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Automated high-speed Hyperloop cargo transportation for a sustainable logistics network

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Abstract:

Hyperloop cargo transportation in an evolving Physical Internet does have the potential to contribute major advances in sustainable, high-speed freight transport. The low-pressure tube transport (LPTT) solution realistically enables a viable zero-emission high-speed transport system to come to market quickly with rather low levels of investment in infrastructure. Switching and merging technologies for cargo pods are the key to a LPTT network, providing much greater flexibility for the TEN-T network. The integration into intermodal cross-docking hubs including the use of standardized transport units and synchromodal algorithms predicting and distributing transport flows is a key characteristic for the success of the implementation of new and more environmentally friendly transport modes to the Physical Internet. Modelling and simulation as well as Life-cycle performance assessment for an industrial use case supplying an ingrown industrial area in an urban environment highlights the benefits of a LPTT connection between an ePI node and an automotive plant.

Keywords: *Hyperloop, Low-Pressure Tube Transport, cross-docking, DES, modelling, LCPA, automation, tube network*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms); business models & use cases; manufacturing networks; PI impacts; vehicles and transshipment technologies*

Physical Internet Roadmap *(Link): ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

Today's logistics is one of the major contributing sectors to greenhouse gas (GHG) emissions in the European Union. Electrification will reduce pollutants such as NO_x and direct CO_2 emissions, but cannot cut down noise and light emissions as well as particle emissions produced through e.g. tire wear. Additionally, the energy demand and thus pollutant emission will increase with the projected increase in transport demand which is estimated to be up to 300% by 2050 (IFT, 2019). The last decades have shown that the demand for faster transportation of goods across the globe has increased significantly and thereby caused correspondingly higher energy consumption. While new powertrain generations could improve direct emissions and efficiencies, they cannot eliminate aerodynamic losses or lower the underlying energy demand of movement.

LPTT technologies such as Hyperloop and CargoTube tackle the problem at its root by operating in a reduced pressure environment within a tube to drastically reduce air resistance and thus energy consumption. By operating at a pressure of only about 1% to 0.1% of normal atmospheric pressure, losses can be reduced by 90%. (cf. Oh et al., 2019, Zhou et al., 2022). CargoTube offers a unique advantage by introducing innovation to the Hyperloop approach and providing an intermodal combination with existing transportation technologies to be rapidly deployed.

The assessed use case in production logistics evaluates the CargoTube connection of two main Physical Internet Nodes (ePI nodes) - a production plant and a Logistics Service Park (LSP). This will greatly improve the congested road infrastructure in the city, which is currently in use to deliver required cargo via trucks to the industrial plant. Additionally, the new LSP ePI node and CargoTube branch of the network shall introduce multiple benefits, commonly observed with the Physical Internet approach such as re-batching along with last mile just-in-time delivery. This avoids only partially loaded trucks, as can often be the case in production logistics due to specific deadlines. The economic and environmental impacts are evaluated through discrete event simulation (Duin et.al., 2023) and Life Cycle Performance Assessment (LCPA).

2 The CargoTube Technology

The CargoTube LPTT transport solution not only brings in new Hyperloop technology such as the introduction of a low-pressure tube environment and a linear motor but combines these innovations with established technologies such as the wheel-rail interface. Velocities between 100 km/h and 200 km/h are the design target for system operation, tuned to the demand curve in production. CargoTube complements emerging Hyperloop standards and has the advantage of quick deployment without requiring further research into levitation or propulsion technologies, which would only be necessary at higher speeds.

