infrastructures

Article

On the Development of a Sustainable and Fit-for-the-Future Transportation Network

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Abstract: Population growth in cities and expanding city territory as well as population decline in rural areas pose a challenge for the existing transport network. Consequently, we observe a rapid change in transport infrastructure and transportation technology within the last few years. Due to novelty or differentness, it will initially be challenging to integrate them into the existing network in Western European cities and to identify suitable corridors leading to especially beneficial effects on the overall transport network. The effects of new technologies and (high-performance) infrastructures are hardly examined. It remains unclear how these novel transportation technologies will change society, our understanding of spatial proximity, mobility, and consequently the logistics sector. In this work, we give an overview regarding first considerations and reflections on the impacts of the changes and developments in the field of freight transportation. Our work mainly focusses on the estimation of the impacts of high-performance transport technologies on the society, spatial proximity, and the logistics sector while extending the European transportation network accordingly. In our understanding, we refer to high-performance transportation technologies as mobility systems with either high throughput (fast and/or high utilization loads) or very flexible application. To be more specific, we focus on Hyperloop technologies, Cargo-Sous-Terrain, freight airships, and drones.

Keywords: transport network design; impacts of high-performance transport technologies; Hyperloop; drones; freight airships; Cargo-Sous-Terrain

1. Introduction

Strongly contrasting developments regarding the population trends in cities and rural areas, meaning population growth in already dense areas and population decline in sparsely populated regions, require new approaches for passenger and freight transport. In addition to requirements on rapidity, efficiency, flexibility, and safe transport, environmental aspects gain their importance. The transport sector is still accountable for a massive proportion of the greenhouse gas emission, and in Austria it, accounted for 28 percent in 2015 [1].

Ambitious targets for climate protection and energy, such as the Paris Agreement [2] on the international level and the 20-20-20 targets [3] on the European level, strongly influence the developments in the transport sector. Within the last few years, these policy papers set the ball rolling with energy efficient products or services, focus on behavioral aspects of usage as well as new or improved transportation infrastructure and transportation technology. Trial parcel distribution in rural areas in Great Britain [4] and Germany [5] as well as medicine distribution in Rwanda, Africa [6], are just some examples of the developments in the field of individually moving drones. A recent development in the land-borne transportation technology is the Hyperloop concept. This concept, presented by SpaceX and Tesla founder Elon Musk, is currently carried out by the companies Hyperloop One and Hyperloop Transportation Technology. In May 2016, the first test of a prototype propulsion system took place [7], and one year later, the first test on tracks was performed [8], both by Hyperloop One.

The mentioned examples of technological developments underline that these new infrastructures in transport logistics are increasingly important. At the same time, it is obvious that the introduction of these technologies and infrastructures into the existing transport network in Western European cities is going to be a challenge due to novelty and differentness. Another important aspect is the identification of corridors that benefit the overall transport network. Currently available strategy papers such as the TEN-T [9] and national guidelines [10] are limited to existing technologies. Uncertainties associated with developments in the transport domain make forecasts especially challenging since the effects of new technologies and (high-performance) infrastructures on society, the concept of mobility, and thus the logistics sector are practically unknown, even though test tracks for some of the transport options (e.g., Hyperloop) are already build.

Changes in emission and/or, more specific, CO_2 emissions require a strategic implementation of measures, which can take place, inter alia, in the provision of sustainable infrastructures. On this account, a preliminary analysis of existing alternative technologies and infrastructures is necessary to assess how sustainable the use of high-performance infrastructures actually is. For example, Hyperloop is regarded as environmental friendly, although the knowledge on this technology is still very limited in this respect, and hardly any information on its effects on spatial, social, or economic structures is available. It is for this reason that our research on intelligent network design ("inned") explores the innovative and novel possibilities for environmental friendly transports in order to reduce CO_2 emissions and negative environmental impacts that come along with growing global population and increasing urbanization.

