

Feasibility of Underground Pneumatic Freight Transport in New York City

Final Report

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SUMMARY

The purpose of this project is to investigate the feasibility of using the modern technology of pneumatic capsule pipeline (PCP), which has been used successfully in Japan, for underground freight transport in New York City. Through a detailed assessment of the technology development, it was found that twin lines of PCPs of various sizes and of both round and rectangular cross-sections can be used in New York City for a number of applications including but not limited to: (1) underground tunnel construction, (2) transportation of municipal solid wastes from transfer stations to a common out-of-state landfill/processing-recycling center, (3) transportation of mail and parcels from (to) the five boroughs of the City to (from) Washington D.C. and other cities along the route, (4) transporting pallet goods via a network of tunnels under New York City, (5) dispatching standard containers from (to) the container ports in New York City to (from) an inland station in rural area for inspection and intermodal transport, and (6) ferrying trucks across the Hunts Point peninsula to reduce traffic jam and air pollution caused by trucks serving the nation's largest food processing center. It was found that all the aforementioned six potential applications are technically feasible by using well-proven technologies such as PCP, blowers, linear induction motors, tunnel boring machines, microtunneling, horizontal directional drilling, barcodes, and radio-frequency identification (RFID), etc. The cost of each application has also been assessed and compared with the current cost of using trucks for the same purpose. It was found that the first five of the six potential applications are more cost-effective than using trucks. In all these five cases, great savings can be accomplished by using PCP instead of trucks. The sixth potential application (i.e., the Hunts Point project) is the only one found to be uneconomical. Even so, the project can still be justified for its social and environmental benefits to the residents of Hunts Point and Bronx. The fifth application (i.e., the container dispatch PCP), is shown to have great values for port security, and hence can be justified on either security or economic grounds, or both. All six applications were found to have great value for reducing air pollution, traffic jams, and accidents caused by trucks, and for economic development of the New York City. Should these six potential applications be fully implemented in the future, New York City could expect a reduction of truck usage by as much as 70%, which would greatly benefit the City in a number of ways. In conclusion, this study finds that the new technology of PCP is both technically and environmentally feasible for a variety of usages in New York City, and future use of this new technology can drastically cut the number of trucks needed to enter the City, resulting in reduced traffic jam, accidents and air pollution, enhanced transportation safety and security, and economic development -- creation of a new industry and a great number of new jobs in the City. Because PCP uses electricity instead of diesel fuel, the use of PCP in New York City also reduces the consumption of imported oil. This report provides detailed analysis and justification for the beneficial use of PCP in New York City, and provides a blueprint for implementation. The study was sponsored by the New York State Energy Research and Development Authority (NYSERDA).

KEY WORDS

Capsule pipeline, freight pipeline, freight transport, New York City, pallet freight, pneumatic capsule pipeline, port security, traffic jam, tunneling cost, underground freight transport.

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INTRODUCTION

1.1 PROBLEM STATEMENT

New York City, being one of the largest cities in the world, suffers from severe traffic congestion on streets and highways. The congestion hurts the City in many ways including: (1) loss of productivity due to extra time spent in travel to and from work by passengers and delays in freight movement through the City; (2) accidents caused by vehicles (trucks and cars) that clog the streets and highways, which in turn cause death and injury to individuals on the street and damage to properties (vehicles); (3) waste of energy (diesel fuel) by trucks tied down in the slow-moving traffic on the City's streets, (4) noise caused by cars and trucks on congested streets; (5) air pollution caused by cars and trucks tied down in traffic jams and moving slowly through streets and highways; (6) increased security risks due to the possible use of trucks or cars as bombs by terrorists as happened to the World Trade Center in 1993, and the difficulty in evacuation of people and vehicles from congested streets following any terrorist attack.

The aforementioned transportation problems are highly detrimental not only to New York City and New York State, but also to the rest of the nation and the world, due to the large number of tourists from other states and countries visiting New York City each day. Even for those U.S. citizens who do not visit New York City, this is an important issue because of their kinship to and patriotic feelings toward New York as demonstrated by the enormous outpour of concern and sympathy from across the nation following the September 11 terrorist attack, and because of state and national revenues (state and federal taxes) spent on the City. Therefore, reduced traffic congestion on the streets and highways of New York City is important to the City, the State of New York, the nation and even the world.

1.2 SOLUTION TO PROBLEM

A multiple of approaches and technologies must be used to solve New York City's transportation problems. The approaches include increased use of bicycles, increased use of mass transit, increased use of rail for passenger and freight transport, limiting truck delivery to off-peak-traffic hours, reduced time for street repair which blocks traffic, building additional tunnels across the Hudson River to alleviate traffic to and from New Jersey and so forth. New technologies should also be mobilized to help solve the problem. They include the use of intelligent transportation systems (ITS), more efficient and less polluting automobiles, increased use of trenchless technologies for the construction and repair of underground infrastructures including sewers, utility lines, fiber optics, etc. [1].

Pneumatic capsule pipeline (PCP) is an important new technology currently not used or considered by transportation authorities and transportation planners for solving the aforementioned traffic congestion problem in New York City and in other cities in the nation. This new technology has not been used nor considered for use because only a handful of transportation professionals know what PCP is and what it can do. Even fewer know how to design it. New York City is the most appropriate city in the United States to consider this new technology, not only due to the severe traffic congestion problem that exists in the City, but also due to the great potential that this new technology has in energy conservation, reducing air and noise pollution, and enhancing the City's ability to cope with future terrorist attacks. Besides, New York City has extensive experience in using underground tunnels for subways, highways, sewers and utility lines, unmatched by other cities in the nation. Such experience facilitates trenchless construction of underground PCP systems.

1.3 PURPOSE OF PROJECT AND SCOPE OF WORK

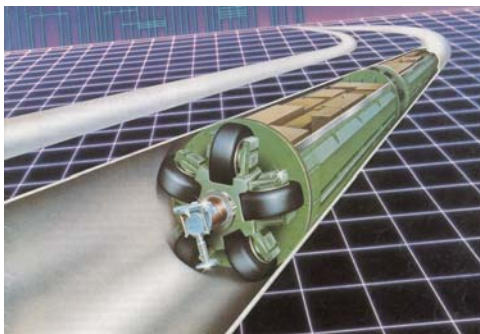
The **purpose** of this research project is to evaluate the feasibility of using the modern PCP technology and other complimentary enabling new technologies for possible use in New York City for underground freight transport, as a means to reduce the City’s reliance on trucks and to alleviate the City’s traffic-related problems. Both the technical and economic feasibilities of using PCPs in New York City are addressed. Social and environmental benefits that can be derived from using PCP for freight transport in New York City are also analyzed.

The **scope of work** of the project includes: (1) a detailed assessment of the modern technologies needed for using PCPs in New York City, (2) identifying and planning various potential applications of PCPs in New York City, (3) analysis and preliminary design of the PCP system involved in each proposed application, (4) a determination of the approximate cost and the cost effectiveness of each proposed application, and (5) analysis of the environmental and social benefits of each proposed application.

The study provides the basic information needed for transportation planners in New York City and New York State to make detailed plans for implementing the most advanced PCP systems in the City for the benefit of its eight million residents.

1.4 TECHNOLOGY DESCRIPTION

PCP (Pneumatic Capsule Pipeline) is the modern and high-tech version of the “**pneumatic tubes**” used over half a century ago in New York City and many other major cities around the world for underground transportation of mail, parcels and many other goods [2]. The current advanced PCP systems, used successfully in Japan [3, 4], utilize wheeled capsules (vehicles) to transport freight through large-diameter underground pipes of the order of 1-meter diameter. Air is blown through the pipe to move the capsules. The system can transport hundreds of cargoes—anything of a size smaller than the pipe diameter. By using modern technology such as high-speed computers and special scanners, the system is highly automated and efficient. Two types of PCP have been developed and used successfully in Japan, one using circular pipes and the other using rectangular conduits—see respectively (a) and (b) in Figure 1 below.



(a) Round (circular) PCP



(b) Rectangular or square PCP

Figure 1. Pneumatic capsule pipeline (PCP) systems developed by and Used in Japan (Courtesy of Sumitomo Metal Industries, Ltd.)

In this study, both the circular and the rectangular types of PCP have been considered for possible use in New York City. The circular type is more suitable for smaller diameter PCPs that use pipes up to approximately 1 m (3.28 ft) in diameter to transport small objects such as crushed minerals, mail, small parcels, groceries and solid waste (garbage). On the other hand, the

rectangular type, using conduits of approximately 1 m by 1 m or larger cross sections, is for transporting packaged large objects including boxes, crates and pallets. As will be seen later in this report, large objects such as the containers carried by trucks, and even the trucks themselves, can be transported by PCPs of very large cross section. This study also explored a third configuration of PCP: a hybrid system that uses box-shape capsules moving in underground tunnels of circular cross sections. This hybrid system is practical only for underground tunnels of circular cross sections, constructed by using modern tunnel boring machines, which result in tunnels of circular cross sections.

This research project uses a novel concept or approach to solve traffic congestion and security problems in large cities—an approach hitherto not seriously considered or studied by any transportation agency in the United States. The study is innovative because of the new technologies used in designing and planning the best system of PCPs for New York City. These new technologies include the most modern and advanced PCP systems used only in Japan so far [3, 4], an electromagnetic pump (linear induction motor) which is an improved capsule propulsion system developed recently at the Capsule Pipeline Research Center (CPRC)¹ of the University of Missouri [5], trenchless technologies for constructing PCPs [1], and use of RFID (Radio Frequency Identification) systems and other modern high-tech equipment for monitoring and automatic control of PCP systems [6]. Success in this study enables the New York City to use the most advanced PCP systems in the world for future freight transport, benefiting the City and the State.

1.5 CURRENT R & D

Current R&D in PCP is centered in Japan. The Sumitomo Metal Industries, Ltd. in Japan has developed and used PCPs of both round and rectangular cross-sections for transporting minerals [3], for constructing long tunnels for bullet trains [4], and for highway-related projects [4]. The Company's current effort is focused on developing and using a vertical PCP system to transport and dispose of solid waste deep underground [7], and ways to improve current systems used in Japan. In the United States, research in PCP exists in three places: (1) The Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia is studying the use of linear induction motor (LIM) to power PCP [5]. Note that LIM is the same technology used for powering magnetically levitated high-speed trains, and for accelerating modern roller coasters. The current PCP systems use blowers (fans) to blow air through pipes; the moving air in turn propels the capsules. Use of LIMs instead of blowers to propel capsules has many advantages such as it simplifies the PCP system design, reduces system costs, and enables capsules to move through pipes of any slope, including vertical. (2) Researchers at the University of Minnesota are also studying the use of LIM to power large diameter capsules in conduits imbedded under highways for future freight transport [8]. (3) Another recent research initiative in PCP is a project to use a linear synchronous motor, which is a technology similar to LIM, to power a PCP for transporting phosphate ore [9]. The project was sponsored by the Florida Phosphate Research Institute. Finally, at present (2004) Freight Pipeline Company in Columbia, Missouri, is undertaking R & D sponsored by the U. S. Department of Energy, to develop an advanced PCP system based on LIM specifically for conveying minerals and mine wastes [10].

¹ CPRC was established in 1991 by the National Science Foundation (NSF) as a State/Industry University Cooperation Research Center (State/IUCRC), and was supported by NSF until 2000.

1.6 RELATION TO REGIONAL TRANSPORTATION PLAN

The future of NYC's transportation is governed by the Regional Transportation Plan. The current (1999) version of the Plan places emphasis on managing demand and focusing on alternative modes of transportation, such as transit, walking, bicycling, ferry service, ridesharing (carpooling), and helping people to make smarter travel choices through the application of new intelligent transportation systems (ITS) technologies. The plan also cites the undesirable increase in the number of trucks for freight transport in the Region, and proposes various measures to reverse the trend, such as by constructing a dedicated rail freight tunnel across the Hudson River, and/or reactivation of the Poughkeepsie Railroad Bridge. This shows that the solution to NYC's transportation problem, as proposed in this study, is consistent with the approaches used in the Regional Transportation Plan even though PCP was not mentioned in it. It is believed that PCP was not mentioned in the 1999 Plan because this technology, being very new, was insufficiently known to the planners of the 1999 Plan. Besides, no study to confirm the technical and economic feasibility of using PCP in New York City had been conducted prior to that time. The Regional Transportation Plan is a document updated every three years. However, due to the September 11, 2001 attack on the World Trade Center, the 2002 Plan was disrupted and suspended. At present, the New York Metropolitan Transportation Council (NYMTC) is preparing for a new plan for publication in 2005. With the completion of this feasibility study in 2004 and with the promising findings of technical and economic feasibility and great potential benefits of PCP to NYC, it is reasonable to expect that the new technology of PCP will be addressed in the 2005 version of the Regional Transportation Plan.

1.7 COMPARISON TO ALTERNATIVE SOLUTIONS

Alternative solutions to the traffic jam and the related noise and air pollution problems in New York City include: more use of bicycles and mass transit, more rails for passenger and freight transport, use of intelligent transportation systems (ITS), better planning for new developments, faster repair of streets, improved coordination between various agencies dealing with constructions and other activities (such as trash pickup) that affect traffic, etc. All these measures contribute to solving New York City's problem, and should be implemented in order to provide greatest benefits to New York City. The proposed solution is not meant to replace any of these alternative solutions. Rather, it constitutes an additional and effective new means to alleviate New York City's transportation problem—a new solution hitherto unrecognized by the public and even by transportation planners of the State and the nation. A full implementation of the potential applications of PCP in New York City in the future is expected to result in at least a 70% reduction in the use of trucks for freight transport in the City. It constitutes the most effective known means to reduce the use of trucks in New York City.

1.8 SUMMARY OF BENEFITS TO NEW YORK CITY

Implementation of the various potential applications of PCPs in New York City as discussed in this report will benefit the City and the State in the following manners:

- (1) Drastic reduction in the need for trucks and the number of trucks that clog the City's streets.
- (2) Drastic reduction in air pollution, noise and accidents generated by trucks.
- (3) More rapid delivery of goods than currently possible by trucks on congested streets.
- (4) Greater reliability in freight delivery—because PCPs are unaffected by inclement weather, traffic jams and road/street repairs.

- (5) Conservation of energy—PCP uses much less energy than trucks use in congested cities where trucks cannot operate efficiently due to traffic jams.
- (6) Reduced reliance on foreign oil—while trucks use diesel fuel, PCP uses electricity, which can be supplied by domestic energy sources, including renewable sources.
- (7) Increased security—Goods to be delivered by PCPs cannot be stolen as easily as those transported by trucks. Terrorists cannot hijack the vehicles (capsules enclosed in an underground pipeline) and use them as car bombs or truck bombs. Also, it is far more difficult for terrorists to attack an underground PCP and inflict catastrophic damage to it than to an aboveground structure such as a building or a bridge. Unlike aboveground structures, which are readily accessible by terrorists and difficult to guard against their attacks, underground PCPs are inaccessible to people except at the inlet and outlet and hence can be more easily guarded against any attack or sabotage. Furthermore, because using PCPs will result in fewer trucks clogging the streets, residents can be evacuated more readily in the event of any emergency.
- (8) Economic development and creation of jobs—Future use of PCPs in New York City will create a large number of jobs in NYC and NYS—not only engineering and construction jobs during the construction of PCPs, but also permanent jobs for running and operating the new system. Furthermore, many materials and equipment used for constructing PCPs will come from existing as well as new companies based in New York State. Because New York will lead the nation in using the PCP technology, it is anticipated that a new industry will be generated in and around NYS for the supply of the equipment, parts and engineering services needed for the rest of the nation to build PCPs in various congested cities and regions across the nation. This will bring huge and lasting benefits to NYS and NYC.

An attempt will be made later in Section 5 BENEFIT ASSESSMENT to quantify some of the foregoing benefits for each of the six potential applications to New York City.

Section 2 POTENTIAL APPLICATIONS TO NEW YORK CITY

Various potential applications of the PCP technology to New York City have been considered and evaluated in this study. They are first described in this section, and later (in the ensuing sections) assessed for their technical and economic feasibility.

2.1 TUNNEL CONSTRUCTION

New York City has a large number of underground tunnels constructed for various purposes including water supply, sewers, mass transit, highway, rail, gas and petroleum pipelines, and cables – including power cables, telephone cables, and TV cables. A good discussion of these tunnels and related underground infrastructures can be found in a number of documents including books such as [11], and Internet articles such as [12]. Some tunnels, such as Water Tunnel No.3, are under construction and will take until year 2020 to complete [13]. Also, there is an increasing need for constructing other underground tunnels in New York City for various purposes, such as the tunnels for a proposed rail system for freight [14], and a new rail system for passengers just announced by Governor George E. Pataki [15].

In the construction of large tunnels, such as Water Tunnel No. 3 which is 20 to 24 ft in diameter, trucks are used to transport construction materials into the tunnel and to transport excavated materials out of the tunnels. Because these tunnels are over 100 m underground, trucks are lowered into the tunnels and hoisted out through large vertical shafts. Using trucks for such tunnel construction is cumbersome and expensive. Besides, it causes serious safety and pollution problems both inside the tunnels and outside the tunnels near their entrances. According to [13], since 1970, twenty-four workers have lost their lives in accidents related to constructing Water Tunnel No. 3. Such tragedies and air and noise problems can be prevented or greatly reduced in the future by using PCP for conveying materials during tunnel construction, as it was done in Japan for constructing the Akima Tunnel shown in Figure 2.

The Akima tunnel is one of the world's longest rail tunnels constructed in Japan in 1997 for bullet trains. The tunnel is 8.3 km (5.2-mile) long and has a cross sectional area of 90 m² (968 ft²) approximately, for accommodating a 2-track railroad. Figure 2 (a) is a photo of the tunnel when it was first completed but before the PCP was dismantled and the railroad was constructed through the tunnel. The PCP was made of prestressed concrete panels and was used for transporting premixed concrete into the tunnel for tunnel lining, and transporting excavated materials out of the tunnel for disposal. The PCP extended outside the tunnel for about 3 km (see Figure 2 (b)) so that the excavated materials generated by the tunnel boring machine (TBM) could be transported to a nearby dump site without using other transportation means such as trucks or conveyors. The type of capsules used in this PCP is shown in Figure 3.

Note that feeding of construction materials such as premixed concrete into each capsule is through the open top of the capsule, whereas discharging the materials is by opening the bottom gates of the capsules. By extending the PCP conduit to the dump site, the excavated materials are discharged directly by capsules reaching the dump site – see Figure 4.



(a) Tunnel entrance



(b) PCP extending outside the tunnel to the dump site

Figure 2. Use of a rectangular PCP for constructing the Akima Rail Tunnel in Japan
(Courtesy of Sumitomo Metal Industries, Ltd.)

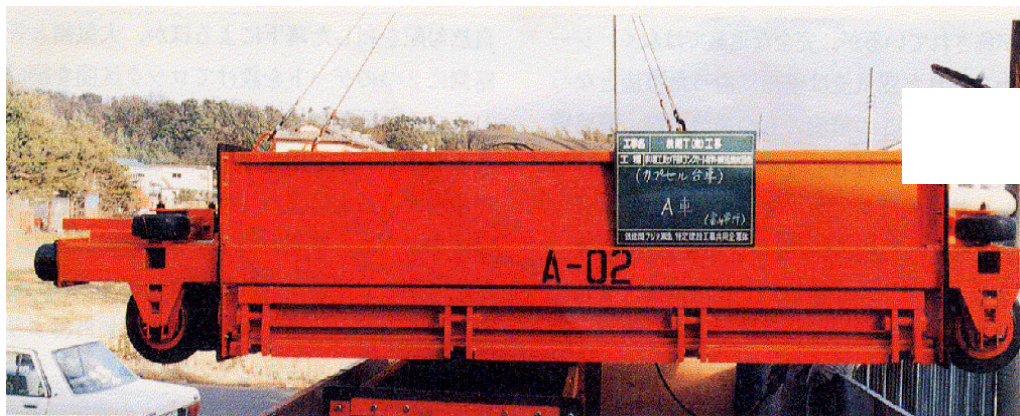


Figure 3 A capsule used in the PCP for constructing the Akima tunnel in Japan.
(Courtesy of Sumitomo Metal Industries, Ltd.)



Figure 4 Capsules reaching the end of the Akima PCP to discharge their load at the dump site (Courtesy of the Sumitomo Metal Industries, Ltd.)

The Japanese experience in using a PCP instead of rails or trucks for conveying materials during tunnel construction showed that the PCP system has a number of advantages including: (1) it has no moving part outside the pipe (conduit) and hence is extremely safe; (2) it is powered pneumatically, and hence it has no exhaust gas and causes no air pollution in the tunnel; (3) the PCP not only conveys capsules but also air, thereby serving a dual purpose – venting the tunnel while transporting solids; (4) the prime movers (i.e., the motor and the blower) are located outside the tunnel and hence do not take up the narrow space in the tunnel; and (5) the system transports materials at high speed and large quantity. For the Akima PCP, it transported excavated materials out the tunnel at the rate of $100 \text{ m}^3/\text{hr}$ ($3529 \text{ ft}^3/\text{hr}$). The only major limitation of the system is that the size of any article to be transported by PCP must be smaller than the size of the capsule opening, whose width is approximately 0.8 m or 30 inches, and length is approximately 3 m or 10 ft. Therefore, large construction materials or equipment cannot be moved in and out of the tunnel by using PCP; conventional vehicles are still needed for occasional movement of large materials and equipment in and out the tunnel. In spite of that, PCP was found to be the most cost effective way to convey the large amount of materials for constructing the Akima Tunnel.

Much of the same PCP technology used successfully in Japan for constructing the Akima Tunnel can be used in New York City for constructing underground tunnels. The only main difference between the Akima Tunnel and New York City tunnels is that the former is a cross-mountains tunnel bored at ground level, whereas New York City tunnels are bored underground. However, this difference does not present any problem to using PCP for tunneling because capsules can be easily lifted and lowered vertically by using a conventional elevator (see Sec.3.3 Vertical Capsule Transport), or a pneumatic lift system reported in [7]. Either way, it is much easier and safer to lift/lower individual capsules than to lift/lower trucks. With tunnels being bored under busy city streets, the advantage of using PCP can be further expanded by extending the aboveground portion of the PCP conduit to a less crowded location away from tunnel entrances. In doing so, the truck traffic aboveground on busy streets near tunnel entrances can also be greatly reduced.

Note that blower-driven PCPs for tunnel construction are a proven technology. It can readily be used in NYC without having to do any research or demonstration. Through proper design, a blower-driven PCP of 1 m by 1 m cross-section has sufficient capacity (throughput) for handling the materials conveying needs of large tunnels up to about 10 m (33 ft) in diameter. Information on PCP design can be found in [16] and other publications, and hence is not repeated here. However, since this technology has not been used before in the United States for tunnel construction, it may be mutually beneficial to collaborate with experienced Japanese companies for the first use of such PCPs in New York City. This will also encourage Japanese investment in the underground infrastructures of the New York City.

As will be shown later in Sec.4.1, using PCP for tunnel construction not only reduces pollution and saves lives, it also costs less than using trucks for the same purpose.

2.2 TRANSPORTING PALLETED AND OTHER GOODS (PALLET-TUBE SYSTEM)

Most of the goods delivered by trucks in New York City come on pallets or in boxes, crates or bags. It would be highly desirable to design an underground PCP system that can transport such goods. Such a system shall hereafter be referred to simply as the “pallet-tube system.” Because a standard pallet in the United States is of the size of 40-inch (1.02 m) width and 48-inch (1.22 m) length, a rectangular capsule of approximate dimensions of 1.22 m (4 ft) width, 1.22 m (4 ft) height and 3.96 m (13 ft) length will be able to carry three fully loaded pallets. Such a capsule will also be able to carry most goods contained in boxes, crates or bags. Some longer capsules can also be used in the system to carry longer objects such as pipes in 20-ft lengths. Capsules like that can run through either a rectangular conduit having an approximate cross-section of 1.52 m (5 ft) by 1.52 (5 ft), or a circular conduit of approximately 2.13 m (7 ft) diameter having a flat floor – see Figure 5. The circular conduit is chosen for New York City because it is easier to construct underground by using a tunnel boring machine (TBM), and also because it is structurally stronger than rectangular cross section. As will be shown in Section 3.5, modern tunnel boring machines (TBM) are the best suited and most economic method for constructing tunnels such as those going through the hard bedrock underneath New York City. Such machines with large rotating cutters produce tunnels of circular cross section. To modify the tunnel cross section to other shapes requires significant extra costs.

As can be seen from Figure 5, the standard capsule designed for the pallet-tube system for New York City uses steel wheels running on steel rails inside a circular tunnel that has a flat floor for the rails. This constitutes a main difference from the capsules used in Japan which use rubber tires. Steel wheels instead of rubber tires are chosen here for New York City for four reasons: (1) They have a rolling friction coefficient about 5 times smaller than that of rubber tires, thereby greatly reducing friction and saving energy; (2) capsules with steel wheels are much easier to control at branching points and in terminals, where standard railroad switching and control equipment can be used; (3) steel wheels are more wear-resistant than rubber tires, thereby minimizing wear and maintenance cost; (4) while capsules with rubber tires cannot run at high speed (more than 15 m/s) without damage caused by heat generation and temperature buildup in the tires, capsules using steel wheels can run at much higher speeds without temperature buildup. A disadvantage of using steel wheels instead of rubber tires is that noise is much higher for the former. However, this is not a serious drawback because most of the noise is generated and dissipated underground, disturbing nobody. The noise will be heard only when capsules are outside the pipe (conduit) and in a terminal (station). Even there, the noise is expected to be much less than what one hears at a subway or train station when a train passes by

or approaches the station. This is so because each capsule is much smaller and lighter than a train, and it does not emit any gas or steam because there is no powerhouse or engine on board of any capsule. The noise of PCPs comes mainly from contacts between the wheels and rails.

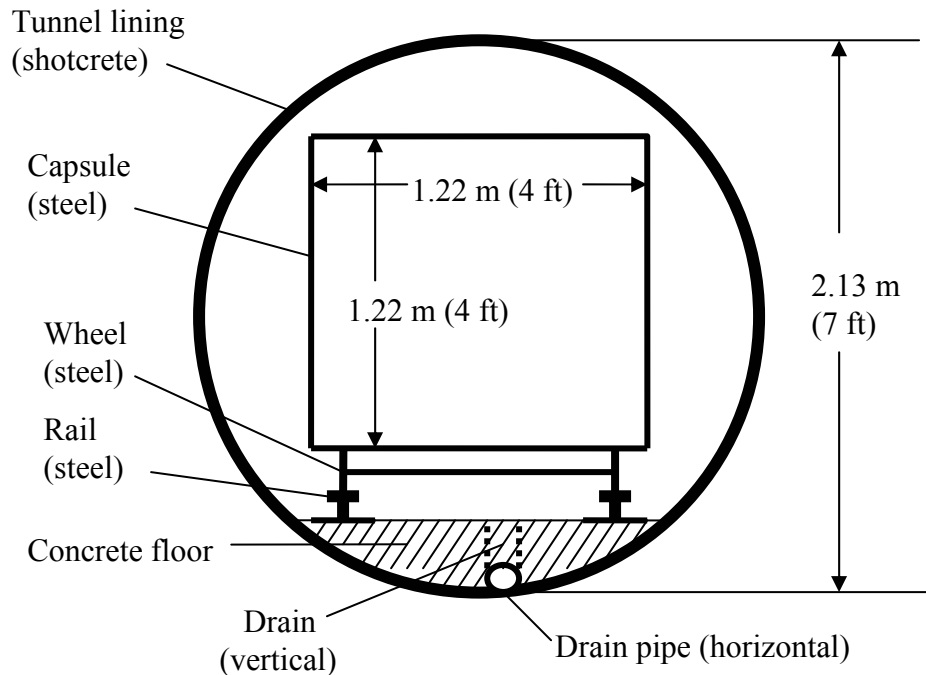


Figure 5 Cross-section of the pallet-tube PCP for New York City

Another main difference between the Japanese PCP systems and the pallet-tube PCP system is that the latter must use electromagnetic pumps instead of blowers. This is due to the complex network of conduits and the multiple inlets/outlets required for the pallet-tube system—a system similar to the current subway system in New York City. The most suitable electromagnetic pump for this application is single-sided linear induction motor (LIM) which will be discussed in detail in Section 3.2.

The pallet-tube system considered here for New York City has a large number of node points (**underground stations**), with each located about 50 m or 150 ft under a City block but serving an entire neighborhood of blocks as shown in Figure 6. The dotted lines radiating out from the underground station in four directions are horizontal tunnels of 10-ft diameter with a flat floor for movement of goods from the station to neighboring streets, using either pallet jacks or small electric vehicles. Vertical elevators are used to lift the pallet jacks and small electric vehicles to the street level, and to lower them to the underground tunnel when they need to go back to the station. Such a system enables the delivery of goods to and from various parts of the City. Dual lines are needed to accommodate freight flow in opposite directions.

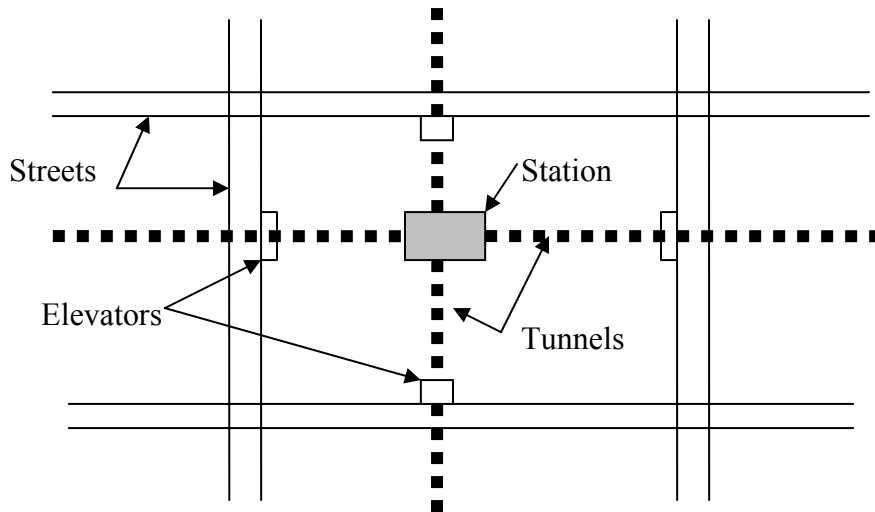


Figure 6 A pallet-tube PCP station and outlet tunnels and elevators. (Note that the station and the tunnels are underground, connected to neighboring streets by elevators.)

The layout (plan) of a typical pallet-tube **station** is shown in Figure 7. Each heavy dotted horizontal line in Figure 7 represents an approximately horizontal PCP conduit (the 7 ft diameter tunnel shown in Figure 5) imbedded in the bedrock approximately 50 m underground, and each heavy solid line represents a double-rail track on the floor of the station which is approximately 90 m underground. The station floor is kept approximately 5 m above the connected conduits so that gravity will cause the capsules to decelerate as they rise to the station platform (such as from S1 to S2), and to accelerate when injected into the line (such as from S3 to S4). Note that the PCP conduits and stations are to be placed deep underground in the bedrock in order to avoid interference with other underground structures such as building foundations, piles, sewers, water pipes, other pipelines, cables, and the subway system, which are normally found within 23 m (75 ft) of the ground surface in New York City. As shown in Figure 6, connection between each station and the streets above is by a set of four tunnels of 10 ft diameter, with their ends connected to the streets via elevators. Cargoes arriving at the station on pallets or in boxes, crates and bags can be transported by pallet jacks or battery-powered small vehicle moving through the tunnels, lifted to the street level by elevators, and then transported over short distances to neighboring stores along streets or side walks. A vertical cross section of the station is shown in Figure 8.

