MF

METROFREIGHT
Volvo Center of Excellence

Trucks, Trains, Tugs, and Tubes: A Model for More-Efficient Collection and Transfer of Solid Waste, the Predominant Form of First-Mile Urban Freight

Project Number: 15-2.1a

FINAL REPORT

June 2015

Principal Investigator

Benjamin Miller

Researcher

Juliette Spertus

**MetroFreight Center of Excellence
University Transportation Research Center
City University of New York**

Title: Trucks, Trains, Tugs, and Tubes: A Model for Rational Collection and Transfer of Solid Waste, the Predominant Form of First-Mile Urban Freight

Abstract

This research explores the feasibility of repurposing existing transportation infrastructure—a former freight rail viaduct now turned into a park and a former freight railroad now underused for passenger trains—for the installation of a pneumatic waste-collection and direct-rail-transfer facility in a densely developed urban center. Affixing a tube to the elevated viaduct could avoid the need for tunneling through a congested corridor, while direct rail-transfer could avoid the need for intermediate truck drayage to central transfer, processing, and disposal locations. The benefits of pneumatic collection have been shown in specific circumstances of adequate density and appropriate geographic configuration, but initial capital requirements are high compared to truck-based collection and the necessity for tunneling through crowded urban surfaces imposes an additional challenge for installing pneumatic systems in built-up areas. In this case study, the feasibility of such an installation was assessed and the economic and environmental costs of pneumatic and truck-based collection in this location were compared, as well as the costs of intermediate truck drayage and direct rail movement. The concept of repurposing such existing infrastructure was shown to be physically and operationally feasible, at lesser equivalent annual costs relative to truck collection, with mixed results in terms of environmental performance. Truck kilometers and fuel requirements were reduced, but electrical demand for pneumatic collection caused overall energy use and greenhouse gases (GHG) to increase. Relative GHG emissions, however, would be expected to decrease in the future were the current shift to non-carbon-based fuels to continue; other public health, environmental, and economic benefits—not quantified here—may compensate for or outweigh any continuing penalties in GHG emissions.

INTRODUCTION

The environmental, economic, public-health, and quality-of-life problems posed by urban freight operations are well known (e.g. Bannister, 1998; Lena et al., 2002; Dablanc, 2011; McKinnon et al., 2012). Trucks, which produce street and roadway congestion, consume significant quantities of fossil fuels, emit significant quantities of greenhouse gases, diesel particulates, and other substances of concern, and require costly, labor-intensive operations, are a major source of these problems. Issues due to inbound urban freight have been the focus of a considerable amount of research (e.g., Holguin-Veras et al., 2005; Dablanc, 2009; Browne et al., 2012). Less-studied are problems associated with outbound urban freight, the predominant form of which, for New York City and many other urban centers, is various forms of solid waste.[1] Again, a major cause of

---

[1] Some 45,000 tonnes of municipal solid waste (MSW), construction-and-demolition debris, and excavation material are exported from New York City every day by truck or train—along with 270 dry tonnes of biosolids (NYC Dept. of Sanitation, 2006, Executive Summary, Attachment V). Most of this material goes to landfills hundreds of kilometers away (Citizens' Budget Commission 2012.) At a more-macro level, the top containerized export from

these problems is the trucks which collect waste at the source—generally, in New York and many other cities, at the street curb—and transport it to the “first-dump” site which (again in the case of New York, but in many other cities as well) is a facility for transferring the material to a larger-capacity truck or to another transport mode for longer-distance transport to a processing or disposal facility. The especial impacts caused by these collection trucks stem from the facts that not only do their routes extend deep into city centers to reach each individual waste-generator at her home or place of business, but that the trucks themselves are typically compactors, of particularly heavy construction, with particularly low fuel efficiency due to the need to carry heavy loads, stop frequently at closely spaced collection points, and use hydraulic power for compaction while idling.

In the case of New York City, which is the focus of this analysis, these problems are exacerbated by the fact that collection routes are highly balkanized rather than being rationally ordered through the use of exclusive collection zones. Municipal forces collect waste materials from residences and governmental or non-profit institutions. Competing commercial carting companies collect waste from all other waste generators. The result is that the number of in-city kilometers traveled by these extra-heavy trucks is significantly greater than would be necessary if all the generators in one geographic zone were served by a single hauler. In addition to the well-established alternative of designating franchise zones to be served by a single carter (as is done, for example, in Portland, OR, San Francisco, and Seattle) (Miller and Spertus, 2015b), cities also have other options for reducing the number of truck-kilometers traveled in their streets for the management of solid wastes.

One such option is pneumatic collection technology which, under appropriate conditions, can offer a variety of advantages over conventional, truck-based collection (e.g., Iriarte, et al., 2009; Punkkinen, et al., 2012; Teerioja, et al, 2012; Aranda Usón, et al., 2013; Miller and Spertus, 2014; Nakou, et al., 2014).[2] It has been used for over fifty years in Europe (and for nearly that long in one New York City neighborhood, Roosevelt Island [Kamga et al., 2013a]) and is now used in dozens of cities in Europe and Asia. (Appendix Table A-1 provides examples of facilities installed in Europe and Asia.)

On the Far West Side of Manhattan—the fastest-growing section of the city’s most densely developed borough—there are circumstances that would appear to offer convenient opportunities for taking advantage of this technology. Harnessing these opportunities, which arise from specific combinations of existing and planned infrastructure, could offer a model for the development of such opportunistic waste-handling solutions not only in other parts of the city but in other cities around the world.

---

the Port of New York and New Jersey (the largest port by volume on the Atlantic seaboard)—as well as the top overall export by weight—is waste paper (Port Authority of New York and New Jersey, 2015).

[2] Note that pneumatic collection inherently offers the potential advantages of zoned collection—the ability to collect materials from all generators, public or private, within a given area. Since pneumatic systems allow the option of identifying the generator who inserts a given amount of material in a given inlet (by requiring the use of a unique key-card to open the inlet door), pneumatic systems allow for the possibility of commingling public- and private-sector wastes, even though the charging structures for waste generators in the two categories may be different. Thus pneumatic systems also offer an alternative way to achieve the benefits of zoned collection without changing the institutional structures involved with current truck operations.

The specific combination of opportunities on Manhattan's Far West Side is: (1) that an historic elevated freight rail viaduct—now turned into one of the most heavily used parks in the world, the High Line—runs through a dense mixed-use corridor that is undergoing intensive new development (Figure 1); and (2) that the northern terminus of this park (since it was once connected to a freight line running northward to offer connections to three of the four other boroughs as well as the rest of the continental U.S.) offers the possibility of a direct rail freight connection. Instead of requiring trenching through the crowded surface of Manhattan, or tunneling through the dense tangle of utility lines beneath it, a pneumatic tube could be affixed to the unused underside (or side) of the High Line to provide pneumatic collection to buildings along that corridor. A pneumatic terminal at the north end of the park could connect directly to a once-heavily-used freight line (now converted to an under-used line for inter-city passenger rail) to add urban goods-movement service to this presently underutilized—but superbly situated—transport asset. Adding to the potential opportunity is the fact that a separate pneumatic waste-collection system is now being installed in the 10.5-hectare Hudson Yards development (the largest private real estate development in the history of the U.S.), which is enclosed on three sides by the High Line (Figure 2) (Related Companies, 2015). This Hudson Yards system in itself will have an appreciable effect on reducing collection kilometers in this area; if it were also to take advantage of the potential for a direct connection between the terminal and the adjacent rail line, it could also avoid the use of truck drays between the terminal and the planned first-dump sites, a waste-to-energy facility across the Hudson River in New Jersey, a truck-to-barge transfer station on the Hudson River, and a processing plant in Brooklyn (NYC Dept. of Sanitation, 2006, Chap. 3; Miller and Spertus, 2015a, b).

Figure 1: The High Line Park
(ClosedLoops, 2011)

Figure 2: The Hudson Yards Complex
(Related Companies, 2015)

While these opportunities are specific to the history and geography of New York, they exemplify the sorts of location-specific opportunities for re-purposing historic urban infrastructure and rights-of-way that could be harnessed to provide more-efficient waste-handling services in other neighborhoods and cities.

PROJECT OBJECTIVES

This research was designed to compare the truck kilometers, truck trips, energy use, greenhouse gas emissions, and capital and operating costs associated with the kind of conventional waste-collection practiced in all North American cities with the costs and impacts of pneumatic collection. Case-specific waste sources, volumes, and composition; transfer, processing, disposal, and garage locations; waste-collection capital and operating costs; truck routes and rail networks; and existing adaptable infrastructure and rights-of-way are used to assess likely outcomes in an actual locale in a way that may offer realistic implications for other localities.[3] The analysis further compares the effects of truck transport of pneumatically collected material, compacted in shipping containers, with transport to the "first-dump" location by truck or by rail.[4] An additional objective was to assess the feasibility and practicality of re-purposing abandoned or under-utilized historic urban rail assets (a rail viaduct now used as park and a freight rail line now under-used for passenger rail) to facilitate the development of non-conventional waste-management systems that may offer potential advantages over existing legacy systems.

PROJECT DESCRIPTION

Pneumatic waste collection systems use negative air pressure to pull solid waste through a network of pipes to a central collection terminal where the waste is compacted and sealed into containers for transport to a processing or disposal facility. Wastes are deposited into gravity-fed inlets (either indoor garbage chutes or outdoor litterbins) where they accumulate (inside the chute or in a reservoir beneath the litterbin) until a remote sensor, noting that the reservoir is full, automatically opens the valves that connect the inlets to the tube transport network. When the material reaches the terminal, it is directed into a compactor, while the air is filtered to remove impurities before it circulates through the exhausters and then out into the atmosphere. A single trunk pipe can transport multiple source-separated waste streams or fractions by pulling them at different times from their separate inlet points.

Figures 3 and 4 illustrate the key components of this technology.