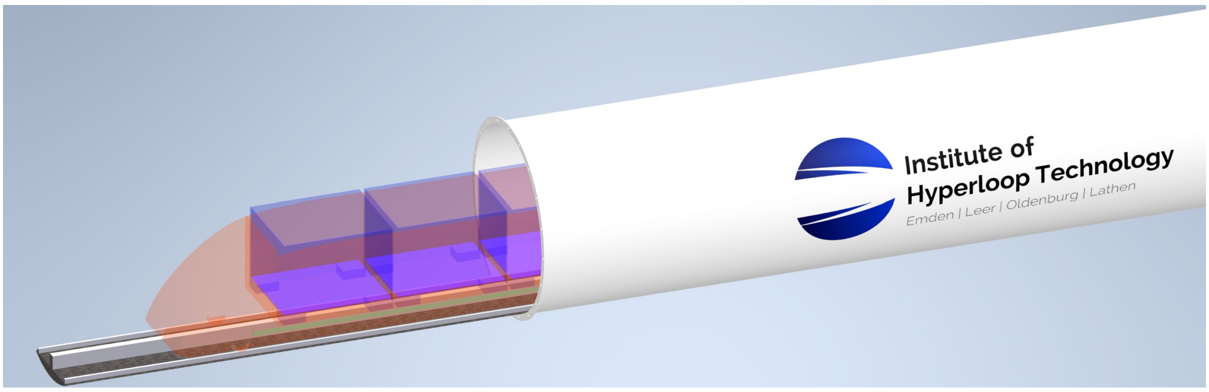

Figure 1: Basic principle of CargoTube: Design sketch using a wheel-rail system with linear motor for acceleration and recuperation for a vehicle with several standardized transport boxes

Figure 1 shows the automated vehicle (pod) inside the tube environment, which can hold up to 10 standardized transport boxes of approximately (1x1x1) m^3 volume each. The system is designed to connect the two ePI nodes completely autonomously. In combination with packing robots in the LSP and an automated loading and unloading process, this connection of two ePI nodes is capable of 24/7 operation. High frequencies resulting in a high capacity means of transport in the smallest possible space are at the heart of CargoTube. Finally, limitations only arise from safety distance considerations and emergency scenarios.

Airlocks are used to transfer the pods from normal atmospheric to low-level pressure levels. Ongoing research aims at advanced airlock designs such as a combination of the pod with the airlock. With this approach, there is no necessity of bringing the complete vehicle out of the low-pressure environment, which can substantially reduce cycle times while simultaneously minimizing wear and extending the lifetime of the vehicle.

The system is optimized and adapted for the respective intermodal connections with regard to Key Performance Indicators (KPI) concerning the environment and transport requirements. Digital Twin Technology is employed and a test facility is under construction at the Campus of the University of Applied Sciences Emden/Leer to generate physical data sets necessary to evaluate simulations and modelling approaches presented in this paper. (Neu et al., 2023)

3 CargoTube Production Logistics use case

While cities and urban areas are growing, industrial sites and production plants formerly located at the outskirts of the cities are nowadays embedded in the growing cities thus sharing the infrastructure network for both, residential and industrial cargo traffic (cf. Figure 2). This poses a major challenge for the constant flow of production supplies in the new Physical Internet and requires solutions to provide sufficient transport capacity for both simultaneously.

Figure 2: Illustration of a shared residential and commercial urban region with an industrial hub in a larger metropolitan area such as the VW automotive plant inside of Wolfsburg, Germany (Google 2022)

Figure 2 is an aerial view of the city of Wolfsburg encompassing the Volkswagen (VW) plant. The automotive plant is supplied by more than a thousand trucks daily according to data from autumn 2022. These trucks, which are on the road in addition to the normal volume of traffic, regularly encounter major traffic jams on the highways, while the entry and unloading of trucks at VW's internal freight hubs are subject to tight schedules. In addition, there are many citizens' groups complaining about pollutant emissions affecting air quality, as well as noise and light pollution at night. A stakeholder and requirements analysis for the Wolfsburg plant's major logistics center revealed the importance of small footprints of logistics areas which are currently competing with the limited capacity of production areas.

A LSP is being considered to consolidate inbound goods and reduce delays and turnaround times of inbound trucks, increasing individual truck productivity and saving valuable driver time. In addition, a more consistent and reliable supply of goods will be realized for the plant, which has proven to be a bottleneck during the recent parts shortage in the automotive industry. Transport of standardized boxes from the LSP to the VW plant can best be realized with a CargoTube connection, which allows for a significant reduction of direct emissions (e.g., GHG, noise, light and particulate emissions) within the city and relieves the burden on local residents. The system is designed for s certain type of standardized box that is used for a majority (approx. 80%) of inbound logistics. One logistics hall is taking delivery of around 10.000 standardized boxes a day, which is the target for the CargoTube simulations. Any freight outside of these dimensions is not considered in this use case. CargoTube can operate around the clock as a highly reliable transport system that delivers goods to the production site while minimizing the space required for storage, logistics or truck parking at the production plant. An additional feature in a LSP is the temporary storage or buffering capacity of sparce goods in the combined CargoTube LSP-facility. This enhances resilience to supply chains disruptions that otherwise lead to sudden parts shortages and costly production shutdowns.