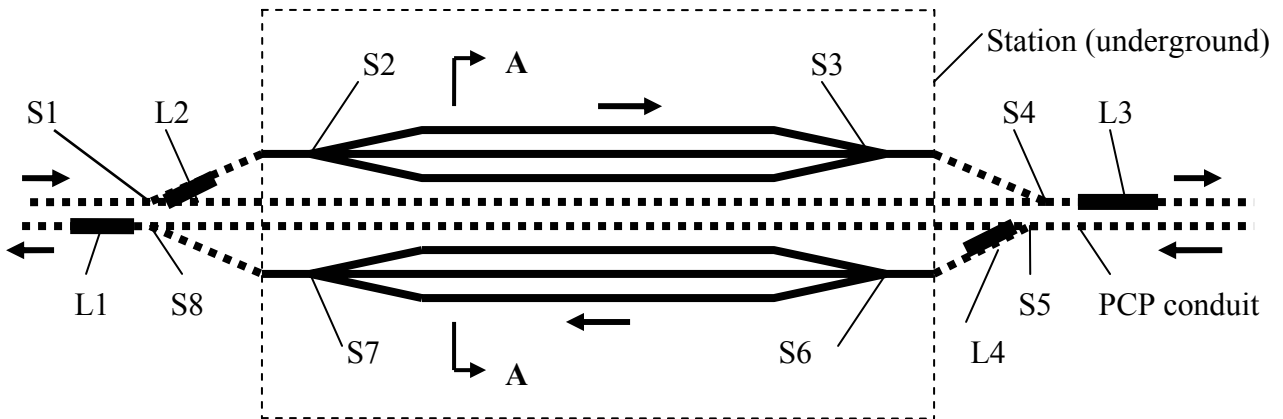


Figure 7 Layout (plan) of a typical underground station for the pallet-tube PCP

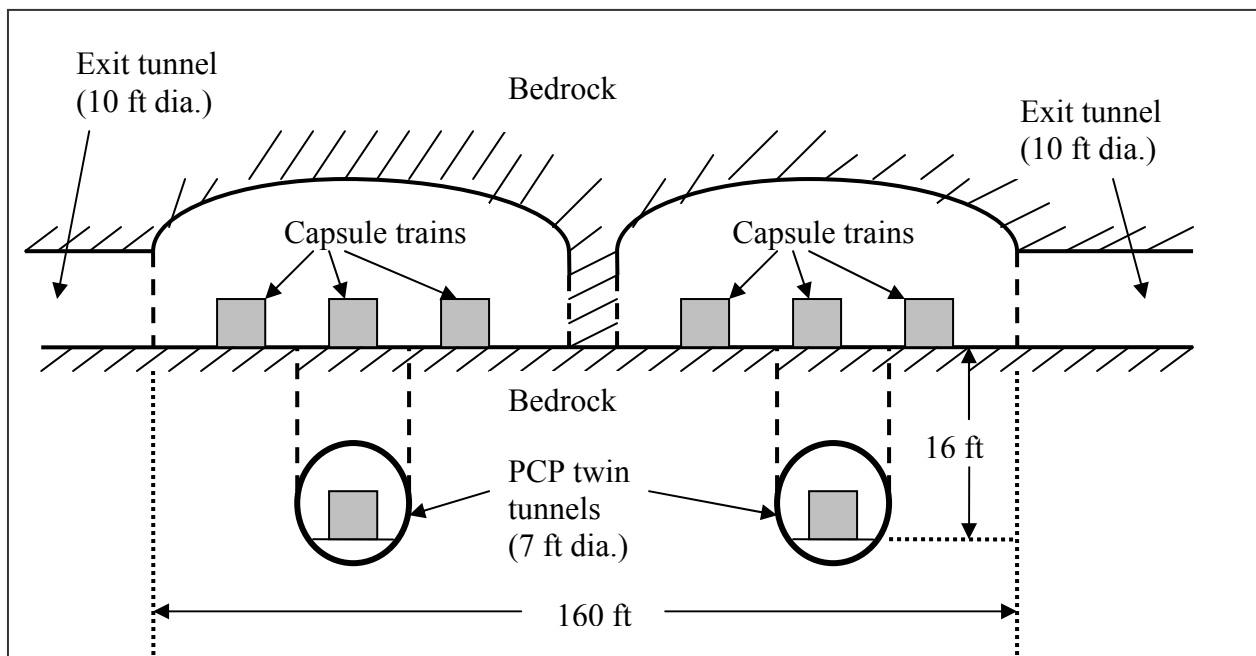


Figure 8 Sec.A-A (vertical cross section of a PCP station with layout shown in Fig.7)

As shown in Figures 7 and 8, three parallel tracks are used on each side of the station floor for simultaneous loading/unloading of capsules. S1 through S8 are switches for rails, and L1 and L2 are LIMs which are needed only at locations where the capsules have reentered the conduits. Design of the LIMs can be done in a manner discussed in [6,17]. The cross-section of the LIM will be rectangular, having a width only 20 mm wider than the outer width of the capsule. The small clearance (gap) between the walls of the capsule and the LIM is necessary to achieve large thrust and good efficiency. Single-sided LIMs will be used. The capsule walls will be made of steel having a thin aluminum cladding 1 to 2 mm thick. The capsules used in such a system can be either single capsules or capsules mechanically linked as trains, similar to the linkage of ordinary railroad trains but with only a few capsules in each train. Using short trains instead of

long trains not only reduces the length of each terminal station but also increases the frequency of goods delivery. A typical station shown in Figure 7 for 5-capsule trains will cover a floor space of be approximately 200 ft (length) \times 160 ft (width).

The pallet-tube PCP system can deliver most of the cargoes currently carried by trucks, including most cargoes inside large containers carried by tractor trailers. For such a system to work for a major city such as New York, it must use an extensive network of underground conduits having numerous inlet/outlet stations. The network should also have several intermodal freight transfer stations (“**main stations**” or “**ports**”) around the network’s outer perimeter, east of the Hudson River. At each port, trucks carrying freight headed for New York City will unload their cargoes from each container onto capsules in the port for dispatch through the underground pallet-tube network to various stations in New York City. The same trucks then return or leave the port with either empty containers, or containers loaded with a different cargo. Using such a system, trucks do not enter New York City, making the City a model for the world in freight transport. The same system can be used not only for freight transport but also for transporting municipal and industrial solid wastes generated inside New York City, for disposal or processing outside the City, by using special capsules assigned for transporting wastes. For a large city such as New York City, such a system will be very costly, but its benefits will be huge. Needless to say, the system must be carefully planned by transportation planners, and implemented step-by-step. It will take decades to build such a large and ambitious system. It is beyond the scope of this project to plan such a network for New York City in detail. All that this project has done is to show how such a system can work in large cities such as New York City, leaving detailed planning and implementation to future transportation planners.

As will be shown in Sec. 4.4, the pallet-tube system proposed for New York City not only reduces truck usage and eliminates problems caused by trucks, it can also transport freight at a cost much less than by trucks.

2.3 DISPATCHING CONTAINERS

New York City has some of the nation’s busiest ports, with thousands of containers lying on the waterfront waiting to be shipped either to inland places by trucks and trains, or to be loaded on outbound ships. The presence of such large numbers of idled containers at any harbor not only wastes the precious space at the busy harbor but also causes security concerns. Concern has heightened recently in view of possible terrorist attacks. The nation’s port authorities have been criticized for not inspecting every container shipped into the nation. To inspect every container would cause much delays and a greater number of containers waiting at each container port to be inspected, which would only exasperate the security problem. The dilemma can be solved by having a specially designed secure transportation system to dispatch the incoming containers to a less crowded inland safe place for inspection and processing by the U. S. Customs, and then for transshipment by trucks and trains to their individual destinations. This can be done by using large PCPs designed specifically for dispatching containers from one or more than one port in New York City to an inland inspection/transfer station. If a dual-tube (twin-tunnel) is used, one PCP tunnel can be used to transport the containers away from the port, and the other parallel tunnel can be used simultaneously to transport the outbound containers from the same inspection/transfer station to the port. Such a new system will not only greatly improve port security, but also eliminate the need for trucks to enter ports, thereby transforming the waterfront from a container storage yard and truck depot to a quiet and nice waterfront with

shops and restaurants for the enjoyment of the local residents and tourists. Such a system will have immense value to New York City.

The PCP system for this purpose will require the use of large underground tunnels or conduits. For the portion near the port and in urban areas, especially if crossing of the Hudson River or the New York Harbor is contemplated, a round tunnel bored in hard bedrock 100 to 150 ft below the water level is required. As soon as the tunnel reaches rural areas, it should rise to only 5 ft below ground level and then change to a rectangular cross section which can be more easily and economically constructed by using the open-cut instead of the tunnel-boring method. Since a standard container is 40 ft long, 8 ft wide and 9.5 ft high, the round tunnel for urban areas should have a diameter of 15 ft (4.57 m) approximately, using a design similar to that shown in Figure 5 except for the much larger size of the cross-section. On the other hand, the rectangular conduit portion constructed by open-cut should have a cross section of 9 ft (width) \times 11 ft (height) approximately, using a construction method similar to that evaluated in Sec.3.5(b) and illustrated in Figure 25. Each capsule used in the system should be 8.5 ft wide, 10 ft high and 42 ft long so that each can carry a 40-ft-long container, or two TEUs (Twenty-foot Equivalent Units). The capsules can be mechanically linked to form a train in order to facilitate operation.

Due to the difference in the cross-section shape of the two portions of the same PCP system, capsules without seal plates must be used which are more conducive to the use of linear induction motor (LIM) than blowers for powering the PCP system. They also can transport far more containers per hour. The maximum capacity for a blower-driven system is approximately one capsule train per 40 seconds. By using 3-capsules in each train, this translates into 270 capsules in an hour, or 2160 capsules for any 8-hour work day. In a year of 350 operating days (96% of system availability), a total of 756,000 capsules (1.5 million TEUs) can be transported through the twin-pipe system in each direction. If LIMs instead of blowers are used, the system throughput can be increased by as many as fivefold [6], which will enable the system to transport 3.8 million capsules (7.6 million TEUs) each year. It is reported that during the year 2003 the ports of New York City and the adjacent New Jersey handled a total of 4.1 million TEUs [18]. This means that a container-dispatch PCP system using LIMs instead of blowers can easily handle the entire volume of containers handled by the Ports of New York City and the adjacent New Jersey ports, with rooms for future expansion.

Figure 9 is a general layout of a typical container-dispatch PCP with a single inlet and a single outlet. Although only a single line is shown in Figure 9, twin lines will be used so that different containers can move in opposite directions simultaneously. While the inlet is on the port side, the outlet is the destination of the dispatched containers – the container inspection and transfer station located inland. Both the inlet and the outlet stations of the PCP are elevated above the natural ground level. This enables the capsules entering the PCP to accelerate due to gravity, and the capsules reaching the outlet to slow down due to gravity. Three or more parallel tracks are used at the inlet and the outlet stations to facilitate loading and unloading of cargoes.

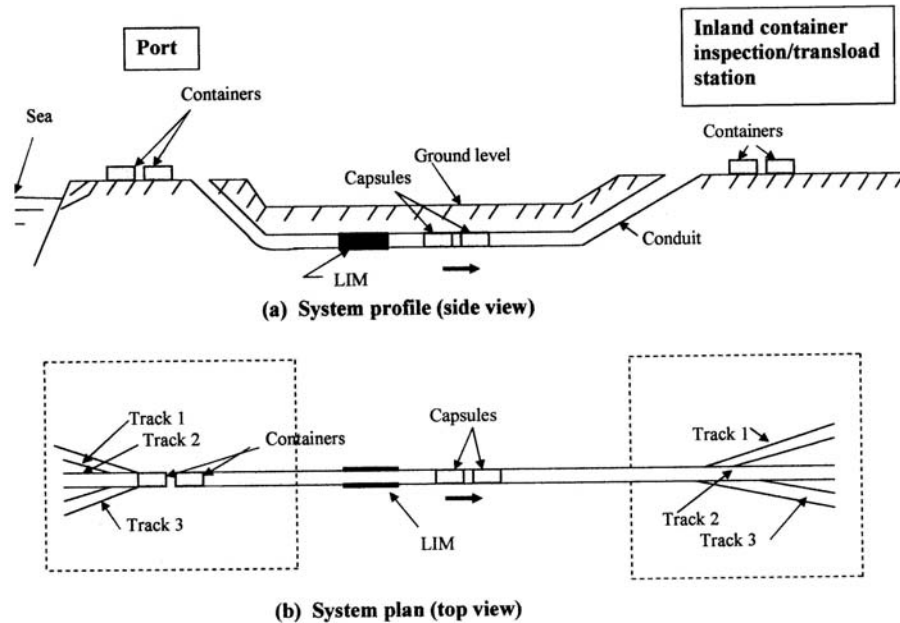


Figure 9 General layout of a PCP system for dispatching containers to and from ports

The capsules going through the line are driven by one or more LIMs (linear induction motors). A long PCP conduit may need more than one LIM placed at suitable intervals along the conduit. At each LIM station, two single-sided LIMs are used as shown in Figure 10. They are two parallel plates containing segments of coils – the stator – that generates the electromagnetic force (thrust) on the capsules passing through the LIM. The LIMs are usually powered by 3-phase current of 480 VAC. Figure 11 shows a cross section of the LIM when a capsule passes through it – section A-A marked in Figure 10. For good efficiency, the air gap between the capsule walls and the LIM must be small -- of the order of 1 cm. This shows the need for precision lining of LIMs at each LIM pump station. The walls of the capsules must be made of a two-layer metal – a steel interior which is a ferromagnetic material and an aluminum outer layer which is a good conductor. More about the LIM is discussed in Section 3.2 Linear Induction Motor.

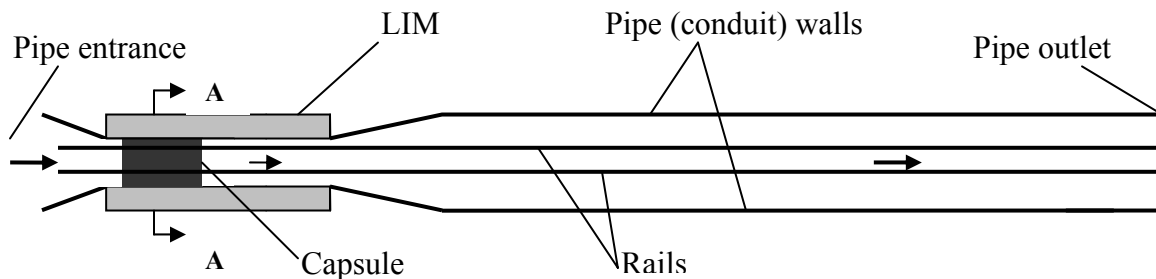


Figure 10 Top view of a simple PCP driven by a LIM. (Note that an exaggerated lateral scale is used. In reality, both the LIM and the pipe are much longer than shown here.)

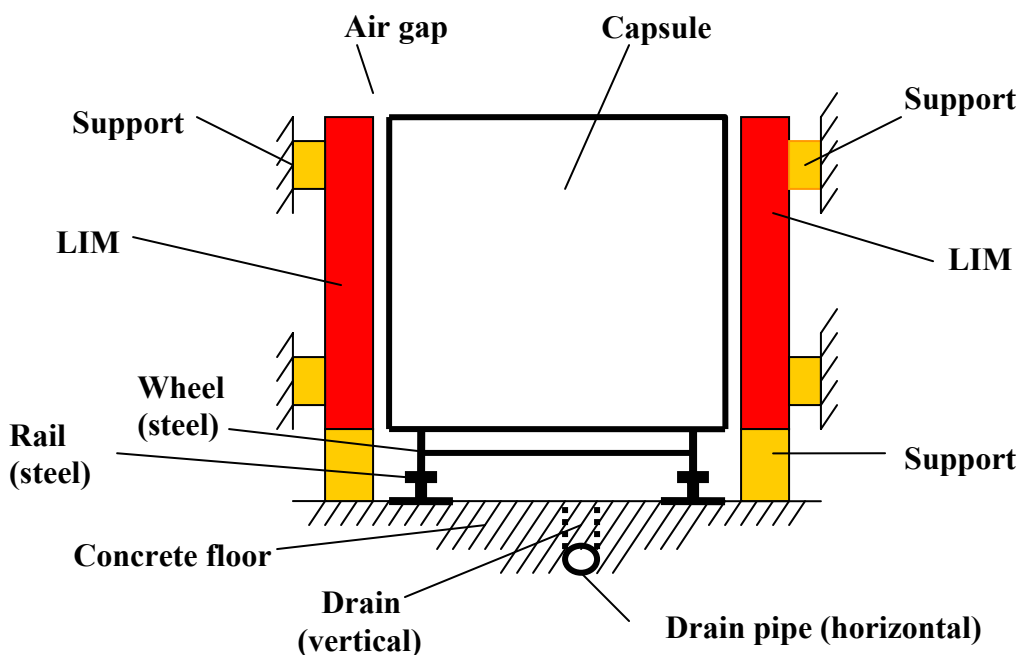


Figure 11 Cross section of a capsule in a LIM (Sec. A-A of Figure 10)

Because New York City and adjacent New Jersey have several container ports scattered around a relatively small geographical area, it is possible to have a single PCP with multiple inlets and only a single outlet to serve these ports, as illustrated in Figure 12. Detailed route planning for the PCP and the selection of the location of the outlet terminal – the container inspection/transfer station – should be left for the Port Authority of New York and New Jersey to do.

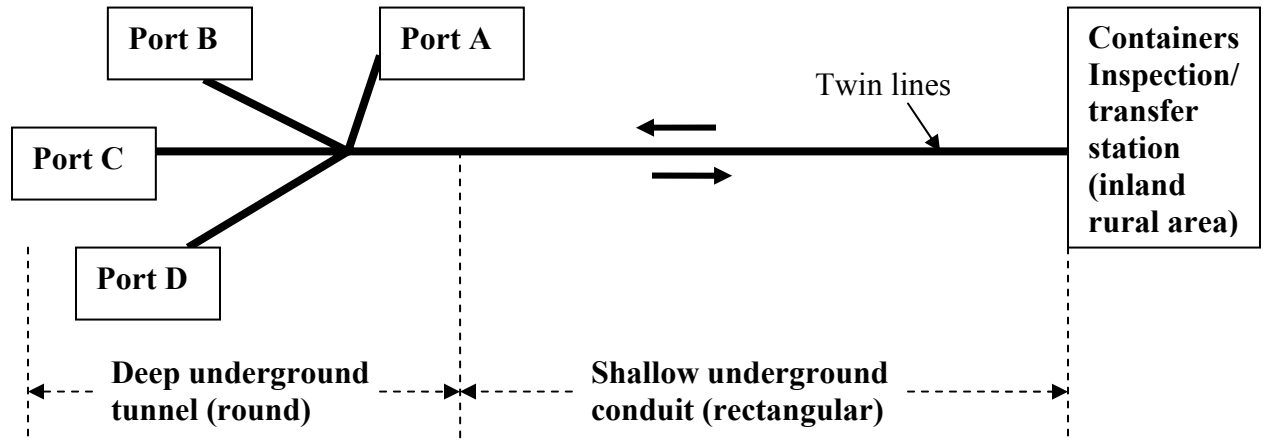


Figure 12 General illustration of a container-dispatch PCP system for serving NY & NJ ports

As will be shown in Sec.4.5, the above PCP system for dispatch containers to and from the ports of New York City contributes not only to port security and a drastic reduction of the number of trucks entering and leaving New York City, but also to the economic development of the City and reduced transportation costs for containers entering and leaving of the City.

2.4 TRUCK-FERRY PCP SYSTEM

The largest PCP system that can be used in New York City involves using large capsules rolling on rails in tunnels or underground conduits, with each capsule carrying an entire truck or tractor trailer. The trucks (including tractor trailers and vans) are piggybacked by the capsule, in much the same manner trucks and cars are piggybacked through the Euro Tunnel from England to France [19]. The only main differences are: the system proposed for use in New York City uses pneumatically driven PCP capsules instead of electric trains, the system is on land instead of undersea, and it is much shorter and simpler than the English Channel Tunnel. Due to these differences, the estimated cost for building the PCP system in NYC is only a fraction of the cost of the Euro Tunnel. Where is such a PCP system applicable to New York City? This project has determined that Hunts Point, a peninsula of Bronx, is the place that may benefit from such a PCP. This is explained briefly below.

Hunts Point is the place in New York City where the City's foods are processed, serving millions of people in the New York Metropolitan area. It has the nation's largest produce processing center, and the nation's largest meat processing center. A large fish market is also under construction there. Each day, over 3,000 trucks of various sizes enter Hunts Point from its north and proceed to its south, either to pick up the processed foods from or deliver the unprocessed foods to the food processing centers, which are located next to each other in the southeast corner of Hunts Point – along the Food Center Drive. The high-density truck traffic in Hunts Point has caused not only accidents but also severe air pollution. Studies by health officials have found that residents of Hunts Point suffer from the highest asthma rate in New York City, which is believed to be an indication of the health problem generated by trucks. Both the residents of Hunts Point and the New York City officials are very concerned about the truck-generated problems in Hunts Point, and have sought various solutions. One solution is to have a dedicated truck route to Food Center Drive. While that solution helps to reduce truck traffic through residential and business areas, it has little impact on air pollution in the area. Another solution – a current practice – is to ban idling trucks (i.e., prohibiting any parked trucks from leaving their engine running for more than three minutes). While this measure does help to reduce air pollution, the benefit is limited because trucks are still polluting air when they are moving, and besides, some trucks carrying refrigerated foods cannot stop their engines for long without affecting the foods that they carry. The implementation of various truck-stop electrification systems also helps to minimize the problem. However, according to the management of the Hunts Point meat market, at present only a small number of refrigerated trucks are properly equipped for hook-up to the electrical facility of the market. Plans have also been made to promote more use of railroads from and to the food processing centers. However, railroads can only provide limited relief because most of the unprocessed foods carried by trucks come from different places of the nation (e.g., Florida, the Midwest, etc.), and most of the processed foods carried by trucks and vans are destined to different parts of the New York Metropolitan area. Only a small percentage of foods can be shipped via railroads. It is believed that using a PCP to ferry trucks underground through a tunnel or underground conduit from north to south along the east coast of Hunts Point peninsula offers a potentially viable solution to Hunts Point's truck problem.

Two alternative routes for the truck-ferrying PCP have been investigated in this study for Hunts Points – AB and CD shown in Figure 13. Various aspects of the two routes have been considered, including geology (ground condition), relative buildup (urban development), intersection with existing underground utilities, construction difficulties, and accessibility to

freeway outlets. The study found that the east route, CD, is preferable. This route connects point D, the north end of the proposed PCP conduit, to two freeways (I-278 and I-895). It enables easy freeway access from and to three different directions. The total distance of the CD route, following a slightly curved path, is approximately 1.8 km (1.1 miles). Some curvatures are included to avoid crossing existing structures, and minimizing construction difficulty. The south end of the route, point C, reaches the southeast end of the produce market (officially called the "Hunts Point Terminal Market"). Trucks ferried to point C via the PCP can reach the various buildings of the Produce Market within 500 ft, and can reach the meat market via the Food Center Drive within 1,000 ft. Once the trucks are ferried from point D to C, they need to drive only for a short distance along the Food Center Drive. Also, the route traverses the least built-up area of Hunts Point, enabling the use of open-cut for construction.

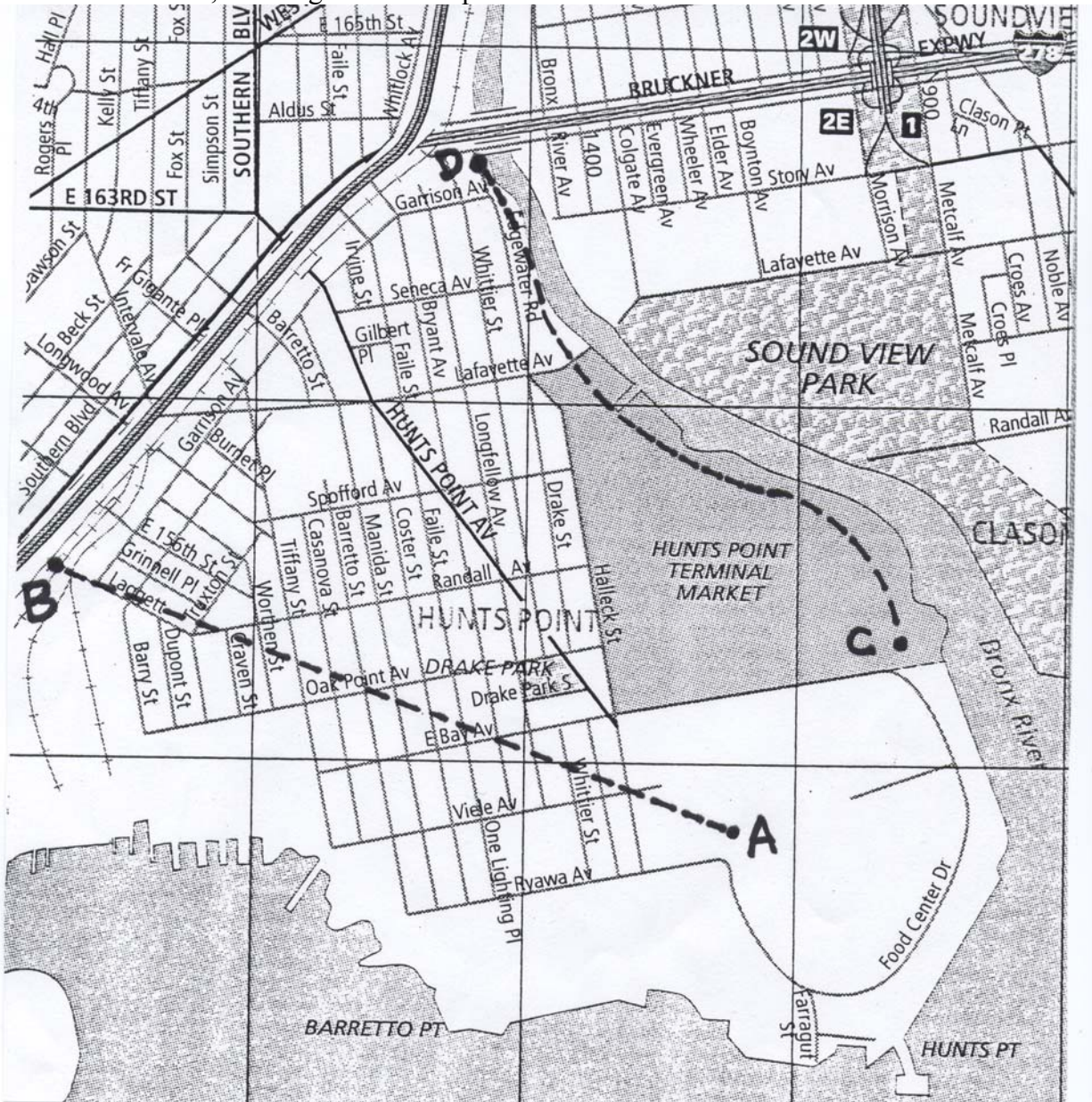


Figure 13. Proposed alternative PCP routes (AB and CD) investigated for ferrying trucks across Hunts Point. (Note that the east route, CD, was found to be the preferred route.)

As with the other PCP systems discussed here, the truck-ferry PCP in Hunts Point will use a dual conduit (twin pipes), so that capsules can move simultaneously in opposite directions. Depending on construction costs, this PCP system in Hunts Point may use either rectangular conduits of 10 ft width and 15 ft height, or circular tunnels of 18 ft diameter. The rectangular shape is more cost effective if the open-cut method is used for constructing the conduits, whereas the circular shape is more cost effective if the conduits (tunnels) are bored through bedrock using tunnel boring machines (TBMs). A preliminary investigation of the selected route (CD) indicated that it is possible to use the open-cut method to construct the truck-ferrying PCP along this route without affecting existing structures. Whenever any existing water or sewer pipes are encountered, careful digging around these pipes will avoid damaging them. Because the top of the underground twin conduits of the PCP can be placed 10 to 20 ft below the ground level, they can cross existing pipes from underneath without problem. An anticipated problem is groundwater and water infiltrating from the Bronx River, which will make construction more difficult and costly than usual. However, by using modern construction methods, the water problem can be handled.

The carriers of the trucks are flatbed capsules of 9 ft width. Three different capsule lengths will be used to carry trucks or vans of different lengths: 60, 40 and 20 ft. Each 60-ft capsule can ferry a 53-ft-length tractor trailer; each 40 ft capsule can ferry a 35-ft truck; and each 20-ft capsule can ferry a van or pickup truck. Figure 14 shows the general layout of the proposed PCP system. Note that due to the relatively small number of trucks that need to be transported by this system – 1,750 trucks per day through each tube or a total of 3,500 trucks per day for two directions – a blower instead of LIM can be used in this case. As analyzed in Appendix B.2, with a blower of 40 kw, one capsule can be propelled through each conduit of 1.7 km in every 50 seconds, at the top speed of 30 mph (48 km/h), and it will take less than 3 minutes for any capsule to move through the conduit. The operation of the system is described next.

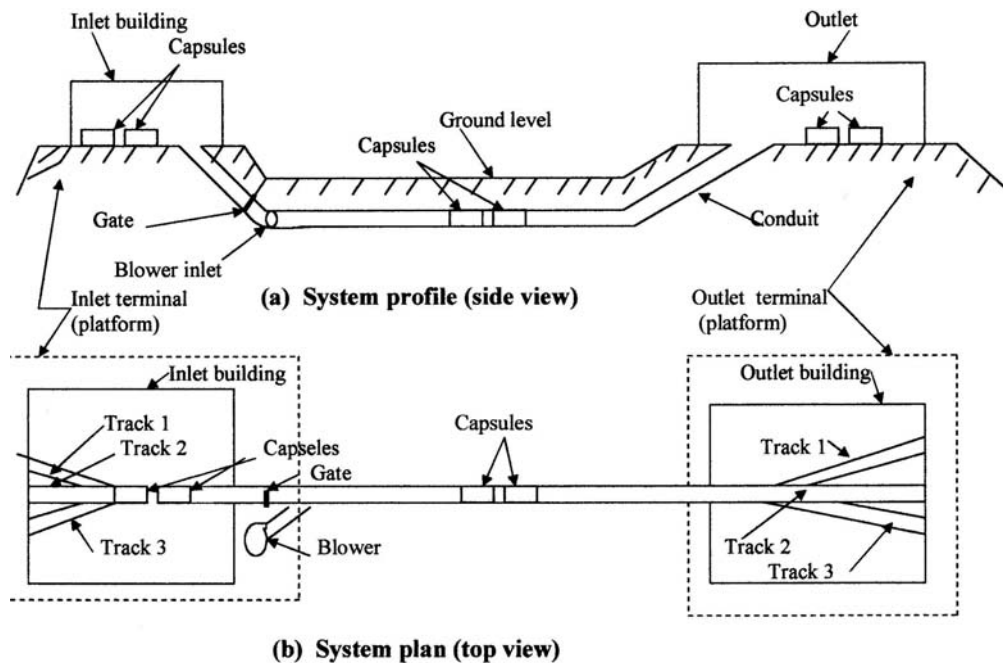


Figure 14. General layout of a truck-ferry PCP system designed for use in Hunts Point.

When a truck carrying foods enters the inlet station of the PCP, the driver drives the truck onto a parked capsule of the appropriate size (length) at the terminal. Different lengths of empty capsules are parked in different lanes. The driver drives the truck onto the flatbed capsule, turns on the parking brake, closes the truck doors and windows, turns off ignition, and remains seated with the safety belt on. This process takes less than 60 seconds. Then, a worker at the terminal closes the rear door of the capsule, and pushes a button to launch the capsule. The capsule is launched by the thrust of a pneumatic ram of appropriate strength, or another suitable means. Due to the sloped entrance of the conduit as shown in Figure 14 (a), gravity accelerates the capsule as it enters the conduit. As soon as the capsule has passed the open gate, the gate will close automatically, and the blower will be turned on automatically, blowing the capsule with its load (the truck) through the 1.7 km distance to the conduit outlet, which is near the food center. The whole trip will take less than 3 minutes – see calculation in Appendix B.2. During transit, the capsule motion is entirely automatic, and the truck driver needs to do nothing except to enjoy a short ride. As has been demonstrated by the Euro Tunnel [19], such rides are convenient, comfortable and safe.

As soon as the capsule approaches the Food Center (point C in Figure 13), it will decelerate automatically due to the rising slope of the exit conduit – see Figure 14 (a) – and will come to a stop outside the conduit in the terminal. Then, a worker at the terminal will open the front door of the capsule to let the truck out. The trucker starts the ignition, and drives the truck to the specific store in the Food Center, as he (she) currently does without using the PCP system. The driving distance within the Food Center will be short, not more than a few hundred yards. After unloading its cargo, the truck can leave Hunts Point with or without carrying foods, by using the same PCP system in the reverse direction.

In passing, it should be mentioned that each capsule will have its own brakes powered by compressed air – the same as for conventional railroad train brakes. The brakes can be activated either manually by the attendants at the PCP terminals, or automatically through remote control using an RFI (Radio Frequency Identification) system.

This truck-ferrying PCP in Hunts Point is expected to bring the following benefits to Hunts Point, Bronx and New York City:

- Avoiding the need for trucks to cross the business areas and the residential areas of Hunts Point in order to enter and leave the Food Center. It will drastically cut down the number of trucks running on the streets of Hunts Point.
- It will drastically cut down the air pollution problem caused by trucks in Hunts Point. This will benefit not only Hunts Point but also Bronx and the entire New York City.
- It will facilitate food delivery, especially during inclement weather such as when the streets are covered by ice and snow.
- The many acres of land above the underground PCP system and along the Bronx River can be turned into a riverfront park. It will provide a much needed outdoor recreational facility to the residents of Hunts Point and Bronx.
- The uniqueness of the truck-ferry system will bring tourists to Hunts Point, thereby helping the economic development of the Hunts Point. This was found to be true for the Euro Tunnel, which attracts tourists.

As will be shown in Sec.4.6, the truck-ferrying PCP in Hunts Point is the only one of the six analyzed potential applications of PCP in New York City that cannot be justified on economic grounds alone.

