Technological Design Considerations of CargoTube Low-Pressure Tube Transport for High-Speed Sustainable Logistics Networks

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Abstract. CargoTube offers the unique advantage of combining existing technologies with innovative hyperloop systems in order to provide a solution for production logistics in urban areas. By offering not only zero emission operation through electrification, but also a confined environment for particle, fine dust, noise, and light pollution, CargoTube is perfectly suited to be applied in urban areas where big production facilities and industrial plants meet growing cities. For the design of the system, various different technologies are available to be operated inside of the low-pressure tube environment. Depending on the operational speed, a wheel-rail system can be used for speeds up to 300 km/h, while a network with higher speeds requires magnetic levitation and contactless high-speed switching. Two systems for propulsion are available, onboard motors and linear electric motors, while the latter can have power supplied either from the vehicle or the infrastructure. The choice of the drive system is heavily dependent on the use case. Lastly, airlocks are necessary to enable high capacity and high throughput for low-pressure tube technologies (LPTT).
For the beginning, networks such as a regionally confined CargoTube networks for production logistics can be seen as point to point connections, as speeds above 300 km/h are not required to link regional logistics hubs and production facilities. This reduces complexity and allows for a combination of innovative technologies with established systems such as the wheel-rail system.

Keywords: Hyperloop, CargoTube, Low Pressure Tube Transport; Tube Network, Sustainable Logistics Transport, Energy Efficient Transport.

1 CargoTube Low-Pressure Tube Transport

The reduction of greenhouse gas (GHG) emissions in transport is one of the major goals of the European Union to become climate neutral. While transport is contributing more than 31% of the emission of EU-28, the effort of electrification is reducing emissions in most sector. Therefore, since 1990 all sectors showed a decline in emissions of 20%, while the transport sector increased its emissions by 20%. [Tiseo 2023]

Innovative transport solutions are needed to change the transport fundamentally in order to become climate neutral. Europe needs to cut down on GHG emissions, but also on pollutants like NO_X, particle- and fine dust emissions as well as decrease noise and light emissions to reduce human made influences on the environment.

LPTT technologies such as CargoTube enable a very low environmental impact not only with regard to Greenhouse gas emissions, but also for multiple other key factors that have an influence on decisions within industrial logistics, especially in urban areas. Through drastically reducing the aerodynamic drag inside of the low-pressure environment, hyperloop technologies can save up to 80% of the operating energy demand of current high-speed transportation. Operating the tube pressure between 1% and 0.1% of normal atmospheric pressure dramatically reduces losses, allowing for the fundamental change in transport emissions that is needed to reach climate neutrality. [Oh 2019, Zhou 2022]

CargoTube is designed to for a point-to-point connection of a logistics hub with a large industrial production facility for high-capacity throughput of standardized containers. While regional logistic hubs and production plants can be served by a known technology stack, the application of CargoTube networks requires more extensive analysis. While the economic and environmental impacts for point-to-point connections are evaluated through discrete event simulation [Duin 2023] and Life Cycle Performance Assessment (LCPA) the technological design considerations are based on literature research and the evolving CargoTube basic data model and technology stack.

2 CargoTube in Production Logistics

Production logistics is facing major challenges to adopt to more environmentally friendly and healthier urban areas as well as increased productivity in industry and therefore a need for higher capacity of the logistics network. LPTT technologies such as CargoTube offer an automated solution for shuttle logistics between two major points in a physical internet, called ePI Nodes, for a high frequency, high volume and reliable cargo connection.

In the ePIcenter project a CargoTube connection is considered to connect an industrial automotive plant with a Logistic Service Park 10 km outside of a city in order to save on logistics space needed inside of the plant and consolidate inbound goods [ePIcenter 2023]. CargoTube is considered as one option for connecting to the production plant, supplying around 10.000 m^3 daily. Compared to other possible solutions, like a shuttle trucks, CargoTube can also save on personnel, saving valuable truck driver time. For the use case, a vehicle inside of the tube, called pod, is designed to fit 10 standardized containers (or pallets) with approximately 1 m^3 each, representing more than 80% of inbound traffic to the plant. By making use of CargoTube's high-frequency, high-capacity capabilities, the need for storage and truck parking at the production plant as well as space concerning the route is reduced to a minimum as well [Hardt 2023]. Figure 1 shows a logistic service park displaying many innovative technologies as well as CargoTube specific solutions.

