ZESZYTY NAUKOWE WYŻSZEJ SZKOŁY TECHNICZNEJ W KATOWICACH
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THE HYPERLOOP CONCEPT COMPARED TO THE ECONOMIC PERFORMANCE OF OTHER MEANS OF TRANSPORTATION

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ABSTRACT

Transportation of passengers and freight on medium and long distances is currently dominated by three basic branches: road, rail and air. One can assume than at least since the 1980s a really groundbreaking innovation has not taken place in any of these industries. The development of electric cars industry and tests of autonomous cars could be considered an exception. However, this does not change the fact that it will not eliminate other disadvantages of cars, i.e. relatively low speed, exposure to congestion, etc. In 2013 Elon Musk proposed assumptions for a new mean of transportation – the Hyperloop: a steel tube with very low air pressure in it stretched on pylons between cities, in which special pods move on air bearings at speeds up to 1220 kph. This article attempts to analyze basic economic performance parameters of existing means of transportation: road, rail and air on selected routes in Poland and to compare them with available data, which now is a bit more precise than this published in Elon Musk's white paper, concerning the predicted effectiveness of the Hyperloop system. It hence tries to prove whether Hyperloop could become a major disruptive transportation innovation, from the point of view of its economic fundamentals. To do that two possible measures of transportation system's performance are proposed and discussed, both based on cost-effectiveness analysis model: 1) Cost of velocity for passenger and 2) Total yearly cost per kilometer per passenger. Calculations for the first one show that high-speed rail could become competitive to road transportation, while Hyperloop might be even 6-7 times cheaper than car, from the point of view of a client. The results of the second one tell that road, conventional rail and Hyperloop (based on assumptions according to currently available data) seem to reach a similar level of cost-effectiveness, while high-speed rail is expected to be ca. 50% more expensive.

KEYWORDS

Hyperloop, performance of passenger transportation systems: road, conventional rail, high-speed rail, air

INTRODUCTION

The purpose of this paper is to begin an academic discussion over the economic potential of implementing the Hyperloop technology for passengers in the foreseeable future. It aims to become an element of technology foresight, more specifically concerning technology assessment, i.e. evaluation of potential influence of a new technology on economy and society. Transportation of passengers and freight on medium and long distances is currently dominated by three basic branches: road, rail and air (in this analysis maritime transportation is skipped due to its specifics, especially its use for cargo transportation only and limitations or inability to use it inland). One can assume than at least since the 1980s a really ground-breaking innovation has not taken place in any of these industries, such as the invention of Diesel engine (1892), high-speed rail (1964), magnetic rail (1979) or supersonic plane (1969), which however finally was withdrawn from use in 2003, even though there are attempts to create its successor.

An exception of this can be spotted in the development of electric cars industry in the recent few years with its most recognized example of California based Tesla Motors. From that point of view one can see as more impressive the tests of autonomous cars, i.e. not needing a driver, that have been held for a couple of years. It however does not change the fact that either the change of propulsion for a more environmentally friendly one nor a situation where a driver in unnecessary will not eliminate other disadvantages of cars, i.e. relatively low speed, exposure to congestion, etc.

In 2013 Elon Musk, founder of two transportation companies: Tesla Motors mentioned above and SpaceX (cosmic rockets), proposed a futuristic concept of Hyperloop technology [1]. In a white paper published at that time he explained the assumptions for a steel tube with a very low air pressure in it stretched on pylons between cities, in which special pods move on air bearings at speeds up to 1220 kph. The first route was supposed to link Los Angeles and San Francisco, allowing a journey of ca. 564 km to last 35 mins. A passenger and cargo version was expected to cost only 11% of the planned cost of high-speed rail for a passenger only version.

Taking this into account it seems reasonable to consider Hyperloop as a potential major transportation innovation. Despite the fact that the technology behind it is still under development, one should consider the economic fundamentals of current and proposed transportation systems. The first step to do that should be an attempt to compare the performance of existing means of transportation on a sample of routes and then have a look on how the Hypeloop system's forecasted performance would do.

This article uses a simplified version of cost-effectiveness analysis [2] to assess the performance of existing and proposed means of transportation on a number of most frequently used routes between major Polish cities. The performance is analysed from a point of view of a taxpayer which in this case can also be treated as the end-user. The goal is to assess the validity of public spending on certain infrastructure types comparing it with final costs and benefits for its end-user (passenger).

Due to limited availability of data, especially concerning the proposed Hyperloop technology, the author humbly acknowledges potential simplifications of the analysis. As said before, the goal is to raise the issue and start a discussion concerning economic validity of implementing this new technology to move around passengers, when it becomes available. This analysis could also help to identify the outermost implementation costs that companies trying to purse the Hyperloop technology should not exceed in order to make the new technology viable for deployment.

Poland seems to be a good field for this kind of study due to heavy investment in new road infrastructure taking place in the last few years, combined with increased spending on modernization of existing railways and some discussions on plans to build its first high-speed rail link.

Analysis includes a total of 12 passenger routes:

- 8 routes with currently available road, conventional rail and air links,
- 4 routes with currently available road and conventional rail links,
- estimates for all 12 routes for improvements in road and conventional rail infrastructure that are currently underway or planned for the next few years,
- estimates for all 12 routes of future implementation of high-speed rail or hyperloop systems.

These 12 routes cover a vast majority of medium and long-distance passenger traffic between the largest Polish cities.

Five different means of transportation are taken into account: currently existing roads (coupled with estimated data for planned routes, i.e. when all projected investments are completed), conventional rail (coupled with estimated data for planned routes, i.e. when all modernization investments are completed), existing airline routes and possible implementations of high-speed rail and Hyperloop (the latter two assumed to be located on existing conventional railway paths and station spots).

