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The Impact of Intelligent Transportation System Implementations on the Sustainable Growth of Passenger Transport in EU Regions

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Abstract: This article discusses original studies that demonstrate the relation between developed elements of the transportation network (road system density; railway system density; number of regional railway and bus connections, length of regional railway and bus connections, online accessibility to transportation services and other services related to the development of IT techniques to benefit mass transit) and the regional GNP. A new development relative to preceding studies (as quoted) is that the correlation coefficients calculated do not indicate any essential interrelations between elements of the transport system, or even the number of regional passenger transport services and regional GNP. A determination of the remaining data interrelations indicated the elements of the network which are considered essential to the development of mass transit, as resulting from a study carried out for the first time in 2015 for the Górnośląska-Zagłębioska Metropolis. Considering the fact that the number of railway connections has proven to be the most important determinant of the overall number of passenger transport services, the second part of the article presents studies that focus on the modeling of the railway network, applying the graph theory (extensively applied for ITS). Selected optimized models were analyzed and assessed in terms of possible implementability of specific improvements and the resultant growth in the number of passenger transport services. The research method applied was not novel, but the conclusions drawn from it were surprising, as they indicated that an optimized network of railway connections would not cause any significant increase in the number of passenger transport services. Successive surveys (supplementing statistical analyses) have confirmed the importance of ITS in increasing the share of mass transit in overall transit. (1) The study was carried out in Polish regions, with particular emphasis on Silesia. (2) Its conclusions emphasize the importance of data accumulated for ITS in decision-making processes aiming to ensure the sustainable development of mass/passenger transport. The article confirms a hypothesis which claims that "modeling the regional public transportation grid, applying the principles of ITS, stimulates a growth in the share of passenger transport in the overall bulk of transport, thus contributing to the sustainable development of the region".

Keywords: ITS; mass transit; development of EU regions

1. Introduction

The article contains original studies that present the relationship between developed elements of the transport network and the GNP of any selected EU region. Particular emphasis is put on the interdependencies between regional passenger transport services and the regional GNP. The authors claim that the results of these studies would facilitate any decisions concerning railway infrastructure and railway connections. The authors propose that data is collected and used for ITS to make investment and organizational decisions. They have proven that the current data is dispersed and non-cohesive, which hinders its processing. The variable correlation results obtained in the study are new. Before, researchers would claim that the development of infrastructure elements was strongly correlated with GNP growth, whereas our study has shown that it is the contrary. Seeking an interdependency between variables, a single element was found, i.e., the number of regional railway connections, which indicates a higher (although not essential with GNP), but nonetheless essential relation with the number of passenger transport services carried out via regional railways. With this result in mind, a study was commenced to optimize the railway network in a selected region. The study can be construed as new due to its geographic range. Optimization of the railway network was carried out for the first time for the Śląsko-Zagłębiowska Metropolis established in 2017. A known graph theory was applied in the optimization process. The simulation has indicated that the proposed network optimization can affect (although insignificantly) the number of passenger transport services carried out with the use of regional railways. The authors recommend periodical modeling of the railway network, applying ITS, due to the Metropolis development dynamic. Unsatisfied with the results of past studies which have not led to the formulation of any specific postulates regarding the sustainable transport policy, the authors conducted their successive studies—ones that were based on surveys. The respondents confirmed that the application of ITS which synchronize the various modes of regional transport could convince them to switch to means of mass transit.

Our comprehensive study of regional transport is an innovative research model, which could be applied when making decisions regarding infrastructural investments and organization of transport network.

1.1. Infrastructure and Regional Development

Many published works have displayed the relationship between infrastructure and the sustainable development of cities and regions [1–6].