The investigation of the potential of high-performance infrastructures is particularly important regarding the aspect of mass performance. Although the mass performance is a major added value for rail and waterways, it is also being mitigated by problems in compatibility (including air transport) and time factors (e.g., in the case of waterways). High-performance infrastructures can be even better suited for that purpose.

Efficiency is an important aspect in our society and is commonly associated with costs that have to be constantly optimized in order to remain competitive on the market. Substantial efficient technologies (high-performance infrastructures) are currently reaching market maturity and are expected to be systematically implemented in the existing transport network over future years. To be able to estimate the effects of such an implementation (positive as well as negative) and therefore to make decisions in favor of certain means of transport, a closer look at the network is necessary. The network design determines the efficiency of the transport, which is why it is necessary to look more closely at the circumstances in which technologies can be integrated. Particularly in Europe, where a well-developed transport network meets comparatively small distances and a high population density (compared to the USA), it affects the flow of goods and people and also spatial, social, and economic structures.

The results presented in this work are based on the outcomes of the research project "inned" (innovative network design) funded by the Austrian federal ministry for transport, innovation, and technology (bmvit). Established as an exploration study, the project mainly focusses on the estimation of the impacts of high-performance transportation technologies on the society and the logistics sector while extending the European transportation network accordingly. In our understanding, we refer to high-performance transportation technologies as mobility systems with either high throughput (fast and/or high utilization loads) or very flexible application. We focus in our work on Hyperloop technologies, high-speed trains, freight airships, and drones. Although the mobility system is considered in its entirety, the focus is on freight transportation.

The work plan foresees the investigation of technological boundaries with respect to network design set by the abovementioned high-performance transportation technologies as a first step. Then, a societal assessment is carried out taking spatial, social, economic, and environmental aspects into account. Both, technology and society are expected to impose constraints that should be considered planning an exemplary future European transportation network based on actual (freight) transportation demand. Finally, conclusions are drawn on additional research and development activities that should be performed to reach a sustainable, reliable and fit-for-the-future European transportation network. The structure of this paper corresponds to this work plan in consideration of the status of the project.

2. High-Performance Transport Infrastructure

When talking about high-performance infrastructure, the first step is to define high-performance. We decided to define high-performance as either high quantities, high speeds, and/or high flexibility. Both high quantities and high-speed result in high throughput. High flexibility results, however, in low-cost results. We mainly focus on novel transport technologies, i.e., technologies, which have not (or at least only limited) been applied in real-world settings.

2.1. Hyperloop

Elon Musk initially introduced the Hyperloop technology as an idea to shift passenger transport toward a new and sustainable technology. The main idea is to develop a large-scale pneumatic post, i.e., a tube of dimensions such that a capsule with transport capacity for approx. 20 persons. The capsule reaches speeds of up to 1200 km/h, which is possible due to reduced air pressure in the tube. The usage of the capsules, also called pods, is for either passenger or freight transport. There are also concepts for pods to be used for freight and passengers at the same time [11]. Construction costs are estimated between EUR 9.5 mil up to EUR 28.5 mi; per kilometer with an extra of EUR 27 mil per kilometer in tunnels [12,13].

Obvious advantages of Hyperloop technologies are high speeds, which enable the (sustainable) connection of areas located further apart (e.g., the often-mentioned example of Los Angeles and San Francisco). Due to the short travel times together with the ease of train travelling (compared to air travelling), one has to rethink the term of local proximity. We assume that the introduction of such a high-speed connection results in noticeable changes in societal behaviors, e.g., daily commuting between cities located up to 1000 km apart becomes not only possible but also physically relevant.

Disadvantages, on the other side, are the necessary construction of tubes, which means that, in addition to often already existing rail tracks and highways, a second transport infrastructure needs to be constructed. Investments are rather high.

Even though our research is limited to freight transportation, Hyperloop can be used for passenger transport. Therefore, there are potential benefits for passengers that should be kept in mind.