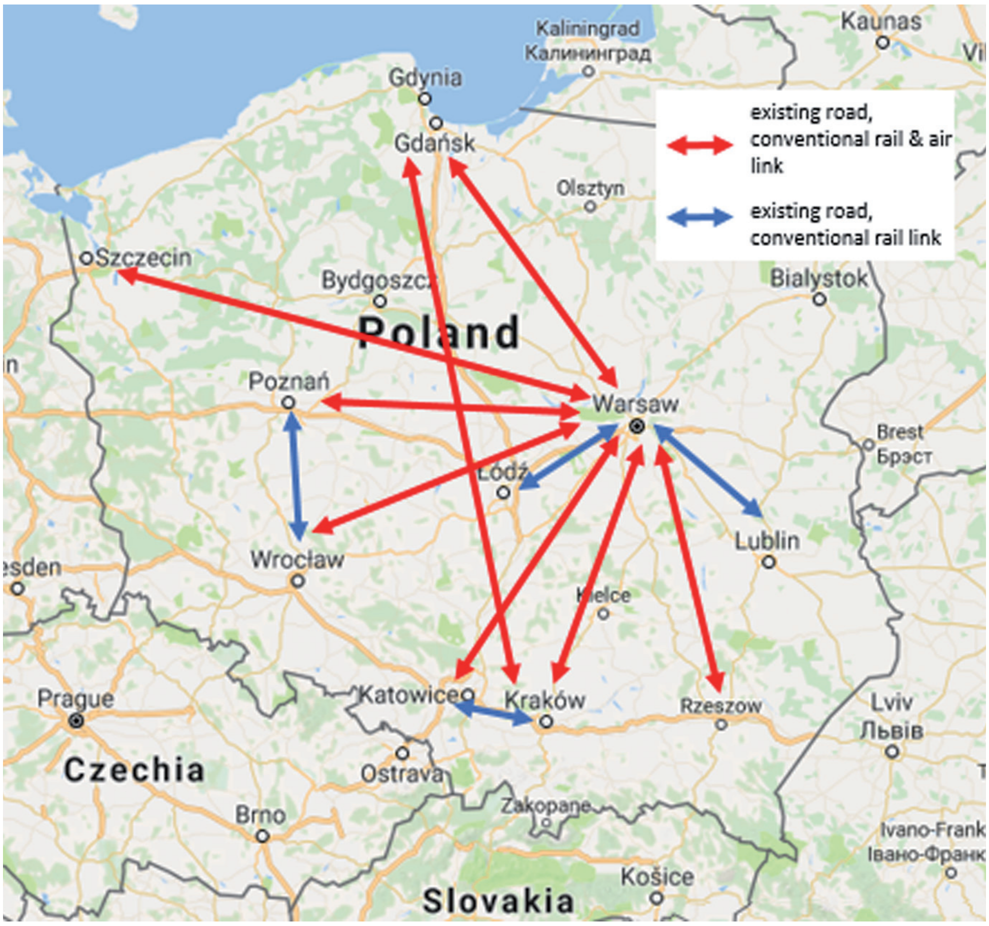

Fig. 1. Map of analyzed routes [3]

1. ABOUT HYPERLOOP

Hyperloop was firstly proposed as an open source project. "The intent of this document has been to create a new open source form of transportation that could revolutionize travel. The authors welcome feedback and will incorporate it into future revisions of the Hyperloop project, following other open source models such as Linux." said the Hyperloop Alpha white paper in 2013 [1]. The idea to do it open source has proved successful so far, as since 2013 thousands of people around the world have committed their time and skills to work on the concept and to take part in competitions such as: SpaceX Hyperloop Pod Competition that attracted more than 1000 applicant teams [4], Build Earth Live Hyperloop that had 65 teams participating [5] and Hyperloop One Global Challenge that attracted ca. 2600 applicant teams [6].
In the case of Hyperloop concept open community cooperation has led to a situation where social networks have became one of the leading forms of organizing interaction in the Internet [7] resulting in a huge boost to the innovation process which results can greatly influence the physical real-life environment in the nearest future.
Coopetition taking place between for-profit companies and non-profit open-source organizations and the ways they transform from one form into another can be seen as an interesting form of application of the Open Innovation Paradigm [8].
There is currently a number of for-profit companies working on the Hyperloop concept, mostly in North America (Hyperloop Transportation Technologies using a crowd-sourcing model and Hyperloop One and Arrivo in the USA and Transpod in Canada working as typical private companies, largely backed by VC funds). One of them signed a contract for a feasibility study in the United Arab Emirates in 2016. Some countries in Europe, e.g. Slovakia, Sweden and Finland have expressed interest in implementing the technology. Poland can also expect a launch of its first Hyperloop company within a few months – Hyper Poland, which currently works on a pod prototype and prepares designs for a test track considering four possible infrastructure solutions: either steel or prestressed concrete for the tubes that could be placed on pylons or on the ground level.
Data concerning costs and performance of Hyperloop system are based on estimates prepared by Hyper Poland [9] and on SpaceX's white paper [1].