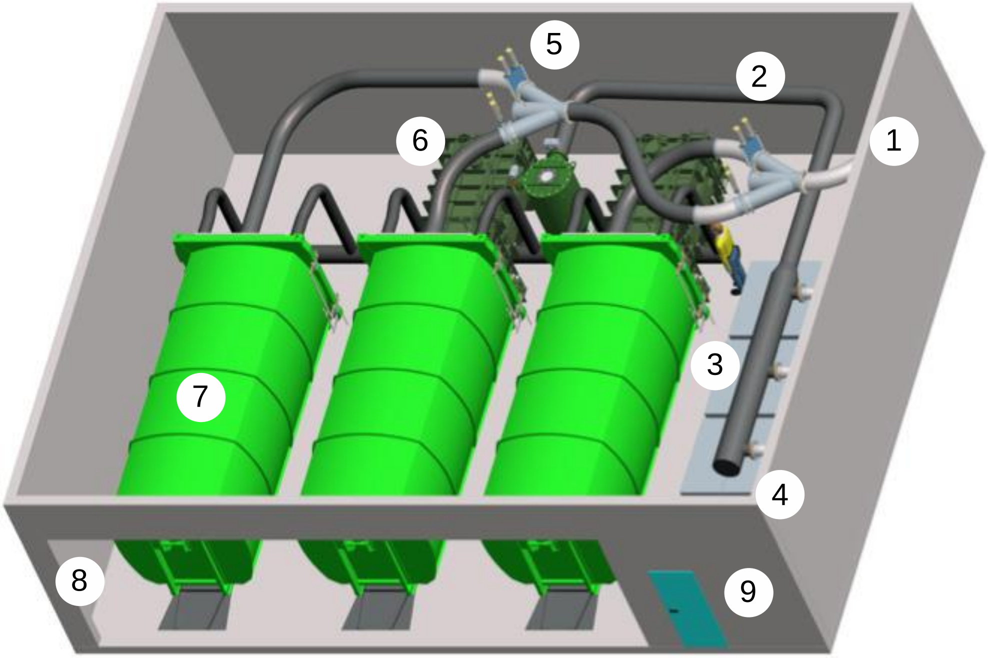
---

[3] In some instances, current practices determined purely by political and/or institutional history rather than by any operational necessity, rational design, or conscious decision-making were modified for purposes of this comparison in order to bring them more in line with generally accepted practice elsewhere and to make the comparison between truck-based and pneumatic collection less biased by arbitrary and idiosyncratic precedents. An example of such a modification from current actuality is the use of a "zone" truck-based collection system for comparison with pneumatic collection (which is inherently "zone"-based).

[4] The "first-dump" is the centralized point where collection trucks empty their loads after completing their collection routes. The distance between the end of the collection route and the first-dump site plays an important role in affecting overall collection costs and impacts. A pneumatic terminal can be considered a "first-dump" (for comparison to conventional truck-based collection) only when there is no further need for intermediate transfer to another for transport to long-distance transport to the ultimate processing or disposal location. In the case of a pneumatic terminal that offers direct transfer to rail (thus avoiding the need for using an intermediate transfer facility), it could be considered the "first-dump" site.

1 Exterior Inlets 2 Interior Inlets 3 Pipeline 4 Collection Terminal

Figure 3. Schematic Representation of Typical Pneumatic Waste-Collection Network (MariMatic Oy)



1 Waste Pipe 2 Air Pipe 3 Air Pumps (turbines) 4 Air Filter 5 Diverter Valve
6 Compactor 7 Container 8 Truck Access 9 Control Room/Offic

Figure 4. Schematic Representation of Typical Pneumatic Waste-Collection Terminal (MariMatic Oy)

Although the initial cost of installing pneumatic systems is relatively high, in comparison to the purchase costs of collection trucks and garages, pneumatic collection offers inherent advantages over truck-based collection, as discussed in Kamga et al, 2013a and 2013b. The benefits that would be directly attributable to a reduction in truck trips, ranging from decreases in such high-risk emissions as $PM_{2.5}$ to economic savings due to reduced congestion-induced time delays, are well understood and can be readily quantified (e.g., Kinney et al., 2000; Shrank et al., 2012). The potential benefits that are specifically linked to effects on urban waste management systems are perhaps less widely known and less-susceptible to measurement. Among these: (1) pneumatic inlets allow collection without the use of indoor space for storing waste in bags or bins and without the use of labor for staging bags or bins onto curbs or loading docks; (2) bags or bins do not occupy public space or produce nuisances in the intervals between staging and pick-up; (3) collection-worker and pedestrian injuries may be reduced; (4) collection frequency is increased to multiple times a day rather than, perhaps, multiple times a week (which, among other things, facilitates the separate collection of food waste in high-density areas); (5) collection reliability is not affected by holidays or weather events; (6) surges in volume can be accommodated relatively easily; (7) eliminating storage and handling requirements may facilitate separation of materials for recycling or organics-processing and thus increase diversion from long-distance transport to remote disposal facilities; (8) separate inlets and containerization may increase material recovery through reduced cross-contamination between material types; (9) the capability for "metering" waste by requiring a unique key-card to access a refuse inlet allows the use of direct economic incentives at the individual household or business level to incentivize waste-reduction and diversion.

Conceptual High Line Corridor Pneumatic-Tube-to-Rail Facility

A trunk tube running the two-km-length of the High Line, affixed to its side or underside, could transport waste inserted in inlets on top of the High Line and in buildings adjacent to the High Line (which would be connected by branch tubes joined to the trunk line) to a terminal at its northern end. There would be three inlets at each location where waste would be inserted into the system: one each for recyclables (metal, glass, plastic, paper), organics, and refuse.[5] These

---

[5] New York City currently requires that waste be sorted into two primary fractions prior to collection by municipal or private forces: recyclables (metal, glass, plastic, paper) and trash. (As of 2015, New York City law requires that recyclables be subdivided into two sub-fractions, with paper and old corrugated cardboard [OCC] kept separate from the metal, glass, and plastic. In April, 2015, however, the City administration announced its intent to modify this arrangement by 2020 so that these two sub-fractions would be collected together [City of New York, 2015, p. 176].) In 2015, the City also announced its intent to expand the existing pilot program for source-separation of food waste citywide, so that a third separation, for organics, may also be required in the foreseeable future (City of New York, 2015, p. 178). These are the three fractions that the pneumatic system is designed to handle separately. Old corrugated cardboard (OCC), which is a significant component of commercial waste, can be handled in a pneumatic system, but this requires the installation of relatively expensive and space-consuming shredding/crushing equipment in front of the inlet. Since it is relatively easy to bundle, store, and collect this high-value material by conventional methods, the pneumatic network is not designed to handle OCC and the waste tonnages presented in Table 1 do not include this component. For a characterization of all waste components included or not included in the pneumatic system design and calculations presented below, see Table A-2 in the Appendix.

separate fractions would be pulsed from their respective inlets, one fraction at a time, so that they could be transported separately through the trunk line and compacted into separate containers at the terminal. These containers of compacted waste fractions could be transported from the pneumatic terminal to centralized transfer, processing, or disposal locations either by roll-on/roll-off truck (RoRos) or by railcars.

Figure 5. Rendering of Pneumatic Network Along High Line
(Colin Curley and ClosedLoops LLC, 2014)

Figure 6. Rendering of Pneumatic Tube Running Between Girders on the Underside of the High Line
(between the 3rd and 4th girders from the left)
(ClosedLoops LLC, 2014)

Since the High Line runs at an elevation of 6.7 meters above the street in the section south of

Hudson Yards where adjacent buildings might be connected, branch lines from the High Line trunk tube would enter the buildings at or around the second-floor level. Recyclables, organics, and refuse would be deposited in separate gravity-fed vertical chutes which would terminate at the second floor. Wastes produced on the ground floor would be brought up to the second floor.

Figure 7 shows the projected High Line Corridor pneumatic waste network. The opportunistic right-of-way and armature for the pneumatic tube is provided by the High Line viaduct—the green line shaped like a shepherd's crook extending north-south along the western shore of Manhattan from the black dot near #7 (which is the site of the projected tube-to-rail terminal) to just beyond the last black dot south of the buildings labeled #1 and #2. The High Line Park is a lushly vegetated pedestrian walkway on the upper side of the viaduct. The black dots on the gray line indicate the locations of inlets for park users, located every 244 meters. A separate inlet is at each point for each of the three fractions collected. Numbers 1-6 indicate buildings projected to be connected to the network. The basis for selecting buildings for inclusion in the system was an assessment of the relative ease of access to the trunk pipe affixed to the High Line.

Number (1) is the Chelsea Market, a block-long complex filled with food-related businesses and offices. Vertical extensions now underway at the east and west ends will add 30,000 square meters of new office space. The High Line runs directly through this building at the second-floor level. Also directly connected to the High Line is Number (2), 85 10th Avenue, another block-large building filled with restaurants and offices. Numbers (3) and (4) are fairly large-scale buildings that, since they are not yet permitted for construction, are considered to be early-enough in the design process to allow a connection to the pneumatic network to be accommodated in final design. Number (3), 76 11th Avenue, will be a mixed-use complex with two towers, 28- and 38- stories high. Number (4), 511-25 18th Street, will be a residential tower which, based on the parcel configuration, may be sixteen or so stories high; it will be developed by the same company that is building Hudson Yards. The Javits Center (Number 6), New York City's convention center, accommodates 3.5 million visitors a year (Javits Center, 2015). Number (7) is the projected location of the pneumatic tube-to-rail terminal, which is on a right-of-way connecting to the rail line that runs north out of Manhattan. The Hudson Yards development, now underway, is being built on a platform over the rail yard nestled within the crook at the High Line's north end. The separate pneumatic system for this complex is projected to collect the same three waste fractions from the 4,888 residential units in the gray buildings indicated on the map.

Figure 7. Pneumatic Waste Network

Table 1 shows the waste volumes predicted from these sources, by fraction, as well as the type of hauler who would pick up this material under current conditions, the type of truck that would be used, and the number of pick-ups. (This total tonnage—about 23 tonnes a day—comes close to the system's design capacity. This is a critical factor, as previous studies have shown [e.g., Kamga et al., 2013a], in determining a pneumatic system's economic efficiency, since the capacity-utilization of a relatively expensive fixed asset is a critical component of financial performance.)

