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"Transporting Freight Containers by Pneumatic Capsule Pipeline (PCP): Port Security and Other Issues"

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1. INTRODUCTION

Most container ports in the United States are located in or near large cities. Trucks are used extensively for carrying the containers delivered by ships at these ports to inland destinations, and for carrying containers from inland to the ports for export. Due to expansion in international trade and urban encroachment, many ports in the United States are short of space for holding a large number of containers for inspection and temporary storage. Most of the containers must be hauled away by trucks as soon as they arrive without inspection, creating security risks in that some of the containers may contain explosives, to be delivered by trucks for detonation at selected targets. This problem can be solved by using the new technology of pneumatic capsule pipeline (PCP), which enables fast underground transportation of containers arriving from sea to an inspection/intermodal transfer station located inland in a remote or rural area. By using dual lines, the same PCP can be used for transporting containers in both directions between the port and the inland station, thereby enhancing the value of the PCP system. Advantages that may be derived from using such a PCP system include the following:

- Having enough space in a remote or less-crowded area to inspect all incoming containers arriving from overseas.
- Greatly reducing the risk of terrorist attacks on seaports and surrounding urban areas by using unsuspecting, un-inspected containers.
- No need for having a large number of trucks traveling to and from seaports, thereby turning ports from being truck depots to nice tourist areas. This enhances tourism and economic development of ports.
- Reducing traffic jam, accidents, and air and noise pollution generated by trucks near ports and in surrounding urban areas.
- Reducing highway and street maintenance cost, due to reduced use of trucks.
- Possible reduction in freight costs, since truck transport in urban areas is inefficient and costly, and a good portion of the freight to and from a seaport is simply through-traffic for the city that surrounds the seaport.

This paper will review and explain how the modern PCP technology can be used to transport 40-ft containers to and from seaports via underground conduits and tunnels. Key technical issues relating to this technology, including using linear induction motors (LIMs) to pump capsules through PCP, construction of underground and underwater conduits for PCP, vertical-to-horizontal transport of capsules at port terminals, controlling capsule speed and spacings in pipe, and use of radio-frequency identification (RFID) for keeping track of capsules and containers, and for controlling capsule motion, will be discussed. A discussion is also provided for the first time to compare PCP with other competing proposed freight transport systems such as the CapsuleCap system developed in Germany and the MagLev system proposed in USA. This paper also includes a brief discussion of a recent investigation of a proposed PCP system for the Ports of New York /New Jersey, including a preliminary cost analysis of the system, and its implications to other container ports in the U.S. and around the world.

2. PCP TECHNOLOGY

2.1. Types of PCP

PCP (**P**neumatic **C**apsule **P**ipeline) is the modern and high-tech version of the "**pneumatic tubes**" used over half a century ago (from 1890-1950 approximately) in five U.S. and many other major cities around the world for underground transportation of mail, parcels and many other goods [1]. The archaic pneumatic tube systems used non-wheeled capsules which are usually plain cylindrical containers fitted with sealing bands on the two ends of each capsule to prevent excessive leakage of air around the capsule and to build up the pressure differential across the capsule needed for propelling it to move through tubes or pipes – see Figure 1 below.

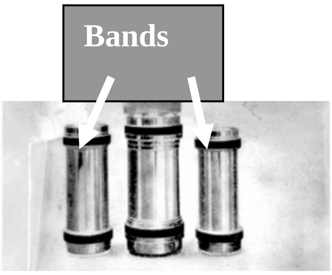


Fig.1. Capsules with bands

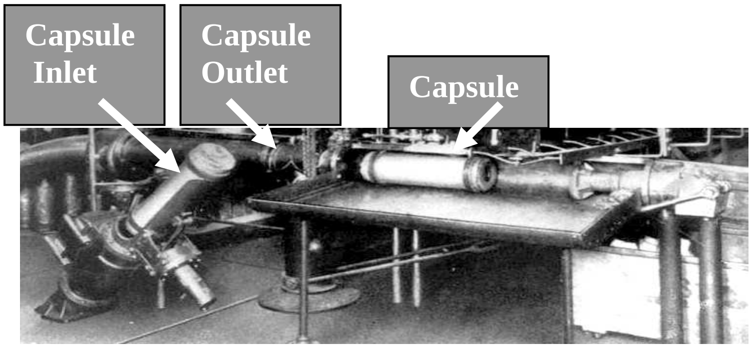


Fig.2. Pneumatic tube system used in New York City for mail transport until 1950 [2]

For capsules without wheels, the contact friction between the capsules and the pipe is normally high, and the energy consumed for the horizontal transport of capsules through pipe is high, especially for heavy capsules. Consequently, the non-wheeled capsules are suitable for horizontal transport only over relatively short distances, using small-diameter capsules containing lightweight cargoes. Typically, such capsules and the tubes or pipes used to convey them are less than 1 ft (approximately 300 mm) in diameter, with each capsule carrying only a few pounds of cargoes. Figure 2 is such a system used by the U.S. Postal Service in the beginning of the last century for transporting mail and parcels in New York City [2]. Using modern electronics and computers for control, new versions of such systems are still widely used today in hospitals, factories, airport terminals, etc.

Realizing that wheels must be utilized in order to have large diameter PCP for transporting heavy cargoes over long distances, since 1970 several nations including USA, Canada, United Kingdom and the Former Soviet Union have developed wheeled PCP systems [3]. The most successful commercial use of such systems is in Japan. The current advanced PCP systems, used successfully in Japan [4, 5], utilize wheeled capsules (vehicles) to transport freight through large pipes of the order of 1-meter diameter. Air is blown through the pipes to move the capsules. The system can transport hundreds of cargoes — practically anything of a size smaller than the capsule internal diameter. By using modern technology such as high-speed computers and special scanners, the system is highly automated and efficient. In what follows, the term "PCP" will be used to denote modern PCP technology using wheeled capsules and large pipe or conduit.

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 3 below. In order for capsules to maintain stability in a round pipe, the capsules must use gimbaled wheel assemblies, one assembly at each end of a capsule as shown in Figure 3 (a). In contrast, for rectangular or square capsules in a rectangular or square pipe or conduit, the capsules can use wheels of ordinary vehicles, with 4 large bottom wheels on the bottom and 4 small guide-wheels on the sides of each capsule, as shown in Figure 1 (b). To reduce the number of trains that must be injected into the pipe during a given period, several capsules may be linked together to form a train as shown in Figure 3.

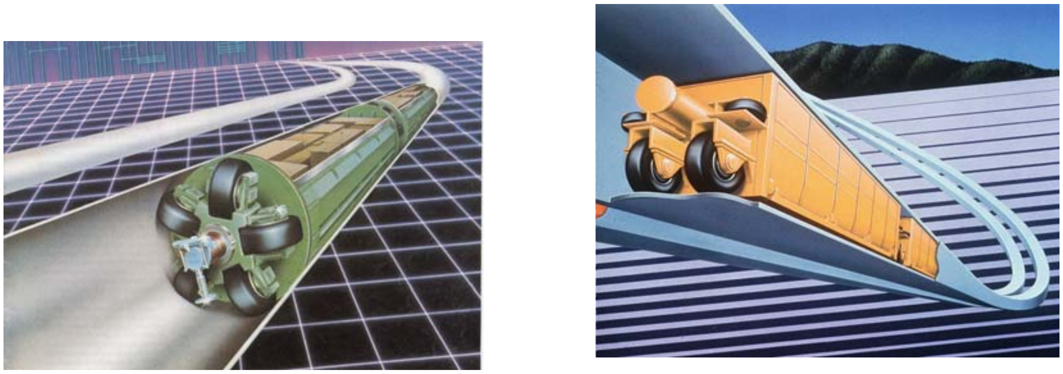

(a) Round (circular) PCP (b) Rectangular or square PCP

Figure 3. Pneumatic capsule pipeline (PCP) systems developed by and Used in Japan (Courtesy of Sumitomo Metal Industries, Ltd.)