2.5 OTHER POTENTIAL APPLICATIONS

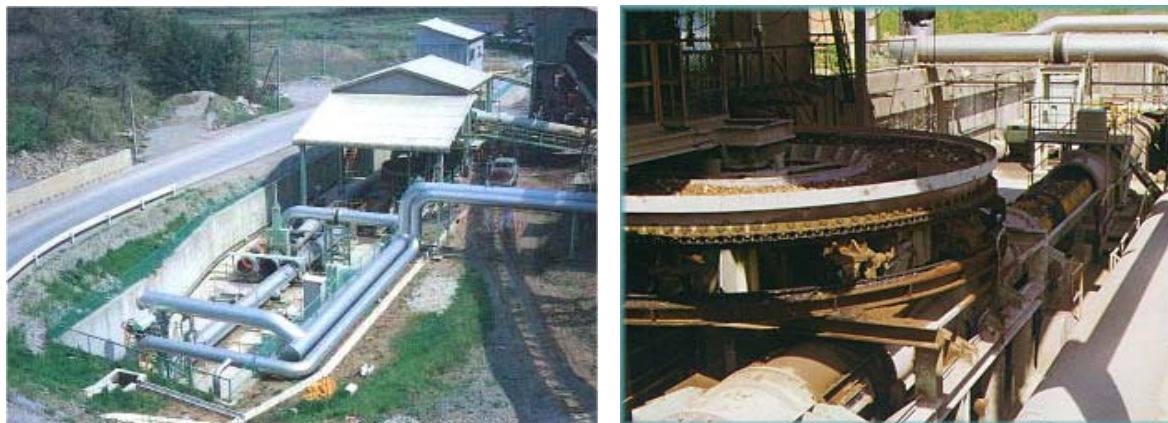
(a) Solid Waste Transport

According to published sources [20-23], the New York City now generates approximately 12,000 tons per day of residential and institutional solid waste, and 27,000 tons per day of commercial wastes. Prior to 2001, all the residential and institutional solid wastes were collected by the City's Department of Sanitation (DSNY) and transported to a single landfill in the City – the Fresh Kills landfill on the Staten Island, and the commercial wastes were collected by private carters and transported to approximately a hundred transfer stations scattered around the city, mostly in Bronx, Brooklyn and Queens, to be processed and then exported – trucked to landfills in New Jersey and other states. However, since the closure of the Fresh Kills landfill by the City in 2001, all the residential and institutional solid wastes collected by the DSNY are now transported by garbage trucks to eight marine transfer stations with at least one in each borough, and one land-based transfer station on Staten Island. At the transfer stations, the wastes are compacted and fit into 20-ft-long containers. The waste containers at the marine transfer stations are carried by river barges that transport the containers to oceangoing ships and then to trucks for export to New Jersey or other states. According to [20], since the closure of the Fresh Kills landfill, the cost of transferring, transporting and disposing the 12,000 tons per day of garbage in New York City has been skyrocketing: \$578 million in 1997, \$996 million in 2001, and expected to reach \$1 billion per year in 2003. In addition to the direct cost paid for the services, the indirect social costs have been high, as quoted below [20]:

“... 425,000 extra trips each year by diesel exhaust-spewing garbage trucks, substantially raising the pollution levels along the routes and around the transfer stations.Managing such huge volume of waste also causes substantial regional and global environmental problems associated with the extraction, manufacture, and transport of excess goods and packaging, impacting on natural resources, energy and materials use, and on global warming.”

A number of measures are being taken by New York City government, industries and residents, in mitigating the aforementioned problems. Such measures include waste prevention (i.e., encouraging measures and habits that reduces waste generation), and measures to recycle waste materials. However, even with the best waste prevention and recycle programs, there will still be a large amount of solid wastes generated in the highly populated New York City that must be exported to landfills and/or waste recycling stations in less populated neighboring areas in New York and other states such as New Jersey. As will be shown next, the same PCP system used successfully in Japan for limestone transport can be used to transport the New York City solid wastes to such sites.

Since 1980, Japan has successfully used a PCP to transport more than 2 million tons of limestone per year from a mine to a large cement plant in Kuzuu, Japan [3]. This PCP was built in 1980 to replace an existing railroad, which had been causing accidents and air pollution problems. The PCP system uses a 40-inch-diameter steel pipe buried underground, using the decommissioned railroad right-of-way. Figure 15 shows the inlet station of this PCP. The pipeline has compiled an impressive record, and is still operating today and will for many more years to come. Not only has this PCP prevented accidents and air pollution that would have been caused by the rail, it also has saved money for the Sumitomo company and has pleased area residents. The system also was found to be highly reliable, achieving over 95% of availability.



(a) Bird-eye view of the Inlet station (b) Close-up view of materials loading into capsules

Figure 15 The inlet loading system of PCP transport of limestone in Kuzuu, Japan; 40-inch-diameter steel pipe is used in this project. (Courtesy of the Sumitomo Metal Industries, Ltd.)

The same system used successfully in Kuzuu for transporting limestone, with minor modifications, can be used to transport the solid waste of New York City. The system as it is, using blowers instead of linear induction motors (LIMs), can be expanded to transport up to 5 million tons of materials a year. In a 24-hour(3-shift)-a-day operation with 95% availability, the amount of compacted solid wastes that this 40-inch-diameter pipeline can transport in a day using the current technology (blowers) is approximately 13,000 tons, which is about the same as the total solid wastes collected by the DSNY. With system improvements such as using LIMs instead of blowers and using parallel loading and unloading lines, the same 40-inch-diameter pneumatic capsule pipeline (PCP) can be used not only to transport the entire amount of the solid wastes handled by the DSNY but also all of the commercial solid wastes handled by private companies. To minimize the system costs and to minimize changes to the current transfer stations, it is proposed that the PCP system for transporting the wastes collected and compacted at each of the current nine transfer stations has nine inlet stations – one at each inlet station—and has a pipe branch connected to each transfer station. The nine branches will intersect downstream and merge into a common line to take all the wastes to a common large landfill in a remote location to be purchased by the City of New York, or to more than one processing/disposable sites along the route of the pipeline. The network of pipes will be similar to that shown in Figure 12 for dispatching containers from ports, except that the pipe is much smaller (40 inches in diameter), and the system has nine intake stations and inlet lines. Most of the pipe near the inlets (i.e. near the marine waste transfer stations) will be laid a few feet under the river beds, which can be done easily with 40-inch steel pipes using modern offshore pipeline construction technology. The land portion of the pipe in rural areas will be buried 3 to 5 ft underground using the open-cut method which is the most economical and the most common way of construction of long-distance pipelines. On land when crossing rivers, roads, buildings and other structures, the modern technologies of directional drilling and pipe-jacking will be used to construct the pipe – see Sec.3.5 (a) Tunneling for details. The ultimate disposal site is a large landfill or waste recycling plant at a relatively remote area where the wastes are first processed to recover and recycle some of the materials, and the non-recyclable part is buried in the landfill. Having such a system for transporting and disposing the solid wastes will benefit New York City in the following ways:

- It will eliminate the need for using barges and ships to move solid wastes from transfer stations to ports and then to haul the wastes by trucks and trains to landfills. Consequently, all the accidents, pollution and traffic problems caused by barges, ships, trucks and trains used for this purpose are eliminated.
- Since barges, ships, trucks and trains all use diesel fuel while PCP uses electricity, the latter is much cleaner and use domestic-generated energy rather than foreign oil. Thus, the PCP system reduces the City's and the nation's dependence on foreign oil.
- The PCP system is highly automated, reliable, and insensitive to inclement weather. It operates continuously 24-hours a day and 365 days a year except for an anticipated less than 5% downtime. Due to this, it does not require nearly as large a storage and processing area as that required currently at each transfer station. This means savings of space at each transfer station which can be converted to other more valuable uses such as commercial or industrial use. Also, the pile of solid waste stored at each transfer station will be significantly reduced, resulting in less foul air and reduced odor and esthetic problems at or near each transfer station.
- Because recycling of waste materials can be done at a lower cost at the remote location of the ultimate disposal site (near or at the landfill) than at the transfer stations in New York City, more waste recovery will be possible than at the current sites.
- The PCP transport system will result in substantial cost savings for the City – see Sec.4.2 for cost estimates.

Notwithstanding the foregoing benefits, switching from the current to the aforementioned future PCP system will not change the way solid wastes are collected in New York City from the source (i.e., each individual homes, buildings, or parks that generate wastes), or the way they are transported from the source to the waste transfer stations. The City will have to wait until the pallet-tube PCP system discussed in Sec.2.2 is built before solid waste can be transported by PCP from the source to each transfer station. The same pallet-tube PCP system for ordinary cargoes can be used also for transporting solid wastes contained in plastic bags. The bags will be loaded into special capsules that have tighter seals than ordinary capsules have, so that the foul odor of the waste materials will not permeate into the pipe outside the capsules.

(b) Mail and Parcel Transport

The U. S. Post Office Department, the ancestor of the current U. S. Postal Service, was the pioneer in the U. S. to use “pneumatic tubes”—the archaic form of the current pneumatic capsule pipelines (PCPs). According to an interesting and detailed review article on pneumatic mail tubes written by Postal Inspector Robert Cohen in 1999 [24], as early as 1892, the U.S. Congress authorized \$10,000 for an investigation of the “rapid dispatch of mail by means of pneumatic tube.” Immediate thereafter, Postmaster General Wanamaker solicited bids for contractors to demonstrate the system; the contract was awarded to the Pneumatic Transit Company of New Jersey. The first test was conducted in Philadelphia in 1893 between the Philadelphia General Post Office and the East Chester Street Post Office, over a distance of 0.58 miles. The test was successful and tube service officially began in Philadelphia; soon it spread to four other cities – New York, Boston, Chicago and St. Louis.

The New York City's system of mail tubes began in 1897, and continued to expand over the years until 1953 when it was discontinued – having well served the city for over a half century. At its peak, the New York City system had about 56 miles of tubes, made of 8-inch-

diameter cast iron pipes. The system connected 23 post offices in Manhattan to two offices in Brooklyn and one in Bronx. The connection to Brooklyn was via the famous Brooklyn Bridge. The entire tube mail system in New York City transported approximately 200,000 letters an hour, constituting approximately 55% of the total mail in New York City in 1953. Figures 16 and 17 are two photographs of the historic system.

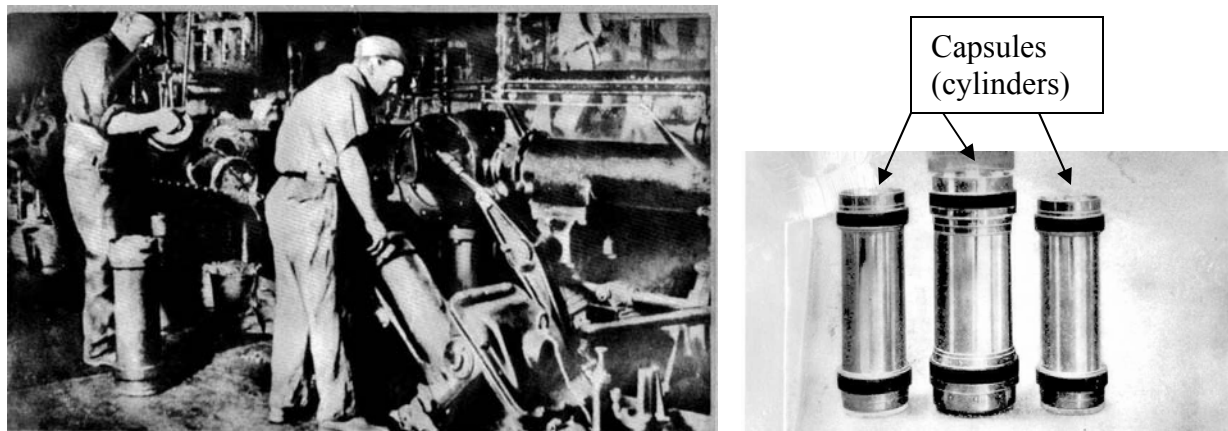


Figure 16 Prior to 1953, New York City postal workers, known then as “racketeers”, are shown feeding capsules (then called “cylinders” or “torpedoes”) containing letters into pneumatic tubes [24].

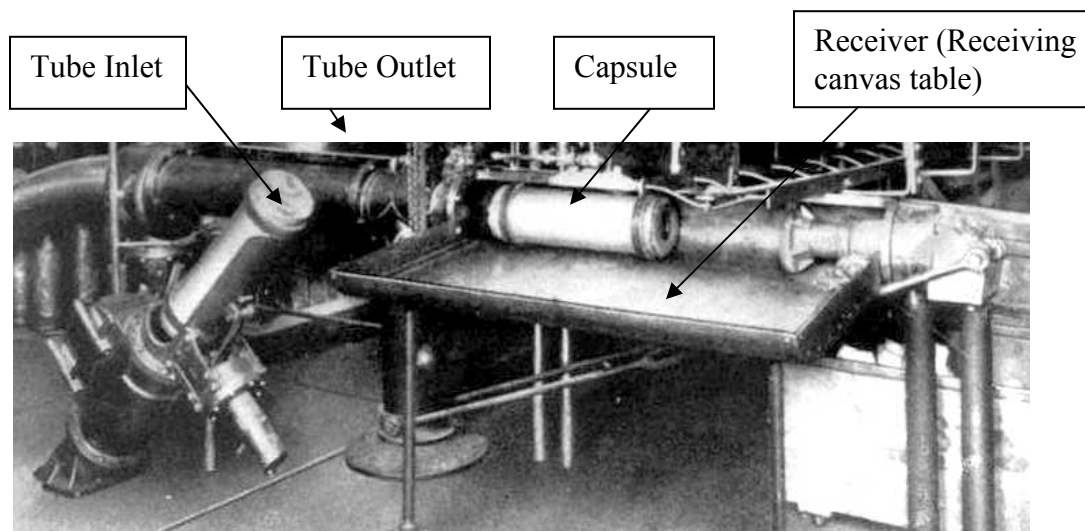


Figure 17 Transmitters and receivers of capsules (“cylinders”) in a post office room in New York City [24].

The main reasons for discontinuing the use of pneumatic mail tubes in New York and other U.S. cities in the 1950s are the following:

- The system, built around the turn of the century (1895-1905), had become increasingly old by 1950 and in need of repair after half a century of usage. With the pipes being underground (3 to 5 ft below the street level) and in buildings, it was costly to replace them with a modern system.

- The tubes, 8 inches in diameter, were too small. They could only transport regular size letters and small parcels. The 200,000-letters-an-hour capacity, which was adequate for New York City in 1900, had become inadequate by 1950. The sizes of letters and parcels had also grown significantly in the 50 years, making the system obsolete by 1950.
- The old system used obsolete technologies, making the system unreliable and labor intensive. For instance, the capsules used were plain cylinders without wheels, which often got stuck in the tubes (pipes) and clogged the pipes. To minimize the clogging problem, the entire interior of the pipe had to be lubricated with oil, which was not only costly but made the capsule surface dirty (oily) and handling more difficult. Also, some letters got contaminated by oil during loading/unloading.

Due to the above reasons, and due to the fact that by 1955 trucks had become popular and could move around cities easily, including New York City, without running into or causing traffic jams, it made perfect sense for the Post Office Department to discontinue the use of the obsolete mail tubes in New York and other cities, and to rely exclusively on trucks for delivering mail from post offices to rail stations or airports.

History has shown that most societies are receptive to beneficial use of new technologies. Whenever a new technology is developed and proved to be beneficial to the society, the new technology will be used sooner or later. This is expected to be the case with pneumatic capsule pipeline (PCP). The modern technology of PCP, using wheeled capsules and large diameter pipes, enables the transport of many cargoes hitherto not transportable by pipelines. In the writer's opinion, it is only a matter of time before the U. S. Postal Service will again be attracted to pipeline transportation of mail and parcels, using the modern PCP technology, and using large diameter pipelines. The following is an envisaged potential future use of PCPs in New York City for transporting mail and parcels:

Sorted mail and parcels destined for any East Coast city between New York and Washington D.C. are first transported by trucks over a short distance to one or more PCP inlets located either in the City or at its outskirts. Then the mail and parcels will be loaded in the same type of capsules that are currently being used in Japan for limestone transport and the type recommended for use in New York City for transporting solid waste, except that the mail-parcel pipeline will be a separate system from the trash pipeline of New York City. As in the trash pipeline case, the mail-parcel PCP will use multiple inlets, and 40-inch-diameter steel pipe. Unlike the proposed trash pipeline which is less than 100 miles in length, the mail-parcel PCP will be over 200 miles long, spanning all the way from New York City to Washington D.C. The mail-parcel pipeline is also different in that it will have many intermediate stations with inlets and outlets, with at least one of such stations to serve each major city along the route. Thus, it constitutes a complex transportation system similar to an interstate highway system that will serve all the states and cities along the pipeline route from New York to Washington D.C. To minimize construction difficulties and costs, the pipeline route should use the right-of-way of an existing interstate highway, such as I-95. It is relatively easy to accommodate two 40-inch steel pipes – one on each side of the highway—along the existing easement of an interstate highway. Because the pipes will be buried 3 to 5 ft underground and will use low-pressure air, they will not impede traffic, nor cause safety problems. However, approval from all the states along the route (New York, New Jersey, Pennsylvania, Delaware and Maryland) and the Federal Highway Administration, and an act of the Congress will be needed before this pipeline can be built along any interstate highway. It will be a major undertaking that will take years to get approvals for the

right-of-way before financing and construction can take place. Still, due to its huge potential benefits to New York City and New York State, the City and the State may want to consider spearheading the project. With the use of linear induction motors (LIMs) instead of blowers, the system has sufficient capacity to transport all the mail and parcels of not only the Postal Service but also the Federal Express, United Parcel Service, and other carriers, along this route. Therefore, it only makes sense for the pipeline to be used and financed not only by the Postal Service but also other private carriers. The system will benefit New York and other states along the route or corridor in the following ways:

- It will significantly reduce the number of trucks along I-95 between New York City and Washington D.C. – one of the busiest highways on the East Coast. Consequently, it will significantly reduce traffic congestion, accidents, air pollution, and road and bridge damages along this important highway caused by trucks.
- It will speed up mail and parcel delivery along this busy corridor. For the longest distance along this corridor (215 miles between New York City and Washington, D.C.), the transportation time will be about 6 hours for capsules traveling at 35 mph, and it can be faster if necessary. Because the system operates continuously – 24-hours a day and 365-days a year – all the mail and parcels going through this pipeline can be easily delivered within 24 hours, to meet the requirement of express mail services.
- The system being underground is unaffected by inclement weather. Theft of cargo during transit is also nearly impossible.
- If fully utilized by various carriers, the transportation cost in \$/TM (dollars per ton per mile of distance) will be much less than by existing transportation means – see cost analysis in Sec.4.3.
- The system uses electricity instead of diesel; therefore, it reduces U.S. reliance on foreign oil. Besides, the energy efficiency of PCPs, in terms of Btu/TM (Btu of energy used per ton-mile of cargo transported), is significantly better than that of trucks [25]. Thus, using PCPs instead of trucks conserves energy.
- As will be seen in Sec.4.3, this PCP is highly cost effective. Mail and parcels can be transported by this pipeline at a fraction of the cost of that transported by trucks and airplanes.

(c) Use of Existing Right-of-Ways

An attempt was made in the beginning of this study to identify the right-of-ways of existing tunnels (including subway tunnels, highway tunnels, rail tunnels and water tunnels) and other structures in New York City that might be utilized for constructing PCPs in the City. Finding such existing right-of-ways that can be utilized for constructing PCPs would greatly reduce the cost and facilitate the use of PCPs in New York City. However, soon it was discovered that it was difficult if not impossible to identify such right-of-ways. The difficulty arises from three factors. **First**, most existing tunnels have little unutilized or underutilized space for a PCP of significant size, such as 3-ft diameter or larger. **Secondly**, there is an institutional barrier. Agencies in charge of tunnels contacted by this project were reluctant to provide information on underutilized tunnels for possible use by PCPs. Because freight transport is not a part of their official duties, they consider possible use of PCPs in their tunnels for freight transport as an intrusion and threat rather than blessing. **Third**, even though there are many reports on abandoned tunnels in New York City, such as those discussed in [11, 26, 27], the

abandoned tunnels are either too short, too difficult to find key information about, or have already been converted to other usages. Due to these, preliminary investigation of this study was unable to identify any existing underground tunnel in New York City that are suitable for constructing a PCP of 3-ft diameter or larger. Even though there are numerous abandoned pipes in New York City (old water pipes, old sewer pipes and old pneumatic mail tubes), they are undocumented and mostly too small in diameter for any significant reuse as a PCP. For these reasons, this project soon discovered that the quest for using existing tunnels for PCPs in New York City was unproductive, and quickly focused on new tunnels and new lines that are more feasible and economically justifiable.

In spite of the focus of this study on constructing new tunnels and new pipelines for PCPs, the study has not exhausted the possibility of the existence of abandoned or underutilized tunnels that can be used. Nor has it examined the feasibility of using or sharing the right-of-way of some existing aboveground structures, such as railroads, highways, or the AirTrain to the John F. Kennedy Airport, for freight transport using PCP. The scope of the study and the project budget prevented such investigations. Therefore, it is quite possible and even likely that future investigators will find it feasible to use the right-of-way of some existing infrastructures in New York City for freight transport using PCP, to the benefit of the City.

Section 3 TECHNOLOGY ASSESSMENT

In this section, important issues pertaining to the technical feasibility of using PCPs in New York City for the potential applications discussed in the previous section are assessed and addressed. The section also provides key technical information needed for future planning, design and construction of PCPs in New York City and elsewhere in the nation and the world.

3.1 Pneumatic Capsule Pipeline (PCP)

(a) Difference between PCP and Tube Transport

Pneumatic capsule pipeline (PCP) is the modern and large version of the “tube transport” such as used for mail transport in New York and four other U.S. cities prior to 1953 [24, 28, 29], and such as those still in use in the U.S. for transporting light-weight articles at drive-in banks, hospitals, airport terminals and large factories and office complexes [16]. Essentially, **PCP** differs from **tube transport** in that it uses large pipes – usually 3-ft-diameter or larger pipes, and the capsules are large and supported by wheels to reduce contact friction – see Figures 1-4. In contrast to the tube transport system which uses non-wheeled capsules each carrying only a few pounds of cargoes, the PCP system uses large wheeled capsules each carrying more than one ton of cargo. For instance, each of the capsules used in Japan for transporting limestone in a 1m diameter pipe can carry approximately 2 tons of limestone. Also, PCPs are highly automated and use a centralized computer system, SCADA (Supervisory Control and Data Acquisition), for control and operation of the pipeline. It is a far cry from the primitive mail tube transport systems used by the Post Office Department over half a century ago [24]. This study sponsored by NYSERDA is focused on using PCPs instead of tube transport systems in New York City.

(b) Readiness of the PCP Technology for Use in New York City

Due to the well documented successful commercial use of the blower-based PCP systems in Japan for various purposes, such as tunnel construction [4], highway construction [4], transport of minerals [3], and transport and disposal of solid wastes [7], and due to less documented yet successful use of the blower-based PCPs in the former Soviet Union for rock transport [30], the blower-based PCP is an existing technology that requires no further research or demonstration before it can be used successfully anywhere in the world, including New York City. It can be used readily for those potential applications in New York City that use blowers to drive the systems. They include the PCP for tunnel construction, the PCP for solid waste transport and disposal, and the PCP for ferrying trucks in Hunts Point. On the other hand, the other three potential applications of PCP in New York City, including the system for pallet-tube freight transport, the system for dispatching containers, and the system for mail transport, all require the use of a linear induction motor (LIM) pump which has not yet be demonstrated beyond the laboratory scale for use in PCP. Therefore, it may be prudent to demonstrate and test either a prototype or a large-scale model of a PCP-LIM before using it in those three aforementioned applications, or as part of the pre-engineering of the commercial project. Such a demonstration/test will enable the designer to design an efficient LIM-based PCP system, and to minimize design mistakes and resultant system modifications following the first commercial use of such a system. However, even for the systems that use LIM, further R & D is not necessary before first commercial use. Societies cannot afford to wait for the perfection of any beneficial major technology before the technology is used. Finally, while no further research is necessary

before the PCP technology can be used successfully in New York City, it does not mean that no research is needed to further improve the PCP technology. As it is the case with other major technologies such as trucks and airplanes, even after a century of commercial use there is still room for R & D to further improve the technology.

(c) Wheels of PCP Capsules

All the existing PCP systems use wheeled capsules. For capsules in rectangular pipes – see Figure 1 (b) – the capsule wheels that support the weight of the capsule are mounted on the bottom of the capsule, in a manner similar to ordinary vehicles. Side wheels (guide wheels) are also used to keep capsules stable during motion and to reduce contact friction between the capsules and the pipe walls. In contrast, for capsules in a round pipe – see Figure 1 (a) – the wheels are very different. They consist of two gimbaled wheel assemblies, one mounted on each end of a capsule, pivoted at the center axis of the capsule. Such wheel assemblies keep the capsule in a stable position in the pipe to prevent spill of cargoes. While the wheel assemblies are free to rotate around the inner circumference of the pipe, the capsule with its center of gravity being below the pivoting point always remains stable.

All the wheels in the capsule pipeline systems in Japan use tires made of a hard synthetic rubber. Such tires have the following advantages: softening the impacts between the wheels and the pipe, reducing the pipe wear, and reducing the noise generated by capsules moving through the pipe. On the other hand, the rubber-tire wheels have the following disadvantages as compared to simple steel wheels without rubber tires, such as those used by railroad trains: greater wheel friction which waste energy, and greater wear of wheels (tires) which increases maintenance need and costs.

Considering the aforementioned advantages/disadvantages, different types of wheels will be needed in different potential applications of PCP to New York City, as follows:

(1) Tunnel construction PCP -- For the tunnel construction PCP system, the same bottom wheels using the same rubber tires as used in Japan for tunnel construction (see Figure 3) will be a good choice. This is so especially if the rectangular pipe of the PCP is made of concrete, as it was the case in Japan. Steel wheels cannot run on a concrete surface without causing severe wear to the concrete.

(2) Solid waste PCP -- For the 50- to 100-mile long PCP required for transporting New York City solid wastes to an out-of-state disposal site, great energy savings can be accomplished by using steel wheels. The steel wheels will also reduce wear of the wheels, resulting in less maintenance cost than using rubber-tire wheels. The disadvantages of steel wheels are more noise and wear of the pipe. However, the noise will not be a problem because the pipeline is underground. Only at the two terminals will the noise be heard, and they will be within the 85 decibel required by OSHA for workplaces, and well below those heard at a train station when a train arrives or leaves. The wear to the pipe will also be minimum because the solid waste is not as heavy as minerals, and because the wear will be uniformly distributed over the lower one-third of the pipe circumference, due to the rotation of the gimbaled wheel assembly inside the pipe. Use of a steel (for wheels) containing less carbon than that used in the steel for the pipe will also reduce pipe wear due to the reduced hardness of the wheels.

(3) Other larger PCP systems – For all the other potential applications that require the use of larger diameter pipes, including the pallet-tube PCP system, the container dispatch PCP system, and the truck-ferry PCP in the Hunts Point, the same types of steel wheels and steel rails used in ordinary railroads should be used. They have the following advantages:

- By using steel wheels on steel rails, the wheel friction coefficient (i.e., the rolling friction coefficient) can be reduced to about 0.002, which is five times smaller than that using rubber tires. This results in great saving of energy.
- Rails guide the motion of capsules, making it easy for capsules to enter a branch through railroad switches. The locations of the capsules in the terminal can also easily be controlled by the rails, thereby facilitating loading and unloading of capsules.
- The need for maintenance of steel wheels is much less than for rubber tires.

Details about using rails in PCP conduits to enhance the capability of PCP freight transport are currently being studied in a project sponsored by the U.S. Department of Energy [10].

(d) Capsule Trains

The operation of PCPs is usually facilitated by tying individual capsules together to form trains, in the same way railroad trains are formed. Usually, each capsule train contains only three to five capsules. Longer trains can also be formed but would require longer stations (which take up more space), less frequent launching and arrival of trains, and longer time for loading and unloading each train. Figure 18 shows a capsule train with bottom wheels in a rectangular PCP containing three capsules for tunnel construction. For simplicity, the wheels were drawn on the bottom of the capsule between the two end plates. In reality, most capsules are designed to locate the wheels on the two ends of the capsules outside the end plates – see Figure 3.

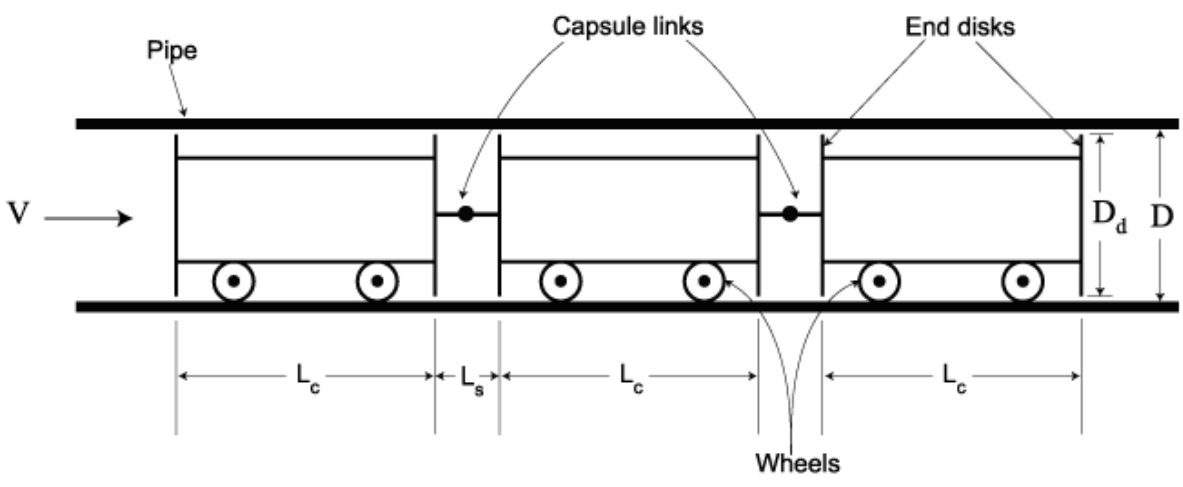


Figure 18 Schematic of a capsule train of three capsules in a rectangular PCP.

(e) Key Equations for System Design

Contemporary PCP systems driven by blowers use capsules that contain two end plates (also called “end disks” or “seal plates”), one on each end of a capsule as shown in Figure 18. The end plates reduce the air leaking around the capsule, increase the drag force on the capsule, and make energy transfer between the air flow and the capsule more efficient. Based on fluid mechanics, the drag force on a capsule with end disks can be calculated from

$$F_D = A_d C_D \frac{\rho(V - V_c)^2}{2} \dots\dots\dots (3-1)$$

where F_D is the drag force, A_d is the area of each end disk, C_D is the drag coefficient, ρ is the density of the air in the pipe at the capsule location, V is the mean velocity of the air in the pipe, and V_c is the capsule velocity. The drag coefficient C_D for any capsule with two end plates can be calculated from the following equation given by Kosugi [31]:

$$C_D = \frac{4k_d^4}{(1-k_d^2)^2} \dots\dots\dots (3-2)$$

where k_d is the ratio of the square-root of the disk area A_d to the square-root of the pipe inner cross-sectional area A , namely, $k_d=(A_d/A)^{1/2}$. Note that Eq. 3-2 is for any capsule having two end disks.

For a capsule that has only one end disk, the factor 4 in the equation should be reduced to 2. For capsules without end disks, a totally different and more complicated approach, described in the final report of a U.S. Department of Energy project [10], should be used to determine C_D . Note that PCP systems that use LIM (linear induction motors) do not use capsules that have end plates. The end plates must not be used for they create a large air gap and poor efficiency of the LIM.

Once the drag coefficient C_D is determined for the capsule and once the capsule velocity V_c is specified for the PCP system, the airflow velocity V in the pipe under steady-state operation can be calculated from the following equation:

$$V = V_c + \sqrt{\frac{2\eta W_c}{C_D A_d \rho}} \dots\dots\dots (3-3)$$

where η is the rolling friction coefficient of the wheels used by the capsule, which is approximately 0.01 for rubber-tire wheels, and 0.002 for steel wheels rolling on a steel surface; and W_c is the capsule weight. For capsules without end disks, Eq.3-3 still holds, but the area A_d should be changed to A_c , the cross-sectional area of the capsule.

Once the velocity is calculated from the above equation, the pressure drop along the entire length of the PCP under steady state operation can be calculated from:

$$\Delta p = \Delta p_c + \Delta p_f = \frac{N\eta W_c}{A} + f \frac{(L - NL_c)}{D} \frac{\rho V^2}{2} \dots\dots\dots (3-4)$$

where Δp_c is the pressure drop due to the capsules in the pipe; Δp_f is the pressure drop due to the motion of the air through the pipe in the capsule-free space; f is the Darcy-Weisbach friction coefficient that can be found from the Moody diagram in fluid mechanics; N is the number of capsules in the pipeline; L is the total length of the pipeline; L_c is the length of each capsule; and D is the pipe diameter. For non-circular pipe, use $4R_H$ where R_H is the hydraulic radius, in lieu of D .

The number N can be calculated from

$$N = \frac{L}{TV_c} \dots\dots\dots (3-5)$$

where T is the time interval between successive injections of capsules into the PCP.

Once the pressure drop Δp is known, the power consumed by the flow of air and capsules through the pipe is

$$P = Q\Delta p = VA\Delta p \quad \dots\dots\dots (3-6)$$

where Q is the volumetric flow rate (discharge) of the air.

