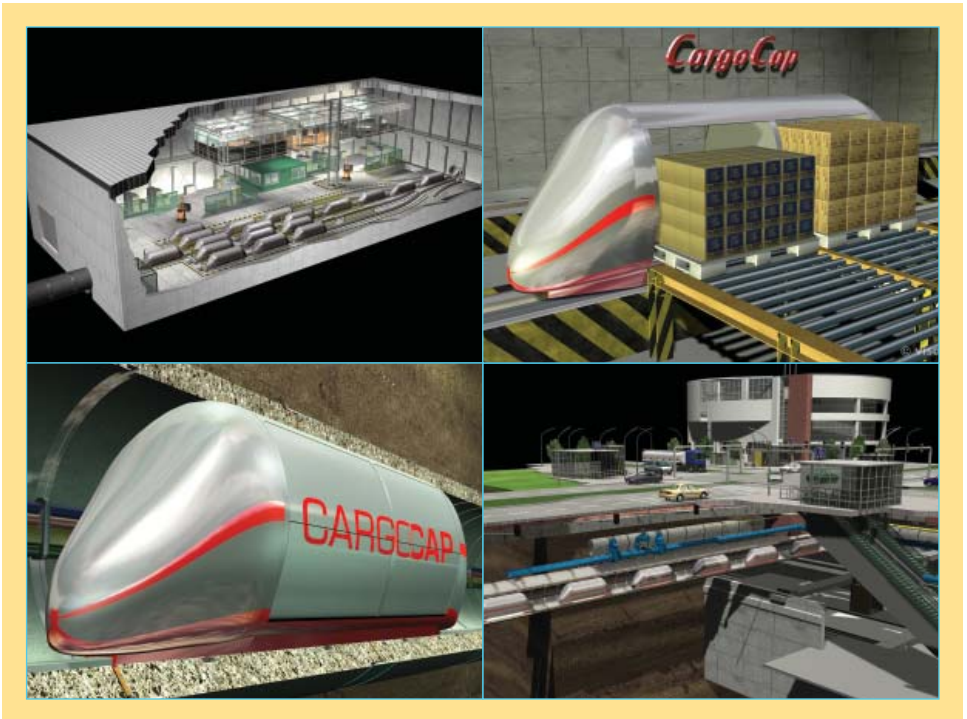


The International Symposium on Underground  
Freight Transportation by Capsule Pipelines and  
Other Tube/Tunnel Systems

Presents

The 5th International Symposium on  
Underground Freight Transport

# ISUFT 2008



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Tunnel Business



## **Pipe\$net: innovation in the transport through high rate small volume payloads.**

**ISUFT 2008, Arlington, March 20-22, 2008**

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5<sup>th</sup> International Symposium on Underground Freight Transportation by Capsule Pipelines and Other Tube/ Tunnel Systems

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## Abstract

“Pipe§net” is an Italian innovative freight transport system for payloads up to 50 Kg, constituted by a network of vacuum-sealed pipes where goods-carrying capsules are moved by electric linear motors in very low friction conditions and at variable speed. The system is at an advanced concept stage with many researches and a feasibility study accomplished. In comparison with other systems Pipe§net focuses on small volume freight, thus avoiding many of the critical issues innovative systems meet in their development: construction complexity, overall size and interference of the new infrastructures with the territory, safety requirements of vehicles transporting both passengers and freight and/or transferring tons of goods, all of these issues affect the progress of untraditional systems due to cost, environmental impact and timing.

With Pipe§net, small volume freight are conveyed at high rate and speed in order to keep transport capability higher than traditional systems and at the same time fulfilling the rising needs of a society which requires a more sustainable and affordable mobility, where *e-commerce* is ever-growing and spreading and where transport door-to-door potential have an increasing attraction for market’s logistic stakeholders.

In this paper the main technical features of the system are presented, considering its distinctive characteristics like high transport capacity, low energy consumption, low environmental impact, high speed in goods delivery, integration with railways and road infrastructures, door-to-door and spreading potential. Through a comparison with road and railways transport systems, economic, environmental and social advantages are presented.

Research status, lab experiments and prototypes accomplished as far, are described; in particular the paper will present the status of development of the in-house electrical linear motor (with controls), tests on magnetic levitation through high temperature bulk superconductors and tests on the performance of air-tight plastic material selected for the tubes.

# 1 Introduction

In the last decades, transport infrastructures have struggled to face the rising mobility needs in the world's economy both for passengers and for goods. In developed and developing countries the continuous increase in traffic congestion, in air and noise pollution, in incidents, gives evidence of the saturation point reached by traditional transport systems, road, railways, airborne and waterborne. As a solution, present transport infrastructures can be adjusted and enhanced, but new innovative systems can be developed as well, in order to deal with the urge of an ever-growing mobility need, in quantity, quality and diversified in the tipology of requested services.

A diverse outline of applications come out from worldwide scenarios of innovative transport systems (at different progress stage): the main industrialized countries have one or more projects under development, concerning the realization of structures and infrastructures alternative to traditional ones, testifying the great interest and strategic relevance of this sector. However, the majority of such applications seem to meet only some of the market's logistic needs. Transport market nowadays looks as if requesting either passengers or freight specific systems more than mixed ones to better exploiting the differences and avoiding negative interference from the two kind of payloads.

Moreover a latent request for small sized and unheavy goods rising together with the spreading and expansion of *e-commerce* seems not to be recognized by other transport systems, traditional and untraditional alike.