2.2. Successful Commercial Use of PCP in Japan

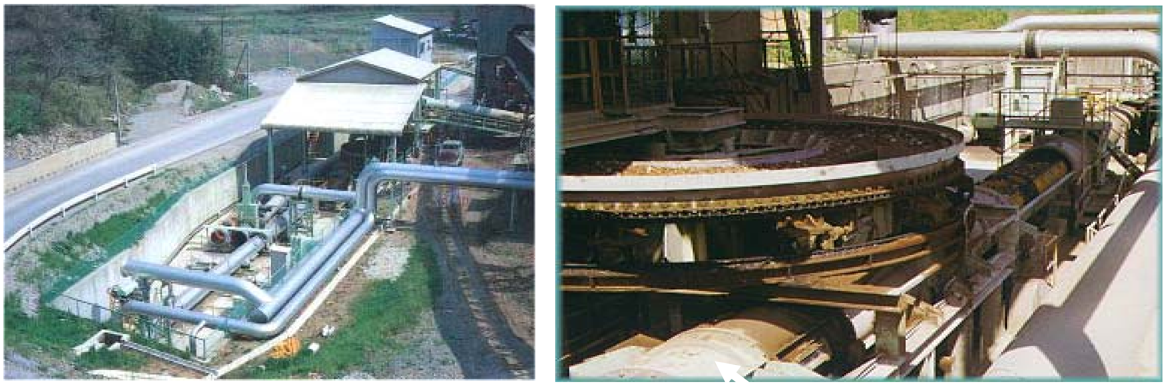
Successful commercial usage of such wheeled PCPs in Japan includes, but is not limited to, the following notable applications:

(1). A PCP for transporting limestone from a quarry (limestone mine) to a cement plant where the limestone is used to manufacture cement. The system uses 1 m diameter steel pipe, and uses capsules similar to that shown in Figure 1 (a). The capsules are operated in trains with 5 capsules in each train; each capsule carries approximately 2 tons of limestone. This PCP system transports 2 million tons of limestone a year. The system, shown in Figure 4, was constructed and started operation in 1980, and it is still in operation today. It has demonstrated a high degree of reliability, safety, and cost-effectiveness, exceeding those that can be provided by truck, train, or conveyor belt [4].

(2). A temporary PCP used for constructing a large and long rail tunnel for bullet trains. A square PCP of 1m by 1m cross section was used. Figure 5 shows one of the capsules used, and Figure 6 shows the PCP conduit. The same capsules were used for transporting both premixed concrete into the tunnel for constructing the tunnel lining and floor, and excavated materials out the tunnel for disposal in a nearby dump site – see Figure 5. As the tunnel boring machine (TBM) advanced in the tunnel, the PCP following the TBM was extended. The PCP was made of prestress concrete panels so that the PCP could be easily assembled and extended during tunnel construction, and dismantled later upon completion of the tunnel.

(3). A temporary PCP for constructing a highway, done in a manner similar to the one for tunnel construction [5].

(4). A PCP for vertical transport of solid waste materials for deep underground disposal of the waste materials [6].



(a) PCP inlet **(b) Rotary loading of limestone at PCP inlet**

Figure 4. The PCP used for transporting limestone at Kuzuu, Japan

(a) Capsule used **(b) Tunnel entrance during construction**

(c) PCP outside the tunnel for waste transport **(d) PCP connection to waste dump site**

Figure 5 The use of a temporary PCP for constructing the Akima rail tunnel in Japan

2.3. Comparison of round to rectangular PCPs

Both round and rectangular (including squared) PCPs have different advantages and drawbacks, and hence they are used in different circumstances or niches. The main advantages of the round type PCP includes:

(1) The pipe can withstand high internal and pressure differential. (Note that long pipelines with pumps spaced at long distances apart have large internal pressure, whereas pipes buried deeply either underground or underwater have high external pressure. In both cases, circular pipe can resist such high pressure differentials the best without deformation or damage.)
(2) Lower construction cost when the pipe diameter is not more than about 4 ft (48 inches). This allows the use of commercially available steel pipes produced in mass production.
(3) PCPs constructed underground using modern tunnel boring machines (TBMs), which inevitably construct tunnels of circular cross section – see Figure 6 for the machine.
(4) PCPs constructed in urban buildup areas, where trenchless construction methods such as horizontal directional drilling (HDD) or microtunneling are used for constructing the PCPs – see [7] and [8].

Figure 6. 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.)

In contrast to the above, PCPs of rectangular (including squared) cross section has the following advantages:

(1) It is more compatible with cargoes in boxes, crates, pallets or standard containers.
(2) Capsules of such PCPs can use bottom wheels, which cost less and wear less than the gimbaled wheel assemblies of the round type PCP.
(3) Capsules can run at much higher speed without wheel damage or overheating of tires. While research in Japan has found that the gimbaled type of wheel assemblies for round PCPs using rubber tires cannot be operated at speeds above 10 m/s (22 mph) without excessive heat buildup, the capsules of the rectangular (including squared) PCPs using vertical wheel can run at much higher speed, exceeding 20 m/s (45 mph), without significant overheating and wearing of tires.
(4) Large rectangular and squared PCP can be constructed at low cost when the buried conduits are near the ground level, using the same technology for constructing large reinforced concrete underground culverts – see Figure 7. Due to the open-cut method used, this type of construction is suitable only in rural or remove areas when ground-based infrastructures can be easily avoided.

Figure 7. 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. [9])

2.4. Advanced PCPs that Use Rails and LIM (Linear Induction Motor)

2.4.1. Shortcomings of contemporary PCP systems

Notwithstanding the success in using PCP in Japan in recent years, the use of the technology has been limited throughout the world (including Japan) because the current system often could not compete with trucks and trains in terms of flexibility and low cost, and because most transportation providers do not know how to use or consider this new technology, in spite of the enormous environmental and safety benefits that can be derived from using PCP instead of truck. For instance, PCP does not pollute air and does not cause traffic jam and accidents on highways as trucks do, etc. In the limited use of PCP in Japan, in each case a careful study was conducted to compare the PCP with alternative transportation modes including truck, railroad and conveyer belt before the PCP was selected, based not only on economics but also on environmental and safety considerations.

The PCP systems used commercially in Japan have two basic problems. First, the system is powered by blowers (fans), which blow the air through the pipe; the moving air in turn creates a drag force on the capsules in the pipe, pushing them forward. However, because blowers have fans or blades that block the passage of capsules, complicated blower-bypass systems must be used in every PCP to cause capsules to bypass the blowers. Such bypass systems are not only complicated and costly, but also impede the capsule flow and limit the throughput (freight capacity) of PCPs. For instance, all the PCPs used commercially in Japan had less than 3% linefill. This means that in each case the capsules occupied only less than 3% of the linear distance along the pipeline; more than 97% of the pipe distance was filled with air. This is rather inefficient because the freight capacity or throughput of any PCP is directly proportional to its linefill. In order to enhance the efficiency and the cost-effectiveness of PCP, a way must be found to greatly increase the linefill of contemporary PCP.

Another basic problem with the PCP systems in use or used in Japan is that they all use or used rubber tires. While rubber tires do reduce noise generated in PCPs, they create large contact friction, causing high power consumption and waste of energy. This greatly affects the energy efficiency and cost-effectiveness of PCPs for long-distance freight transport.