Table 1. MSW Tonnes/Yr, by Source, Fraction, Collection Truck Type , Current Hauler, Number of Pick-Ups

	Recyclables	Pickups/Y	**Organics**	Pickups/Y	**Refuse**	Pickups/Y	Hauler/Truck
High Line Park	**288**	52	**131**	52	**191**	260	PRL
Chelsea Market	**288**	364	**987**	364	**627**	728	CRL
85 10th Ave	**1,006**	312	**668**	312	**420**	312	CRL
76 11th Ave, Commercial	**548**	312	**210**	312	**201**	312	CRL
76 11th Ave, Residential	**301**	52	**75**	156	**62**	156	DRL
511-525 West 18th St	**51**	52	**10**	156	**8**	156	DRL
Javits Convention Center	**7**	174	**541**	52	**1,004**	142	CRo
TOTALS	**889**	**1,318**	**2,622**	**1,404**	**2,513**	**2,066**	
Key:							
PRL=NYC Dept of Parks rear-loader							
DRL=NYC Dept of Sanitation rear-loader							
CRL=Commercial carter rear-loader							
CRo=Commercial carter RoRo							

Figure 8 shows the location of the High Line Corridor (HLC) in relation to the rest of Manhattan and parts of the Bronx, Brooklyn, Queens, Staten Island, and New Jersey. It also shows the location of the garages which are currently the origin points for collection trucks serving the Corridor (1). For reasons discussed below, only the two Department of Sanitation (DSNY) facilities are used in the comparison between conventional collection and potential alternatives (one houses rear-loader trucks for the HLC, one houses roll-on/roll-off [RoRo] trucks). The map also shows the locations to which the three waste fractions from the HLC area are currently driven to be transferred, processed, or disposed. Again, for reasons discussed below, only the DSNY dump locations (the marine transfer station [MTS] for recyclables, (2); the organics-pre-processing facility, (5); the materials recovery facility [MRF] for recyclables, (6); the waste-to-energy [WTE] incinerator for refuse, [7]) and a projected rail siding for refuse (8) are used in the comparative analysis. The black line shows the rail routes over which the three types of containers (recyclables, organics, refuse) could be transported from the pneumatic terminal to DSNY dump sites. The dotted line shows the barge route between the MTS and the MRF.[6]

---

[6] This MTS is not yet in operation; design began in early 2015. (NYC Dept. of Sanitation, 2015)

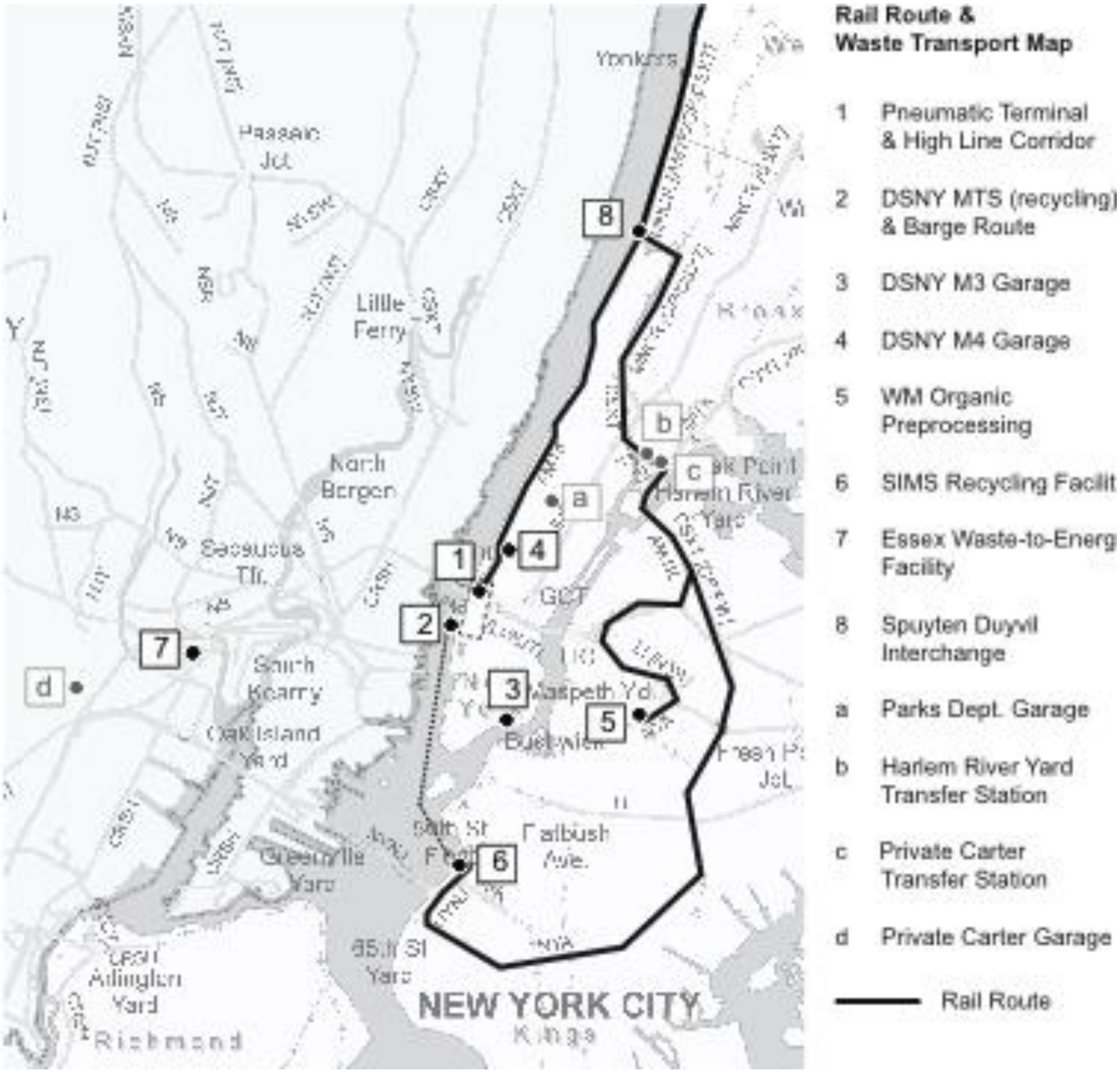


Figure 8. Rail Network and Facility Locations

COMPARISONS OF ALTERNATIVE SCENARIOS

The current status quo, with balkanized collection forces composed in the aggregate by municipal employees and competing private carters, generates a level of truck kilometers traveled (TKT) that tends toward the extreme case of the maximum possible number of TKT rather than the minimum case that could be achieved by modifying current institutional arrangements to permit one entity to collect all material (or all material of a given waste type) within a defined area. It is not possible to accurately predict the quantity of these kilometers because current New York City laws and regulations (1) allow any licensed carter to compete for the waste-removal contract from any business establishment in any building in the city and (2) limit the length of contract terms to two years. To estimate status quo/baseline TKT, therefore, it was convenient to assume the best case for the collection of commercial waste, which was that a single carter collected all the commercial waste generated by the buildings projected to be connected to the HLC system. Although this is the best case in terms of minimizing TKT, it also tends toward the most likely range of TKT since the carter selected for this purpose has more customers than does any other in the city (more than a tenth of overall market share), has a concentrated presence in this area, and has been the sole provider of services to all of the hundred businesses in the largest building that is assumed to be connected to the projected HLC pneumatic waste-collection terminal (the Chelsea Market).

First Comparison: Truck Collection v. Pneumatic Collection

For purposes of providing a comparison of the effects of conventional truck-based collection with pneumatic collection, even this "best-case" status quo calculation was thought to be too extreme to make it of general applicability for other cities where pneumatic collection might be considered. The major reason for this idiosyncratically extreme situation (since about 90 percent of the waste estimated to be generated by buildings to be connected to the HLC system is commercially generated) is that the origin and destination points for the truck trips (from a private garage located in New Jersey to dump sites in the Bronx and Brooklyn) are more-distant than the parallel garage sites and one of the dump sites used by municipal collectors. Therefore, the scenario designed for the purposes of producing a more-generally applicable comparison of pneumatic vs. truck-based collection assumes the hypothetical (but potentially practicable) [7] case that all waste in the HLC "zone" is picked up by municipal trucks and taken to the same municipal dump sites.[8] The recycling fraction is taken to an adjacent MTS where truckloads of waste are emptied into barges that are towed 11 km to a citywide processing facility on the Brooklyn waterfront.[9] The organics fraction is taken to a pre-processing facility in Brooklyn where it will be prepared for injection into an anaerobic digester at a nearby sewage treatment plant.[10] The refuse is taken to the waste-to-energy facility in Newark, NJ, to which all non-recycled/non-source-separated organic waste from the west side of Manhattan has been taken for over a decade and for which the city has a delivery contract extending decades into the future.

In the pneumatic case, it is likewise assumed that all material from these sources is collected in the same three fractions by the HLC network and is delivered to the same three first-dump sites. This material is transported between the HLC terminal and these dump sites by RoRo trucks, in

---

[7] New York City is currently considering some form of exclusive franchise system (City of New York, 2015, p. 186). Such a zoned system, if eventually implemented, might combine residential/institutional routes with commercial routes, or it might (as currently envisioned) pertain only to commercial generators.

[8] Another reason that it is more useful to assume that DSNY is the sole collector for the zone, rather than a private carter, is that the DSNY's dump sites are under municipal control. They are therefore more likely to represent stable locations for long-term investments in infrastructural upgrades.

[9] It is a fortunate coincidence (for the sake of minimizing truck miles in this particular location) that the MTS nearly abuts the southern terminus of the High Line Park. It is planned that this facility will receive all municipally collected recyclables from anywhere in Manhattan.

[10] This facility, scheduled to begin operations at the end of 2015, will not be large enough to accommodate more than a fraction of the organic material produced in the city, but since it will be the only in-city facility capable of processing such material in the foreseeable future, this location was chosen for purposes of this comparison (Miller and Spertus, 2015a, 2015b).

standard-size shipping containers with custom pressurization to contain compacted waste without releasing air (or odor) to the environment.

