# CargoTube network analysis based on an agent-based modelling: Lower Saxony Case Study

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**Abstract.** This research considers the case of a CargoTube physical Intranet network in Lower Saxony, connecting multiple automotive production sites. Through the economic growth of the region and its companies including the Volkswagen plant in Wolfsburg increased freight, especially on trucks, is brought to the region which brings along a lot of traffic, noise and pollution. For green transportation of goods, we need zero-emissions vehicles and new transport systems like CargoTube. The CargoTube 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. A system based on CargoTube transport solution autonomously loads and unloads standardized containers. Transporting containerized cargo hundreds of kilometers in minutes enables the just-in-time supply chains needed for an economy and increases company profits. The research is devoted CargoTube transport network analysis with the help of the multi-agent simulation system TraPodSim created based on AnyLogic software. The questions to be answered by the simulation are related to analyse the CargoTube Transport Network for a certain set of KPI's and analysis of effectiveness of integration with other transport mode.

**Keywords:** Transportation; CargoTube; Simulation; Indicators; Effectiveness.

## 1 Introduction

Today, the transportation industry is the fastest-growing source of global carbon emissions, and achieving sustainability principles in such areas requires multi-disciplinary research and innovation. For green transportation of goods, we need zero-emissions vehicles and new transport systems like CargoTube. Innovative cargo vehicles should offer services at lower prices, with less environmental impact, improved safety, and with a higher degree of reliability of operations. However, costs will arise for logistics companies when introducing innovative vehicles (the purchase of new vehicles, software, and other costs) that may arise before their scaling and wide coverage by users, etc. Regarding emissions, most of these new vehicles are 100% powered by electricity, and thus emissions are not produced directly by the EU requirements and be avoided with a fully renewable electric grid. All these changes can become a catalyst for more fundamental changes in transport systems, as well as in the overall design of transport infrastructure.

The CargoTube transport solution realistically enables a high-speed transportation system to come to market quickly with reasonably low levels of investment in infrastructure and provides much greater flexibility for the TEN-T network. A system based on the CargoTube transport solution autonomously loads and unloads standardized containers to reduce congestion and increase operational efficiency. Transporting containerized cargo hundreds of kilometers in minutes enables the just-in-time supply chains needed for an economy and increases company profits.

We provide CargoTube transport network analysis with the help of the simulation system TraPodSim, created based on AnyLogic simulation software (Yatskiv et al, 2022). This system, TraPodSim, is designed to create a multi-agent simulation model for the process of transporting goods by vehicles along the routes of the transport network specified for a particular region. The questions to be answered by the simulation are related to analyzing the CargoTube Transport Network for some set of KPIs and analysis of the effectiveness of integration with another transport mode.

## 2 CargoTube concept

Hyperloop is a transport system in which cargo is transported inside a tube with virtually no air resistance, since ambient air pressure is reduced down to a given low pressure, approx. 1% normal pressure at sea level (Motwani and Gupta, 2021). Cargo is transported using vehicles, which are commonly referred to as pods. The highest transport speeds can be achieved using linear induction motors and magnetic levitation. The terminals of the Hyperloop system are airlock chambers in which loading/unloading operations are performed at atmospheric pressure.

The CargoTube system is based on the Hyperloop concept, but its feature is the usage of a rail track that is laid inside the tube, resulting in reduced infrastructure costs for transportation. It also becomes possible to abandon the production of special steel tubes of large diameter and use tubes that are already used in the infrastructure of gas pipelines or water pipes. These factors led to a significant reduction in costs both-during the creation of the CargoTube system and during its operation (Duin et al., 2023). The CargoTube system will allow you to reach a transportation speed of up to 300 km/h, but even at a speed of 150 km/h, such a system can be very effective both in terms of productivity and in terms of environmental impact (ePIcenter, 2023).

## 3 Case description

This research considers the case of a CargoTube physical Intranet network in Lower Saxony, connecting multiple automotive production sites. Volkswagen, for example, identified the production sites in Wolfsburg, Braunschweig, and Salzgitter as key to their electric mobility strategy as they are forming their “Battery Valley”. Many additional locations within northern Europe could be connected, including suppliers.

