KULeuven Faculteit Ingenieurswetenschappen

Freight Transport Management

# Pipeline-as-a-service: towards new business concepts in pipeline transportation

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# List of Figures



# List of Tables

# Contents

# 1 Introduction

It is generally accepted in the scientific community that the current dominant modes of freight transport, namely trucking and aviation, contribute significantly to climate change and are the source of other environmental nuisances such as air and noise pollution, and traffic accidents (Egbunike & Potter, 2011; Rijsenbrij et al., 2006; Visser, 2018; Gordijn, 1999; Ren et al., 2019; Mark et al., 1993; Dong et al., 2018). Road freight is widely recognized for its flexibility and therefore a very popular mode choice for shippers and carriers globally (Pienaar, 2010; Steadieseifi et al., 2014). This mode of transport however falls victim to traffic congestion, reducing its reliability (Dong et al., 2019). In the light of e-commerce, there exists a current tendency to decentralize logistics operation due to highly volatile demand patterns in consumer demand (Lu et al., 2021; Chenglin et al., 2014).

In attempt to (1) render the logistics sector more sustainable, (2) and its operations efficient, solution strategies focus on making activities cleaner and bundling flows (Egbunike & Potter, 2011). Those ambitions however should not jeopardize future economic sustainability. They will furthermore be constrained to market requirements. This paper will investigate to what extent pipeline systems can help to shape a sustainable and efficient future for freight transportation. A first section will therefore look into the existing network of pipelines, its operation and benefits. Careful attention will be paid to the lessons to be learned from current applications. Freight pipelines will then constitute the main scope of this report. First, a societal perspective is given on the matter as requirements for such systems are analyzed. Secondly, several typologies of pipeline systems are considered which may offer solutions. Section 3.3 then covers the decision making process in designing and operation freight pipelines on a strategic, tactical and operational level. A SWOT analysis will combine the insights from the aforementioned sections in order to provide a nuanced overview. A discussion will summarize the most important results and suggest approaches for future research.

# 2 Background: Pipeline Transportation

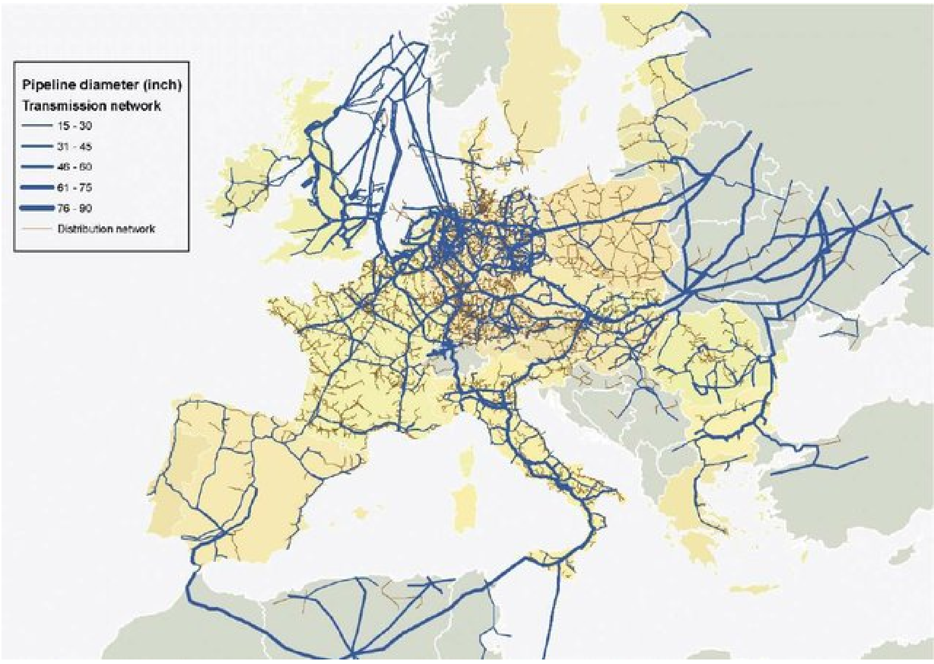


Figure 1: Extent of the European pipeline network for natural gas (Carvalho et al., 2009)

This section will give a brief overview of the current extent of pipeline network, with a focus on the European context. The use of pipeline for efficient means of transportation dates back to the Romans and Egyptians (Razvarz et al., 2021; Milz, 2007). Pipeline system were put in place mainly to transfer water. They were considered efficient, due to their enclosed form, meaning there was no influence of weather conditions (e.g. vaporization) or external sources of pollution such as waste.

Those advantageous characteristics continue to be recognized today. Pipelines are also the most cost efficient solution for the transportation of gas and fluids (Cunha, 2012). In 2014, Razvarz et al. estimated the total extent of the oil & gas pipeline network alone at 3.5 million kilometers in 120 countries, 65% of which is located in the United States. The extent of the European natural gas network is displayed in Figure 1 (European Commission, 2019). In terms of usage, only 5% of all freight - expressed in tonne-kilometers - is transported by pipeline, which suggests that the core market for pipeline transport is a niche one as of today and furthermore that the technology is associated with several disadvantages.