Second Comparison: RoRo Transport v. Direct Rail Transfer

In order to compare the effects of conventional truck transfer to the impacts of a direct-rail-transfer alternative, another hypothetical-but-potentially-practicable departure from the current status quo was necessary. The majority of the refuse generated in New York City is sent to landfills that are 500 to 1,000 kilometers away (Citizens Budget Commission, 2012, p. 11). The City's plan, which as of 2015 is only partially implemented, is to send all of this waste by rail (as opposed to the tractor-trailer trucks that are still used to export refuse from some areas of the city). In about half of the city, refuse destined for a rail transfer station will first be sent to an MTS, where trucks will dump it on a tipping floor for re-loading into shipping containers that will be placed on barges, the barges will be towed to one of at least two port facilities (at least one of which remains to be sited) where the containers will be lifted from barges and placed onto railcars. Again, in a fortunate coincidence (in terms of minimizing the kilometers of the truck-based alternative—as well as eliminating the additional hyper-inefficiency of an intermediate barge trip), refuse from *this* part of Manhattan will be trucked, in its original collection trucks, only 21 kilometers to a waste-to-energy facility in New Jersey (see Fig. 8, #7). Since there is no direct rail connection across the Hudson to New Jersey (making New York City unique among major port cities in the world in having no direct freight rail connection to the rest of its continent), this direct comparison could not be modeled. Instead, in the RoRo version, trucks are sent to New Jersey as per current practice. In the rail version, railcars are sent up the northward extension of the High Line track to the nearest river crossing (225 kilometers north of the city), where it heads west to a waste-to-energy plant in Niagara Falls, NY. Although this is *not* where other refuse from this section of Manhattan would go, it *is* the location where refuse from the eastern side of Manhattan would be sent, as of the end of 2015—after an extraneous barge trip from the Upper East Side to Staten Island, from which trains will begin this trip up the west side of the Hudson (Fair Disclosure Wire, 2015). In order to provide a more-balanced comparison of the rail and RoRo alternatives in this situation, the railcars carrying pneumatically collected refuse are taken by the shortline operator only as far as a rail siding projected to be built at the intersection of rail lines running north from Manhattan and the Bronx. Trains carrying refuse from Brooklyn and Queens on behalf of DSNY pass this point six days a week and could pick up these cars on their way out of the city.

DATA SOURCES

The City of New York will not disclose any data on waste volumes generated by businesses or collected by private carters.[11] Data from confidential industry sources, proprietary databases, and unit generation data for urban businesses by type (Cascadia Consulting Group, 2006) were therefore used to provide estimates of commercial waste generation and composition by business type. Estimates of residential waste generation and composition were based on DSNY data for

---

[11] A Freedom of Information request for these data from the New York City Business Integrity Commission, which requires each licensed carter to submit periodic reports on its waste collections by customer, was denied (personal communication, Business Integrity Commission to Miller, 9-2011).

areas with the density and income characteristics of the HLC area (NYC Dept. of Sanitation, 2005). Information on projected costs and operations (numbers of trucks, numbers of trips, truck speeds, truckload weights, labor hours, fuel use, electricity use) were obtained from DSNY data, confidential industry sources, field observations, and an analysis of DSNY cost data prepared by DSM Environmental (DSM, 2008). Distances for calculating KMT were based on the locations of existing or planned origins (garages) and first-dump sites and on an operationally feasible location for the projected pneumatic terminal. Rail distances were calculated for existing tracks and rail yard locations. Rail terminal requirements and short line service costs were provided by Thomas Erickson of Rail Cents Enterprises Inc. Pneumatic system capital and operating costs were provided by MariMatic Oy, based on a system design developed by the authors in collaboration with Albert Mateu, P.E. of Green Bending, S.L.. Electricity consumption for the projected pneumatic terminal is based on the average used by MariMatic for 30cm-diameter pipe systems (MariMatic Oy, 2013).[12] Greenhouse gas emissions (GHG, in the form of CO2-equivalent tons) associated with KMT, rail kilometers traveled (RKT), and electricity use were based on current New York City-specific factors for stationary- and mobile-source emissions (electricity generated from a mix of natural gas [54%], nuclear [30%)] hydroelectric [9%], coal [6%] and oil [1%]; diesel emissions based on NYC operating conditions) (City of New York, 2011).

In situations where the waste fractions collected in the conventional, truck-based case do not constitute a full truck-load, truck kilometers were multiplied by a factor representing this fraction of the truck's average load capacity in order to account for the fact that the truck trip would also be expected to include waste from other sources. Likewise, since the recyclable volumes in this case study would not constitute a typical barge load, barge kilometers were adjusted by a factor representing the portion of capacity used. Fuel use for rail was calculated on a tonne-kilometer basis, as is standard in the industry.

In cases where it was not possible to assign a cost to the collected or transported load (as was done, for example, in the case of estimating the cost of moving a rail carload), a per-ton factor was applied (as in the case of capital and operating-and-maintenance costs for rear-loaders, which were based on estimates of aggregate, system-wide costs, and as in the case of the per-tonne cost of using MTS capacity). All of these factors are presented in tables in the Appendix, along with their sources and/or rationales. Other summary data inputs for the comparisons presented below are also provided in the Appendix.

---

[12] A smaller diameter requires less air to move material through the pipe and therefore less energy to maintain the vacuum. Other factors, such as the composition of the pipe (e.g., composite plastic vs. steel), the use of devices to shape inserted materials to the interior dimensions of the pipe, and the use of propulsion as well as vacuum forces (which can be achieved in situations where network loops are possible) can also affect energetic efficiency (MariMatic Oy, 2013; Envac AB, 2014). Energy efficiency of 50 kWh-or-less per tonne has been demonstrated for 30cm pipe, while 100 kWh/tonne is a rule-of-thumb figure for 50cm pipe. Until recently, all systems for residential or commercial refuse used 50cm-diameter pipe and, as far as we are aware, all of the literature on pneumatic collection to date has been based on this equipment (e.g., Al-Ghamdi, 2003, Teerioja, 2012; Kamga et al, 2013a). Most articles do not mention pipe diameter.

ANALYSIS AND RESULTS

Comparison #1: Truck Collection v. Pneumatic Collection

Converting the "best-case" status quo truck collection (assuming a single private carter for the HLC area) to the zoned case (assuming that all waste fractions from all sources are collected by a single hauler, in this case, the DSNY) produces a dramatic reduction in TKT—and therefore in all of the other compared impact elements. TKT goes from 66,000 km (with both DSNY and a private carter collecting material from different garages and taking it to different first dumps) to 30,000 km (when all collection is done by DSNY, with trucks based in DSNY garages and with dumps at DSNY-controlled facilities). (See Table A-3 in the Appendix for a summary of this Best-Case Status Quo-to-Zone comparison.)[13] Optimizing in this way the efficiencies that could be achieved with truck-only collection provides a more valid basis for considering any incremental benefits that could be achieved by substituting pneumatic for conventional collection.

A comparison between the overall capital and operating costs associated with conventional truck-based collection (assuming collection by only a single hauler within the HLC zone) and those associated with the pneumatic alternative is presented in Table 2. In both cases, the collected waste fractions end up at the same first-dump sites; in the case of the pneumatic system, this means that shipping containers of compacted, pneumatically collected waste are drayed from the pneumatic terminal to the centralized dump sites on RoRo trucks. (In the case of recyclables, for both truck-based and pneumatically-collected material, a barge takes the material the last leg of the trip, from the MTS to the MRF.) This comparison shows, as expected, that significantly greater capital costs are involved with the development of long-term pneumatic-collection infrastructure. It also shows that operating costs would be about 40% less than those of conventional collection.

---

[13] Capital costs between the Best-Case Status Quo and the DSNY-only collection do not differ appreciably, because the costs of trucks and garages are expected to be similar. But the fact that operating costs in these two cases are also similar, despite significant differences in TKT, is a result of the fact that per-ton costs of private collection, given current institutional parameters in New York City, are significantly less than those of municipal collection (Citizens Budget Commission, 2014). These institutional parameters (which have to do with administrative boundaries, operational practices, historical union agreements, and other non-immutable conditions) could be modified over time.

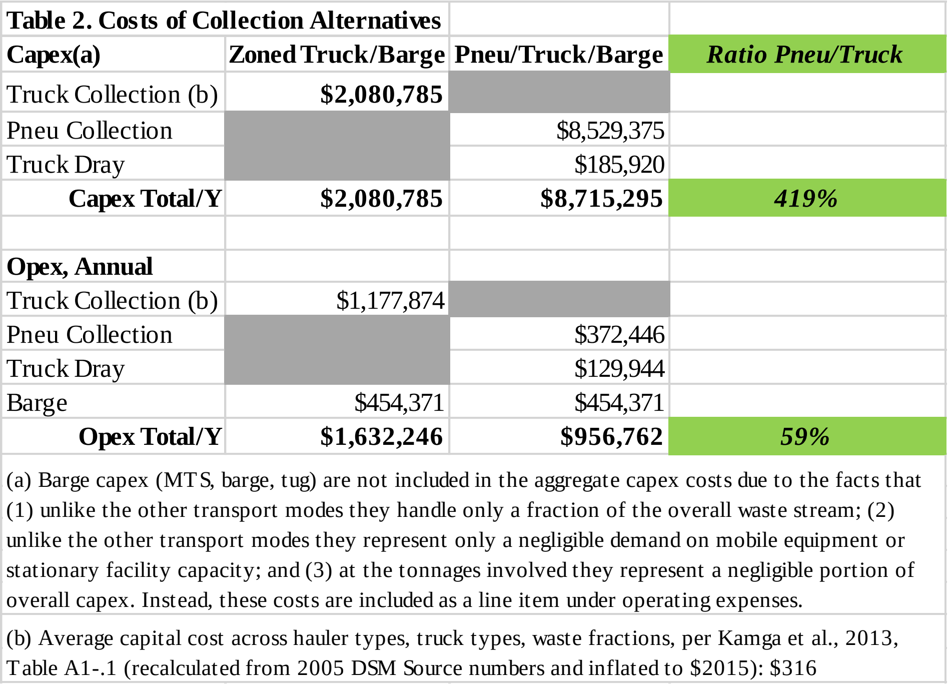


Table 2. Costs of Collection Alternatives

Capex(a)	**Zoned Truck/Barge**	**Pneu/Truck/Barge**	***Ratio Pneu/Truck***
Truck Collection (b)	**$2,080,785**	▨	
Pneu Collection	▨	$8,529,375	
Truck Dray	▨	$185,920	
Capex Total/Y	**$2,080,785**	**$8,715,295**	***419%***
Opex, Annual			
Truck Collection (b)	$1,177,874	▨	
Pneu Collection	▨	$372,446	
Truck Dray	▨	$129,944	
Barge	$454,371	$454,371	
Opex Total/Y	**$1,632,246**	**$956,762**	***59%***

(a) Barge capex (MTS, barge, tug) are not included in the aggregate capex costs due to the facts that (1) unlike the other transport modes they handle only a fraction of the overall waste stream; (2) unlike the other transport modes they represent only a negligible demand on mobile equipment or stationary facility capacity; and (3) at the tonnages involved they represent a negligible portion of overall capex. Instead, these costs are included as a line item under operating expenses.