Pipe\$net's concept relies on the assumption that the same transport capability can be achieved both by slowly moving huge masses and transferring small payloads at high rate.

In comparison with other systems Pipe\$net focuses on small volume freight, thus avoiding many of the critical issues innovative systems meet in their development: construction complexity, overall size and interference of the new infrastructures with the territory, safety requirements of vehicles transporting both passengers and freight and/or transferring tons of goods, all of these issues affect the progress of untraditional systems due to cost, environmental impact and timing.

Optimization of supply chains through intermodal and comodal (multimodal) solutions is considered today a top priority both by the business community and the institutions ([5]): it would benefit by the introduction of a "fifth" freight transport systems with features very different from the others and intrinsic characteristic of sustainability. Unique Pipe\$net's potential is disclosed in scenarios which are "difficult" for traditional systems like crossing environmentally fragile areas, highly dense urban zones, territory with a complex orography, valuable historical city centers, etc.

With Pipe\$net, small volume freight are conveyed at high rate and speed in order to keep transport capability higher than traditional systems and at the same time fulfilling the rising needs of a society which requires a more sustainable and affordable mobility, where e-commerce is ever-growing and spreading and where transport door-to-door potential have an increasing attraction for market's logistic stakeholders.

## 2 Technical features

“Pipe\$net” is an innovative freight transport system for payloads up to 50 Kg and volume of 200 ÷ 400 liters, constituted by a network of vacuum-sealed pipes where goods-carrying capsules are moved by electric linear motors in very low friction conditions and at variable speed.

Pipe\$net’s main features are:

- high transport capability (through high speed and high linefill rate);
- traffic relief potential;
- low energy consumption;
- low environmental impact both from air and noise emissions;
- fast delivery of goods;
- seamless and affordable connections by flexible integration into existent transport facilities;
- intermodal/comodal integration with traditional transport systems to increase the quantity and quality of the solutions for the optimization of logistic supply chains;
- potential for widespread distribution and door-to-door features;
- reduction in the number of incidents, injured and deads on the streets.

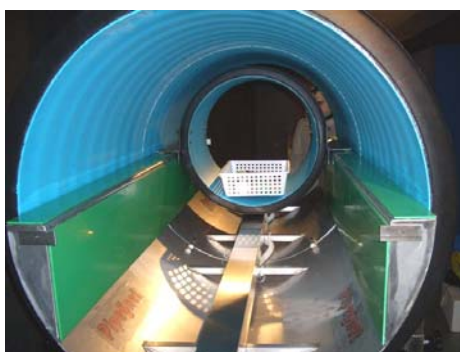


Fig. 1: a view of the prototype of Pipe\$net

### 2.1 Propulsion

Traction of Pipe\$net’s capsules is achieved by linear electrical synchronous motors. This is similar to a rotative synchronous motor in which rotor translates in a translational magnetic field instead of rotating around his axe. Linear electrical synchronous motors can recover up to 70% of kinetic energy during deceleration.

### 2.2 Low motion friction

Motion friction is decreased by specific suspension systems (depending on application and typology of line, i.e. maximum velocity, number of switches, etc.) and by enforcing vacuum inside the pipes.

#### 2.2.1 Suspension

In case of long connections, magnetic levitation is envisaged as a solution to reduce friction in order to reach high speed of the capsules and to keep energy

consumption to a minimum. Currently there are several lines of research being carried on in the world, concerning magnetic levitation, in different stages of development: permanent magnets, High Temperature Superconductors (HTS), Electro-Magnetic Suspension (EMS), Electro-Dynamic Suspension (EDS).

With the exception of EDS, all those systems seem to be compatible with Pipe\$net. EMS in particular has a great potential due to its advanced state-of-art (MagLev train currently running in Shanghai): application to a lighter vehicle (a capsule with a payload of 50 kg instead of a train) seems most promising, without the huge infrastructures and comfort level required for a passenger mass transport system.

More traditional solutions can be considered concurrently with levitation in case of urban or regional connections. Anyway, even on longer routes many of Pipe\$net's innovative features would keep their potential even with a conventional suspension system.

### **2.2.2 Vacuum**

In order to reduce drag, air pressure is kept very low inside Pipe\$net's lines: pumping systems will maintain a vacuum-sealed environment.

Due to its high blockage ratio (cross-sectional area of the capsule divided by the inside cross-sectional area of the pipe) and design speed, negative aerodynamic effects like shock waves or transonic flow could affect performance, thus vacuum will help to reduce them as well.

## **2.3 Traffic management**

Highly reliable control technology will be used to manage capsule traffic in the pipes. Capsules use the less congested and rapid route available in the network to optimize delivery time. On the analogy of Internet, a set of procedures and transmission protocols could be defined for managing the transfer and routing of capsule. Its inputs will be quantity, type and destination of goods, number of pipes and capsules available, other modes of transport which can be used in comodality, intermodal availability at nodes, etc; its output will be a scheduling of capsules conveying and the programming of batches for the optimization of Pipe\$net network's usage.

## **2.4 Capsule and line**

Capsules are cylindrical containers which match the pipe; they are fireproof with vacuum integrity. By a statistical survey on parcels dimensions and weight, the parameters shown in the following table have been established which fulfill the largest transport needs.

