Paper presented at the 12th International Symposium on Freight Pipelines,
Prague, Czech Republic, September 20-24, 2004

USE OF PNEUMATIC CAPSULE PIPELINE FOR UNDERGROUND TUNNELING

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Pneumatic capsule pipeline (PCP) has been used successfully in Japan to construct the Akima tunnel, which is a cross-mountain rail tunnel 8 km long. A similar system has been considered recently for possible use in New York City for constructing deep underground tunnels. This paper presents the result of the New York study, which is one of several potential applications of PCP to New York City considered and analyzed in a recently completed research project. Although this study was conducted with application to New York City in mind, it is rather general in scope and hence is believed to be applicable to also many other major cities around the world that need to build deep underground tunnels. The study found that with the use of a PCP system similar to the one used for the Akima tunnel, and with the use of a vertical lift system for transporting capsules from underground tunnels to aboveground streets, the PCP technology can be used for deep underground tunneling not only to enhance construction safety and reduce air pollution generated by trucks but also to reduce the tunnel construction cost.

KEY WORDS: capsule pipeline, pneumatic capsule pipeline, tunneling, tunnels, underground

1. INTRODUCTION

Pneumatic capsule pipeline (PCP) is the modern version of the “tube transport” system used throughout the world for over a century as discussed in Liu (2003) and many other publications such as Zandi (1976), ASCE (1998), and Cohen (1999). In contrast to the tube transport technology which uses small-diameter pipe (usually less than 200mm) and non-wheeled capsules each of which carrying less than 10 kg of materials (usually less than 1 kg), the newer technology of PCP uses larger pipes of the order of 1m, and uses wheeled capsules each of which carrying more than one tonne (1000 kg) of cargo. Such PCPs have been used successfully in both the Former Soviet Union (FSU) for transporting rocks (Jvarsheishvili, 1981), and in Japan for transporting: limestone to a large cement plant (Kosugi, 1992), excavated materials for disposal in a tunnel construction project (Kosugi 1999), vertical transport of soil in underground excavation (ASCE 2002), and other applications (Yanida, 1982).

In 2003, the New York State Energy Research and Development Authority (NYSERDA) awarded a contract to the Freight Pipeline Company to investigate the feasibility of using PCP for underground freight transport in New York City. The project, completed in June 2004, explored various potential applications of PCP to New York City. Six different potential applications were studied in detail. They are: (1) tunnel construction, (2) solid waste transport, (3) mail and parcel transport, (4) transporting goods on pallets and in boxes, crates and bags, (5) container dispatch from ports, and (6) transporting entire trucks.

The first of the six applications mentioned above, tunnel construction, is the focus of this paper and will be discussed in detail in the next section. The other five applications will be described only briefly here. In the application to solid waste transport, a PCP was designed to transport 18000 short tons (16400 tonnes) of solid waste per day to a common large landfill at a distance 55 miles (89 km) away. This PCP would use steel pipe of 40-inch (1 m) diameter, and would use blowers to drive the air and capsules through the pipeline. In the application to mail and parcel transport, a 1m diameter steel pipe would be used to transport mail and parcels from New York City to Washington D.C. over a distance of 210 miles (338 km). This system, driven by linear induction motor (LIM) pumps instead of blowers, would operate at a linefill rate of 10% and a cargo throughput of 31030 short tons (28210 tonnes). Note that linefill is the portion of the pipeline occupied by capsules divided by the total length of the pipeline. The system would have five inlet/outlet stations in New York City, one in Washington D.C., and one in each of the four major cities en route: Newark, Trenton, Philadelphia and Baltimore. In the application to transporting pallet goods, a network of PCPs consisting of circular tunnels of 7 ft (2.13 m) diameter would be used. These tunnels would be constructed by using modern tunnel boring machines (TBM) through the bedrock under New York City, at a depth between 50 m and 100 m underground. The network would have multiple cells; each cell would contain an underground inlet/outlet station similar to that of ordinary subway stations, with vertical connection to the streets through elevators. Most of the freight that needs to be transported in New York City, whether on pallets or in boxes, crates and bags, can be transported by this system between underground stations. Once a cargo has reached its destination, it would be unloaded from the capsule and transferred to one or more battery-powered vehicles, which would then be transported by elevators to streets above for local delivery. The system has a capacity of transporting 205000 short tons (186000 tonnes) of freight in each direction, more than enough to handle most of the freight that need to be transported at present.