4 Logistic Service Park integration

The integration and implementation of a CargoTube handling system also requires a focus on processes carried out by logistics service providers. A LSP has a secured gated area to handle and control inbound and outbound traffic that is either road or possibly rail. The fenced area (approximately 30,000 square meters) has an ideal rectangular shape to ensure optimal use of the functionality of the LSP, which combines several logistical functions. These include e.g., truck parking lots, trailer yards, empty container storage, control points, and last but not least a Cross-docking (CD) logistics system attached directly to the CargoTube station. Cross-docking is an almost inventory-less distribution process in which shipments (if possible) are no longer (temporarily) stored. The LSP with integrated CD hall has various spatially separated loading/unloading points for inbound and outbound logistics processes and crossdocks in covered hall areas called unloading tunnels, which are used specifically for unloading megatrailers (cf. Figure 3).

The shipments can usually be unloaded from the trucks using industrial trucks/floor conveyors and transported directly to the relation areas (corresponding to the individual unloading points in the production plant). CD is usually executed with little or no storage, so that no further steps are necessary between the automated unloading / loading of trucks and pods. Nevertheless, an automated high bay storage can be added if necessary or advantageous to the supply chain. Subsequently they are loaded into pods at precisely the right cycle. In principle, this process bears the possibility to be partially carried out in an automated manner, especially if the pods are on the same ground level in the CD hall. The essence of the cross-docking approach is that shipments have already been pre-picked by the suppliers. To handle deliveries which are either not or incorrectly pre-picked, CD systems have so-called "clearing" areas on the outskirts of the hall. To ensure a permanent supply to the production plant, it is also advisable to set up a "buffer area" in the middle of the hall, which serves as a short interim storage or "reserve".

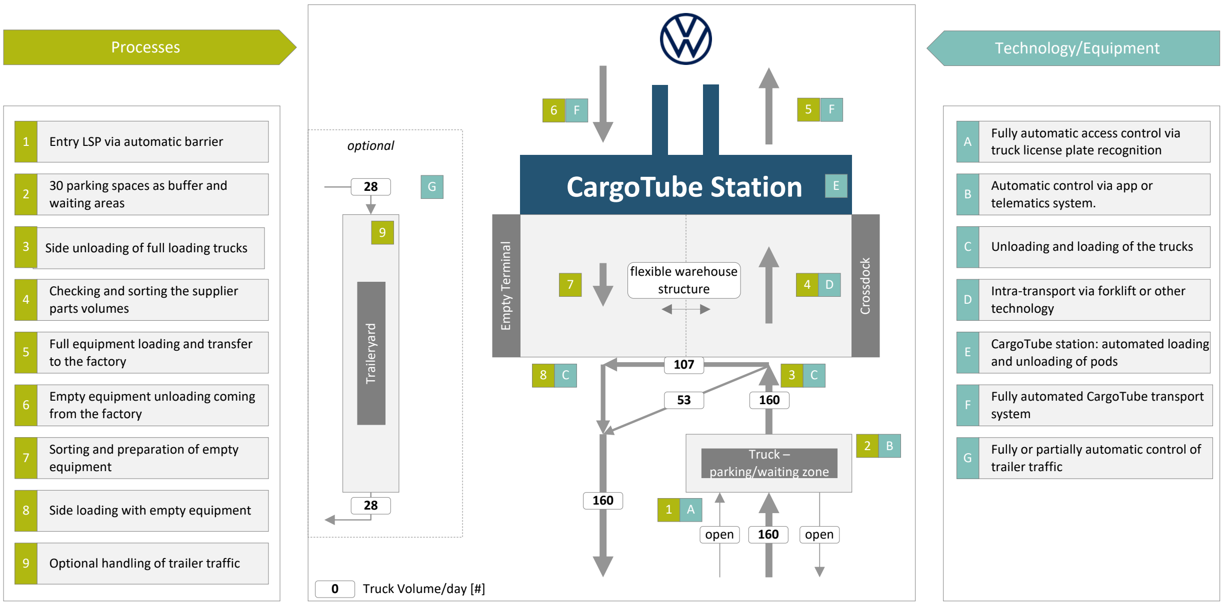

Figure 3: Integration of Hyperloop into a combined CargoTube LSP facility with illustration of the process-oriented steps (left column) and listing of the technological implementations (right column)