Table 1: An overview of pipeline typologies (Razvarz et al., 2021; Milz, 2007; Zahed et al., 2018; Egbunike & Potter, 2011; Asim & Mishra, 2016).

| | Type | Usage |
|---|---|---|
| **Gas & Fluids** | Water and sewer lines | Household scale (small diameter), urban water distribution |
| | Oil pipelines | Crude oil and product oil transportation |
| | Gas pipelines | Transportation and distribution of natural gas |
| | Other fluids | LNG, liquified fertilizer |
| **Solids** | Slurry pipelines | Ores (coal, gold, copper), mixed with water for conveyance |
| | Pneumatic pipelines | Propulsion of bulk goods such as grain, flour or coal dust via pressurized air, possibly in containers. |
| | Capsule pipelines | Conveyance of (wheeled) capsules in water (HCP) or in vacuum (PCP). |

Before examining the benefits and challenges related to pipeline operation, a brief overview of pipeline typologies is extracted from Razvarz et al. (2021); Milz (2007); Zahed et al. (2018); Egbunike and Potter (2011); Asim and Mishra (2016) and displayed in table 1. Although the exact working principles differ per technology, a system operator's main objective is to minimize the power consumed to convey goods - be it due to compressors in pneumatic, or pumps in fluid applications, while maximizing the throughput and respecting deliveries (Demissie et al., 2017). Attaining optimal flow rates at a low cost starts in the design of a pipeline network. Pienaar (2010) suggests that the decision maker should at least consider the following parameters when constructing a pipeline:

- **Location**: close to the port, or rather close to the market?
- **Alignment**: above ground or below surface? Is there topographic hindrance? Legal constraints?
- **Diameter of the pipeline**: larger diameter requires higher initial cost, but possible to exploit economies-of-scale.
- **Transported goods**: A more viscose fluid usually requires a larger amount of energy.

A well-designed pipeline for the conveyance of fluids and gas, then enjoys the following operational benefits. The transportation of solids will be looked into in the next section. Pienaar (2010) highlights the fact that pipelines enjoy economies-of-scale, due to the uninterrupted and continuous flow of goods. When dealing with bulky goods, costs related to packaging and material handling are reduced to a minimum, making pipeline operations a labor extensive technology. In terms of energy usage, pipelines consume the least amount of energy per unit of transported commodity. Demissie et al. (2017) add that natural gas networks can in principle be self-sustaining, as a fraction of the flow is diverted to powering the pumps. Those factors combined render pipelines a very low-cost solution for the transportation of natural gas and liquids (Zahed et al., 2018). In addition, according to Pienaar (2010), it is considered the safest mode of transportation for petroleum commodities. Pipelines are up to a certain extent, not as intrusive as other infrastructures in landscape. Lastly, the delivery of goods is assumed to be quite reliable (although not the fastest), which means that there is less need for (expensive) emergency stock (Pienaar, 2010).

There are however some deficiencies associated with conveyance of liquids and gas through pipes. Pienaar (2010) addresses low flexibility as the major disadvantage. First of all, there is no flexibility in geographic location, which makes pipelines inconvenient for markets with highly volatile demand. Pipes are also often tailored to the good to be transported. Capacity cannot easily be extended.

Finally, there is a certain range of adaptability within petroleum fuels, but conversion to other uses such as for food-related products is impossible. The considerations above are reflected in the relative performance of pipelines as opposed to other modes of transport (Fig. 2).

| Service characteristics | Relative performance in general terms | | |
|---|---|---|---|
| | Highest | ⟵⟶ | Lowest |
| Suitability | Pipe | Rail | Road |
| Accessibility | Road | Rail | Pipe |
| Goods security | Pipe | Road | Rail |
| Journey speed | Road | Rail | Pipe |
| Reliability | Pipe | Road | Rail |
| Flexibility | Road | Rail | Pipe |

Figure 2: Relative performance of pipelines for petroleum commodities (Pienaar, 2010).

While unit transportation costs may be relatively small, pipeline construction is considered to be very capital intensive Pienaar (2010). Furthermore, pipelines are prone to several failures. Those could either be human induced, be it due to an accident or an act of terrorism (Kidd, 2008; Cunha, 2012). Internal and external corrosion of pipes also poses problems, as it requires extra maintenance and replacements (Cunha, 2012). Environmental damage due to leakage of harmful liquids or ignition in the case of gasses is also reported to be a societal (Razvarz et al., 2021).

Nevertheless, the carbon footprint of pipelines is revealed to be the lowest among all modes of transportation. In addition, pipelines are employed in several sectors to attain a reduction of GHG emissions. X. Liu et al. (2016) for example eleborate on the use of pipelines in Combined Heat and Power units (CHP), that is transfering excess heat from power plants to industrial facilites in order to achieve higher production effiencies. Knoope et al. (2013) predict the future role of pipelines in Carbon Capture and Storage (CCS) and carbon sequestration. Could pipelines aid the transport sector, being accountable for 16% of all greenhouse gas emissions, in reducing their impact (Our World in Data, 2016)? And if so, would they present an efficient solution for the problems associated with freight traffic? The next section will present the research in the field of freight pipelines. Using the combined insight of this section and the next one, a role for pipelines in an environmentally and economically sustainable world might be stipulated.

# 3 Freight Pipelines

As stated in the introduction, several attempts are made to render the supply chain more efficient and sustainable. While some researcher look to reduce the impact of the current vehicle fleet, others look at the potential role of new modes in achieving similar goals. This section will investigate the extent to which freight pipeline transportation can fit within these ambitions. As a one-fit-all solution generally does not exist, a first subsection will determine the specific needs within an urban and international context. A second subsection will dive deeper into several typologies of systems and their characteristics. Research related to the optimal design and operation of freight pipeline systems will be presented next.

## 3.1 Identification of system requirements

This paper will distinguish two scales at which a solution for the issues mentioned above will be sought, namely an urban or industrial level (i.e. within a city or an industrial site) and an international level (i.e. between cities or distribution centers) . The reason is that a suitable solution at an urban level might not satisfy the requirements on a larger scale. Table 2 summarizes the most important challenges at each level.

Within an urban context, the main objective is to mitigate the impact of trucks and vans within the city center. Although on average, the traffic share of those vehicle is only 20%, their environmental impact in terms of air pollution, noise pollution and traffic safety is larger than that of regular passenger car traffic (Dong et al., 2019). Most notably, the reliability of last-mile delivery is vurnerable to traffic congestion, as urban areas are at risk of becoming logistics bottlenecks (Lu et al., 2021). A strategic solution would thus mitigate these effects, while at the same time presenting a (financially) interesting alternative to carriers and ensuring quality of life in the city center (Gordijn, 1999).