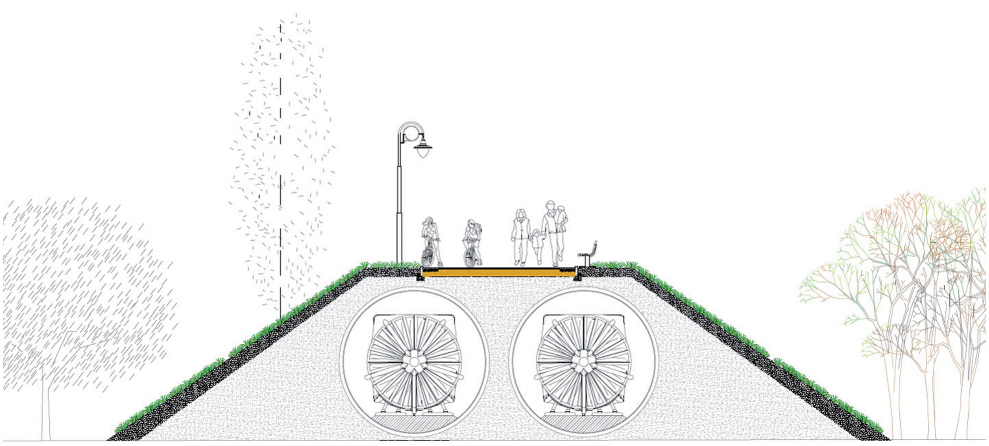

Fig. 2. Hyperloop's covered steel tubes on the ground level [9]

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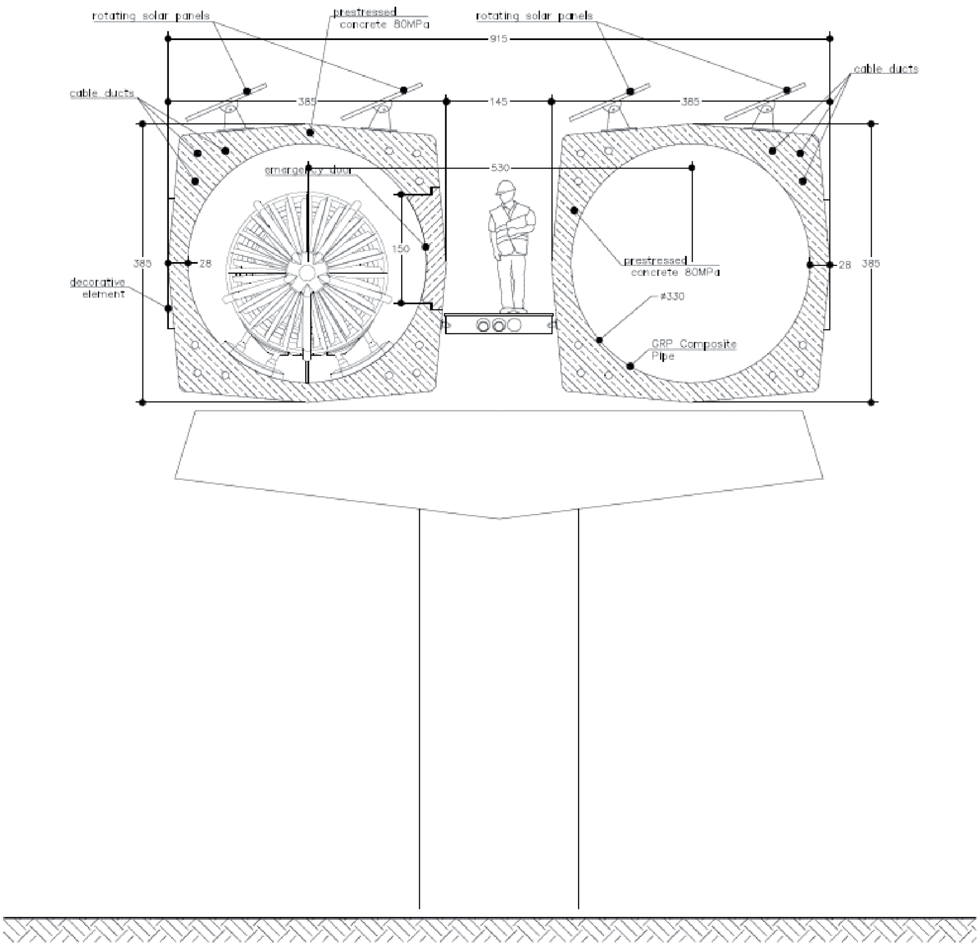

Fig. 3. Hyperloop's prestressed concrete tubes on pylons [9]

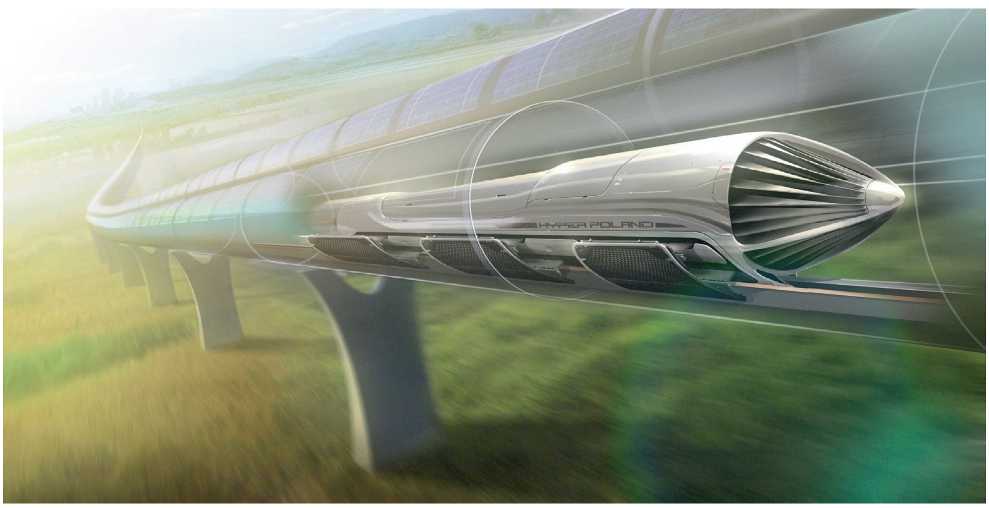

Fig. 4. Hyperloop's pod visualization [9]