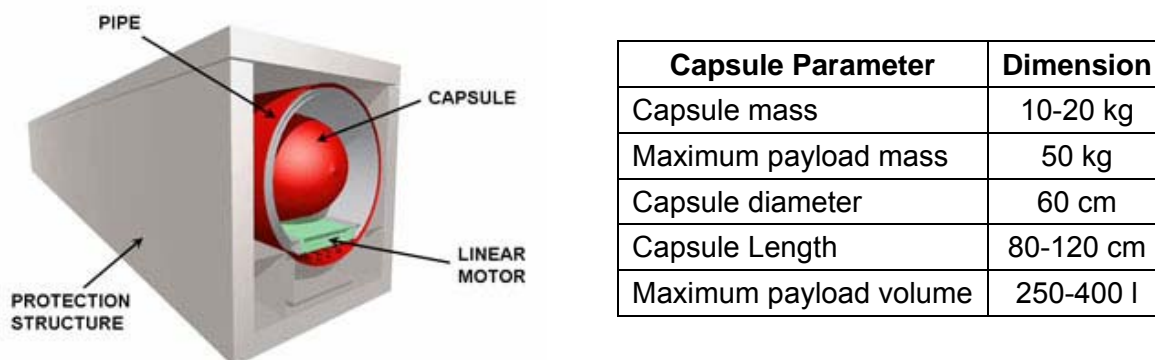


Fig. 2: a sketch of PipeŞnet and a table with its dimensions

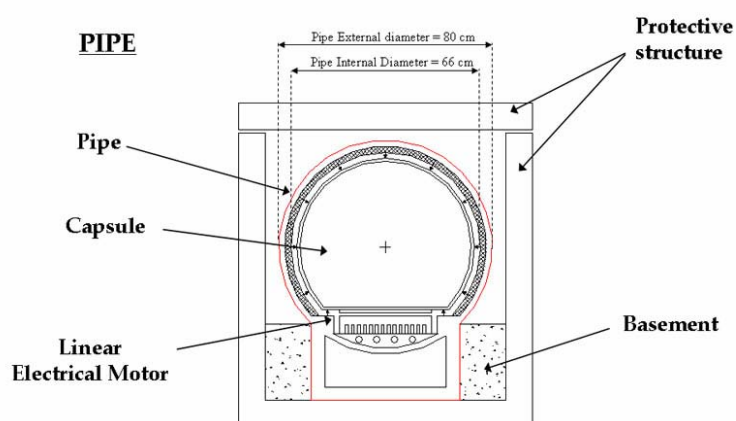


Fig. 3: section of PipeŞnet

The pipe is made of metal, composites or high resistance corrugated polymeric material and it can be placed, if necessary, inside a protective structure of concrete boxes. Motor and capsule guides are located inside the pipe.

A possible line could be made of 4 different pipes (Fig. 4):

- 2 for ordinary traffic;
- 2 for emergency and/or maintenance.

Interchange Stations (SI in the picture) are located every 10 Km to provide switching points between ordinary and emergency lines due to ordinary line malfunctioning, maintenance and temporary traffic jam;

Supply Stations (SA in the picture) are located every 2 Km to provide electrical power, traffic control and vacuum pumping. Each Interchange Station is equipped with a Supply Station as well.

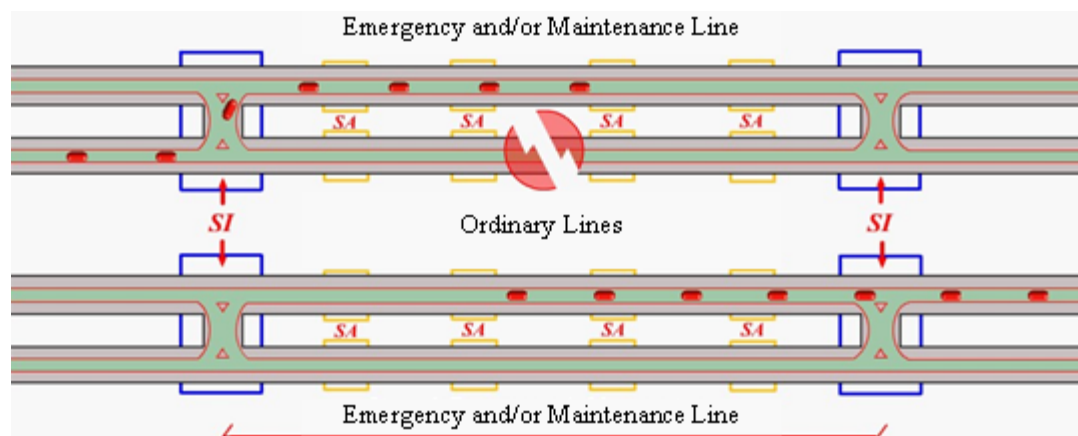


Fig. 4: a possible configuration of PipeŞnet's lines

## 2.5 Shipping & Receipt stations

Capsules are conveyed in the line through shipment and receipt stations (Fig. 6) with the following features:

- automatic loading & unloading system;
- air lock;
- checking of capsule integrity;
- checking chemical/physical parameters of freight.

Security and safety protocols similar to airport ones are enforced in PipeŞnet's shipment & receipt stations.

## 2.6 Multimodal integration

It is possible to use existent transport network facilities (railways or roads in particular) to lay PipeŞnet network, either underground or on surface, in order to obtain an environmental low-impact smooth integration in the territory and reduce costs (Fig. 5). Integration of PipeŞnet with traditional transport systems extends to logistic functionality as well. Using PipeŞnet together with other means, according to comodality/intermodality principles, will optimize the services offered by the freight supply chains.