On an international level, from a societal perspective, there is a need to reduce the carbon footprint. Speed as a parameter also becomes much more important, as opposed to the urban level (David J Hyde, 2016). In order to maintain a reliable and accessible service, great caution has to be taken in selecting locations for network access. Ports and airports present the most suitable candidates, also due to the processing of large flows, and to ensure easy transfer to other modes (Alves, 2020; Pijnenburg, 2019). Longtime industrial standards, such as the maritime container need to be manageable, without introducing extra handling costs (Visser, 2018). After all, just like on the urban level, a competitive solution is highly desirable in order for the system to be successful.

Table 2: A distinction between system requirements for a freight pipeline on an urban level, and on an international level (Gordijn, 1999; Lundgren & Zhao, 2000; Visser, 2018; Ren et al., 2019; Hai et al., 2020).

| **Urban level** | **International level** |
|---|---|
| Lower carbon footprint | Lower carbon footprint |
| Integration with existing modes of transport (small trucks, railway) | Integration with existing modes of transport (trucks, aviation, railway) |
| Accesibility of local distribution centers/ clusters of industrial activity | Accessibility of ports, airports and large distribution centers |
| Abate traffic congestion, especially in the city center, ensuring quality of life | Creating incentive for bundling of large flows |
| Non-intrusive infrastructure | Non-intrusive infrastructure |
| Reliable service | Reliable service |
| Able to handle standard delivery sizes (e.g. pallets or crates) | Able to handle standard industrial equipment (e.g. containers) |
| Competitive mode of transport, at low service cost | High speeds |
| Automated system | Competitive mode of transport, at low service cost |
| | Automated system |

## 3.2 Typology of systems and their characteristics

Chenglin et al. (2014) indicates that the conception of a freight pipeline is not new (Fig. 3). Early experiments with pneumatic tubes as means of transfering written messages date back to the late 19th century, and Mail Rail could be considered the first freight pipeline application on an urban scale (Visser, 2018; Egbunike & Potter, 2011). This section will provide an overview of current conceptions within the field of freight pipelines and their technical characteristics.

**Electrically powered wheeled applications**

Much like suburban rail, wheeled applications of freight pipeline involve carts, usually autonomously driven, which use rails to guide themselves and rely on electrical propulsion by linear induction motors (Egbunike & Potter, 2011). The advantage of driving on rails being an on average lower resistance due to friction. CargoCap (Fig. 4) in Germany is one system which relies on the technology stated above (Rijsenbrij et al., 2006). Individual vehicles are able to attain average speeds of 40 km/h and are able to carry to pallets (Egbunike & Potter, 2011; Chenglin et al., 2014). Rijsenbrij et al. (2006) suggests that these kind of systems are most effective in small-range alignments.

| Transportation | Project Name | Location | Pipe diameter | Construction Time |
|---|---|---|---|---|
| Pipeline Transportation | London Pneumatic Despatch System | London | 30×33in | 1863–1869 |
| | Hamburg postal system | Hamburg, Germany | 450mm | 1962 |
| | Pipeline Express（Tubexpress） | USA and Georgia State | 910 | 1971 |
| | | Houston, United States | 450 | 1973 |
| | Transprogress | Russia | 1220 | 1971–1983 |
| | Subtrains | New York | 1050 | |
| | Sumitomo system | Japan | 1000 | 1983 |
| | Japan LSM cabin systems | Kawasaki | 300 | 1994 |
| | Demonstration Project | Florida | 610 | 2000 |
| Tunnel Rail transport | London Postal (subway freight) system | London | 2740 | 1927 |
| | Automated network of underground tunnels | Tokyo, Japan | 5500 | |
| | ULS | Netherlands | 1150–5000 | |
| | CargoCap system | Bochum | 1600 | 1998- |

Figure 3: An overview of historical applications of underground freight transportation and freight pipelines.

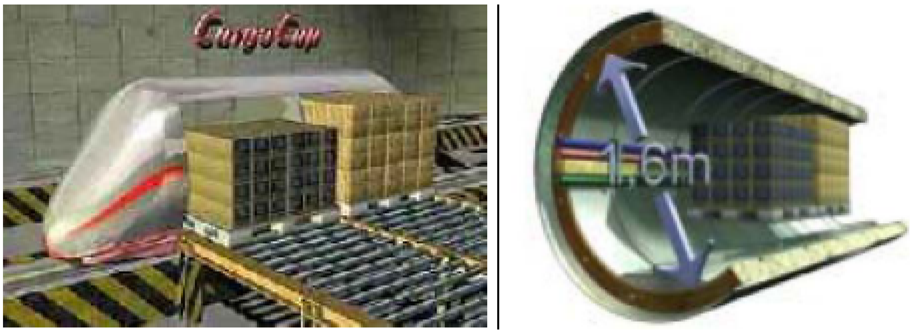


Figure 4: An impression of the CargoCap system, drawn from a simulator (Rijsenbrij et al., 2006).

**Capsule pipelines**

In an attempt to decrease travel times of individual capsules by travelling in a fluid environment such as air or water (PCP and HCP respectively), several researchers have proposed using fluid propulsion within freight pipelines (Chenglin et al., 2014). Within this category, pneumatic wheeled applications with linear induction motors seem to be popular, again due to their favorable friction characteristics and higher speeds (Visser, 2018; Chenglin et al., 2014; Hai et al., 2020) (Fig. 5). However, as this concept has not been put into practice on a viable scale, reliable key performance indicators are lacking. Rijsenbrij et al. (2006) , however, suggests that average speeds of PCP units in its most extended form would be around 50 km/h, which is considered slow. Lundgren and Zhao (2000) cite 90 km/h as a maximum speed.

