside recyclables pickup service could electronically manage a range of targeted rebate programs for different products, different consumers, and different geographic regions.

Product codes could be implemented as a UPC bar code as well as through RFID. If the codes are to be read during curbside pickup or anywhere that items are picked up in bulk and dumped quickly into a truck, RFID may have an advantage over bar codes because RFID tags can be read simultaneously and through other products. RFID also has an advantage for products such as computers that may be upgraded internally; the tag on the new part can be read through the case. On the other hand, if the codes are to be read in a store or at a drop-off center, bar codes might be the cheaper and easier approach because bar code readers are already available and the customer or the clerk could scan the items in one by one.

Cost is a significant issue. The benefits of recycling are unlikely to be sufficient to justify the

Figure 16. An RFID tag on a recyclable container. (If employed in practice, the tag would likely be placed under or inside a label, rather than outside, as shown.) (Alex Parlini, 2008)

Figure 17. Mercury-containing compact flourescent bulb. Recycling procedures could be coded in an RFID database or tag. (Matthew Bowden, 2004)

> **"An RFID tag inside the item could link to a database showing both the parts and how to recycle the item."**

cost of item-level RFID tags (Thomas 2007). But if RFID is put on items for other reasons, RFID-assisted recycling could provide a significant secondary benefit.

There are a number of possible ways to manage the first step of the reverse supply chain: consumers could have to sort their own recyclables into different bins, consumers could get a rebate for returning packaging to a recycling center, consumers could have to call for pickup of special items for recycling like refrigerators or furniture. Or items could be mixed in the recycling bin and sorted later at a materials recovery facility. Different choices could be made for different geographic regions, for different products, and for different customers, but all could use the same RFID code.

A number of specific applications are discussed below: use of RFID for (1) electronics refurbishing, (2) curbside recycling, (3) home-based smart trash cans, (4) managing product deposits and take-backs at stores and recycling centers, and (5) sorting of trash and recyclables at incinerators, landfills, and material recovery facilities.

RFID for Electronics Refurbishment: Electronics recyclers typically receive many makes and models of computers, printers, and cell phones, working and nonworking, some with valuable parts and others with little recoverable value. Product-code-accessible instructions could indicate which parts have greatest value and provide links to markets for the disassembled parts. These instructions might be developed by the recycling industry, by the product manufacturers, or by an industry-wide consortium.

An RFID tag inside the item could link to a database showing both the parts and how to recycle the item. Each key component could have its own RFID tag, so that replacements and upgrades could be quickly identified by refurbishers (Saar, et al. 2004).

Item-Level Curbside Recycling: The use of RFID transponders on curbside waste and recycling bins was discussed under Scenario 2. Extension of this type of system could allow item-level identification of the contents of the waste or recycling bin. This would open the potential for a wide range of incentive systems. Incentives and disincentives (rebates and fees) could go to the consumer, depending on what they put in which bin. In addition, municipalities could pay recyclable collectors extra for taking hazardous, difficult to manage items such as mercury-containing fluorescent lamps. And recyclable collectors could more easily sell what they collect if they knew in detail what they had.

Figure 17 illustrates the potential use of RFID tags on hazardous items such as mercury-containing fluorescent lamps, paint thinner, and batteries.

There are technical challenges with this approach. Items in a recycling bin may be a foot or more from the antenna on the recycling truck, and may be sideways and behind other products that might absorb the radio signal. Detecting RFID tags on items in a recycling bin while the bin is being emptied into the truck is technically feasible, but has yet to be demonstrated commercially.

Smart Trash Cans: An RFID reader on household recycling bins could read each item as it is put in the bin. Products put in the bin could sell themselves on the Internet or to scrap dealers. Consumers and businesses might automatically search the content of recycling bins and schedule pickup of items via a combined recycling and resale service. The resellers could check online for what has been put out in the recycling bins, swoop in to buy the items that can be refurbished and resold, return a share of the profits to the consumer, and the basic recycling service would take care of the rest (paper, plastics, metals).

Household-based smart trash cans would largely perform the same function as item-level curbside collection. Household-based smart trash cans are technically easier to develop, although they may be a more expensive option than curbside item identification. Pilot projects for both types of system would be useful.