## 2.7 High transport capacity

Transport capability of a system is defined as the maximum transportable weight per unit time. The following relations show a comparison among different transport means and their transport capability ( $C_{MAX}$ ):

$$(1) \quad C_{MAX,LS} = \frac{V_{LS} \cdot P_{max}}{4 \cdot \lambda_{LS}} = 456 \text{ kg/s} \quad \text{Low Speed (LS) PipeŞnet}$$

$$(2) \quad C_{MAX,HS} = \frac{V_{HS} \cdot P_{max}}{4 \cdot \lambda_{HS}} = 977 \text{ kg/s} \quad \text{High Speed (HS) PipeŞnet}$$



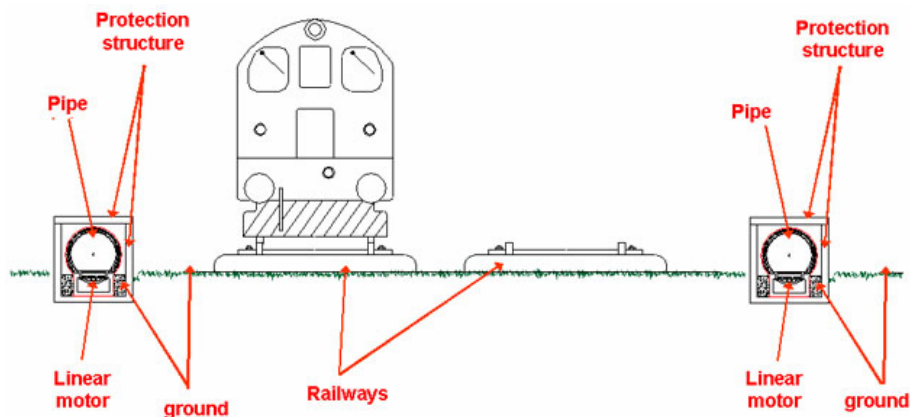


Fig. 5: example of integration of PipeŞnet with pre-existent infrastructures

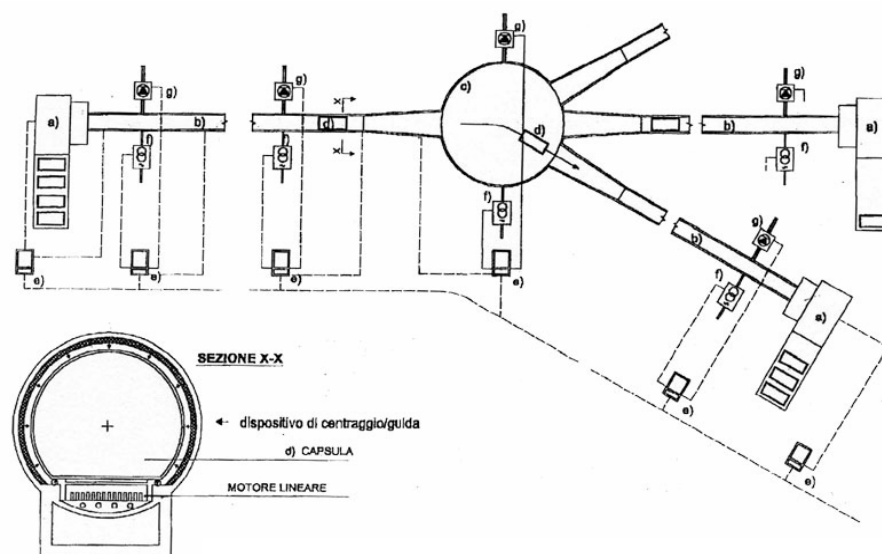


Fig. 6: concept of PipeŞnet's delivery stations (from patent's drawings)

$$(3) \quad C_{MAX,R} = \frac{V_R \cdot P_R}{d_R} = 222 \text{ kg/s} \quad \text{Road}$$

$$(4) \quad C_{MAX,T} = \frac{\alpha \cdot T_{\%} \cdot P_T}{f} = 481 \text{ kg/s} \quad \text{Railways}$$

Parameters are defined as follows:

$V_{LS} = 300 \text{ km/h}$

Low Speed PipeŞnet (LSP) velocity

$V_{HS} = 1500 \text{ km/h}$

High Speed PipeŞnet (HSP) velocity

$P_{MAX} = 30 \text{ kg}$

PipeŞnet capsule's payload

$\lambda_{LS} = 1.6 \text{ m}$

LSP wavelength of propulsion magnetic field

$\lambda_{HS} = 3.2 \text{ m}$

HSP wavelength of propulsion magnetic field

$V_R = 80 \text{ km/h}$

Road speed

$P_R = 2000 \text{ kg}$

Payload on roads

$d_R = 200$  m  
 $\alpha = 70\%$   
 $T_{\%} = 22/24$   
 $P_T = 450$  ton  
 $f = 10$  minutes

Safety distance on roads  
 % of railways line's usage for freight transport  
 % of operational time in the day for railways  
 Cargo of freight train  
 Frequency of trains

Fig. 7 pictures the same comparison: by conveying at high speed and high rate, payloads with small dimensions and weight, the same or better transport capability (ton/hrs) than conveying huge loads at low speed can be achieved.