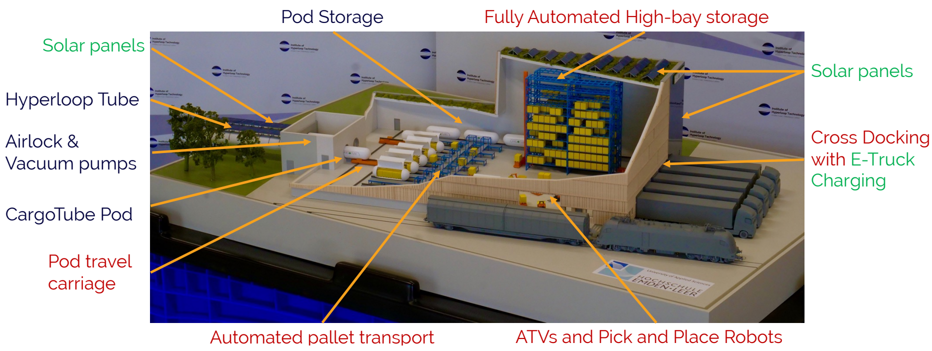

Fig. 1. Logistic Service Park with innovative technologies and CargoTube connection

In summary CargoTube offers the following advantages next to the savings in GHG emissions due to its high efficiency:

- High degree of automation, aligning well with industry optimization and just in time as well as just in sequence supply chains
- Resilient transport operation, cut off from extreme weather and personnel influences as well as unforeseen disruptive events, providing a reliable stream of goods
- Low operational energy demand resulting from lower aerodynamic drag
- Reduced noise impact, fine dust, particle, and light pollution through a confined tube environment

A network of production facilities and logistic hubs can also be considered with CargoTube, while a more in-depth technological analysis is required when speeds go up and a more complex network with high-speed switching is introduced.

3 Technological Design Consideration

For the technical design considerations of CargoTube, point to point connections are assumed at first. A small-scale network like a CargoTube Physical Intranet is also assumed as point-to-point connections, as distances would be short. Therefore, velocity can be kept below 300 km/h, decreasing the wear and eliminating the need for high-speed switching or contactless levitation systems. These would on the other hand need to be considered for high-speed connections and a large-scale LPTT network.

CargoTube makes use of innovative hyperloop solutions such as the low-pressure tube environment and airlocks while combining the system with established technologies such as the wheel-rail system. This is made possible by keeping speeds below 300 km/h, above wear and maintenance is drastically increased for wheel-rail systems, but also possible systems for energy transfer such as pantographs and current collectors. The ePIcenter use case of CargoTube considers a speed of approx. 100 km/h, balancing speed, capacity and energy demand.

Specific to the use case different technological variations of LPTT are proposed. Some of the design decisions and implications for the transport system are outlined. Cargo applications require several choices with regard to the infrastructure and the pod to be weighted and well-balanced to optimize the exchange of cargo with high throughput: an energy efficient propulsion and recuperation, a high degree of automation as well as an efficient airlock design using very little volume to be pressurized and therefore very little energy to transfer goods into and out of the vehicles in the tube.

Technological design choices for the CargoTube system are also highly dependent on quick deployment, providing a solution for current logistic needs. On the cost side, the net present value is an indicator for balancing the cost of subsystems with regard to the overall expenditures. At the same time the carbon footprint in form of the lifetime emissions, calculated as the carbon dioxide equivalent is very important to the choice of materials and form of operations.

3.1 Tube

With regard to tube technologies there are currently two readily available options that can be manufactured to the dimensions that are necessary for low-pressure tube transport technologies: concrete and steel tubes. While there is a general roadmap for steel to become carbon neutral, especially when looking at green hydrogen, there are fundamental emissions coming from the production of cement that cannot be avoided [Peper 2019]. Due to its widespread use, availability and the proven strength and durability, steel tubes are currently considered the first choice with regard to CargoTube logistics applications.

