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Łukasz Lach*, Marcin Suder**, Rafał Kusa***,
Joanna Duda****

Forecasting the economic impact of a vacuum tube high-speed transport system in Poland: An input-output approach

1. Introduction

Numerous studies have investigated the impact of infrastructure on the economy (Holmgren, Merkel, 2017). The findings suggest that infrastructure has a positive impact on economic growth (Khan et al., 2020). In particular, infrastructure lowers the cost of the input factors of the production process (Agénor, Moreno-Dodson, 2006) and affects both employment and economic growth (Bristow, Nellthorp, 2000). Additionally, infrastructure enhances the quality of life of a society (Baldwin, Dixon, 2008).

Investments in transport infrastructure have also been investigated. Cigu et al. (2019) argued the unidirectional long-run causality relationship among growth, transport infrastructure, and public sector performance in the EU-28 countries. In a similar line, Gherghina et al. (2018) found that road, inland waterway, maritime, and air transport infrastructures positively influenced the gross domestic product per capita (GDPC) in the EU-28 countries during the period of 1990–2016. Meersman and Nazemzadeh (2017) reported that the lengths of motorways, the

* AGH University of Science and Technology, Faculty of Management, Krakow, Poland; e-mail: llach@zarz.agh.ed.pl
** AGH University of Science and Technology, Faculty of Management, Krakow, Poland; e-mail: msuder@agh.ed.pl
*** AGH University of Science and Technology, Faculty of Management, Krakow, Poland; e-mail: rkusa@zarz.agh.ed.pl
**** AGH University of Science and Technology, Faculty of Management, Krakow, Poland; e-mail: aduda@zarz.agh.ed.pl

rail network, and investments in the port infrastructure had a positive impact on Belgium's GDP per capita. The contribution of the transport infrastructure to regional economic growth could also be observed in Korea during the period of 2000–2010 (Lee, Yoo, 2016) as well as China during the period of 2007–2015 (Ke et al., 2020). Mentolio and Solé-Ollé (2009) reported that public investment in the transport infrastructure positively affects the productivity of a region. According to Zou et al. (2008), public investment in road construction in poor areas significantly impact growth and poverty alleviation. The relationship between a transport infrastructure and economic development can be observed in developing countries as well. Based on studies that were undertaken in Sub-Saharan and South Asian countries, Quium (2019) argued that the development of transport infrastructures can have significant positive impacts on economic growth as well as on poverty alleviation, employment, equity, and inclusion. In their long-term studies (including the period of 1971–2017), Alam et al. (2020) found a long-running and causal relationship between transport infrastructure and economic development in Pakistan. Myszczyszyn and Mickiewicz (2020) investigated Germany's economic growth between 1872 and 1913; they found that railways had positively affected economic growth; in parallel, high economic growth influenced the development of transport.

In Poland, a significant development in the transport infrastructure is planned. In particular, the development of a rail network that links the newly planned airport (the Solidarity Transport Hub, which is located in the central part of Poland) with the largest cities around the country (Stryhunivska et al., 2020). One of the considered technologies is a vacuum tube high-speed train (known as a Hyperloop) (Białas et al., 2020). The main element of this concept is a tube that contains air at a reduced pressure (close to a vacuum). The vehicles moving inside the tube can reach speeds of 1,200 km/h. The vacuum tube high-speed train technology would enable the journey time to be shortened; for example, a journey between Stockholm and Helsinki (ca. 500 km) would take approximately 28 minutes (KPMG, 2016). The Hyperloop is a promising idea that aspires to become the "fifth mode of transport" (the other modes are cars, planes, trains, and ships) that can be used in both passenger and cargo transport. However, this innovative means of transportation is at its early stage of development. The existing solutions (including tubes) are prototypes that are designed to test the proposed solutions. To date, several feasibility studies have been published around the world (for example, these pertain to projects in the United States [in the Great Lakes region as well as in California], the UAE [Abu Dhabi], and China [Tongren]). Among these, there is one that refers to Central Europe (that analyzes transportation issues that are related to potential routes linking Vienna, Bratislava, Budapest, Brno, Linz, and Graz [Schodl et al., 2018]). Additionally, the determinants of vacuum tube high-speed train development in Poland have been analyzed with technology roadmapping (Duda et al., 2021). Despite the many unanswered questions related to the Hyperloop technology, it is obvious that the Hyperloop infrastructure (in particular, the tubes) will require extraordinary investments. Among the questions associated with Hyperloop infrastructure investment decisions are the following:

- What will be the impact of a Hyperloop investment on a country's economy?
- Which tube technology (tunnels versus trestles) will impact the economy to a greater extent?
- Which particular industries will benefit the most from the investments (in total, and dependent on the construction technology)?

The impact of high-speed rail (HSR) on the development of an economy and society has been the subject of numerous studies (e.g., Diao, 2018; Yu et al., 2018; Chen, 2019). These studies pertain to regional development (e.g., Li et al., 2020), strengthening social cohesion (e.g., Naranjo Gómez, 2016), and the growth of the tourism industry (e.g., Yin et al., 2019). The negative impact of HSR on the environment is also indicated, along with the methods of its reduction (e.g., Chang et al., 2018). Wang et al. (2018) found that the introduction of HSR leads to a significant increase in city-level housing prices. Hromadka et al. (2020) presented annual impacts of the subcategories of HSR infrastructure (such as railway stations) in the socio-economic context.

To assess the impact of HSR, researchers employ different tools and methods. These include a dynamic and spatial computable general equilibrium (CGE) modeling framework (Chen, 2019), an aggregate growth-modeling and causality test (Meersman, Nazemzadeh, 2017), a Granger causality test (Alam et al., 2020), the auto regressive distributed lag (ARDL) (Muvawala et al., 2020) and vector-autoregressive models (VAR), which include the error correction model (ECM) and long-term relationship research (Myszczyszyn, Mickiewicz, 2020), and a sensitivity analysis (to estimate the efficiency and quality of the HRS services) (Moyano et al., 2019). To identify the associations among the highway and railway transports and the regional economy, Sun et al. (2018) employed the Lotka-Volterra model. Hromadka et al. (2020) used the cost-benefit analysis method to evaluate the socioeconomic impacts of occurrences that emerge from a railway infrastructure.

The aim of this paper is to specify the multiplier effects that are induced in the national economy in reference to the construction of Hyperloop lines in Poland using tunnel and trestle technology. In particular, we calculate the added value and employment growth for several industries that will contribute to the construction process. Additionally, this paper intends to indicate those industries that would benefit the most as well as the construction technology (tunnels versus viaducts) that would have the greatest impact on the economy. We employ an input-output (IO) analysis and the study is based on detailed data from 77 industrial sectors. The scope of the study, its methodology, and the results made this study original in the Polish context as well as for Central Eastern Europe; such a study (investigating the impact of a Hyperloop on the economy) is among the first attempts in this part of Europe. This study offers theoretical and managerial implications.

