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Feasibility of Using Pneumatic Capsule Pipelines in New York City for Underground Freight Transport

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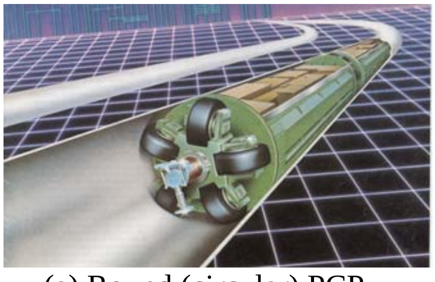
Abstract

Under the sponsorship of the New York State Energy Research and Development Authority (NYSERDA), a project has been completed in 2004 to assess the technical and economic feasibility of using pneumatic capsule pipelines (PCPs) for underground transportation of freight in New York City. Six different applications, using various sizes of PCPs, have been examined. They include using PCPs for: (1) tunnel construction, (2) transporting municipal solid waste, (3) transporting mail and parcels, (4) delivering goods on pallets, (5) dispatching containers from seaports to an inland inspection/transfer station, and (6) ferrying trucks with their cargoes. The sixth application, using large conduits (tunnels) to ferry trucks, has been examined for possible use in a particular area of New York City – Hunts Point. Results of this study showed that all six of the aforementioned applications to New York City are technically feasible, and will bring significant benefits to New York City in terms of enhanced transportation safety and security, and reduction in air pollution and traffic jams caused by trucks. The first five of the six applications are also found to be economically attractive (cost-effective). The promising results of this study are expected to prompt future use of PCPs in New York City and elsewhere in the nation, which will significantly reduce the number of trucks on streets and highways in urban areas, thereby reducing traffic jams, accidents, and air pollution caused by trucks. It may also reduce the chance of any terrorist attack using truck bombs and containers, and hence improving transportation security in overcrowded cities and harbors. The need for federal assistance to demonstrate this meritorious new technology for underground freight transport is also addressed.

Introduction

Pneumatic capsule pipeline (PCP) is the use of air to convey or transport cargoes in capsules (containers or wheeled vehicles) moving through pipelines. Modern systems of PCPs, used with great success in Japan (Kusugi 1992, 1999, 2003), use capsules and pipes (conduits) of either circular or rectangular cross-sections—see Figure 1.



(a) Round (circular) PCP

(b) Rectangular PCP

Figure1. PCPs of circular and rectangular cross-sections (courtesy of SumitomoMetal Industries)

The circular type of PCP, using steel pipe of approximately 1 m (3.28 ft) diameter, is currently used by the Sumitomo Company to transport limestone from a mine to a cement plant over a distance of 3.2 km (Kosugi 1992). This PCP, with each capsule carrying 1.6 tonnes (1.76 tons) of limestone, transports 2.0 million tonnes (2.2 million tons) of limestone annually. It has been in use since 1980 with great success – achieving an impressive record of 95% availability. A similar system has been used for underground transport and disposal of hazardous waste (Kosugi 2003). Finally, a temporary PCP of rectangular cross-section (approximately 1 m x 1 m) was used in Japan to construct a long tunnel for bullet trains—see Figure 2. The system, using (b) type capsules shown in Figure 1, transported premixed concrete into the tunnel, and carried out excavated materials (soil and rock). It had many advantages over the use of truck or rail for tunnel construction, including greater safety and less pollution, and cost savings (Kosugi 1999, Liu 2003).

(a) PCP conduit entering/leaving the Tunnel

(b) PCP conduit outside the Tunnel

Figure 2. Use of a rectangular-conduit PCP for construction of the Akima rail tunnel in Japan

All the PCP systems used in Japan use blowers (fans) to blow air through the pipes (conduits); the moving air in turn drives the capsules through the pipe. Because blowers block the passage of capsules, a special system is used to cause capsules to bypass the blowers. The bypass system limits the capsule throughput (freight capacity) and increases costs. Still, the PCP technology was used successfully and economically in Japan as discussed before. In recent years, two types of electromagnetic capsule pumps have been developed in the United States to drive PCPs, one using the technology of linear induction motors (Liu 1999), and the other using linear synchronous motors (Montgomery et al. 1999). Both types enable free passages of capsules, and a large increase in capsule throughput. The choice between the two types depends on both throughput (freight capacity) and system complexity. For a simple PCP that has only one inlet and one outlet, and that needs no booster pumps, the blower system can be used if the required throughput is within a certain limit. In contrast, if the required throughput is very large, and/or if the system is complex (involving booster pumps and/or a network of interconnected conduits with multiple inlets and outlets), then the non-intrusive electromagnetic capsule pumps must be used. Two types of electromagnetic capsule pumps have been investigated for use in PCPs -- the ***linear induction motor (LIM)*** and the ***linear synchronous motor (LSM)***. As assessed and compared in (Liu 2000), the former appears to be more promising than the latter for use to drive PCPs.