It is known that Volkswagen Group has begun construction of its factory for the production of batteries for electric vehicles in the city of Salzgitter (Salzgitter, 2022). One of the consumers of these batteries will be a factory in Wolfsburg, where starting from 2025, the number of electric vehicles produced will be increased to 500,000 per year. That means that every year 500,000 batteries weighing from 800 to 1000 kg must be transported from Salzgitter to Wolfsburg (with 320 working days on average, 1563 batteries must be transported per day). With a known load capacity of the vehicles that will be used to transport batteries, it is easy to estimate the number of trips per day, and the associated fuel costs and greenhouse gas emissions.

As an alternative for the transportation of batteries, it is proposed to use the CargoTube system, which in the form of a loop route will connect the plants in Salzgitter and Wolfsburg (Fig. 1). Batteries will be transported from Salzgitter to Wolfsburg, and empty containers will be transported in the opposite direction, that is, special equipment used when placing batteries on the pod. A constant number of pods will circulate in the system. In the route variant shown in Fig. 1, the distance between the terminals of the network, which are loading/unloading stations, is approximately 45 km. It is assumed that the maximum speed of pods will be 150 km/h.


**Fig. 1.** Sketch of the movement of 24 pods along a circular route (the size of pods is not in scale).

## 4 Conceptual Model

Two types of processes need to be modeled: a) the process of moving the pod fleet along the ring route and b) the processes of processing pods at two stations located at enterprises in the cities of Salzgitter and Wolfsburg. The purpose of the simulation is to check the technical feasibility of options for creating a CargoTube system, calculate the required number of pods, as well as estimate the amount of energy consumed and $CO_2$ emissions. Within this work, two variants have been investigated that differ in pod capacity: a) one pod carries 2 batteries and b) one pod carries 4 batteries. Part of the conceptual model is analytical calculations, which are used to determine the values of the input parameters of the model. These values must be mathematically consistent with each other since there are certain spatial and temporal dependencies between them. Without such coordination, the model will not be able to correctly display the process of simultaneous synchronized movement of several dozen pods.

A special group of input parameters is formed by energy consumption indicators in various modes of pod movement. Since there is currently no data for measuring such indicators in a real system, the analogy between the pod movement in CargoTube and the movement of a conventional tram was taken into account (Light rail, 2023). All input parameters of the model are shown in Table 1. Table shows the power values for one pod at the beginning of acceleration P_max, when driving at maximum speed P_norm and the beginning of braking in regenerative mode P_reg.

A feature of the pod's movement along the route is the speed change shown in Fig. 2 for one direction of travel.

**Table 1.** Input parameters of the simulation model.

| Name of data | Variable notation | Value | |
|---|---|---|---|
| **Specified parameters** | | | |
| number of cargo units per day (units) | X1 | 1562.50 | |
| number of working hours per day (hours) | X2 | 16 | |
| distance between stations (km) | X3 | 45.126 | |
| number of cargo units in the pod (units) | X4 | **2** | **4** |
| maximum pod speed (km/h) | X5 | 150 | 150 |
| acceleration time to maximum speed (min) | X6 | 0.71 | 0.71 |
| deceleration time to zero speed (min) | X7 | 0.71 | 0.71 |
| power on beginning of acceleration (kW) | X8 | 60 | 80 |
| power when driving at maximum speed (kW) | X9 | 20 | 28 |
| power at the beginning of braking (kW) | X10 | -60 | -80 |
| **Calculated parameters** | | | |
| number of cycles per day (number) | Y1 | 781.25 | 390.63 |
| maximum handling time (min) | Y2 | 1.23 | 2.46 |
| minimum number of pods (number) | Y3 | 32.53 | 17.27 |
| **specified number of pods** (number) | X11 | 33 | 18 |
| waiting time in front of station (min) | Y4 | 0.29 | 0.90 |
| distance between pods (km) | Y5 | 2.73 | 5.01 |