Fiber reinforced plastics, fiber metal laminates with polymeric or cement-based foams and various new composite materials are also suggested for more rapid deployment of the infrastructure while reducing cost for transport and construction of the superstructure as well [Zeleros 2021]. Nevertheless, these materials are not ready to be used for large infrastructure projects yet.

3.2 Airlock

CargoTube's ability to transport goods with a high frequency is deeply dependent on the ability to transfer cargo from and to the pods in the low-pressure environment with highly adapted airlock solutions. The faster the airlocks can transfer cargo, the lower the number of required airlocks and therefore also the footprint of the station. Gate valves which in pairs form an airlock chamber are available even for larger diameter tubes but require a large volume around the pod to be evacuated due to aerodynamic surfaces and systems mounted inside of the tube, which makes an airlock chamber solution with this technology slow and costly. For a more rapid cycling time in the airlocks the gas exchange during each cycle of the airlock must be minimized. Additionally, this saves on energy consumption as well, as less pumps are needed for the same number of airlocks.

One solution, mostly talked about in LPTT for passengers are bridge door solutions, where an airtight seal is created between the vehicle and the tube, allowing for pressurization of the remaining volume and opening of hatches on the tube and the vehicle. While this solution is great for passenger transport, as can be seen in subways where these are used in a pressurized way with sliding doors on the vehicle and the platform, such a solution would require a more complicated design for the automated process of loading and unloading goods, as is seen in airplanes. [Gerritse 2021]

Another solution is an end-door airlock, which similar to the bridge door relies on seals and a strong connection to enable a reduced low-pressure volume. An advantage of the end-door airlock is the possibility for a moveable floor, allowing for a quick exchange of cargo as can be seen in the truck industry already. Nevertheless, the construction and operation of such an airlock would be very difficult. [Gerritse 2021]

A low-pressure tube transport system can probably be operated with an adapted design for a bridge-door airlock solution or an end door airlock, whereas both systems need to be optimized for a rapid exchange of cargo with minimal handling times. With regard to the time necessary for the required movement and alignment of the pod with the airlock and the required handling steps, a solution with a one step process and combined exchange of all cargo units simultaneously is probably most beneficial for the system, if costs can be kept in an acceptable range. In general, airlocks are certainly still one of the most crucial technologies for LPTT as well as CargoTube solutions.

3.3 Propulsion

All propulsion systems that are evaluated are electric propulsion systems, limiting the emissions and allowing for recuperation of energy during braking. While onboard rotary motors are currently used in most electric vehicles due to lower capital expenditures, a linear drive powered by the infrastructure can be very effective for high-frequency connections. Implementing the drive and power systems in the tube, results in lighter vehicles which reduces energy demand and losses during acceleration and braking. Additionally, thermal losses by power electronics do not need to be mitigated in the vehicle but instead are diverted by the tube. Considering the timely deployment of CargoTube, this is a major part of the design choice, making an infrastructure powered linear drive system a good choice, despite the increase in capital expenditure.

4 Evaluation & Conclusion

The CargoTube transport system combines the advantages of innovative hyperloop solutions that reduce the impact of transport on the environment with existing and proven technologies in order to rapidly deploy a reliable and high-frequency transport of industrial cargo. Point-to-point connections and small-scale networks that can be assumed to be direct connections show the capabilities of connecting production plants and logistics hubs to reduce the impact on the environment.

Some of the outlined technologies such as the vacuum systems and the steel tube environment will be proven with a demonstrator that is constructed at the University of Applied Sciences Emden/Leer. A linear motor is set to be included in a later stage with airlock technology to be tested in small-scale lab demonstrators before being scaled up for large-scale testing.

Lastly, network simulations are planned to evaluate the underlying technological design choices and assumptions with regard to feasibility, economics and environmental impact and compare the results to other modes of transport.

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