Shipments can then be delivered from the relation areas (exit areas) to the plant by the CargoTube system. Another functional area of the LSP includes a trailer yard used for any larger freight transports that cannot be fitted in the standardized box. These therefore cannot be transported with pods and will be transported from the LSP facility to the production plant via megatrailers with high utilization through consolidation processes at the LSP. Very large freight that is transported with other means than trucks such as railways or ships is not addressed in this process. A further area for handling the various smaller VW transport containers and returning empty boxes from the production plant is very important as well. Unloading of the trucks and/or pods at the plant then depends on the internal logistics processes. Spatially separate unloading zones for trucks and pods could play a role here.

5 Modelling and Simulation - Performance Assessment

CargoTube case: The questions to be answered by the simulation relate to the comparison of the Hyperloop transportation link with traditional approaches for a specific set of KPIs and the analysis of effectiveness. A discrete simulation model is created using the JaamSim simulation system (King and Harrison, 2013). Figure 4 shows the basic layout for that simulation model. The central elements are the two tubes that connect the LSP bidirectionally to the production plant. On each side there are six bays which can be switched on and off individually (e.g., for simulating maintenance). In each of the bays the single pods are cycling through a process of waiting (when the bay is in use), repressuring, unloading and/or loading, and evacuation. When the process in a bay is finished the pod is sent into the tube keeping a safety distance of 1,000 m to the previous pod. The handling process on the side of the production plant is the same with the exception that empty boxes are loaded to be sent back.

Initial simulations employing that model reveal the following results:

- The whole system is capable of transporting more than 16,000 boxes from the LSP to plant using six bays on each side and running fully loaded (no waiting times).
- The maximum number of pods in the system fully loaded is 33.
- With only five bays in operation on each side, the system is still capable of handling more than 13,600 boxes per day at full capacity.
- With only four bays in operation on each side, the system is capable of handling more than 10,900 boxes per day at full capacity.
- With a specific demand curve, where the demand of the plant is not equally distributed throughout the day (typically with peaks around noon and lower demand during the night), there are a few waiting times which do not last longer than 60 minutes.