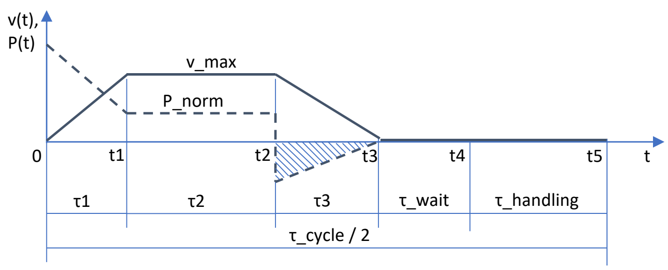


**Fig. 2.** Diagram of the changes in pod speed and power for one direction of movement**.**

Diagram on Fig.2 can also be shown for movement in the opposite direction, but at the same time, some input parameters, except $v_{max}$, $t_{cycle}$ and $\tau_{handling}$ may be different since the direction of Wolfsburg pod carries a payload, and in the direction of Salzgitter – an empty container. It also shows the change in power consumed by pod motors. The amount of energy consumed is numerically equal to the area under the graph P(t). In Fig. 2 the area corresponding to the energy returned to the grid when braking the pod in regenerative mode is shaded.

It is necessary to specify the number of hours in the working day, as well as the time intervals τ1 and τ3, shown in Fig. 2. Based on these data, additional input parameters of the model are calculated. To calculate these parameters, simple formulas are used, the most complex of which is the formula for calculating of minimum number of pods:

$$Y3 = 2*(1 + X6/2/Y2 + X7/2/Y2 + X3/X5/Y2*60) \quad (1)$$

The user must specify a specified number of pods, which must not be less than the parameter Y3.

## 5 Development and application of a multi-agent model

To simulate the movement of pods along a circular route, a multi-agent paradigm was applied in the AnyLogic software environment. Fig. 3 shows a state chart that defines the behavior of each agent of the "pod" type. The depo1 and depo2 blocks are used only when initializing the model, that is when directing pods to a route at precisely defined points in time.

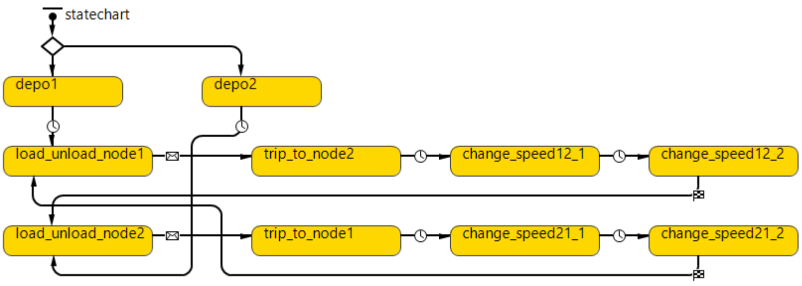


**Fig. 3.** Statechart, which defines the behavior of an agent of the pod type.

The discrete event paradigm has been applied to simulate pod processing processes at two stations located at both ends of the route. To do this, an agent of the pod type goes to process flow with the name Node1 or Node2.

The main limitation that applies to any variant of the model is the parameter Y2 (maximum handling time), since its value is uniquely determined by the number of goods transported during the working day. As the number of pods used increases, the waiting time in front of the station increases, but the distance between pods decreases.

Results related to the energy consumption for the movement of pods and for pumping air out of the space of the processing station before the start of the pod shown in

Table 2. If the methods of generating electricity consumed by CargoTube are known, then it will be possible to calculate the corresponding volumes of $CO_2$ emissions.

**Table 2.** Main simulation results.

| Name of indicator | Value | |
|---|---|---|
| number of cargo units in the pod (units) | **2** | **4** |
| energy consumed per cycle, taking into account recuperation and evacuation of air at the station (kWh) | 14.23 | 19.45 |
| energy expended by all pods per day (kWh) | 11120.00 | 7596.50 |

## 6 Conclusions

The developed model is designed to conduct simulation experiments in which the user can adapt any specified parameters shown in Table 1. By simply copying model elements to AnyLogic and adding new tables similar to Table 1, this model can be used to study the CargoTube transport network scaled to an arbitrarily complex structure.

The innovative transport system CargoTube is most likely capable for a much higher capacity with increased automation and frequency without overload on the existing networks and while reaching for climate neutrality for Europe, it can drastically reduce operating energy demand and emissions in the future.

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