In another application, a large pipe has been considered for transporting standard size containers between four ports in New York City and a container inspection/intermodal-transfer station located in an inland rural location 24 miles (39 km) away from the City. This PCP would use a combination of circular tunnels (for the portion under urban areas and the bays where construction is by boring tunnels through bedrock) and rectangular conduit (for the portion in rural areas where construction can be done by open-cut). The PCP would be driven by LIM pumps, and would have a capacity of transporting 30200 TEUs (twenty-foot-equivalent units) of containers per day in each direction, which is more than adequate for handling the large number of containers currently arriving at the ports of New York City each day. Finally, a PCP system of large rectangular cross-section and 1.8 km length has been considered for ferrying trucks through a special region of New York City – the Hunts Point. The system is similar to the Euro Tunnel between England and France, except that it would be much shorter, be on land instead of undersea, would use PCP capsules instead of electric trains to ferry trucks, and would cost much less than the Euro Tunnel. More about each of these applications can be found in the final report of the project written by Liu (2004). The project concluded that all the six potential applications can be justified on combined merits of cost-effectiveness, environmental values and social values. Five of the six applications, except for the truck ferrying system in Hunts Point, are cost effective. Benefits that can be derived from implementing these applications in New York City would include the following:

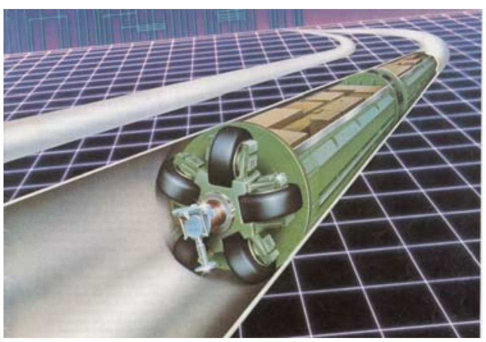
- Drastic reduction in the need for trucks and the number of trucks that clog the City's streets.
- Drastic reduction in air pollution, noise and accidents generated by trucks. Since PCP uses electricity instead of diesel fuel, it causes much less air pollution in New York City.
- More rapid delivery of goods than currently possible by trucks on congested streets.
- Greater reliability in freight delivery—because PCPs are unaffected by inclement weather, traffic jam and road/street repairs.
- Conservation of energy—PCP uses much less energy than truck uses in congested cities where trucks cannot operate efficiently due to traffic jam.
- Reduced reliance on foreign oil—while trucks uses diesel fuel, PCP uses electricity, which can be supplied by U.S. domestic energy sources, including renewable sources.
- 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 pipeline 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 pipelines are inaccessible to people except at the inlet and outlet and hence can be more easily guarded against any attack or sabotage. Even though the routes of certain PCPs would be under major structures of the New York City, they don't pose serious security threats because they are deeply underground inside bedrocks. Even if a terrorist could sneak a bomb into the pipe and cause an explosion, it would not damage the building aboveground during to the containment of the explosion by the thick layer of hard bedrock above the pipeline. Besides, due to security protection at the inlet and outlet of the pipeline, it would be very difficult for any terrorist to sneak a bomb into the pipeline. It would be much easier and more damaging if they bomb the aboveground structure directly from aboveground. This is different from the subway system of New York City, which is hard to protect the stations due to the movement of a large group of passengers through it, and due to the fact that the subways are closer to the street level and not imbedded in bedrock. Thus, comparing the vulnerability of the subway system with that of underground PCPs is like comparing apples with grapes. The subways that transport people are much more vulnerable than the PCPs for transporting freight.

- 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 NYS for the supply of the equipment, parts and engineering services needed for the rest of the nation to built PCPs in various congested cities and regions across the nation. This will bring huge and lasting benefits to NYS and NYC.
- The use of these large PCP systems in New York City will encourage other large cities in the United States and around the world to use similar systems. Therefore, this study targeted for New York City will benefit not only the City but also other major cities in the United States and around the world.