The majority of studies suggest that the population of a given area is directly related to economic growth, although there are no exact estimates as to how investments in urban infrastructure, including transport infrastructure, contribute to this positive effect. A transport infrastructure that facilitates the development of urban areas and reduces the costs of transport should theoretically be related to faster development of cities and regions, and to the faster development of the entire economy, although a surprisingly small number of studies have scrutinized these effects (probably due to limited access to data). The smart city concept, which has recently gained considerable momentum, promotes the growth of social capital (development of knowledge and social activity) through the development of telecommunication, education and research infrastructure. What is noteworthy, is that infrastructure is an important factor in increasing the attractiveness of a city/region for potential investors, business owners, workforce, which translates into GNP growth [7]. As Glaeser and Gottlieb (2009) [8] have indicated, the correlation between the size of urban population and the level of growth (regional GNP growth) is very close. In turn, Ciccone and Hall (1999) [9] have proven that this relationship is causal by nature—the more people live in large cities, the higher productivity is in this region. This is consistent with the theory of growth coined by Robert Lucas, who accentuated the spread of knowledge in urban areas. These conclusions are confirmed by many other studies, such as [10]. The interrelation between transportation infrastructure and productivity growth is displayed by Caragliu and associates (2009) [11]. The author points to a high correlation between the development of the public transportation network and productivity in cities. He confirms a hypothesis that mass transit contributes to the development of urban areas, among others, by reducing the crowding and providing a better access from the suburbs. For instance, basing on US data, Duranton and Turner (2007) [12] have estimated that a 10% increase in the number of bus connections has resulted in an 0.8% growth in urban population. In turn, Baum-Snow (2007) [13] has indicated that the post-war development of the highway network in the US resulted in the development of suburban areas, reducing the populations of city centers. However, in discussing the roles of cities, transport infrastructure is more and more often superseded by telecommunication or social infrastructure, which determine the speed, in which knowledge or the quality of life spread throughout the city. Above all, many studies point to the fact that the pace of productivity growth in the city is primarily determined by the percentage of (well-) educated people. Yet, this is not a simple effect of higher productivity of people with higher education. According to the development economics theory, it is the positive effect of knowledge spreading. Moretti (2004) [14] has estimated that a 1% increase in the number of people with higher education resulted in an average salary increase of 0.6–1.2% for those with lower education. Shapiro (2005) [15] has displayed that only slightly more than half of the positive effects on the labor market, as resulting from the growing percentage of people with higher education, are the direct effects of higher productivity exercised by these people. The remaining effects are indirect ones, consisting predominantly in growth in demand, and thus growth in supply by such facilities as bars, restaurants, cinema houses, theaters, etc. In the opinion of this author, the quality of life in cities with a high percentage of educated people has been growing, entailing so-called snowball effects—more and more people are coming to the city, which generates high demand, and leads to economic development of the region and of the entire country. Local authorities often face a dilemma: whether to build a road, a library, a park, or a family activity zone? A simple economic theory accentuating the role of infrastructure in the reduction of private-sector costs would probably point to the greater benefits of a road. However, a consideration of the role of cities/regions must include additional factors, aside from the traditional cost-benefit calculation, i.e., the role of an investment in stimulating the development of a smart city. In their article, the authors claim that building roads, organizing and modeling connections and developing smart telecommunication networks dedicated to facilitating mass transit in the region are all important for raising the regional GNP [16–18].

1.2. Intelligent Public Transportation Systems

The very term of Intelligent Transportation Systems has been officially defined at the 1994 world congress in Paris [19] and encompasses all systems incorporating a wide variety of technologies (telecommunication, IT, automation, measuring) and management techniques applied in transportation for the purpose of protecting the life and health of traffic participants, increasing the effectiveness of the transportation system, and protecting the natural environment with all its resources. Figure 1 presents the ITS architecture. Table 1 presents a breakdown of Intelligent Transportation Systems according to ISO TC 204.