(b) Average capital cost across hauler types, truck types, waste fractions, per Kamga et al., 2013, Table A1-.1 (recalculated from 2005 DSM Source numbers and inflated to $2015): $316

In order to compare the overall, long-term cost effects of these two types of systems, which have different capital and operating cost structures and different lengths of useful life, these costs were compared on an Equivalent Annual Cost (EAC) basis. An EAC calculation divides the investment cost of an asset by the Present Value of Annuity factor to determine the cost of owning and operating an asset over its entire lifespan. This factor is $A_{t,r}$, where t is the useful life of the asset and r is the interest rate. The inputs for this EAC calculation are shown in Table 3, using an interest rate of 4%. (Given the negligible effect the HLC recycling tonnage would have on overall demand for barge-system capacity, capital costs of barges are not shown in Table 3; instead, the per-tonne costs of using the barge system are included as an operating cost. The cost of locomotive service is likewise treated as an annual service fee.) The result shows that the EAC for the pneumatic system would be over 30% less than that of conventional collection.

Table 3. Zoned Trucks v. Pneu/Truck/Barge								
		PV of Costs (a)	**UseLife (b)**	**O&M (c)**	**At,r**	**EAC**	**Total EAC**	***Ratio Pneu/Truck***
Zoned Trucks/Bar	Trucks (collection)	-$9,347,253	5.0	$1,632,246	4.452	-$2,099,646	**$2,099,646**	
Pneu/Truck /Barge (d)	Pneu System	-$15,901,123	40	$372,446	19.793	-$803,380		
	Trucks (dray)	-$2,555,961	5.0	$568,316	4.452	-$574,138		
	Containers	-$267,724	7.5	$16,000	6.371	-$42,022		
	TOTAL						**$1,419,541**	***68%***
(a) Interest rate, 4%								

(b) NYC DSNY truck life: DSNY, cited in Kamga et al., 2013, Table A1-3. Pneu system life: the existing NYC pneu system (on Roosevelt Island, see Kamga et al. 2013b) has been in continuous operation for 40 years without replacement of any significant components. Other systems elsewhere have been in operation for longer than that. Since the O&M costs shown above include the ongoing replacement of system components--as in a standard sewer system--the actual useful life of the initial investment is indefinite.

(c) All O&M without debt service; O&M for trucks includes per ton lease cost for barge transport; O&M for track includes per ton lease charge for rail transport.

(d) Barge capex (MTS, barge, tug) are not included in the aggregate capex costs due to the facts that (1) unlike the other transport modes they handle only a fraction of the overall waste stream; (2) unlike the other transport modes they represent only a negligible demand on mobile equipment or stationary facility capacity; and (3) at the tonnages involved they represent a negligible portion of overall capex. Instead, these costs are included as a line item under operating expenses.

Table 4. Annual Impacts of Collection/Transfer Alternatives			
	Trks, Zoned/Brge	**Pneu/Trk/Brge**	***Ratio Pneu/Trks***
Tonnes	8,226	8,226	
Truck Kilometers	29,702	20,162	*68%*
Barge Kilometers	417	417	*100%*
Diesel Fuel (Liters)	25,761	15,283	*59%*
Electricity Use (Kwh)		453,365	
Combined Energy (Btus)	945,271,478	2,107,726,055	*223%*
GHG (Tonnes)	70	180	*259%*
Capital Cost	$2,080,785	$8,715,295	*419%*
Operating Cost	$1,632,246	$956,762	*59%*
Equivalent Annual Cost	$2,099,646	$1,419,541	*68%*

The environmental impacts of conventional collection and pneumatic collection with a truck dray from the pneumatic terminal to the centralized first-dump sites are shown in Table 4. Truck kilometers and diesel fuel, as expected, are reduced in the pneumatic scenario, but not eliminated, since RoRo trucks are still required to dray containers from the pneumatic terminal to the centralized first-dump sites. GHG emissions are 259% higher in the pneumatic scenario, however, due to the use of electricity—for which the primary generating source in New York City's case is natural gas (City of New York, 2011). The total energy use, including electricity, is also more than doubled.

Comparison #2: Truck Dray v. Direct Rail Transfer

The second comparison considers the effects of eliminating the use of trucks for draying containers of waste materials to the centralized dump sites by taking advantage of the adjacent rail line to allow direct rail transfer and transport from the pneumatic terminal. The annual capital and operating costs of these two options are shown in Table 5. Capital costs are nearly five times higher for the rail alternative, primarily due to the need for more than three times as many pneumatic-compaction containers in order to meet the longer cycle time associated with rail transport.[14] (Again, barge costs, due to the low demand on barge capacity, are shown only in the operating-cost section.) Operating costs for the rail alternative, however, are about 40% less than those of truck drayage.

Table 5. Annual Costs of Transfer Alternatives			
Capex (a)	**Pneu/Truck/Barge**	**Pneu/Rail**	***Ratio Rail/Truck-Barge***
Truck Dray	$185,920		
Rail Transfer		$900,000	
Capex Total/Y	**$185,920**	**$900,000**	***484%***
Opex (b)			
Truck Dray	$129,944		
Barge	$454,371		
Rail		$342,320	
Opex Total/Y	**$584,316**	**$342,320**	***59%***
See Table 2 Notes for (a) and (b)			

When these costs are considered on an EAC basis, using the cost factors shown in Table 6, again using a 4% municipal-bond interest rate, the equivalent cost of rail is about 25% less than that of truck drayage.

---

[14] In the case of refuse, since, for the reasons noted above, the cars would be taken to a WTE facility nearly 800 kilometers from New York City, the cycle time relative to truck draying is increased from a few hours to the 9 days shown in Appendix Table A-7. Pneumatic containers are more costly than standard containers because they are custom-made to withstand high-pressure compaction.

Table 6. Truck Dray v. Direct Rail Transfer

		PV of Costs (a)	UseLife (b)	O&M (c)	At,r	EAC	Total EAC	*Ratio Rail/Trk-Brge*
Truck/Barge	Trucks (dray	-$2,555,961	5.0	$568,316	4.452	-$574,138		
	Containers	-$267,724	7.5	$16,000	6.371	-$42,022		
							$616,160	
Direct Rail	Track	-$5,392,491	50.0	$237,056	21.482	-$251,022		
	Containers	-$1,308,710	7.5	$105,263	6.371	-$205,417	**$456,439**	*74%*
Interest rate	4%							

(a) Barge capex (MTS, barge, tug) are not included in the aggregate capex costs due to the facts that (1) unlike the other transport modes they handle only a fraction of the overall waste stream; (2) unlike the other transport modes they represent only a negligible demand on mobile equipment or stationary facility capacity; and (3) at the tonnages involved they represent a negligible portion of overall capex. Instead, these costs are included as a line item under operating expenses.

(b) NYC DSNY truck life: DSNY, cited in Kamga et al., 2013, Table A1-3. Pneu system life: the existing NYC pneu system (on Roosevelt Island, see Kamga et al. 2013b) has been in continuous operation for 40 years without replacement of any significant components. Other systems elsewhere have been in operation for longer than that. Since the O&M costs shown above include the ongoing replacement of system components--as in a standard sewer system--the actual useful life of the initial investment is indefinite.

(c) All O&M without debt service; O&M for trucks includes per ton lease cost for barge transport; O&M for track includes per ton lease charge for rail transport.

A comparison of environmental impacts shows a reduction in TKT and diesel fuel, which translates into significant reductions in overall energy use and GHG emissions, as shown in Table 7, as well as a reduction in equivalent costs. From every perspective (except initial capital investment), pneumatic collection with direct rail transfer offers benefits over pneumatic collection relying on truck drayage to central dump sites.

Table 7. Annual Impacts of Truck Dray v. Direct Rail Transfer

		Pneu/Trk/Brge	Pneu/Rail	*Ratio Rail/Trk Dray*
Tonnes		8,226	8,226	
Truck Kilometers		20,162	0	
Rail Kilometers		0	7,147	
Barge Kilometers		417	0	
Diesel Fuel (Liters)		15,283	6,306	*41%*
Combined Energy (Btus)		348,046,084	231,396,293	*66%*
GHG (Tonnes)		45	18	*39%*
Capital Cost		$185,920	$900,000	*484%*
Operating Cost		$584,316	$342,320	*59%*
Equivalent Annual Cost		$616,160	$456,439	*74%*

Table 8. Annual Impacts of Truck v. Pneumatic Collection With and Without Rail

	Trks, Zoned/Brge	Pneu/Trk/Brge	Pneu/Rail	*Ratio Pneu-Tr-Bar/Trks*	*Ratio Pneu-Rail/Trks*
Tonnes	8,226	8,226	8,226		
Truck Kilometers	29,702	20,162	0	*68%*	
Rail Kilometers	0	0	7,147		
Barge Kilometers	417	417	0	*100%*	
Diesel Fuel (Liters)	25,761	15,283	6,306	*59%*	*24%*
Electricity Use (Kwh)	0	453,365	453,365		
Combined Energy (Btus)	945,271,478	2,107,726,055	1,778,341,194	*223%*	*188%*
GHG (Tonnes)	70	180	155	*259%*	*223%*
Capital Cost	$2,080,785	$8,715,295	$9,429,375	*419%*	*453%*
Operating Cost	$1,632,246	$956,762	$714,766	*59%*	*44%*
Equivalent Annual Cost	$2,099,646	$1,419,541	$1,259,819	*68%*	*60%*

Compared with the optimal scenario for conventional collection by truck (collection of all waste materials by one entity for delivery to one set of facilities), pneumatic collection with direct rail transfer still produces a penalty in terms of overall energy use (almost twice as much) and GHG emissions (more than twice as much), as shown in Table 8. Offsetting this, at least in part, however, are reductions in TKT—which would be expected to produce corresponding reductions in diesel particulate, congestion, noise, accidents, and roadway maintenance costs. From an energy-use perspective, reductions in diesel fuel use are more-than offset by increased use of electricity, but it could be expected that the GHG emissions penalty thus incurred would be reduced over time as non-carbon-burning sources of electricity come into broader use, as current trends suggest may be the case.