2.2. Freight Airships

The concepts of airships are rather old and well-known to a broad mass of people due to dramatic historic incidents. Caused by these incidents, the concepts were not pursued over a long period. In the last years, however, the idea became more and more popular again, resulting in the fact that currently novel airship concepts are developed and are already being tested. The novel concept aims at freight transport only. The main idea is to lift cargo into the air with the clear advantage that it is not necessary to construct additional transport infrastructure except at the two ends of a connection. In addition, it would be possible to construct interim terminals for airships or, in extreme situations, to just guarantee that a large enough empty (and smooth) area is available. The construction companies plan different model types with a payload of up to 500 t and up to 220 km/h max speed [14]. However, only smaller variants successfully performed test flights during the last few years.

Beside the advantage that airships are rather flexible with respect to origin and destination of transports, they also build a valuable addition with respect to special transports. Drawbacks are, surely, that the area needed for landing/take-off and cargo handling is rather large compared to the size of cargo transported. In addition, the price for one individual airship is approx. EUR 40 mil [15].

2.3. Drones

The absolute opposite to airships are drones. They are rather small, fast, and agile. The basic concepts are, however, quite similar. They allow for a flexible and easy to plan transport even in areas where no (or rather limited) transportation infrastructure is available. Good examples are the parcel distribution trials in Great Britain [4] and Germany [5] or medicine distributions in Rwanda, Africa [6].

While drones themselves are rather cheap and there is a wide range of possible application, drones suffer from the fact that they are relatively sensitive to windy weathers. Furthermore, depending on the actual manufacturer, the payload of drones is limited to at most 100 kg, with many of them being in the range of up to 20 kg. Furthermore, the range of drones is limited—especially for the electric ones. At the same time, current laws forbid autonomous flights in some countries (incl. Austria). Even more, based on reports in local media, one can expect that societal acceptance of (a high number of) drones in the air will be rather low.

Due to the differences in typical ranges and payloads, it was found that a direct comparison of drones with other high-performance infrastructures is not practical. With focus on local distribution, drones are considered in conjunction with other innovative means of transport in this research.

2.4. Cargo-Sous-Terrain

Strictly speaking not a mode of transport, Cargo-Sous-Terrain (CST) is a further innovative freight transport concept. Cargo-Sous-Terrain as proposed by the research project and company with the same name combines different ideas and concepts for city logistics [16]. First, the main idea is to shift land transport from roads to underground. An analysis of the Federal Office of Transport in Switzerland confirmed the potential in terms of modal shift. Therefore, Switzerland is eager to build a connection between the logistic hub in Swiss Plateau and the Zurich region as a first step for a system connecting cities in Northern Switzerland [17]. Second, Cargo-Sous-Terrain relies on a city hub concept, i.e., a logistics concept where a small depot is installed in the city center, while a large consolidation hub is established at the outer rim of the city. The city hub and consolidation hub are linked via an underground connection. The last mile (from the city hub) is realized by employing sustainable modes of transport like bikes or small e-vans.

Advantages are obvious, like bundling of cargo as well as a shift of freight cargo to the underground. Disadvantages are the extra handling of cargo at the consolidation and city hub. Further, it is necessary that one (neutral) operator oversees all city distributions. In addition, construction costs are rather high, as additional infrastructure is needed.

3. Impacts of High-Performance Transport Technologies

To assess the impact of (novel) transport technologies on the societal and economical parameters in regions, an impact assessment was performed. We assumed that an easy accessible high-speed connection between two cities, which reduces the travel time below one hour, leads to increased commuting between these cities. However, this implies that these two cities close ranks with each other, i.e., in terms of labor and housing market. Thus, the meaning of a "region" is changing, since the spatial limitations set by distance and connected travel time are softened.

To analyze the concrete impact, we chose the following approach: First, we decided on the transport technologies to be assessed (described in the previous section). Then, we estimated effects of these technologies on the elements of the transport system. Together with experts, we assessed these effects. Finally, we performed a multidimensional impact analysis. Details on this procedure are given in Schodl et al. [18]. The result of this impact assessment is a benefit analysis for "typical" network links. These values are then a major input for the network-planning presented in the following section.