2.4.2. Improved advanced PCP system

To enhance the attractiveness of PCP so that it will be used more widely, especially in the United States, the cost-effectiveness of PCP relative to other freight transport modes must be improved. Such improvement has been made by the Freight Pipeline Company in a recently completed project sponsored by the U.S. Department of Energy [10]. The improvement consists of two fundamental changes in contemporary PCP systems: (1) using linear induction motor (LIM) instead of blowers (fans) to drive the system, and (2) using capsules with steel wheels that run on rails inside the PCP conduit.

LIM for PCP

LIM is the same technology used for the propulsion of the people mover at the Disney World in Florida, for accelerating and stopping roller coasters at the Six Flags in St. Louis, and for many other existing commercial applications in which a large linear driving force is needed to propel vehicles or move objects. The main advantage of using LIM instead of blowers to propel capsules through a conduit is that the LIM is a non-intrusive capsule pump. Capsules can move through the LIM unhindered, deriving the driving force from the electromagnetic field of the LIM. With small clearance between the LIM and the capsules moving through it, the capsules passing through the LIM not only accelerate but also behave as a piston pump, pushing the air forward through the entire length of the conduit. The moving air in turn propels the capsules in the entire length of the conduit. Thus the improved system driven by LIM combines the advantage of LIM with the advantage of pneumatic conveying – energy transfer from the air to the capsule. For long PCP systems, LIMs can be placed at intermediate stations along the long conduit, in the same manner booster pumps are used in ordinary long-distance oil and natural gas pipelines.

Figure 8 is a typical LIM capsule pump to be used for PCP of rectangular or square cross-section, with capsules running on steel rails. The stator or the stationary part of the LIM pump is a pair of typical single-sided LIMs consisting of coils wound in a special manner described in [11] and [12]. The rotor or the moving part of the LIM is the capsule passing through it. As the capsules pass through the LIM, they are accelerated by the magnetic force generated by the stator. The energy transfer in the LIM is from the stator to the capsules, which in turn pushes the fluid (air) in the entire PCP forward. Due to the need for a small air gap between the capsule and the LIM in order to achieve high efficiency, the width of the LIM cross-section is slightly reduced as shown in Figure 8. Liu and Lenau have shown that through proper design, the motor efficiency can exceed 90%, and the pump efficiency can exceed 80%. The concept of electromagnetic capsule pump was first introduced by Liu and Rathke in 1976 [13], and it was patented in 1984 [14]. The concept is applicable to both pneumatic capsule pipeline (PCP) and hydraulic capsule pipeline (HCP). Use of LIM has several advantages over using linear synchronous motor (LSM) including: (1) the capsule speed through the LIM need not be the same as the synchronous speed of the motor, which greatly simplifies control, (2) thrust exist even at standstill or zero capsule speed, (3) the capsules need not carry magnets on its surface, which reduces capsule cost and maintenance cost, etc. The LIM-based PCP has been studied extensively at the University of Missouri-Columbia [11-16], including tests – see Figure 9.

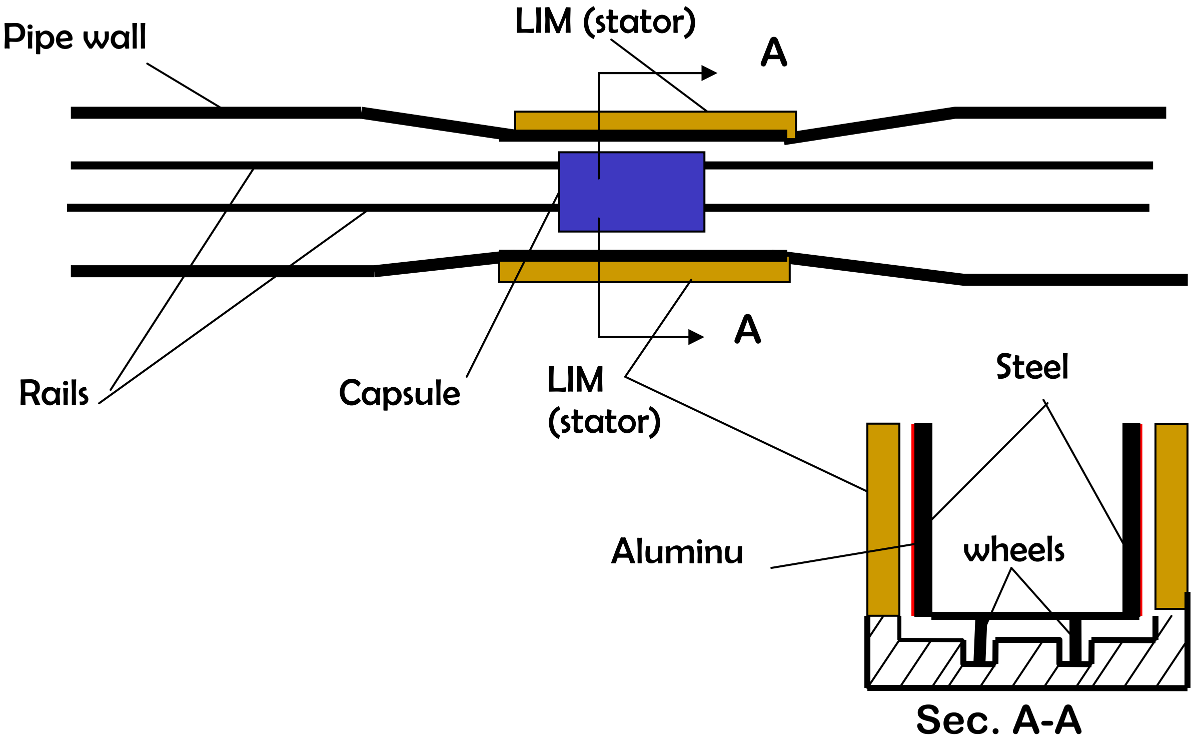


Figure 8. Use of LIM capsule pump in PCPs of rectangular or square cross-section.

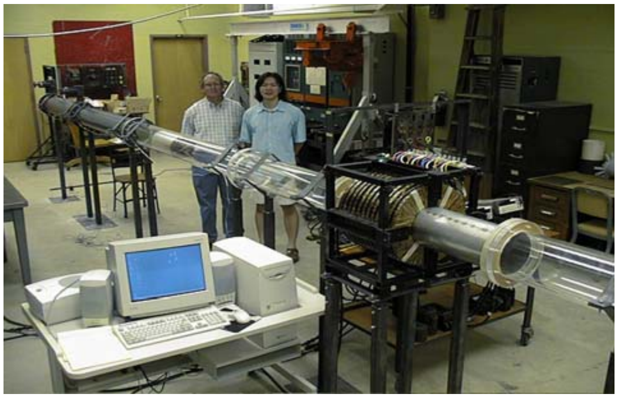


Figure 9. Test of PCP-LIM at the Power Electronic Laboratory of the University of Missouri-Columbia (From left to right, Professor Robert O'Connell and his former Ph.D student W. Plodpradista.)

Use of steel wheels on rails

For any type of wheeled vehicles, there are two sources of drag force: (1) the aerodynamic drag which increases with the square of the velocity of the vehicle, and (2) the contact friction that is independent of speed but proportional to the rolling friction coefficient of the wheels. The smaller the rolling friction coefficient, the smaller the contact friction becomes, and hence the more energy efficient the vehicle becomes. The rolling friction coefficient of rubber-tired vehicles such as trucks is of the order of 0.01 (i.e., 1%). In contrast, for steel wheels rolling on steel rails, the coefficient is of the order of 0.002 or 0.2%, which is approximately five times smaller than that of trucks. For this reason, by using steel wheels instead of rubber tires for capsules, much energy can be saved, especially for vehicles that travel at relatively low speed where the aerodynamic drag is not dominant. This shows a main advantage of using rails for PCP. Another advantage of using rails is to offer good control of vehicles, in terms of controlling the path of the vehicles (capsules) automatically, as for instance using standard rail switches for switching capsules into branches, and controlling the path and the speed of the capsules when they have moved outside the conduit and entered an open space – the terminal.