The remainder of the paper is as follows. First, the methodology for calculating the multiplier effects is presented. Second, possible routes are described, along with their accompanying costs. Third, the results are showed and discussed. Finally, the study's implications and limitations are discussed, and recommendations for future studies are proposed.

2. Calculating multiplier effects

In order to determine the possible multiplier effects in the Polish economy that will likely result from the construction of a new transport connection using Hyperloop technology, three types of input-output (IO) multipliers were calculated by using the linear static demand-driven Leontief IO model (Lach, 2020). In addition to computable general equilibrium (CGE) modeling, IO analysis remains a leading tool that was used in previous reports on the analysis of the economic effects of high-speed railway construction in other countries (Lee et al., 2018).

From a formal point of view, IO multipliers can be understood as interindustry multipliers. In general, such multipliers describe the sectoral impact of changing a particular economic category in one branch on all of the other branches in an economy (Tomaszewicz, 1983; Przybyliński, 2012). This idea often supports the economic policies of governments, as it allows for testing the direct and indirect sectoral impact of stimulating specific branches or making particular investments (e.g., the construction of a new factory will also increase the number of jobs in the factory's suppliers, increase the demand on particular services, etc.). Although 70 years have passed since the Leontief IO model was formulated, its modifications and extensions are still emerging; the applicability and interpretation of IO multipliers continues to be the subject of a lively scientific debate (Lach, 2020).

The empirical calculations that were carried out for this study were based on the assumption that the structure of the interindustry links in the Polish economy is described by the most recent input-output table at basic prices for domestic output that were published in 2019 by the Central Statistical Office of Poland (CSO)[1]. This table gives the possibility of calculating material cost coefficients

[1] The most recent IO table is based on 2015 data – for details, visit https://stat.gov.pl/en/topics/national-accounts/annual-national-accounts/input-output-table-at-basic-prices-in-2015,5,3.html.

that express the share of the costs of domestic raw materials and materials in the overall production costs of the products that are manufactured in the country.

In the further parts of this paper, we will follow the usual notation in the IO literature; therefore, the matrices will be indicated by bold capital letters, the vectors by bold lowercase letters, and the scalars by italicized capital and lowercase letters. Transposition will be indicated by a prime symbol, and a circumflex will denote a diagonal matrix (for example, $\hat{\mathbf{x}}$ has elements of vector **x** on the main diagonal, and $\hat{\mathbf{x}}^{-1}$ denotes a diagonal matrix with the inverses of the elements of nonzero vector **x** on the main diagonal).

Before deriving the basic linear form of the static Leontief model, one should recall the typical setting and assume that the economy under study consists of n productive sectors and that the respective data is available for year t. Let x_i^t also denote the output of sector i and f_i^t stand for the total final demand for sector i's product for period t[2]. Under this notation one may write a basic balance condition that explains the distribution of sector i's product through sales to all sectors in the economy and to final demand (Miller and Blair, 2009; Lach, 2020)

$$x_i^t = z_{i1}^t + \ldots + z_{in}^t + f_i^t = \sum_{j=1}^{n} z_{ij}^t + f_i^t \tag{1}$$

where z_{ij}^t represents the value of the flow of goods and services that were produced in sector i in the economy under study and consumed in sector j during year t.

After combining the accounting formulas in (1) across all sectors, one can obtain the following compact matrix formula

$$\mathbf{x}_t = \mathbf{Z}_t \mathbf{i} + \mathbf{f}_t \tag{2}$$

where

$$\mathbf{x}_t = \begin{bmatrix} x_1^t \\ \vdots \\ x_n^t \end{bmatrix}, \mathbf{Z}_t = \begin{bmatrix} z_{11}^t & \cdots & z_{1n}^t \\ \vdots & \ddots & \vdots \\ z_{n1}^t & \cdots & z_{nn}^t \end{bmatrix}, \mathbf{f}_t = \begin{bmatrix} f_1^t \\ \vdots \\ f_n^t \end{bmatrix} \tag{3}$$

and **i** denotes an $n \times 1$ vector of 1's[3]. Static IO analysis is based on the fundamental assumption that the interindustry flows from sector i to sector j during period t depend entirely on the output of sector j for the same time period. This

[2] Throughout this paper, we will use the terms 'period' and 'year' interchangeably to denote the time interval of interest.

[3] For each sector i, final demand f_i^t is the sum of the final consumption expenditure by households, the final consumption expenditure by non-profit organizations serving households (NPISH), the final consumption expenditure by the government, the gross fixed capital formation, and the changes in inventories and valuables.

assumption makes room for deriving the following definition of the so-called 'technical coefficients' (Miller and Blair, 2009; Lach, 2020)[4]

$$a_{ij}^{t} = \frac{z_{ij}^{t}}{x_{j}^{t}} \tag{4}$$

where $i, j = 1,...,n$. The coefficients given in (4) measure the fixed relationships between a sector's j output and its inputs. Thus, production in a Leontief system operates under what is known as constant returns to scale, as the economies of scale in production are ignored (Miller and Blair, 2009). For example, if sector i stands for a sector of services and sector j stands for the automotive sector, a_{ij}^{t} represents the ratio of the value of the services bought by automotive producers during year t to the value of the automotive production of year t (Lach, 2020).

After combining the technical coefficients that are defined in (5) across all possible flows in an n-sector economy, one can obtain the following matrix formula

$$\mathbf{A}_t = \mathbf{Z}_t \hat{\mathbf{x}}_t^{-1} \tag{5}$$

where

$$\hat{\mathbf{x}}_t = \begin{bmatrix} x_1^t & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x_n^t \end{bmatrix}, \mathbf{A}_t = \begin{bmatrix} a_{11}^t & \cdots & a_{1n}^t \\ \vdots & \ddots & \vdots \\ a_{n1}^t & \cdots & a_{nn}^t \end{bmatrix} \tag{6}$$

The usual terminology in the IO literature is to interchangeably refer to matrix $\mathbf{A}_t$ as the 'input matrix' or 'technology matrix.' Using (5), we may rewrite the set of accounting relationships in (2) in the following form

$$\mathbf{x}_t = \mathbf{A}_t \mathbf{x}_t + \mathbf{f}_t \tag{7}$$

or equivalently

$$\left(\mathbf{I} - \mathbf{A}_t\right) \mathbf{x}_t = \mathbf{f}_t \tag{8}$$

where $\mathbf{I}$ is an $n \times n$ identity matrix. The Leontief model given in (7) allows one to explicitly study the dependence of the interindustry flows on the outputs of each sector.