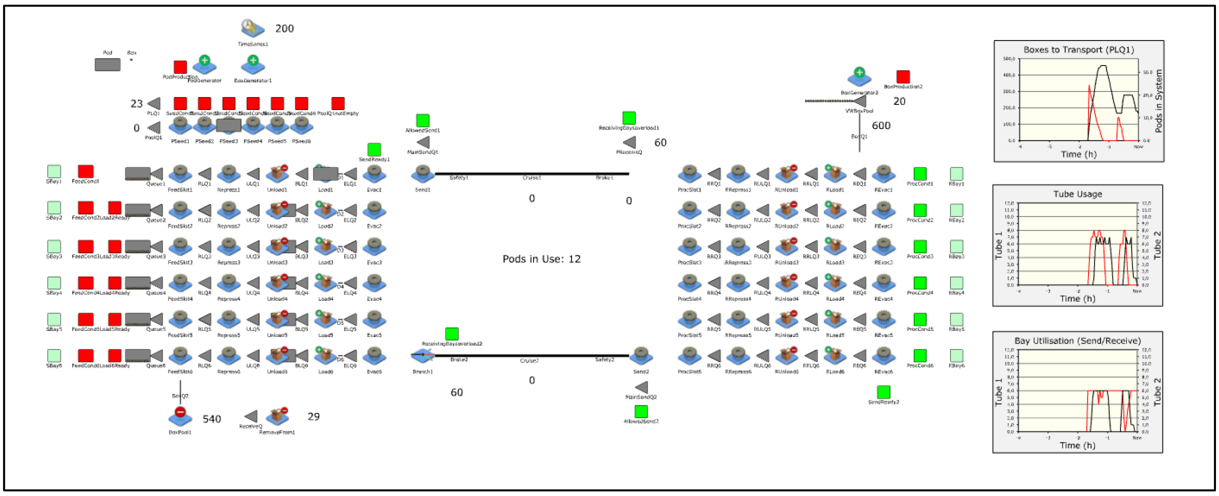

Figure 4: Simulation sketch visualizing the Integration of Hyperloop in a LSP

Truck case: Since truck electrification is widely discussed, the paper also includes simulations comparing conventional diesel and potential electric trucks. However, this does not reduce certain environmental impacts or nullify air friction losses. Using a universal model created on the basis of AnyLogic simulation software (Borshchev, 2013), various scenarios with both diesel and electric trucks are studied and modeled. 135 standard truck units are needed to transport cargo from the LSP to the VW production plant. This number decreases to 108 when using consolidated cargo on mega trailers, which are not electrified yet. In the developed simulation model, indicators of the transportation process are estimated. An analytical spreadsheet model is developed for preliminary calculations.

The main conclusion is that, assuming it is possible to charge several times per day, it would be most effective to use electric trucks with customized small battery packs of rather low capacity and thus low weight in combination with wireless charging technology. The use of the most advanced wireless charging technology eliminates time-consuming pre- and post-processing, i.e., the typical plugging and unplugging of charging cables.

6 Life cycle assessment

In addition to the positive environmental aspects, cost efficiency or simply a quick return on investment (RoI) of a CargoTube system is of immense importance. For the assessment of the financial and environmental impacts of the CargoTube connection, a LCPA is performed. The analysis focuses on a subset of the available KPIs. Financial aspects are mainly covered by CAPEX, OPEX and NPV, while the environmental impact is represented by the GWP (Global Warming Potential), measured as a CO2 equivalent.

Three scenarios are compared: The use of diesel trucks shuttling cargo from the LSP to the industrial plant is the current method of performing the transport task. An innovative CargoTube connection will be compared against this baseline scenario in order to calculate the differences in financial and environmental impact. However, since the realization of a CargoTube prototype will most probably take several years, battery electric trucks will be considered as a third scenario as current developments show that a widespread use of these vehicles might become the baseline scenario by the time the LSP will be built. For a more detailed analysis, a combination of both truck scenarios might be considered as well.

Relying on the Basic Data Calculations some key results are highlighted for the LCPA. For the setup of one tube for each direction of the approximately 10 km distance, the current material choice results in approx. 14,000 tons of steel and 11,000 tons of concrete, which are making up the primary emission expenditure during construction. Pod and infrastructure costs are estimated to sum up to approximately 51 million € in 2022. On the other hand, it is assumed that for the same transport task, 25 trucks are needed with a monthly leasing rate of 2,100€ (diesel) and 4,200€ (EV). While the setup of new infrastructure of CargoTube is included in the calculations, only the maintenance of roads is considered, not the construction of new roads itself, which estimates to be 50 million € for one lane of 10km (Hahn and Hoppe, 2022; Fritz et al., 2022). The graph in Figure 5 shows the costs over net present value and operating costs, while Figure 6 shows the lifetime emissions (carbon dioxide equivalent) for the three scenarios.