In-Store Recyclables Collection: RFID could assist in the collection of recyclables in stores or recycling centers. Some stores already take products back for recycling: the Rechargeable Battery Recycling Corporation (RBRC) provides battery collection boxes to hardware and electronics stores in the United States and Canada (RBRC 2002). Costco has a trade-in-and-recycle program, as do a number of electronics manufacturers (GreenSight 2007). Cell phone companies also accept used phones.

UPC bar codes are regularly used by retailers for returns management. It would be straightforward and inexpensive to use a product code to provide a rebate to the consumer using an RFID tag inside the product. Stores could benefit from the rebate program in the same way that they benefit from other coupons and trade-in programs.

Also, reverse vending machines could accept recyclables and provide a cash rebate, or credit, based on the information on the product tag.

RFID at Materials Recovery Facilities: RFID readers could be used to sort items at material recovery facilities, municipal waste incinerators, and landfills. Today's material recovery facilities already have magnets to sort steel, eddy current separators to sort aluminum, and infrared detectors to sort plastics. The RFID system could be designed to detect products such as batteries and small electronics. A preliminary assessment indicates that products with RFID tags, such as batteries, small electronics, and small appliances, could be collected at material recovery facilities significantly more cost-effectively than existing recycling programs (Thomas 2008).

"Products with RFID tags, such as batteries, small electronics, and small appliances, could be collected at material recovery facilities significantly more cost-effectively than existing recycling programs."

"Deactivation of the tag at the point of purchase, as proposed by some privacy advocates, would eliminate any potential to use RFID for end-of-life management."

IV. GETTING FROM HERE TO THERE

The four RFID applications discussed here—congestion pricing, curbside collection, consumer information and advanced recycling—each will have their own development paths, depending partially on the development of RFID technology, but even more on the development of environmental programs and policy for traffic, waste management, recycling, and product stewardship.

The use of active RFID transponders for congestion pricing and for curbside collection falls most directly within the scope of local governments. The environmental applications of passive RFID are more national and international in scope. The comprehensive nature of a UPC, and the long-term implications for waste management, recycling, and environmental outcomes suggests the value of a more comprehensive assessment and strategy. Three points in particular suggest the potential value of a federal role in evaluating and facilitating the environmental potential of RFID:

(1) To use product RFID for end-of-life management, the code or tag needs to remain on the product, not on the packaging. In addition, if the end-of-life application uses the same tag as is used for product sales, the code needs to be conveniently readable both at the point of sale and at end-of-life. This needs special attention for RFID tags, as different types of tags and readers are not necessarily compatible with one another. Product manufacturers and engineers could encourage good end-of-life management by putting permanent, standard identifiers on every product and by linking product information, such as owner's manuals and recycling information, to the product identifier. Deactivation of the tag at the point of purchase, as proposed by some privacy advocates, would eliminate any potential to use RFID for end-of-life management.

(2) Both because there could be significant economic implications of product self-management and because standardization is important, discussions across industries and with environmental regulators could be helpful. RFID on products is most useful if many manufacturers use the same type of tag. Moreover, building environmental applications into existing or growing systems will be easier and more cost effective than creating new add-ons later. Developing a broad consensus on the potential benefits and impacts of product self-management and on the effectiveness of various approaches could provide a framework for standardized and compatible steps to promote product self-management. There are a number of technical questions that need to be resolved, such as:

- Who would have access to the database?
- Which parts would be labeled, and where would the tags be placed on products?

(3) Companies, industries, states, and other organizations should be encouraged to experiment. Development of even simple product-code rebates could require cross-industry cooperation and present a number of complex choices. A great deal might be learned from experimental efforts and pilot programs.

V. APPENDIX: ENVIRONMENTAL DRAWBACKS OF RFID

It has been suggested that a large fraction of consumer products, including food packaging, might someday have RFID tags. The number of tags produced and disposed might grow to one tag per person per day, or more. In the U.S., this would come to 100 billion tags per year. Global tag consumption could approach 2 trillion tags per year. Most of these tags would end up in municipal solid waste, or in the recycling streams for paper, cardboard, metals, glass and plastics.