4. Design of Future Transport Networks

The main idea was to design a transportation network that is fit for future transport requests. This includes, but is not limited to, freight transport. Quite the contrary, it is essential that the transport network fulfills all requirements stated by passenger and freight.

Based on the results obtained via the impact assessment presented in the previous section, it is possible to apply basic service network optimization algorithms [19] with additional constraints, which are motivated by the technological constraints stated by the transport technologies (e.g., capacity and/or meaningful range). Obviously, the main objective is to maximize the benefit of the transport network. This includes that, for some regions conventional, already existing transport modes will still be heavily used, while the algorithms suggest implementing novel transport technologies for other connections.

4.1. Network Graph

To be more precise, we model the network as two separate graphs. First, the infrastructure network is a multi-layered graph $G^I = \left(V^I, A^I\right)$ where the node set V^I represents stations in major cities $v \in V$ and the edges A^I represent the connections between them. Each layer is assigned to one transport mode $m \in M = M^{classic} \cup M^{inno}$ where classical transport modes are denoted by $M^{classic} = \{road, rail, ship\}$ and the innovative transport modes are denoted by $M^{inno} = \{hyperloop, zeppelin, CST\}$. Each transport mode $m \in M$ is a layer or subgraph in G denoted by $G^m = (V^m, A^m)$ where V^m consists of station nodes for cities where a station for transport mode m exists or can be built and A^m the existing or possible connections between them. For the classical transport modes $m \in M^{classic}$, V^m are existing stations and A^m the existing connections. For each city $v \in V$, transfer arcs $A^t = \left\{\left(v^{m1}, v^{m2}\right) \mid m1, m2 \in M \wedge v^{m1} \in V^{m1} \wedge v^{m2} \in V^{m2}\right\}$ model the possibility of transferring/handling goods from a station of transport mode $m1$ to a station of transport mode $m2$.

Furthermore, we model the freight transportation on an abstract graph, the so-called service network $G^s = (V^s, A^s)$, where $V^s = V$ represent the cities and direct edges and $(u, v) \in A^s$ denote the flow of goods between two cities without specifying the actual route and the transport mode(s). In our approach, we must synchronize the freight transport between these two networks. For the service network, we search for future transport requests that should be fulfilled (e.g., because of high importance or high profit), and for the infrastructure network, we optimize the actual realization with respect to specific key performance indicators (KPIs). The following KPIs are considered:

1. Minimization of infrastructure costs (for the new connections);
2. Minimization of transport costs for the transported goods;
3. Maximization of effectiveness for each transport mode where it is implemented. The effectiveness is a weighted cumulative rating consisting of speed, throughput, flexibility, reliability, noise and emission of the transport technology;
4. Maximization of regional bonus effects. This is also a cumulative rating, applied only to the high-performance transportation technologies where social, spatial, economical, ecological, political, and technological impacts are considered.

The first two goals are straightforward in terms of minimizing costs and maximizing transport volume. KPI 3 results from the multicriteria analysis by Pfoser et al. [20], where the innovative transport technologies are analyzed. KPI 4 results from Schodl et al. [18], where regional effects were assessed for possible connections via high-performance transport technologies.

Figure 1 presents an example of this modelling approach on a small scenario. Figure 1a shows the infrastructure network that contains six cities and six transport modes on four layers. The black layer in this figure represents three existing transport modes: road, rail, and water. Orange, purple, and red layers represent possible connections for cargo airship, Hyperloop, and Cargo-Sous-Terrain (CST), respectively. In this scenario, while airship and CST are less restrictive with respect to the geographical conditions, Hyperloop cannot be built between Graz and Budapest due to mountain slopes. The green line is an example for a transport request between Budapest and Linz, realized as road transport between Linz and Vienna and Hyperloop between Vienna and Budapest. In Figure 1b, the same transport request is represented by a direct connection between Linz and Budapest in the service network.