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2. METHODOLOGY

Cost-effectiveness analysis is used as a basis for the study. It however, for simplification reasons, does not include discounting and sensitivity analysis.
The basic formula is:
Formula 1.

$$\text{Cost-Effecvtiveness Ratio}=(\text{Total Cost})/(\text{Units of Effectiveness})$$

Source: [2]

Using this methodology two performance measurements are proposed:

2.1 COST OF VELOCITY FOR PASSENGER

Which is a calculation of price which a passenger (end-user) has to pay for a unit of effective speed (kph), i.e. speed of travel between the centers of cities A and B taking into consideration transfer times to/from the city centers to the railway stations and airports and waiting times spent there).

2.2. TOTAL YEARLY COST PER KILOMETER PER PASSENGER

Which includes cost of public spending on infrastructure depreciated per year combined with travel costs for all passengers on a route and valuation of time lost on slower means compared to the fastest option (social cost) divided by a combined length of routes and then by a total number of passengers.

AD. 2.1. COST OF VELOCITY FOR PASSENGER

Formula 2.

$$C\_v=C/V\_e$$

where:
C_v = Cost of velocity for passenger

C = Average travel cost per passenger:

- Road: average petrol and highway toll costs of a one-way trip calculated as a weighted average of current prices and average consumption per 100 km of three major fuels (gasoline, diesel and LPG) and their share in the total quantity of cars in use; toll costs for the planned version include tolls for sections which will become payable in the nearest years.
- Conventional rail: standard price of normal one-way second class tickets for the same or following day.
- Air: average price of one-way tickets for the same and the next two days, including tickets in both directions.
- High-speed rail: standard price of normal one-way second class tickets for the same or following day of AVE service in Spain adjusted to GDP PPP in Poland.
- Hyperloop: estimates of SpaceX Hyperloop Alpha white paper's one-way ticket cost for Los Angeles – San Francisco trip adjusted to GDP PPP in Poland and multiplied by a coefficient of uncertainty of 200% (the coefficient is arbitrary and can be discussed).

Additionally for all types of rail, air and hyperloop: minimum taxi fare for getting from the center of the departure city to the railway station or the airport and from the railway station or the airport to the center of the destination city.

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C_v = Effective average travel speed:
fraction of distance between the centers of cities A and B and average travel time:

- Road: current time calculated as an average of current time at data collection moment, no traffic time, minimum time and maximum time showed by maps.google.com; planned time based on estimates of coefficients of maximum speeds when the whole highway/expressway system is completed.
- Conventional rail and air: current time calculated as a mean of all available journeys, planned time for rail based on data provided by the network administrator concerning travel times when all planned modernization for speeds up to 160 kph is completed.
- High-speed rail and hyperloop: estimates based on AVE's effective speed coefficient.

All except road: additional transfer times and distances to/from the city centers to the railway stations and airports and supposed average waiting times spent there.

AD. 2.2. TOTAL YEARLY COST PER KILOMETER PER PASSENGER

Formula 3.

$$C_{kp}=(C_{di}+C+C_t)/(D/P)$$

where:
C_{kp} = Total yearly cost per kilometer per passenger
C_{di} = Infrastructure costs depreciated per year:
average or estimated costs of construction of linear infrastructure on all routes.
C = Average travel cost per passenger:
cost of travel including fares, tolls and transfers to/from the city center to the station.
C_t = Value of time lost per year by all passengers compared to hyperloop:
multiplication of time lost on a single trip on other means of transportation while compared to hyperloop and number of passengers per year and average hourly gross wage in the enterprise sector.
D = Total length of all routes:
sum of distances of all analyzed routes.
P = Total number of passengers per year on all analyzed routes:
sum of yearly number of passengers on all analyzed routes.
Sources of specific data are given in the References section.

3. FINDINGS

3.1. GENERAL DATA

Explanation of abbreviations:

R: road
CR: conventional rail
A: air
R-c: road – current
R-p: road – planned
CR-c: conventional rail – current
CR-p: conventional rail – planned
A: air
HSR-e: high-speed rail – estimated
HYP-e: hyperloop – estimated

WAW: Warsaw
GDA: Gdansk
SZCZ: Szczecin
POZ: Poznan
WRO: Wroclaw
KAT: Katowice
KRA: Cracow
RZE: Rzeszow
LOD: Lodz
LUB: Lublin

Types of data used in the analysis influencing finality of presented results:

empirical data	mix of empirical data and assumptions based on empirical data	assumptions based on empirical data tested elsewhere	assumptions that have not been tested in practice

Table 1. Distances in kilometers [3], [10]

Route		R-c	R-p	CR-c, CR-p, HSR-e, HYP-e	A
WAW	**GDA**	342	337	330	322
WAW	**SZCZ**	572	572	515	497
WAW	**POZ**	310	310	305	299
WAW	**WRO**	354	354	407	323
WAW	**KAT**	289	294	301	268
WAW	**KRA**	294	295	294	272
WAW	**RZE**	297	345	415	260
KRA	**GDA**	583	595	622	521
WAW	**LOD**	136	136	134	
WAW	**LUB**	169	178	178	
KRA	**KAT**	81	81	79	
WRO	**POZ**	176	163	167	
AVERAGE		*300.3*	*305.0*	*312.3*	*345.3*
MEDIAN		295.5	302.5	303.0	310.5
SUM		**3 603**	**3 660**	**3 747**	