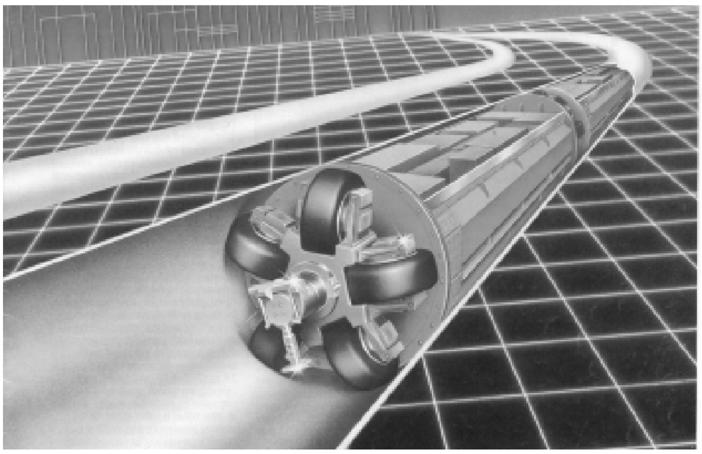

Figure 5: An artist impression of wheeled a PCP system, suitable for the transportation of multiple pallets (H. Liu, 2007).

### Applications using magnetic levitation and Hyperloop

Hyperloop was coined by Elon Musk in a white paper from one of its companies, SpaceX, in 2013 (Hansen, 2020). This futuristic technology tackles the two main mechanisms which limit current modes of transports: friction due to the soil, and air resistance. It combines the idea of propulsion of capsules by linear induction motors in a semi-vacuum environment, with the already proven concept of magnetic levitation (Opgenoord & Caplan, 2017; Sayeed et al., 2018; Kumar & Khan, 2017). A thin layer of air - also referred to as air bearings - separates a capsule from its infrastructure. The air is provided by an on-board compressor, which sucks in air in front of the pod, thus maintaining the low pressure environment (Opgenoord & Caplan, 2017; Sayeed et al., 2018; Kumar & Khan, 2017). The entire structure would be mounted on pillars, and as such could be constructed adjacent to highways (Hansen, 2020) (Fig. 6).

Theoretically, maximum speeds of 1200 km/h could be attained and vehicles could maintain gaps of 30 seconds in between. Not only is Hyperloop proclaimed to be a cheap future alternative to current modes of transport, it does so in a self-sustaining way, due to the instalment of photo-voltaic cells along its infrastructure (Hansen, 2020).

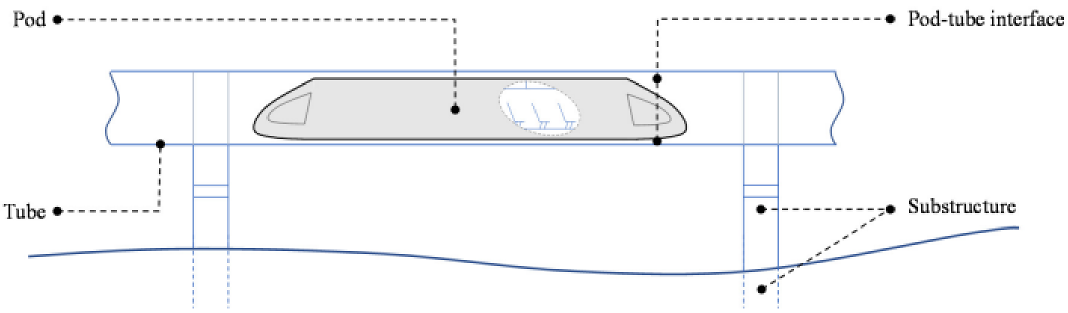


Figure 6: A sketch of the Hyperloop infrastructure (Gkoumas & Christou, 2020).

Although the concept of Hyperloop has enjoyed immense popularity within research, Hansen (2020) and Krawiec and Markusik (2021) have expressed concerns regarding the "hype" related to Hyperloop. According to previously mentioned researchers, Hyperloop is most likely to attain average speeds of 400 km/h - comparable to Maglev trains, and larger gaps in between vehicles in order to ensure safety, meaning a lower than expected capacity. Moreover, its ability to be completely self-sustaining energy-wise is being contested by Dudnikov (2017). Other comments regarding the technology's integration within the supply chain and the environment follow in the SWOT analysis.

## 3.3 Design & Operation of a Freight Pipeline

As will be elaborated in a later section, pipeline infrastructure is highly capital intensive and non-flexible, regardless of the technology used within the pipeline (Werner et al., 2016; Rijsenbrij et al., 2006). Once built, the owner should ensure systems to be exploited at their full capacity, to gain a return on investment (Lundgren & Zhao, 2000). To attain that ambition, the alignment, capacity and service cost and other parameters should be such, that large good flows make use of them. This section will cover the steps required in designing and optimizing transport in pipes at a strategic, tactical and operational level in order to achieve those goals.

### Strategic level

Within the context of multimodal transport, freight pipeline systems are identified as being an alternative for long-haul transportation, pre-haul and last-mile delivery requiring a higher flexibility (Steadieseifi et al., 2014; Ren et al., 2019; Shin et al., 2018). Pan et al. (2019) thus suggests to design pipeline systems in a hub-and-spoke configuration. On the short-term however, direct connections are to be expected as test projects (Alves, 2020). Kidd (2008) envisions direct connections on a long distance only, e.g. an "Eurasian Landbridge", however such ideas seem outdated given the current objectives in multimodal transport. Gordijn (1999) conceptualized the idea of selling pipeline systems to specific companies on an urban scale with guaranteed large and stable flows, such as supermarkets, in order to achieve economies-of-scale. Regardless of the exact network topology, a system design should be able to consolidate as many flows as possible in order to be viable given current and expected trends, without becoming a bottleneck of its own (Ren et al., 2019).