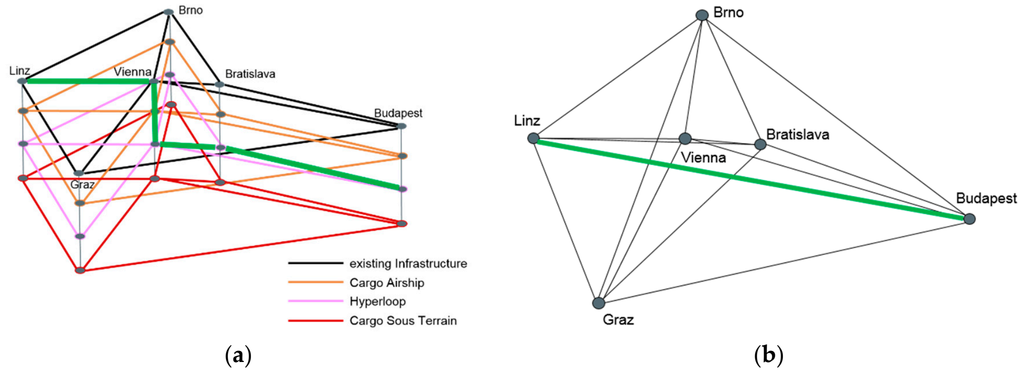


Figure 1. (**a**) Example of an infrastructure network graph; (**b**) Example for a service network graph.

4.2. Mathematical Model

Based on the network graph, we present a basic mathematical model. The following parameters are given.

- c_i: costs for building a station $i \in V^I$. In case the station already exists (for the classical transport modes), the costs are zero;
- a_{ij}: indicates if it is possible to build the connection between stations i and j;
- c_{ij}: costs for building the connection. In case of existing infrastructure, they are zero;
- d_{ij}: transport duration;
- k_{ij}: transport capacity;
- r_{ij}: transport cost per ton;
- b_{ij}: bonus for regional effect;
- e_{ij}: weighted cumulative effectiveness (speed, reliability, emission, etc.);
- d_{ij}: transfer and handling duration between two stations in a city;
- q^{uv}: required quantity of transported goods from city u to city v in the service network.

The model contains following decision variables:

- x_{ij}: binary, connection: equals 1 if and only if the connection from station i to station j is built (or already exists) on the infrastructure network;
- y_i: binary, station: equals 1 if station i is built (or already exists);
- f_{ij}^{uv}: positive, flow: goods transported on arc $(i,j) \in A^I$ designated for city u to city v;
- g^{uv}: positive, flow: goods transported from city u to v in the service network.

Further notations:

- $road(u)$: road station of city u;
- $mode(i,j)$: transport mode of connection $(i,j) \in A^I$.

The objective is a weighted combination of:

- $max \sum_{(u,v)\in A^S} g^{uv}$ (quantity of transported goods);
- $min \sum_{(i,j)\in A^I} x_{ij}c_{ij} + \sum_{i\in V^I} y_i c_i$ (infrastructure costs);
- $min \sum_{(u,v)\in A^S,(i,j)\in A^I,} f_{ij}^{uv} r_{ij}$ (transport costs);
- $max \sum_{(u,v)\in A^S,(i,j)\in A^I,} f_{ij}^{uv} e_{ij}$ (weighted cumulative effectiveness of the transport mode);
- $max \sum_{(i,j)\in A^I} x_{ij} b_{ij}$ (regional bonus effect for constructing the high-performance connection).

Although the weights for the individual parts of the objective function can be chosen arbitrarily, we set them to 0 (quantity of goods), 1 (infrastructure costs), 1 (transport costs), 0.00005 (effectiveness), and 500 (regional bonus) for our (preliminary) tests. The value of 0 for quantity of goods is reasoned by constraint (6) below. If this constraint would be changed to less or equal, the quantity of goods would be needed in the objective function. The other values are chosen such that an equivalent of costs is achieved, i.e., for example one point regional bonus is worth EUR 500.The model includes following constraints:

$$\sum_{i\in V^I} f_{ij}^{uv} - \sum_{k\in V^I} f_{jk}^{uv} = \begin{cases} -g^{uv} & j = road(u) \\ g^{uv} & j = road(v) \\ 0 & else \end{cases}, \forall (u,v) \in A^S \quad (1)$$

$$\sum_{(u,v)\in A^S} f_{ij}^{uv} \le x_{ij} k_{ij}, \ \forall (i,j) \in A^I \quad (2)$$

$$x_{ij} \le y_i, \ \forall (i,j) \in A^I \quad (3)$$

$$x_{ji} \le y_i, \ \forall (i,j) \in A^I \quad (4)$$

$$x_{ij} \le a_{ij}, \ \forall (i,j) \in A^I \quad (5)$$

$$g^{uv} = q^{uv}, \ \forall (u,v) \in A^S \quad (6)$$

$$x_{ij} \in \{0,1\}, \ \forall (i,j) \in A^I \quad (7)$$

$$y_i \in \{0,1\}, \ \forall i \in V^I \quad (8)$$

$$f_{ij}^{uv} \ge 0, \ \forall (u,v) \in A^S, \ (i,j) \in A^I \quad (9)$$

$$g^{uv} \ge 0, \ \forall (u,v) \in A^S \quad (10)$$

Constraints (1) are typical flow formulations to ensure that each commodity of transported good finds its way from the road station of the origin city to the road station of the destination city. Constraints (2) make sure that the capacity limits for each connection are not exceeded. We further ensure that a connection is only feasible if the incident stations are built by constraints (3) and (4) and if the construction is possible at all by constraints (5). Equations (6) set the transported volume to the required volume. These equations can be turned into "≤" if the goal is to maximize the transport volume. Lines (7)–(10) set the variable ranges. This model uses only basic techniques in terms of mathematical programming for simplicity. Using a state-of-the-art solver such as IBM CPLEX, it can solve small- to medium-sized instances with up to 20 cities.

We want to highlight that the regional bonus effect (as considered in the objective function) is based on a rather complex evaluation methodology that is explained in more detail in Berkowitsch et al. [21]. However, the basic principle is that effects of high-performance infrastructure is assessed based on spatial, economic, social, and environmental impacts.

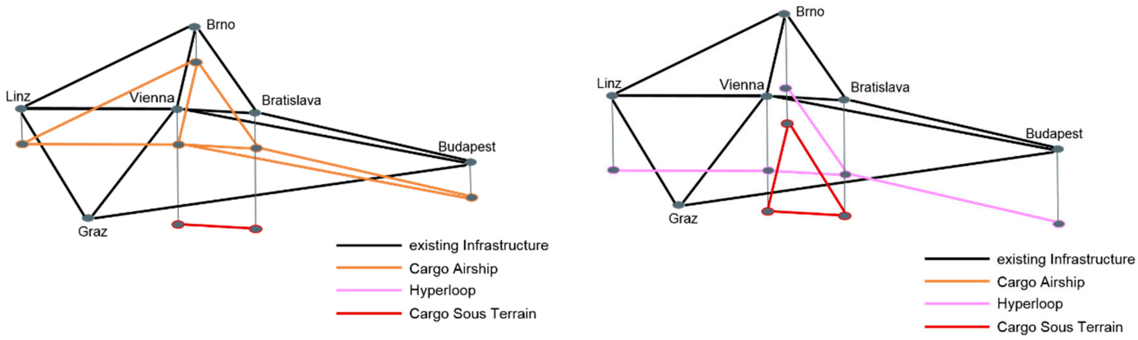
4.3. Computational Experiments

In the experimental computation, we considered the amount of goods transported between the six cities based on Eurostat [22]. The effectiveness ratings were taken from Pfoser et al. [23] and the regional effects ratings from Schodl et al. [18]. Costs for the high-performance transportation technologies were taken from preliminary information [12,13,15,16] and are summarized in Table 1. The costs for freight transportation via Hyperloop were reduced since the infrastructure is designed to be used for passenger and freight. We further set a capacity limit on the existing infrastructure since otherwise the high-performance transportation technologies will not be used due to high investment costs.