Assuming the blower or LIM pump efficiency to be E, where E is a number smaller than 1.0, the power input to the blower or LIM pump is

$$P_{in} = EQ\Delta p = EVA\Delta p \quad \dots\dots\dots (3-7)$$

For large blowers, E is in the neighborhood of 90%, and for large LIM pumps E is approximately 70%.

(f) Brakes for Capsules

The capsules used in contemporary systems such as those in Japan do not have brakes. However, for the large PCP systems considered here for potential use in New York City (i.e., for the large systems that use steel wheels and rails), it is desirable to have a braking system for each individual capsule. The braking system recommended for use here is basically the same as used on ordinary railroad trains, which use compressed air as the energy source to activate brakes. In ordinary railroad trains, each car contains its own compressed air tank which is connected to the locomotive for central control by the conductor (engineer) of the train seated in the locomotive. For PCP each capsule will carry its own compressed air tank as in the case of ordinary railroad trains. However, the air tanks will not be connected to the locomotive because PCPs have no locomotives and no human driver or conductor. Therefore, activation of the brakes of each capsule must be done externally through automatic remote control and an onboard PLC (Programmable Logic Controller). Whenever there is a need for the capsule brakes to be applied, such as when a capsule approaches a terminal, a remote signal will be sent to the capsule to activate the brake. The capsule brakes will also be applied automatically whenever capsules have come to a complete stop. This will prevent any accidental movement of the capsules after they have come to a stop, until the capsules in a train are ready to move again and a remote signal has been sent to release the brakes of the capsules in this train.

(g) Drive Types

All conventional PCPs use blowers to drive the system. However, in many circumstances, it is better to use linear induction motors (LIMs) instead of blowers for the following reasons:

- Blowers are intrusive and do not allow passage of capsules through them. In contrast, LIMs are non-intrusive, allowing the passage of both air and capsules through them unimpeded. Therefore, long PCP systems that require booster pumps cannot use blowers but can use LIMs. This greatly facilitates the use of PCP for long distances.
- The LIM-based PCPs can have much larger (3 to 5 times larger) throughput than possible with the blower-driven PCP systems. This reduces unit freight transport cost in terms of \$/TM (dollars per ton of cargo transported per mile of distance). However, this economic advantage cannot be realized until and unless the system demand (i.e., the throughput of cargoes required) is very high.
- The LIM-based PCPs can have multiple inlets and/or multiple outlets. It is necessary for sophisticated PCP systems that have multiple inlets and/or multiple outlets.
- To be efficient, blower-based PCP systems must use seal plates (end disks) on each capsule. In contrast, the efficiency of LIM-based PCP is insensitive to the use of seal

plates. Since seal plates are difficult to use in any PCP that has non-uniform pipe geometries -- such as a round pipe constructed by tunneling followed by a rectangular conduit constructed as a result of open cuts – use of LIMs is more suited in such special cases.

Due to the foregoing reasons, both the blower type and the LIM type PCPs are applicable to New York City for different applications – the blower type for tunnel construction, solid waste transport, and ferrying trucks in Hunts Point, and the LIM type for the pallet transport system, the container dispatch system, and the mail transport system.

(h) Operation of PCP Systems

The operation of various blower-based PCP systems is basically the same. A loaded capsule train consisting of 3 to 5 capsules is injected into the pipe one at a time. The motion of the capsule train is initiated by an external thrust force generated at the inlet station. The thrust can be provided either by a pneumatic cylinder or a linear motor. Shortly after the capsule train has started to move, the train arrives at a man-made decline as shown in Figure 14 (a) which accelerates the train until it reaches the bottom of the pipe inlet. Then a gate near the inlet is closed behind the capsule, and a fan is started which blows the air through the pipe which in turn drags the train along. A short time (say, 40 seconds) later, the inlet gate is opened and another capsule train is fed into the pipe in the same manner as the first train. This continues for some time until the first capsule train in the pipe exits the pipe. The upward slope or incline at the pipe exit causes the capsule train to slowdown by gravity as soon as the train enters the outlet station. Then the brakes are triggered which bring the train to a quick stop. Control of train motion, from start to stop, is automatic. Sensors will be used to control the motion of the gate at the inlet, to turn the blowers on and off, and to activate the brakes as soon as the train has entered the outlet station. Launching of any loaded capsule train will be done manually by pushing a button, as soon as the train is ready to go. As soon as any capsule train has been unloaded of its cargoes, it can reenter the pipe in the opposite direction in much the same manner as during the cargo delivery trip. The operation of the entire system will require a SCADA and one or more than one PLC. Each capsule will carry a RFID (Radio Frequency Identification) tag, the same used at highway toll booths for keeping track of and controlling the flow of automobiles. Whenever the PCP system is shutdown, both the inlet gate and a similar outlet gate will be closed, preventing unwelcome would-be intruders from entering the pipe.

The operation of a LIM-based PCP will be slightly different from that discussed above for a blower based PCP. First of all, the inlet and outlet gates will be always open when the system is in operation. Secondly, the LIM will be controlled automatically by a PLC in a manner to be discussed in Sec.3.2, Linear Induction Motor. Launching of capsule trains into the pipe at the PCP inlet station, and exiting of such trains from the pipe into the outlet station, are both identical to that for the blower-based PCPs.

(i) Maintenance of PCP Systems

For any PCP system, maintenance of the pipe itself is easy and infrequent, similar to those of maintaining ordinary pipelines (gas and oil pipelines) for systems without rails, and similar to those of maintaining railroads for those PCPs containing rails. More frequent maintenance is expected for the wheels of the capsules, and for the blowers of the blower-based PCP systems. The wheels must be examined and lubricated after every 10,000 miles of use, and the blower

should be examined and greased after every 6 months. The LIM, being a stationary device, is expected to need little maintenance. The only part of the LIM that needs frequent inspection is the inner surface of the LIM and the gap between the LIM and the capsule – making sure that the LIM’s internal surface is not damaged, and the air gap is properly maintained. Should the air gap be altered due to extended operation, adjustment can be made by resetting and tightening the screws and bolts used to set the air gap.

3.2 Linear Induction Motor (LIM)

(a) Basic Concept

Generally, there are two types of electric motors: the **rotary motor** and the **linear motor**. They differ in windings, shape and types of motion, but they share common principles and use similar design equations. For any rotary motor, the “**primary**” of the motor, which is a set of stationary windings around a rotating central shaft, generates a rotational electromagnetic field and a torque that makes the central shaft of the motor, which is known as the “**secondary**”, to turn or rotate. In contrast, for any linear motor, the primary generates a sweeping magnetic field and linear force (thrust) in the longitudinal direction (i.e., along the shaft), causing the shaft (i.e., the secondary) to move in the longitudinal direction instead of rotating. For both the rotary motors and the linear motors, the primary (outside windings) is also called the “stator” because it is stationary. Likewise, for both the rotary motors and linear motors, the secondary that moves is often referred to as a “rotor”, no matter whether it rotates (in rotary motors) or undergoes linear motion (in linear motors). So, the term “rotor” is also used in the literature of linear motors, when referring to the secondary of the linear motor. While rotary motors are the most commonly used type of motors, linear motors are also used for linear motions such as closing a sliding door or a sliding window, accelerating and decelerating a roller coaster, driving magnetic-levitated, high-speed trains, etc. It is a well-studied and well-known technology [32-34].

For use in PCPs, each LIM should have a length approximately 50 times the diameter of the pipe when the pipe is round, or 50 times the width of the pipe when the pipe is of square cross-section. Such a LIM can serve a pipeline 100 times the length of the LIM. According to this rule of thumb for designing PCPs, for a PCP that uses 1 m diameter pipe, a LIM of approximately 50 m long will be needed for every 5 km distance along the pipeline. This usually produces a pressure drop along the pipe between LIM stations of no more than 0.3 atmospheric pressure, for a capsule speed about 20 m/s (meters per second) and a maximum linefill of about 20%. Note that linefill is the length of the pipeline occupied by capsules, divided by the total length of the pipeline.

(b) LIM versus LSM

There are several different designs of linear motors-- linear induction motor (LIM), linear synchronous motor (LSM), linear D.C. motor, etc. They can all be used as electromagnetic pumps for driving capsule pipelines [35]. However, most research efforts to date in linear motors for use in capsule pipelines have been focused on LIM [36-41]; only one is known to be focused on LSM [9]. The LIM appears to be a better choice than the LSM for use in pneumatic capsule pipelines (PCPs) for the following reasons:

- LIM uses capsules made of plain metals (steel wall with an aluminum cladding), which is easy to construct, relatively inexpensive, and durable. In contrast, LSM requires a

large number of magnets attached to the capsule surface. It not only drives up the capsule cost, but also requires frequent maintenance to replace damaged magnets.

- LSM requires capsules to operate at a fixed speed – the synchronous speed. Since it is difficult if not impossible to maintain capsule speed at synchronous speed, in practice the synchronous speed is adjusted to fit the capsule speed. This requires a complicated and costly speed control system. In contrast, the LIM can operate at any capsule speed.
- LSM generates zero thrust at standstill, and hence the system cannot self-start. Once the capsules have come to a stop in the LSM, they must be accelerated by another means to the synchronous speed before the system can continue to operate. In contrast, LIM develops maximum thrust at standstill, and can self-start.

Notwithstanding the above advantages of LIM, it should be mentioned that LSM also has some advantages over LIM including the following: (1) It has a slightly higher efficiency at synchronous speeds; (2) its efficiency is less sensitive to the size of the air gap; and (3) it presents a power factor burden on the power supply system. However, these advantages do not outweigh the three severe disadvantages stated above. Consequently, in balance LIM is a better technology than LSM for driving PCPs. In all the potential applications of PCP to New York City in which electromagnetic capsule pumps are required, LIM is the only type recommended.

(c) Planar versus Tubular LIMs

Depending on its geometry, LIM can be further divided into two types: planar and tubular. The planar LIMs have stators of the shape of planes or plates, and the tubular LIMs have stators of tubular shape. The planar LIMs are further divided into two types: single-sided LIMs and double-sided LIMs – see Figure 19.

As shown in Figure 19 (a), the single-sided LIM has a planar stator parallel to an adjacent planar rotor, with a small gap filled with air between them—the air gap. Figure 19 (b) shows a double-sided LIM, with a stator on each side of the rotor. Note that a double-sided LIM is not simply two single-sided LIMs with one on each side of the rotor. For any single-sided LIM, as shown in Figure 19 (a), the rotor plate must have a double layer, with the layer facing the stator being a good conductor such as aluminum or copper, and the layer on the back being a good ferromagnetic material such as iron or steel. Wiring of the stator is such that the electromagnetic flux lines generated by the stator, upon penetration through the conducting layer, enter the ferromagnetic layer and then make a U-turn back through the conducting layer to enter the stator. In contrast, for a double-sided LIM, the rotor plate is simply a conductor instead of a double-layer. Wiring is such that it causes the magnetic flux lines to leave one stator plate toward the other plate on the opposite side of the LIM, so that the flux lines link the two plates together forming closed loops. Finally, as shown in Figure 19 (c), a tubular LIM is a single-sided LIM constructed in the tubular shape. It requires a double-layer rotor as in the case of the single-sided planar LIM. Both the stator and the rotor of the tubular LIM are tubular in shape.

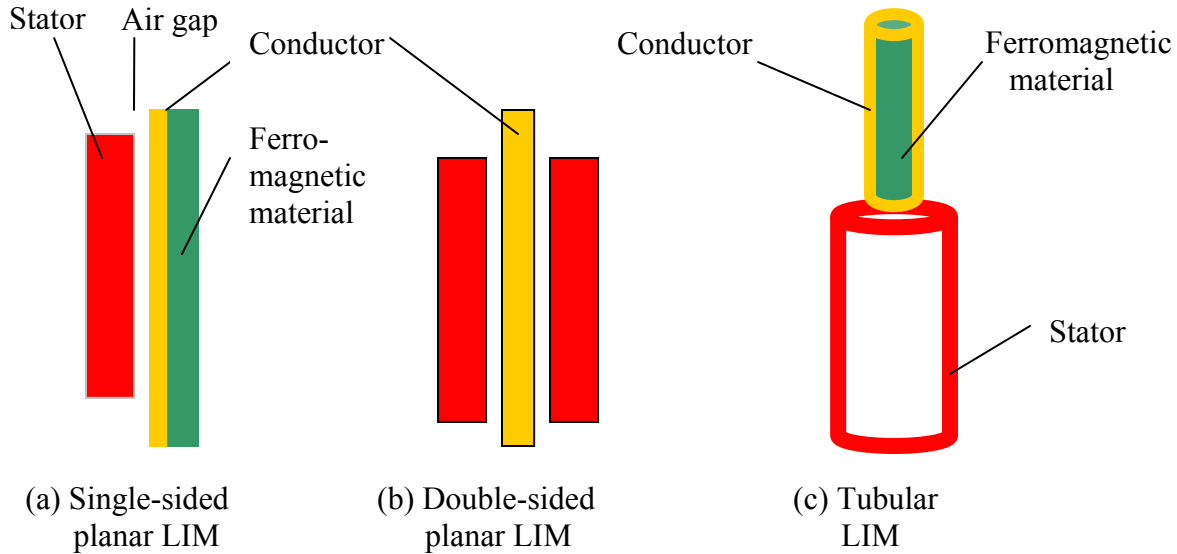


Figure 19 Three types of LIM according to geometry and design

(d) LIMs for PCP Applications in New York City

In three of the six potential applications of PCP for New York City discussed in Section 2, LIMs are required for driving the PCPs. They are assessed briefly as follows:

- For the PCP to transport mail and parcels, the pipeline is a 40-inch-diameter steel pipe. Because the pipe is circular, the tubular type of LIM must be used. The bore (inner diameter) of the LIM will be slightly (about 20 mm) smaller than the inner diameter of the pipe, so that an air gap of approximately 10 mm will be encountered. A smooth transition is required between the pipe and each LIM.
- For the PCP to transport pallet goods, even though the use of tunnel boring machines results in tunnels of circular cross-section, the cross-section of the LIM should be rectangular because the capsule cross-section is rectangular – see Figure 5. In this case, two single-sided planar LIMs will be needed – one on each side of the capsule as shown in Figure 11. While the clearance between the capsule and both the top (ceiling) and the bottom (floor) of the LIM can be relatively large – say 6 inches (152 mm), the clearance between the side walls of the capsule and the LIM walls must be small (10 to 20 mm) in order to maintain a small air gap to achieve high motor efficiency. Smooth transitions are needed between each LIM and the adjoining pipes or tunnels.
- For the PCP to transport containers, regardless of the cross-sectional shape of the tunnel or conduit, the cross-section of the LIM must be rectangular. Therefore, as in the case for pallet goods transport, small clearances of the order of 10 to 20 mm must be maintained between the capsule walls and the LIM walls. Also, smooth transitions must be provided between LIMs and the adjoining pipes or tunnels.

(e) Readiness of the LIM Technology for Use in PCPs

In the last three decades (since around 1975), extensive research and development has been conducted on using the tubular type of LIMs (i.e., TLIMs) for capsule pipelines, most of which at the University of Missouri-Columbia (UMC) [5, 17, 35-37, 39-43]. These studies

included theoretical analyses, laboratory experimentation, and design. Also, large LIMs of the single-sided type (i.e., SLIMs) have been successfully used in a number of commercial applications other than for PCPs, including applications for roller coasters and magnetically levitated high-speed trains. As a result of such extensive R & D in TLIMs for PCPs, and commercial applications of SLIMs for other purposes, sufficient knowledge has been gained to date for the proper design of both TLIMs and SLIMs for use in PCPs. Therefore, it is not necessary to wait for further R & D before TLIMs and SLIMs can be used successfully in New York City and elsewhere for driving PCP systems. However, this is not to say that there is no need for further research and development in TLIMs and SLIMs focused on PCP. In fact, it is beneficial to have both research and commercial applications to progress simultaneously. As it is the case with many other new technologies, through a combination of research and operational experience of commercial systems, the new technology can be further improved to increase its reliability and efficiency. The following is a suggested important R & D project in PCP-LIM that can greatly enhance the state-of-the-art of PCP-LIM at this stage of its development:

Because previous testing of LIMs for use in PCP has included only small-scale laboratory experiments, which used a TLIM of 10-inch diameter and 14-inch length, mounted in a 10-inch-diameter straight pipe of 22-ft length (see Figure 20), and because SLIM has not been tested before for use in PCPs, it is highly desirable to conduct a pilot plant test of a SLIM-driven PCP system, the type needed for transporting pallet freight and containers as shown in Figure 11. The pilot plant test should use a rectangular conduit of a minimum cross section of 1 ft by 1 ft, and a minimum length of 200 ft. This will enable collection of meaningful test data on both the performance of the TLIM and the aerodynamic properties of the system, and comparison of the data with predictions from theory. Such a study will enable the validation of the design equations for PCPs driven by TLIMs, and will provide data on the efficiency and other key properties of TLIMs used for PCP. The test will also provide information needed for the optimum design of any TLIM-driven PCP system. Finally, potential users and financiers of the future PCP systems in New York City will also feel more confident to invest in this new technology when they see such a pilot plant in operation.

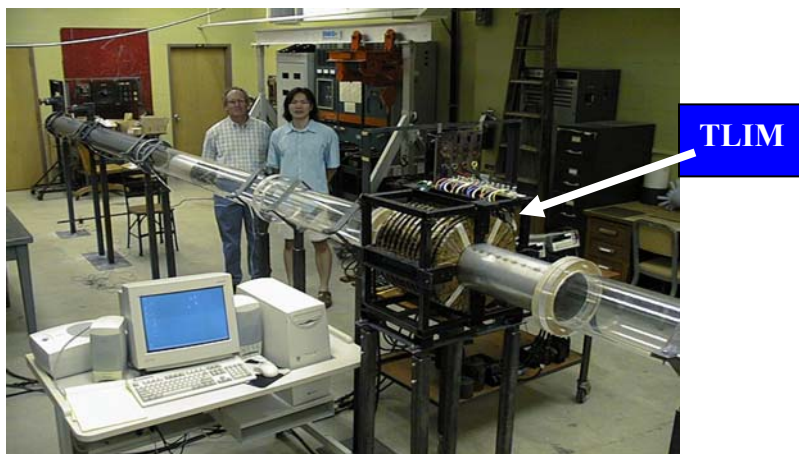


Figure 20 A TLIM of 10-inch diameter and 14-inch length tested at University of Missouri- Columbia. In the background are the two key persons involved in the test: Electrical Engineering Professor Robert O’Connell and his Ph.D student Plodpradista [37].

3.3 Vertical Capsule Transport (Capsule Lift)

Both the PCP system considered herein for use in New York City for tunnel construction, and the system considered herein for pallet-goods transport, would operate deep underground below the City. For the cargoes (raw materials or commercial products) transported by such systems to reach the street level, vertical lifts must be provided. The most practical approach for such vertical lifts appears to be conventional elevators. The vertical lift system for the pallet-tube PCP has already been discussed in Sec.2.2 and hence is not repeated here. The vertical lift system for the PCP for tunnel construction is illustrated in both Figure 21 (vertical profile) and Figure 22 (top view), and described briefly as follows:

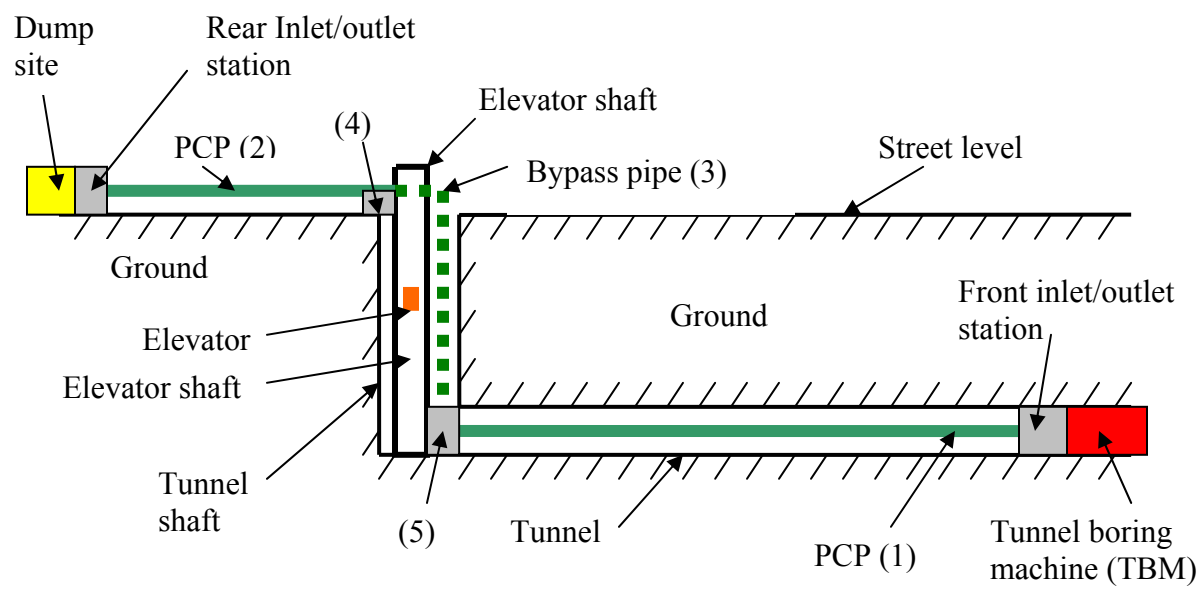


Figure 21 PCP system for underground tunneling (vertical profile).

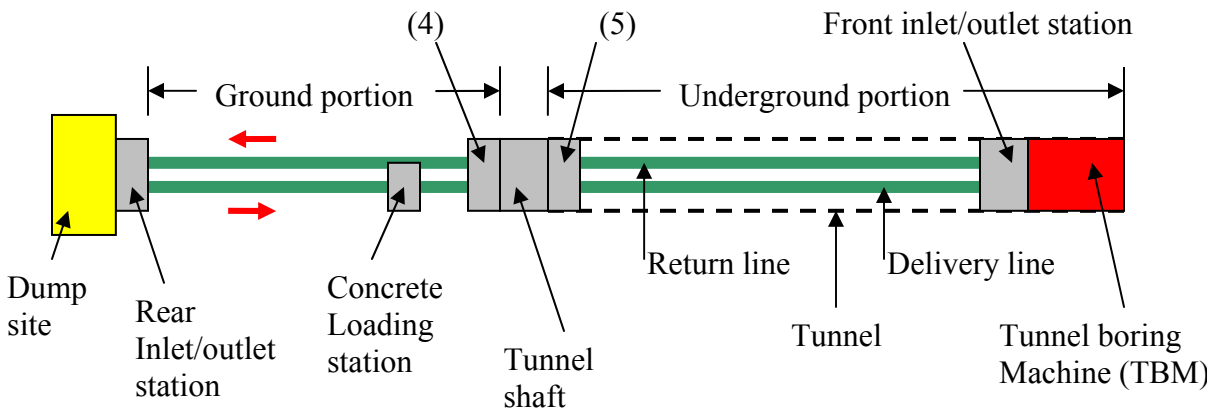


Figure 22 PCP system for underground tunneling (top view)

Referring to Figures 21 and 22 above, the PCP system for tunnel construction consists of six major parts:

(1) The horizontal part down below, and inside the tunnel under construction – This part, designated as “**PCP (1)**” in Figure 21, is extended forwards as the tunnel construction progresses. Dual lines are used with one line – the delivery line – to deliver the premixed concrete needed for tunnel lining, and the other line – the return line—to return capsules filled with excavation materials. Each line has a cross-section of 1m × 1m, and it is made of prefabricated prestressed concrete panels.

(2) The horizontal part at the street level – This part, designated as “**PCP (2)**” in Figure 21, also uses dual-line conduits of 1m × 1m cross-section made of prestress concrete. While one line delivers the premixed concrete for transport into the tunnel, the other line returns the capsule filled with excavation materials – see Figure 22.

(3) The vertical lift – This vertical lift system, shown in Figure 21, is a specially designed industrial elevator system capable of transporting both loaded and unloaded capsules in and out of the tunnel entrance. It serves as the link between the PCP conduit in the tunnel and the one on the street level. The same elevator used to transport capsules from the delivery line going downward can be used later to transport capsules going upwards in the return line. Depending on the size of the elevator, one or more than one capsule can be transported by a single elevator at any given time.

(4) The bypass line -- Inside this tunnel shaft is a bypass conduit or pipe, marked “**bypass pipe (3)**” in Figure 21, connecting PCP (1) with PCP (2). The bypass pipe (3) is parallel to the elevator, and can be operated independent of the elevator. The use of the bypass line will enable the entire PCP to work with a single blower placed at the pipeline entrance – the entrance of PCP (2) which is aboveground; there will be no need for placing a blower in the tunnel where the space is greatly limited. When the two ends of the bypass are connected to PCP (1) and (2), air will flow through the bypass line, causing the capsules in both PCP (1) and (2) to move. A simple outlet structure is located at the end of PCP (2), marked “**(4)**” in Figure 21, to divert capsules from the delivery line to the elevator, and a simple inlet structure, marked “**(5)**”, is located at the beginning of PCP (1) to re-inject capsules from the elevators into the delivery line of PCP (1). The same inlet/outlet structures also serve the return line of the PCP.

(5) Rear inlet/outlet station -- The rear inlet/out station, located at the rear of the PCP system (left of Figures 21 and 22), is the place where capsules arriving with excavated materials discharge their loads into a dumpsite or transfer station, and the emptied capsules are re-injected into the delivery line. It is also where the blower and control room of the system are located.

(6) Front inlet/outlet station – The front inlet/outlet station, located at the front of the tunnel immediately behind the tunnel boring machine (TBM) and designated as “**(5)**” in Figures 21 and 22, allows capsules carrying premixed concrete to dump their loads into a tank behind the TBM so that the concrete can be used for tunnel lining. Then the empty capsules are loaded with excavated materials and re-injected into the pipeline for return to the dump site. The front inlet/outlet station is a moving station. Periodically, it is moved forward as the tunnel construction advances.

3.4 Capsule Identification and Sorting

In PCP applications dealing with cargo transport, capsule identification/sorting (I/S) systems are needed in two places: (1) at the PCP inlet and outlet terminals where individual capsules must be identified and sorted according to their cargo contents, shippers, receivers

(destinations), shipping dates, and so on; (2) inside the pipeline at each branching point where the approaching capsule must be identified and its destination must be determined so that the computer can decide whether to activate a switch and send the capsule to the branch. It has been determined that different types of I/S systems may be needed for inlet/outlet than for use inside the pipeline, and the I/S systems used for different types of PCP systems may also be different, depending on factors such as the pipe size and capsule speed. There are two general types of commercially available I/S systems that can be used for PCP: the barcode system and the radio-frequency identification (RFID) system. They are separately evaluated as follows:

(a) Barcode

At PCP terminals, conventional linear barcodes can be used easily to identify each capsule with a simple hand-held bar code scanner. However, identifying and sorting out moving capsules in the pipe for branching or other purposes cannot be done easily with conventional bar codes because: (1) the barcode system does not work when the object affixed with a barcode is moving at high speed relative to the scanner (say, greater than 20 ft/sec), and (2) when the distance between the barcode (attached to the capsule) and the scanner (attached to the pipe wall) is greater than a few inches, which is the case for large-diameter PCPs.

However, in consultation with T. J. Tarrant of the Accu-Sort System, Inc., a U.S. company that specializes in both barcodes and RFID systems, it is discovered that the low-velocity-response problem of the conventional linear bar code can be remedied by using horizontal (longitudinal) instead of vertical or circumferential bars on capsules. When using barcodes, two types of scanners are needed: stationary scanners when capsules are moving through the pipe, and hand-held moving scanner when capsules are in the terminals. The distance limitation will also not be a problem for PCP systems that are relatively small, such as the 3-ft-diameter PCP recommended for transporting mail and parcel, and the 3-ft-diameter PCP for transporting municipal solid wastes. Therefore, for these two relatively small and smaller systems of PCP, the barcode system is recommended.

(b) RFID System

For large-diameter PCPs, such as those proposed for use in New York City for transporting pallet goods, dispatching containers, or ferrying trucks in Hunts Point, they should use an appropriate RFID system instead of barcode. In consultation with representatives of the barcode industry, it appears that the same system used for identifying moving automobiles that approach toll booths, such as the E-ZPass used in New York City, is applicable to PCPs. This system, based on RFID (Radio Frequency Identification), includes a transponder (identification tag) attached to each vehicle (capsule), an antenna attached to the toll booth (wall of the pipe for the PCP case), a stationary reader placed near the antenna, and a central computer that can be located above ground in a building. The transponder transmits a high-frequency radio signal, which is picked up by the antenna. The signal is read by the reader, which communicates the data to the central computer for processing. By using re-programmable transponders, the same tag can be reused indefinitely for different loads of cargoes headed to different destinations at different time. The system can handle high-speed vehicles or capsules, up to 70 mph. Detection of capsules is unaffected by light, dust, visibility, moisture and vehicle vibration, and hence is highly reliable.

It can be concluded from the assessment that both barcodes and RFID are suitable for use in PCPs under different conditions, and that little research is required before these systems can be used for PCPs. They are both mature technologies that are commercially available.

3.5 Construction (Digging/Pipe-laying) Methods

Different applications of the PCP technology to New York City will require different methods to construct (dig or lay) the pipeline or conduit in order to best suit the individual situations. For instance, the proposed pallet-tube system, being deep underground, will need tunneling; the proposed container dispatch system from seaports to inland rural area will need tunneling for the urban and underwater portions and open-cut method for rural areas; the proposed truck-ferry system for Hunts Point will require a combination of tunneling and open-cut; the proposed PCP for transporting mail and parcels, and the proposed PCP for transporting solid wastes, both using 40-inch steel pipes, will require directional drilling in urban areas, barge laying of pipe in the marine environment, and open-cut in the rural areas; finally, the proposed PCPs for transporting construction materials and excavated materials during tunnel construction, being assembled on the floor of existing tunnels under construction, need no digging of any kind. In what follows, the various construction (digging or pipe-laying) methods for using PCPs in New York City are assessed one by one.

(a) Tunneling Technology

The tunnels needed for future applications of PCPs in New York City will be deep underground—between 100 ft and 200 ft below the street level inside hard bedrock. For constructing tunnels through such bedrock, two methods are applicable: *drill-and-blast*, and *boring*. Drill-and-blast is the century-old technology used for constructing tunnels through hard rocks. It is labor-intensive, relatively slow, and it raises safety concerns when used in urban areas, due to the need for blasting with dynamite. In contrast, large *tunnel boring machines (TBMs)* have been developed and used successfully in recent years. They are relatively fast (advance at an average speed of 30 to 100 ft per day depending on machine type and rock conditions), cost-effective (as compared to the drill-and-blast method), and have a better safety record than the drill-and-blast method. Therefore, the TBM method should be used for constructing the future PCPs under New York City. It is the same method used currently for constructing New York City Water Tunnel No. 3, which is a tunnel of 24 ft diameter, being bored deeply underground (approximately 300 ft below the ground level) through hard bedrocks. Figure 23 shows a typical TBM.

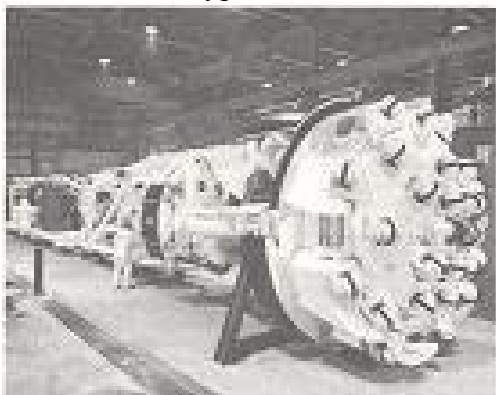


Figure 23. Robbins TBM . (Note that the machine head, i.e., the front part of the machine, contains the rotating cutters which bore through the rock to make a circular hole. The machine advances on legs, and is pushed forward by a hydraulic ram.)

Tunneling underground by TBM is done in several steps. First, a vertical shaft is dug through the soil and the rock to reach the elevation where the tunnel is to be bored. The upper layer of the ground is soil which can be removed by a crane-operated clamshell. The lower layer, consisting of rock, can be broken by the drill-and-blast method and then removed by the clamshell. Sheet piling made of interlocking steel plates, precast concrete ring segments, or slurry walls may be needed during the construction of the shaft to keep groundwater out and to prevent the adjacent soil from collapsing or moving into the shaft. The shaft is finished with an impermeable concrete lining using either cast-in-place concrete or shotcrete. The latter is applied by using a pneumatic nozzle that shoots the concrete onto the walls to be lined. After the shaft has been constructed, the TBM is lowered into the bottom of the shaft and set up to perform boring. Usually, more than one shaft may be needed if the tunnel is longer than a mile. However, if a PCP (pneumatic capsule pipeline) of 1 m by 1 m cross-section is used to remove the excavated rocks out and bring premixed concrete into the tunnel, it becomes practical to construct tunnels much longer than a mile using a single shaft and a single TBM. The special PCP installed for tunneling not only facilitates materials transport in-and-out the tunnel, but also brings fresh air into the tunnel from outside during construction.