This project assessed the feasibility of using modern PCPs in New York City for various possible applications. The study is important to New York City due to its heavy dependence on trucks for freight transport, and the many problems caused by the overuse of trucks. Since almost anything transported by trucks can be transported by PCPs, use of PCPs provides an effective way of reducing the use of trucks. The feasibility of each application was assessed by considering key issues pertaining to each case, including but not limited to technical and economic issues. In each application, a different type of PCP was selected in terms of conduit cross-section (circular or rectangular) and driver system (blower or LIM), whatever is the best (most practical or economical) for each case. This paper presents a concise discussion of the findings of this New York City project; details can be found in (Liu 2004).

Potential Applications

Six types of potential applications of the PCP technology in New York City have been considered and evaluated in this study. They are discussed one-by-one as follows:

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 (National Geographic 1997). Some tunnels, such as Water Tunnel No.3, are currently under construction and will take, according to official plan, until year 2020 to complete (NYCDEP 2004). Also, there is an increasing need for other underground tunnels to be constructed in New York City for various purposes, such as bringing railroads to the City (NYCEDC 2000). During the construction of large tunnels, such as Water Tunnel No. 3 which is 20 to 24 ft in diameter, trucks are used in the current practice to transport construction materials into the tunnel and excavated materials out of the tunnels. Because these tunnels are over 100 m underground, trucks are lowered into the tunnels and hoisted out the tunnels 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 on streets near the tunnel entrances.

According to (NYCDEP 2004), 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 may be prevented or greatly reduced in the future by using PCP instead of trucks for conveying materials during tunnel construction. 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. This conclusion is reached through a detailed assessment conducted in this study. 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 the 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, or a pneumatic capsule lift system reported in (ASCE 2002). Either way, it is much easier and safer to lift or lower individual capsules than to lift/lower trucks. With tunnels being bored under busy streets, the advantage of using PCP can be expanded by extending the aboveground portion of the PCP conduit to a less crowded location away from tunnel entrances, as shown in Figure 2 (b). In doing so, the truck traffic aboveground near tunnel entrances can also be greatly reduced.

Note that the blower-driven PCP for tunnel construction is 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. Such a typical PCP system for use in NYC has been designed and analyzed in this study. The analyzed system is for constructing a tunnel of 24-ft diameter and 10- mile length. The excavated material is to be transported to a landfill 3 miles away from the tunnel entrance. One of every three capsules that carry the excavated material out the tunnel, upon dumping its load at the landfill, carries premixed concrete back into the tunnel for constructing the tunnel lining. By running capsules in the system at the rate of one capsule per 3.3 minutes, a total of 397,000 cubic yards of excavation materials can be removed per year, which equals the amount excavated by a 24-ft diameter tunnel boring machine (TBM) advancing at an average speed of 50 ft/day. Analyses showed that at capsule velocity of 25 mph, the PCP system of 13-mile length develops a pressure drop of 3.9 psi and requires an input power of 640 kw. The capital cost of the entire system is approximately $11 million, and the annual operation/maintenance cost is about $ 4 million. With an economic life of 2.9 years (the time to complete the tunnel), the cost for transporting each cubic yard of material by this system is $17 for an average transportation distance of 8 miles. This cost is significantly less than can be achieved by using trucks for the same purpose.

2. Solid Waste Transport

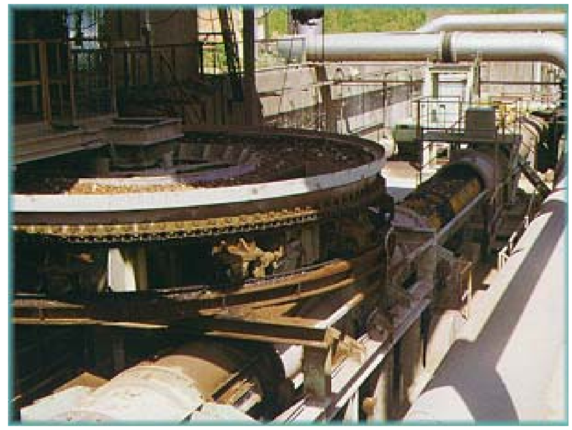
According to the websites of the New York City Department of Sanitation (2004), and the New York City Waste Coalition (2004), the Department picks up approximately 12,000 tons per day of residential and institutional solid waste. The wastes are picked up by trucks and transported to nine transfer stations. The wastes are compacted at the transfer station and then exported by conventional modes, including truck, barge and train, to landfills in New Jersey and other states. The cost of transferring, transporting and disposing the 12,000 tons per day of this 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 (NYC Waste Prevention Coalition 2004):

"… 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 in less populated neighboring areas in New York and/or other states such as New Jersey.