2.5. Advanced PCP for Container Transport at Seaports

The new PCP system studied in the DOE project [10] combines the advantages of LIM with the advantages of rails, creating a super-performing and revolutionary advanced transportation system that is especially suitable for cargoes that do not require high speed, as for instance with capsules traveling at the average speed of 20 m/s which is equivalent to approximately 45 mph, a speed faster than the average speed of trucks. Note that due to the need for truckers to stop for meals, rest and sleep in long-distance hauling, and due to traffic jam on many highways, the average speed of track traveling on highway in most cases is less than 45 mph, much less than 45 mph on city streets.

Using the knowledge generated from the DOE project, an advanced PCP system is presented here for transporting the kinds of containers transported normally by trucks (tractor trailers), to and from seaports. The system is described next.

2.5.1. The Capsule

Each capsule is a flat-bed box car designed to carry a standard 40-ft container of dimensions 40 ft (length) x 9.5 ft (height) x 8 ft (witdth). The capsule dimensions are 42 ft (length) x 11 ft (height) x 9 ft (width). Since each 40-ft container can be replaced by two 20-ft containers or two TEUs (twenty-foot equivalent units), each capsule can also carry two TEUs.

Figure 10 shows the capsule in a circular conduit or tunnel, whereas Figure 11 shows the same capsule in a rectangular conduit. The only differences between the two cases are the geometry and the size of the conduit around the capsule. The rest -- including the capsule, the rail, and the rail bed (floor) -- are the same. Note that imbedded steel rails – the same used for streetcars or trams --are used here to minimize the clearance between the capsule and the floor, and to make crossing of rail tracks at terminals by human and other vehicles easy. As will be explained later, the smaller the clearance between the capsule and the conduit, the better the energy transfer between the capsule and the air, and the better the system efficiency becomes. The rail bed is made of reinforced concrete, with drainage pipes imbedded in it at appropriate places to drain any unexpected seepage into the conduit.

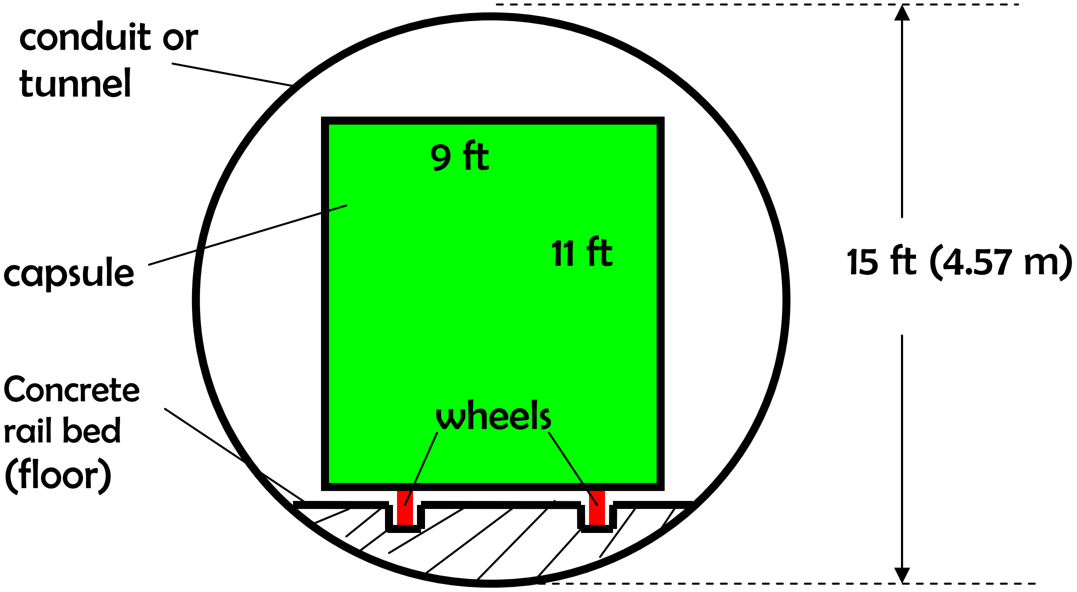


Figure 10. PCP capsule for carrying container through circular conduit or tunnel

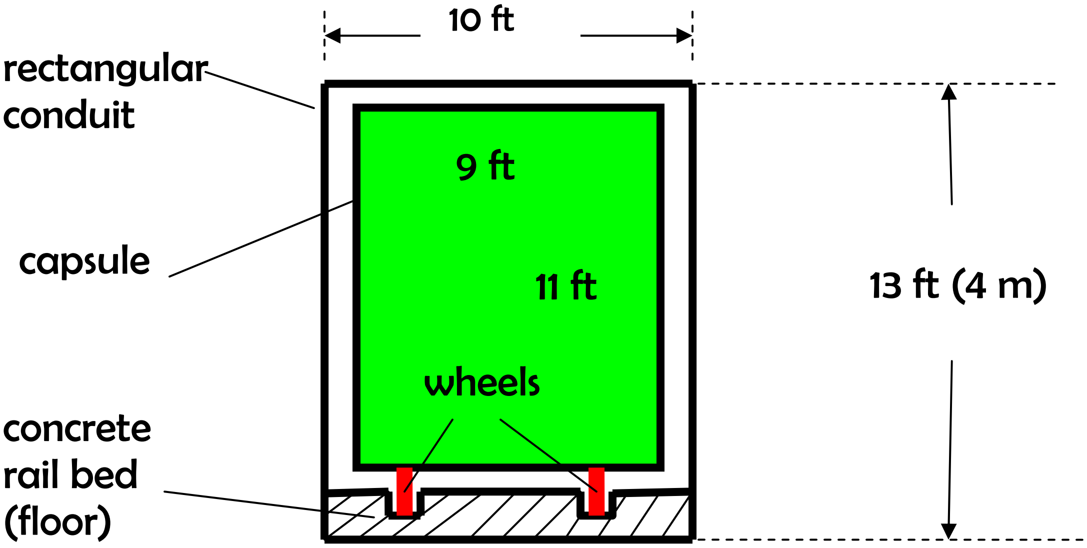
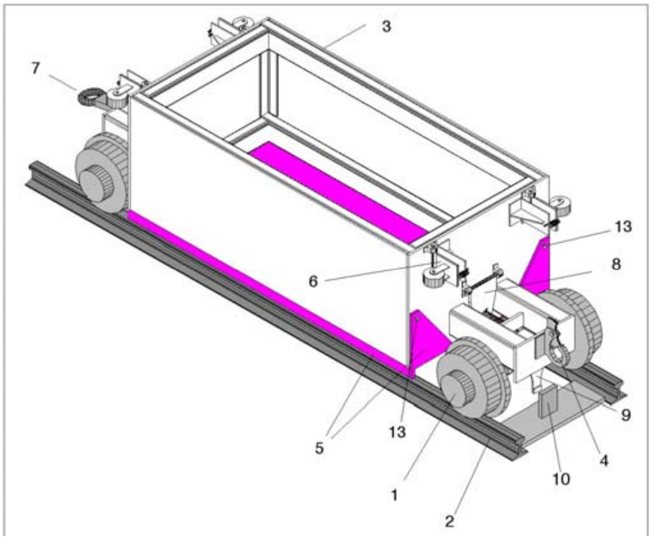


Figure 11. PCP capsule for carrying container through rectangular conduit or tunnel

Figure 12 is a 3-D drawing of the capsule. Key parts of the capsule are marked and listed in the drawing. In addition (not shown in Figure 12), the capsule has an automatic braking system powered by a compressed air tank as shown in Figure 13. The same compressed air is also used to propel the capsule over short distances when the capsule is outside the conduit and in the inlet/outlet terminals. Note that compressed air is a preferred power source for braking and speed control over short distances. It can be recharged more rapidly than a battery can, allowing recharge of the compressed air during the short period that the capsule is loading/unloading cargo or container in the inlet/outlet terminals. Details on capsule design can be found in [10].