As the tunnel is being bored, shotcrete is again used over the rock surface of the tunnel to form a tunnel lining. To have a strong and lasting lining, it may be necessary to attach rock bolts and wire mesh to the tunnel surface before the shotcrete is applied. The tunnel for PCP needs a flat floor to support a railroad track – see Figure 5. Consequently, as soon as the tunnel lining is completed and the TBM is removed from the tunnel, concrete must be brought in to construct the flat floor of the tunnel. The same 1m × 1m cross-section PCP used in the earlier state of the construction can now be used to bring premix concrete for constructing the tunnel floor. With proper construction planning, a portion of the excavated rock can be used to make the concrete for the tunnel lining and the floor – rail base.

For those underground tunnels whose two ends must rise gradually to the ground level, such as the one proposed for ferrying trucks at Hunts Point, portals must be built using the open-cut method. In such cases, after the tunnel construction is completed, construction can be shifted to the portals, which are sloped channels or ramps of about 30° incline. The portals can be built by digging with large construction clamshells and/or excavators for the upper part of the ground consisting of soil, and using the drill-and-blast method for the lower part in hard rocks. The cross-sectional shape of the portals will be rectangular for the upper part connected to the outside, and circular for the lower part connected to the tunnel. A smooth transition will be needed between the two shapes. Sheet piling or another excavation wall support system may again be needed during the construction of portals to prevent soil movement and groundwater infiltration. The portals are finished by constructing a concrete wall and lining.

(b) Open-cut Method

In rural as well as sparsely built-up urban areas, the open-cut method, often referred to alternatively as “cut-and-bury method”, “ditching” or “trenching”, is usually the most common and economical way to lay pipes of any size. This assumes that the pipe will be buried only a few feet underground, normally below the frost line of the ground, below the depth of plowing by farmers (when the pipe is under farmland), or below the depth of ordinary construction activities that requires shallow digging. If a pipe must be laid deep underground (say 50 ft underground to cross a river from under the riverbed), then open-cut would be impractical, and an alternative method, such as directional drilling or microtunneling, will have to be used.

For the various potential applications of the PCP technology in New York City, the open-cut method will be needed in the following places:

- For the PCP to transport municipal solid wastes to a rural disposal site, which is an out-of-state landfill, the bulk of the pipe will be on land and in rural areas. It can be laid most economically by the open-cut method.
- For the PCP to transport mail and parcels from New York City to Washington, D.C., the bulk of the pipe will be laid along the easement of an interstate highway such as I-95. It can be laid most economically by the open-cut method except at the crossings of roads and other obstacles, where either directional drilling or microtunneling will be needed – see (c) in this Section.
- For the PCP to dispatch containers from seaports to an inland station for inspection and intermodal transport, a significant portion of the PCP will be on land and in sparsely built-up or rural areas. This portion again can be constructed most economically near the ground level by the open-cut method.
- For the PCP to ferry trucks in Hunts Point, a route has been selected that enables most if not all of the PCP be built by the open-cut method.

The open-cut method for burying steel pipes, such as the 40-inch pipe for solid waste transport and the 40-inch pipe for transporting mail and parcels, is the same as that used by the oil and natural gas industries for burying oil and natural gas pipes. It is simple and economical. Details as to how to weld and lay such pipes can be found in standard pipeline engineering books such as [44]. On the other hand, for pipes larger than 4 ft diameter, most often they are made of prestress concrete, with or without a steel cylinder inside the concrete. An example is the large prestress concrete pipe of 21 ft diameter used by the Bureau of Reclamation in parts of the Colorado River Aqueduct – see Figure 24. It is constructed in segments along the pipeline right-of-way. Then the segments are lowered into the ditch and joined together, and then buried. Large rectangular conduits made of reinforced concrete such as those used for culverts [45]—see Figure 25 -- also can be used for PCP using the open-cut method. By using the open-cut method, the cost of constructing large conduits can be greatly reduced from that of boring tunnels of the same size through deep underground bedrock. The former often costs only a fraction of the latter.



Figure 24 Construction of the large “tunnel” (inverted siphon) in the Colorado River Aqueduct.



Figure 25 Large box culvert made of reinforced concrete that can be used for constructing large rectangular conduits for PCP using the open-cut construction method. (Photo reprinted from the web page of the Hanson Pipe & Products, Inc. [45])

(c) Microtunneling

Microtunneling is an automated and remote-controlled tunnel boring method for relatively small horizontal tunnels needed usually for gravity pipes to cross roads, streets, runways, and certain other surface structures, without damaging the structures that must be crossed by the pipes from underneath. It is the modern high-tech version of the traditional method of pipe jacking in which a pipe is jacked (i.e., pushed) horizontally through earth at the same time the excavated earth is removed through the jacked pipe by an auger or another means. As is the case with pipe jacking, in microtunneling a vertical shaft (pit) is first dug on both sides of the structure to be crossed by the pipeline. The microtunneling machine is lowered into one shaft to bore the tunnel and jack the pipe. The system is laser guided so that precision control of the horizontal direction and the grade of the jacked pipe is possible. The system is remotely controlled, without having to have any worker inside the tunnel or the jacked pipe. Consequently, it is fast, precise, automated, safe, and economical. The method was first use in Japan in the 1970s, and it is now in widespread use throughout the world [44].

Microtunneling will be needed in the construction of two of the PCP systems in New York City discussed before – the one for transporting municipal solid wastes and the one for transporting mail and parcels. In both cases, a 40-inch-diameter steel pipe will be used, and the pipe will have a large portion (many miles) crossing countryside or being laid along existing highways. There will be hundreds of road crossings for each of these two pipelines, where microtunneling will provide the best and most economical solution.

(d) Horizontal Directional Drilling

Horizontal directional drilling (HDD) is a relatively new technology for laying steel and other flexible pipes across rivers and other obstacles without having to dig a trench across the obstacle. The technology was developed in the mid-1970s, derived from the sophisticated vertical drilling technology used for oil and gas exploration. Unlike oil and gas drillings which

are in the vertical direction, HDD is mainly horizontal. The technology is also simply referred to as “directional drilling” because the drill head is guided by an operator or a computer to maintain a predetermined drill path, and to alter the path as needed. As shown in Figure 26, the path is usually curved of the shape of a parabola in a vertical plane.

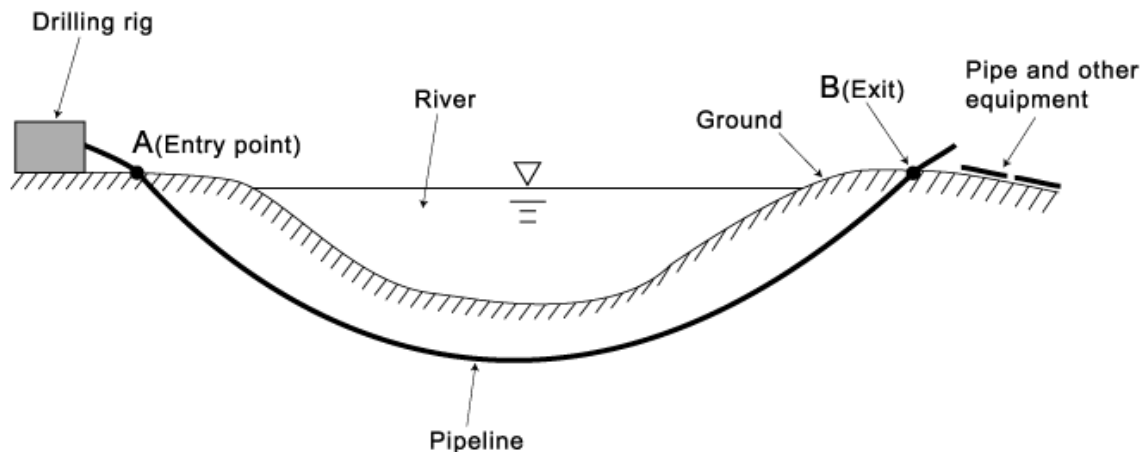


Figure 26 Horizontal directional drilling (HDD) method for laying pipe across wide obstacles.

The HDD laying of pipes is usually done in three essential steps. In step one, a drill rig placed on one side of the obstacle, Point A in Figure 26, drills a hole of a few inches in diameter along the predetermined path of the pipe crossing. In step two, the hole is enlarged by using the drill rig to pull a reamer back using the same drill line. For large holes, reamers of increasing sizes are needed in two or more passes to pierce holes of increased diameters. In step three, which takes place when the hole is sufficiently large, the pipe stored on the opposite side of the obstacle, Point B in Figure 26, is pulled back behind the reamer.

HDD will be needed in the construction of the two PCPs in New York City discussed before that use 40-inch-diameter steel pipe – the one for transporting municipal solid wastes and the one for transporting mail and parcels. In both cases, the pipes can cross rivers such as the Hudson River by using the HDD method. HDD will provide the best and most economical solution to cross such wide obstacles. Current state-of-the-art is such that HDD can go more than 150 ft deep and can have a path length longer than a mile. It is best suited for steel pipes up to 60-inch diameter. More information on HDD can be found in [44].

(e) Marine Pipeline Construction

A significant portion of the 40-inch-diameter steel pipelines for solid waste transport and for transporting mail and parcels can be laid underwater using modern construction technologies for offshore pipelines. This involves the use of a lay barge, which is a barge specially constructed and equipped to lay marine pipelines. The pipeline process is rather sophisticated and efficient – being able to lay more than a mile of pipe a day under normal conditions. Details on how to lay marine pipelines can be found in standard text such as [44], and hence are not repeated here.

3.6 Technological Readiness for Use in New York City

The foregoing technology assessment has shown that all the proposed potential usages of the PCP technology in New York City are based on proven and commercially available technologies such as pipelines, tunnels, railroads, blowers, linear induction motors (LIMs), barcodes, radio-frequency identification (RFID), micro-tunneling, directional drilling, etc., and are within the current capabilities of these technologies. Therefore, no further research is necessary before any of these applications can be implemented in New York City. However, this does not mean that further research is not needed to improve the PCP technology. In reality, research and commercial applications must progress hand-in-hand for many years before any new technology is fully developed and requires no more research. Society cannot afford to wait for the perfection of any beneficial new technology before using it. Special need for R & D at this stage of the development of PCP-LIM has been discussed in Sec.3.2 (e) and hence is not repeated here. Also, as it is the case with other transportation infrastructure systems, all the future applications of PCP in New York City and elsewhere must be carefully planned and designed before they can be built and used successfully. This project sponsored by NYSERDA is merely a feasibility study and not a substitute for the detailed planning and design of such infrastructures for beneficial use in New York City.

Section 4 ECONOMIC ASSESSMENT

In this Section, an economic assessment is made of each of the six applications of the PCP technology to New York City, to be described in the following subsections. Each of the applications to be assessed corresponds to a system described and analyzed in detail in Appendix B. Engineering Calculations. For example, Sec. 4.1 corresponds to Sec. B.1 and so on. Due to the crudeness of the cost data used in this general feasibility study, the engineering cost models used herein to determine the “*total project cost*” and the “*average annual cost*” are also the simplest in engineering economics. It does not warrant the inclusion of many complicating factors such as depreciation rate, return-on-investment (ROI), inflation rate, taxes, etc. More sophisticated economic analyses that include these complicating factors, as used by the author in the analysis of coal log pipeline [48], can be used in the future when any of these projects has developed to a more advanced stage and a more accurate cost analysis is warranted.

4.1 Tunnel Construction

Tunnel construction is an economic use of PCP because the tunnel is constructed **by** rather than **for** the PCP. As such, the tunneling cost is not charged to the PCP cost, which makes this application rather attractive. In what follows, the capital cost and the operation/maintenance cost of this application will first be assessed for the tunneling system described and analyzed in Appendix B.1 The case involves constructing 10 miles of an underground tunnel such as the Water Tunnel No. 3 that is currently being constructed in New York City.

(a) Capital Cost (in million dollars):	<u>\$ Million</u>
1. Prestress concrete panel conduit (1m × 1m cross-section, 26-mile length, assembled on site, reusable 5 times)	\$4.0 ²
2. Blowers (3 blowers, 530 hp each, at \$200/kw).....	\$0.24
3. Speed controllers for blowers (3 controllers, 530 hp each)	\$0.48
4. Inlet/outlet station	\$1.50
5. Loading/unloading at tunnel end	\$0.70
5. Capsules (32 capsules at \$20,000 each)	\$0.64
6. Elevator (6 tons for 300-ft fast lift)	\$2.00
7. Control and communication equipment	\$0.10
8. Engineering (15% of above)	\$1.10
Total capital cost (C_c): \$ 11.1 Million	
(b) Operation/Maintenance Cost (annual cost):	<u>\$ Million/Yr.</u>
1. Salary/wages (for a crew of 15 persons, including fringe benefits)	\$1.50
2. Electricity (900 kw continuously for 365 days at 20 cents/kwh)	\$1.58
3. Others (miscellaneous)	\$1.00
Total operation/maintenance cost (C_{om}): \$ 4.08 million	

(c) Economic Life of the PCP (same as the tunnel construction time, T_T): **2.89 years**

² The concrete panels can be used and reused for at least five times for tunnel construction. The cost for using them only once for 26 miles of conduits is \$12.4 million. If used 5 times, the cost reduces to \$3 to \$4 million for each use.

(d) **Total project cost** for using PCP for tunnel construction:

$$C = C_c + T_T C_{om} = \$11.1 + 2.89 \times \$4.08 = \$11.1 + \$11.8 = \mathbf{\$22.9 \text{ million}}$$

(e) **Bulk volume of excavated materials** transported by the PCP system during tunnel construction (assuming that the bulk volume has 30% voids):

$$10 \times 5280 \times 452 \times 1.3 = \mathbf{31,030,000 \text{ ft}^3}$$

(f) **Volume of premixed concrete transported by the same PCP system** for tunnel construction

(assumed to be 30% of the volume of excavated materials): **9,310,000 ft³**

(f) **Total volume of materials transported by the PCP system during construction:**

$$31,030,000 + 9,310,000 = 40,340,000 \text{ ft}^3 = \mathbf{1,494,000 \text{ c.y. (cubic yards)}}$$

(g) **Average distance that materials are transported** between the tunnel face and the dump site during tunnel construction: $(3 + 13)/2 = 8$ miles.

(h) **Transportation cost per cubic yard of materials transported over 8-mile distance:**

$$\$22,900,000/1,494,000 = \$15.3 \text{ (for 8 miles)}$$

(Note: The above cost of \$15.3 for transporting each cubic yard of excavation and other construction materials over an average distance of 8 miles in tunnels and on city streets is believed to be less than one half of the current cost of using trucks to transport the same materials over the same distance in New York City. The PCP system also has significant benefits in terms of improved safety and reduction in air pollution caused by trucks, as discussed elsewhere in this report.)

4.2 Solid Waste Transport

Solid waste transport is also a promising potential use of the PCP technology in New York City. Its cost effectiveness is now to be determined through the following cost analysis. The system to be analyzed below corresponds to the system calculated in Appendix B.2. The cost for landfill and waste processing center at the end of the PCP that transports the solid waste is not included because it does not belong to transportation cost. It should be assessed separately, and recovered financially from the tipping fees collected at the landfill, and income made by operating the recycling center.

(a) Pipeline Construction Cost (40-Inch-Diameter Steel Pipe)	<u>\$ million</u>
100 miles by open-cut (use Eq.C-12)	124.70
70 miles submarine pipeline (from Sec.B.)	174.58
20 miles to be laid by microtunneling and HDD	249.40

Total pipeline construction cost: \$548.68 million

(b) Capital Cost (C_c):	<u>\$ million</u>
1. Pipeline construction -- from Item (a) above.....	548.68
2. Blowers ³ (total of 32.66 mw at \$200,000 per mw)	6.53
3. Speed controllers for blowers (twice the cost of blowers)	13.06
4. Substation (transformer stations at \$500,000 per mw)	16.30
5. Inlet stations (9 for delivery line and 1 for return, \$1.5 million each).....	15.00
6. Outlet stations (9 for return line and 1 for delivery line, \$1.5 million each).	15.00
7. Capsules (4740 capsules at \$15,000 each)	71.10
8. Valves (20 butterfly valves at \$6,000 each, and 20 gate valves at \$8,000 each, including actuators).....	0.28
9. Control and communication equipment	1.50
10. Others (miscellaneous equipment)	1.00
11. Engineering (10% of above)	68.85
Total capital cost (C_c):	
	\$ 757.30 million

(c) Operation/Maintenance Cost, C_{om} (annual):	<u>\$ Million/Yr.</u>
1. Salary/wages (for a crew of 80 persons, including fringe benefits)	\$ 8.00
2. Electricity (5 mw continuously for 365 days at 20 cents/kwh)	8.76
3. Others (miscellaneous)	\$5.00
Total annual operation/maintenance cost (C_{om}):	
	\$ 21.76 million

(d) Economic Life of the PCP : **T = 30 years** (minimum)

(e) Average annual total cost for this PCP system (C_A):

$$C_A = C_c / T + C_{om} = \$757.3/30 + 21.76 = \$25.24 + \$21.76 = \mathbf{\$47.0 \text{ million}}$$

(f) Weight of solid wastes transported by this PCP system:

$$18,000 \text{ tons/day} = 6,570,000 \text{ tons/year}$$

(g) Cost of transporting each ton of the solid waste through the PCP system:

Average annual total cost of the PCP/ Total weight of solid wastes transported annually through the system = $\$47,000,000/6,570,000 = \mathbf{\$7.15 /ton}$.

(Note: The above cost of \$7.15 for transporting each ton of solid wastes generated in New York City to an out-of-state landfill 55 miles away from the City for disposal is only a fraction of the cost of that paid by the City currently. Using this new system (PCP) instead of the current system (trucks) can save the City at least \$20 per ton of wastes transported. For a total of 6,570,000 tons per year, the annual saving to the City is in the neighborhood of \$130 million, which is rather substantial. In addition to this monetary savings, the City

³ The system requires 27 blowers for the nine intakes of the delivery line for a total of 30 mw, and 3 blowers for the single intake of the return line for a total power of 2.66 mw. The total power rating of the 30 blowers is 32.66 mw.

will benefit from this PCP in other ways as well: reduced traffic jams, accidents and air pollution generated by trucks, which are assessed elsewhere in this report.)

4.3 Mail and Parcel Transport

The PCP for transporting mail and parcel is similar to the PCP for solid waste transport in that it has multiple branches (5 in this case) originating from New York City and a main pipe leading to a place outside the City (Washington D.C. in this case). As in the solid waste case, the PCP uses steel pipes of 40-inch diameter, and uses twin lines. Unlike the solid waste PCP, the twin lines in this PCP move mail and parcels in both direction. Furthermore, this mail/parcel PCP uses linear induction motors (LIMs) instead of blowers, and the capsules use a two-layer wall (steel and aluminum) for efficient interaction with the LIMs. The cost of this system is now to be determined. The data used in making this cost analysis are based on the calculations detailed in Appendix B.3.

(a) Pipeline Construction Cost (40-Inch-Diameter Steel Pipe):	<u>\$ Million</u>
380 miles by open-cut (use Eq.C-12)	\$473.86
40 miles submarine pipeline (from Sec.B.)	99.76
60 miles to be laid by microtunneling and HDD	748.20

Total pipeline construction cost: \$ 1,322 million

(b) Capital Cost (C_c):	<u>\$ Million</u>
1. Pipeline construction -- from Item (a) above.....	1322
2. LIM pumps ⁴ (total of 42 mw at \$800,000 per mw)	33.6
3. Speed controllers for LIM pumps (42 mw at \$400,000/mw)	16.8
4. Substations (transformer stations for 50 mw at \$500,000 per mw)	25
5. Inlet/Outlet stations (10 at \$5 million each).....	50
6. Capsules (29,146 capsules at \$18,000 each)	524.6
8. Valves (48 gate valves at \$8,000 each, including actuators).....	0.38
9. Control and communication equipment	2
10. Others (miscellaneous equipment)	10
11. Engineering (10% of above)	161.04

Total capital cost (C_c): \$ 2,183 million

(c) Operation/Maintenance Cost, C_{om} (annual cost):	<u>\$ Million/Yr.</u>
1. Salary/wages (for a crew of 30 persons at each of the 10 stations, or a total of 300 persons, \$100,000 each including fringe benefits)	30.00
2. Electricity (50 mw continuously for 365 days at 15 cents/kwh)	65.70
3. Others (miscellaneous)	20.30

Total annual operation/maintenance cost (C_{om}): \$ 116 million

⁴ The system requires 48 LIM pumps spaced at an average distance of 10 miles apart, approximately. The total input power to the 48 LIM pumps is 30 mw, with each LIM rated at 625 kw. LIM pumps are assessed at \$500/kw for the LIMs and \$300/kw for the structure to house the LIMs. The total is \$800/kw.

- (d) **Economic Life** of the PCP : **T = 30 years** (minimum)
- (e) **Average annual total cost** for this PCP system (C_A):
 $C_A = C_c / T + C_{om} = 2183/30 + 116 = 72.76 + 116 = \$ 188.76$ million
- (f) **Weight of mail and parcels** transported by this PCP system:
 $W_m = 31,030$ tons/day = 11,320,000 tons/year
- (g) **Cost of transporting each ton of mail and parcels through the PCP system:**
 $C_A / W_m = 188,760,000/11,320,000 = \16.7 /ton.

(Note: Since the total length of the twin pipes is 480 miles, the above cost of \$16.7 is for transporting each ton of mail and parcels for a distance of 480 miles. This is equivalent to 3.5 cents per ton per mile distance, or \$3.50 per ton per 100 miles. It is only a fraction of the cost of that using trucks to transport mail and parcel, and much less than using aircraft to transport mail. Because mail can be transported from New York City to Washington D.C. through this pipeline in as short as 6 hours, the system will be very competitive against contemporary modes of transport of mail and parcel. In addition, New York City and the region will benefit from this PCP in other ways as well: reduced traffic jams, accidents and air pollution generated by trucks, which are assessed elsewhere in this report.)

4.4 Pallet-Tube PCP

A typical cell of the pallet-tube system of PCP for use in New York City has been analyzed in Appendix B.4. The cost effectiveness of the system is assessed as follows:

(a) **Volume of bedrock to be excavated for PCP station: 675,000 ft³**

- Station Chamber – 480,000 ft³
- Walkway Tunnels – 131,000 ft³
- Elevator Shafts (4 shafts, 8 ft × 10 ft × 200 ft for each) – 64,000 ft³

(b) **Capital Cost (C_c):**

	<u>\$ Million</u>
1. Station excavation (675,000 ft ³ at \$75/ft ³)	50.63
2. Tunneling (2000 ft of 7-ft-dia. tunnel, \$1503 per ft as obtained from Eq.C-4.)	3.00
3. Rails (2000 ft in tunnel and 1200 ft in station, at \$300 per ft)	0.96
4. Elevators (4, each for 200 ft of fast lift, \$2 million each)	8.00
5. LIM pumps (207 kw at \$800/kw)	0.17
6. Speed controllers for LIM pumps (207 kw at \$400/kw)	0.08
7. Substations (transformer stations for 400 kw at \$500 per kw)	0.20
8. Equipment in station (other than rails, capsules and battery-operated cars)	1.00
9. Capsules (36 capsules at \$40,000 each)	1.44
10. Battery operated cars for goods delivery to streets (40 cars at \$30,000 each)	1.20
11. Valves (4 gate valves at \$10,000 each, including actuators).....	0.04

12.. Control and communication equipment	2.00
10. Others (miscellaneous equipment)	1.00
11. Engineering (10% of above)	6.97

Total capital cost (C_c): \$ 76.69 million

(g) Operation/Maintenance Cost, C_{om} (annual cost):	<u>\$ Million/Yr.</u>
1. Salary/wages (80 persons, \$100,000 each including fringe benefits)	8.00
2. Electricity (400 kw continuously for 365 days at 20 cents/kwh)	0.70
3. Others (miscellaneous)	2.00

Total annual operation/maintenance cost (C_{om}): \$ 10.7 million

(h) Economic Life of the PCP : T = 30 years (minimum)

(i) Average annual total cost for this PCP system (C_A):

$$C_A = C_c / T + C_{om} = 76.69/30 + 10.7 = 2.56 + 10.7 = \text{\$ } 13.26 \text{ million}$$

(j) Weight of freight transported by this PCP system:

$$W_m = 205,000 \text{ tons/day} = \text{\textbf{74.8 million tons/year}}$$

(g) Cost of transporting each ton of cargo through the PCP system:

$$C_A / W_m = 13,260,000/74,800,000 = \text{\$ } 0.177/\text{ton.}$$

(Note: Since the total length of the twin tunnels is 2,000 ft, the above cost of \$0.177/ton is for transporting each ton of cargoes for a distance of 2,000 ft.. This is equivalent to \$0.468 per ton per mile or \$4.68 per ton per 10 miles. For transportation of goods on pallets or in boxes, crates and bags in New York City where freight transport cost is the highest in the nation, \$4.68 per ton per 10 miles is much below the current cost by using trucks to transport freight in New York City. This shows the cost-effectiveness of the pallet-tube PCP for use in New York City. In addition to cost saving, the use of PCP for this purpose reduces the number of trucks used in New York City, thereby helping to solve the traffic and air pollution problems caused by trucks. Once a dense network of the pallet-tube PCP system is constructed in New York City in a way similar to the City's current subway system, the entire City will be served by the system, resulting in at least 70% reduction in the number of trucks used in the City, which in turn generates great safety and environmental benefits to the City as assessed in the next section of this report.)

4.5 Container Dispatch PCP

The PCP for dispatching containers to and from seaports in New York City to an inland inspection/intermodal-transfer station is similar to the PCPs for solid waste and mail/parcels in that it has multiple branches (4 in this case) originating from New York City and a main pipe leading to a place outside the City (a safe rural area in this case). This pipeline of this system

consists of both round tunnels deep underground for the urban portion and a rectangular conduit near the surface (approximately 5-ft below the surface) for the rural portion. The tunnel portion includes 16 miles for the four branches and five miles for the main, or a total of 21 miles of tunnels of 15-ft diameter. On the other hand, the rectangular conduit portion consists of 15 miles of a reinforced-concrete conduit of 9-ft width and 11-ft height. As with all other cases, twin pipes are used so that capsules can move in both directions and recirculate through the system. The cost of this system is now to be determined. The data used in making this cost analysis are based on the calculations detailed in Appendix B.5.

(a) Pipeline Construction Cost :	<u>\$ Million</u>
42 miles of tunnels of 15-ft diameter (use Eq.C-4)	\$1,218
30 miles of rectangular conduit of 9 ft x 11 ft cross-section (use Eq.C-10)	100.82
<hr/> Total pipeline construction cost: \$ 1, 319 million	
(b) Capital Cost (C_c):	<u>\$ Million</u>
1. Pipeline construction -- from Item (a) above.....	1319
2. Rails-in-pipeline (72 miles at \$300/ft or 1.584 million/mi)	114
3. LIM pumps ⁵ (total of 141 mw at \$800,000 per mw)	112.8
3. Speed controllers for LIM pumps (141 mw at \$400,000/mw)	56.4
4. Substations (transformer stations for 160 mw at \$500,000 per mw)	80.0
5. Inlet/Outlet stations (5 at \$10 million each).....	50.0
6. Capsules (1,504 capsules at \$50,000 each)	75.2
8. Valves (5 gate valves at \$20,000 each, including actuators).....	0.1
9. Control and communication equipment	2
10. Others (miscellaneous equipment)	10
11. Engineering (10% of above)	181.95
<hr/> Total capital cost (C_c): \$ 2,001 million	
(c) Operation/Maintenance Cost, C_{om} (annual cost):	<u>\$ Million/Yr.</u>
1. Salary/wages (for a crew of 30 persons at each of the 5 stations, or total of 150 persons, \$100,000 each including fringe benefits)	15.00
2. Electricity (141mw continuously for 365 days at 20 cents/kwh)	247.0
3. Others (miscellaneous)	50.0
<hr/> Total annual operation/maintenance cost (C_{om}): \$ 312 million	

⁵ The system requires 14 LIM pumps for the twin lines – 2 at the inlet of each of the four branches, and 6 spaced at an average distance of 5 miles apart along the main. The total input power to the 14 LIM pumps is 141 mw, with each LIM rated at about 10 mw. LIM pumps are assessed at \$500/kw for the LIMs and \$300/kw for the structure to house the LIMs. The total is \$800/kw.

- (d) **Economic Life** of the PCP : $T = 30$ years (minimum)
- (e) **Average annual total cost** for this PCP system (C_A):

$$C_A = C_c / T + C_{om} = 2001/30 + 312 = 66.7 + 312 = \$ 378.7 \text{ million}$$
- (f) **Number of containers (TEUs)** transported by this PCP system in either direction:

$$N_{TEU} = 30,210 \text{ TEUs/day} = 11,027,000 \text{ TEUs/year}$$
- (g) **Cost of transporting each TEU from port to inspection/transfer station or vice versa by this PCP system:**

$$C_A / (2N_{TEU}) = 378,700,000 / (2 \times 11,027,000) = \$17.2 / \text{TEU}.$$
- (h) **Gross annual income received by charging a toll of \$30 per TEU for each one-way trip:** $\$30 \times 11,027,000 \times 2 = \660 million
- (i) **Gross annual income with system operating at 50% capacity:** $\$660 \text{ million} \times 0.5 = \$330 \text{ million}.$
- (j) **Net annual profit by operating system at capacity:** $\$660\text{M} - \$379\text{M} = \$281 \text{ million}$
- (k) **Net annual profit by operating system at 50% capacity:** $\$330\text{M} - \$270\text{M} = \$60 \text{ million}.$

(Note: The above calculation shows that when the PCP for dispatching containers in New York City is used to its design capacity, it costs only about \$17 to transport a 20-ft container from a port of the City to an inland rural area for inspection and intermodal transport, and it costs the same for transporting a 20-ft container from the inspection/transfer station to any New York City port for loading on outbound ships. While the dispatching of inbound containers to an inland safe place for inspection can only be justified on grounds of national security, it should be realized that a good portion of the containers arriving from sea at ports of New York City are not for local customers. Rather, they are destined to cities, areas or regions west of the Hudson River or west of the Newark Bay. It costs much more than \$17 to transport any such a TEU across the River or the Bay. Also, the same PCP system for dispatching containers out the seaports of the City to the inland inspection/transfer station is also used to transport containers arriving from west, northwest and southwest of the City, heading for the New York City ports for export. Normally, it costs much more than \$17 to truck a 20-ft container across the Hudson or the Bay to reach the ports. If the Port Authority builds this PCP and charges a one-way toll of \$30 per TEU, which is rather reasonable, the Port Authority will make a net profit of \$13 per TEU. At maximum capacity, the system can transport 22 million TEUs per year in both directions, resulting in a net annual profit of \$286 million. Even at 50% capacity, the system can still make a net annual profit of about \$60 million. This shows that the proposed PCP system for dispatching containers can be justified both on grounds of national security (security to the New York City), and on economic grounds, for cost-effective movement of containers across the Hudson and the Bay area. Use of this PCP system will also reduce the use of trucks in New York City, resulting in significant environmental and safety benefits that will be assessed in the next section of this report.)

4.6 Truck-Ferrying PCP in Hunts Point

The 1.1-mile length, twin-conduit PCP for ferrying trucks between the food center of Hunts Point and the intersection of I-278 and I-895, is shown in Figure 13 and discussed in Sec.2.4. An engineering analysis and calculation of the system is given in B.6. In what follows, the cost-effectiveness of this system is assessed.

(a) Pipeline Construction Cost :

Based on a site evaluation of the proposed route of the PCP for Hunts Point, it was concluded that the CD route (see Figure 13) chosen for this project will allow this PCP to be constructed by using the open-cut method with minimum disturbance to existing structures. By marking all types of existing underground pipelines (gas pipelines, water mains, sewers, power lines, fiber-optic cables, etc.) along the route prior to construction using the current “one-call” system in Bronx, followed by exercising extreme care in open-cut excavation to avoid disturbance of any existing underground structure, the entire PCP in Hunts Point can be excavated by using conventional open-cut construction techniques. The PCP will be constructed of a rectangular conduit of 10-ft width and 15-ft length, made of reinforced concrete – see Figure 25. The top of the conduit will be 5 to 10 ft below the ground level. Due to the need to avoid damage to underground pipes and to fight groundwater infiltration from the Bronx River during construction, it is expected that the cost for open-cut construction in this case will be approximately twice that predicted from Eq.C-10. Consequently, the cost for constructing this 1.1-mile twin-conduit system (of a total length of 2.2 miles) is estimated at **\$ 93.6 million**.