2. PCP FOR TUNNEL CONSTRUCTION

2.1 Technology Discussion

Advanced PCP systems, used successfully in Japan and the Former Soviet Union, utilize wheeled capsules (vehicles) to transport freight through large-diameter underground pipes of the order of 1-meter diameter. Using blowers, air is blown through the pipe to move the capsules. Two types of PCP have been developed and used successfully in Japan, one using circular pipes with capsules wheels mounted on a gimbaled assembly as shown is Figure 1(a) below, and the other using rectangular conduits with bottom wheels as shown in Figure 1(b) 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.)

Both the circular and the rectangular types of PCP have been considered for possible use in New York City—Liu (2004). Generally, the circular type is more suitable for most small-diameter PCPs that use steel pipe less than 2 m diameter, such as the one for transporting solid waste, and the one for transporting mail and parcels. On the other hand, the rectangular type, using capsules of cross-section of 1m × 1m or larger, is usually more suitable for transporting packaged large objects including boxes, creates, pallets and containers. Other factors also must be considered in the selection between circular and rectangular types. For instance, for large-diameter PCPs that must be bored through underground using tunnel boring machines (TBM), the circular type PCP is more practical, as in the case of the PCP for transporting pallets – Figure 2.

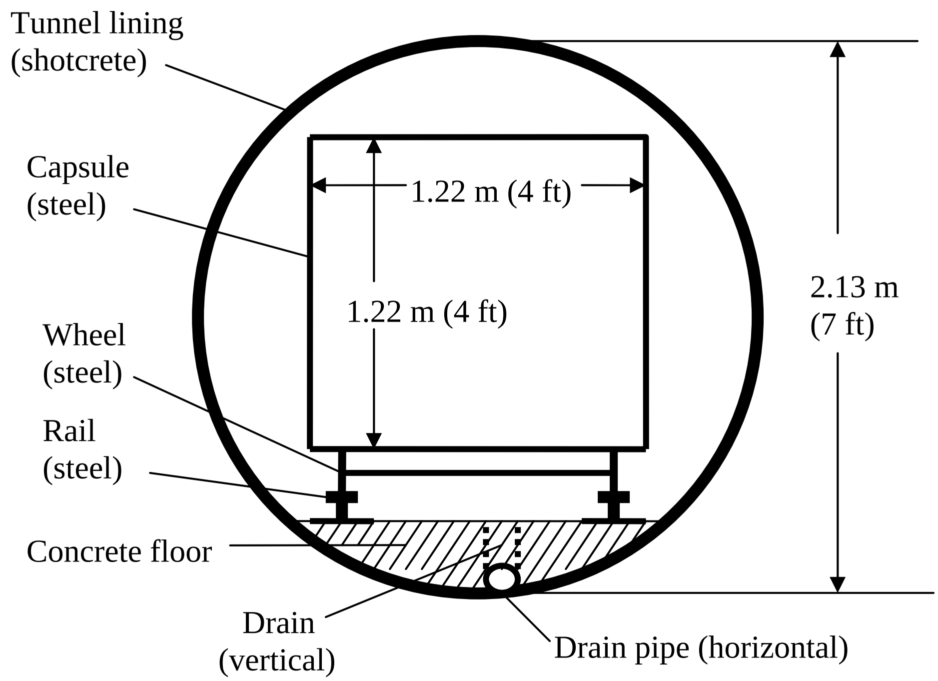


Figure 2 Cross-Section of PCP used for transporting pallets, boxes, crates and bags

In contrast to the PCP for transporting goods on pallets or in boxes, crates and bags, which uses rectangular capsules in a circular tunnel, the PCP for tunnel construction uses rectangular capsules in rectangular conduits of 1m × 1 m cross-section. The conduit, in turn, is placed on the tunnel floor – Figure 3(a) -- and on the ground outside the tunnel leading to the dumpsite – Figure 3(b) and (c). A photograph of the capsule is shown in Figure 4.