However, a different question is usually the case in practical applications of the static Leontief model; i.e., given the forecasts of the demands of the exogenous sectors ($\mathbf{f}_t$), find the output from each of the ($\mathbf{x}_t$) sectors that are necessary to

[4] In the input-output literature, the terms 'input-output coefficient' and 'direct input coefficient' are used interchangeably.

meet these forecasted final demands. Under the assumption that $(\mathbf{I} - \mathbf{A}_t)^{-1}$ exists, this question may easily be answered by using the following formula

$$\mathbf{x}_t = (\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{f}_t = \mathbf{L}_t\mathbf{f}_t \tag{9}$$

where matrix $\mathbf{L}_t = (\mathbf{I} - \mathbf{A}_t)^{-1} = \left[l_{ij}^t, i, j = 1,...,n\right]$ is called the 'Leontief inverse.' Formula (9) explains why the model under consideration is called 'demand-driven' – this follows from the fact that the interindustry relationships in a given economy are analyzed from a demand-driven perspective, as $\mathbf{f}_t$ is exogenous and $\mathbf{x}_t$ is endogenous in (9). In this case, the Leontief inverse relates the sectoral gross outputs to the amount of the final product (final demand) – that is, to a unit of the product that leaves the interindustry system at the end of the process (Panek, 2003; Miller and Blair, 2009). In order to shed more light on the interpretation of the elements of the Leontief inverse, let $\bar{\mathbf{f}}_t = \left[\bar{f}_s^t, s = 1,...,n\right]$ correspond to a unit of final demand in sector j during period t; i.e.,

$$\bar{f}_s^t = \begin{cases} 1, \text{ if } s = j \\ 0, \text{ if } s \neq j \end{cases} \tag{10}$$

Model (9) implies that the vector of production that is required to satisfy the demand $\bar{\mathbf{f}}_t$ (i.e., $\bar{\mathbf{x}}_t = \mathbf{L}_t\bar{\mathbf{f}}_t = \left[\bar{x}_s^t, s = 1,...,n\right]$) is equal to the j-th column in matrix $\mathbf{L}_t$. Therefore, l_{ij}^t represents the production of good i; i.e., $\bar{x}_i^t$, which is directly and indirectly needed for each unit of the final demand of good j (Lach, 2020).

Using Formula (9), only the output multipliers can be directly determined; however, the values of these multipliers can serve as a starting point for the calculation of the multipliers that describe the impact of a change in final demand on many types of clearly interpretable economic and non-economic indices. For this purpose, one uses the so-called 'generalized demand-driven Leontief model' given by the following formula

$$\mathbf{e}_t = \hat{\boldsymbol{\pi}}_t\mathbf{L}_t\mathbf{f}_t \tag{11}$$

where the following occur:
$\mathbf{e}_t = \left[e_i^t, i = 1,...,n\right]$ stands for the vector of factor production/use; i.e., e_i^t stands for sector i's production (or use) of a given type of factor during period t (e.g., the number of people employed, the generated income, etc.);

$\hat{\boldsymbol{\pi}}_t = \left[\pi_i^t, i = 1,...,n\right]$ is a vector of direct sectoral coefficients; i.e., π_i^t denotes sector i's direct coefficient that expresses the ratio of production (or use) of a given type of factor in sector i during period t (e.g., the number of people employed, income, etc.) per unit of output in sector i during period t; technically, $e_i^t = \pi_i^t x_i^t$ for $i = 1, ..., n$.

What is worth emphasizing is the fact that Model (11) is extremely versatile, as it can be employed to analyze any phenomenon that results from conducting a given economic activity. These phenomena include effects that are of a strictly economic nature (like imports, employment, or labor productivity) as well as phenomena with purely social and ecological dimensions (Przybyliński, 2012; Lach, 2020, 2021). In practical applications, it is commonly assumed that the input matrix defined in (5) as well as the vector of direct coefficients defined in (11) are both stable in the short run[5]. Thus, if one assumes that $\mathbf{A}_{t_0} = \mathbf{A}_{t_1} = \mathbf{A}$, $\boldsymbol{\pi}_{t_0} = \boldsymbol{\pi}_{t_1} = \boldsymbol{\pi}$ for initial period t_0 and final period t_1 the linearity of Model (11) implies the following

$$\Delta\mathbf{e} = \hat{\boldsymbol{\pi}}\mathbf{L}\Delta\mathbf{f} \tag{12}$$

where

$\Delta\mathbf{e} = \mathbf{e}_{t_1} - \mathbf{e}_{t_0} = [\Delta e_i, i = 1,\ldots,n]$,

$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$,

$\Delta\mathbf{f} = \mathbf{f}_{t_1} - \mathbf{f}_{t_0}$.

Model (12) allows one to assess the impact of a change in final demand between t_0 and t_1 (i.e., $\Delta\mathbf{f}$) on the sectoral distribution of the production (or use) of a given type of factor (i.e., $\Delta\mathbf{e}$); e.g., this allows one to track any sectoral changes in the number of employees due to a specific change in sectoral final consumption.

3. Planning a Hyperloop system in Poland

3.1. Description of possible routes

As previously mentioned, one of the key elements of the ongoing "Potential for the development and implementation of vacuum tube high-speed train technology in Poland in the social, technical, economic and legal context" research project is an examination of various hypothetical Hyperloop routes for connecting the largest cities in Poland with the STH. The main goal of the STH will be to integrate all air, rail, and road transport in Poland. Figure 1 shows a diagram of the planned connections between the STH and four Polish cities; namely, Warsaw, Lodz, Krakow and Katowice.

[5] Cf. Carter (1970); Pan (2006); Gurgul and Lach (2018, 2019a, 2019b); Lach (2020).