This study investigated the use of a PCP system for transporting the 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 using PCP for 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 singe large 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, and the other to return the empty capsules. 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 on ground in rural area by using the open-cut method, 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 essential to the determination of the cost of the system.

Twin pipes are used-- one serving as the **delivering line,** which delivers the compacted solid waste from each waste transfer station to the landfill for disposal or processing. The other twin pipe serves as the **return line**, which returns empty capsules back to each transfer station. Note that at any given time, the main pipe receives loaded capsules from and returns empty capsules to only one of the nine transfer stations. The system is schedule to operate 24 hours a day, and to switch to different transfer stations at different time of each 24-hour day. Thus, 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 New York City Department of Sanitation (DSNY). This will allow the system to handle expected increasing demand in the next 20 years. 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 (Kosugi 1992). The system use the round capsules shown in Figure 1(a), and uses the same loading/unloading equipment shown in Figure 3. To facilitate operation, five capsules will be linked together to form a capsule train.



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

Figure 3 The inlet loading system of PCP transport of limestone in Kuzzu, Japan; 40-in-diameter steel pipe is used in this project. (Courtsey of the Sumitomo Metal Industries, Ltd.)

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 whether. It operates continuously 24-hours a day and 365 days a year except for an anticipated less than 5% downtime. Due to this, the proposed system will not require nearly as large a storage and processing area as that used currently at each transfer station. This means saving of space at each transfer station; the saved space can be converted to other more valuable use such as commercial or industrial usages. 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 ensuing discussions.

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, or the way they are transported from the source (i.e., each individual homes, buildings, or parks that generate wastes) to the waste transfer stations.

An analysis of this 9-branch PCP system for solid waste transport showed that to achieve the designed capacity of 18,000 tons per day of solid wastes transport, one must link five capsules together to form each train, and a train must be injected into the pipe at the interval of 19 seconds. While this train injection interval is only one-half of that used in the limestone transport project in Japan, there is no technical difficulty to do so because the New York City system has 9 inlets working alternately one at a time. Thus, the time to load/unload any capsule train at each station is actually much longer than the 40 seconds in the Japanese project. By using capsule speed of 25 mph, the pressure drop along the entire PCP from inlet to outlet was found to be 27.6 psi, which can easily be achieved by using commercially available blowers. The power to run the entire system is calculated to be 2.2 mw for the delivery line with loaded capsules, and 1.8 mw for the return line with empty capsules. So, the total power to be used is 4.0 mw which is quite reasonable for such a major pipeline. The system will be highly automated. A radio frequency identification (RFID) tag, the same used at highway toll both to keep track of automobiles, 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 automatically. 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.

The cost analysis showed that the total capital cost of the system would be $757 million, the annual opertation/maintenance cost would be $22 million, and the cost for transporting each ton of the solid waste through this system would be about $7. The unit cost of $7 per ton is only a fraction of what is paid currently by DSNY for transporting solid wastes to out-of-state disposal sites. By using this PCP system, New York City would save over $20 per ton of solid waste transported, resulting in over $100 million dollars in annual saving to the City.

3. Mail and Parcel Transport

A PCP system was designed in this project to transport mail and parcels between New York City and Washington D.C., serving all cities along this East-Coast Corridor. 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 in New York Metropolitan 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 open-cut 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, unless otherwise indicated, are single-line lengths. For the twin lines, the values are simply doubled. How these pipelines are laid is essential to the determination of the cost of the system. 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 6, except 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.

The PCP system analyzed here is designed to 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 beyond the current daily volume of mail and parcel transported by the U.S. Postal Service via 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.

The cost analysis showed that the total capital cost for this major mail-parcel PCP between New York City and Washington D.C., if built along I-95 using a part of the highway's easement, would be approximately $2.2 billion, and the annual operation/maintenance cost would be about 116 million. The cost for transporting each ton of cargo over the 480 miles of the twin lines would be approximately $17. This translates into a cost of $3.50 per ton for 100 miles, or 3.5 cents per ton per mile. 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 along this corridor. Because mail can be transported from New York City to Washington D.C. through this pipeline in as short as 6 hours, the system would be very competitive against contemporary modes of transport of mail and parcel. In addition, New York City and the region would benefit from this PCP in other ways as well: reduced traffic jam, accidents and air pollution generated by trucks.

4. Transporting Goods on Pallets, Boxes and Crates (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 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 6.40 m (21 ft) length will be able to carry five fully loaded pallets. Such a capsule will also be able to carry goods in most boxes, creates or bags. 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 4. The circular conduit is chosen for New York City because it is easier to construct underground using a tunnel boring machine (TBM), and also because it is structurally stronger than rectangular cross section.