1. Wheel
2. Rail
3. Box
4. Latch (for capsule linkage)
5. Gate
6. Guide wheel assembly
7. Drawbar (to match latch)
8. Front latch assembly
   (for bottom gates)
9. Trigger
10. Front barrier plate
11. Rear latch assembly

Figure 12. Capsule design (front 3-D siometric view)

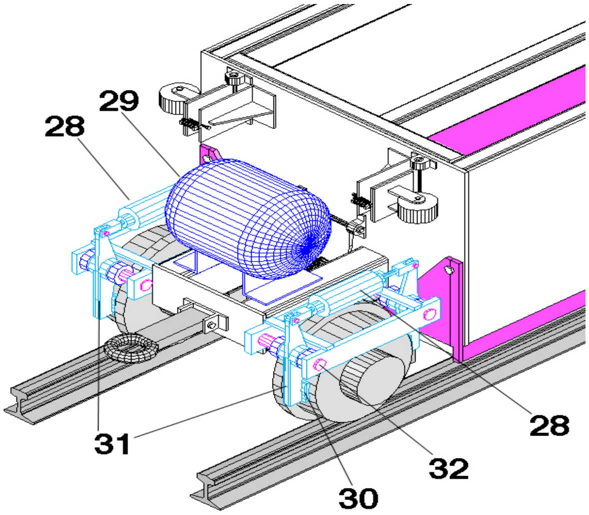


Figure 13. Compressed air tank (part 29) and other parts for capsule braking and speed control.

2.5.2. The System

The proposed PCP system for transporting containers to and from seaports has the general layout as shown in Figure 14. The system includes the following key components: (1) capsules, (2) LIM capsule pumps, (3) the conduit, (4) inlet/outlet terminals, and (5) the control system. Note that although a single-pipe system is shown in Figure 14 for simplicity, in reality dual pipe must be used, one to deliver containers from seaport to an inland container inspection and transloading station, and the other to deliver containers from the inland station to the seaport.

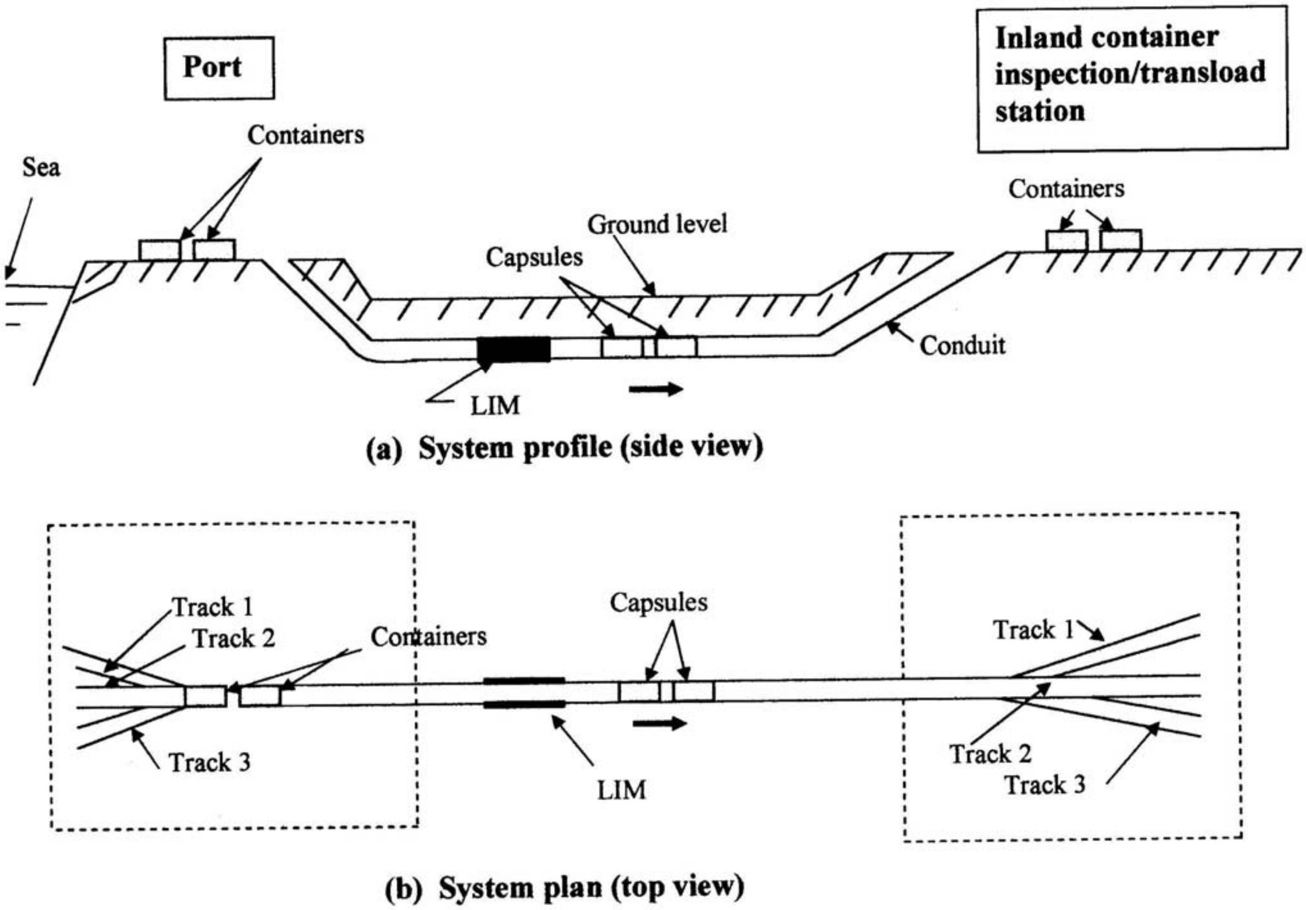


Figure 14. General layout of PCP system for transporting containers to and from ports.

The capsules used in the system are wheeled vehicles running on steel rails inside a closed conduit buried underground. The capsules are propelled mainly by the LIMs with supplementary drive provided by compressed air stored on the capsules as shown in Figure 13. Depending on need and other conditions, the capsules may move through the conduits either as single capsules, or capsule trains.

Depending on terrain conditions and the buildup environment, the conduit can be circular pipes and/or tunnels, or rectangular conduits, or a combination of them in series. In rural areas where there are few manmade structures, the rectangular conduit using open-cut construction method shown in Figure 7 may be the most cost-effective. In contrast, under water or deep underground, the circular conduit or tunnel may be necessary.

As shown in Figure 14, both the inlet/outlet terminals at the port and at the inland station are on elevated land or platforms so that gravity can be used to accelerate capsules into the conduits, and to decelerate capsules as they exit the conduits. At both terminals, parallel tracks of rails will be used to enhance the rate of loading/unloading of capsules. For instance, if one container must be transported in every 20 seconds and if it takes one minute to load/unload a capsule, a minimum of 3 parallel tracks will be needed with parallel loading/unloading in order to transport one container in every 20 seconds. Alternatively, one may connect three capsules into one train, and provide simultaneous loading/unloading for all three capsules in the train. Then the train can be injected into the conduit at the rate of one train per minute, which has the same capacity as one capsule per 20 seconds. Note that long trains are undesirable due to the length of the tracks needed at the terminals to accommodate long trains, and due to delays and cueing caused in shipping containers. Many pros and cons must be considered to determine whether to use trains, and if so the optimal train length in each case.