(b) Capital Cost (C_c):

	<u>\$ Million</u>
1. Pipeline construction -- from Item (a) above.....	93.6
2. Rails-in-pipeline (2.2 miles at \$300/ft or \$1.584/mi)	3.48
2. Blowers (total of 852 kw at \$200/kw)	0.17
3. Speed controllers for blowers (852 kw at \$400/kw)	0.34
4. Substations (transformer stations for 700 kw at \$500 per kw)	0.35
5. Inlet/Outlet stations (2 at \$5 million each).....	10.0
6. Capsules (9 capsules at \$60,000 each)	0.54
8. Valves (4 gate valves at \$20,000 each, including actuators).....	0.08
9. Control and communication equipment	1.00
10. Others (miscellaneous equipment)	5.00
11. Engineering (10% of above)	11.46

Total capital cost (C_c): \$ 126 million

(c) Operation/Maintenance Cost, C_{om} (annual cost):

	<u>\$ Million/Yr.</u>
1. Salary/wages (for a crew of 15 persons at each of the 2 stations, or total of 30 persons, \$100,000 each including fringe benefits)	3.00
2. Electricity (568 kw continuously for 365 days at 20 cents/kwh)	0.995
3. Others (miscellaneous)	0.50

Total annual operation/maintenance cost (C_{om}): \$ 4.50 million

- (d) **Economic Life of the PCP : T = 30 years** (minimum)
- (e) **Average annual total cost** for this PCP system (C_A):

$$C_A = C_c / T + C_{om} = 126/30 + 4.5 = 4.2 + 4.5 = \$ 8.7 \text{ million}$$
- (f) **Number of trucks ferried through this PCP system:**
 N_1 (Each direction): 1728/day = 630720/year
 N_2 (Both directions): 3456/day = 1,261,440/year
- (g) **Cost of ferrying a trucks through the PCP:**
One-way: $C_A/N_2 = \$8,700,000/1,261,440 = \6.90
Round-trip: $C_A/N_1 = \$8,700,000/630,720 = \13.8

(Note: The above calculation shows that by using this PCP for ferrying trucks in Hunts Point, the cost is \$6.90 per truck for one-way or \$13.8 for round-trip. Given a choice, most truckers will not want to pay such tolls and take this PCP trip since they can drive this 1.1 miles of one-way distance on regular city streets in Hunts Point without having to pay the toll. The cost saving for them from the fuel saved by taking the PCP and avoiding the driving of 1.1 mile is simply not attractive enough for truckers to pay the toll of this PCP. To finance this project, the City must either subsidize the toll or require truckers to use this toll PCP for access to the Food Center, both of which are unpopular measures. This is the only one of the six potential applications of PCP in New York City studied in this report that cannot be justified purely on economic grounds. Still, the City may like to consider this project for the social and environmental benefits that such a PCP can bring to the City and residents of Hunts Point and Bronx, as discussed before.)

Section 5 BENEFIT ASSESSMENT

In the previous section, it has been shown that except for the truck-ferry application in Hunts Point, the other five potential applications (projects) of PCP to New York City analyzed in this study are all justifiable on economic grounds. In each of these five cases, the cost for transporting freight by a PCP was found to cost much less than transporting the same freight by truck over the same distance. Thus, constructing the PCP for each of the five cases will result in much cost-saving for the City over the life span of the PCP. In addition to this “*direct economic benefit*”, there are other economic, environment and social benefits for all the six cases which were not included in the cost calculations given in the previous section. These additional benefits for each case, referred to as “*external benefits*” in this report”, will be assessed in this Section. However, before assessing each case for these external benefits, the methodology used to make the assessment is first described herein.

5.1. Methodology Used for Assessing External Benefits

The most rigorous method to assess the external benefits of freight transport for any given proposed project in New York City or anywhere else in the nation is to use the STEAM software developed by the Federal Highway Administration [48], which allows an estimate of various benefits that can be developed from the project in terms of the reduction in truck use, travel-time saving, reduced maintenance, noise abatement, and the reduction in vehicular emission of harmful air pollutants such as hydrocarbon (HC), carbon monoxide (CO), nitric oxides (NO_x), and engine-generated particulate matters (PM), which are known carcinogens. However, to use STEAM requires a massive amount of data collected for each project, which is not possible to do in this feasibility study with very limited scope and budget. Consequently, this project did not use STEAM or any other complicated software that requires massive data input. Rather it utilize the results of a major investment study of a related freight project in New York City conducted in 2000 for the NYC Economic Development Commission (NYCEDC) [14]. This EDC project utilized STEAM to assess the potential impacts of several proposed alternatives for improving freight transport across the New York City harbor between the City and New Jersey. In Section 5 of its final report [14], the annual diversion from using trucks for each alternative, in terms of vehicle miles traveled (VMT) by trucks, is given along with the corresponding environmental impacts in terms of the reduction of various air pollutants. For instance, for the rail tunnel alternative with connection to ports, the total project cost was estimated at \$2.15 billion. The project was found to be able to reduce annual truck VMT by 93 million, with a corresponding annual reduction of air pollutants of: 150 tons of HC, 1311 tons of CO, 325 tons of NO_x, and 37 tons of PM. The total is 1823 tons. The above findings shows that for each million of VMT reduced, the tonnage reduction of air pollutants for this cross harbor tunnel rail project is: 1.61, 14.1, 3.49, 0.392 and 19.6, respectively for HC, CO, NO_x, PM, and total air pollutants.

Utilizing the above information extracted from the NYCEDC report, and making the simplifying assumption that for each million of truck VMTs reduced by using any PCP in New York City the reductions of various air pollutants are the same as that given above for the cross harbor freight project, the impacts of each PCP project or potential application studied here in terms of air pollution reduction in New York City can be quantified. This will be the methodology used in Section 5.2 below for assessing the external benefit of each PCP project (potential application). This simplifying assumption used for assessing PCP is believed to be

conservative because it involves switching from truck to PCP rather than from truck to rail. Since the rail planned for the cross-harbor project also uses diesel while the PCP projects use electrical power, diverting from trucks to PCP rather than from truck to rail results in greater reduction in pollutants on the basis of VMT (vehicle-miles traveled) by trucks.

5.2 External Benefits of Each Potential PCP Application

(a) Tunnel Construction

It has been shown in Sec.4.1 that by using a PCP instead of trucks to transport the materials needed for constructing a 10 mile long tunnel of 24-ft diameter (the same type of tunnel currently being constructed by the New York City Department of Environmental Protection (NYCDEP) for water supply), the construction materials can be moved an average distance of 8 miles (5 miles in the tunnel underground plus 3 miles on city street to a dumpsite) at a cost of \$15.3 per cubic yard, which is less than half the current cost by using trucks. In addition to this direct economic advantage, which amounts to over \$ 20 million for a tunnel of 24-ft-diameter and 10-mile length, the external benefits (extra benefits to society) are assessed as follows:

- **VMT (Vehicle-Miles Traveled)** – The total weight of excavated rock to be transported by the PCP for this 10-mile-length tunnel is, from Appendix B.1(b), approximately 2.0 million tons. Since this quantity of material needs to be transported over an average distance of 8 miles to the dumpsite, the weight-distance of the excavation waste materials of this tunnel is $2 \times 8 = 16$ million ton-miles. Assuming that each truck carries 8 tons of materials as assumed in the Cross-Harbor EDC study, $16/8 = 2$ million VMT by trucks are needed for hauling the excavated rocks to the dumpsite, and an equal number of VMTs will be needed for the return trip of 8 mile for the capsules. Thus, the total vehicle-miles of trucks diverted by using PCP in this case is 4.0 million. Considering the fact that this PCP application for a 10-mile tunnel costs only \$11 million to build (capital cost) and \$4 million/yr to operate and maintain, this relatively inexpensive use of PCP causes a significant reduction in the use of trucks and in problems generated by trucks.
- **Air Pollutants Reduced** – Using the figures generated in Section 5.1, by reducing 4 million VMT of truck use the PCP project will reduce pollutant emission for the following amounts: 6.44, 56.4, 13.96, 1.57 and 78.4 tons, respectively for HC, CO, NO_x, PM and the total pollutant.
- **Other External Benefits** – Other external (societal) benefits resulting from a reduction of 4 million VMT of truck use by using PCP for tunnel construction includes: reduced travel time to work and reduced fuel use due to reduced traffic jams caused by trucks, reduced death, hospitalization and loss of work resulting from truck-related accidents, reduced noise generated by trucks, reduced time loss in constructing tunnels resulting from inclement weather, and economic development resulting from the new jobs created and new products sold for use in PCP tunnel construction. These intangible benefits are difficult to assess quantitatively, but are believed to be significant even for a single PCP of 10-mile length. The benefits will be much greater in the future when PCP is used routinely for tunnel construction in New York City. As the City is running out aboveground space and as tunnel-boring cost continues to come down with improvement of tunnel technologies, it is inevitable that more and more underground tunnels will be built in the future in New York City not only for freight and passenger transport but also

for other purposes such as storage, underground shops and shelter from highly unlikely but possible future nuclear attacks. The PCP technology greatly facilitates the construction of such tunnels.

(b) Solid Waste Transport

It has been shown in Sec.4.2 that by using a 40-inch diameter PCP instead of trucks to transport solid wastes from the nine current waste transfer stations in New York City to an out-of-state rural landfill 55 miles away from the City for disposal/processing, a maximum of 6,570,000 tons of solid wastes can be transported through this PCP at an approximate cost of \$ 7.15/ton approximately. This new way of transporting solid wastes can save the city more than \$20 per ton, resulting in a total annual saving of approximately \$130 million. The external benefits (extra benefits to society) are assessed as follows:

- **VMT (Vehicle-Miles Traveled)** – Assuming that each truck carries 8 tons of solid wastes, the number of truck sorties needed for transporting the entire solid wastes of this project is $6,570,000/8 = 821,250$. Considering the fact that each truck sortie includes transporting the solid wastes for 55 miles to the landfill and then returning empty to the transfer station for another 55 miles, the annual VMT of truck transport would be $821,250 \times 55 \times 2 = 90,337,500$ vehicle miles. This means by using this PCP instead of trucks to transport solid waste, approximately 90 million of VMT by trucks will be avoided, which is about the same as can be accomplished by constructing the cross-harbor rail tunnel, which costs \$2.3 billion [14] for the capital cost and \$5 million for the annual operation/maintenance cost. In contrast, the capital cost of the PCP project for solid waste transport is only \$757 million, whereas the operation/maintenance cost is \$22 million. This shows that in terms of replacing trucks, the PCP solid waste project is more cost-effective than the cross-harbor rail project. However, this does not mean that the solid waste PCP is more meritorious than the cross-harbor project because while rail can transport almost all kinds of freight, this particular PCP is for transporting a single cargo only – solid wastes. It cannot be used to transport other cargoes. Each is justified on its own merits.
- **Air Pollutants Reduced** – Using the figures generated in Section 5.1, by replacing 90 millions VMT by trucks, this PCP for solid waste transport can reduce pollutant emission of the following amounts: 145, 1269, 314, 35.3 and 1763 tons, respectively for HC, CO, NO_x, PM and the total pollutant.
- **Other External Benefits** – Other external (societal) benefits resulting from a reduction of 90 million VMT by using PCP for tunnel construction include: reduced travel time to work and reduced fuel use due to reduced traffic jams caused by garbage trucks, reduced death, hospitalization and loss of work resulting from garbage-truck-related accidents, reduced noise generated by garbage trucks, reduced need for storage of garbage at garbage transfer stations, reduced downtime in transporting solid wastes resulting from inclement weather, and economic development resulting from the new jobs created and new products sold for use in PCP tunnel construction. Finally, due to the automatic control of capsules through pipeline, the chance of capsule accidents inside the pipeline is much less than that of trucks, and besides, accidental spills of solid wastes, if any, will be confined within the pipe and hence will not harm the environment or the public. These intangible benefits are difficult to assess quantitatively, but are believed to be huge due to the large number of truck-miles displaced – 90 million VMT each year. Moreover, once

the garbage is centralized at a single large out-of-state rural landfill as in this PCP application, processing of the solid wastes for recycling or beneficial use will be facilitated.

(c) Mail and Parcel Transport

As shown in Appendix.B.3, by using a 40-inch diameter PCP instead of trucks to transport mail and parcels from New York City to cities along the East Coast reaching Washington D.C., the pipeline can move 11.32 million tons of mail and parcels annually, at a cost of 3.5 cents per ton per mile. Since this is only a fraction of the cost paid currently by the U.S. Postal Service and private carriers for moving mail and parcels along this corridor, huge savings of the order of hundreds of million dollars a year can be saved by using this PCP. In addition, the system has the following external benefits:

- **VMT (Vehicle-Miles Traveled)** – Assuming that each mail truck carries 8 tons of mail and parcels, the number of truck sorties needed each year for transporting the entire mail and parcels transported by the PCP will be $11,320,000/8 = 1,415,000$. Assume that each truck sortie transports mail and parcel to an average distance of 100 miles, the annual VMT for mail and parcels transported in both directions is $1,415,000 \times 100 \times 2 = 2.83 \times 10^8$ vehicle miles. This means by using this PCP instead of trucks to transport mail and parcels along this East Coast corridor, **approximately 283 million VMT of trucks will be avoided**, which is approximately 3 times the avoided VMT of the cross-harbor rail tunnel project. The capital and annual operation/maintenance costs of this PCP stretching from New York City to Washington D.C. are \$2.18 billion and \$116 million, respectively. The capital and annual operational cost of the cross-harbor tunnel project are \$2.15 billion and \$5 million, respectively. Again, comparing them does not mean either of the two projects is better than the other. While the cross-harbor rail project can transport almost any kind of freight including freight in containers, this particular PCP is for transporting mail and parcels only, and if capacity allows, to transport some other materials or cargoes that can be fitted in a 38-inch-diameter capsule 10-ft long. Besides, they are for different purposes serving different customers in different places. Comparing them will be like comparing apples with oranges. Each of the two projects is justified on its own merits.
- **Air Pollutants Reduced** – Using the figures generated in Section 5.1, by replacing 283 millions VMT by trucks, this PCP for solid waste transport can reduce pollutant emission of the following amounts: 456, 3990, 988, 111 and 5545 tons, respectively for HC, CO, NO_x, PM and the total pollutant.
- **Other External Benefits** – Other external benefits derived from a reduction of 283 million VMT resulting from using PCP for tunnel construction includes: faster and more secure transport of mail, reduced travel time to work and reduced fuel use due to reduced traffic jams caused by mail trucks, reduced death, hospitalization and loss of work resulting from mail-truck-related accidents, reduced noise generated by mail trucks, reduced downtime in transporting mail and parcel resulting from inclement weather, and economic development resulting from the new jobs created and new products sold for use in the PCP. Finally, due to the automatic control of capsules through pipeline, the chance of mail or parcels lost during transportation by PCP is much less than that for trucks. These intangible benefits are difficult to assess quantitatively, but are believed to be huge due to the large number of truck-miles displaced – 283 million VMT each year.

(d) Pallet-Tube PCP

As discussed before, by using a network of 7-ft-diameter tunnels bored through the bedrock from 100 ft to 200 ft under the streets of New York City, any freight that is normally shipped on pallets or in crates, boxes or bags can be transported through such a network from and to any neighborhood of New York City, in much the same manner that passengers are transported by the current subway system. A typical cell of the network, consisting of a PCP inlet/outlet station and encompassing an area of 1,000 ft by 1,000 ft approximately, has been analyzed in Appendix B. Each tunnel can operate with a maximum cargo throughput of 74.825 million tons per year. As shown in Section 4.4, the total capital cost for the cell is \$76.7 million, and the operation/maintenance cost is \$10.7 million. It was determined that the average transportation cost of cargoes through this PCP network is \$0.468 per ton per mile, which is less than 50% of the average freight transport cost by trucks in New York City today. Therefore, using this PCP network can bring not only great convenience but also great cost savings to New York City. In addition, the system has the following external benefits:

- **VMT (Vehicle-Miles Traveled)** – Assuming as before that an average truck carries 8 tons of goods, the number of trucks passing through a PCP cell as shown in Figure B-1 is then $74,825,000/8 = 9,353,000$ trucks each year. Because the cell length is 1,000 ft one-way and 2,000 ft in both directions, the VMT for the cell is $9,353,000 \times 2,000/5280 = 3,543,000$ VMT per year per cell. This means by using the pallet-tube PCP instead of trucks to transport freight in New York City, approximately 3.543 million VMT of trucks will be avoided each year by each cell. For a dense network of cells that covers the entire New York City of 320 square miles, which contains 2920 of such cells, the total VMT avoided each year will be $3,543,000 \times 2920 = 10,350,000,000 = 10.35$ billion VMT, which is huge. Even if only 10% of the system capacity is reached, each year approximately 1 billion VMT would be avoided by this future pallet tube PCP system operating in New York City, which is still huge – approximately 10 times that can be avoided by implementing the cross-harbor rail freight project.
- **Air Pollutants Reduced** – Using the figures generated in Section 5.1, by replacing 3.543 million VMT by trucks, each 1,000 ft by 1,000 ft cell of PCP for transporting goods in New York City can reduce pollutant emission of the following amounts: 5.7, 50.0, 12.4, 1.4, and 69.4 tons, respectively for HC, CO, NO_x, PM and the total pollutant.
- **Other External Benefits** – Other external benefits resulting from a reduction of 3.543 million VMT caused by using PCP for freight transport in a cell of an area of 1,000,000 ft² include: faster and more secure transport of freight, reduced travel time to work and reduced fuel use due to reduced traffic jams caused by trucks, reduced death, hospitalization and loss of work resulting from truck-related accidents, reduced noise generated by trucks on City streets, reduced downtime in transporting freight resulting from inclement weather, and economic development resulting from the new jobs created and new products sold for use in the pallet-tube PCP. These intangible benefits are difficult to assess quantitatively, but are believed to be significant for each cell, and huge for a network covering the entire New Year City. Over 70% of trucks in New York City can be displaced by such a network, having far-reaching implications for the City.

(e) Container Dispatch PCP

The purpose of the container dispatch PCP is to take containers delivered by ships arriving at the ports of New York City and quickly send them through an underground/underwater PCP to an inland inspection station in a less populated area. The same system also takes containers arriving on trucks from continental U.S.A., inspect them at the inspection station, and then send them through the same PCP system to New York City ports for export. The PCP system is needed mainly for the security of the container ports of New York City and the adjacent New Jersey areas. However, as seen from the cost analysis in Section 4.5, at the design capacity of 11 million TEU the cost for transporting each TEU through the system of 24-mile one-way distance is \$17.2. If a toll of \$30/TEU is assessed, the system can earn a net profit of 281 million per year. Even when operating at 50% capacity, the system can still make a profit of \$60 million approximately. This shows that the system can make money at the same time meet an important national security need. With such a system, NYC will be able to inspect every container entering the City from overseas at a remote location, so that terrorists will not be able to smuggle in explosive in containers and detonate it in the City. The system also has many other advantages to be discussed next.

- **VMT (Vehicle-Miles Traveled)** – Assuming that when trucks are used to transport containers to and from New York City ports, each TEU is carried by a separate truck. The average one-way distance for transporting the container from the inspection/intermodal-transfer station to a New York City port is 24 miles. If the proposed PCP is used to its design capacity, the number of VMT (vehicle-miles traveled) avoided by the PCP is $22,000,000 \times 24 = 528$ million, which is an enormous amount of use of trucks. Even at 50% capacity, the system still avoids $528,000,000 \times 0.5 = 264$ million VMT which is a huge amount of truck usage for New York City.
- **Air Pollutants Reduced** – This PCP at 50% capacity can reduce annual emission of pollutants of the following amounts: 425, 3720, 921, 103 and 5170 tons, respectively for HC, CO, NO_x, PM and the total pollutant. These figures will be doubled if the system is used at design capacity.
- **Other External Benefits** – Other external benefits resulting from a reduction of 264 million VMT (at 50% capacity) caused by using PCP for dispatching containers to and from the seaports of New York City include: faster and more secure transport of containers to and from ports, freeing up a large amount of space at each port currently used to store containers, changing each container port in New York City from a large truck depot to a truck-free area which can be used to build stores and restaurants for the enjoyment of local residents and tourists, reduced travel time to work and reduced fuel use due to reduced traffic jams caused by container trucks, reduced death, hospitalization and loss of work resulting from container-truck-related accidents, reduced noise generated by container trucks on City streets, reduced downtime in transporting containers resulting from inclement weather, and economic development resulting from the new jobs created and new products sold for use in the container-dispatch PCP system. These intangible benefits are difficult to assess quantitatively, but are believed to be huge for New York City.

(f) Truck-Ferrying PCP in Hunts Point

The PCP in Hunts Point is to ferry (piggyback) entire trucks on large capsules over a short distance of approximately 1.1 miles, so that the large number of trucks (including tractor trailers and other smaller vehicles for freight transport) that come to the Hunts Point peninsula to pick up foods at the large food-processing centers at the southeast corner of the peninsula can bypass the downtown area. The purpose here is to reduce problems caused by trucks in Hunts Point, solving mainly a social-environmental problem. It has been found from the cost analysis presented in 4.6 that this proposed PCP system cannot be justified on economic grounds. However, since the economic analysis does not include external benefits such as reduced air pollution and accidents caused by trucks, the project is still worthwhile to pursue if external benefits are taken into account, as to be discussed next.

- **VMT (Vehicle-Miles Traveled)** – Since the system designed here can avoid the use of 3,450 trucks a day for a distance of 1.1 miles, the daily VMT of the system is $3450 \times 1.1 = 3795$, and the annual VMT is 1.385 million. This represents a large number of trucks concentrated in a small area, making it an acute problem for the residents of Hunts Point.
- **Air Pollutants Reduced** – Because the annual VMT of trucks avoided by this PCP is 1.385 million, the system can reduce annual emission of pollutants of the following amounts: 2.2, 19.5, 4.8, 0.54 and 27.1 tons, respectively for HC, CO, NO_x, PM and the total pollutant. Even though these numbers are small as compared to the other more costly projects, it should be realized that these air pollutants are concentrated in a small area – Hunts Point -- and hence has stronger impact on the residents in Hunts Point than elsewhere in New York City.
- **Other External Benefits** – Other external benefits resulting from this PCP in Hunts Point include the following: (1) the ground surface above this underground PCP can be turned into a waterfront park along the Bronx River--the park provides a nice recreational area for the residents of Bronx, (2) much improved traffic through Hunts Point, resulting in reduced noise, accidents and damages to streets caused by trucks, and (3) better quality of air and less health problems (fewer asthma and cancer) caused by the emission of diesel trucks. The dollar values of these intangible benefits are difficult to assess quantitatively. Nonetheless, these benefits are believed to be very significant for the residents of Bronx, especially of Hunts Point.

Section 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the investigation conducted through this study, the following conclusions can be reached:

(1) It is both technically and economically feasible to use the technology of pneumatic capsule pipeline (PCP) to transport freight in New York City for a variety of cargoes including construction materials, municipal solid waste, mail and parcels, goods normally transported on pallets or in boxes, crates and bags, and entire containers.

(2) Six different applications of PCP in New York City have been evaluated in this study, five of which were found to be justifiable on economic grounds. The one that does not pay off economically, a project in Hunts Point for reducing truck use in the peninsula, can be justified for its benefits to community and environment.

(3) All of the six applications of PCPs in New York City can bring great social and environmental benefits to the City, derived from the reduced use of trucks in the City for freight transport. For instance, the use of PCP for tunnel construction not only cuts cost but also eliminates the use of trucks entirely for removing the excavated materials out of the tunnel for disposal, and for bringing in construction materials such as concrete for tunnel lining. By doing so, all the truck-related accidents and pollution generated by using trucks for tunnel construction can be avoided. In the case of using PCP to transport solid wastes from the waste transfer stations to an out-of-state landfill using a 40-inch-diameter steel pipe, the PCP will not only save more than \$100 million a year for the City but also eliminates the need for all the diesel powered vehicles and vessels currently used for transporting the City's wastes to out-of-state landfills. In the case of the PCP system that uses 7-ft-diameter tunnels under New York City for transporting goods that are placed on pallets or in boxes, crates and bags, again the system saves money and eliminates most of the trucks currently used for delivering goods to buildings.

(4) The PCP for dispatching containers from (to) the ports of New York City to (from) an inland remote station for inspection and intermodal transport is needed primarily for port security. Such a PCP system will enable inspection of every container arriving from overseas, and will make it very difficult for terrorists to use uninspected containers in their criminal activities. However, even though this system is needed primarily for security reason, the Port Authority of NY/NJ can derive great financial benefits from the toll collected, and the City can derive great economic and social benefits from this PCP, in terms of increased use of waterfront land for shops and entertainment, and reduced air pollution, traffic jam and accidents – all resulting from a drastic reduction of trucks in and out the ports.

(5) The PCP for transporting mail and parcels from (to) New York City to (from) Washington D.C. and cities between, using a 40-inch-diameter steel pipe, significantly reduces the cost of mail and parcel transport, and reduces delivery time. The pipeline also has enormous social and environmental values, such as reduced traffic jam and accidents on highways, and reduced air pollution and noise, all resulting from a drastic reduction of trucks used for mail and parcel transport.

(6) If all the six applications evaluated in this study are fully implemented in the future, the use of trucks for transport in New York City would reduce by approximately 70%, which in turn would bring enormous advantages to New York City in terms of reduced traffic jam and accidents, reduced air pollution, reduced noise, and quicker and more reliable delivery of freight

than possible today using trucks. It is not an exaggeration to say that PCP is one of the most effective way to reduce truck use in New York City. This is not to say that existing plans to use other means to reduce truck use, such as building a cross-harbor tunnel for connecting rail to New York City, is not meritorious. They all help to reduce the use of trucks and improve the quality of life in the City.

(7) The use of PCPs in New York City would bring great economic development opportunities to the City and the State. Such opportunities will create new jobs and increase the tax base of the City/State. A new industry – the PCP industry-- will be created in and around the City, offering services in PCP not only for the City and the State but also for the rest of the nation and the world. Many allied industries that serve the PCP industry will also grow in the City/State or be attracted to the City/State.

(8) It will take decades and billions of dollars to fully implement PCP in New York City. However, planning should start as soon as possible so that the City and the State can benefit from this meritorious new technology as soon as possible. Delays in planning will also increase the difficulties and cost of constructing future PCPs. As time passes, there will be more and more infringements of the underground space needed for PCPs by other unplanned infrastructures.

(9) To best plan the future use of the underground space of New York City for PCP and other purposes, the City would need to start a new zoning process for the underground (vertical zoning) in a manner similar to the zoning of the aboveground (horizontal zoning). Incidentally, in 2004, a new Japanese law, called “Ultra-Deep Underground Law,” came into effect. The law, aimed at three Japanese metropolises – Tokyo, Osaka and Nagoya—grants the right of using underground space deeper than 40 m to public utilities only, and restricts private developments in this zone.

(10) Large amounts of capital are required to finance the various PCP projects in New York City. The best way to finance such projects is through a partnership between government and industry. Different projects may require different roles for the government and the industry. For instance, for using PCP to construct tunnels, the government’s role would be simply to encourage such use in the bidding process of all future tunneling projects, by pointing out in the bid requests that the bidders (private contractors) should consider using PCP as a possible alternative to trucks for transporting construction materials during tunnel construction. For the solid waste transport project, the government (City of New York) must play a much stronger role. The City should plan the PCP system, issue a government bond to attract the necessary capital needed for constructing the project, and issue a bid request for the project once the financing is secured. Since the landfill connected to the PCP would be outside the City, possibly in New Jersey, the City should either purchase the landfill or form a compact with the state and/or local government housing the landfill for long-term use of the facility. The City may choose to operate the pipeline and the landfill either by City employees or by private contractors. For the PCP to dispatch containers, the Port Authority of NY/NJ would need to make similar arrangements. Due to its high value in enhancing port security and preventing terrorist attacks, this port project is also an excellent candidate for a major grant from the federal government (Department of Homeland Security and the Congress) to plan and even to finance part of the construction. For the PCP network to transport pallet freight in New York City, different government agencies may be involved in different stages. For instance, initial planning and sponsorship of a major investment study may be done by the Economic Development Commission. Financing could be done by issuance of bonds and/or other means. As with all other PCP projects, construction would be done by private contractors selected through bids.

Once the system is built, either a new agency similar to the Metropolitan Transportation Authority (MTA) could be created to run this network of underground tunnels for freight transport, or the duties of the MTA could be expanded to include running this system. In the PCP project for transporting mail and parcels, any of the beneficiaries of the project – the New York City, U.S. Postal Service, United Parcel Services, Federal Express, Airborne, one or more pipeline companies, etc. – could take the lead in the initial planning process. Through a planning study, a joint partnership may emerge with multiple partners involving all or most of the beneficiaries, the U.S. Department of Transportation, and the transportation departments of the states through which the pipeline will pass. Final financing of the project would come from the principal beneficiaries, and the mail/parcel pipeline may be run by a consortium of the beneficiaries. In the case of the Hunts Point PCP for ferrying trucks, EDC which is in charge of the economic development of Hunts Point should first determine whether there is sufficient local interest in Hunts Point and in Bronx for the project. If sufficient interest is found, the agency could then sponsor a detailed planning study to pave the way for implementation. Finally, inclusion of these potential applications of PCP in the transportation planning of the region would be within the realm of responsibility of the New York Metropolitan Transportation Council (NYMTC).

6.2 Recommendations

Recommendations to the sponsor of this feasibility study and to individual stakeholders are given next:

(a) To the Sponsor—New York State Energy Research and Development Authority

(NYSERDA): Consider sponsoring a project to demonstrate the PCP technology using linear induction motors and special capsule identification/sorting technologies including both bar codes and radio-frequency identification (RFID). Such a project would pave the way for future applications of PCPs in New York City. The demonstration project would be justified due to the promising results found through this feasibility study, and the readiness of the enabling technologies. However, due to the high cost anticipated of any demonstration project, which may be beyond the ability of NYSERDA to support, alternately the agency may want to consider a pilot plant study, as discussed in Sec.3.2 (e), which would cost much less to pursue.

(b) To individual stakeholders:

New York City Department of Environmental Protection (NYCDEP) – Consider and encourage the use of PCP technology in current and future construction of City Water Tunnel No. 3, and in all other future projects of the Department that involve construction of new tunnels. The Department may benefit greatly from the use of this new tunneling technology, in terms of safety, emission reduction, and cost saving.

New York City Department of Sanitation (DSNY) – Consider the use of PCP for transporting municipal solid wastes in the manner considered and analyzed in this report. Conduct or commission a detailed planning study to pave the way for beneficial use of the system.

U.S. Postal Service, Federal Express, United Parcel Service and DHL (Airborne) – Start considering the mail/parcel PCP considered and analyzed in this report. Sponsor a more detailed planning study to pave the way for implementation.

Port Authority of New York and New Jersey (PANYNJ) – Consider the use of PCP for dispatching containers at ports considered and analyzed in this report. Sponsor a detailed

planning study to pave the way for beneficial use of the system. Discuss with the Department of Homeland Security and the U.S. Department of Transportation about this new technology and the possibility of securing a federal grant to demonstrate this new technology in New York and New Jersey.

New York City Economic Development Corporation (NYCEDC) – Consider the Hunts Point project and the pallet-tube PCP system. Consider sponsoring a detailed planning study for one or both of these projects.

APPENDICES:

A. REFERENCES

B. ENGINEERING CALCULATIONS

C. CONSTRUCTION COST OF PCP

Appendix A

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Appendix B

ENGINEERING CALCULATIONS

In what follows, preliminary engineering calculations are performed on each of the six applications of PCP in New York City discussed in Section 2. The calculation determines the key parameters of each case such as the capsule throughput, number of capsules needed for operation, freight throughput, pressure drop along the pipeline, power required to run the pipeline, etc. These parameters are then used in the determination of the approximate cost of each PCP system in Section 4 ECONOMIC ASSESSMENT. It should be realized that the calculations here are based on somewhat arbitrary designs rather than optimized designs, which are beyond the scope of this project. Therefore, future engineers who consider the final design of each of these projects should optimize the design parameters and perform more accurate computations for each case than conducted here, so that the performance of the systems designed will be even better than those obtained here through a somewhat arbitrary design.

B.1 PCP for Tunnel Construction

(a) System Description

A PCP is considered here for transporting materials in and out of a 24-ft-diameter tunnel under the New York City. The tunnel is constructed by using a TBM (tunnel boring machine) that advances at 50 ft/day. The PCP conduit, of 1m x 1m cross-section, is made of prestressed concrete panels – the same kind used for constructing the Akima railroad tunnel in Japan shown in Figure 2. The New York City tunnel considered here is 300 ft underground, and has a total length of 10 miles. Twin conduits are used, one stacked on the top of the other. One of the conduits serves as the **receiving line**, which receives the excavated material from the tunnel for disposal at a landfill 3 miles away from the tunnel entrance. The other twin conduit serves as the **delivery line**, which delivers into the tunnel both empty capsules and capsules carrying premixed concrete. So, the total length of the PCP, including the pipes both inside and outside the tunnel, is 13 miles for the delivery line and 13 miles for the receiving line. The system is similar to the one shown in Figures 21 and 22. Because the volume of the premixed concrete needed for tunnel construction is only about 30% of the volume of the excavated materials, two out of three capsules entering the tunnel will be empty, and the third will carry concrete. The same type of capsules and the same type of equipment for operating the PCP in the Akima Tunnel will be used here – see Figures 3 and 4. The PCP uses a 300-ft vertical lift (elevator) at the tunnel entrance to transport capsules in and out the tunnel, as illustrated in Figure 21.