As can be seen from Figure 4, the standard capsule designed for the pallet-tube system for New York City uses steel wheels running on steel 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 four reasons: (1) They have a rolling friction coefficient approximately 5 times smaller than that of rubber tires, thereby greatly reducing friction and saving energy; (2) capsules with steel wheels running on rails 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, 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 regular 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, and air blowing through the pipe.

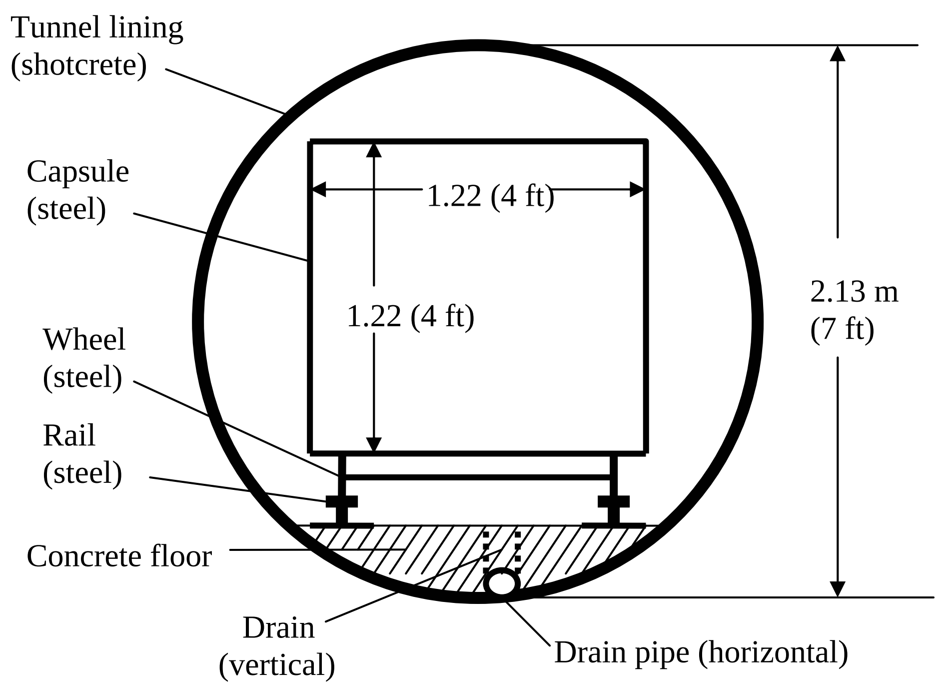


Figure 4. Cross-section of the pallet-tube PCP for New York City

Another main difference between the Japanese PCP systems and the pallet-tube PCP system is that the latter must uses electromagnetic pumps instead of blowers. This is due to the complex network of conduits and the multiple inlets/outlets required for the latter—a system as extensive as the current subway system. The system has a large number of node points (**stations**), with each located under a city block as shown in Figure 5. This enables the delivery of goods from and to various parts of the City. Dual lines are used to accommodate freight flow in opposite directions. The most suitable electromagnetic pump for this application is single-sided linear induction motor (SLIM). Figure 5 shows the layout of a typical station.

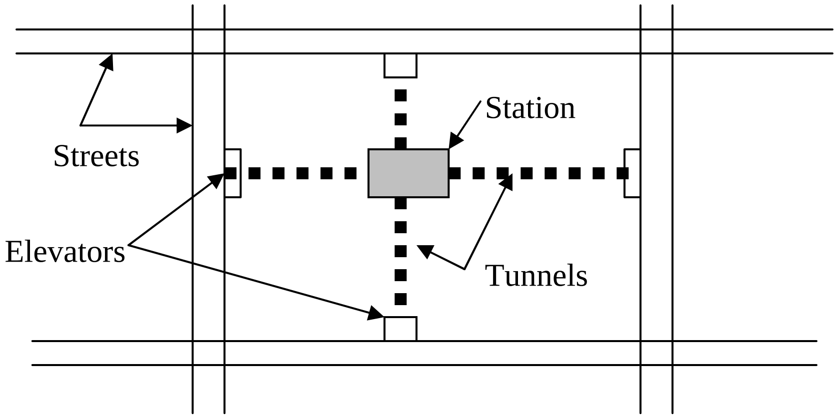


Figure 5. Pellet-tube PCP station and outlet tunnels and elevators. (Note that the station and the tunnels are underground, connected to the streets by elevators.)