Normally, for PCP systems less than 50 miles (80 km) in length, a single LIM of about 50 m length located near the inlet of the conduit, as shown in Figure 14, is sufficient to power the entire system. The system must be designed using both fluid mechanic equations for the capsule flow and electromagnetic equations for the LIM capsule pump, as derived and provided in details in [10]. The system for a given freight throughput and a given transportation distance can be designed and analyzed for several mean capsule velocities, from which the preferred operational speed of the capsules can be determined, along with its power consumption, maximum pressure drop, and other operational characteristics. Results of such an analysis will be illustrated through an example in the next sub-section.

The sloped inlet/outlet sections shown in Figure 14 (a) cause the capsules to accelerate at the inlet, and decelerate at the outlet, which are needed in the operation. The slope can be very large (say 45^o), as with roller coasters. With capsules on a platform entering a sloped inlet at a low velocity (say 3 ft/s), if the elevation change of the sloped section is 10 ft, the velocity increase of the capsules upon dropping 10 ft down the slope will be in the neighborhood of 20 fps, which is quite sufficient at the inlet of the LIM. The LIM will further accelerate the capsules to a much higher velocity before the capsules exit the LIM. Larger LIM entrance velocity can be achieved by using larger drops. Due to the buildup environment normally encountered at seaports, to minimize interference with neighboring underground or underwater structures it is desirable to have the PCP inlet inclined at a steep slope, or even vertical slope. Vertical slope is possible for PCPs either by using elevators (Figure 15), or by using LIM (Figure 16). The latter has the advantage over the former in that it requires no elevator platform, and hence more than one capsule can be moving through the vertical shaft simultaneously.

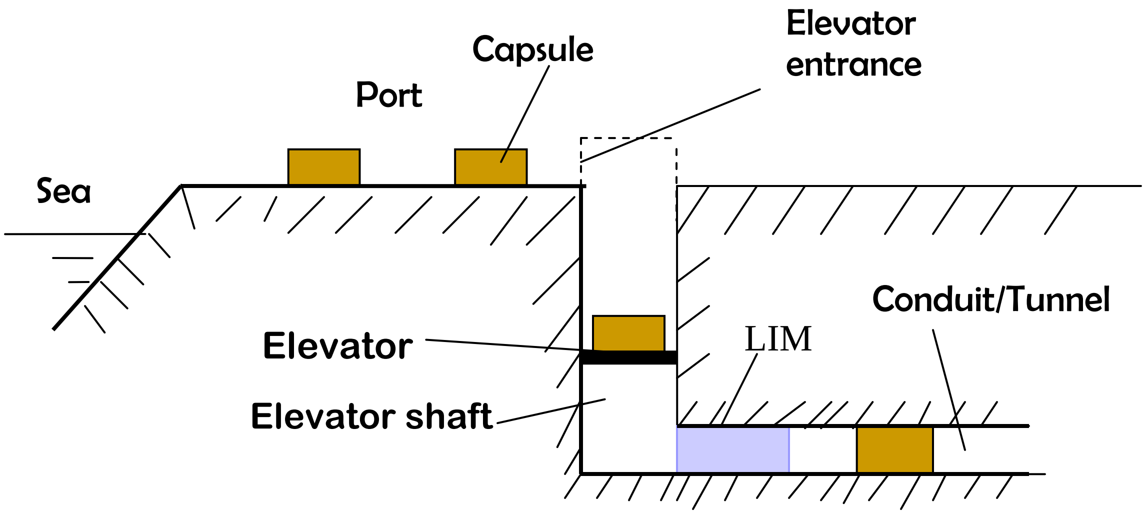


Figure 15. Horizontal-to-vertical transport of capsules by using elevators.

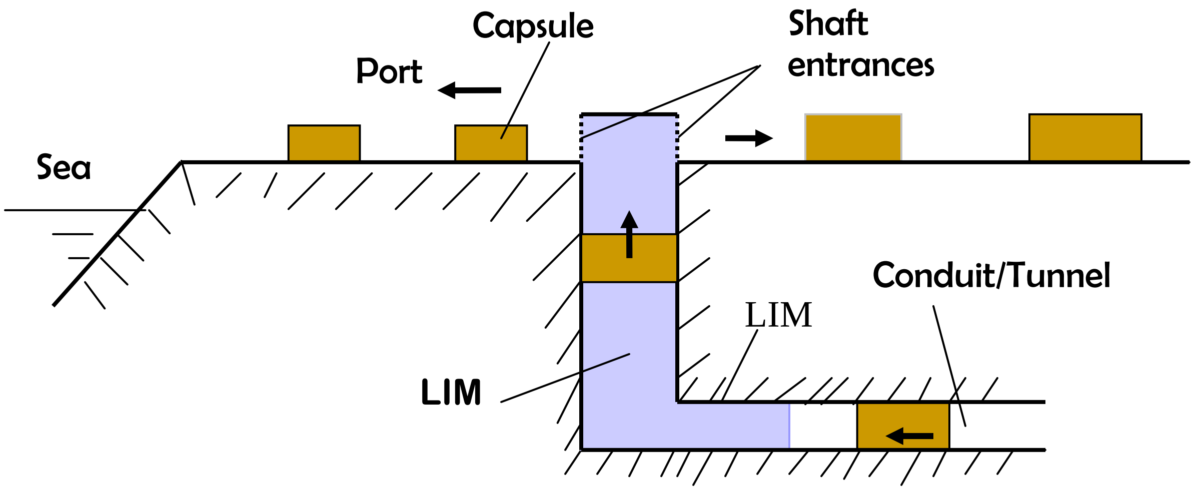


Figure 16. Horizontal-to-vertical transport of capsules by using LIMs.

Due to the difference in weight of different containers, without speed control the capsules in a conduit will move at different speeds and hence may collide with each other before reaching the end of the conduit. By using seal plates around capsules, the air entrapped between the seal plates of neighboring capsules serves as a cushion to soften the impact of collisions and to prevent collision damage. Still, it is undesirable to allow even soft collisions or "capsule staining" since they make control of capsules more difficult when they have exited the conduit and entered terminals (container loading/unloading stations). Therefore, it is desirable if not necessary to be able to control the speed of capsules while they are moving through the conduit, so that adequate spacing can be maintained between capsules in the conduit. Capsule speed can be controlled in three different ways: (a) by using the brakes of the capsule to slow down the motion of fast-moving capsules, (b) by speeding up the slow-moving capsules in the conduit by using the compresses air to turn a wheel faster, and (c) by using adjustable seal plates. Note that the clearance between the seal plates and the conduit affects the speed of capsules. Therefore, by using adjustable seal plates, the capsule speed can be controlled. Note that if (a) and (b) are used, it is not necessary to use (c). On the other hand, if (c) is used, (a) and (b) would still be needed outside the conduit if not within the conduit, because (c) works only when capsules are inside the conduit. For this reason, normally only (a) and (b) are needed for capsule speed control, both inside and outside the pipe. For speed control within the conduit and for moving capsules outside the conduit (within the small space of the terminals), the amount of energy required is small and hence the air tank carried on each capsule (see Figure 13) is small. The tank can be recharged with compressed air each time when the capsule stops for loading and/or unloading cargoes. Speed control can be executed by using motion sensors and stand remote control equipment for vehicles.