Table 2. Average travel time in minutes [1], [3], [11], [12], [13], [14], [15]

Route		R-c	R-p	CR-c	CR-p	A	HSR-e	HYP-e
WAW	**GDA**	262	240	186	186	154	117	45
WAW	**SZCZ**	320	318	326	291	182	168	56
WAW	**POZ**	185	185	174	170	151	107	41
WAW	**WRO**	210	210	244	247	161	137	48
WAW	**KAT**	213	193	171	169	161	106	40
WAW	**KRA**	261	215	156	156	156	104	40
WAW	**RZE**	278	240	335	254	146	139	49
KRA	**GDA**	357	356	330	330	179	200	64
WAW	**LOD**	104	104	113	98		67	38
WAW	**LUB**	160	128	166	116		78	39
KRA	**KAT**	73	73	155	86		49	32
WRO	**POZ**	188	119	169	110		79	42
AVERAGE		*217.6*	*198.4*	*210.4*	*184.4*	*161.3*	*112.6*	*44.5*
MEDIAN		211.5	201.5	172.5	169.5	158.5	106.5	41.5

Currently, as one could expect, air is the least time-consuming option (however its prevalence is much lower than one could think due to important transfer and waiting times). High-speed rail seems much more competitive, while Hyperloop should be the most appealing option in terms of journey time.

Table 3. Effective average travel speed in kph [3], [10], [11], [12], [13], [14], [15]

Route		R-c	R-p	CR-c	CR-p	A	HSR-e	HYP-e
WAW	**GDA**	78.3	84.3	106.5	106.5	125.5	169.2	440,0
WAW	**SZCZ**	107.3	107.9	94.8	106.2	163.8	183.9	551,8
WAW	**POZ**	100.5	100.5	105.2	107.6	118.8	171.0	446,3
WAW	**WRO**	101.1	101.1	100.1	98.9	120.4	178.2	508,8
WAW	**KAT**	81.4	91.4	105.6	106.9	99.9	170.4	451,5
WAW	**KRA**	67.6	82.3	113.1	113.1	104.6	169.6	441,0
WAW	**RZE**	64.1	86.3	74.3	98.0	106.8	179.1	508,2
KRA	**GDA**	98.0	100.3	113.1	113.1	174.6	186.6	583,1
WAW	**LOD**	78.5	78.5	71.2	82.0		120.0	211,6
WAW	**LUB**	63.4	83.4	64.3	92.1		136.9	273,8
KRA	**KAT**	66.6	66.6	30.6	55.1		96.7	148,1
WRO	**POZ**	56.2	82.2	59.3	91.1		126.8	238,6
AVERAGE		*80,3*	*88.7*	*86.5*	*97.6*	*126.8*	*157.4*	*400.2*
MEDIAN		78,4	85.3	97.5	102.6	119.6	170.0	443.7

For now, car is the slowest mode and even finalization of highway and expressway construction program will not change it. Completion of modernization of all major conventional railways for the speed of 160 kph (200 kph is already available on a part of Central Rail Line between Warsaw and Katowice/Cracow) will add only 5,1 kph to the average speed of the system.

Table 4. Average travel cost per passenger in EUR [1], [3], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]

Route		R-c	R-p	CR-c=p	A	HSR-e	HYP-e
WAW	**GDA**	19.72	19.26	36.66	89.79	46.87	13,69
WAW	**SZCZ**	43.85	45.24	36.43	115.77	71.69	19,72
WAW	**POZ**	24.82	26.22	36.19	51.97	44.55	13,92
WAW	**WRO**	20.18	21.58	37.35	111.13	58.00	16,94
WAW	**KAT**	16.47	19.02	36.19	55.68	43.85	13,46
WAW	**KRA**	16.94	16.94	35.27	73.31	40.83	11,14
WAW	**RZE**	16.94	19.72	30.63	83.99	58.70	16,94
KRA	**GDA**	41.07	47.10	47.56	94.66	84.22	21,58
WAW	**LOD**	7.66	9.05	10.90		22.04	8,58
WAW	**LUB**	9.74	10.21	12.99		27.38	9,51
KRA	**KAT**	7.66	7.66	6.96		12.53	4,64
WRO	**POZ**	9.98	9.28	13.22		26.68	9,74
AVERAGE		*19,59*	*20.94*	*28.36*	*84.54*	*44.78*	*13.32*
MEDIAN		16,94	19.14	35.73	86.89	44.20	*13.57*

Individual car remains the least expensive travel option. High-speed train, if implemented on the basis of Spanish tariffs [11], would cost ca. half of an airplane fare. Hyperloop, if able to achieve no more than 2 times the level of ticket price estimated by Elon Musk in 2013, would become ca. one third cheaper than car. HSR and HYP tariff estimates have been adjusted to Poland's economic reality using coefficients based on comparison of GDP PPP.

Table 5. Current estimated number of passengers per year in thousands [23]

Route		R	CR	A	TOTAL
WAW	**GDA**	2 117	365	192	**2 674**
WAW	**SZCZ**	621	292	41	**953**
WAW	**POZ**	2 519	365	41	**2 924**
WAW	**WRO**	1 205	146	247	**1 598**
WAW	**KAT**	2 117	438	41	**2 596**
WAW	**KRA**	2 519	584	82	**3 184**
WAW	**RZE**	2 227	110	41	**2 377**
KRA	**GDA**	1 424	146	57	**1 626**
WAW	**LOD**	14 053	6 205	0	**20 258**
WAW	**LUB**	10 658	1 205	0	**11 863**
KRA	**KAT**	19 491	110	0	**19 601**
WRO	**POZ**	9 344	438	0	**9 782**
AVERAGE		*5 691*	*867*	*62*	***6 620***
MEDIAN		2 373	365	41	**2 778**
SUM		**68 292**	**10 403**	**741**	**79 435**