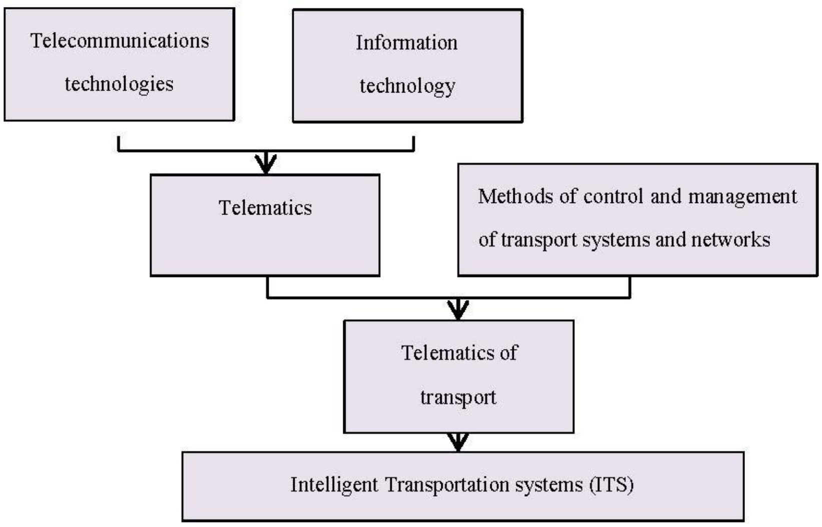

Figure 1. The counterparts of Intelligent Transportation Systems [20].

The benefits of applying Intelligent Transportation Systems [20,21]:

Increase of street throughput by 20–25%.

Increase of road traffic safety (traffic accident reduction by 40–80%).

Improvement of traveling comfort and traffic conditions for drivers, mass transit passengers and pedestrians.

Reduction of rolling stock management costs.

Reduction of paving management and repair costs.

Increase of the economic benefits of the region.

Table 1. A breakdown of Intelligent Transportation Systems as per ISO TC 204 [22].

Service Category	No	Name of Service
Traveler information	1	Pre-trip information
	2	On-trip driver information
	3	On-trip public transport information
	4	Personal information services
	5	Route Guidance and Navigation
Traffic management	6	Transportation planning support
	7	Traffic control
	8	Incident management
	9	Demand management
	10	Policing/Enforcing traffic regulations
	11	Infrastructure maintenance Management
Vehicle	12	Vision enhancement
	13	Automated vehicle operation
	14	Longitudinal collision avoidance
	15	Lateral collision avoidance
	16	Safety readiness
	17	Pre-crash restrain deployment
Commercial Vehicle	18	Commercial vehicle pre-clearance
	19	Commercial vehicle administrative process
	20	Automated roadside safety inspection
	21	Commercial vehicle on-board safety monitoring
	22	Commercial vehicle fleet management
Public transport	23	Public transportation management
	24	Demand responsive transport management
	25	Shared transport management
Emergency	26	Emergency notification and personal security
	27	Emergency vehicle management
	28	Hazardous Materials and incident notification
Electronic Payment	29	Electronic financial transaction
Safety	30	Public travel safety
	31	Safety enhancement for vulnerable road users
	32	Intelligent junctions

The physical architecture of Intelligent Transportation Systems is illustrated in Figure 2.