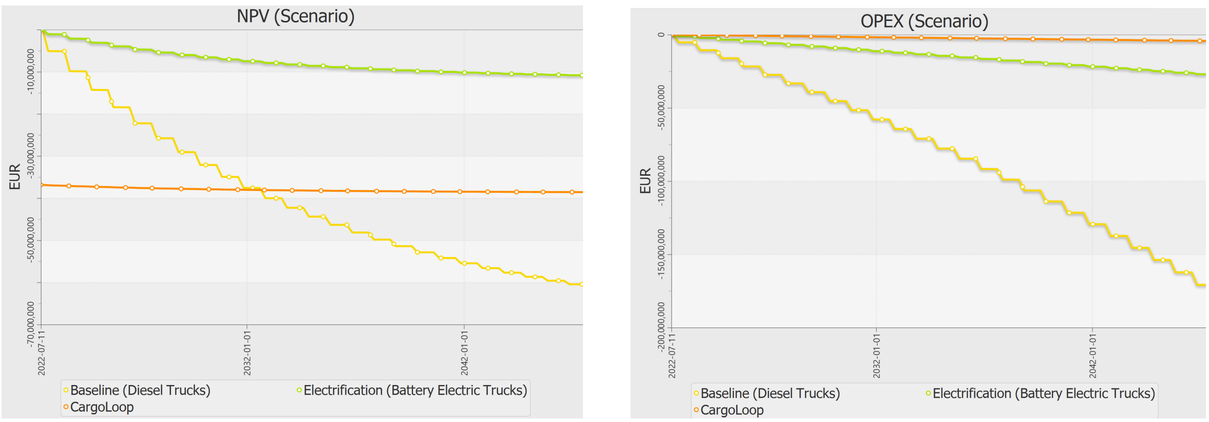

Figure 5: Comparison of NPV and OPEX for Hyperloop, diesel, and electric truck connections between a LSP and the VW production plant

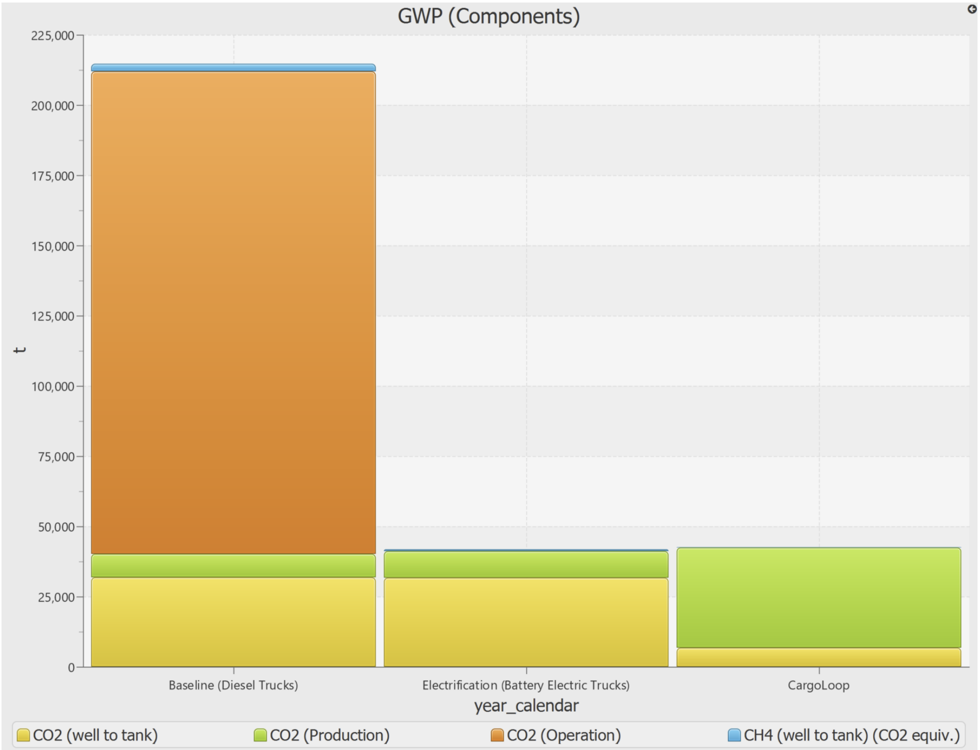

Figure 6: Lifetime emissions (carbon dioxide equivalent) for the Hyperloop, diesel, and electric truck solution

These preliminary numbers will be updated and refined as more accurate data is collected during the development of the demonstrator, assuming scenarios with different projections for fuel prices, energy prices and energy sources (e.g., EU mix for electricity vs. sustainable energy only). As seen fit, new developments in civil engineering will be modelled so that enhanced and low impact construction methods such as circular concrete, carbon neutral steel and low impact asphalt will be added to the model.

Currently, both CargoTube and battery-electric trucks perform much better in terms of NPV and GWP. However, both innovative approaches emit nearly the same amount of CO_2 over a lifetime of 25 years, the NPV is still better for electrifying the trucks. The main reason for this is the high investment cost which dominates the values. Nevertheless, considering infrastructure additions for more capacity on roads could equal the two approaches and will be investigated in future scenarios. When only considering the OPEX it becomes apparent that the CargoTube solution causes less costs than the truck in the operational phase. The emissions for both approaches are mainly bound to the installation phase. In the operational phase, a CO_2 neutral operation is possible when using sustainable energy sources.