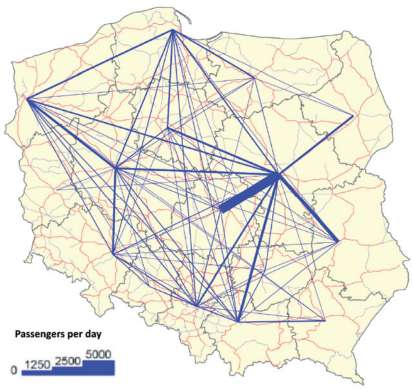

Fig. 5. Passenger flows - road [23]

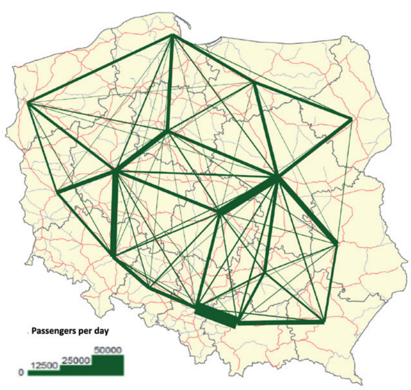

Fig. 6. Passenger flows - rail [23]

Due to limited availability of specific data on number of passengers travelling on specific routes the author has used estimates from maps presented in Fig 6 and Fig. 7 which are based on data (aggregated to a voivodeship level) from an official document: Regulation of Minister of Transport and Construction [23]. The document cites PKP Intercity S.A. (the largest provider of passenger railway services) and GDDKiA (the national administrator of national routes and highways) as sources of primary data.
Important notice: as soon as more detailed data sources for estimations provided in Table 5. become available, the calculations of total yearly cost per kilometer per passenger should be performed once again, as their results are heavily based on the number of passengers. The results of the cost of velocity for passenger calculation should not be subject to change in case the number of passengers proves to be different. No increase in number of passengers in the future due to reduced time of journey is assumed in calculations. Possible correlations should be subject of separate studies.

3.2. COST OF VELOCITY FOR PASSENGER

Table 6. Cost of velocity in EUR per kph [3], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]

Route		R-c	R-p	CR-c	CR-p	A	HSR-e	HYP-e
WAW	**GDA**	0.25	0.23	0.34	0.34	0.71	0.28	0,03
WAW	**SZCZ**	0.41	0.42	0.39	0.34	0.71	0.39	0,03
WAW	**POZ**	0.25	0.26	0.34	0.34	0.44	0.26	0,03
WAW	**WRO**	0.20	0.21	0.37	0.38	0.92	0.32	0,03
WAW	**KAT**	0.20	0.21	0.34	0.34	0.56	0.26	0,03
WAW	**KRA**	0.25	0.21	0.31	0.31	0.70	0.24	0,03
WAW	**RZE**	0.26	0.23	0.41	0.31	0.79	0.33	0,03
KRA	**GDA**	0.42	0.47	0.42	0.42	0.54	0.45	0,04
WAW	**LOD**	0.10	0.12	0.15	0.13		0.18	0,04
WAW	**LUB**	0.15	0.12	0.20	0.14		0.20	0,03
KRA	**KAT**	0.12	0.12	0.23	0.13		0.13	0,03
WRO	**POZ**	0.18	0.11	0.22	0.15		0.21	0,04
AVERAGE		*0,23*	*0.23*	*0.31*	*0.28*	*0.67*	*0.27*	*0.03*
MEDIAN		0,22	0.21	0.34	0.32	0.70	0.26	0.03

Effective average travel speed (Table 3.) is an important characteristic of a transportation system, however it seems not to tell the whole story. Cost of velocity (Table 6.) seems an important additional metric showing how much a passenger has to pay in order to travel at a certain speed. Comparison of average and median results shows that high-speed rail could become competitive to road transportation, while Hyperloop might be even 6-7 times cheaper than car, from the point of view of a client.

3.3. COST STRUCTURE

The goal of this part is to set ourselves up as a decision-maker who is forced to choose only one mean of transportation that could satisfy current demand for travel on analyzed routes in a generally most cost effective manner. Due to insufficient data availability possible limitations of the analysis are important: each route is treated separately and the model does not take into account a situation where certain sections are being used for more than one inter-city route and by local commuters as well. The sum of all routes. which is used for the final calculation, however outweighs and balances out to a large extent the double counting of costs of shared sections and not taking into account local commutes. Thanks to this, in overall, the final results seem to offer a rather sufficient level of credibility.

Air transportation is excluded from this part due to limited possibility of attributing infrastructure costs to certain routes.

Spending on linear infrastructure construction only is taken into account. Preparatory, land acquisition, station construction. public spending on exploitation and similar costs are not included.

Operation costs are expected to be included in travel costs (fares).

All items not sufficiently analyzed in this paper should be subject to further investigation.