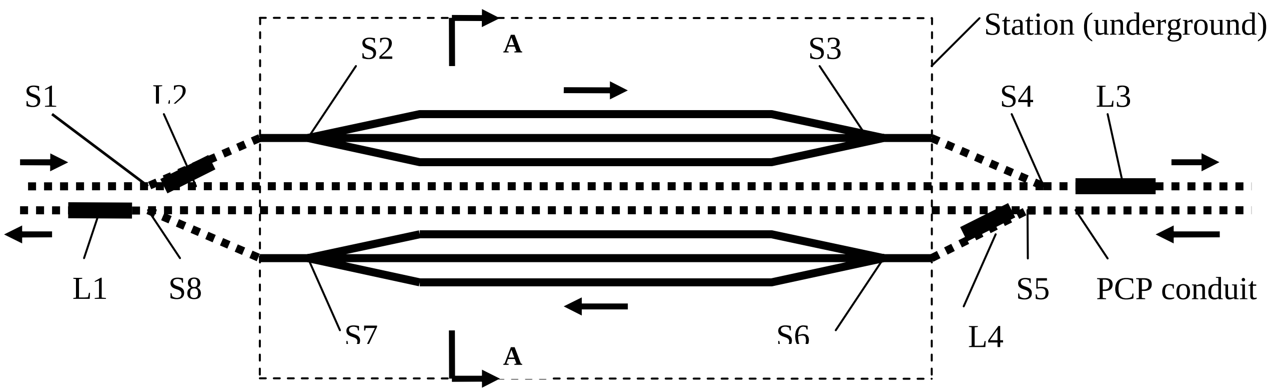


Figure 6. Layout (plan) of a typical underground station for pallet-tube PCP

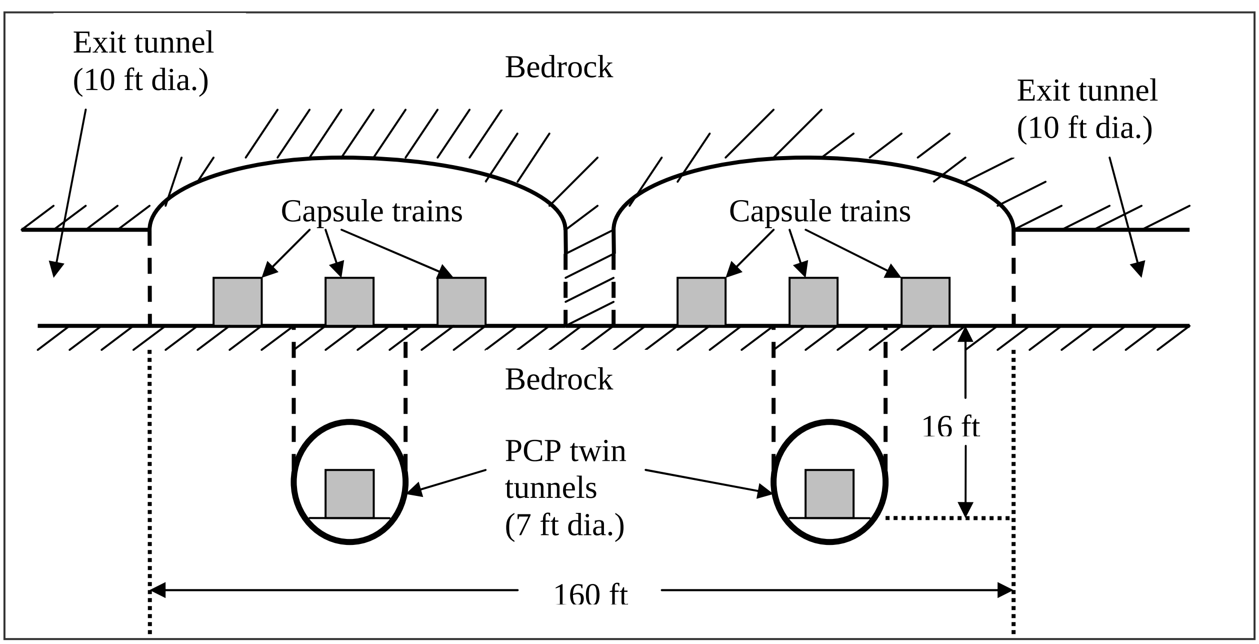


Figure 7 Sec.A-A (vertical cross section of a PCP station with layout shown in Fig.6)

In Figure 6, each heavy dotted horizontal line represents a horizontal PCP conduit imbedded in the bedrock approximately 100 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 10 m above the connecting conduits so that gravity will cause the capsules to decelerate as they rise to the station platform (such as from S1 to S2), and 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 subways, building foundations, piles, sewers, water pipes, other pipelines, and cables, which are normally found within 30 m of the ground in New York City. As shown in Figure 5, connection between each station and the streets above is by a set of four narrow tunnels of 6 ft width and 7 ft height, with their ends connected to the streets by elevators. Cargoes arriving at the station on pallets or in boxes, crates and bags can be transported by pallet jacks or battery-powered small vehicles moving through the tunnels, lifted to the street level by the elevators, and then transported over short distances to neighboring stores along streets or side walks.

As shown in Figure 6, 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 (Liu 1999). 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.