Table 1. Costs for high-performance transport technologies.

	Station Costs	Track Costs	Transport Costs
Hyperloop	€ 200 mio	€ 40 mio per km	€ 0.05 per ton per km
Freight airships	€ 100 mio	€ 1 mio per km	€ 0.45 per ton per km
Cargo-Sous-Terrain	€ 150 mio	€ 45 mio per km	€ 1.10 per ton per km

In Figure 2a,b, we present two example results of our model. Figure 2a shows that the cargo airship infrastructure is nearly fully built since it has the cheapest infrastructure costs. It is mainly used for freight transport whenever the capacity of the existing infrastructure is exhausted. Graz is only connected via the existing infrastructure because the transport demand is relatively low compared to the other cities. CST is used on a relative short route between Vienna and Bratislava (~70 km) where the construction cost is still bearable in relation to the efficiency of the technology. Hyperloop is not built at all due to its high costs.



(**a**) (**b**)

Figure 2. (**a**) Example of result for the scenario in Figure 1a; (**b**) Example result for the scenario in Figure 1b if infrastructure costs are neglected.

In Figure 2b, we modified the scenario settings by neglecting the infrastructure costs. This hypothetical scenario shows a possible outcome if a massive transnational subvention lowers the construction costs. In reality, the costs are likely to be something in-between these two scenarios. The biggest impact is that the cargo airship is not used anymore. Compared to the other technologies, it is less effective in the cumulative rating. While the CST operates on the triangle between Vienna, Brno, and Bratislava, the Hyperloop network now reaches every city except Graz. We can see the main connection goes from Linz to Budapest, and a branch extends from Bratislava to Brno. The reason why Bratislava is selected as a branching point instead of Vienna is the much higher transport demand between Brno and Bratislava.

We want to highlight that the basic idea of the overall approach is to (re-)plan the transport network. We are not only focusing on a small region or one country but address the problem as a European one. Therefore, it is essential that the methods developed and employed during the assessment step allow a deduction from showcases toward a more general level. Nevertheless, we emphasize that the results obtained via this approach only represent a supporting tool that should be thoroughly evaluated by the planners in a subsequent step. Further, we want to report that computation times for the small scenario with six cities is below one minute. For the large scenario with 20 cities, the calculation was terminated after 48 h with a gap of 1.75%. Although the computation times for the 20 cities scenario seems rather long, we have to highlight that the planning of the transportation infrastructure is a long-term project with application time of several decades. Therefore, thorough planning periods are more than acceptable.

5. Conclusions

We are facing, on the one hand, an increasing demand and high expectations for passenger and freight transportation because of population growth and urbanization. On the other hand, goals such as the Paris Agreement force us to rethink our current transport system. This opens the door for the introduction of novel transport technologies, which have the potential to be more sustainable with respect to social, economic, and ecological aspects. We therefore dare to propose a novel holistic network planning approach that aims at optimizing the whole (European) transport network to gain the most positive effects. As the planning (and building) of a transport network is a rather costly and time-consuming task, we emphasize the importance of such supra-regional planning approaches. Even if these cannot come up with an optimal final decision, they can support the planners in their decision-making.

The purpose of this approach is to showcase the possibility of integrating a diverse number of aspects from multiple studies into a holistic model, covering the technical parameters from future transport technologies and regional effects through large-scale infrastructure development. The data and assumptions are not all realistic or accurate, but the model shows that a recommendation can be made based on data availability and scenario settings. With this respect it can be used as a decision-support tool for planning authorities to assess impacts for transport volume, costs and regional development. For our small artificial scenario, we conclude that the cargo airship is a cheap and versatile technology for the medium range and that the Hyperloop and CST, due to their high costs as for now, are only applicable with a large subvention. Once again, we want to highlight that these conclusions are drawn on a preliminary scenario with the main purpose to show that the modelling and implementation method is feasible for the proposed infrastructure planning approach.

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