(b) Calculations

Freight volume estimates:

$$D_T \text{ (Diameter of tunnel)} = 24 \text{ ft}$$

$$L_T \text{ (Length of tunnel)} = 10 \text{ miles} = 52,800 \text{ ft}$$

$$A_T \text{ (Cross-sectional area of tunnel)} = \pi D_T^2 / 4 = 452 \text{ ft}^2$$

$$S_T \text{ (Tunnel construction speed)} = 50 \text{ ft /day}$$

$$T_T \text{ (Time to complete tunnel construction)} = L_T / S_T = 52,800 / 50 = 1056 \text{ days} = 2.8932 \text{ years}$$

$$V_R \text{ (Volume of rock excavated per day by tunneling)}$$

$$= A \times S_T = 452 \times 50 = 22,600 \text{ cu.ft}$$

$$S \text{ (Specific gravity of the rock)} = 2.67 \text{ (assumed to be a hard rock such as granite)}$$

$$w_R \text{ (true weight of rock per cu.ft.)} = 2.67 \times 62.4 = 167 \text{ lb/ft}^3$$

$$w_B \text{ (Bulk weight of rock per cu.ft, assuming 30\% air volume)} = 128 \text{ lb/ft}^3$$

$$W_D \text{ (weight of rock excavated per day)} = V_R \times w_R = 22600 \times 167$$

$$= 3,770,000 \text{ lbs} = 1,890 \text{ tons}$$

$$V_B \text{ (Bulk volume of excavated rock per day)} = 30\% \text{ more than } V_R = 29,400 \text{ cu.ft}$$

$$V_{BY} \text{ (Bulk volume of excavated rock per year)} = 365 V_B$$

$$= 10.731 \times 10^6 \text{ cu.ft} = 397,444 \text{ cu.yard.}$$

$$V_{BT} \text{ (Total bulk volume of rock removed for entire tunnel of 10-mile length)}$$

$$= T_T \times V_{BY} = 2.8932 \times (10.731 \times 10^6) = 31,047,000 \text{ cu.ft} = 1,149,000 \text{ cu.yard.}$$

$$W_T \text{ (Total weight of rock to be transported for the entire tunnel)}$$

$$= w_B \times V_{BT} = 128 \times 31,047,000 = 3.974 \times 10^9 \text{ lbs} = 2.0 \text{ million tons approximately.}$$

Capsule calculation:

$$L_c \text{ (length of capsule)} = 3\text{m} = 9.84 \text{ ft}$$

$$V_O \text{ (Volume of each capsule)} = 0.7\text{m} \times 0.9\text{m} \times 3\text{m} = 1.89 \text{ cu.m} = 66.7 \text{ cu.ft}$$

$$W_{RC} \text{ (weight of rock carried in each capsule, assuming 80\% full)} = V_O \times w_B \times 0.8$$

$$= 66.7 \times 128 \times 0.8 = 6830 \text{ lbs} = 3.4 \text{ tons}$$

$$W_O \text{ (Dead weight of each capsule)} = 2.0 \text{ tons}$$

$$W_C \text{ (Weight of each loaded capsule)} = W_{RC} + W_O = 3.4 + 2.0 = 5.4 \text{ tons} = 10,800 \text{ lbs}$$

$$V_C \text{ (Capsule velocity -- design value)} = 25 \text{ mph} = 36.7 \text{ ft/s}$$

$$S_O \text{ (Number of capsule sorties launched per day)} = V_B / V_O = 29400/66.7 = 441$$

$$S_T \text{ (Number of capsule train sorties per day for 3-capsule trains)} = S_O/3 = 147$$

$$T \text{ (Capsule injection interval)} = 24 \times 60 \times 60 / 441 = 196 \text{ sec.} = 3.27 \text{ min}$$

$$N \text{ (Number of capsules in single pipe calculated from Eq.3-5)} = 68,640/(196 \times 36.7) = 9.54$$

$$N_2 \text{ (Number of capsules in twin pipes)} = 2N = 2 \times 9.54 = 19.1$$

$$N_O \text{ (Total number of capsules needed to operate the system including 70\% spare)}$$

$$= 1.7 \times 19.1 = 32 \text{ (round-off figure).}$$

Pipeline calculation:

$$L \text{ (Pipeline length)} = 13 \text{ mi} = 13 \times 5280 = 68,640 \text{ ft.}$$

$$L_O \text{ (Total length of the pipeline)} = 2L = 2 \times 13 \text{ mi} = 26 \text{ mi} = 137,280 \text{ ft}$$

$$R_H \text{ (Hydraulic radius)} = (1 \times 1)/(4 \times 1) = 0.25 \text{ m} = 0.82 \text{ ft}$$

$$D \text{ (Diameter of pipe -- equal to } 4R_H \text{ for non-circular pipe)} = 4 \times 0.82 = 3.28 \text{ ft}$$

$$A \text{ (Inner cross-section of the pipe)} = 1\text{m} \times 1\text{m} = 1 \text{ m}^2 = 10.76 \text{ ft}^2$$

$$A_d \text{ (Area of the end plate)} = 0.98\text{m} \times 0.98\text{m} = 0.9604 \text{ m}^2 = 10.33 \text{ ft}^2$$

$$k_d^2 \text{ (End-plate-to-pipe area ratio)} = A_d/A = 0.9604/1 = 0.9604$$

$$T_O \text{ (travel time for each capsule to move through the 13-mile-length pipe)}$$

$$= L/V_C = 68,640/36.7 = 1870 \text{ s} = 31.2 \text{ min}$$

Fluid mechanic calculation:

$$C_D \text{ (Drag coefficient calculated from Eq.3-2)} = 2350$$

$$\rho \text{ (density of air)} = 0.0023 \text{ slug/ft}^3$$

$$V \text{ (Airflow velocity in conduit calculated from Eq.3-3)}$$

$$= 36.7 + [(2 \times 0.01 \times 10800)/(2350 \times 10.33 \times 0.0023)]^{1/2} = 36.7 + 1.97 = 38.7 \text{ ft/s}$$

$$\begin{aligned} \Delta p & \text{ (pressure drop along the 13-mile-length PCP calculated from Eq.3-4)} \\ & = (9.54 \times 0.01 \times 10800) / 10.76 + 0.013 \times (68640 - 9.54 \times 9.84) \times 0.0023 \times 38.7 \times 38.7 / (2 \times 3.28) \\ & = 95.8 + 467.9 = 564 \text{ psf} = 3.91 \text{ psi} \\ P & \text{ (Power consumed by flow of air and capsules in each pipe calculated from Eq.3-6)} \\ & = 38.7 \times 10.76 \times 564 = 235,000 \text{ ft-lb/s} = 427 \text{ hp} = 319 \text{ kw} \\ P_O & \text{ (Total power for twin pipes of a total length of 26 miles)} = 2P = 2 \times 319 = 638 \text{ kw} \\ P_{in} & \text{ (Power input to blower assuming 80\% efficiency)} = 638 / 0.8 = 797 \text{ kw} = 1,068 \text{ hp} \end{aligned}$$

(c) Summary of Key Information Generated:

The PCP system analyzed here for tunnel construction in New York City is basically the same as the one used for constructing the Akima Tunnel in Japan except that it has a vertical lift of 300 ft and that the tunnel length is 10 miles instead of 5 miles for the Akima Tunnel. The New York City system will need 32 capsules in which 19 are in use and 13 are spare. Each capsule will carry 3.4 tons of excavated rocks for disposal at a landfill 3 miles away from the tunnel entrance. The system will transport 23,000 ft³/day of excavated materials, which corresponds to the daily amount of materials excavated by a 24-ft-diameter tunnel boring machine advancing at 50 ft/day. The same system also can transport all the concrete and some other materials needed for tunnel construction. The system will be driven by a blower that generates an air flow of about 39 ft/s through the pipe at a pressure of 3.9 psi approximately. The blower will be rated at approximately 1,068 hp (horsepower) which uses approximately 797 kw of electric power. To be practical, three identical blowers will be purchased for this pipeline, each having a power rating of 399 kw, approximately. Two will be used to provide 797 kw; one will be the spare.

B.2 PCP for Transporting Solid Wastes

(a) System Description

A PCP system is to be used to transport municipal solid waste collected at the nine current solid waste transfer stations in New York City operated by the New York City Department of Sanitation (DSNY), in a manner as described in Sec.2.5 (a). In this case, there will be nine branch pipes (one for each transfer station), connected to a single main pipe, which conveys all the capsules carrying solid waste to a single landfill in a rural area of an adjacent state such as New Jersey. Both the branches and the main pipe will use 40-inch-diameter steel pipe of Standard (0.375-inch) thickness. Twin pipes are used for each branch and the main, one to deliver the solid waste, which is referred to as the “**delivering line**”, and the other to return the empty capsules, which is referred to as the “**return line**”. In what follows, all the pipeline lengths mentioned are for a single line – either the delivery or the return line. The total lengths of the pipe for both lines are twice the values to be mentioned. It is assumed that the total length of the nine branches is 45 miles, and the main is 50 miles. Thus, the total length of the pipe used for each line is 95 miles. The average length of each branch is 5 miles, and the average length of the distance from a transfer station to the landfill is 55 miles. Furthermore, assume that of the total of 95 miles of pipelines, 40 miles can be laid by the open-cut method on ground in rural area, 35 miles can be laid as marine pipeline, and the remaining 20 miles are to be laid by a combination of horizontal directional drilling (HDD) and microtunneling. How these pipelines are laid is non-essential at this point, but will be essential in the determination of the cost of the system in Sec.4 ECONOMIC ASSESSMENT. Note that at any given time, the main pipe receives loaded capsules from and returns empty capsules to only one of the nine transfer station. The system is

schedule to operate with, and to switch to, different transfer stations at different time of each 24-hour day. So, different stations will send loaded capsules into the delivery line and receive empty capsules from the return line during different hours of each day. The total system is designed to handle 18,000 tons of compacted solid wastes per day – 50% higher than the amount currently collected by the Department of Sanitation (DSNY). The system is assumed to use the same kind of capsules and the same solid waste loading/unloading equipment used by the Sumitomo Metal Industries, Ltd. for transporting limestone in Japan – see Sec.2.4(a) for description, see Figure 1(a) for the type of capsules, and see Figure 15 for the loading/unloading equipment. To facilitate operation, five capsules will be linked together to form a capsule train.

(b) Calculations

Freight volume estimates:

W_D (Design daily weight of wastes transported through the system) = 18,000 tons/day

w_B (Bulk unit weight of compacted solid waste) = 40 lb/ft³

V_D (Design daily volume of wastes transported through the system)

$$= W_D/w_B = 18000 \times 2000/40 = 900,000 \text{ ft}^3/\text{day}$$

Capsule calculation:

L_c (length of capsule) = 10 ft

V_O (Volume of each capsule) = 40 cu.ft

W_{SC} (weight of solid waste carried in each capsule)

$$= V_O \times w_B = 40 \times 40 = 1600 \text{ lbs} = 0.8 \text{ ton}$$

W_O (Dead weight of each capsule) = 1.6 ton = 3,200 lbs

W_C (Weight of each loaded capsule) = $W_{SC} + W_O = 0.8 + 1.6 = 2.4 \text{ tons} = 4,800 \text{ lbs}$

V_C (Capsule velocity -- design value) = 25 mph = 36.7 ft/s

S_O (Number of capsule sorties launched per day) = $V_D / V_O = 900,000/40 = 22,500$

S_T (Number of capsule train sorties per day for 5-capsule trains) = $S_O/5 = 4,500$

T (Capsule injection interval) = $24 \times 60 \times 60 / 22,500 = 3.84 \text{ s}$.

T_T (Capsule train injection interval) = $5T = 19.2 \text{ s}$.

N (number of capsules in single pipe calculated from Eq.3-5)

$$= 290400/(3.84 \times 36.7) = 2061$$

N_2 (Number of capsules in twin pipes) = $2N = 2 \times 2061 = 4,122$

N_O (Total number of capsules needed to operate the system including 15 % spare)

$$= 1.15 N_2 = 1.15 \times 4122 = 4740.$$

Pipeline calculation:

L (pipeline length – average single-pipe length for 9 transfer stations)

$$= 55 \text{ mi} = 55 \times 5280 = 290,400 \text{ ft}.$$

L_O (Total Pipeline length for the system) = 95 mile (501,600 ft) for single line, and double for the twin lines

D (Diameter of pipe) = 40 in = 3.333 ft

D_a (Diameter of the end disk or plate) = 39 in = 3.25 ft

A (Inner cross-section of the pipe) = $\pi D^2/4 = 3.1416 \times (3.333)^2/4 = 8.73 \text{ ft}^2$

A_d (area of the end plate) = $\pi D_a^2/4 = 3.1416 \times (3.25)^2/4 = 8.30 \text{ ft}^2$

k_d^2 (End-plate-to-pipe area ratio) = $A_d/A = 8.30/8.73 = 0.947$

$$T_O \text{ (travel time for each capsule to move through the 55-mile-length pipe)} \\ = L/V_C = 290,400/36.7 = 9713 \text{ s} = 132 \text{ min} = 2.2 \text{ hr}$$

Fluid mechanic calculation:

$$C_D \text{ (Drag coefficient calculated from Eq.3-2)} = 1280$$

$$\rho \text{ (density of air)} = 0.0023 \text{ slug/ft}^3$$

$$V \text{ (Airflow velocity in conduit calculated from Eq.3-3 for } \mathbf{\text{delivery line with loaded capsules}}) = 36.7 + [(2 \times 0.002 \times 4800)/(1280 \times 8.30 \times 0.0023)]^{1/2} = 36.7 + 0.886 = 37.6 \text{ ft/s}$$

$$V' \text{ (Airflow velocity in conduit calculated from Eq.3-3 for } \mathbf{\text{return line with empty capsules}}) = 36.7 + [(2 \times 0.002 \times 3200)/(1280 \times 8.30 \times 0.0023)]^{1/2} = 36.7 + 0.724 = 37.4 \text{ ft/s}$$

$$\Delta p \text{ (Pressure drop along the 55-mile-length } \mathbf{\text{delivery pipe}} \text{ calculated from Eq.3-4)} \\ = (2061 \times 0.002 \times 4800)/8.73 + 0.013 \times (290400 - 2061 \times 10) \times 0.0023 \times 37.6 \times 37.6 / (2 \times 3.333) \\ = 2266 + 1711 = 3977 \text{ psf} = 27.6 \text{ psi}$$

$$\Delta p' \text{ (Pressure drop along the 55-mile-length } \mathbf{\text{return line}} \text{ calculated from Eq.3-4)} \\ = (2061 \times 0.002 \times 3200)/8.73 + 0.013 \times (290400 - 2061 \times 10) \times 0.0023 \times 37.4 \times 37.4 / (2 \times 3.333) \\ = 1511 + 1693 = 3204 \text{ psf} = 22.3 \text{ psi}$$

$$P \text{ (Power consumed by flow of air and capsules in } \mathbf{\text{delivery line}} \text{ calculated from Eq.3-6)} \\ = 37.6 \times 8.73 \times 3977 = 1,305,000 \text{ ft-lb/s} = 2,374 \text{ hp} = 1,771 \text{ kw} = 1.77 \text{ mw approximately.}$$

$$P' \text{ (Power consumed by flow of air and capsules in } \mathbf{\text{return line}} \text{ calculated from Eq.3-6)} \\ = 37.4 \times 8.73 \times 3204 = 1,046,000 \text{ ft-lb/s} = 1,902 \text{ hp} = 1,419 \text{ kw} = 1.42 \text{ mw approximately.}$$

$$P_{in} \text{ (Power input to blower of } \mathbf{\text{delivery line}} \text{ assuming 80\% efficiency)} \\ = 1771/0.8 = 2,214 \text{ kw} = 2.21 \text{ mw} = 2,966 \text{ hp.}$$

$$P'_{in} \text{ (Power input to blower of } \mathbf{\text{return line}} \text{ assuming 80\% efficiency)} \\ = 1419/0.8 = 1,774 \text{ kw} = 1.77 \text{ mw} = 2,377 \text{ hp.}$$

$$P_2 \text{ (Total power input for the twin lines)} = P_{in} + P'_{in} = 2214 + 1774 = 3,988 \text{ kw} = 4.0 \text{ mw.}$$

(c) Summary of Key Information Generated:

The PCP system analyzed here has the capacity for transporting 18,000 tons per day of the municipal solid wastes, which is 50% more than currently collected by the City's Department of Sanitation (DSNY), so that the system will be adequate for at least 25 years. The PCP system proposed for this purpose is basically the same as that used for transporting limestone by the Somitomo Metal Industries, Ltd. in Japan. It uses the same kind of pipe (40-inch-diameter steel pipe), and the same kind of capsules (see Figure 1(a)), as used in the limestone project in Japan. The only main differences are: (1) the cargo carried is solid waste which is much lighter than the limestone, (2) the train injection interval, 19 seconds, is only about one half of that used for the limestone project, (3) the system has nine instead of a single inlet, and (4) the system is much longer than the one used for the limestone project. While the lighter cargo carried by the PCP for solid waste transport will make the capsule wheels to wear much less than the wheels used for limestone transport, the much shorter train injection interval presents a greater challenge in terms of loading and unloading, and capsule injection. However, since the New York system will have 9 inlets, the number of capsules that must be injected through each inlet is actually must less than that in the limestone project. Therefore, the demand at each station is not greater than for the limestone project. Finally, the longer length of this PCP than the one used for limestone transport means that the pressure drop of the former is much higher than that of the latter, and hence the blowers of the former must generate higher pressure and use more power. The fact that the

pressure drop of the delivery line of this PCP is found here to be 27.6 psi is a relief. Blowers for such air pressure are within the range that can be ordered from existing commercial sources. Three identical blowers will be installed at each of the nine intake stations with a total power of 3.33 mw, or 1.11 mw for each station. Only two of the three will be used at any given time to supply the 2.22 mw of power needed to run the delivery line; the third one is a spare. Note that only one intake station of the delivery line will be operating at any given time; the rest will be idling and waiting for their respective turns. For the common outlet station at the landfill side, three identical blowers of total power of 2.661 mw will be installed to return the empty capsules. They will be operating continuously. The system will use 5-capsule trains injected at an interval of 19 seconds; each capsule train will carry 4 tons of solid wastes. An RFID tag will be placed on the front of the first capsule in each train, so that the origin of the waste (transfer station number) and the type of the waste (whether it is plastic, glass, metals, paper, waste wood, etc.) can be identified. The identification of the waste type will greatly facilitate handling at the disposal site, which can be designed to process different types of waste materials for reuse -- such as recycling of glass, plastics and metals, and use of biomass (waste wood, non-recyclable waste paper, etc.) for generating energy.

B.3 PCP for Transporting Mail and Parcels

(a) System Description

A PCP system is to be used to transport mail and parcels between New York City and Washington D.C., serving all the cities along this East-Coast Corridor, in a manner as described in Sec.2.5(b). Along this pipeline, there will be an inlet/outlet station in each of the following five cities: Newark, Trenton, Philadelphia, Baltimore and Washington D.C. The New York City end of the pipeline will have five branches, connected to five different inlet/outlet stations in New York City, one serving each borough of the City. As in all other cases, double lines (parallel twin pipes) will be used so that mail and parcels can move in both directions simultaneously. Linear induction motors (LIMs) instead of blowers will be used as booster pumps scattered along the pipeline to facilitate operation of this complex mail/parcel pipeline system. As in the previous case for solid waste transport, both the branches and the main pipe will use 40-inch-diameter steel pipe of standard (0.375-inch) thickness. It is assumed that the total length of the five branches is 30 miles, and the length of the main is 210 miles. Thus, the total length of the pipe used is 240 miles. Furthermore, of the total of 240 miles of pipelines, 190 miles can be laid by the open-cut method on ground along I-95, 20 miles can be laid as marine pipeline, and the remaining 30 miles are to be laid by a combination of horizontal directional drilling (HDD) and microtunneling. All the pipeline lengths mentioned here, unless otherwise indicated, are single-line lengths. For the twin lines, the values are simply doubled. How these pipelines are laid is non-essential at this point but will be essential in the determination of the cost of the system in Sec.4 ECONOMIC ASSESSMENT. The inlet/outlet stations of this PCP are functionally similar to the inlets/outlets of divided highways in that different capsules can enter and leave any station simultaneously and independently, thereby greatly facilitating the free motion of capsules. Each inlet/outlet station is arranged physically in a manner similar to that of the pallet-tube system shown in Figure 7, except for the fact that the stations are all aboveground. The system uses the same kind of capsules used for the solid waste transport – illustrated in Figure 1(a). To facilitate operation, five capsules will be linked together to form a capsule train.

(b) Calculations**Pipeline calculation:**

L (pipeline length – total length for single-line pipe including branches in NYC)
 $= 240 \text{ mi} = 240 \times 5280 = 1,267,200 \text{ ft}$.

L_O (Total pipeline length for double lines) $= 2L = 480 \text{ mile} = 2,534,400 \text{ ft}$

D (Diameter of pipe) $= 40 \text{ in} = 3.333 \text{ ft}$

A (Inner cross-section of the pipe) $= \pi D^2/4 = 3.1416 \times (3.333)^2/4 = 8.73 \text{ ft}^2$

T_O (Travel time for each capsule to move through the 240-mile-length pipe)
 $= L/V_C = 1267200/36.7 = 34530 \text{ s} = 575 \text{ min} = 9.6 \text{ hr}$

Capsule calculation:

L_c (Length of capsule) $= 10 \text{ ft}$

D_c (Outer diameter of capsule) $= 38 \text{ in} = 3.167 \text{ ft}$

A_c (Area of the capsule) $= \pi D_c^2/4 = 3.1416 \times (3.167)^2/4 = 7.88 \text{ ft}^2$

k^2 (Capsule-to-pipe area ratio) $= A_c/A = 7.88/8.73 = 0.902$

V_O (Volume of each capsule) $= 40 \text{ cu.ft}$

w_B (Bulk unit weight of mail/parcels) $= 35 \text{ lb/ft}^3$

W_{MC} (weight of mail/parcel carried in each capsule)

$$= V_O \times w_B = 40 \times 35 = 1400 \text{ lbs} = 0.7 \text{ ton}$$

W_O (Dead weight of each capsule) $= 1.6 \text{ ton} = 3,200 \text{ lbs}$

W_C (Weight of each loaded capsule) $= W_{MC} + W_O = 0.7 + 1.6 = 2.3 \text{ tons} = 4,600 \text{ lbs}$

w_c (Unit weight of loaded capsule) $= W_C/V_O = 4600/40 = 115 \text{ lb/ft}^3$

V_C (Capsule velocity -- design value) $= 35 \text{ mph} = 51.3 \text{ ft/s}$

T_m (Time for mail and parcel to transport through the entire PCP between
 New York City and Washington D. C.) $= 210/35 = 6.0 \text{ hours}$

T_T (Maximum capsule train injection interval at each station) $= 30 \text{ s}$.

T (Maximum capsule injection interval at each station) $= T_T/5 = 30/5 = 6.0 \text{ s}$

S_T (Maximum capsule train sorties per day per line for each station using
 5-capsule trains) $= 24 \times 60 \times 60/T_T = 86400/30 = 2880$

V_D (Maximum daily volume of mail/parcels handled per line at each station)
 $= 5S_T V_O = 5 \times 2880 \times 40 = 576,000 \text{ ft}^3/\text{day}$

W_D (Maximum daily weight of mail/parcels handled per line at each station)
 $= w_B V_D = 35 \times 576,000 = 20,160,000 \text{ lbs/day} = 10,080 \text{ tons/day}$

(Note: The actual volume or weight of mail handled through each station depends
 on supply and demand, and is much less than the maximum calculated above.)

α (Average linefill in PCP between stations) $= 0.1 = 10\%$

V_m (Volume of mail transported through each pipe based on linefill)
 $= \alpha V_C V_O/L_C = 0.1 \times 51.3 \times 40/10 = 20.52 \text{ ft}^3/\text{s} = 1,773,000 \text{ ft}^3/\text{day}$

W_m (Weight of mail transported through each pipe) $= w_B V_m = 35 \times 1,773,000$
 $= 62,050,000 \text{ lbs/day} = 31,030 \text{ tons/day} = 11,320,000 \text{ tons/year}$

N (Number of capsules in single pipe of 240-mile length calculated from linefill)
 $= \alpha L/L_c = 0.1 \times 1267200/10 = 12,672$

N_2 (Number of capsules in twin pipes) $= 2N = 2 \times 12672 = 25,344$

N_O (Total number of capsules needed to operate the system including 15 % spare)
 $= 1.15 N_2 = 1.15 \times 25,344 = 29,146$.

Fluid mechanic calculation:

$$\rho(\text{Density of air}) = 0.0023 \text{ slug/ft}^3$$

$$V (\text{Airflow velocity in conduit calculated from an approach described in [10]}) = 52.0 \text{ ft/s}$$

$$F_D (\text{Drag force on each capsule calculated from an approach described in [10]}) = 18.5 \text{ lb}$$

$$C_D (\text{Drag coefficient of the capsule calculated from Eq.3-1}) = 3200$$

$$\begin{aligned} \Delta p (\text{Total pressure drop along the 240-mile-length PCP calculated from Eq.3-4}) \\ &= (12672 \times 0.002 \times 4600) / 8.73 + 0.013 \times (1267200 - 12672 \times 10) \times 0.0023 \times 52 \times 52 / (2 \times 3.333) \\ &= 13,355 + 13831 = 27186 \text{ psf} = 189 \text{ psi. (Note: This is the sum of the pressure drops} \\ &\text{across various sections of the pipe, rather than the actual pressure drop across the} \\ &\text{pipe.)} \end{aligned}$$

$$\begin{aligned} P (\text{Total power consumed by flow of air and capsules in each pipe calculated from Eq.3-6}) \\ &= 52.0 \times 8.73 \times 27186 = 12,340,000 \text{ ft-lb/s} = 22,440 \text{ hp} = 16,750 \text{ kw} = 16.8 \text{ mw} \end{aligned}$$

$$\begin{aligned} P_{in} (\text{Total power input to blower of each line assuming 80\% efficiency}) \\ &= 16,750 / 0.8 = 20,900 \text{ kw} = 20.9 \text{ mw} \end{aligned}$$

$$P_2 (\text{Total power input for the twin lines}) = 2P_{in} = 2 \times 20,900 = 41,900 \text{ kw} = 41.9 \text{ mw.}$$

(c) Summary of Key Information Generated:

The PCP system analyzed here can transport mail and parcels at 35 mph non-stop. It enables mails and parcels to be transported from (to) New York City to (from) Washington D.C. in as short as 6 hours. Since this pipeline operates continuously 24-hours-a-day and seven-days-a-week unaffected by inclement weather, mail and parcels can be transported through this PCP faster than by trucks or even airplanes, considering the time that trucks spend in fighting traffic in order to reach airports. This PCP system has a capacity to transport 1,773,000 cu.ft of mail and parcels per day along this East Coast corridor, which is equivalent to about 31,000 tons of mail and parcels per day moving through any part of the pipeline between New York City and Washington D.C. Since this is much beyond the current daily volume of mail and parcel transported by the U.S. Postal Service through this corridor, to fully utilize this PCP will require that private companies such as the United Parcel Service and the Federal Express also use this pipeline for mail and parcels. This PCP system will use approximately 42 mw of electric power, which in a year uses 3.68×10^8 kwh of energy. Since the annual consumption of electrical energy per capita in the United States is 12,000 kwh, the energy used by this PCP system is about the same as used by 30,000 people, which is quite reasonable for this major mail/parcel pipeline serving not only New York City but also a significant population of the East Coast.

B.4 Pallet-Tube PCP System**(a) System Description**

The PCP system capable to transport goods on pallets, boxes, crates and bags is referred to in this report as the “pallet-tube PCP”. It is to be constructed of tunnels of 7-ft diameter in the bedrock underneath New York City from 100 ft to 200 ft below the street level. The capsules are box shaped cars of 4-ft height, 4-ft width and 13-ft length, having steel wheels running on steel rail as shown see Figure 5. To serve the entire city, a dense grid of such PCPs must be built under the City, with each cell of the grid containing an inlet/outlet station to serve a number of blocks as shown in Figure 6. Two or more intermodal transfer stations will be set up on the west side of Hudson River so that trucks will transfer their loads to capsules at the transfer stations

outside the City. Each transfer station will be connected by a twin pipes (7-ft-diameter tunnels) to the network of the pallet-tube PCP.

Due to the complexity of this PCP system that serves the entire New York City, it is neither possible nor necessary to plan and analyze the entire system at this stage. For the purpose of this report, it suffices to analyze one unit (cell) of this network, consisting of a typical inlet/outlet station that serves an area of 1,000 ft by 1,000 ft as shown in Figure B-1. If the average area of a cell is 1,000,000 ft² as shown in Figure B-1, New York City which covers a geographical area 320 square miles will have 2920 of such cell. In reality, in less densely populated areas, larger cell will be appropriate. The station layout is shown in Figures 7 and 8. The station covers an area of 200-ft length and 160-ft width.

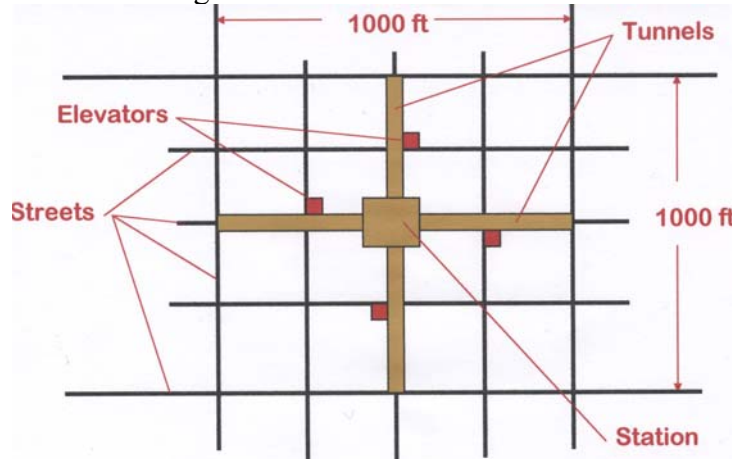


Figure B-1. A typical unit (cell) of the network of pallet-tube PCPs for New York City

(b) Calculations (for a Unit Cell)

Pipeline calculation:

$$L \text{ (7-ft-diameter tunnel length – total length for single-line)} \\ = 1,000 \text{ ft.}$$

$$L_0 \text{ (Total tunnel length for double lines)} = 2L = 2 \times 1000 = 2,000 \text{ ft}$$

$$D \text{ (Diameter of tunnel)} = 7 \text{ ft}$$

$$A \text{ (Cross-section area of the tunnel)} = \pi D^2/4 = 3.1416 \times 7 \times 7/4 = 38.5 \text{ ft}^2$$

$$T_0 \text{ (Travel time for each capsule to move from one station to the next)} \\ = L/V_C = 1000/36.7 = 27.2 \text{ s}$$

(Note: The time T_0 does not include the time for an inbound capsule to decelerate and stop, and the time for an outbound capsule to accelerate from zero velocity at the station. Including the time for acceleration or deceleration, the total time for transporting a capsule from one station to the next will be approximately 60 seconds or one minute, which is still rather fast as compared to the speed of truck moving on the congested streets of the New York City.)