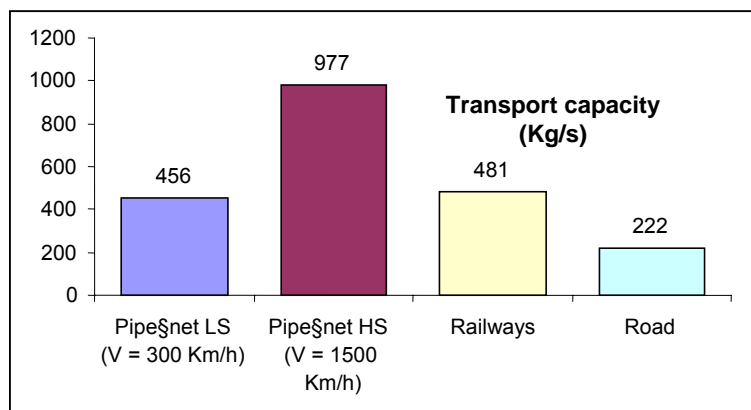


Fig. 7: comparison among transport capacities

## 2.8 Cost reduction and energy saving

A major advantage of Pipeşnet is the reduction of energy consumption compared with road transport. Fig. 8 shows an overall saving of about 40%.

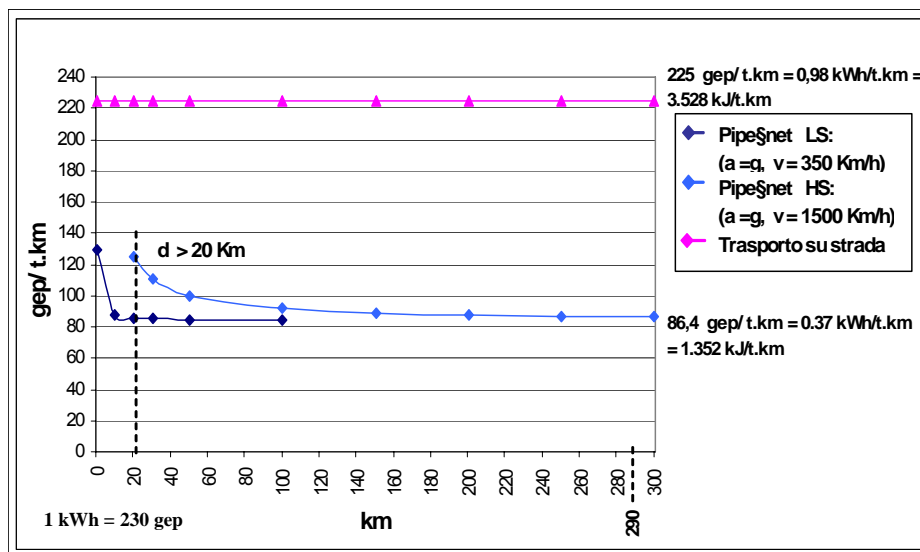


Fig. 8: comparison among energy consumptions

## 2.9 Fast delivery

Pipeşnet LS e HS, due to high transfer rate of capsules, show fast delivery times. In Table 1 a comparison is reported among different transport means.

Table 1: comparison between delivery times

Distance (km)	Delivery time		
	Road transport	Pipeşnet LS (V = 300 Km/h)	Pipeşnet HS (V=1500 Km/H)
10	10'	1' 54''	-
20	20'	3' 36''	-
50	50'	8'48''	2'42''
100	1h 15'	17' 18''	4' 42''
200	2h 30'	-	8' 42''
500	5h 33'	-	20' 41''
1000	11h 6'	-	40' 40''

## 2.10 Low environmental impact

Pipeşnet allows to decrease both pollutant emissions in the atmosphere and noise compared to road transport. Local emissions from Pipeşnet are absent; emissions due to the energy production industry in Italy are reported in Table 2.

Table 2: comparison of emissions

Type of emission	CO <sub>2</sub> eq. (g/t-km)	NO <sub>x</sub> (g/t-km)	PM10 (g/t-km)	Rumore SEL dBA at 7.5 m
Pipeşnet (distributed emissions)	0	0	0	~ < 40
Pipeşnet (centralized emissions)	~ 244	~ 0.27	~ 0.02	-
Trasporto su strada (distributed emissions)	~ 300	~ 1.4	~ 0.3	80

Finally, easy integration with pre-existent transport infrastructures (roads, railways, etc.) and small cross-section of pipes, lead to both a reduced visual impact on landscape and low effect on the environment when laying Pipeşnet's lines.

## 2.11 Social-economic consequences

Substituting part of road freight transport with Pipe\$net would allow a relevant reduction in the number of road incidents, consequently of deads and injuries.

From a statistical italian survey (AISCAT 2004, Conto Nazionale delle Infrastrutture e dei Trasporti - Ministero delle Infrastrutture e dei Trasporti, 2002), if 30% of freight traffic shifted on Pipe\$net system, the following effect would take place:

- decrease of 3200 incidents/year on italian highways (- 7%);
- decrease of 1100 injured/year on italian highways (- 5.5%);
- decrease of 55 deads/year on italian highways (- 10%).

## 2.12 Typology of transportable goods

Pipe\$net is designed to transport goods which can be packed in parcel-wise items of about 50 kg and volume between 200-400 l; internal dimension of capsules can be designed to fit one single euro-pallet in order to use a standardized unit of transport. Whatever size is decided for capsules, a unified measuring for all the networks of Pipe\$net should be used in order to ease spreading and connections of lines just like what happened for railways gauges in the past.