2.5.3. Case Study for New York/New Jersey Container Ports

In 2004, Freight Pipeline Company completed a sponsored study to determine the feasibility of using PCP for underground freight transport in New York City [17]. Six potential applications were investigated, including: (1) tunnel construction, (2) transporting municipal solid waste, (3) transporting mail and parcels, (4) delivering goods on pallets, (5) dispatching containers between seaports and 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 the 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).

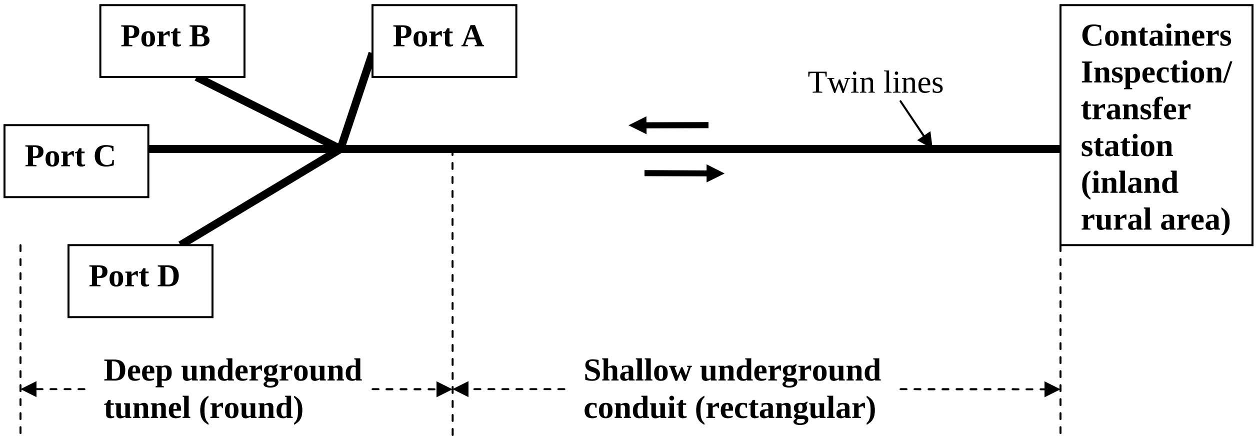


Figure 17. Layout of a PCP system for container transport to and from NY/NJ ports.

In the 5th application, a PCP system to transport containers from four neighboring New York and New Jersey container ports to an inland inspection & intermodal transport station was analyzed. As shown in Figure 17, the system involves four PCP branches each connecting to a different container ports A, B, C and D. Dual pipe was used throughout so that containers can be transported both to the ports from the inland station, and from the ports to the inland station, simultaneously. The pipe or conduit used consists of both round tunnels constructed deep underground for the urban portion, and a rectangular conduit 5 ft below the ground surface for the rural portion. The tunnel portion for each of the dual line 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 of each dual line consists of 15 miles of a reinforced-concrete conduit similar to that discussed previously.

The PCP system was designed to transport a maximum of 30,210 TEUs containers per 24-hours, which is equivalent to 11millions 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 in 2003, 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 requires the use of 1,504 capsules of which 15% is spare. At the air velocity of 43 mph in the tunnel, the capsule 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 is about 6 seconds. Should this injection time of 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.

An analysis of the approximate costs of the system showed the following:

(a) Pipeline Construction Cost :	**$ Million**
42 miles of tunnels of 15-ft diameter	$1,218
30 miles of rectangular conduit	101
Total pipeline construction cost:	**$ 1, 319 million**

(b) Capital Cost (C_c):	**$ Million**
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 (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 $20,000 each, including actuators)	0.1
9. Control and communication equipment	2
10. Others (miscellaneous equipment)	10
11. Engineering (10% of above)	181.95
Total capital cost (C_c):	**$ 2,001 million**

(c) Operation/Maintenance Cost, C_{om} **(annual cost):**	**$ Million/Yr.**
1. Salary/wages (for a crew of 30 persons at each of the 5 stations, or total of 150 persons, $100,000 each including fringe benefits) ………	15.0
2. Electricity (141mw continuously for 365 days at 20 cents/kwh) ………	247.0
3. Others (miscellaneous) …………………………………………….…...	50.0
Total annual operation/maintenance cost (C_{om}):	**$ 312 million**

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

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

$C_A = C_c /T + C_{om} = 2001/30 + 312 = 66.7 + 312 =$ \$ 378.7 million

(f) Number of containers (TEUs) transported by this PCP system in either direction:

N_{TEU} = 30,210 TEUs/day = 11,027,000 TEUs/year

(a) 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 /TEU.

(b) Gross annual income received by charging a toll of $30 per TEU for each one-way trip: $30×11,027,000×2 = $660 million

(c) Gross annual income with system operating at 50% capacity: $660 million ×0.5 =$330 million.

(d) Net annual profit by operating system at capacity: $660M - $379M = $281 million

(e) Net annual profit by operating system at 50% capacity: $330M - $270M = $60 million.

The above calculation shows that when the PCP for dispatching containers in New York/New Jersey ports 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 of the ports 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/New Jersey 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 will 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 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 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. Although the above analysis is for New York ports, similar analysis can be made for other major ports in U.S.A. and around the world.

It should be realized that the above analysis is based on a preliminary design that was not optimized. An optimization of the system would lead to reduction in system cost, and the increased cost-effectiveness of the system. Also, as shown above more than 50% of the capital cost of this project is tunneling cost. For other ports in the nation and around the world where the PCP conduit can be constructed with significantly fewer miles of deep underground and underwater tunnels, the capital cost will be much reduced.

3. COMPARING PCP WITH OTHER PROPOSED NEW TECHNOLOGIES FOR FUTURE FREIGHT TRANSPORT

It is of interest to compare the PCP system with other proposed tube transport systems, and an elevated tubeless system competing for the same purpose-- to transport containers to and from seaports. Through such comparison, one can then understand their individual characteristics, and determine their salient differences, and advantages/disadvantages. Three systems are compared with PCP; they include: (1) the automatic-guided-vehicles-in-tube (AGVIT) system, (2) the automatic-guided-rail-in-tube (AGRIT) system, and (3) the magnetic levitatation (MAGLEV) system.

3.1. AGVIT systems

AGVIT systems use special automobiles, usually electric vehicles with rubber tires, to transport freight through tubes. The vehicles are fully automatic (no human drivers), guided by a track with electric wires imbedded in the track floor. The tubes (conduits) that enclose the vehicles and the track may be either aboveground or underground, depending on individual circumstances. A notable example of such a system is the OLS (underground logistic system) developed in the Netherlands in 1999 – 2000 [18]. Several automatically guided full-size vehicles (AGVs) were designed, built, tested and demonstrated in a large laboratory of the Delft University of Technology. The system was a great technical success. However, implementation of the system in the Netherlands was stalled due to discovery of the high cost of the system. Without being able to compete with trucks running on existing roads on a unit cost basis (in dollars per ton of cargo transported per unit distance), and due to the high capital cost of building an AGV-OLS system, initial backers of the project decided not the implement the project in any commercial application in the Netherlands in the foreseeable future.

Comparison of the PCP with the AGVIT reveals the following:

(1) While AGVIT systems use **active vehicles**, which must have engines, motors or other powering devices on board of the vehicle in order to propel the vehicles through the otherwise stationary air in the conduit, the capsules of PCP are **passive vehicles** which have no engine or other powering device on board, and which derive its energy for motion from the thrust generated by the moving air passing through the conduit. Due to this inherent difference, the capsules of PCP without having power on-board are generally simpler vehicles and cost less to build. For systems of large throughput and long distance, numerous capsules will be needed to operate the system. Thus, using less costly vehicles (capsules) can safe a great deal of money in terms of capital cost.