The difficulty constitutes in identifying locating hubs, and allocating (distribution) facilities or nodes to them. Ren et al. (2019) proposed a Minimum Set Covering Problem (MSCP) to do so (Fig. 7), in which the most amount of nodes are attributed to a minimal amount of access points or hubs. A trade-off exists between construction costs and transportation costs. The more nodes included, the more pipelines need to be constructed, but in operating more pipelines, economies of scale could become interesting. On the other hand, an extra node could slow down travel speeds (David J Hyde, 2016). Ren et al. (2019) further suggest to add weights to nodes according to characteristics like: (1) the avoided congestion, (2) avoided air pollution, or (3) freight volume. Especially the last extension allows for the inclusion of possibly distant, yet very interesting from a volume perspective. This weighting also enables hubs to be used at near or full capacity.

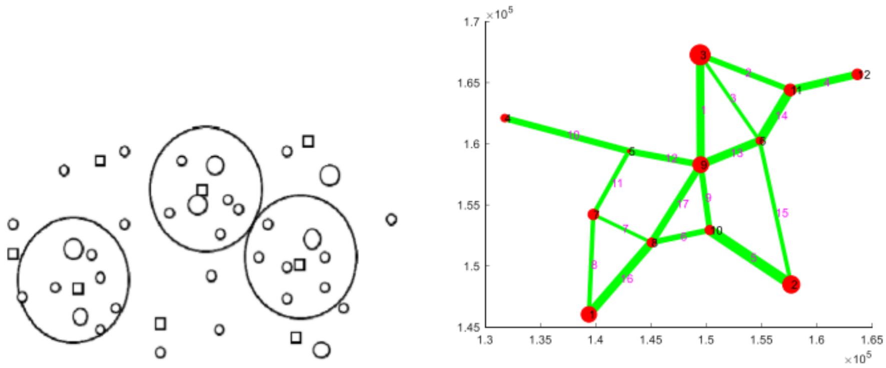


Figure 7: An illustration of the Minimum Set Covering Problem and its solution, the thickness of the lines indicating the magnitude of the flow (Ren et al., 2019).

Once the hubs are decided, the alignment of spokes in between them is to be examined. Estimation of future demand flows should help to get an assessment on the required capacity on each branch (Ren et al., 2019). The latter calibration is however complicated by a yet unknown induced demand from other modes, which may cause congestion. Steadieseifi et al. (2014) suggest as much sources of network congestion into account as possible. Congestions or delays due to transhipment problems are for example not to be underestimated. Ren et al. (2019) also stress the need for dynamic decision making, as not all of the network will be finished simultaneously, and achieving the desired density might take several years or decades. The order of construction is thus to be examined.

The construction of a pipelines should above all fit within a certain use case, be it as an underground logistics system for a city, or as international connection between large logistical hubs. Further decisions should indicate towards which how goods are to be contained - as pallets, crates or as containers, which will have an impact on the network design and the transshipment process (Rijsenbrij et al., 2006). Research conducted by Overman and Phillips (2001) suggests the network optimization to be further subjected to geographical constraints. A network of underground tunnels cannot be built everywhere, due to characteristics of the soil. Furthermore, public opinion does not always endorse the alignment of a pipeline network, underground or above ground, as it leads to spatial fragmentation and forced migration. This exercise proofs to be difficult in Flanders especially, where space is a very limited recourse (Vlaams Departement Omgeving, 2021).

**Tactical level**

As mentioned earlier, optimal utilization of the infrastructure is necessary in order to justify its construction. Therefore, on a tactical level, one should investigate which services the network could offer to which carriers. Mark et al. (1993) implies supply chains with a strong and stable supplier-customer relationship to be candidate users. Stimulating cooperation between carriers is crucial in this stage, in order to attain consolidated and synchronized flows (Steadieseifi et al., 2014). Careful attention should be paid to the management of empty capsules or carts, as these charge the network without rendering benefit.

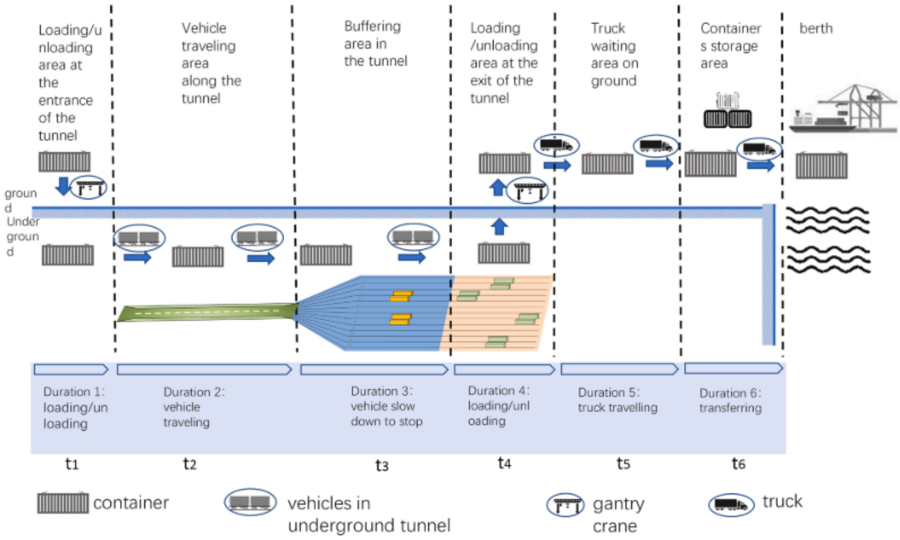


Figure 8: An outline of the key components of the entire chain, of which the pipeline transportation might be part (Pan et al., 2019).