The pallet-tube PCP system can deliver most of the cargoes currently carried by trucks, including the 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 (**ports**) around the network's outer perimeter. At each port, trucks carrying freight headed for New York City will unload their cargoes from each container onto capsules in the PCP system for dispatch through the network to various stations. 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 details. What 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. This project also showed the cost-effectiveness of this system.

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. If the average area of a cell is 1,000,000 ft^2, New York City which covers a geographical area 320 square miles will have 2920 of such cells. In reality, in less densely populated areas, larger cells will be appropriate. The station layout of a cell is shown in Figures 6 and 7. The station covers an area of 200-ft length and 160-ft width.

An analysis has been performed on a typical pallet-tube PCP cell of 1,000 ft by 1,000 ft. In this system, each capsule can carry 4.2 tons of cargo, and the speed of the capsule is 25 mph. The maximum number of capsules that can pass through the tunnel, corresponding to 20% linefill[1], is 49,200 per day. The tunnel transports a total freight of 1.02×10^7 ft^3/day, equivalent to 205,000 tons/day, or 75 million tons/year. This is an enormous freight capacity.

To facilitate handling, trains of five capsules are used in this system. With the ability to inject/eject one train in every minute, the cell analyzed here has a capacity of launching (injecting) 1440 trains per day, carrying 30,000 tons of cargoes. The cell 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 one-minute-per-train injection interval will be greatly relaxed. 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 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 such a cell.

The cost analysis of this system shows that capital cost of the cell is $77 million, the operation/maintenance cost is $11 million, and the cost for transporting each ton of cargo over a distance of 2,000 ft is about $0.177/ton. 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 an estimated 70% reduction in the number of trucks used in the City, which in turn generates great safety and environmental benefits to the City.

3. PCP for Dispatching Containers

New York City has some of the nation’s busiest ports, with thousands of containers lying on 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 number 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 for inspection, which would only exasperate the current security problem. The dilemma can be

[1] Linefill is the fraction of the pipe length occupied by capsules – i.e., the ratio total length of the pipeline filled with capsules divided by the total length of the pipeline.

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 a large PCP designed specifically for dispatching containers from one or more than one port to an inland inspection/transfer station. If a dual-tube (twin-conduits) is used, one PCP conduit can be used to transport the containers away from the port, and the other parallel conduit 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 transferring 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 security and commercial values to New York City.

The PCP system for this purpose will require the use of large underground circular tunnels or conduits. Because a standard container is 40 ft long, 8 ft wide and 9.5 ft high, the PCP conduit (tunnel) for transporting containers should have a minimum diameter of 15 ft (4.57 m), using a design similar to that shown in Figure 4 except for the much larger size of the cross-section. Each capsule should be 40 ft long so that each can carry a 40-ft-long container, or two TEUs (Twenty-foot Equivalent Units). The capsules will be similar to flatbed trains, and they can be mechanically linked to form a train in order to facility operation. Figure 8 is a general layout of the system. As shown in Figure 8, the capsules going through the PCP conduit will be driven by one or more than one LIM (linear induction motor). Long tunnels may need more than one LIM placed at suitable intervals along the tunnel. Single-sided LIMs will be used, each consisting of a coiled plate (stator) placed on each side of the conduit, as it is with the pallet-tube system discussed before. The LIM will be powered by 3-phase current of 480 VAC. Although only a single tunnel is shown in Figure 8, twin tunnels will be used so that containers can move in opposite directions simultaneously. Where such a system should be used in New York City is a question that can best be answered by transportation planners and Port Authority of New York and New Jersey.