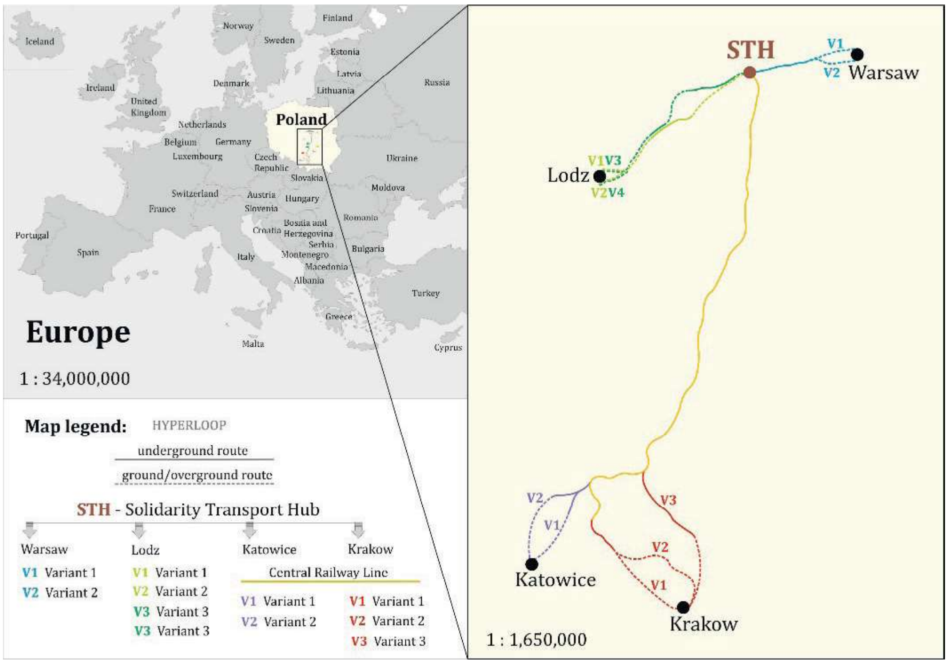

Figure 1. Hypothetical Hyperloop tracks in Poland

source: own elaboration

Different variants (which differ in their construction technology [tunnel and trestle]) are analyzed in reference to each route. Table 1 presents the length of each route (including its variants) while indicating the lengths of the tunnels and trestles. In some cases, the proportion between the lengths of the tunnels and trestles vary significantly.

One of the selection criteria was to ensure that there will be a significant demand for using the proposed routes by passengers. In addition to being able to transport people from the largest Polish cities to the planned STH, the routes that connect Lodz and Warsaw to the STH will also provide more than a 100-km-long direct connection between these two largest agglomerations in Poland. Finally, much longer hypothetical Hyperloop routes were also examined in order to conduct a complete analysis of the possibilities of constructing a Hyperloop system in Poland; i.e., the possibility of constructing a Hyperloop system that connects the STH with slightly smaller cities and agglomerations such as Krakow and Katowice was additionally discussed. This could function as a general pre-feasibility study.

Table 1

Examined variants of Hyperloop lines in Poland

Connection	Variant	Lengths of trestles [km]	Lengths of tunnels [km]	Total lengths of routes [km]
STH-Warsaw	1	14.55	21.36	35.91
	2	14.55	21.10	35.65
STH-Lodz	1	24.77	58.43	83.20
	2	24.77	65.26	90.03
	3	49.31	37.88	87.19
	4	49.31	44.71	94.02
STH-Krakow	1	242.01	47.10	289.12
	2	242.01	55.43	297.44
	3	220.49	34.37	254.86
STH-Katowice	1	205.40	30.99	236.39
	2	223.98	30.99	254.97

Environmental measures were also included in the process of route-planning. In particular, efforts were made to avoid forests, rivers, and large concentrations of people as much as possible. In the surroundings of each city, it was decided to run routes only in tunnels under the surface of the earth. An important assumption was to avoid interfering with the surroundings while at the same time optimizing the routes so that none of the curvatures would result in lowering the Hyperloop's speed limits.

3.2. Cost analysis

In this study, our analysis of the impact of Hyperloop construction on the national economy focuses on examining the costs of the route itself without the infrastructure or capsules[6]. Since the planned Hyperloop routes are partly designed to run on trestles and partly through tunnels, the total construction cost is determined by the costs of the construction of these two particular transport

[6] According to our calculations, the cost of the Hyperloop capsules is only about 3–5% of the total cost of the construction of the Hyperloop routes and, thus, was not taken into account in this analysis.

structures. Table 2 provides information on the construction cost of 10 km of trestles and tunnels, along with information on the share of imports in these costs[7].

Table 2

Average construction costs of 10 km of Hyperloop trestle and tunnel infrastructure in Poland

Type of Hyperloop construction	Total cost (at basic prices) [€]	Share of goods and imported services in total cost [%]	Change in final demand (excluding imported goods for final consumption) [€]
Trestle	695,118,658	16.20	582,509,436
Tunnel	689,565,846	29.06	489,178,011

As mentioned in Section 1, it is of particular importance from the point of view of the analysis carried out in this study that the costs that are reported in Table 2 are broken down into different sections of the Polish Classification of Activities and that the share of the planned imports is also estimated. Table 3 presents the respective details.

Table 3

Sectoral distribution of average costs of building Hyperloop trestles and tunnels in Poland with breakdown of domestic and imported goods[8]

Sector (according to Polish Classification of Activities 2008)	Trestle construction cost		Tunnel construction cost	
	Share of domestic goods [%]	Share of imported goods [%]	Share of domestic goods [%]	Share of imported goods [%]
Crude petroleum and natural gas; metal ores; other mining and quarrying products	1.07	0.00	24.77	0.00

[7] Data on the change in final demand (Tabs 1 and 2) as well as the sectoral distribution of the change in final demand (not including final imported goods) on all of the Hyperloop routes analyzed in this study have been provided by the Polish YLE Engineers design office (http://www.yle.com.pl/).

[8] The distribution of the change in final demand includes those sections for which the change was more than 0.1%. There were 12 such sections out of the 77 sectors listed in Polish Classification of Goods and Services 2008 (https://stat.gov.pl/en/metainformations/classifications/#Polish%20Classification%20of%20Activities%20(PKD)).

Table 3 cont.

Sector (according to Polish Classification of Activities 2008)	Trestle construction cost		Tunnel construction cost	
	Share of domestic goods [%]	Share of imported goods [%]	Share of domestic goods [%]	Share of imported goods [%]
Chemicals and chemical products	0.24	0.00	0.53	2.13
Basic metals	0.56	15.48	0.00	0.00
Machinery and equipment n.e.c.	0.77	0.59	0.23	1.82
Electricity, gas, steam, and air conditioning	0.22	0.00	0.25	0.00
Construction and construction work	77.10	0.00	42.17	24.87
Land and pipeline transport services	1.29	0.00	1.18	0.00
Accommodation services	0.22	0.00	0.21	0.00
Telecommunication services	1.51	0.00	0.75	0.00
Legal and accounting services	0.22	0.00	0.21	0.00
Architectural and engineering services; technical testing and analysis services	0.31	0.00	0.31	0.00
Scientific research and development services	0.30	0.13	0.34	0.22
Total	83.80	16.20	70.96	29.04

When analyzing the data in Table 3, one should pay attention to the fact that imports account for a fairly significant share of the overall construction costs of both Hyperloop transport structures. For the trestles, the costs of the imported goods and services represents more than 16% of the total cost. In the case of trestles, the high value of imports is likely due to the need to use steel in their construction. In Poland, the steel industry has all but disappeared over the last couple of years. Steel is mainly imported from Ukraine, Luxembourg, and the Czech Republic. This does not mean that one cannot produce steel in Poland, but the decisions to import steel are mainly driven by purely economic aspects (as imported steel is much cheaper).