(a) Tunnel entrance

(b) PCP conduit extending outside the tunnel to the dumpsite

(c) PCP at the dumpsite

Figure 3 The PCP used in Japan for constructing the Akima rail tunnel

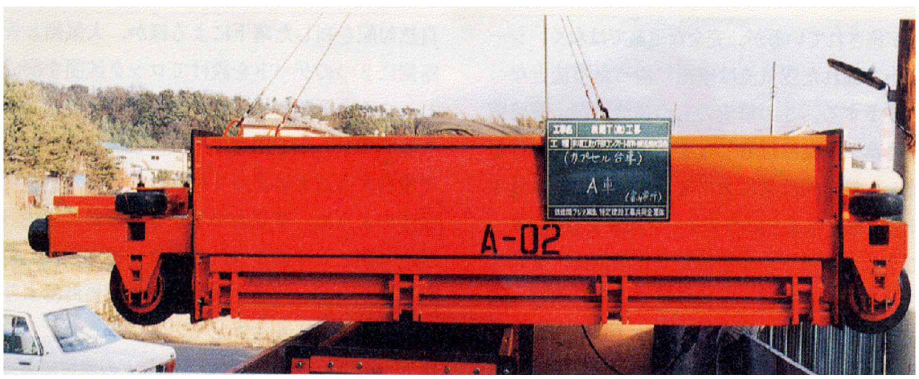


Figure 4 A capsule of the rectangular type used in the construction of the Akima tunnel

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 m^2 (968 ft^2) 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 railroads was constructed through the tunnel. The PCP was made of prestress 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 3 (b)) so that the excavated materials generated by the tunnel boring machine (TBM) could be transported to the dump site without using other transportation means such as trucks or conveyors. The type of capsules used in this PCP is shown in Figure 4. Note that rectangular capsules in a rectangular conduit are the best choice of PCP for tunnel construction, due primarily to the need for using the same system to transport premixed concrete. Rectangular capsules have vertical walls which facilitate unloading the concrete from the concrete. Due to the adhesiveness of the wet concrete, had the capsule wall been curved, it would be difficult to discharge the concrete simply by opening the bottom gates of the capsules. Rectangular capsules also use bottom wheels which experience less contact friction and wear than circular capsules with gimbaled wheel assemblies.

3.2 Use of PCP for Underground Tunneling in New York City

(a) System Description

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 more than 50 m 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 Figure 5. Currently, in constructing large underground tunnels in New York City, entire trucks are lifted up and down the vertical shaft of the tunnel. It is 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, during tunnel construction the truck traffic aboveground on busy streets near tunnel entrances can also be greatly reduced.

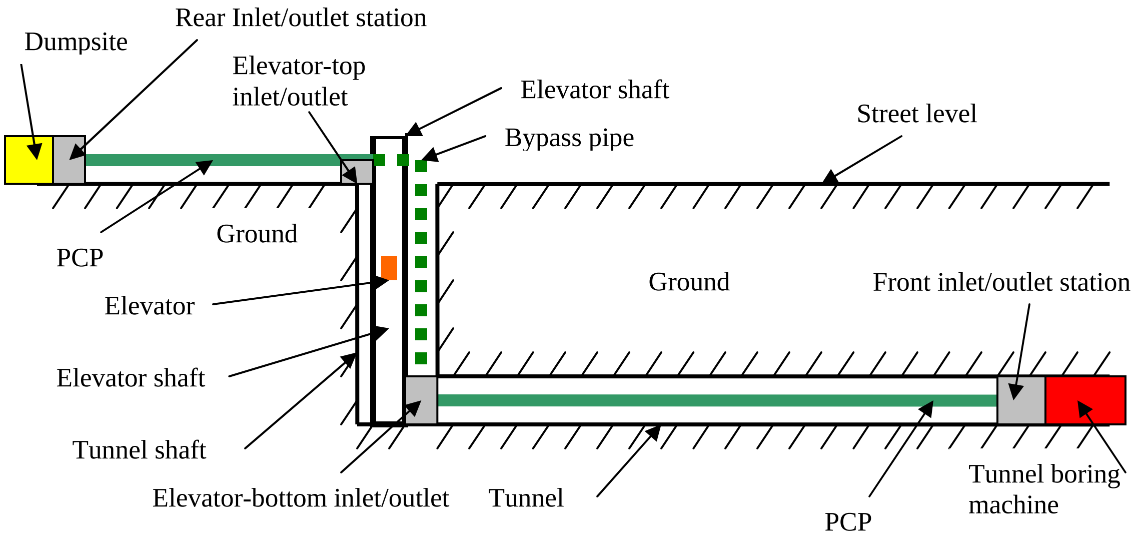


Figure 5 PCP system for underground tunneling (vertical profile).