System costs, operation times, network layout and customer requirements are key to balance in this exercise. Figure 8 gives an overview of several components and interaction points for a hypothetical road-pipeline-maritime haul. Given these system costs, decisions regarding service frequency, departure times and goods aggregation are to be made. In the light of possible delays or unexpected failures, a network must be resilient (Steadieseifi et al., 2014). A sensitivity analysis should provide insight in the allocation of system buffers, in order to anticipate such events (Mark et al., 1993; Werner et al., 2016).

### Operational level

Just as any other network, a pipeline system will be in need of appropriate traffic management (David J Hyde, 2016). This will require the operator to possess all necessary information on capsule position, speed and loads. This information is then fed back the operator in order to send out the correct amount of vehicles, to assign loads to them and to schedule departures (Mark et al., 1993). Real time information is of particular importance when unexpected delays occur (e.g. an accident, or a transhipment taking much longer), in order to make the appropriate decision adjustment (Steadieseifi et al., 2014). Only suitable operational management can render pipeline transportation a reliable mode of transportation on the aggregate.

## 4 A SWOT Analysis for Freight Pipelines

Table 3 presents the SWOT analysis, based on findings in literature. Some elements have been featured in previous sections already, but will be highlighted here for completeness. Note that a distinction is made between base characteristics, applicable to both a ULS and a Hyperloop system, and properties uniquely pertinent to Hyperloop. Each individual set of properties will then be discussed separately: what are strengths of such applications, and under which assumptions are they viable? What are the identified weaknesses, and how can they be assessed? What are properties not yet exploited? And what are threats to the success of those systems?

### Strengths

Basic freight pipeline systems exhibit speeds similar to the average speeds of trucks. Depending on the technology, a range of speeds in between 40 and 90 km/h is achievable (Rijsenbrij et al., 2006; Lundgren & Zhao, 2000). Hyperloop forms the exception, being able to attain an average speed of 400 km/h (Hansen, 2020). Reliability is deemed to be a key benefit of capsule pipeline systems of all sorts, as they can be computer steered. If well-designed and demand is sufficient, both ULS and Hyperloop systems would be able to achieve economies-of-scale due to consolidation of flows (Rijsenbrij et al., 2006; Werner et al., 2016). Zahed et al. (2018) confirm that statement, by suggesting that large container applications have a larger benefit-cost ratio, than palletized systems. Hyperloop technology, in addition, would benefit from economies-of-distance. The service costs for pipeline technology is thus expected to be lower than for truck and rail services. Werner et al. (2016) estimated service costs for a Hyperloop application in northern Germany to be 4 to 8 cents/tonkm, as opposed to the 10 cents/tonkm for trucks. In this case study, rail services were found to be cheaper (2 - 2.5 cents/tonkm). (Lundgren & Zhao, 2000) however suggests cost per tonkm in freight pipelines to be 4 to 9 times higher, when only 10% of the capacity is used. The costs are however difficult to compare, due to the fact that Hyperloop is not yet in operation (Werner et al., 2016).

Major benefits of freight pipelines are to be sought in their shared added value for society (Werner et al., 2016). First of all, a well-designed ULS in an urban context should reduce freight traffic by a significant amount. Both Werner et al. (2016) and Dong et al. (2018) estimate vans and trucks in cities to constitute on average 20% of the total traffic. Hai et al. (2020), in designing a hypothetical freight pipeline system for Shanghai, found that freight traffic in the urban area as a whole decreased, except near access points to the pipeline system. The latter observation is to be expected, although the authors warn for the area surrounding such a hub to become a potential bottleneck. The impact of pipeline system on urban traffic is thus ambiguous, and careful attention is to be paid to allocating access point to a ULS. The impact on urban livability and emissions is deemed to be relatively higher (Dong et al., 2019). That is mostly due to the fact that trucks and vans emit on average more particulate matter (PM) and $CO_2$. What researchers however tend to forget, is that the effects of reduced freight traffic might be counteracted by an induced demand of passenger car traffic (Hai et al., 2020).

Werner et al. (2016) computed the effects of a Hyperloop implementation in a social cost-benefit analysis. They valued that Hyperloop technology would be able to render benefits up to a third of the initial investment in worst case. According to their findings, major advantages would be due to avoided road accidents and the increase in travel speeds (in monetary terms). They estimated a 2% decrease in daytime traffic and 0.025% of abated air pollution. They assumed reliability to play a key role in shared value creation, although such figures are difficult to estimate, let alone monetize. From a emission efficiency point of view, some authors suggest rapid freight pipelines, to be more sustainable than electric vehicles in the end (Dong et al., 2019). The idea of the energy self-suffiency of Hyperloop is often brought forward as an argument to support that claim, although it is contested by Hansen (2020), Dudnikov (2017) and Krawiec and Markusik (2021).

### Weaknesses

The high investment associated with construction is generally considered as a drawback for any freight pipeline configuration, tunnel constructions being more expensive than above ground infrastructure (Zahed et al., 2018; Egbunike & Potter, 2011; David J Hyde, 2016; Werner et al., 2016; Kidd, 2008). Costs increase proportional with tunnel diameter, and consequently tunnels or pipes suitable for container transportation are the most expensive (Rijsenbrij et al., 2006). Estimations for urban applications vary widely, due to the variaties in technology. Hyperloop infrastructure is estimated to cost anywhere between 20 and 60 million dollars per mile. That is not significantly cheaper when compared to the cost of high-speed rail infrastructure in Europe (approximately 43 million dollars per mile) (David J Hyde, 2016).