In the case of tunnel construction, the share of imported goods and services is almost 13 percentage points higher than for trestles. This value is mainly due to the need to use suitable machines. Tunnel-building machines (TBM) play an important role in the construction of tunnels (recall the significant share of imported goods in the case of the *Machinery and equipment* sector in Table 3), which are rather technologically advanced and are produced only by companies in a few countries around the world (including China, Turkey, South Korea, Germany, Italy, Australia, and Japan). The prices of these machines are very high because they are based on highly specialized and unique technology.

Tunneling is not only about specialized machines but also about the logistics of operating such machines and equipment; hence, one may note the high value of imports in the *Construction and construction work* sector. Thus, building a Hyperloop system requires the labor input of specialized staff to operate the machines that are used for tunneling.

In the process of constructing Hyperloop tunnels, so-called construction chemicals (the *Chemicals and chemical products* sector) play a major role, as they are a key element regarding the use of sealant. The high value of imports in the case of the *Chemicals and chemical products* sector is due to the fact that the majority of chemical companies in Poland are rather engaged in importing and selling construction chemicals rather than producing them. This is mainly because of the fact that meeting the very high quality standards of producing building chemicals is difficult and costly.

Another important requirement in the process of constructing tunnels is designing and providing development services; hence, the *Scientific research and development services* sector was also included in Table 3. In this respect, Poland has very limited experience with individual projects. This limited experience is due to the simple fact that only few high-tech projects have been implemented to date in Poland. It is worth noting, however, that the central authorities' plans include the need for initiating a number of further tasks of this type, which is likely to result in an increase in the national competencies in this area.

4. Empirical results

In order to simulate the reaction of the national economy to the change in total final demand that is triggered by a particular investment, final demand for imported products should be excluded from the overall cost of the investment (Przybyliński, 2012). Similarly, constructing an input matrix in such a case implies the need for using an interindustry flow table with imports excluded; that is, using an IO table that only describes the flows of domestic goods.

Taking both of these facts into account, the following statistics were used in further parts of this study:

- **A** – domestic input matrix in Poland (i.e., with imports excluded) covering 76 sectors[9] of the economy according to Polish Classification of Goods and Services 2008 (the most recent IO table is based on 2015 data and was published in CSO [2019]);
- $\Delta\mathbf{f}$ – vector of change in final demand due to the particular transport investment (e.g., building a Hyperloop system) covering only domestic products (the initial value is the vector of final demand published in the input-output table for domestic production in Poland in CSO [2019]);
- $\boldsymbol{\pi}$ – vector of direct coefficients defined in two ways:
  - number of people employed in sectors of Polish economy (data for 2015 taken from CSO [2016]) per unit of output (data retrieved from input-output table for domestic production in 2015 [CSO, 2019]),
  - vector of sectoral value added per unit of output (data retrieved from input-output table for domestic production in 2015 [CSO, 2019]).

Table 4 shows the established sectoral distribution of the change in final demand in the Polish economy (without imported final goods and services) implied by the construction of Hyperloop trestles and tunnels. From a formal point of view, this table allows one to obtain vector $\Delta\mathbf{f}$ in Model (12)[10] and then determine the multiplier effects for the three examined policy goal variables.

Table 4

Sectoral distribution of change in final demand
(without imported final goods and services)
caused by construction of Hyperloop trestles and tunnels in Poland

Sector (according to Polish Classification of Activities 2008)	Trestles [%]	Tunnels [%]
Crude petroleum and natural gas; metal ores; other mining and quarrying products	1.28	34.92
Chemicals and chemical products	0.29	0.75

[9] In general, the national IO table published by the CSO (2019) is of a size of 77 × 77. However, there were no inflows and no outflows in the case of the *Private Households with Employed People* sector. Thus, we excluded this sector from the empirical analysis and focused on an IO table of a size of 76 × 76.

[10] To obtain vector $\Delta\mathbf{f}$ in Model (12) for a particular Hyperloop track, one should split the total cost of the construction (Tab. 2) into trestle- and tunnel-related components and then multiply each of these components by the respective vector of sectoral distribution of the change in final demand (without imported final goods and services) given in Table 4.

Table 4 cont.

Basic metals	0.67	0.00
Machinery and equipment n.e.c.	0.91	0.33
Electricity, gas, steam, and air conditioning	0.26	0.35
Construction and construction work	92.00	59.45
Land and pipeline transport services	1.54	1.66
Accommodation services	0.26	0.30
Telecommunication services	1.80	1.05
Legal and accounting services	0.26	0.30
Architectural and engineering services; technical testing and analysis services	0.37	0.44
Scientific research and development services	0.36	0.45

Table 5 presents the aggregate multiplier effects (calculated by using the methodology described in Section 1) implied by the construction of 10 kilometers of trestles and 10 kilometers of tunnels regarding the Hyperloop technology in Poland[11].

Table 5

Aggregate change in output, value added, and number of employees in Polish economy implied by construction of 10-km-long Hyperloop trestles and tunnels in Poland (source: own elaboration)

Type of Hyperloop construction	Output [mln €]	Number of employees [no. of people]	Value added [mln €]
Trestle	1,114.345	13,481	449.931
Tunnel	874.693	10,666	372.468

[11] Since IO analysis remains one of the few analytical tools that does not explicitly present error bounds in data tables (Lach, 2020), a sensitivity analysis of the empirical results that were obtained in this study was additionally carried out. Simply put – for each examined IO model, the validation procedure consisted of independently drawing 5,000 input matrices from a uniform distribution that was centered on the actual input matrix (i.e., based on the data published by the CSO) with symmetrical ±5% bounds on any possible coefficient change and then constructing the IO models on the basis of the resampled input matrices. Since the empirical confidence intervals for all of the multiplier effects turned out to be extremely narrow, we have not reported the results of the sensitivity analysis in detail. These supplemental results are available from the authors upon request.