(2) Furthermore, for active vehicles moving through a conduit, the air present in the conduit hinders the motion of the vehicle by creating aerodynamic drag. The drag can be minimized by

taking two measures: streamlining the body of the vehicles, and using conduits of large diameter or cross-section. However, streamlining the vehicles not only increases the cost of the vehicles but also reduces the space available inside the vehicle needed for large rectangular cargoes, such as containers. Enlarging the conduit to provide large clearance between the vehicles and the conduit so as to minimize aerodynamic drag, on the other hand, is not only costly for systems with long conduits, but also increases construction difficulties when the right-of-way for construction is restricted, as in urban areas. In contrast, with passive vehicles used in PCP, the air present in the conduit is a blessing rather than a hindrance. In such a system, the aerodynamic drag is no longer a negative factor. In fact, the larger the aerodynamic drag is, the larger a thrust is generated on the capsule by the moving air, and the more energy is transferred from the air to the capsule. It is for this reason that for PCPs, the capsules are generally required to be bluff bodies (either box shape or plain cylindrical shape) instead of streamlined bodies, and the conduits must be as small as practical – significantly smaller than that used for a corresponding AGVIT system. Using bluff-bodied vehicles for capsules and using a smaller conduit than that required by AGVIT again makes the PCP system more cost effective than the AGVIT system.

(3) While AGVIT systems use rubber tires for vehicles, the PCP system proposed herein uses steel wheels rolling on steel rails. As a result, the wheel friction and the energy consumed by wheel friction of PCP is only 20% (one-fifth) of that of AGVIT. This makes the PCP system much more energy efficient than the AGVIT system. For long distance freight transport, the savings in energy cost that can be achieved by using rail-based PCP instead of AGVIT can be rather substantial.

(4) For rail-based PCP, the rails structurally guide or restrict the lateral motion of the capsules. Only the longitudinal motion of capsules needs to be controlled, which makes the control system much simpler than that required for any AGVIT system.

(5) All active vehicles, including trucks, railroad trains, and AGVIT, rely on the traction between the wheels or tires and the road to pull the vehicles forward. Due to this, they are severely limited in the slopes that they can climb. In contrast, the capsules in PCP being passive vehicles that derive their force or thrust from the moving air have no slope limit. They can operate even in vertical slope when the system is properly designed for it.

Due to the foregoing, it is expected that the rail-based PCP system costs significantly less than the AGVIT system for transporting the same cargo under the same conditions.

3.2. AGRIT system

AGRIT systems use specially-designed railroad cars or trains (linked cars) to carry cargoes through conduits. The cars or trains are fully automated, requiring no human on-board to operate the vehicle. Either monorails or double rails can be used. The best known AGTIT system is the CargoCap system developed at the Ruhr University of Bochum, Germany [19]. It is a system designed for carrying standard EURO pallets, using streamlined (sharp-nosed) vehicles running on steel rails in tunnels. Each capsule is designed to carry two standard EURO pallets, each of 0.8 m (width) x 1.2 m (depth) x 1.05 m (height). The capsules are powered by 3-phase synchronous motors on board of each capsule, and electric power is transmitted to each capsule by conductor rails. The system is similar to electric tram, except that the capsules and the rails are inside an underground conduit or tunnel. In 2006, researchers at the Texas Transportation Institute (TTI) unveiled a new design of AGRIT for transporting whole containers [20]. The vehicles used are similar to the CargoCap in shape, except that they are to be powered by linear induction motors (LIM), and are much larger in size so that each capsule can carry a standard container.

Comparing the AGRITs with the advanced PCP discussed here, the former employs active vehicles and hence has the same drawback as mentioned in items (1) and (2) of the AGVIT systems discussed before – namely, they require vehicle streamlining and a larger conduit than that for PCP for transporting the same cargo. Because AGRITs don't use rubber tires, their energy consumption should be compatible to that of rail-based PCPs, and much less than that of the AGVIT system. As to the mechanical guidance system, the AGRIT for transporting containers uses a guideway structure in addition to rail. In contrast, the rail-based PCP uses only rails for both moving and guiding capsules; no additional guideway structure is needed. Due to the foregoing, it is expected that the rail-based PCP system costs less than the AGRIT for use to transport the same freight under the same conditions.

3.3. MAGLEV system

In recent year, Germany and several other nations have developed the technology of magnetically levitated trains (commonly referred to as "MAGLEV"). In such systems, the trains are not only magnetically propelled but also magnetically levitated (lifted). As a result of magnetic levitation, during high speed the train is completely levitated or suspended in air by the magnetic force. This eliminates contact friction of wheels at high speeds, thereby enabling the train to reach top speed exceeding 300 mph (480 kph). Using the German developed technology and international expertise, China is the first nation in the world that has constructed such a train system commercially, between the Pu-Dong International Airport and the City of Shanghai, for a total length of 30 km (19 miles). The system, built in 2003, has a top speed of 431 km/h (268 mph). So far it has operated successfully without accidents.

Due to its high cost, MAGLEV systems are generally accepted only as rapid transit for moving people, though it can be designed to move freight as well. Because freight must be transported at a cost much less than that of transporting people, it is far more difficult to justify MAGLEV for moving freight than for rapid transit. Still, MAGLEV is being considered currently for transporting containers from and to the ports of Los Angeles and Long Beach [21]. It would be of interest to see how the researchers and proponents of the system can design a MAGNEV system much less costly than the current MAGLEV system in Shanghai, so that it can compete with other freight transport systems including PCP, AGVIT, and AGRIT. To be meaningful, comparison of the costs of such systems must be based on the same transportation purpose (e.g., all systems must transport the same cargo over the same distance at the same place) and under the same conditions (for example, all must be elevated, or all must be underground). It would not be appropriate, for instance, to compare the cost of an elevated MAGLEV system with the cost of a tunneled underground PCP, since both can be either elevated or tunneled. Likewise, it would not be appropriate to compare an AGRIT system enclosed in an aboveground tube (conduit) with an underground PCP, as both can be built either aboveground or underground.

4. CONCLUSION

Based on the foregoing discussion/analysis, the following is concluded:

(1) Due to the close proximity of most container ports to major cities, and due to the acute security risk of terrorist attacks of such ports using unsuspected and uninspected containers, it is highly desirable to build a container inspection/intermodal transfer station in an inland rural or less-populated place near the container ports, for inspection and intermodal transport of the containers to and from the port. Transportation of containers between the station and the port can be done by capsules or vehicles moving through underground pipelines (conduits or tunnels).

(2) Transportation of containers through such underground conduits can be done by using either active vehicles that carry with them engines, motors and/or other powering devices, or passive vehicles (capsules) propelled by air moving through the conduit. Because the former requires powering devices on board of each vehicle, requires vehicle streamlining, and must use a conduit larger than that required of the latter, it is anticipated that the cost of using active-vehicle tube systems to transport freight is more expensive than using passive-vehicle tube systems or wheeled PCP (pneumatic capsule pipeline) to transport freight.

(3) The wheeled PCP technology has been studied and tested extensively in the last 30 years, and has been used successfully in Japan in several commercial projects. However, their usage was limited due to the use of fans (blowers) which hinder the motion of capsules through pipes.

(4) By using linear induction motor (LIM) capsule pumps, and by using capsule with steel wheels running on rails, a revolutionized new system of PCP is now available to transport cargoes of any size, including standard 40-ft containers, through conduits. The system combines the advantages of LIM (being non-intrusive and highly efficient) with the advantages of steel wheels on rail (being very low in friction as compared to vehicles with rubber tires). Furthermore, the system uses passive vehicles (capsules) and hence has the advantage of low-cost capsules and a smaller conduit.

(5) Due to the foregoing, it is anticipated that the new advanced PCP system that uses LIM and rails provides the most cost-effective solution to moving freight containers underground.

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