Typical goods which could be transported by Pipe\$net are: almost all the items one can find in shopping centers and department stores like food, clothes, household and personal care products, toys, stationery, electronics, only cumbersome and heavy goods like furniture would not fit in a Pipe\$net capsule; mail and all parcels sent through national postal service or private couriers which could have their own fleet of capsules along with their vans, trucks and aircrafts; medicines and the like; inward and outward laundry material from hospitals; vegetables and harvest from crop fields.

Not only finished goods but also work in process products could be transferred from manufacturing site to manufacturing site using Pipe\$net.

Pipe\$net is suitable also for disposal of garbage provided that it can be fit inside the dimension of capsules.

## 2.13 Applications

A distinguishing feature of Pipe\$net is its application flexibility, in particular when it is associated multimodally (through inter and comodal services) with other traditional transport systems: Pipe\$net can be applied to urban scenarios with a high density of logistic service needs, thanks to its low environmental impact, its traffic relief capacity and the high rate of freight delivery; Pipe\$net can connect several strategic areas of one or more industrial zones, and it could get to the artistically relevant city centers due to the small infrastructural size and its building integration with pre-existent facilities (like railways, underground, etc.); Multi-modal potential of Pipe\$net allows also for functional integration with the logistic services provided by road and rail transportation; through intermodal

interfacing the last mile of the supply chain can be covered, whereas specific comodal strategies allow to satisfy all the logistic needs in any scenario.

A major advantage relies on Pipeşnet system when timely delivery of perishable goods is critical.

Flexibility can be found also in the intrinsic on-demand feature of Pipeşnet's logistic services, fit on final customer needs more than on shipping companies' ones, allowing for a wide range of delivery hours, size and typology of batches, rate of replenishment, etc. Thus, the following list is just an indication of possible applications, as examples of the high degree of adaptability of Pipeşnet system in many different logistic backgrounds:

- connection of intermodal transfer nodes with city centers;
- connection of one or more industrial areas one with the other, with transfer nodes, city centers or any kind of goods distribution site;
- spread logistic services supplied along a "metropolitan for goods".

In all the above cases, Pipeşnet offers advantages in terms of delivery time, pollution reduction, traffic relief and "just in time" quality of granted service.

### 3 Research status

Beginning from 2006 a first series of experiments concerning suspension were conducted; focus was on preliminary testing some of the technology issues behind the whole concept like suspension, vacuum, propulsion, etc. (Cotana [1] and [2]).

Low friction using iced surfaces with sliding blades (Fig. 10) and permanent magnets (Fig. 9) have been studied for the suspension of the capsules. Both results were unsatisfactory but not conclusive, thus it could be possible to consider either solutions for future studies or applications in Pipeşnet

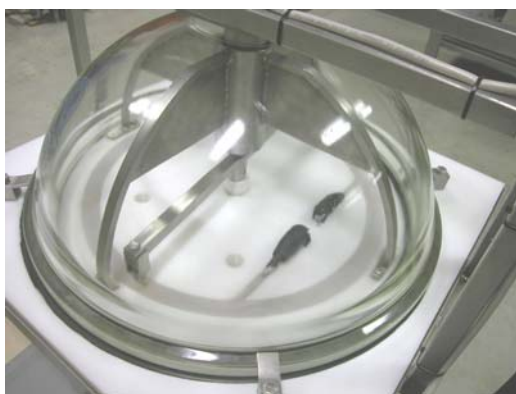


Fig. 9: lab experiment of ice-gliding suspension

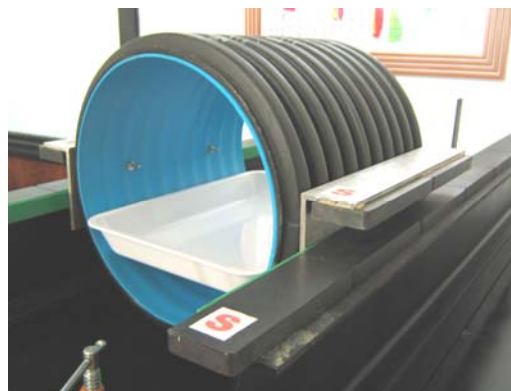


Fig. 10: lab experiment with permanent magnets

in particular together with other more effective suspension systems.

In 2006 a first prototype was also constructed for preliminary tests of the whole concept (Fig. 11 and Fig. 12): it has a limited length (2 m), but it keeps some of the final characteristics of the system like the propulsion. The tube is made out of a commonly used corrugated high density polyethylene (HDPE); the



Fig. 11: view of 2 m long prototype



Fig. 12: prototype exhibition in Rome (2006)

internal capsule is simulated by a short section of a smaller pipe and its movement is achieved by a linear motor which generates a translating magnetic field. Simple sliding supporting surfaces in Teflon operate the needed suspension. The prototype has been used extensively for demonstration purpose as well.

Currently the most promising solutions for frictionless suspension systems for Pipe§net seem the Electro-Magnetic Suspension (EMS) and the High Temperature bulk Superconductors (HTS), which have both undergone some experiments, whose only the latter is briefly reported in the present paper (Fig. 13).