As can be seen in Table 5, the aggregate multiplier effects implied in the Polish economy by the construction of 10 km of the two selected types of transport structures are higher in the case of the construction of a Hyperloop trestle than that of a tunnel. This is the case for the aggregate multiplier effects calculated for both the value added and output as well as employment. There is a discernible difference between the output and employment multipliers, however. For example, the construction of 10 kilometers of Hyperloop trestles will generate nearly 13,500 additional jobs; in the case of tunnel construction, this employment effect will be about 10,700 new jobs. The analogous difference between the global production multipliers is also quite significant (nearly €350 million). On the other hand, the (important) indicator of total value added is approximately €70 million higher for the construction of a 10-km-long Hyperloop trestle. This effect is largely due to the much higher share of imported goods in the total cost of building a Hyperloop tunnel in Poland as compared to the construction of a Hyperloop trestle.

Table 6 presents the sectoral distribution of output, value added, and number of employees in the Polish economy that are likely to be generated by the construction of 10 km of Hyperloop trestles and tunnels in Poland.

Table 6

Sectoral distribution of output, value added, and number of employees in Polish economy implied by construction of 10-km-long Hyperloop trestles and tunnels

Sector (according to Polish Classification of Activities 2008)	Trestle			Tunnel		
	Output [mln €]	Number of employees [no. of people]	Value added [mln €]	Output [mln €]	Number of employees [no. of people]	Value added [mln €]
Agriculture and hunting products	1.165	118	0.396	0.945	96	0.321
Forest management products	2.222	43	1.029	1.523	30	0.705
Fish and other fishery products	0.010	0	0.005	0.007	0	0.003
Hard and brown coal	2.586	54	1.552	2.099	44	1.260
Crude oil and natural gas, metal ores, other mining products	17.923	208	8.592	195.336	2265	93.639
Groceries	2.106	20	0.469	1.527	15	0.340

Table 6 cont.

Drinks	0.582	3	0.169	0.440	2	0.128
Tobacco products	0.010	0	0.006	0.008	0	0.005
Textile goods	0.290	6	0.074	0.217	5	0.056
Clothing	0.263	9	0.137	0.208	7	0.108
Leather and leather goods	0.067	2	0.022	0.066	1	0.022
Wood and wood products	13.613	206	4.142	7.760	118	2.361
Paper and paper products	3.179	22	0.916	2.442	17	0.703
Printing and reproduction services	1.078	19	0.357	0.835	15	0.276
Coke, refined petroleum products	12.963	14	1.472	10.944	12	1.243
Chemicals, chemical products	8.291	44	2.447	8.419	44	2.485
Medicines and pharmaceutical products	0.038	0	0.011	0.036	0	0.010
Rubber and plastic products	27.082	312	7.505	16.164	186	4.479
Products from other non-metallic raw materials	41.850	498	14.638	23.395	278	8.183
Metals	12.135	56	2.457	4.979	23	1.008
Finished metal products	33.404	491	12.503	19.982	294	7.479
Computers, electronic, and optical products	1.021	8	0.168	0.665	5	0.109
Electrical and non- electrical appliances, household appliances	3.561	29	1.021	2.154	17	0.618
Machines and devices not elsewhere classified	7.424	90	2.698	3.594	44	1.306
Motor vehicles, trailers, and semi-trailers	2.691	18	0.440	2.560	17	0.419
Other transport equipment	0.480	4	0.168	0.568	5	0.198
Furniture	1.278	24	0.421	0.894	17	0.294
Other products	0.243	5	0.098	0.185	3	0.075

Table 6 cont.

Sector (according to Polish Classification of Activities 2008)	Trestle			Tunnel		
	Output [mln €]	Number of employees [no. of people]	Value added [mln €]	Output [mln €]	Number of employees [no. of people]	Value added [mln €]
Repair, maintenance, and installation services of machines and devices	11.508	139	5.279	11.520	139	5.284
Electricity, gas, steam, and hot water	15.056	75	6.594	15.231	76	6.670
Water; water treatment, and supply services	1.141	26	0.807	1.003	23	0.710
Waste-related services; recovery of raw materials	2.601	23	0.976	1.558	14	0.584
Sewage services; sediments; remediation services	1.492	41	0.960	1.691	47	1.088
Building objects and construction work	691.434	7523	269.305	377.276	4105	146.944
Sales of motor vehicles; vehicle repair	2.990	63	1.845	2.840	60	1.752
Wholesale trade	33.887	654	17.316	21.095	407	10.780
Retail trade	12.848	367	8.874	9.600	275	6.631
Land and pipeline transport	36.469	554	14.443	35.077	533	13.891
Water and air transport	0.575	1	0.184	0.698	1	0.224
Storage; postal and courier services	9.008	65	4.241	10.052	72	4.733
Accommodation services	2.875	66	1.446	2.530	58	1.273
Food-related services	1.465	38	0.565	1.054	27	0.407
Services related to publishing activities	0.639	9	0.283	0.664	9	0.295
Services related to production of films, television programs, and recordings	0.093	1	0.035	0.075	1	0.028

Table 6 cont.

Related services with broadcasting	0.404	3	0.201	0.369	3	0.184
Telecommunication services	13.788	74	6.106	7.638	41	3.382
Computer software and consultancy services	4.034	64	2.388	2.990	47	1.770
Information services	1.186	21	0.577	0.891	16	0.433
Financial services	7.278	117	4.746	6.375	102	4.158
Insurance services	1.590	9	0.518	1.200	7	0.391
Services auxiliary to financial and insurance services	0.629	12	0.254	0.451	9	0.182
Related services with real estate market services	6.334	37	3.360	5.002	29	2.653
Legal and accounting services	6.879	170	4.622	5.948	147	3.997
Management consulting services	5.999	104	3.388	4.580	80	2.587
Architectural and engineering services; technical research and analysis services	10.929	188	6.342	8.421	145	4.887
Research and development services	2.144	26	1.479	2.253	27	1.555
Advertising services; market research and public opinion-polling services	7.708	52	3.372	6.369	43	2.786
Other professional, scientific, and technical services	1.165	21	0.728	1.673	31	1.046
Veterinary services	0.036	1	0.026	0.024	0	0.017
Rent and lease	7.150	29	4.635	6.240	25	4.045
Employment-related services	4.053	243	3.045	2.543	152	1.910
Tourism organizer services	0.090	1	0.016	0.074	0	0.013

Table 6 cont.