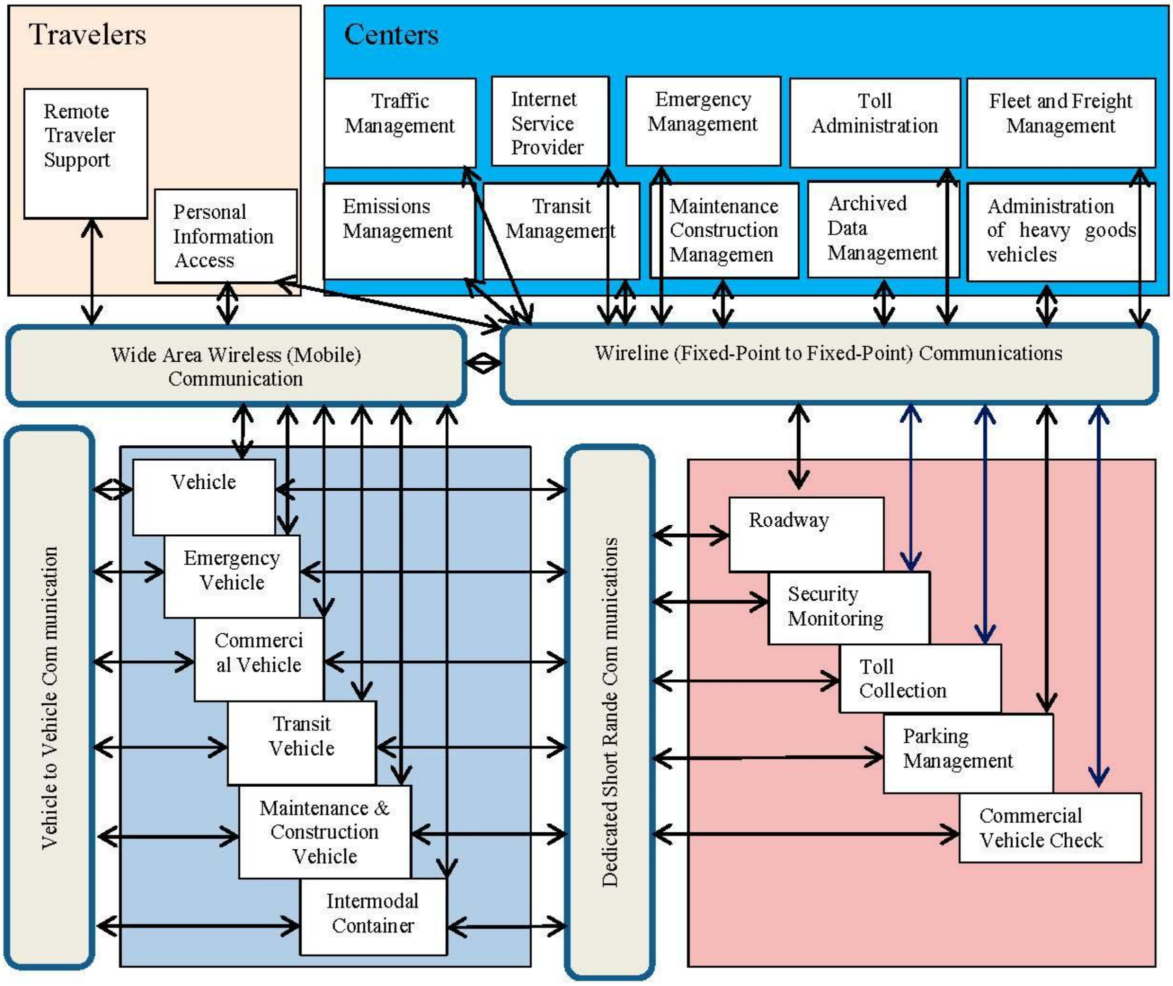

Figure 2. Physical ITS architecture [22].

One of the most important goals set by countries/regions/cities for themselves when implementing smart solutions in transportation is establishing an ITS architecture, i.e., a series of interconnections (logical, physical and transit) among elements of systems comprising Intelligent Transportation Systems to crease scalable solutions which are also easy to maintain and manage [23]. ITS can also support the development and maintenance of transport infrastructure (including railway infrastructure) as described in more detail later in this article. In Poland, the authorities have not indicated any specific ITS technologies or suppliers, thanks to which they are open systems that increase the competitiveness of implemented solutions. These are however "isolated" by nature, i.e., they separately fulfill their intended roles, but, combined, they may become incompatible, incapable of supporting one another. Data from different ITS areas should however be consolidated. The information generated can serve as support in decisions concerning transportation systems and their performance, as illustrated by numerous studies [24].

To facilitate data uniting and to enable the cooperation of many independent systems, measures should be taken under ISO 24014-1:2015-12, as this very standard defines the basic notions related to the implementation of an interoperative payment system in transport.