CONCLUSIONS

There are inherent benefits to reducing TKT in dense urban settings. There are also inherent benefits in providing waste-collection, transfer, and transport systems that produce the public health, environmental, economic, and quality-of-life advantages over conventional systems cited above. From a physical and operational perspective, the combination of alternatives considered here—providing access to pneumatic collection to buildings along the HLC by using the viaduct structure as the armature for a pneumatic pipeline in order to avoid subsurface tunneling; providing direct rail transfer from a pneumatic collection terminal to a disused urban freight railroad to avoid the need for double-handling at an intermediate transfer station and/or truck-drayage through city streets—has been shown to be practicable. The economic costs, despite the relatively high initial investment required, have been shown to be advantageous in the long run. Although pneumatic collection may (and in this site-specific case, would) impose a net energy cost, since the use of electricity does not outweigh the fuel savings achieved by reduced truck travel[15], there are advantages from a sustainability perspective of replacing liquid, carbon-based fuel with electricity, which can be generated from non-carbon sources. If the global energy transition from high-carbon inputs continues, the advantages of electricity over liquid fuels will increase and the current penalties paid by pneumatic collection over conventional waste collection, with regard to GHG emissions, will be reduced.

---

[15] Again, this particular location is advantaged in having an unusually proximate network of garages and first-dump sites, along with a high waste-generation density, even by Manhattan standards.

REFERENCES

Al-Ghamdi, Abdullah Saeed and Asad Sereaj Abu-Rizaiza, 2003, "Pipeline Transport of Solid Waste in the Grand Holy Mosque in Makkah," *Waste Management Research*, 2003 21:744

Aranda Usón, Alfonso, Ferreira, Germán, Vásquez, David Zambrana, Bribián, Ignacio Zabalza, Sastresa, Eva Llera, 2013, "Environmental-Benefit Analysis of Two Urban Waste Collection Systems," *Science of the Total Environment*, 463:72–77

Bannister, David, 1998, *Transport Policy and the Environment*, London: Routledge

Browne, Michael, Julian Allen, Toshinori Nemoto, Daniele Patier, Johan Visser, 2012, "Reducing Social and Environmental Impacts of Urban Freight Transport: A Review of Some Major Cities," *Procedia, Social and Behavioral Sciences*, 39: 19-33

Cascadia Consulting Group, 2006, "Waste Disposal and Diversion Findings for Selected Industry Groups," http://www.calrecycle.ca.gov/Publications/Documents/Disposal%5C34106006.pdf

Citizens' Budget Commission, 2012, *Taxes In, Garbage Out: The Need for Better Solid Waste Disposal Policies in New York City*, May 2012, http://www.cbcny.org/sites/default/files/REPORT_SolidWaste_053312012.pdf

Citizens' Budget Commission, 2014, *12 Things New Yorkers Should Know About Their Garbage*, May, 2014, http://www.cbcny.org/sites/default/files/REPORT_GarbageFacts_05222014.pdf

City of New York, 2015, *One New York*, http://www.nyc.gov/html/onenyc/downloads/pdf/publications/OneNYC.pdf

Dablanc, Laetitia, 2009, *Urban Freight*, Washington, D.C.: World Bank

Dablanc Laetitia, 2011, "City Distribution, a Key Element of the Urban Economy: Guidelines for Practitioners," in Cathy Macharis and Sandra Melo (eds.), *City Distribution and Urban Freight Transport: Multiple Perspectives*, Northampton, MA: Edward Elgar Publishing

DSM Environmental, 2008, *Analysis of New York City Department of Sanitation Curbside Recycling and Refuse Costs*, Prepared for Natural Resources Defense Council, http://docs.nrdc.org/cities/files/cit_08052801A.pdf

Envac A.B., 2014, *Quantum: Half the Energy—Twice the Capacity, Double the Value*

Fair Disclosure Wire, 2015, "Q1 2015 Covanta Holding Corp Earnings Call," 4-23-2015.

Holguin-Veras, J., J.M. Polimeni, B. Cruz, G. List, 2005, "Off-Peak Freight Deliveries to New York City: Challenges and Policy Measures." In E. Taniguchi and R. Thomson (eds.), *City Logistics IV*, Amsterdam: Elsevier.

Iriarte, Alfredo, Gabarrell, Xavier, Rieradevall, Joan, 2009. "LCA of selective waste collection systems in dense urban areas," *Waste Management*, 29 (2) 903–914. http:// dx.doi.org/10.1016/j.wasman.2008.06.002

Javits Center, 2015, "General Fact Sheet," https://www.javitscenter.com/images/file/GeneralFactSheet.pdf

Kamga, Camille, Benjamin Miller, Juliette Spertus, Lisa Douglass, Brian Ross, 2013a, *A Study of the Feasibility of Pneumatic Transport of Municipal Solid Waste and Recyclables in Manhattan Using Existing Transportation Infrastructure*, Final Report, July 2013, New York State Energy Research and Development Authority Report Number 14-14; New York State Department of Transportation Report Number C-10-21, http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Transportation/Feasibility-of-Pneumatic-Transport.pdf

Kamga, Camille, Benjamin Miller, Juliette Spertus, Lisa Douglass, Brian Ross, 2013b. *Eliminating Trucks on Roosevelt Island for the Collection of Wastes*, Final Report, July 2013, New York State Energy Research and Development Authority, Report Number 14-13, http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Transportation/Eliminating-trucks-on-Roosevelt-Island-for-the-Collection-of-Wastes.pdf

Kinney, Patrick L., Maneesha Aggarwal, Mary E. Northridge, Nicole A. H. Janssen, Peggy Shepard, 2000, "Airborne Concentrations of $PM_{2.5}$ and Diesel Exhaust Particles on Harlem Sidewalks: A Community-Based Pilot Study," *Environmental Health Perspectives*, 108 (3, March), http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1637978/pdf/envhper00304-0069.pdf

Lena, T. Suvendrini, Victor Ochieng, Majora Carter, Jose Holguin-Veras, Patrick L. Kinney, 2002, "Elemental Carbon and $PM_{2.5}$ Levels in an Urban Community Heavily Impacted by Truck Traffic," *Environmental Health Perspectives*, 110 (10, Oct.) 1009-1015

MariMatic, 2013, MetroTaifun Automatic Solid Waste Collection: The Next Generation of Waste Collection Systems, 10-2013.

McKinnon, Alan; Michael Browne; Anthony Whiteing, 2012, *Green Logistics: Improving the Environmental Sustainability of Logistics* (2nd ed.), London: Kogan Page Ltd.

Miller, Benjamin, Juliette Spertus, 2014, "Costs and Benefits of Pneumatic Collection in Three Specific New York City Cases," *Waste Management*, 34:1957-66

Miller, Benjamin, Juliette Spertus, 2015a, "Encouraging the Development of Processing Infrastructure for New York City's Organics Waste Stream, Part I" *Environmental Law in New York*, 26 (5, May), 75-85

Miller, Benjamin, Juliette Spertus, 2015b, “Encouraging the Development of Processing Infrastructure for New York City's Organics Waste Stream, Part II” *Environmental Law in New York*, 26 (6, June), 95-103

Nakou, D., Benardos, A., Kaliampakos, D., 2014, “Assessing the Financial and Environmental Performance of Underground Automated Vacuum Waste Collection Systems,” *Tunneling and Underground Space Technology*, 41: 263–271

New York City Dept. of Sanitation, 2005, *NYC Waste Characterization Study*, http://www1.nyc.gov/assets/dsny/downloads/pdf/studies-and-reports/2004-2005-waste-characterization.pdf

New York City Dept. of Sanitation, 2006, Sept. 2006 http://www1.nyc.gov/site/dsny/about/laws/solid-waste-management-plan.page

New York City Dept. of Sanitation, 2015, “Sanitation News Online,” http://www1.nyc.gov/assets/dsny/downloads/pdf/about/newsletter/Mar15.pdf

Port Authority of New York and New Jersey, 2015, “2014 Trade Statistics,” http://www.panynj.gov/port/pdf/2014_trade_statistics_sheet.pdf

Punkkinen, Henna., Merta, Elina., Teerioja, Nea., Moliis, Katja., Kuvaja, Evelliina., 2012, “Environmental Sustainability Comparison of a Hypothetical Pneumatic Waste Collection System and a Door-to-Door System,” *Waste Management*. 32 (10) 1775–1781

Related Companies, 2015, “Hudson Yards Press Kit,” http://content.related.com/Lists/HYNewsAndPress/Attachments/134/Hudson-Yards-Press-Kit-6.12.2015.pdf;
“Hudson Yards, the Story,” http://www.hudsonyardsnewyork.com/the-story

Shrank, David, Bill Eisele, Tim Lomax, 2012, “2012 Urban Mobility Report,” Texas Transportation Institute, December, http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/mobility-report-2012.pdf

Teerioja, Nea, Moliis, Katja, Kuvaja, Eveliina, Ollikainen, Markku, Punkkinen, Henna, Merta, Elina, 2012, “Pneumatic vs. Door-to-Door Waste Collection Systems in Existing Urban Areas: A Comparison of Economic Performance,” *Waste Management*, 32 (10) 1782–1791, http://dx.doi.org/10.1016/j.wasman.2012.05.027

Acknowledgements

This research is supported by the Volvo Research and Education Foundations through the MetroFreight Center of Excellence and the City University of New York's University Transportation Research Center, Region 2. Data was provided by MariMatic Oy; Envac, A.B.; Albert Mateu of Green Bending, S.L.; Thomas Erickson of Rail Cents Enterprises Inc.; the New York City Department of Sanitation; and the Related Companies. All errors and omissions are the responsibility of the authors.