Sector (according to Polish Classification of Activities 2008)	Trestle			Tunnel		
	Output [mln €]	Number of employees [no. of people]	Value added [mln €]	Output [mln €]	Number of employees [no. of people]	Value added [mln €]
Detective and security services	2.133	114	1.277	1.989	106	1.191
Services related to maintaining order in premises	0.884	32	0.405	0.755	27	0.346
Office administrative services	3.262	52	1.899	4.141	66	2.411
Public administration services	0.993	36	0.754	1.247	45	0.947
Education services	0.938	51	0.722	0.771	42	0.593
Healthcare services	0.642	19	0.367	0.505	15	0.289
Social assistance services	0.000	0	0.000	0.000	0	0.000
Cultural and entertainment services	0.067	2	0.036	0.049	1	0.026
Libraries, archives, and museums	0.026	3	0.013	0.029	3	0.014
Gaming and betting services	0.000	0	0.000	0.000	0	0.000
Sports, entertainment, and recreation services	0.140	3	0.059	0.095	2	0.040
Member organization services	0.158	17	0.043	0.136	15	0.037
Repair and maintenance services for computers and household goods	1.351	13	0.994	1.327	13	0.976
Other individual services	0.719	23	0.493	0.693	22	0.473

In general, the empirical results that are presented in Table 6 support the claim that there is a discernible difference between the sectoral distributions of the analyzed multiplier effects that are implied by the construction of Hyperloop trestles and tunnels. In the case of the construction of a 10-km-long Hyperloop trestle, the largest sectoral multiplier effects induced in the Polish economy concern the *Building objects and construction work* sector, because this sector accounts for 50% of the overall induced value added and the additional employment falls on this sector. Significant multiplier effects were also achieved (around 3–4%) in the case of the following sectors: *Products from other non-metallic raw materials*, *Land and pipeline transport*, *Wholesale trade*, *Finished metal products*.

In the case of tunnel construction, also the greatest multiplier effects (by far) were achieved in the case of the *Building objects and construction work* sector in the case of constructing a 10-km-long Hyperloop tunnel. This sector accounts for about 40% of the total induced employment and value added. A significant share of the overall induced employment and value added (around 20–25%) was reported in the case of the *Crude oil and natural gas, metal ores, other mining products* sector.

As the costs of building a 10-km Hyperloop trestle and a 10-km Hyperloop tunnel in Poland are very similar, the decision as to whether a particular section of a Hyperloop route should be led by a trestle or a tunnel may be based on the need to support specific sectors of the economy. Although the multiplier effects presented in Table 6 were induced by the construction of 10 kilometers of a Hyperloop trestle and 10 kilometers of a Hyperloop tunnel, they straightforwardly translate into the total size of these effects that would occur after constructing all of the planned Hyperloop routes as well as the variants discussed in this study. Table 7 shows the results of the aggregate multiplier effects that would be induced by the construction of the Hyperloop routes depicted in Figure 1[12].

The aggregate multiplier effects that are presented in Table 7 vary significantly among the proposed Hyperloop routes. This is mainly related to their lengths; however, it is to some extent also related to the type of route (one mainly leading along trestles as opposed to one leading mainly through tunnels). Therefore, it seems reasonable at this stage to individually compare the variants of the Hyperloop routes that connect the STH with a chosen city. In the case of the STH-Warsaw connection, the resulting multiplier effects are very similar for both of the examined variants of the Hyperloop route. In the case of this connection, the number of generated new jobs comes to more than 42,000 regardless of the variant of the route. On the other hand, the value added that results from the construction of these two variants of the Hyperloop route is equal to approximately €1,450 ml. Thus, the multiplier effects do not significantly differentiate the proposed variants of the Hyperloop route in terms of the impact on the economy in the case of this connection. Also, there are no significant differences between the multiplier

[12] To save space, the sectoral distributions of the connection-specific multiplier effects of all of the examined Hyperloop routes are not given in detail. However, these supplemental results are available from the authors upon request.

values that are reported for Route Variants 1 and 2 in Table 7 in the case of the route that connects the STH with Katowice.

Table 7

Aggregate change in output, value added, and number of employees in the Polish economy induced by construction of Hyperloop routes depicted in Figure 1

Connection	Output [mln €]	Number of employees [no. of people]	Value added [mln €]
STH-Warsaw (V1)	3,477.95	42,259	1,444.46
STH-Warsaw (V2)	3,458.48	42,024	1,436.19
STH-Lodz (V1)	7,821.20	95,229	3,271.89
STH-Lodz (V2)	8,422.49	102,534	3,525.39
STH-Lodz (V3)	8,677.05	105,443	3,578.28
STH-Lodz (V4)	9,356.34	113,580	3,863.52
STH-Krakow (V1)	30,511.95	369,458	12,409.63
STH-Krakow (V2)	31,432.06	380,950	12,801.62
STH-Krakow (V3)	27,515.45	333,359	11,179.59
STH-Katowice (V1)	25,530.78	309,488	10,370.09
STH-Katowice (V2)	27,188.37	329,603	11,041.81

The discussed dependencies are slightly different in the cases of STH-Lodz and STH-Krakow connections. For Variant 1 of the STH-Lodz connection, the number of additional employees comes to more than 95,000, and for Variant 4, this effect creates 113,000 new jobs (nearly 19% more). Variants 1 and 4 also differ in terms of the value added, as the induced value added is more than €3,860 million in the case of Variant 4 (which is more than 118% of the corresponding multiplier effect that is reported for Variant 1 of STH-Lodz Hyperloop connection). Therefore, if one assumes that the induced value added is the leading indicator of the impact of Hyperloop construction on the national economy, one should decide to build Variant 4 of the STH-Lodz connection. Analogously, among the variants of Hyperloop routes that connect the STH with Krakow, one can easily identify the variant that has the greatest multiplier effects regardless of the chosen policy goal variable (i.e., output, value added, new jobs). Namely, the construction of Variant 2 of this Hyperloop connection would generate more than 381,000 jobs, while in Variant 1 of this particular connection, the number of generated new jobs is only approximately 333,000 (which is nearly 50,000 fewer new jobs).

5. Conclusions

The purpose of this study was to specify the multiplier effects that are potentially induced in the national economy in reference to the construction of Hyperloop lines in Poland using tunnel and trestle technologies. Our examination focused on the cost of constructing a 10-km-long tunnel as well as a 10-km-long trestle. Due to the lower utilization of imported goods, the impact of trestle construction (value-added and employment) is greater than tunnel construction. The purpose of the multiplier analysis was not only to determine the overall impact of such an investment on the national economy but also to list the sectors of the economy that could be expected to experience the greatest stimulation. According to the conducted analysis, constructing Hyperloop links in Poland would have the greatest stimulating impact on several sectors of the Polish economy, including *Building objects and construction work*, *Crude oil and natural gas, metal ores, other mining products*, *Products from other non-metallic raw materials*, *Finished metal products*, *Land and pipeline transport*, and *Wholesale trade.* Additionally, we compared the impact of the construction of tunnels as well as trestles on the development of a particular industry. Our results indicated that the costs of both technologies are similar; however, the impact of each technology is different on particular industries. We also identified those routes (and their construction technologies) that are the most efficient in terms of multiplier effects.