1.3. ITS Facilitating the Management and Maintenance of Road Infrastructure towards Increasing the Economic Benefits of the Region

Managing infrastructure maintenance is particularly difficult on so-called rising markets, since countries which only recently joined EU structures have insufficient data which could support national-/regional-/municipal-level authorities in making many important decisions. It is difficult to measure the productiveness of public capital, i.e., the impact of public funds invested (e.g., in transport infrastructure and ITS to support infrastructure management) on the level and pace of GNP growth. The majority of studies conducted on developed markets have indicated a positive and relatively high productivity of capital invested in infrastructure. Researchers further suggest that much depends on the effectiveness of administration. Studies of public capital productivity were pioneered by Aschauera (1989) [25]. In turn, Straub (2007) [26] calculated that approx. 90% of contemporary studies pointed to the positive effect of infrastructural investments on the level and pace of economic development, with 10% having negative effect. What is interesting, these effects are most visible when the impact of specific infrastructure (e.g., transit or telecommunication) is examined. Bom and Ligthart (2008) [27] meta-analyzed 76 studies devoted to the end productivity of public capital. An analysis carried out by the authors has indicated that a flexibility indicator of 0.087 GNP was the best value to summarize all studies, which means that a 1% increase in public capital resources generates a 0.089% GNP increase. To obtain end capital productivity, this value should be divided by the share of public capital resources in the GNP. In the majority of developed countries, the share of public capital in the GNP is approx. 0.4-0.6, which translates into approx. 0.15–0.22% in end productivity of this capital maintaining a flexibility of 0.087. This is a lot, considering that the end productivity of private capital is close to the real interest rate applied in the majority of developed countries, i.e., to 2–4%.

It is even more difficult to calculate the productivity of invested capital on a regional level, primarily due to the aforementioned data insufficiency, hindered access to data, or access to misleading data, e.g., doubled for infrastructural investments implemented by several regions or cities. The precision of calculations can be determined by integrating the monitoring of infrastructural investments, by implementing regional legislative and IT solutions. Monitoring, decisions made, and expenditure must be preceded by a determination of pertinent goals, as illustrated in Figure 3.

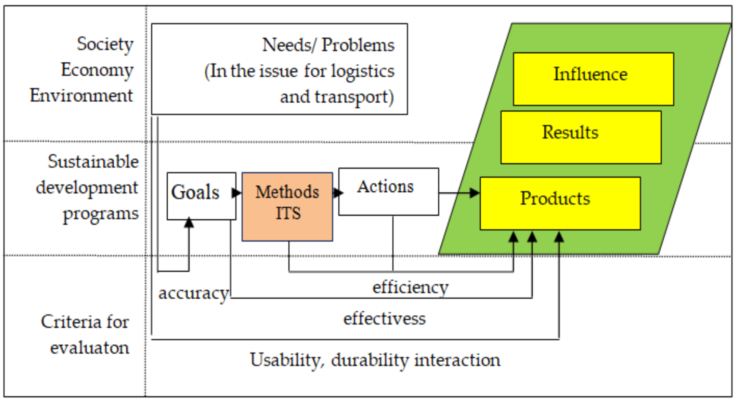

Figure 3. Evaluation of the regional infrastructure and public transport network [28].

Detailed, achievable goals depend on the economic, industrial and social properties of the region, and on the past development of the region. However, their main assumptions are established by the EU and are specified for Poland in the White Book of Infrastructure—16 initiatives for infrastructure. In this document, the planned development of transportation infrastructure considers the needs of particular means of transport (road, railway, inland water, sea, air transport) and changing models of social mobility and economic needs, in a breakdown into areas. A distribution of financing on the development of transport infrastructure must be tied to the mechanism for financing municipalities and poviats [29].

There are many methods of designing transport infrastructure. Methods applying dynamic modeling (as exemplified by the graph theory) have recently become very popular. In the case of dynamic modeling methods, when selecting the sites to locate transportation facilities, all types of fluctuations of source data concerning, among others, mobility patterns, the sizes of transit streams, transit costs and environmental damage are taken into account [30]. Hence the modeling of transportation infrastructure in the region is completed by modeling a network comprising various branches of public transportation (applying network profile measures and the properties of complex networks and IT systems). The development of a modeled transportation system is supported by public campaigns promoting sustainable mobility, i.e., abandoning private cars in favor of mass transit (particularly railway transport) [31]. Management of these campaigns is an element of the overall management of public transportation utilizing ITS.