Table 7. Infrastructure costs depreciated per year in EUR million [9], [24], [25], [26], [27]

Route		R-p	CR-p	HSR-e	HYP-e
WAW	**GDA**	76	60	134	172
WAW	**SZCZ**	148	94	209	269
WAW	**POZ**	83	55	124	159
WAW	**WRO**	86	74	165	212
WAW	**KAT**	72	55	122	157
WAW	**KRA**	66	53	119	153
WAW	**RZE**	77	75	168	217
KRA	**GDA**	159	113	252	325
WAW	**LOD**	35	24	54	70
WAW	**LUB**	40	32	72	93
KRA	**KAT**	21	14	32	41
WRO	**POZ**	36	30	68	87
AVERAGE		*75*	*57*	*126*	*163*
MEDIAN		74	55	123	158
SUM		**899**	**681**	**1 518**	**1 955**
Total distance (km)		3 660	3 747	3 747	3 747
Cost per km		0.25	0.18	0.41	0.52
Cost (EUR) per km per passenger		**0.0031**	**0.0023**	**0.0051**	**0.0066**

Table 8. Construction costs of infrastructure per kilometer in EUR million [3], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [28], [29]

Value	R-p: high-way	R-p: express	R-p: other	CR-p	HSR-e	HYP-e
General cost per kilometer	8.59	7.10	6.18	5.78	9.00	11.60
Share of passenger traffic	70.8%	70.8%	70.8%	69.8%	100%	100%
Passenger cost per kilometer	6.09	5.02	4.38	4.04	9.00	11.60

Modernization of conventional rail seems to be the most cost-efficient option. Hyperloop seems to be the most expensive option (calculation includes more expensive

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prestressed concrete tubes on the ground level, it should be repeated when more specific data becomes available), followed by high-speed rail.

Table 9. Yearly travel costs for all passengers in EUR million [3], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [24], [25], [26], [27], [28], [29]

Route		R-p	CR-p	HSR-e	HYP-e
WAW	**GDA**	52	98	125	37
WAW	**SZCZ**	43	35	68	19
WAW	**POZ**	77	106	130	41
WAW	**WRO**	35	60	93	27
WAW	**KAT**	49	94	114	35
WAW	**KRA**	54	112	130	35
WAW	**RZE**	47	73	139	40
KRA	**GDA**	77	77	137	35
WAW	**LOD**	183	221	446	174
WAW	**LUB**	121	154	325	113
KRA	**KAT**	150	136	245	91
WRO	**POZ**	91	129	261	95
AVERAGE		*81*	*108*	*185*	*62*
MEDIAN		65	102	134	39
SUM		**978**	**1 296**	**2 214**	**742**
Total distance (km)		3 660	3 747	3 747	3 747
Cost per km		0.27	0.35	0.59	0.20
Cost (EUR) per km per passenger		**0.0034**	**0.0044**	**0.0074**	**0.0025**

Travel cost per km per passenger of conventional rail is estimated at 129% of road, while for high-speed rail and Hyperloop it is likely to be 221% and 74%, respectively.

Table 10. Subtotal yearly costs for all passengers in EUR million [3], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [24], [25], [26], [27], [28], [29]

Route	R-p	CR-p	HSR-e	HYP-e
SUM	**1 877**	**1 976**	**3 732**	**2 697**
Total distance (km)	3 660	3 747	3 747	3 747
Cost per km	0.51	0.53	1.00	0.72
Cost (EUR) per km per passenger	**0.0065**	**0.0066**	**0.0125**	**0.0091**

After adding up travel costs, road and conventional rail are on a similar level per unit of effectiveness. HSR is expected to be 94% and Hyperloop 40% more expensive.

Table 11. Time lost yearly by all passengers compared to hyperloop in hours [3], [10], [11], [12], [13], [14], [15], [23]

Route		R-p	CR-p	HSR-e
WAW	**GDA**	8 690 942	6 284 220	3 208 963
WAW	**SZCZ**	4 163 093	3 734 072	1 779 643

WAW	**POZ**	7 018 512	6 287 417	3 216 818
WAW	**WRO**	4 314 125	5 299 450	2 370 106
WAW	**KAT**	6 619 494	5 581 142	2 855 468
WAW	**KRA**	9 287 425	6 156 236	3 396 544
WAW	**RZE**	7 566 401	8 121 007	3 565 320
KRA	**GDA**	7 913 920	7 209 256	3 685 935
WAW	**LOD**	22 283 250	20 257 500	9 791 125
WAW	**LUB**	17 596 042	15 223 542	7 710 625
KRA	**KAT**	13 393 675	17 640 450	5 553 475
WRO	**POZ**	12 553 567	11 086 267	6 032 233
AVERAGE		*10 116 704*	*9 406 713*	*4 430 521*
MEDIAN		8 302 431	6 748 337	3 480 932
SUM		**121 400 445**	**112 880 557**	**53 166 255**

Table 12. Value of time lost per year by all passengers compared to hyperloop in EUR million [3], [10], [11], [12], [13], [14], [15], [23], [30]

Route		R-p	CR-p	HSR-e
WAW	**GDA**	54	39	20
WAW	**SZCZ**	26	23	11
WAW	**POZ**	44	39	20
WAW	**WRO**	27	33	15
WAW	**KAT**	41	35	18
WAW	**KRA**	58	38	21
WAW	**RZE**	47	50	22
KRA	**GDA**	49	45	23
WAW	**LOD**	138	126	61
WAW	**LUB**	109	94	48
KRA	**KAT**	83	110	34
WRO	**POZ**	78	69	37
AVERAGE		*63*	*58*	*27*
MEDIAN		52	42	22
SUM		**753**	**700**	**330**
Total distance (km)		3 660	3 747	3 747
Cost per km		0.21	0.19	0.09
Cost (EUR) per km per passenger		**0.0026**	**0.0024**	**0.0011**

Lost time can be considered a social cost of a transportation system and should be taken into account by decision makers when considering new investments in linear infrastructure. Potential advantages of Hyperloop in these terms are subject to confirmation when more detailed data from feasibility studies and possibly first operating systems are available. The calculations should be also done once again upon receipt of more detailed data on the number of passengers for every analyzed route.

3.4. TOTAL YEARLY COST PER KILOMETER PER PASSENGER

The measure calculated in this point is another proposal for taking into account effective speed while analyzing performance of transportation systems.