The PCP investigated for use in New York City for tunnel construction assumes the following: The PCP is for transporting materials in and out a 24 ft (7.32 m) diameter tunnel 300 ft (91.5 m) underground in New York City being constructed by a TBM (tunnel boring machine) that advances at 50 ft/day (15.2 m/day). The PCP conduit, of 1m x 1m cross-section and 10-mile (16.1-km) length, is made of prestress concrete panels – the same kind of material used for constructing the Akima railroad tunnel. Twin conduits are used, one stacked on the top of the other in order to save horizontal space. One of the conduits serves as the **receiving line,** which receives the excavated material from the tunnel for disposal at a landfill 3 miles (4.83 km) away from the tunnel entrance. The other conduit serves as the **delivery line**, which delivers into the tunnel both empty capsules and capsules carrying premixed concrete. The total length of the PCP, including the pipes inside and outside the tunnel, is 13 miles (20.9 km) for the delivery line and the same length for the receiving line. The total length of the conduit used is 26 miles (41.9 km). The system is similar to the one used for the Akima tunnel except for the PCP length. 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. The PCP uses a 300-ft (48.3m) vertical lift (elevator) at the tunnel entrance to transport capsules in and out the tunnel, as in Figure 5.

(b) Engineering Calculations

A preliminary engineering analysis has been carried out for the foregoing system. Some of the key assumptions and results are listed as follows:

T_T (Time to complete tunnel construction) = 2.89 years
V_R (Volume of rock excavated per day by tunneling) = 641 m^3
S (Specific gravity of the rock) = 2.67 (assumed to be a hard rock such as granite)
W_D (weight of rock excavated per day) = 1,715 tonnes
w_B (Bulk density of rock, assuming 30% air volume) = 2053 kg/m^3
V_B (Bulk volume of excavated rock per day) =30% more than V_R = 833 m^3
V_{BY} (Bulk volume of excavated rock per year) = 365 V_B = 304,000 m^3
V_{BT} (Total bulk volume of rock removed for entire tunnel of 10-mile length) = 879,000 m^3
W_T (Total weight of rock to be transported for the entire tunnel) = 1.81 million tonnes approximately.
L_c (length of capsule) = 3m
V_O (Volume of each capsule) = 1.89 m^3
W_{RC} (weight of rock carried in each capsule, assuming 80% full) = 3.10 tonnes

W_O (Dead weight of each capsule) = 1.82 tonnes
W_C (Weight of each loaded capsule) = 4.91 tonnes
V_C (Capsule velocity -- design value) = 11.2 m/s
S_O (Number of capsule sorties launched per day) = 441
n (Number of capsules in each train) = 3
S_T (Number of capsule train sorties per day for 3-capsule trains) = 147
T (Capsule injection interval) = 196 sec. = 3.27 min
N (Number of capsules in single pipe) = 9.54
N_2 (Number of capsules in twin pipes) = 19.1
N_O (Total number of capsules needed to operate the system including 70% spare) = 32 (round-off figure).
L (Pipeline length, one-way) = 20900 m.
L_O (Total length of the pipeline) = 41800 m
A (Inner cross-section of the pipe) = 1 m^2
A_d (Area of the end plate) = 0.960 m^2
k_d^2 (End-plate-to-pipe area ratio) = 0.9604
T_O (travel time for each capsule to move through the pipe, one-way) = 1870 s = 31.2 min
C_D (Drag coefficient of each capsule) = 2350
V (Airflow velocity in conduit) = 11.8 m/s
Δp (pressure drop along the pipe, one-way) = 27000 Pa = 27.0 kPa
P (Power consumed by flow of air and capsules in each pipe) = 319 kw
P_O (Total power for twin pipes) = 638 kw
P_{in} (Power input to blower assuming 80% efficiency) = 797 kw

In summary, the system will need 32 capsules in which 19 are in use and 13 are spare. Each capsule will carry approximately 3 tonnes of excavated rocks for disposal at a landfill 4.83 km away from the tunnel entrance. The system will transport a bulk volume 833 m^3/day of excavated materials, which correspond to the daily quantity of materials excavated by a 7.32 m diameter tunnel boring machine advancing at 15.2 m/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 11.8 m/s through the pipe at a pressure of 27 kPa approximately. The blower will be rated at approximately 797 kw. To be practical, three identical blowers should 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.