1.4. Graph Theory in the Analysis of Transport Networks

Network analysis methods have been used for several years now, whether to analyze social systems [32–34], or to analyze neuron systems [35–37], biological systems [38] and computer systems [39]. This was a result of considerable mathematical development of these methods. The possibilities of analyses carried out with the use of the graph theory are also presented in [40]. According to [40–45], the same methods and coefficients which have been successfully applied by sociologists in the analysis of social systems can be now used to analyze transportation networks. [41] contains a comparative analysis of three types of systems which, in terms of parameters, correspond to actual networks. An analysis of their immunity to disturbances was also conducted. In turn, [42] includes an analysis of transportation networks in Poland, assuming three different branches: air transport, railway transport and road transport.

According to information provided in [32–45], networks (social systems, transportation networks, etc.) can be analyzed with the use of three measures, which are sufficient for determining their characteristic features and the "quality" of the entire network. The majority of measures applied and calculations performed produce information which serves as the "leader" from the point of view of the network, serving as a central point for the analyzed network.

Each network can be described as a collection of nodes and their interrelations:

$$G = \langle V,\ E \rangle \tag{1}$$

where:

V—a collection of nodes.
E—a collection of their interrelations.

Of course, the following interrelation applies to every network analyzed:

$$|V| = N,\ |E| = M \tag{2}$$

As described in detail in [40,42], the following coefficients are most frequently applied in analyses:

Normalized degree (dc_i) for an i-th node:

$$dc_i = \frac{k_i}{N-1} \tag{3}$$

where:

k_i—degree of this i-th node in the network (the number of node connections with other nodes).
N—number of nodes in the network.

The higher the dc_i coefficient value for this i-th node, the more important role this node serves in the network, or the closer the node is situated to its center.

Eccentricity (ec_i) of an i-th node in the network:

$$ec_i = \max_{j \in V} d_{ij} \tag{4}$$

where:

d_{ij}—number of links among the nodes, wherein a link is understood as the shortest distance between node i and node j.

The lower the ec_i coefficient value for this i-th node, the more important role this node serves in the network, or the closer the node is situated to its center.

Radius (rc_i) of this i-th node in the network:

$$rc_i = \frac{1}{\max\limits_{j \in V} d_{ij}} = \frac{1}{ec_i} \quad (5)$$

where:

d_{ij}—number of links among the nodes, wherein a link is understood as the shortest distance between node i and node j.
ec_i—eccentricity of this i-th node in the network.

The higher the rc_i coefficient value for this i-th node, the more important role this node serves in the network, or the closer the node is situated to its center.

Closeness (cc_i):

$$cc_i = \frac{N-1}{\sum_{j \in V} d_{ij}} \quad (6)$$

where:

N—number of nodes in the network.
d_{ij}—number of links among the nodes, wherein a link is understood as the shortest distance between node i and node j.

Betweenness (bc_i) for an i-th node in the network:

$$bc_i = \sum_{l \in V} \sum_{k \neq l \in V} \frac{p_{l,i,k}}{p_{l,k}} \quad (7)$$

where:

$p_{l,i,k}$—number of connections with the lowest number of nodes between nodes l and k (containing node i).
$p_{l,k}$—number of connections with the lowest number of nodes between nodes l and k (which do not contain node i).

The higher the bc_i coefficient value for this i-th node, the more important role this node serves in the network, or the closer the node is situated to its center.

Clusterization (gc_i) of this i-th node in the network:

$$gc_i = \frac{2E_i}{k_i(k_i - 1)},\ k_i > 1 \quad (8)$$

where:

E_i—number of links among nodes which are situated closest (neighbors) to the i-th node.
k_i—degree of this i-th node in the network (number of node connections to other nodes).

The higher the gc_i coefficient value for this i-th node, the more important role this node serves in the network, or the closer the node is situated to its center.

Formulas (2)–(8) describe the parameters of particular nodes in a network. However, coefficients used to determine the parameters of an entire network are also applied. These are [40,42].