APPENDIX

Table A-1. Selected Pneumatic Waste-Collection Facilities

Year*	Country	City	Project	Type	Owner	Manufacturer
1961	Sweden	Stockholm	Solleftea	Hospital	Private	Envac
1975	USA	New York	Roosevelt Island	New develop.	Public	Envac
1972	germany	Munich	Olimpic Village	New develop.	Public	Envac
1992	Spain	Barcelona	Olimpic Village	New develop.	Public	Envac
1997	Sweden	Stockholm	Hammarby Sjostad	New develop.	Private	Envac
2004	Spain	Barcelona	Forum 2004	New develop.		Ros Roca
2004	Malaysia	Kelangor	Royal Malaysian Customs Kelana Jay	New develop.	Private	Stream
2005	Spain	Barcelona	Sta. Caterina	Retrofit	Public	Envac
2008	UK	London	Wembley	New develop.	Private	Envac
2009	Singapore	Singapore	Resort World Sentosa	New develop.	Private	Stream
2010	UAE	Abu Dhabi	Marina Square Reem Island	New develop.	Private	Stream
2011	Spain	Pamplona	Pamplona	Retrofit		Ros Roca
2011	USA	Denver / Colorado	Centura St. Anthony Hospital	Hospital	Private	Transvac
2011	USA	Seattle, Washington	Swedish Medical Center	Hospital	Private	Transvac
2012	France	Romainville	Romainville	Retrofit	Public	Envac- veolia
2012	Finland	Tampere	Vuores	New develop.	Public	Marimatic
2012	Spain	Barcelona	22@ - Llevant	Retrofit		Ros Roca
2014	Canada	Quebec	La Cite Verte	New develop.		Envac
2012	Malaysia	Johor	Tropez Residences	New develop.	Private	Stream
2014	UAE	Abu Dhabi	Yas Mall	New Mall	Private	Stream
2014	Malaysia	Selangor	Airport KLIA2	New develop.		Stream
2014	USA	Chicago, Illinois	Rush University Medical Center	Hospital		Transvac
2015	Canada	Toronto	Humber River Hospital	Hospital		Transvac
2015	Saudi Arabia	Mecca	Masjid al haram	New develop.		Marimatic
2015?	France	Vitry-sur-Seine	Vitry-sur-Seine	Retrofit	Public	Ros Roca- Sita
2015	Quatar	Doha	Barwa Financial District	New develop.	Private	Stream
2016?	Finland	Vantaa	Marja-Vantaa	New develop.	Public	Marimatic
2016?	France	Saint-Ouen / Paris	ZAC des Docks	New develop.	Public	Ros Roca- Sita
2016?	France	Paris	Clichy-les-Batignolles.	New develop.	Public	Envac - Veolia
2016	Sweden	Linköping	Bo2016	New develop.	Private	MariMatic

*Start of operations

Source: ClosedLoops, 2015

Table A-2. Materials Handled by Pneumatic System, By Inlet Fraction; Materials Not Handled

Included in 3-Inlet Pneumatic System		
Recycling	Recyclable paper (non OCC)	Bags/kraft; news; ledge; computer, mags/catalogues, phone bks, misc.
	Recyclable glass	bottles/containers
	Recyclable metal	cans, other metal
	Recyclable plastic	PET, HDPE, #3-#7 bottles/conts; bags, indust'l pkg film, film prods
Organics	Food waste (non-grease)	food waste
Refuse	Composite paper	
	Flat glass, composite glass	
	Composite metal	
	Plastic trash bags	
	Plastic film, other	
	Plastic durable items	
	Composite plastic	
Excluded From Pneumatic System		
OCC		
grease		
electronics		
C&D waste		
yard waste		
carpet		
special (bulk, medical,etc)		
household hazardous		
Notes:		
OCC=Old Corrugated Cardboard		
Composite=Materials made of more than one material, making the predominant material NR		

Table A-3. Truck Collection: Best-Case Status Quo v. Zoned

	Best-Case Status Quo	**Trucks, Zoned**	***Ratio Zone/BCSQ***
Tonnes	8,226	8,226	*100%*
Truck Kilometers	66,091	29,702	*45%*
Barge Kilometers	47	417	*894%*
Diesel Fuel (Liters)	42,242	25,761	*61%*
Combined Energy (Btus)	1,550,003,171	945,271,478	*61%*
GHG (Tonnes)	114	70	*61%*
Capital Cost	$2,081,101	$2,080,785	*100%*
Operating Cost	$1,076,259	$1,632,246	*152%*
Equivalent Annual Cost	$1,543,731	$2,099,646	*136%*

Table A-4. Pneumatic Network Specifications								
Distance from terminal at W 34th St & 11th Ave (incl. branch pipe)						**Waste Volumes Per Day**		
Location	Meters	El.. above grade (m)	inlet type/size m3	Input period	Large bag (>35 liter)		**kg/day**	**m3/day**
High Line: set of 3 inlets 1 org, 1 ref, 1 recy every 240m/ 800ft						**(public park) assume equal use across inlets, waste type: pedestrian litter, food & beverage containers**		
Inlets 1-3	168	0.0	Poste	10:00 - 19:00	no	Recycling (mixed, no OCC)	790	8.8
inlets 3-6	411	4.6	Poste	10:00 - 19:00	no	Food waste	360	1.8
inlets 6-9	1143	7.6	Poste	10:00 - 19:00	no	Refuse	524	7.0
inlets 10-12	1631	7.6	Poste	10:00 - 19:00	no			
inlets 13-15	1143	7.6	Poste	10:00 - 19:00	no			
inlets 16-18	1387	7.6	Poste	10:00 - 19:00	no			
inlets 19-21	1631	7.6	Poste	10:00 - 19:00	no			
inlets 22-24	1875	7.6	Poste	10:00 - 19:00	no			
inlets 25-7	2118	7.6	Poste	10:00 - 19:00	no			
Chelsea Market: 2 waste rooms at High Line level: set of 3 tanks						**(ofc, restaur)assume equal use across waste rms**		
recycling tank 1			15m3	end of shift	yes	Recycling (mixed, no OCC)	2765	30.7
organics tank 1			5m3	end of shift	yes	Food waste	2711	9.0
refuse tank 1	2178	7.6	10m3	end of shift	yes	Refuse	1722	10.8
recycling tank 2			15m3	end of shift	yes			
organics tank 2			5m3	end of shift	yes			
refuse tank 2	2293	7.6	5m3	end of shift	yes			
Branch pipe (lm)	183							
85 10th Ave: 1 waste room at High Line level: set of 3 tanks						**(office, restaurants)**		
recycling tank 3			15m3	end of shift	yes	Recycling (mixed, no OCC)	1507	16.7
organics tank 3			5m3	end of shift	yes	Food waste	1835	6.1
refuse tank 3	2176	7.6	10m3	end of shift	yes	Refuse	1154	7.2
Branch pipe (lm)	61							
76 11th Ave: 1 waste room for com waste HL level, 2 sets of res waste chutes, valve at HL level						**(Retail, Office, 300-unit Resident'l bldg, Hotel)**		
recycling chute 1			Chute	morning, evening	no	Recycling (residential)	141	1.6
organics chute 1			Chute	morning, evening	no	Food waste (residential)	206	1.0
refuse chute 1	1999	7.6	Chute	morning, evening	no	Refuse (residential)	169	2.3
recycling chute 2			Chute	morning, evening	no	assume divide above by 2		
organics chute 2			Chute	morning, evening	no	assume divide above by 2		
refuse chute 2	1954		Chute	morning, evening	no	assume divide above by 2		
recycling tank 4			10m3	end of shift	yes	Recycling (mixed, no OCC)	828	9.2
organics tank 4			5m3	end of shift	yes	Food waste	578	1.9
refuse tank 4			5m3	end of shift	yes	Refuse	553	3.5
Branch pipe (lm)	76							
511-525 W 18th St.: 1 waste room at HL level fed by 1 set of res waste chutes						**(40-unit Residential building)**		
recycling chute 3			Chute	morning, evening	no	Recycling (residential)	19	0.21
organics chute 3			Chute	morning, evening	no	Food waste (residential)	28	0.14
refuse chute 3	1893	7.6	Chute	morning, evening	no	Refuse (residential)	23	0.18
Branch pipe (lm)	21							
Javits Center: 1 waste room adjacent to terminal with tanks						**(Convention Center)**		
recycling tank 5			15m3	end of shift	yes	Recycling (mixed, no OCC)	2441	27.1
organics tank 5			10m3	end of shift	yes	Food waste	1486	7.4
refuse tank 5	3.0	0.0	10m3	end of shift	yes	Refuse	2759	22.1
refuse tank 6			10m3	end of shift	yes			
Branch pipe (lm)	3.0							
Notes:								
Waste Densities								
Park (loose waste/litter	kg/m3	ton/m3	ton/cy					
Recycling (park)	90	0.10	0.13					
Organic (park)	200	0.22	0.29					
Refuse (park)	75	0.08	0.11					
Residential								
Recycling (residential)	90	0.10	0.13					
Organic (res, conv. cent	200	0.22	0.29					
Refuse (res, conv. cente	125	0.14	0.18					
Commercial								
Recycling (commercial)	90	0.10	0.13					
Organic (commercial)	300	0.33	0.43					
Refuse (commercial)	160	0.18	0.23					

Table A-5. Total Pneumatic System Capital Costs

	Units	Unit Cost (d)	Cost (d)
Pipe Network			
trunk pipe, lm (a)	2118		
trunk pipe installation under HL(b)			
branch pipe	1130		
Input Points			
15m3 tanks	5		
10m3 tanks	4		
5m3 tanks	9		
Total Tanks	*18*		
poste inlets for refuse	9		
poste inlets for recycling	9		
poste inlets for organics	9		
Total Inlets	*27*		
chutes for refuse	3		
chutes for recycling	3		
chutes for organics	3		
Total Chutes	9		
Total Formators	0		
Terminal Equipment			
cyclone, recycling	1		
cyclone, refuse	1		
compactor	3		
air pump	1		
air compressor	1		
control system	1		
air filter	3		
triverter valve	1		
bridge crane	2		
equipment costs			
Terminal Installation Cost			
Components			
Engineering			
Project Management (700 hours)			
Installation			
Supervision			
Commissioning			
Subtotal			$6,303,500
Freight, import taxes, local codes			$630,350
Contingencies			$945,525
Terminal Facility	1	$650,000	$650,000
TOTAL			**$8,529,375**
Sources:			
Costs of pneumatic installation from MariMatic Corp. and Albert Mateu, Green Bending, 6-12-15, 6-14-15			
Bridge crane: http://www.allcostdata.info/browse.html/146600010/Overhead-bridge-cranes			
30yr bond term and 4% interest rate assumptions based on DSNY E 91st St MTS actuals, http://www.ibo.nyc.ny.us/iboreports/2014e91stwtsLetter.pdf, App. A			
DSNY Cost Structure worksheet: Manual Capex back-calculated from per-ton debt service, based on DSNY refuse-collection costs			
Notes:			
(a) 300mm composite			
(b) Terminal and trunk line capex refers to system equipment and installation (but does not include installation costs inside participating buildings or within the HL park)			
(c) No containers are included in the pneu system costs because the container type and number varies on the haul type (truck or rail); container costs are therefore included oi the transport capex and opex. A cyclone for organic is not included in the system costs because the organics are injected directly into the shipping container, which is customized to include an air-filtration system.			
(d) All costs 2015$			