Table 13. Total yearly costs including value of lost time in EUR million 3], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [24], [25], [26], [27], [28], [29]. [30]

Route		R-p	CR-p	HSR-e	HYP-e
WAW	**GDA**	181	197	279	209
WAW	**SZCZ**	217	152	288	288
WAW	**POZ**	203	200	274	200
WAW	**WRO**	147	167	272	240
WAW	**KAT**	163	183	253	192
WAW	**KRA**	177	204	270	189
WAW	**RZE**	171	199	330	257
KRA	**GDA**	285	235	412	360
WAW	**LOD**	357	371	561	244
WAW	**LUB**	270	281	445	206
KRA	**KAT**	254	260	312	132
WRO	**POZ**	205	228	366	183
AVERAGE		*219*	*223*	*338*	*225*
MEDIAN		204	202	300	207
SUM		**2 630**	**2 677**	**4 062**	**2 697**
Total distance (km)		3 660	3 747	3 747	3 747
Cost per km		0.72	0.71	1.08	0.72
Cost (EUR) per km per passenger		**0.0090**	**0.0090**	**0.0136**	**0.0091**

When all three expense aspects are taken into account:

1. linear infrastructure costs financed usually with public money,
2. travel expenses paid by a passenger which should include each system's operating expenses (which however may also be subject to subsidies),
3. estimated value of time lost while travelling by means slower than the fastest option (possibly Hyperloop),

road, conventional rail and Hyperloop (based on assumptions according to currently available data) seem to reach a similar level of cost-effectiveness, while high-speed rail is expected to be ca. 50% more expensive.

Additional probable characteristics of Hyperloop system that should be taken into account for further evaluation:

- immunity to weather conditions and decreased vulnerability for accidents,
- extremely low energy usage and minimal CO2 emission,
- low footprint and possibility to reclaim some portions of valuable land currently used by other infrastructure,
- on-demand functionality and high-frequency of operation.

This features could be subject to further research and comparison of performance of existing and proposed transportation solutions, both for passenger and cargo uses.

CONCLUSION

Based on the analysis described in this paper one can assume that Hyperloop seems a reasonable alternative for current modes of transportation and its economic, social and environmental potential should be carefully examined in the coming years, while the technology is being developed.

Application of two new proposed metrics of performance of transportation systems based on cost-effectiveness analysis proves that this new technology should be cost effective while compared to currently available options and above all to its main competitor: high-speed rail.

Cost of velocity for passenger (Table 6.) shows how much a passenger has to pay in order to travel at a certain effective speed. Comparison of average and median results shows that high-speed rail could become competitive to road transportation, while Hyperloop might be even 6-7 times cheaper than car, from the point of view of a client.

Total yearly cost per kilometer per passenger (Table 13.) takes into account three cost categories: linear infrastructure costs, travel expenses paid by a passenger and estimated value of time lost while travelling by means slower than the fastest option (possibly Hyperloop). Application of this measurement shows that road, conventional rail and Hyperloop (based on assumptions according to currently available data) seem to reach a similar level of cost-effectiveness, while high-speed rail is expected to be ca. 50% more expensive. Probable low operation costs (fares) and important travel time savings of Hyperloop are likely to balance out construction costs, that for the moment seem higher than for other options.

When one takes into consideration other important aspects, among them energy and environmental issues, Hyperloop seems even more desirable. The above statements should be subject to constant verification while more and more precise economic data about the system is revealed. To sum up, Hyperloop seems able to become a truly disruptive transportation innovation, if its economic fundamentals confirm themselves at levels not worse than assumed in this paper.

Finally, the two possible measures of transportation system's performance proposed and discussed is this paper seem reasonable metrics for evaluation of performance of existing and proposed transportation systems and should be subject to further development and enhancement.

The results however, need to be carefully verified with other sources of data, concerning both passenger flows on routes analyzed in this article, as well as using data for other geographies. Results of such verified proposed metrics should also be confronted with standard measurements used in transportation economics, such as ROI and others.

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KONCEPCJA HYPERLOOP NA TLE EFEKTYWNOŚCI INNYCH ŚRODKÓW TRANSPORTU

STRESZCZENIE

Transport pasażerów i towarów na średnich i długich dystansach zdominowany jest obecnie przez trzy podstawowe gałęzie: transport drogowy, kolejowy i lotniczy. Można przyjąć, że co najmniej od lat osiemdziesiątych XX w. w żadnej z wymienionych wyżej gałęzi transportu nie miała miejsca naprawdę przełomowa innowacja technologiczna. Wyjątek stanowi rozwój branży samochodów elektrycznych oraz testy samochodów autonomicznych. Nie zmienia to jednak faktu, że powyższe rozwiązania nie wyeliminują pozostałych wad samochodu, tj. stosunkowo niskiej prędkości, podatności na korki, etc. W 2013 roku Elon Musk przedstawił założenia dla nowego środka transportu - Hyperloop: stalowej rury o bardzo niskim ciśnieniu rozciągniętej na pylonach pomiędzy miastami, w której specjalne kapsuły poruszają się na poduszkach powietrznych z prędkością nawet 1220 km/h. Niniejszy artykuł ma na celu dokonanie oceny podstawowych parametrów efektywnościowych istniejących środków transportu drogowego, kolejowego i lotniczego na wybranych trasach w Polsce i zestawienie ich z dostępnymi danymi na temat przewidywanej efektywności systemu Hyperloop.

SŁOWA KLUCZOWE

Hiperloop, wydajność systemów pasażerskiego transportu: drogowego, konwencjonalnej kolei, kolei dużych prędkości, lotniczego