Our examination corresponds with numerous studies on the socioeconomic impact of transport infrastructure – especially railway infrastructure (some of these are presented in the Introduction section). The results of our study confirm the positive impact of investments in transportation infrastructure. The results of our study induce other questions and highlight other challenges. For example, the construction process will result in an increase in employment; however, we have not examined the long-term impact of Hyperloop infrastructure development on employment. Our analysis focused on the short-term impact of construction investments but the long-term impact of Hyperloop passenger and cargo transportation can be analyzed as well.

This study contributes to the body of literature on transport infrastructure and public investments as well as Hyperloop technology development. Additionally, it contributes to the econometric methodology by employing input-output analysis for forecasting the multiplier effects of constructing a Hyperloop network. This study has practical implications for the decision-making process on Hyperloop network planning and development in the future. In particular, this study delivers indications for decision-makers who will need to decide whether or not to invest in technologies that are necessary for the construction of a Hyperloopnetwork (which would enable an increase in the multiplier effect of the Hyperloop construction on the economy).

When interpreting the obtained empirical results, one cannot forget that the input-output table as well as both vectors of the direct coefficients (one related to the number of employees, and the other expressing the value added per unit of output) were all based on data from 2015. The application of 2015 data in constructing short-run forecasts was caused by the lack of availability of more-recent statistical IO datasets on Poland. In other words, we assumed the short-term stability of the parameters of IO models in this paper, which is a common practice in empirical IO analyses; comp. Carter (1970), Pan (2006), Gurgul and Lach (2018, 2019a, 2019b), Lach (2020), etc.

On the one hand, the linear form of the IO model is a rather far-reaching simplification of reality; on the other hand, it ensures an ease of calculation and clarity of interpretation of the obtained results. These simplifications are mainly caused by equating the average and marginal quantities in the IO model (Przybyliński, 2012). What is most important, the interpretation of input-output multipliers is based on the assumption that there are capacity reserves in the economy under analysis that allow for increasing production accordingly without the need for technological progress (Przybyliński, 2012). This assumption is relatively restrictive, as it assumes that there are no supply constraints in the economy (Cardenete and Sancho, 2012). To some extent, this issue can be avoided by using CGE-class models, which – among the many advantages – allow us to introduce supply constraints in the equations that describe the production processes (Lach, 2020). Due to the need to establish the exact values of a very large number of hyperparameters as well as a relatively high degree of complexity and sensitivity to the choice of the closure (Dietzenbacher et al., 2013), the calibration and correct application of CGE-class models does not seem possible at the current stage of analytical work on assessing the feasibility and efficiency of a Hyperloop system in Poland. In other words, we fully agree with Blanquart and Koning (2017) and Lee et al. (2018), who underlined that the linear IO model still seems to be the most reliable quantitative tool that is available in the context of forecasting the multiplier effects of constructing a Hyperloop infrastructure.

It should also be underlined that the calculated multiplier effects relate to the full period of constructing a Hyperloop system in Poland. As previously mentioned, Model (12) assesses the sectoral effects of the change in final demand for the sectoral distribution of the production/use of a given factor over a whole time period between t_0 and t_1. The way the particular aggregate multiplier effect will be distributed over time during period t_0 to t_1 depends on the actual detailed plan of the investments (including the details of a financial schedule). Our analysis does not take inflation into account, which can change over time and impact our calculations.

Our analysis focused on several aspects that are associated with developing a Hyperloop infrastructure in Poland. However, some questions remain to be answered. One of these relates to a comparison of investments and the impact of a Hyperloop on other transportation technologies (e.g., highways and traditional/high-speed railways) as an alternative for the routes examined in our study. Such a comparison would be an important argument in the decision-making process. Our results do not reflect the potential profits that may be sourced in licensing as well as the sale of construction services abroad. As an additional long-term source of income, spin-off technologies are not included in our calculations (even though many new solutions may appear along with the development of the Hyperloop technology); some of these technologies may be bases for new products and markets.

Finally, it should be highlighted that the presented project has not yet been implemented (as is true with any other Hyperloop network projects around the world; there are only some pieces of testing the infrastructure that have been constructed). Moreover, it has not been decided whether the examined infrastructure within this study will be implemented in the future; however, this analysis was triggered by a governmental research project that was focused on Hyperloop technology, which suggests that such an investment is under consideration. Thus, we can posit that some obstacles and negative consequences may appear. Many of these will likely be connected with the technology; for example, there have been some safety issues that have not yet been addressed. In the area of socio-economic determinants, we need to consider the impact of long-term global economic development and economic prosperity; these can affect demand, costs, resources, and capital availability. In particular, a potential economic crisis (which is a part of any economic reality) could affect public investment; the current COVID-19 pandemic is a good example. However, we still do not know the scale and scope of its impact – especially in the long term. In this context, the EU recovery plan (which is intended to promote environment-friendly solutions) may be a favorable factor for the development of technologies such as Hyperloop (for example, as an alternative to short- and middle-haul air transportation routes). Consequently, the presented analysis may require modifications in the future depending on the numerous conditions that can affect the implementation of Hyperloop as a mode of transportation.

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Summary

The aim of this paper is to specify the multiplier effects that are induced in the national economy in reference to the construction of Hyperloop lines in Poland using tunnel and trestle technology. In particular, we calculate the added value and employment growth for several industries that will contribute to the construction process. We use an input-output analysis that enables us to take the detailed structure of interindustry linkages in Poland into account. According to our results, constructing a Hyperloop infrastructure in Poland would have the greatest stimulating impact on several sectors of the Polish economy, including crude oil and natural gas, metal ores, other mining products, building objects and construction work, products from other non-metallic raw materials, finished metal products, land and pipeline transport, and wholesale trade. However, this impact will be affected by the choice of construction technology (tunnel versus trestle). In addition, our calculations relate to particular routes of the potential Hyperloop network. This study contributes to the body of literature on transport infrastructures and public investments as well as Hyperloop technology development. Additionally, it contributes to the econometric methodology by employing an input-output analysis for forecasting the multiplier effects of constructing a Hyperloop system. This study has practical implications for the decision-making process on Hyperloop network development in the future.

JEL codes: M21, O11, O14, O33, O41, O47, R42

Keywords: *vacuum tube high-speed train; Hyperloop; input-output (IO) analysis; economic development; technology development; interdisciplinary studies*