For Pipe§net's suspension test, small blocks of "type II" superconductors have been used which are made of YBCO (yttrium barium copper oxide) melt textured material. Several studies from many researches carried out throughout the scientific community show the particular suitability of such ceramics to levitation applications and transport:

- their superconducting state is reached by cooling with liquid nitrogen which is easy to get, handle and much less expensive than liquid helium;
- they show intrinsic stability features through "pinning" forces which allow guidance improvability of suspension and passive lateral control of dislocation.

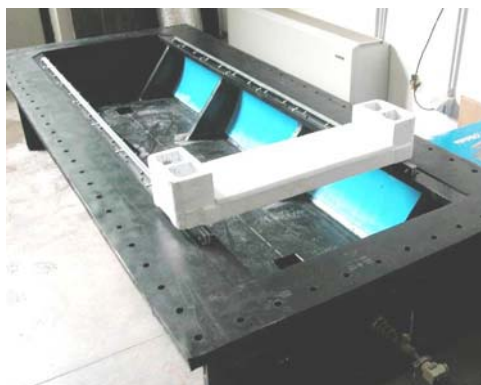


Fig. 13: experiment with superconductors

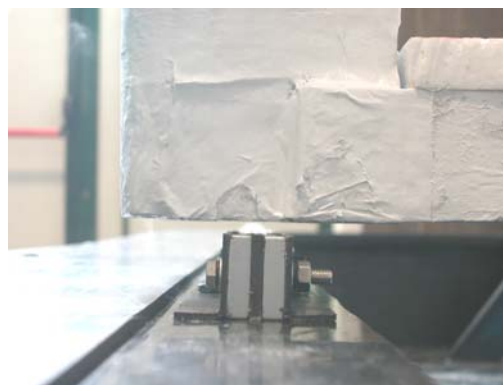


Fig. 14: levitation with high temperature superconductors



On the basis of a research in the scientific literature (among others Wang [3] and D'Ovidio [4]), a specific design has been chosen for the magnet tracks needed to supply the requested magnetic field (Fig. 14); magnetic flux concentration above the tracks is achieved with a high intensity of B field and its gradient, which is important for the pinning effect.

Results are interesting but a deeper understanding of the relation and interference between the Meissner effect and the pinning effect need further extensive studies. The former, which grants the levitating force, is proportional to the cooling gap (defined as the distance between the superconductors and the permanent magnets at cooling), whereas the latter, which supplies the stability lateral forces, is in inverse proportion to the cooling gap.

Moreover scientific literature reports that superconducting performance is strongly affected by a highly dynamic behaviour like the one envisaged in transport applications of HTS.

### 3.1 Vacuum

In order to test the performance under vacuum conditions of material preliminary chosen for the pipe, an experimental tube 2.5 m long has been constructed, using two half shells obtained from a single standard HDPE corrugated pipe. Internal volume is 1400 liters (Fig. 15).



Fig. 15: tube for vacuum experiments

Plates and ribs in HDPE are welded in different positions in order to improve structural stiffness and create an internal chamber to be depressurized. The two sections can be joined by a series of bolts and a rubber gasket to guarantee airtight conditions; a Leybold rotary vane pump of 16 m<sup>3</sup>/h has been used to depressurize.

After a preliminary set-up of the system and a few repairs of major leaks, a final internal pressure of 40 mbar was reached in 30 minutes; a pressure leakage of 1 mbar/min was observed leading to an evaluation of power needed to maintain vacuum of about 6÷7 kW / km. The plastic corrugated configuration of the pipe has proved to satisfactorily resist to the stress caused by pressure differential. More deeper researches are needed to better understand the relation among gasket, pump connections, walls and the pressure leakage detected.

### 3.2 Linear motor

In 2007 the development of a customized synchronous linear motor has been started, specifically designed for Pipe§net's application. Tests are currently run on a 4 meters prototype.

The capsule movement inside the pipe needs to be controlled by electromechanical devices. In particular a control is needed both for the capsule longitudinal position along the path and its altitude.



Fig. 16: segment of customized electric linear motor for Pipe§net

The position control system of each module is based on a double feedback loop. The inner loop feedbacks the motor stator currents and, depending on current error, it opportunely switches transistor of the IGBT inverter in order to impress the desired voltages on the three phases of the linear motor.

The outer loop generates the desired currents depending on the cursor position error by means of a PID regulator. Moreover the overall system control needs a mechanism of synchronization of current phases as the capsule passes between two adjacent modules.

The capsule altitude control can be performed either by regulation of stator current, which would bring to a MIMO system with 2 input and 2 outputs, needing to regulate position and altitude by means of 2 control input (the 2 orthogonal components of the stator current derivable from Park transformation), or by varying the current of an electromagnet fixed to the capsule.

This last solution would considerably simplify the longitudinal position control, avoiding coupling terms, but it would be to the detriment of the weight and the size of the capsule and would make it necessary to power it.

## 4 Partnership

All researches and experimentations have been currently conducted by University of Perugia (Italy) through CIRIAF (Centro Interuniversitario per la Ricerca sull'Inquinamento da Agenti Fisici, "Interuniversity Research Center on Pollution from Physical Agents"). CIRIAF was founded in 1997 by the University of Perugia and University of Roma Tre. University of Florence, Pisa, Aquila, Rome "La Sapienza" and Polytechnic of Bari have later joined the agreement. Actually the members of the Scientific Council of the CIRIAF are more than 100 from 14 different Universities. CIRIAF's laboratories at the University of Perugia are one of the main scientific and technical resources of the Faculty of Engineering.