Approaches of Hyperloop applications such as CargoTube show environmental benefits that even electric trucks cannot offer. Due to the enclosed environment of the tube, no noise or light pollution disturbs the outside environment, i.e., residential areas, during its 24/7 operation. Particulate/fine dust emissions from tire abrasion and brake pads, which are still by far the most important source of particulate emissions today and especially in the future, are also avoided. Finally, operation has no impact on social aspects such as local traffic congestion and is independent of external environmental influences such as snow or ice. Studies to demonstrate these impacts and improvements to the system, such as the implementation of a linear motor in the infrastructure, will be conducted in a later phase of the ePIcenter project as part of the transition to full life cycle analysis (LCA). (ePIcenter, 2023)

7 Interconnected CargoTube in the European Physical Internet

The creation of a Hyperloop network will take into account all the important logistical aspects, such as the integration of digital twin technology to control and monitor virtual pod traffic, the high flexibility and large capacity throughput between nodes, the distributed storage capabilities, the fully automated mode of operation and the closed system without additional security controls. Intermodal transport and cross-docking enable logistics node to destination transport in small batches with direct connection to last mile transport. This Hyperloop freight network can evolve from small node connections to a comprehensive intermodal networked European transport system. In general, a European network for passengers and freight would benefit and drive the most use cases, as it connects the most nodes and thus achieves the best network effects. Direct and indirect network effects are achieved by connecting new ePI nodes to the network, increasing value, usage, and the number of possible routes. Operating a small network with high throughput and low capital investment can demonstrate the feasibility, design, and deployment of a use case for connecting a larger manufacturing plant with a number of smaller industrial centers and a network of suppliers in a regional context. Nevertheless, as stakeholders of this project are discussing standardization of Hyperloop technologies in JTC 20 of CEN/CENELEC. A European wide freight network can only be realized through standardized technology including all mayor stakeholders.

CargoTube Physical Intranet. Such a Physical Intranet could, for example, connect several of a company's production facilities with its network of suppliers in the region, dramatically reducing the number of just-in-time truck connections and the environmental and socioeconomic impacts. In addition, there is the possibility for trusted shippers to collaborate in a network without the need for security checks or waiting times in such a highly automated logistics system with advanced scheduling algorithms. Intelligent ePI nodes can connect the Physical Intranet to the Physical Internet on demand to allow incoming goods into the CargoTube Physical Intranet system.

Direct network effects are realized when existing users directly benefit from the addition of new users. Any direct network effect is proportional to the number of users connected to the transport network. Indirect network effects arise when users of the original transport network increase because of some complementary ePI nodes that trigger the use of additional serviceable connections. If the value of the transport service is higher than the price, the customer base is expected to increase. New adopters are attracted to that service because of the extra value they are getting. Unfortunately, there is a huge dependency on prior adoption to critical mass level.

The CargoTube ePI nodes could be fully integrated with the Electronic Freight Transport Information (eFIT) and the European Technology Platform (ETP). Such digital IOT technologies allow for faster transfer of freight within the European network. Essential for large scale networks are innovative and disruptive technologies such as ultrafast Hyperloop applications with magnetic levitation and high-speed-switching technology to realize point to point connections within a large network without intermediate stops. Levitation technologies are indispensably required for operating speeds above 400 km/h as wear of contact-based track-wheel and energy supply systems such as pantographs increases dramatically. Complementary, highly efficient propulsion technology can also be realized magnetically through linear drives incorporated either on the vehicle or in the track.

8 Discussion & Outlook (HSEL)

While a LPTT CargoTube connection of a LSP to an industrial manufacturing plant can create several qualitative improvements, such as reduction of traffic congestions, better air quality and less noise and light pollution in urban areas, network effects create the potential for improvements with a variety of quantitative benefits in the future. Modelling approaches estimate with very conservative technological assumptions are already at the same level as highly sophisticated electric trucks. This does not consider nowadays congested road capacity and an increasingly tight labor market with a lack of drivers or improved frequencies in the CargoTube system. The innovative transport system is most likely to scale to much higher capacity with increased automation and frequency without overload on the existing networks. While reaching for climate neutrality for Europe, Hyperloop systems can drastically reduce operating energy demand and emissions in the future.

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