Capsule calculation:

$$L_c \text{ (Length of capsule)} = 13 \text{ ft}$$

$$A_c \text{ (Cross-sectional area of the capsule)} = 4 \text{ ft} \times 4 \text{ ft} = 16 \text{ ft}^2$$

$$k^2 \text{ (Capsule-to-pipe area ratio)} = A_c/A = 16/38.5 = 0.416$$

$$V_0 \text{ (Volume of each capsule)} = 4 \text{ ft} \times 4 \text{ ft} \times 13 \text{ ft} = 208 \text{ ft}^3$$

$$w_B \text{ (Average bulk unit weight of cargo)} = 40 \text{ lb/ft}^3$$

$$\begin{aligned}
W_{MC} & \text{ (weight of cargo carried in each capsule)} \\
& = V_O \times w_B = 208 \times 40 = 8320 \text{ lbs} = 4.16 \text{ ton} \\
W_O & \text{ (Dead weight of each capsule)} = 4 \text{ ton} = 8,000 \text{ lbs} \\
W_C & \text{ (Weight of each loaded capsule)} = W_{MC} + W_O = 4.16 + 4.0 = 8.16 \text{ tons} = 16,320 \text{ lbs} \\
w_c & \text{ (Unit weight of loaded capsule)} = W_C/V_O = 16320/208 = 78.5 \text{ lb/ft}^3 \\
V_C & \text{ (Capsule velocity -- design value)} = 25 \text{ mph} = 36.7 \text{ ft/s} \\
\alpha & \text{ (Maximum allowed linefill of capsules in the tunnel)} = 0.2 = 20\% \\
N & \text{ (Number of capsules in 1000 ft of tunnel corresponding to maximum linefill)} \\
& = \alpha L/L_c = 0.2 \times 1000/13 = 15.4 \\
N_2 & \text{ (Number of capsules in twin pipes)} = 2N = 2 \times 15.4 = 30.8 \\
N_O & \text{ (Total number of capsules needed to operate the unit including 15 \% spare)} \\
& = 1.15 N_2 = 1.15 \times 30.8 = 35.4. \\
& \text{(Note: This is the number of capsules needed by each unit or cell. For the network} \\
& \text{covering the entire system with } N_C \text{ cells, the number will be 35.4 times } N_C.) \\
N_T & \text{ (Number of capsule trains in 1000 ft of tunnel corresponding to max. linefill)} \\
& = N/5 = 15.4/5 = 3.1 \\
T_T & \text{ (Average time interval for capsule trains to pass a given point in tunnel corresponding} \\
& \text{to maximum linefill)} = L/(N_T V_C) = 1000/(3.1 \times 36.7) = 8.79 \text{ s} \\
n_T & \text{ (Number of capsule trains passing through tunnel in unit time)} \\
& = 1/T_T = 1/8.79 = 0.114 \text{ trains/sec} = 6.83 \text{ trains/min} = 410 \text{ trains/hr} = 9,840 \text{ trains/day.} \\
n & \text{ (Number of capsules passing through tunnel in unit time)} \\
& = 5n_T = 5 \times 9840 = 49,200 \text{ capsules/day.} \\
V_D & \text{ (Daily volume of cargoes passing through the tunnel)} \\
& = nV_O = 49200 \times 208 = 1.02 \times 10^7 \text{ ft}^3/\text{day} \\
W_D & \text{ (Daily weight of cargoes passing through the tunnel)} \\
& = w_B V_D = 40 \times 1.02 \times 10^7 = 4.09 \times 10^8 \text{ lbs} = 205,000 \text{ tons/day} \\
W_Y & \text{ (Yearly weight of cargoes passing through the tunnel)} = 365 W_D = 74,825,000 \text{ tons/yr.}
\end{aligned}$$

(Note: Most of the trains passing through the tunnel are through-traffic; only a small fraction of them are destined for this station. For a major station, assume that there is one train per minute entering the station and 1 train per minute leaving the station. With this rate of trains entering and exiting the station, the station must be able to handle (load and unload) one train per minute. The ensuing analysis uses this assumption for a major (busy) station.)

$$\begin{aligned}
T_i & \text{ (Average capsule train injection interval at the station)} = 60 \text{ s} \\
S_T & \text{ (Number of capsule train sorties from one station per day per line for 5-capsule trains)} \\
& = 24 \times 60 \times 60 / T_i = 86400/60 = 1440 \\
V_{DS} & \text{ (Daily volume of cargoes handled through the station)} \\
& = 5S_T V_O = 5 \times 1440 \times 208 = 1,500,000 \text{ ft}^3/\text{day} \\
W_{DS} & \text{ (Daily weight of cargoes processed through each station)} \\
& = w_B V_{DS} = 40 \times 1,500,000 = 60,000,000 \text{ lbs/day} = 30,000 \text{ tons/day.}
\end{aligned}$$

(Note: The 30,000 tons/day is an enormous amount of freight that can be transported through a major station of the PCP system. To fully utilize this capacity, the system should be used as a general cargo carrier for transporting not only ordinary commercial products on pallets or in boxes, crates and bags, but also other special cargoes such as municipal solid wastes (both residential and commercial wastes) and mail (including parcels) for local delivery within the

City. This should not be confused with the special PCP systems discussed before -- one for transporting solid wastes from waste transfer stations to an out-of-state landfill for ultimate disposal, and the other for transporting mail and parcel along the East Coast Corridor between New York City and Washington D.C. These systems are complementary rather than duplicative.)

Fluid mechanic calculation:

$$\rho(\text{Density of air}) = 0.0023 \text{ slug/ft}^3$$

$$V \text{ (Airflow velocity in tunnel calculated from an approach described in [10])} = 58.9 \text{ ft/s}$$

$$F_D \text{ (Drag force on each capsule calculated from an approach described in [10])} = 32.8 \text{ lb}$$

$$C_D \text{ (Drag coefficient of the capsule calculated from Eq.3-1)} = 3.62$$

$$\begin{aligned} \Delta p \text{ (Total pressure drop along the 1,000-ft-length PCP calculated from Eq.3-4)} \\ = (15.4 \times 0.002 \times 16320) / 38.5 + 0.013 \times (1000 - 15.4 \times 13) \times 0.0023 \times 58.9 \times 58.9 / (2 \times 4.0) \\ = 13.1 + 10.4 = 23.5 \text{ psf} \end{aligned}$$

$$\begin{aligned} P \text{ (Power consumed by flow of air and capsules in each tunnel calculated from Eq.3-6)} \\ = 58.9 \times 38.5 \times 23.5 = 53,300 \text{ ft-lb/s} = 96.9 \text{ hp} = 72.3 \text{ kw} \end{aligned}$$

$$\begin{aligned} P_{in} \text{ (Power input to the LIM pump of each line assuming 70\% efficiency)} \\ = 72.3 / 0.7 = 103.3 \text{ kw} \end{aligned}$$

$$P_2 \text{ (Total power input to the two LIMs for the twin lines)} = 2P_{in} = 2 \times 103.3 = 207 \text{ kw}$$

(c) Summary of Key Information Generated:

With the use of 5-capsule trains and with the ability to inject one train in every minute, the single-station PCP unit analyzed here has a capacity of launching (injecting) 1440 trains per day, carrying 30,000 tons of cargoes. The unit will receive the same number of capsules per day coming from other stations so that there will be no need to store a large number of capsules at the station. Since the handling capacity of 30,000 tons a day is greater than the need of most stations, in reality most stations will handle far fewer capsules per day, and hence the 60-second-per-train injection interval will be greatly extended. Since most capsules will bypass instead of enter any station, the number of capsules per day passing through the PCP tunnel will be much higher than the number of capsules handled by the station. The maximum number of capsules that the tunnel can handle, corresponding to 20% linefill, is 49,200 per day, which carry a total freight of $1.02 \times 10^7 \text{ ft}^3/\text{day}$, equivalent to 205,000 tons/day. This is an enormous freight capacity. The power consumption by the LIM pumps of this cell for a major station is 207 kw, which is rather reasonable for the large volume of freight handled through this cell.

B.5 Container-Dispatch PCP

(a) System Description

Assume that the container-dispatch PCP system described in Sec.2-3 has four inlets and one outlet as shown in Figure 12. Each inlet is at a separate current seaport in New York City, and is connected to the main PCP by a branch which is a tunnel of 15-ft diameter constructed in the bedrock of the New York City Harbor at a depth 100 to 150 ft below the water level. The outlet is a centralized large inspection/transfer station at which containers arriving from the ports are inspected and then transported by trucks or trains to elsewhere in the nation. The station is also used to inspect containers brought in by trucks and trains for dispatch to the ports for loading on outbound ships. Assume that the average length of the four branches is 4 miles, so the total length of the four branches is 16 miles. The main PCP, measured from the first junction

with a branch to the container inspection/transfer station, is assumed to be 20 miles. The first 5 miles of the main being a 15-ft-diameter tunnel constructed in the bedrock under water or urban areas, whereas the remaining 15 miles being a rectangular conduit of 9-ft width and 11-ft height, constructed by the open-cut method in rural areas. Thus, the entire PCP consists of 21 miles of tunnels of 15-ft diameter, and 15 miles of a rectangular conduit of 9-ft width and 11-ft height, buried with an average of 5 ft of earth coverage.

The analysis of this system is similar to that of the PCP system for solid-waste transport in that the system has multiple inlets and a single outlet. However, it differs from the solid-waste PCP in that the pipe consists of two parts with different shapes – circular tunnel followed by rectangular conduit. Also, the system uses LIM pumps instead of blowers, thereby allowing booster pumps to be used. One LIM pump will be used at the entrance of each branch, and then one booster pump at every 5 to 10 miles along the main conduit.

(b) Calculations

Pipeline calculation:

$$L \text{ (Pipeline length – total length for single-line pipe including 4 branches)} \\ = 36 \text{ mi} = 36 \times 5280 = 190,080 \text{ ft.}$$

$$L_O \text{ (Total pipeline length for double lines)} = 2L = 72 \text{ mi} = 380,160 \text{ ft}$$

$$L_T \text{ (Tunnel length – total length for single-line tunnels including 4 branches)} \\ = 21 \text{ mi} = 21 \times 5280 = 110,880 \text{ ft.}$$

$$L_{OT} \text{ (Total tunnel length for double lines)} = 2L_T = 42 \text{ mi} = 221,760 \text{ ft}$$

$$L_R \text{ (Rectangular conduit length – total length for single-line conduit)} \\ = 15 \text{ mi} = 15 \times 5280 = 79,200 \text{ ft.}$$

$$L_{OR} \text{ (Total rectangular conduit length for double lines)} = 2L_R = 30 \text{ mi} = 158,400 \text{ ft}$$

$$D_T \text{ (Diameter of tunnel)} = 15 \text{ ft}$$

$$A_T \text{ (Inner cross-section of the tunnel)} = \pi R_T^2/4 = 3.1416 \times (15)^2/4 = 176.7 \text{ ft}^2$$

$$A_R \text{ (Inner cross-section of the rectangular conduit)} = 9 \text{ ft} \times 11 \text{ ft} = 99 \text{ ft}^2$$

Capsule calculation:

$$L_c \text{ (Length of capsule)} = 42 \text{ ft}$$

$$D_c \text{ (Outer diameter of capsule)} = 38 \text{ in} = 3.167 \text{ ft}$$

$$A_c \text{ (Cross-sectional area of the capsule)} = 8.5 \text{ ft} \times 10 \text{ ft} = 85 \text{ ft}^2$$

$$k_T^2 \text{ (Capsule-to-tunnel area ratio)} = A_c/A_T = 85/176.7 = 0.481$$

$$k_R^2 \text{ (Capsule-to-rectangular-channel area ratio)} = A_c/A_R = 85/99 = 0.8586$$

$$V_O \text{ (Volume of each capsule)} = A_c L_c = 85 \times 42 = 3,570 \text{ cu.ft}$$

$$w_B \text{ (Bulk unit weight of loaded capsules)} = 50 \text{ lb/ft}^3$$

$$W_C \text{ (Average weight of each loaded capsule)} \\ = V_O w_B = 3570 \times 50 = 178,500 \text{ lbs} = 89.25 \text{ tons}$$

$$V_{CT} \text{ (Capsule velocity in tunnel-- design value)} = 25 \text{ mph} = 36.7 \text{ ft/s}$$

$$\alpha_T \text{ (Maximum linefill in the tunnel)} = 0.2$$

$$N_T \text{ (Number of capsules in 21 miles of single-line tunnels)} \\ = \alpha_T L_T / L_C = 0.2 \times 110,880 / 42 = 528$$

$$N_{OT} \text{ (Total number of capsules in 21 miles of twin tunnels)} = 2N_T = 1056$$

Fluid mechanic calculation:

$$\rho(\text{Density of air}) = 0.0023 \text{ slug/ft}^3$$

$$V_T (\text{Airflow velocity in tunnel calculated from an approach described in [10]}) = 63.1 \text{ ft/s}$$

$$F_D (\text{Drag force on each capsule calculated from an approach described in [10]}) = 357 \text{ lb}$$

$$C_D (\text{Drag coefficient of the capsule calculated from Eq.3-1}) = 5.24$$

$$\begin{aligned} \Delta p_1 (\text{Total pressure drop along the 21-mile-length tunnel of PCP calculated from Eq.3-4}) \\ = (528 \times 0.002 \times 178500) / 176.7 + 0.012 \times (110880 - 528 \times 42) \times 0.0023 \times 63.1 \times 63.1 / (2 \times 15) \\ = 1067 + 325 = 1392 \text{ psf} = 9.67 \text{ psi.} \end{aligned}$$

$$\begin{aligned} V_R (\text{Total pressure drop along the 15-mile rectangular channel calculated from continuity}) \\ = V_T A_T / A_R = 63.1 \times 176.7 / 99 = 112.6 \text{ ft/s} \end{aligned}$$

$$V_{CR} (\text{Capsule velocity in rectangular channel calculated from an approach described in [10]}) = 110 \text{ ft/s}$$

$$\begin{aligned} T_O (\text{Average travel time for a capsule to move through the PCP – dispatch time}) \\ = L_1 / V_{CT} + L_2 / V_{CR} = 9 \times 5280 / 36.7 + 15 \times 5282 / 110 = 1295 + 720 = 2,015 \text{ s} = 33.6 \text{ min} \end{aligned}$$

$$\alpha_R (\text{Linefill in rectangular conduit}) = \alpha_T V_{CT} / V_{CR} = 0.2 \times 36.7 / 110 = 0.0667$$

$$\begin{aligned} N_R (\text{Number of capsules in 15-mile-length rectangular conduit}) \\ = \alpha_R L_R / L_c = 0.0667 \times 79200 / 42 = 125.8 \end{aligned}$$

$$\begin{aligned} N (\text{Total number of capsules in single pipe}) \\ = N_T + N_R = 528 + 126 = 654 \end{aligned}$$

$$N_2 (\text{Total number of capsules in twin pipes}) = 2N = 2 \times 654 = 1308$$

$$\begin{aligned} N_O (\text{Total number of capsules needed to operate the system including 15 % spare}) \\ = 1.15 N_2 = 1.15 \times 1308 = 1504. \end{aligned}$$

$$\begin{aligned} T (\text{Average time interval for capsule to pass a given point in pipe}) \\ = L_R / (N_R V_{CR}) = 79200 / (125.8 \times 110) = 5.72 \text{ s} \end{aligned}$$

$$T_s (\text{Average capsule injection interval at each of 4 stations}) = 4T = 23 \text{ s}$$

$$\begin{aligned} N_{CD} (\text{Number of capsules or 40-ft containers transported each day}) \\ = 24 \times 60 \times 60 / T = 86400 / 5.72 = 15,105 \end{aligned}$$

$$\begin{aligned} N_{TEU} (\text{Number of TEU – Twenty-foot Equivalent Units – transported per day}) \\ = 2 N_{CD} = 2 \times 15105 = 30210 \text{ TEUs} \end{aligned}$$

$$\begin{aligned} \Delta p_2 (\text{Total pressure drop along the 15-mile-length rectangular conduit calculated from Eq.3-4}) \\ = 125.8 \times 0.002 \times 178500 / 99 + 0.012 \times (79200 - 125.8 \times 42) \times 0.0023 \times 112.6 \\ \times 112.6 / (2 \times 9.19) = 454 + 1407 = 1861 \text{ psf} = 12.9 \text{ psi} \end{aligned}$$

$$\begin{aligned} \Delta p (\text{Total pressure drop along entire single line of PCP}) \\ = \Delta p_1 + \Delta p_2 = 1392 + 1861 = 3253 \text{ psf} = 22.6 \text{ psi} \end{aligned}$$

$$\begin{aligned} P (\text{Total power consumed by flow of air and capsules in each line calculated from Eq.3-6}) \\ = V_T A_T \Delta p = 63.1 \times 176.7 \times 3253 = 36,270,000 \text{ ft-lb/s} = 65,900 \text{ hp} = 49,200 \text{ kw} \end{aligned}$$

$$\begin{aligned} P_{in} (\text{Total power input to LIM pumps assuming 80% efficiency}) \\ = 49200 / 0.7 = 70,300 \text{ kw} = 70.3 \text{ mw} \end{aligned}$$

$$P_2 (\text{Total power input for the twin lines}) = 2P_{in} = 2 \times 70300 = 141,000 \text{ kw} = 141 \text{ mw.}$$

(c) Summary of Key Information Generated:

The PCP system analyzed here for container dispatch to and from ports in New York City has a maximum capacity for transporting 30210 TEUs containers per 24-hours, which is equivalent to 11 millions of TEUs per year if operated 24 hours a day and 365 days a year, and equivalent to 4.5 million TEUs per year if operated only 10-hours a day and 360 days a year including downtime. Note that at present, the ports of New York City and adjacent New Jersey

handle a total of 4 million TEUs per year. This shows that the proposed PCP system has more than enough capacity to handle all the containers at these ports. The system uses 1504 capsules of which 15% is spare. The dispatch time (i.e., the time for a capsule or container to travel through this PCP having an average distance of 24 miles) is approximately 34 minutes, the average capsule injection time at each of the four seaports is 23 seconds, and the injection time for capsules returning from the injection station 5.72 seconds. Should this injection time of less than 6 seconds be difficult to achieve, several capsules can be linked together to form a train, which will increase the injection time several times. At the designed peak capacity, this PCP system will use a total of 141 mw of electric power.

B.6 Truck-Ferry PCP in Hunts Point

(a) System Description

As explained in Sec.2.4, the PCP for ferrying trucks in Hunts Point along the selected route is approximately 1.1 miles in length, using a conduit of rectangular cross-section of 10-ft width and 15-ft height. Capsules of three different lengths will be used: 60 ft, 40 ft and 20 ft, respectively for carrying (piggybacking) 53-ft tractor trailers, 35-ft trucks, and 20-ft van or pickup trucks. To simplify the analysis, it is assumed that each capsule is 40-ft long, and it has two end plates of 9-ft width and 14-ft height. Unlike the other applications, the capsules in this case are not linked into trains; each capsule carries (piggybacks) only one truck, and each capsule is injected separately into the pipe. This is done for the convenience of the truckers who do not need to wait for other truckers to arrive before being transported by capsules. As soon as a truck arrives at the terminal, it is ready to be transported. The capsules are designed to move through the PCP conduit at an average speed of 30 mph, and the minimum interval for injecting capsules is 50 second per capsule.

(b) Calculations

Pipeline calculation:

$$L \text{ (Length of single conduit)} = 1.1 \text{ miles} = 5808 \text{ ft}$$

$$L_O \text{ (Total length of twin conduits)} = 2L = 5808 \times 2 = 11,616 \text{ ft}$$

$$A \text{ (Inner cross-section of the conduit)} = 10 \text{ ft} \times 15 \text{ ft} = 150 \text{ ft}^2$$

$$R_H \text{ (Hydraulic radius)} = (10 \times 15) / (2 \times 10 + 2 \times 15) = 150 / 50 \text{ ft} = 3 \text{ ft}$$

$$D \text{ (Diameter of pipe – equal to } 4R_H \text{ for non-circular pipe)} = 4 \times 3 = 12 \text{ ft}$$

Capsule calculation:

$$L_c \text{ (length of capsule)} = 40 \text{ ft}$$

$$A_d \text{ (Area of the end plate)} = 9 \text{ m} \times 14 \text{ m} = 126 \text{ m}^2$$

$$k_d^2 \text{ (End-plate-to-pipe area ratio)} = A_d / A = 126 / 150 = 0.84$$

$$k_d \text{ (End-plate-to-pipe diameter ratio)} = 0.9165$$

$$W_C \text{ (Weight of each loaded capsule)} = 100 \text{ tons} = 200,000 \text{ lbs}$$

$$V_C \text{ (Capsule velocity -- design value)} = 30 \text{ mph} = 44.0 \text{ ft/s}$$

$$T_O \text{ (travel time for each capsule to move through the 1.1-mile-length conduit)} \\ = L / V_C = 5808 / 44 = 132 \text{ s} = 2.2 \text{ min}$$

$$T \text{ (Capsule injection interval)} = 50 \text{ sec.}$$

$$S_O \text{ (Number of capsule sorties launched per day)} = 24 \times 60 \times 60 / T = 86400 / 50 = 1728$$

$$N \text{ (Number of capsules in single conduit calculated from Eq.3-5)} \\ = L / (TV_C) = 5808 / (50 \times 44) = 2.64$$

$$N_2 \text{ (Number of capsules in twin conduits)} = 2N = 2 \times 2.64 = 5.28$$

$$N_O \text{ (Total number of capsules needed to operate the system including 70\% spare)} \\ = 1.7 \times 5.28 = 9 \text{ (round-off figure).}$$

Fluid mechanic calculation:

$$C_D \text{ (Drag coefficient calculated from Eq.3-2)} = 110.3$$

$$\rho \text{ (density of air)} = 0.0023 \text{ slug/ft}^3$$

$$V \text{ (Airflow velocity in conduit calculated from Eq.3-3)} \\ = 44 + [(2 \times 0.002 \times 200,000) / (110.3 \times 126 \times 0.0023)]^{1/2} = 44.0 + 5.0 = 49.0 \text{ ft/s}$$

$$\Delta p \text{ (pressure drop along the 1.1-mile-length PCP calculated from Eq.3-4)} \\ = (2.64 \times 0.002 \times 200,000) / 150 + 0.012 \times (5808 - 2.64 \times 40) \times 0.0023 \times 49 \times 49 / (2 \times 12) \\ = 7.04 + 15.75 = 22.8 \text{ psf} = 0.158 \text{ psi}$$

$$P \text{ (Power consumed by flow of air and capsules in each conduit calculated from Eq.3-6)} \\ = 49 \times 150 \times 22.8 = 167,580 \text{ ft-lb/s} = 305 \text{ hp} = 227 \text{ kw}$$

$$P_O \text{ (Total power for twin conduits)} = 2P = 2 \times 227 = 454 \text{ kw}$$

$$P_{in} \text{ (Power input to blower assuming 80\% efficiency)} = 454 / 0.8 = 568 \text{ kw}$$

(c) Summary of Key Information Generated:

The PCP system analyzed here for ferrying trucks in Hunts Point can handle a total of 1728 trucks per day in either direction of the system. The system requires 9 capsules of which 3 are spares. The capsules move through the conduit at the average speed of 44.0 ft/s, creating a maximum pressure drop along the conduit of 22.8 psf, and using 568 kw of electrical power supplied to the blowers, one at each end of the pipe. Capsules are injected into the conduit at the rate of one capsule in 50 second. The system capacity can be doubled if the capsules are linked into trains of two-capsules each, etc. The travel time for any capsule to go through this 1.1-mile underground PCP is 2.2 minutes.

Appendix C

CONSTRUCTION COST OF PCP

In the various applications of the PCP technology in New York City discussed in this report, the dominating cost is the construction cost of the pipeline – be it a rectangular conduit, a round pipe, or a round tunnel. In general, this construction cost varies greatly with a number of factors including structural type, construction method, construction materials, soil and rock conditions, groundwater level, location (site) of construction, cost of labor and electricity, etc. It is beyond the scope of this general feasibility study to determine all these factors of each application in New York City. Consequently, the construction cost of any basic structure (pipeline) given in this report is only a rough estimate. Still, an effort has been made in this project to search for reliable construction cost data and estimating methods. In what follows, the costs of five different types of PCP construction are considered. They are: (a) deep underground tunnels in New York City, (b) rectangular conduits made of reinforced concrete laid in ditches, (c) steel pipe laid in ditches, (d) submarine steel pipes laid by barges, and (e) steel pipe laid by microtunneling and directional drilling. They are separately assessed as follows:

C.1 Tunneling Cost in New York City

Because some of the potential applications of PCPs in New York City, such as the pallet-tube system and the contain-dispatch system, require the construction of new tunnels which are costly, an effort has been made in this study to determine the cost of tunneling in New York City for such applications. In general, tunneling costs vary greatly with many different factors including the tunnel length, tunnel diameter, depth of the tunnel below the ground surface, hardness of the rock through which the tunnel must go through, the tunneling method used (whether by using drill-and-blast or tunnel boring machines), labor cost rate of the locality (New York City in this case), distance to transport and dispose the excavated materials, etc. This makes it difficult if not impossible to determine accurately the tunneling cost of each proposed application without a detailed site exploration, including numerous drillings to obtain soil and rock samples at various depths along the route of the proposed tunnel. Since such detailed engineering site investigation is beyond the scope and the budget of this feasibility study, only a rough estimate of the tunneling cost is possible, which is done as follows:

The best way to estimate the tunneling cost in New York City is to find out the unit-length cost of similar tunnels built in New York City using tunnel boring machines, in \$/ft (dollars per linear foot of tunnel), and then to adjust the unit-length cost for each case according to the tunnel diameter, which is the single most important factor affecting the unit cost of tunnels built under similar conditions in New York City. This assumption enables us to use a simple formula of the following form for estimation purpose:

$$C = KD^N \dots\dots\dots (C-1)$$

In Equation C-1, the quantity C is the cost in dollars per linear foot (\$/ft) of tunnel; K is a constant that must be determined from reliable existing cost data; D is the tunnel diameter in feet (ft); and N is a constant greater than one but less than 2. If the tunneling cost is assumed to be proportional to the volume of the earth and rock removed during tunneling, then N will be equal to 2. In reality, due to cost-effectiveness of using large tunnel boring machines (economy of

size), the value of N is expected to be somewhat smaller than 2 – in the neighborhood of 1.7. Therefore, unless otherwise proven by reliable cost data, the value of N is assumed to be 1.7 for use in this project, and Equation C-1 reduces to:

$$C = KD^{1.7} \dots\dots\dots (C-2)$$

The constant K in Equation C-2 can be found from reliable existing cost data for similar tunnel projects in New York City. A search of literature found that the New York City Economic Development Corporation (NYCEDC) had commissioned a Cross-Harbor Freight Movement Major Investment Study [14]. The final report of this study contains useful information on tunneling cost using TBMs. In Table B.3 of the report, it gives the cost for a 31,000-ft tunnel, including 2 portals and a ventilation system, plus a 25% contingency, to be approximately \$852,000,000. This was in 1999 dollars. From the Cost-of-Construction Index [46], it appears that from 1999 to the beginning of 2004, construction costs have increased by about 12%. Therefore, when adjusted to the 2004 cost, the 31,000-ft-length cross-harbor tunnel in New York City will cost approximately \$920,000,000 in 2004 dollars. This yields a C value of $\$920,000,000 \div 31,000 = \$29,700$ per foot. Note that the proposed cross-harbor tunnel has a diameter of 33 ft. Substituting $D = 33$ ft and $C = \$29,700/\text{ft}$ into Equation C-2 yields $K = 77.9 \approx 78$. Thus, Equation C-2 becomes:

$$C = 78D^{1.7} \dots\dots\dots (C-3)$$

Using Equation C-3, the cost of constructing a tunnel of 7-ft diameter for the pallet-tube PCP system in New York City, as discussed in Sec.2.2, will be \$2,130 per ft, or \$11 million per mile, approximately. By the same token, for the proposed PCP for dispatching containers to and from seaports, the tunnel diameter is 15 ft, and hence the tunneling cost is \$7,790/ft or \$41 million per mile, approximately.

Further refinement of the above equation has been made by using information provided by the NYC Department of Environmental Protection (NYCDEP). The information pertains to the tunnel construction cost of City Water Tunnel No. 3 and two other smaller tunnels. Based on the information provided, Equation C-3 is revised as:

$$C = 55 D^{1.7} \dots\dots\dots (C-4)$$

where C is the tunneling cost in dollars per linear foot of the tunnel, and D is the tunnel diameter in feet. Note that the above equations are for tunnels constructed by using modern tunnel boring machines (TBMs). The cost would be significantly higher if the traditional drill-and-blast method is used.

For a 24-ft diameter tunnel such as the City Water Tunnel No. 3 currently under construction in New York City, Equation C-4 yields a tunneling cost of \$ 12,200 per foot approximately, which is equivalent to \$ 64.5 million per mile approximately. This yields a total cost of \$3.9 billion for a total of 60 miles of tunnel as for City Water Tunnel No. 3. The project cost for City Water Tunnel No.3, reported in [13], is \$5.5 billion to \$6 billion, which includes not only tunneling but also valve chambers and equipment, which are costly. This shows that Equation C-4 yields reasonable comparison with the tunneling cost of City Water Tunnel No. 3, which uses a modern tunnel boring machine (TBM) for constructing the tunnel. Henceforth, **in**

this final report, Equation C-4 will be used to predict tunneling cost in deep bedrock using modern TBMs in New York City.

Due to the great variability of tunnel construction cost with the construction method used and local conditions, Equation C-4 is recommended for use only as a rough estimate under the following conditions:

- Use of modern tunnel boring machine (TBM) for constructing the tunnel.
- Boring is through hard rock or medium-hard rock, such as that encounter in the bedrock of New York City.
- Tunnel is deep underground (100 ft to 400 ft below the street level).
- Tunnel diameter is within the range of 7 ft and 35 ft.
- Tunnel is constructed under a major city, such as New York City.
- Labor cost is high – as in New York City.
- The equation is for year 2004. For future years, the equation should be adjusted according to the Cost-of-Construction Index.
- The cost is for a completed tunnel with conventional concrete lining but without expensive structures or equipment inside the tunnel. For instance, if a railroad runs through the tunnel, the cost of installing the railroad in the tunnel is not included in this equation.

C.2 Cost of Large Rectangular Reinforced Concrete Conduits Laid in Trenches

For the large PCP system to dispatch containers to and from harbors, and for the large PCP to ferry trucks in Hunts Point, it is possible to use the open-cut (trenching) method to construct a large portion of the conduits. In these cases, it is better to use rectangular conduits (such as the one shown in Figure 25) than to use circular conduits (such as the one shown in Figure 24). The former is more compatible with the open-cut method and the flat-bed rail system that must be installed in the PCP, and it costs less. Even though the round pipe can withstand much higher internal pressure, it is not necessary for PCP due to the low pressure encountered, generally less than 5 psi (pounds per square inch). Therefore, whenever it is practical to use the open-cut method to construct large concrete conduits for PCPs, rectangular conduits should be used.

The cost of unit length of a prefabricated rectangular conduit made of reinforced concrete is mainly a function of the size of the conduit as follows:

$$C = KB^N \dots\dots\dots (C-5)$$

where C is the unit cost in dollars per linear foot (\$/ft), K and N are different constants, and B is the size of the rectangular conduit which can be defined as the arithmetic mean of the width, w, and the height, h, of the rectangle, namely,

$$B = \frac{w + h}{2} \dots\dots\dots (C-6)$$

If the unit cost is assumed to be proportional to the volume of the materials used to construct the conduit, then N should be equal to 2. In reality, n will be less than 2.0. It is assumed here to be 1.7, as it is the case for round tunnels. Thus, Equation C-5 reduces to

$$C = KB^{1.7} \dots\dots\dots (C-7)$$

From [45], the cost of 4775 ft of a rectangular concrete conduit of 10 ft × 9 ft cross-section, in June 2000, was \$1,500,000. Using this cost information, and using Equations C-6 and C-7, the constant K is approximately 6.84. So, in terms of 2004 dollars, K is approximately 7. Therefore, Equation C-7 reduces to

$$C = 7B^{1.7} \dots\dots\dots (C-8)$$

Note that Equation C-8 is covers the approximate cost for purchasing the conduit from a commercial source without inclusion of the transportation cost. Assuming that the transportation cost is 30% of the purchase value, Equation C-8 further changes to:

$$C = 9.1B^{1.7} \dots\dots\dots (C-9)$$

The above equation does not include the cost for digging the trench needed for laying the conduit, nor does it include the cost for dumping the excess amount of excavated materials, backfill, and compaction of the backfilled soil. From a study conducted by a consultant of this project [47], these extra cost items are approximately 40% of the cost of the reinforced concrete conduit as estimated by Equation C-9. Therefore, including all major components of the construction costs of a near surface rectangular conduit made of reinforced concrete, Equation C-9 is further changed to:

$$C = 12.7 B^{1.7} \dots\dots\dots (C-10)$$

Note that the above equation holds approximately under the following conditions:

- Rural areas of the eastern states of the U.S.
- Rectangular conduit made of reinforced concrete, with the top of the conduit being about 5 ft below the ground surface.
- The soil is clay and/or silt.
- No groundwater is encountered at construction site.
- No existing structures, such as buried sewers or water mains, are crossed, and no relocation of such structures is needed.
- 10% profit is included in the cost
- The size of B is in the range of 5 ft to 20 ft

C.3 Cost of Steel Pipes Laid in Ditches (Open-Cut Method)

A large portion of the steel-pipe PCP for transporting solid wastes and a large portion of the steel-pipe PCP for transporting mail and parcels are laid either in rural areas or along the easement of I-95, using standard pipeline construction techniques perfected by the gas and oil industries. Under average rural conditions, the construction cost of such steel pipelines using the open-cut method can be estimated from [48]:

$$C = 129D^{1.34} + 102D^{0.87} + 24D + 20 \dots\dots\dots (C-11)$$

In Equation C-11, D is pipe diameter in ft, and C is the construction cost of one mile of pipeline, in thousand dollars -- \$1000/mile. The cost is given in 1992 dollars. Converting to 2004 dollars by using the Cost-of-Construction Index [46], Equation C-11 yields

$$C = 155D^{1.34} + 122D^{0.87} + 29D + 24 \quad \dots\dots\dots (C-12)$$

The quantity C in Equations C-11 and C-12 is in thousands of dollars per mile, and D is pipe diameter in ft.

Using Equation C-12, the average construction cost of a PCP using 40-inch steel pipe using the open-cut method in rural area is \$1,247,000 per mile, approximately.

C.4 Cost of Laying Submarine Pipelines

For both the proposed PCP in New York City, one for transporting solid wastes and the other for transporting mail and parcels, a significant portion of these two pipelines using 40-inch-diameter steel pipe will be laid underwater using lay-barges, in a manner similar to laying offshore steel pipelines by the oil and gas industries. **In this study, the cost for laying submarine steel pipelines in 2004 is assumed to be approximately twice the cost given by Equation C-12.**

C.5 Cost of Microtunneling and Horizontal Directional Drilling (HDD)

As assessed in Sec.3.5 (c) and (d) , to construct the PCP for solid waste transport and the PCP for transport mail and parcels, the technique of microtunneling will be needed for road crossings, and the technique of horizontal directional drilling (HDD) will be needed for river/estuary crossings. The costs of microtunneling and HDD are usually approximately ten times the cost of that given by Equation C-12. **Thus, in this project the costs of microtunneling and directional drilling will both be estimated by using Equation C-12 multiplied by a factor of ten**, which is believed to be reasonable for cost estimates in this study.