The latter costs are referred to as sunk, and so the built infrastructure will have to be used at full capacity in order to manage a return on investment (Zahed et al., 2018). Construction of a pipeline system, especially in a hub-and-spoke configuration, regardless of the project scale, will take a significant amount of time when compared to infrastructure for other modes (Egbunike & Potter, 2011). Once built, extensions are of course possible, but have a possibly even higher price tag

(Egbunike & Potter, 2011). Zahed et al. (2018) also expects that maintenance and administration costs are not to be underestimated either, but as of yet hard to enumerate. Any reasonable pipeline operator will have to impose tariffs to its users, in order to break even (Zahed et al., 2018; Pijnenburg, 2019). An operator is faced with the trade-off of attracting enough users to charge a competitive service cost versus having to charge higher tariffs. But if charges are too high, it risks losing customers to alternative modes.

Although the first strategy of finding more customers to compensate the costs seems easy, it is not. Other modes will dominate over any international connections, as long as they have the advantage of having a denser network (David J Hyde, 2016). On the transportation market for fast services, airlines and associated companies have built an extensive hub-and-spoke system already. The market for high-value and time sensitive costs, such as perishables and medicine, is a niche one. On an international level, many goods do not require delivery within a day or travel less than 500 km (the distance a truck can travel within a day) and are thus are already captured by the road freight transport market, also due to its higher flexibility (David J Hyde, 2016). Nonetheless, Alves (2020) does not reject the possibility of Hyperloop for cargo becoming a dominant player on the intracontinental transportation market, shifting the aviation market to intercontinental transportation.

On an urban scale, Visser (2018) is convinced that use cases exist for ULS applications. Palletized systems could be used for intra-urban transportation of retail, or solid waste processing. Other utilizations could be hinterland transportation of containers. The author concludes that overall however, the markets - rather than the technology itself - remain the most binding constraint.

Pipeline systems also require intensive planning and operational management. Transshipment is mentioned as the most delicate component in such configurations, as the process imposes additional unloading and loading, storage costs and possibly unexpected delays (Rijsenbrij et al., 2006; Mark et al., 1993). In order to remain a competitive elemement within supply chains, these components require careful optimization (Egbunike & Potter, 2011). The latter will however be constrained to customer requirements, and the solution space might be narrow due to tight JIT time windows (Visser, 2018; Steadieseifi et al., 2014). One is also faced with the decision of adding stops to the network (David J Hyde, 2016). The more stations, the lower average speed, but the more accessible the system, which in turn might be needed to be integrated within the supply chain.

**Opportunities**

Statements above suggest that, although given several benefits, future pipeline operators are faced with the challenge of finding users in order to render their systems viable. Multiple authors turn to the passenger transportation market as a collaboration opportunity (Gordijn, 1999; Kikuta et al., 2012; Dong et al., 2018). Hyperloop for example was conceived to be able to carry both passengers and cargo (Krawiec & Markusik, 2021). On an urban scale, Kikuta et al. (2012) considered the Japanese metro system as being a potential carrier for cargo. A stated preference survey conducted by the same authors however revealed that this would render subways less attractive for passenger. (David J Hyde, 2016) contests the idea of combining passenger and freight flows, stating that if it would have been economically interesting, it would have been done already on a large scale. He refers to high-speed trains only carrying a limited amount of cargo. In the same line of thought, Alves (2020) expects Hyperloop technology to be far less impactful in freight transportation, but not necessarily insignificant.

Meanwhile, Gordijn (1999) launches another idea to eradicate construction cost, namely the idea of multi-core systems. He states that there is a potential of using already existing tunnel infrastructure, in which smaller freight pipeline applications could fit. He perceives a pipeline system as a way to strengthen ties between carriers, and make them unitedly more competitive towards non-pipeline carriers. A lot of opportunity however still lies in research and development. Egbunike and Potter (2011) state that in order to be able to sell pipeline concepts to carriers, key performance indicators such as reliability, robustness and service costs are in need of quantification. Furthermore, advanced dynamic models are required to cope with supply chain dynamics in a multimodal environment. The results of those efforts might then stimulate institutions such as the European Committee for Transportation to develop a policy and set out guidelines and regulatory frameworks, which enable pipeline systems from a legal point of view (Visser, 2018).

**Threats**

As mentioned above, freight pipeline systems are associated with high initial investment costs. Furthermore, such investments involve serious risk of which many potential investors are well aware. The Swissmetro project is an example of such a project which initially enjoyed private support, but after careful cost-benefit analysis did not turn out financially feasible and thus filed bankruptcy in 2009 (Hansen, 2020). Egbunike and Potter (2011) therefore suggests such systems not be uniquely privately funded, but rather implies a public-private partnership. The vision of policy makers is however often constrained to the current transportation network and its need, while innovation and spinning-out technology originates from private companies. Although the latter might be enthusiastic about their technology, without sufficient funding, they fear not finding enough shippers willing to use their services. The latter have expressed doubts on the actual gains expected from replacing flexible road freight transport by a fixed pipelines (Egbunike & Potter, 2011). Visser (2018) reassures however that fortunately the attitude towards corporation and consolidation in the logistics sector has positively evolved, as compared to 20 years ago.

As is the case with any technology, failures of various nature are expected, each with a certain likelihood of occurrence. Among the most unlikely, yet to be accounted risks involve human damage due to terrorism (Kidd, 2008). The probability of such events would give an incentive to operators to perform security checks, creating additional costs (Hansen, 2020). Aforementioned regulations might extend service times and potentially generate bottlenecks, especially in a combined passenger-freight system. Other events to take into account in the design stage are earthquakes and other natural hazards (Kumar & Khan, 2017). Kumar and Khan (2017) also report that systems reliant on linear induction motors for propulsion are vulnerable to power outages.