Pipe§net s.r.l. is the firm which owns the patent rights.

Several enterprises have been directly and actively involved in the project on the basis of:

- participation on prototyping (Italiana Corrugati for the tubes, Mechatronic for the linear motor) ;



- participation on fundraising projects (Angelantoni Industrie, AnsaldoBreda).  
It is very important to involve a wide audience of Italian mobility stakeholders, like public administrations (municipalities, national and regional government agencies) and NGOs, to better support the project and disseminate its concepts, potentiality, vision of future and up-to-date experimental results. For this purpose, Pipeşnet's demonstration prototype has been showed in various occasions, like:
  - exhibition celebrating the 60th Anniversary of the Italian Republic held in Rome in 2006, organised under the patronage of the President of the Republic;
  - MotorShow exhibit in Bologna, 2006, with the collaboration of Associazione Italiana Familiari e Vittime della Strada onlus ("association of families and victims of the roads");
  - The "Meeting in Rimini" and "Festa Nazionale dell'Unità" in 2007, both two major political and social gathering events in Italy.

## 5 Financing

Researches and experimentations up till now have been accomplished under two grants, a public one from Ministry of Environment and a private one from Fondazione Cassa di Risparmio di Perugia.

Pipeşnet project takes part in the following financing scheme calls (yet to be approved):

- with CIRIAF, to the CIVITAS Plus programme, under the 7th Framework Programme of the European Union; leader of this 20 millions euros project is Municipality of Perugia, which chose Pipeşnet to implement part of the logistic objectives;
- with CIRIAF, to the EU Framework Program 7, under the Sustainable Surface Transport theme.

## 6 Critical issues

There are some most crucial issues concerning Pipeşnet's development which need extensive researches and are expected to be analysed in depth during future studies.

**Performance of electrical linear motor at high speed in vacuum conditions.** Even if linear motors are a small part of the total market of electrical engines, they have been used for a long time by the industry, especially in tooling and packaging machinery. However their use in the transport sector is still recent, although the development of maglev trains technology has started to enrich the scientific literature on the subject. Performance of linear motors in vacuum conditions at very high speed (1500 km/hrs) are unknown.

**Suspension.** The possibility to apply suspension through contactless systems like magnetic levitation to Pipeşnet is another important issue which needs further investigation. Nevertheless the frictionless suspension and the high velocity don't seem critical for Pipeşnet's progress, as the system would keep most of its potential even using a traditional mechanical low friction suspension

and speeds up to 300 km/h. High velocity trains has proved such technology viable.

More critical to the project are the following issues which are briefly described.

**Accessibility and maintenance operations.** Pipe\$net's infrastructure is a net of pipes with a relatively small diameter and electrical linear motors laid out along all their extension; capsules move at very high rate inside the tubes, which are in vacuum conditions. All those features make the accessibility for inspection or maintenance operations difficult to manage especially for long pipes: the section to be operated upon need to be re-pressurized and allow full clearance for manned assistance. Extensive FMEA and specific solutions for such peculiar technology have to be studied: examples could be intermediate valves positioned at optimized locations (the trade-off being between cost of infrastructure and time to perform a complete maintenance), inspection trolleys to speed up operators' access to the required section, etc.

**Terminal bottleneck and batch size.** The overall transport capability is strictly dependant by the operations performed at terminal stations and the time to complete them, which represent the bottleneck of the system (in terms of distance bewtween two consecutive capsules): operations include the positioning of capsules (or more likely batches of them) at arrival/departure pads, airlock valves closing/opening, depressurize/pressurize, acceleration/deceleration. Solutions with buffers, multiple cargo bays and optimized batch size may be explored to manage higher rates of capsules.

**Intermodality issues and capsule load unit.** The small dimension of Pipe\$net's unit of transport (capsule) is the foundation of the whole concept, but it raises at the same time a critical issue concerning intermodality as it goes against the current "container" paradigma of logistics. Full integration of Pipe\$net in the multimodal freight transport chain is crucial for the success of the system: investigations is required to guarantee solutions for smooth interoperability and develop requirements for comodal effectiveness; the most critical issue is the design of a standard loading unit (capsule or clusters of them) which is the best to integrate in the current logistic market for stackability, handling ease and flexibility. For instance impact on Pipe\$net's profitability and market penetration should be analysed whether system's size was increased to fit euro-pallets inside cargo cell. A double parallel strategy should be used to tune the research activity in this sector: together with an approach focused on adapting Pipe\$net the most to the present situation, a future vision of "how it could be" should be used as well, considering a fully developed Pipe\$net as one of the driving force of the market.

## 7 Conclusions

The path towards a more sustainable, available and affordable freight mobility is a key issue in any government's agenda. Conveying goods through a network of pipes may add a strategically important "fifth" mode of transport, to fulfill optimization of supply chains and enhance the offer of the logistic market. Yet, cost and environmental impact of innovative infrastructures struggle to be

accepted by public and private investors and decision-makers. Pipeşnet focuses on supplying a high capability of transport through small-sized capsules transferred at high rate and velocity. Thus, infrastructures can be kept relatively small and they can easily be integrated in pre-existent transport facilities like roads and surface or underground railways.

The system is at an advanced concept stage with many researches and a feasibility study accomplished. All major technology required by Pipeşnet are already developed and industrialized for other purposes, they just need to be gathered to fit the new system.

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