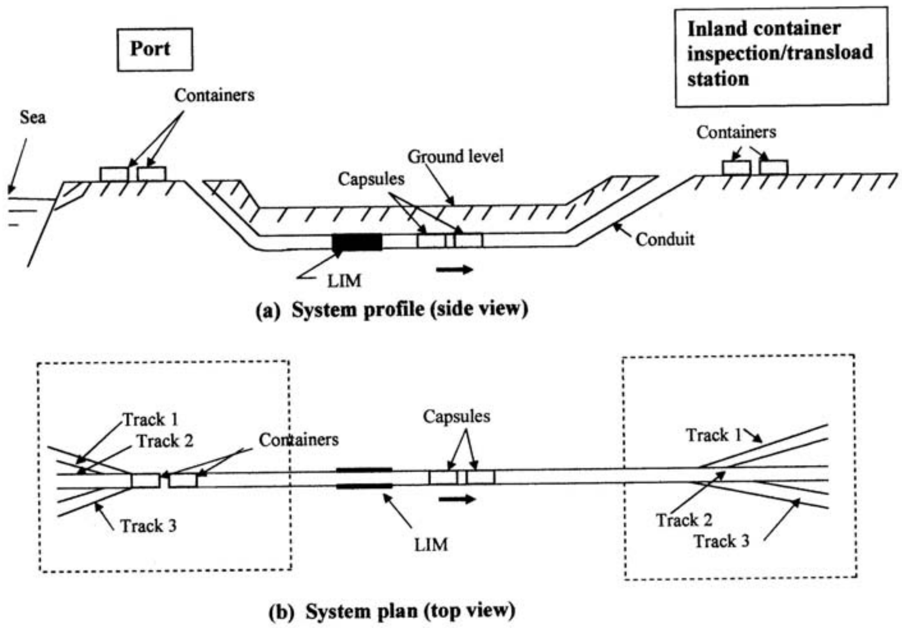


Figure 8. General layout of a PCP system for dispatching containers from and to ports

An analysis of the container dispatch system has been conducted using four inlets and one outlet. 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, 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 under an average of 5 ft of earth cover. These construction details are needed for assessing the cost of the system analyzed.

The analysis of this system is similar to that of the PCP system for solid-waste transport in that the system has multiple inlets with a single outlet. However, it differs from the solid-waste PCP in that the pipe consists of two parts with different shapes – circular tunnel first 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.

The PCP system analyzed here for container dispatch to and from the ports in New York City has a maximum capacity for transporting 30,210 TEUs (twenty-feet equivalent units) of containers per 24-hours, which is equivalent to 11 millions TEUs per year if the system is 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 sufficient capacity to handle all the containers at these ports not only at present but also for years to come. The system requires the use of 1,504 capsules of which 15% is spare. The dispatch time (i.e., the time for a capsule 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 is 5.72 seconds. Should this injection time of less than 6 seconds be difficult to achieve, several capsules can be linked together to form trains which will increase the injection time by several folds. At the designed peak capacity, this PCP system will use a total of 141 mw of electric power.

The cost analysis shows that the PCP for dispatching containers in New York City would have a capital cost of $2.0 billion approximately, and an annual operation/maintenance cost of $312 million when used to its full design capacity. At the design capacity, it would cost only about $17 to transport a 20-ft container (i.e. one TEU) from a port of the City to an inland rural area for inspection and intermodal transport, and it would cost 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 can also be 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 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.

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, with each capsule carrying an entire truck or tractor trailer. The trucks (including tractor trailers and vans) would be piggybacked by the capsule, in much the same manner trucks and cars are piggybacked through the Euro Tunnel from England to France via an underground tunnel (Euro Tunnel 2004). The only main differences are: the system proposed for use in New York City would use pneumatically driven PCP capsules instead of electric trains, the system would be on land instead of undersea, and it would be smaller and much shorter 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? This project has determined that Hunts Point, a peninsula of Bronx, is the place that can benefit from such a PCP. This is explained briefly next.

Hunts Point is the place in New York City where the City's foods are processed, serving 8 millions people in the New York Metropolitan area. It has the nation's largest produce processing center, and the nation's largest meat processing center. 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 two processing centers, which are located next to each other in the southeast corner of Hunts Point – 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 are seeking 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 region. 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, and some as far as the West Coast), 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 side of Hunts Point 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 9. Various aspects of the two routes have been considered, including geology (ground condition), relative buildup (urban development), interference 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 or tunnel, to two freeways (I-278 and I-895). It enables easy freeway access from and to three different directions. 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.

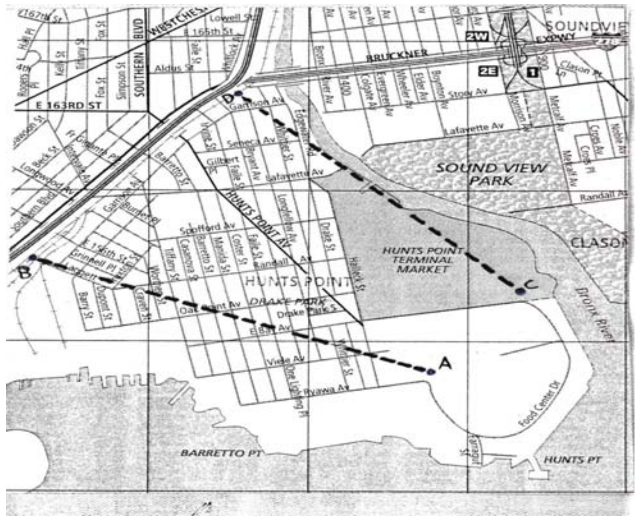


Figure 9. Proposed alternative PCP routes (AB and CD) investigated for ferrying trucks across Hunts Point. (Note that the east route, CD, is found to be the preferred route.)