(c) Cost Analysis

Based on the above assumptions and engineering calculation, a cost analysis is performed with the following results. The $ values given are in U.S. dollars in 2004.

Capital Cost (in million dollars):	**$ Million**
1. Prestress concrete panel conduit (1m × 1m cross-section, 41.9 km length, assembled on site, reusable 5 times) …………………..…	$4.0[1]
2. Blowers (3 blowers, 396 kw each, at $200/kw)……………………….	$0.24
3. Speed controllers for blowers (3 controllers, 396 kw 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 91.5 m 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**

[1] The concrete panels can be used and reused for at least five times for tunnel construction. The cost for using them only once for 41.9 miles of conduits is $12.4 million. If used 5 times, the cost reduces to $3 million for each use.

<u>Operation/Maintenance Cost (annual cost)</u> : **<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

Economic Life of the PCP (same as the tunnel construction time, T_T): **2.89 years**
Total project cost for using PCP for tunnel construction:

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

Bulk volume of excavated materials transported by the PCP system during tunnel construction: 812000 m^3
Volume of premixed concrete transported by the same PCP system for tunnel construction: 243000 m^3
Total volume of materials transported by the PCP system during construction: 1055000 m^3
Average distance that materials are transported between the tunnel face and the dump site during tunnel construction: 12.9 km.
Transportation cost per cubic meter of materials transported over the average distance: $21.7
Transportation cost per cubic meter per km: $1.68.

Note that the above unit transportation cost of $1.68 per km for transporting each cubic meter of excavation and other construction materials in tunnels and on city streets is estimated to be less than one half of the current cost of using trucks to transport the same materials over one km distance in New York City. The PCP system also has significant benefits in terms of improved safety and reduction in air pollution caused by the trucks used in constructing this tunnel.

3. CONCLUSION

Based on this study, it can be concluded that the same PCP technology used for transporting construction materials in the Akima Tunnel in Japan, with minor modifications, can be used for underground tunneling in New York City and perhaps many other cities in the world. Use of PCP for such purpose not only reduces the air pollution, noise and accidents generated by using trucks for tunneling but also reduces tunnel construction cost. It is a meritorious new technology that needs be considered for possible use in all future constructions of long tunnels.

4. ACKNOWLEDGMENT

Sponsorship of this study by the New York State Energy Research and Development Authority (NYSERDA) is much appreciated.

REFERENCES

ASCE, 1998. "Freight pipelines: Current status and anticipated future use," report of the Task Committee on Freight Pipelines, American Society of Civil Engineers*, J. of Transportation Engineering*, 124(4), 300-310.

ASCE, 2002. "Pneumatic Capsule Pipeline Removes Soil Vertically," <u>Civil Engineering</u>, Vol. 72, No.3, American Society of Civil Engineers, page 22.

Cohen, R. A., 1999. "The Pneumatic Mail Tubes: New York's Hidden Highway and Its Development," *Proceedings of the 1st International Symposium on Underground Freight Transport by Capsule Pipelines and Other Tube/Tunnel Systems,* Columbia, Missouri, 1999, 189-202.

Jvarsheishvili, A.G., 1981. "Pneumo-Capsule Pipelines in U.S.S.R.", *Journal of Pipelines,* 1 (1), 109-110.

Kosugi, S., 1992. “A Capsule Pipeline System for Limestone Transportation,” *Proc., 7th Int. Sym. on Freight Pipelines*, Wollongong, Australia, Institution of Engineers, 13-17.

Liu, H., 2003. *Pipeline Engineering, (Chapter 7. Capsule Pipelines)*, CRC Press (Lewis Publishers), Boca Raton, Florida, 175-204.

Liu, H., 2004. *Feasibility of Underground Pneumatic Freight Transport in New York City,* final report for project sponsored by the New York State Energy Research and Development Authority (NYSERDA), contract no. 7643, 95 pages.

Yanaida, K., 1982. Capsule Pipeline Research in Japan, *Journal of Pipelines*, 2 (4), 117-131.

Zandi, I., 1976. *Transport of Solid Commodities via Freight Pipeline*, Vol.2, Freight Pipeline Technology, U.S. Department of Transportation, Report No. DOT-TST-76T-36, Washington, D.C.