RFID tags typically contain antennas made of copper, aluminum, or silver compounds, as well as a silicon integrated circuit, and adhesives, plastics, and paper (DOD 2004). Specific concerns have been raised about contamination of recycling of glass, steel, aluminum, paper, and plastic (Krauchi, et al. 2005). These are discussed in turn below.

Glass recycling: Silicon chips in RFID can present a problem for RFID tags attached to glass containers because silicon melts at a different rate than glass. If the silicon stays with the glass through the recycling chain and into the glass furnace, this can result in silicon "balls" in new packaging. These are potential weak spots, especially of concern for pressurized containers. This suggests that RFID tags used on glass products need to be completely removable, or be placed in the caps rather than on the glass itself (British Glass 2005).

Steel recycling: An RFID tag may contain about 20 mg of copper (Copper Development Association 2005). If used on a typical steel can weighing 20 g, this would correspond to an effective copper concentration of 0.1%, and with continuing recycling, the copper content in steel would build up (Igarashi et al. 2007). This would reduce the quality of the steel (Steel Recycling Institute 2006). Thus, RFID tags used on steel products need to be completely removable or made with a non-copper antenna. Aluminum-based RFID tags would not interfere with steel recycling. At the very high temperatures of steel making, any incidental scrap aluminum from such tags would be removed in an exothermic reaction.

Contamination of aluminum recycling: Aluminum can be recycled multiple times with very high levels of purity. No contaminants of any type are allowed in the feed stream; contaminants must be screened out or removed via other means (DOD 2004). Accordingly, RFID tags on aluminum products should be completely removable or made of benign materials.

Contamination of paper recycling: RFID tags can be expected to enter recycling mills as part of old corrugated containers. Testing by the National Council for Air and Stream Research indicates that copper foil antennae are likely to remain intact through the hydropulping process and be readily captured and removed. Silver ink antennas, however, contain 2-3 micron particles of silver. Using tags containing about 16 mg of silver, a pilot study indicated that most of the silver remains with the pulp, although enough silver was found in the effluent water to indicate that levels could approach regulatory limits in some circumstances (Maltby et al. 2005).

Contamination of plastic recycling: High-density polyethylene (HDPE) is used for milk jugs, detergent bottles and other applications; polyethylene terephthalate (PET) is used for soda and water bottles and other applications. Together, HDPE and PET are the two most commonly recycled plastics. RFID tags are typically attached to a PET substrate. RFID tags are expected to be readily separable from HDPE bottles during the recycling process, because RFID tags are denser than HDPE and will separate out in the first separation step of the HDPE recycling process: HDPE floats while RFID tags will sink. However, separating RFID tags from PET bottles is more of a challenge. PET has a specific gravity larger than one (1.2-1.4 g/cm^3), so both RFID tags and PET flakes sink in water. In fact, since RFID tags typically are made on a PET substrate, there may not be enough of a mass difference to separate PET from RFID tags using cyclonic separation (personal communication, Randy Stigall, UPM Raflatac, February 19, 2007). Thus, any RFID tags used on PET bottles should be designed to be easily removable, whether by using a non-PET substrate, or through other means.

Active, battery-powered RFID transponders will be less widely consumed than passive RFID tags at a rate of perhaps one per person per year. This would add to the already wide use of battery-powered devices, currently approximately 10 batteries per person per year (Environment Canada 2007). The low recycling rate for consumer batteries suggests that RFID will add to the disposal of batteries in municipal solid waste.

In summary, today's RFID tags are neither biodegradable nor recyclable. RFID tags may get in the way of recycling of many types of packaging and other materials. Choice of RFID material, and removability of tags, would seem to be readily able to avoid these problems.

With carbon-based conducting inks as antennas and careful choice of the plastic or paper substrate, the bulk of the RFID tag could be biodegradable or otherwise environmentally benign. The silicon chip, however, may have environmental impacts that are harder to address, if not at the end-of-life stage then certainly at the production stage; the manufacture of silicon chips requires significant amounts of energy and water and has significant pollutant emissions (Williams, et al. 2002).

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