As with other PCP systems discussed here, the truck-ferrying PCP in Hunts Point would use a dual conduit or twin tunnel, 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). In either case, the length of the conduits or tunnels, from C to D, is approximately 1.7 km (1.06 miles). 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 furry a van or pickup truck. Figure 10 shows the general layout of the 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. Analysis shows that 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 takes less than 3 minutes for any capsule to move through the conduit. The operation of the system is described as follows:

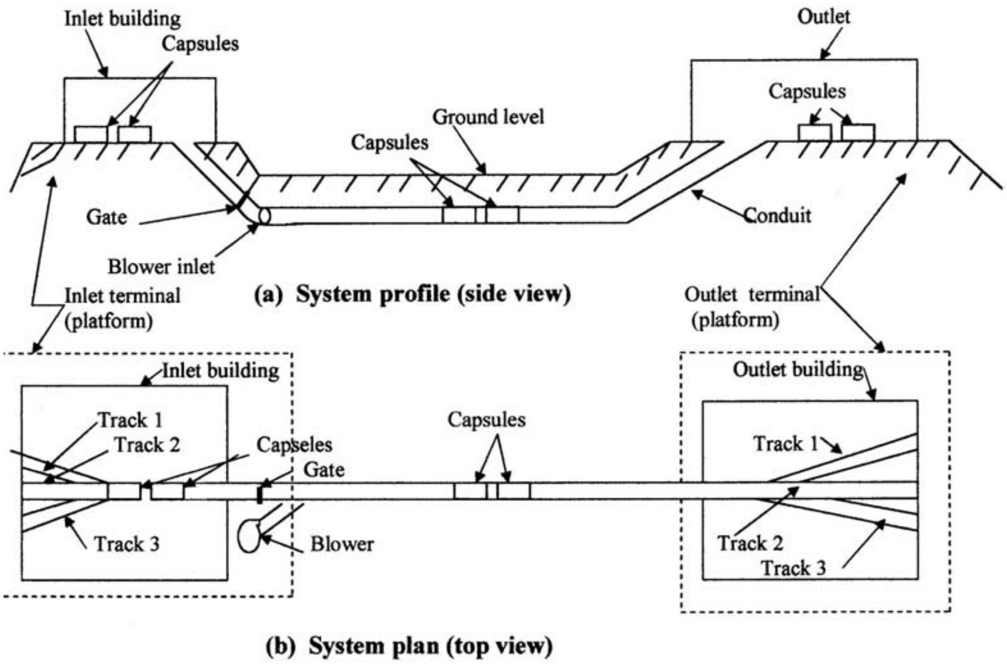


Figure 10. General layout of a truck-ferry PCP system designed for use in Hunts Point.

As soon as 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 capsules are parked in different lanes. The driver parks the truck on 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. Due to the sloped entrance of the conduit as shown in Figure 10 (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. 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, such rides are comfortable and safe.

As soon as the capsule approaches the Food Center (point C in Figure 9), it will decelerate automatically due to the rising slope of the exit conduit -- see Figure 9 (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.

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 speed of 30 mph, creating a maximum pressure drop along the conduit of 22.8 psf or 0.158 psi, and using 568 kw of electrical power supplied to the blowers, one at each end of the twin conduits. 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.

The cost analysis showed that the capital cost of this PCP system for ferrying trucks in Hunts Point would be approximately $126 million, the annual operation/maintenance cost would be about $4.5 millions. The cost would be $6.90 per truck for one-way or $13.8 for round-trip. Given a choice, most truckers would not want to pay such tolls and take this ferry trip due to the fact that they can drive this short 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 ferry and avoiding the driving of 1.1 miles of one-way distance 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 project that cannot be justified 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 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 who much deserve to have such a park, (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 significant for the residents of Bronx, especially of Hunts Point.

Conclusion

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

(1) It is 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 payoff 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 the six applications of PCPs in New York City can bring great social and environmental benefits to the City, derived from 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 tunnels 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-driven

vehicles 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 containers arriving from overseas, and will make it difficult if not impossible for terrorists to bomb the City using uninspected containers. However, even though this system is needed primarily for security reason, the NY& NJ Port Authority can derive great financial benefits, and the City can derive great social benefits from this PCP, in terms of reduced air pollution, traffic jam and accidents -- 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 benefits, 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) When all the six applications evaluated in this study are fully implemented in the future, the use of trucks for transport in New York City can reduce by approximately 70%, which in turn will 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 the most effective way to reduce truck use in New York City.

(7) The use of PCPs in New York City will 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 or 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 the various applications of 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) Once the PCP technology is implemented in New York City, it is expected that many other cities in the nation and around the world will follow the example of New York City, and will benefit from this advanced new transportation technology. Due to this, a commercial demonstration project of PCP in New York City warrants the support of not only the New York City and New York State, but also the federal government. Agencies such as the U.S. Department of Transportation should actively support such a project in order to hasten the use of this beneficial new technology in the nation.

Acknowledgment

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