Table A-6. Pneumatic System Operating & Maintenance Costs					
(Including On-going Component Replacement)					
	Units	**Unit Cost**	**Cost**		
Personnel (a) (b)	1.7	$149,804	$250,586		
Vehicles		$12,000	$12,000		
Supplies		$3,500	$3,500		
Spare Parts		$18,000	$18,000		
Electric Power kwh (c-f)	453,365	$0.06	$28,071		
kw (c-g)	180	$23.83	$4,289		
Total Electricity			$32,360		
Misc		$6,000	$6,000		
Equip/Component Replacement		$50,000	$50,000		
TOTAL			**$372,446**		
Total Tn/Y; $/Tonne	8,226	$45.28			
Notes:					
(a) 1.5 employee 8h/day from Monday-Friday and 1 employee 4h Sat & Sun /52 wks/year					
Total Annual Weekend Hours	Day Eq	Work Days/	Portion of a Shift		
416	52	301	0.172757475		
(b) Typical DSNY Stationary Engineer Salary					
2015$					
$149,804					
(c) DSNY Electricity Rates Inflated to 2015$:					
Cost Factors	DSNY Actual, Rate as of April, 2012			2015$	
kwh @	$0.06			$0.06	
kw @	$23.12			$23.83	
(d) NYC DCAS, “Core Report, Facility-Level Energy Cost, Usage, and CO2e Emissions," 4-2011.					
(e) Donald Porter, DSNY Bureau of Building Mgt, to Steven Brautigam, DSNY Asst. Comr., Envi. Affairs, 2-11-13					
(f) Brautigam to Miller, 1-28-13					
(g) KW calculation:	2 Blowers @ 55 kw ea		110		
	Other Cons. @ 70 kw		70		
		Total kw	180		

Table A-7. Rail Factors				
Capex	**Units**	**Cost/Unit**	**Cost 2015 $**	**Useful Life (Ys)**
Track and installation (ft)	1000	$300	$300,000	50
Container purchase	30	$20,000	$600,000	7.5
Total			**$900,000**	
Opex				
Car haul cost/yr	156	variable	$189,800	
Car lease/yr	8	$5,000	$40,000	
Fuel cost	1669	$3.15	$5,256	
Track maintenance		$2.00	$2,000	
Subtotal			*$237,056*	
Container maintenance		$3,508.77	$105,263.16	
Total			**$342,320**	
Units Needed				
Pickups/Wk	1			
Containers/Wk	8			
Cars/wk	3			
Containers/wk adjusted for peak factor	11			
Cycle time, days	9			
Containers needed	30			
Flatcars needed	8			
Notes				
Ref 1 Container Useful Life Ys	10			
Ref 1 #containers	3324			
Ref 1 Cont. Maint.$/Y	$13,125,000			
Ref 1 Maintenance/Y/Container	$3,949			
Ref 1 Tot Cont Capex/Opex	$74,812,500			
Ref 1 cont maint % tot cost	0.18			
Wks/Y	52			
Opex: Assume rail transfer operations are handled by terminal staff				
"Train contract" includes use of track, crew, locomotive				
Haul cost/carload recycling/organics	$1,600			
Haul cost/carload refuse	$450			
Container life=average of the values in Refs 1 and 2 below	7.5			
Sources				
Ref 1: Container life, maintenance cost (derived as ratio of capex): Transload America, "Baled Waste for Los Angeles County," 8-20-2009,				
Ref 2: Container, car factors: RI Dept. of Environmental Management, 3-28-03, http://www.dem.ri.gov/programs/ombuds/outreach/integsw/econ/pdf/railhaul.pdf, inflated to $2015				
Fuel price: US Energy Information Administration, diesel, East Coast, Central Atlantic region, June, 2015, http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epd2d_pte_dpgal_w.htm				
Rail factors (car haul, lease, cycle times, track installation, number of containers) from Thomas Erickson, RailCents, personal communication, May 7, June 6, and June 12, 2015				

Table A-8. Summary of Input Values Used in Calculations				
Truck Collection Factors	cy	m3		
Rear-load packer, DSNY/Private (a)	25.0	19.1		
Rear-load packer, Parks (b)	16.0	12.2		
Private Ref:Assumed avg wt refuse collected by private carters w/ dense routes	13.0	9.9		
Private Rcy:Assumed avg wt of recycling collected per load	10.0	7.6		
Private Org:Avg wt of organics collected in custom rear-loader trucks	13.5	10.3		
DS Rcy:Assumed avg wt of recycling collected in DSNY Trucks©	5.1	3.9		
DS Ref/Org:Assumed avg wt refuse or organics collected in DSNY Trucks(a)(d)	12.7	9.7		
Park Ref: Assumed avg tons of refuse collected in Parks Trucks (b)	5.4	4.1		
Sources:				
(a) New West Technologies, LLC, "Multi-Fleet Demonstration of Hydraulic Regenerative Braking Technology in Refuse Truck Applications," 12-2011, p. 19				
(b) http://www.nycgovparks.org/greening/sustainable-parks/fleet, accessed 6-10-15				
(c) NYC Mayor's Office of Operations, "Mayor's Management Report, FY2013," p. 57, http://www.nyc.gov/html/ops/downloads/pdf/mmr2013/dsny.pdf, accessed Jun 2015				
(d) Rate in M4 district (which is higher than NYC avg): Citizens Budget Commission, FY2012, http://interactive.cbcny.org/maps/household-refuse-collected-truck-shift-nyc				
Baseline Annual Opex Cost Rear-loader Collection from Residential Bldgs	**Cost/T**	**Cost/Tonne**		
Recycling	$174	$158		
Organics	$174	$158		
Refuse	$174	$158		
Source (a):				
http://docs.nrdc.org/cities/files/cit_08052801A.pdf, accessed 12-12-11				
(a) p23, Table 4c without recycling revenues (with DSM adjustments, which do not include correcting for the fact that all enforcement costs are inappropriately assigned to the recycling budge and do not include parallel adjustments UTRC would recommend related to collection, e.g., not charging all Bureau of Waste Prevention, Reuse, and Recycling costs, which include a waste composition study and public education initiatives, along with processing costs for recyclables, to the cost of collecting recyclables, while not apportioning items that are related to collection, such as revenues from enforcement				
Container Sizes	**cy**	**m3**	**ft*ft*ft**	**m*m*m**
RoRo Containers	43	33	20*8*8.5	6.1*2.4*2.6
Rail Containers	62	47	20*8*12.5	6.1*2.4*3.8
Barge Load Factor	**Tons**	**Tonnes**		
Avg recyclable load/barge	500	454		
Source:				
Communication from Thomas Outerbridge, general manager, Sims Metal Management, NYC, 5-18-2015				
Barge Fuel Efficiency (Barge Ton Miles/Gallon, Barge Tonne Kilometers/Liter)	**BTM/G**	**BTK/L**		
Source:	576	244.9		
Kendell W. Keith, TRC Consulting, Ltd, "Maintaining a Track Record of Success: Expanding Rail Infrastructure to Accommodate Growth in Agriculture and Other Sectors," 1-2013, Table 3, http://unitedsoybean.org/wp-content/uploads/2013/07/Rail-Study-Maintaining-a-Track-Record-of-Success-January-20131.pdf, accessed 6-11-15				
Pneumatic Terminal Compaction Factors (kilogram/meter)		**kg/m**		
Refuse		500		
Recycling		350		
Organics		500		
Source:				
Envac FAQ, 3-2012, p. 7				
Projected Rail Operations				
Shortline railroad with equipment based at an interchange at Spuyten Duyvil, Bronx, sends a locomotive to the pneu terminal as convenient, but at least 1x/wk, brings the 3 kinds of carloads to Spuyten Duyvil and leaves them there for the interchange railroad to pick up and return				
Interchange railroad takes organics and recycling cars to Fresh Pond Yard, Queens for interchange with NY&A RR, picks up empty cars, takes back to SDI				
NY&A takes filled organics cars to pre-processor at 123 Varick Ave., Queens, picks up empties and returns them to Fresh Pond Yard				
NY&A takes filled recycling cars to MRF at 29th St & 2nd Ave, Bklyn, picks up empties and returns them to Fresh Pond Yard				
Rail Fuel Efficiency (Route Ton Miles/Gallon, Route Tonne Kilometers/Liter)	**RTM/G**	**RTK/L**		
For loaded cars	400	170		
For empty cars	195	83		
Avg	**298**	**126**		
Source:				
"Analysis of Railroad Energy Efficiency in the United States," 5-2013, p. 56, http://www.mountain-plains.org/pubs/pdf/MPC13-250.pdf				
CO2equivalent Factors (Tons CO2/Gallon, Tons CO2/Liter)	**TCO2/ir**	**TnCO2/L**		
Tons CO2/gal (NYC standard for diesel trucks, 2014)	0.01127	0.0027		
Tons CO2/gal (NYC standard for diesel locomotive, 2014)	0.01066	0.0026		
Tons CO2/gal (NYC standard for ships & boats, 2014)	0.01125	0.0027		
Tons CO2/kwh (NYC standard for electricity generation, 2014)	0.00034	0.0001		
Source:				
NYC standards for diesel trucks, diesel locomotives, ships & boats, electricity generation, 2014				