The alignment of pipeline systems is further subjected to certain spatial constraints, which in some cases could threaten the realisation of projects at all. Areas characterized by high population density, often considered the best locations for access point for international rapid pipeline transportation, are coincidentally the most difficult places to allocate associated infrastructure (Hansen, 2020). For high-speed transport applications, large curves are required. (Egbunike & Potter, 2011) imply that even at low speeds (such as in ULS), elbows and bends complicate the conveyance of capsules. Above arguments support the hypothesis that pipeline infrastructure will need space, which could lead to harmful fragmentation in urban areas.

Rijsenbrij et al. (2006) nuances that underground applications cause less fragmentation than above ground applications. Examples such as the proposed chemical pipeline between Antwerpen and the Ruhr region, however, suggest that underground constructions might be just as intrusive in the urban landscape, and furthermore evoke public protest (Vlaams Departement Omgeving, 2021). (David J Hyde, 2016) finally mentions that there is ambiguity, both within the scientific community and among investors, related to the technical feasibility of technologies such as Hyperloop, especially when it comes to the transportation of maritime containers. Until now, it is unclear whether Hyperloop would be compatible with such industrial standards and if so, at which speeds. First approximations mention 12 tons per capsule - a quarter of the maximum European truckload - as a maximum weight limit, but that is not approved by the whole scientific community (Werner et al., 2016). The latter uncertainty further supports the need for tests and research to stimulate investments.

Table 3: A SWOT analysis for freight pipeline systems in general, and additional characteristics for a Hyperloop implementation based on findings in literature (Opgenoord & Caplan, 2017; Sayeed et al., 2018; Hansen, 2020; Werner et al., 2016; Krawiec & Markusik, 2021; Dudnikov, 2017; David J Hyde, 2016; Pijnenburg, 2019; Alves, 2020; Gordijn, 1999; Dong et al., 2019; Shin et al., 2018; Vernimmen et al., 2007; Hai et al., 2020; Kikuta et al., 2012; Visser, 2018)

| | **Strengths** | **Weaknesses** | **Opportunities** | **Threats** |
|---|---|---|---|---|
| **Baseline characteristics** | Reliable service | Highly capital intensive | Multi-core design | Lack of public support |
| | Automated system | Long construction time | Stimulating inter-carrier corporation | Lack of funding |
| | Low service costs (EoS) | Complex planning and operations | Passenger-freight combination | Geographical construction constraints |
| | Reduced air pollution | Fixed capacity | Research from testing | Potential system bottlenecks |
| | Reduced (urban) traffic congestion | Niche market applications | Position within EU Transportation Policy | Technical failures |
| | Reduced carbon emissions | Additional transshipment and storage | Legal framework | Uncertainties on departure/arrival times on long distances |
| | Flow consolidation | Landscape fragmentation | | Implementation induces other (urban) traffic |
| **Characteristics specific to a Hyperloop implementation** | Very high speeds | High curves required | | Technical infeasibility |
| | Theoretical energy self-sufficiency | High-value cargo to justify transport costs | | |

# 5 Discussion and conclusion

This paper summarized the current, and envisioned the future role of pipelines in efficient and sustainable supply chains. Research suggests that pipelines are already chosen over other modes for fluids and gasses, the main advantages being (1) reliability, and (2) economies-of-scale due to uninterrupted flow. Combined with low energy consumption and a small carbon footprint, they constitute a sustainable solution as well in those markets. Alignment of infrastructures alike is however fixed, and so is capacity. Although requiring a high initial investment, pipelines present a low service costs nonetheless.

Attempts to mirror those ideas onto a system for freight, have resulted in numerous proposed technologies. As they differ in size, manner of propulsion and purpose, this paper identified two main applications: within urban logistics, systems are referred to as underground logistics systems (ULS), while on an international scale the concept of Hyperloop is introduced. Both are proclaimed to run in an energy-efficient way at a relatively low service cost, ULS being able to attain speeds between 40 and 90 km/h and Hyperloop reaching up to 1200 km/h. The scientific community furthermore predicts significant benefits of these technologies in terms of reducing (urban) traffic congestion and related environmental nuisances (noise, air pollution, carbon emissions).

Careful analysis should point out the most suitable solution in a given context. Not only should one decide on the technology to be implemented, the network lay-out is of major importance as well. Several researchers put forward a dense hub-and-spoke as the ideal network, as it guarantees accessibility to multiple markets, in order to reach high saturation levels. Others in stead suggest that long direct connections are more desirable, in order to achieve economies-of-distance. All however agree that an operator's objective should be to maximize the throughput by flow consolidation, in order to justify the heavy investments associated with the construction and the maintenance of these infrastructures.

Other proposed strategies to cut costs are raising higher tariffs or combining pipeline systems with (existing) systems for passenger transportation. The former strategy however, risks of reducing competitiveness, while the latter requires dual optimization of the network, which is not always feasible. Some authors have expressed concerns regarding the fragmentation brought along by these infrastructures, regardless of their alignment. While small diameter pipelines installed above ground are suitable for piece goods, they induce additional transshipment costs. Much more so than underground systems, and systems able to handle maritime containers.

Table 4: An overview of the trade-offs to be made when considering a freight pipeline system.

| Trade-offs | | |
|---|---|---|
| Urban scale | ↔ | International scale |
| Dense network | ↔ | Sparse network |
| Hub-and-spoke | ↔ | Direct connections |
| Small capsules | ↔ | Large capsules |
| Low usage, high tariffs | ↔ | High usage, low tariffs |
| Single purpose | ↔ | Multipurpose |

It is partly due to these trade-offs, summarized in Table 4, that freight pipelines need further research. Up until now, only niche markets have been identified as potential users of such applications, candidate goods being more numerous on an urban level. Investors need to be convinced about properties such as reliability, robustness and other key performance indicators in order for them to take the risk. Furthermore, technical feasibility of applications such as Hyperloop is still in need of confirmation. Given those efforts and provided a legal framework, we might expect freight pipelines to become a part of the existing transportation network on the mid- to long-term horizon.

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