Average shortest paths length (L):

$$L = \frac{1}{N(N-1)} \sum_{i \neq j \in V} d_{ij} \tag{9}$$

where:

N—number of nodes in the network.
d_{ij}—number of links among the nodes, wherein a link is understood as the shortest distance between node i and node j.

The lower the value of the average shortest path length, the better the analyzed network.
Clusterization coefficient (C):

$$C = \frac{1}{N} \sum_{i \in V} gc_i \tag{10}$$

where:

N—number of nodes in the network
gc_i—clusterization coefficient

The higher the value of the clusterization coefficient, the better the analyzed network.
Diameter (D):

$$D = \max_{i \in V} ec_i \tag{11}$$

where:

ec_i—eccentricity of the i-th node in the network

The smaller the diameter, the better the network.
Radius of a network (R):

$$R = \min_{i \in V} ec_i \tag{12}$$

where:

ec_i—eccentricity of the i-th node in the network

The smaller the radius of the network, the better the network.
Average nodes degree ($\bar{k}$):

$$\bar{k} = \frac{1}{N} \sum_{i \in V} k_i \tag{13}$$

where:

N—number of nodes in the network
k_i—degree of this i-th node in the network (number of node connections to other nodes);

The higher the average node degree in the network, the better the network.

Instances when all networks have the same "importance" level practically are not encountered in any of the existing networks. In turn, all networks have key nodes which, more than others, bear the load of correct functioning of the entire network. Determining and locating these nodes can contribute to identifying the current condition of the entire network, providing tips for its improvement.

The studies presented below consisted in the modeling of a railway carrier network in a virtual environment, as well as the calculation of coefficients for individual nodes using the "Gephi" software.

2. Research Methodology—Stages, Goals, Hypotheses, Research Model

At the first stage of the study, the relationship between the number of passenger transport services using means of mass transit and the transportation infrastructures in individual regions, the number and lengths of regional bus and railway connections was identified. The relationship between the GNP of these regions and the mobility of their residents (the number of passenger transport services using means of mass transit, the number of transport services using own means of transport) was also studied. Correlation coefficient is calculated using the following formula:

$$r = \frac{\frac{1}{N}\sum_{1}^{n}(x - \overline{x})\left(y - \overline{\overline{y}}\right)}{\delta_x \delta_y} \tag{14}$$

where:

r—correlation coefficient.
N—number of observations.
x, y—empirical variable values.
δ_x; δ_y—standard variable deviations.

Then, the region to be further analyzed at the next stage of the study was selected. In the selected region, the strongest relationship was identified between the number of railway connections and the number of passenger transport services.

At the second stage of the study, the structure of the network of railway connections and simulated optimization was analyzed, where improving the overall network parameters served as the optimization criterion. The purpose of stage two was to display that the optimization of the railway system (improvement of its parameters) would slightly contribute to an increase in the number of passenger transport services.

Optimization results were presented to passengers-respondents participating in stage three of the study. The survey carried out at the third stage of the study indicated that passengers were expecting synchromodal solutions.

The main purpose of the study was to answer several research questions, i.e.,

- Whether there's a connection between the elements of the transportation grid from different branches, the number of passenger transport services in the region and the regional GNP?
- Whether an ITS facilitating the optimization of a transportation grid in one branch of regional transit is capable of contributing to a growth in the number of passenger transport services, or whether synchromodal optimizations are necessary?
- Which of the ITS supporting passengers would contribute to increasing the number of regional passenger transport services and would thus affect the transit decisions of the local population, i.e., convincing them to switch from their own means of transport to mass transit?

These research questions are interesting and worth answering, as there are few studies that examine the connections among the number of mass transit transport services and the transportation infrastructure and the mobility of passengers and the regional GNP. There is also insufficient data and expert ITS measuring these interconnections. For the purposes of answering the questions formulated above, a statistical analysis was carried out on secondary and resultant data presented in Tables 1 and 2 (concerning selected regions and the year 2015, 2016 and 2017). A primary study was also conducted to indicate the most important modern ITS solutions (from the "passenger support" and "network and traffic maintenance" groups—see Figure 2), the purpose of which is to convince passengers to switch from their own means of transport to mass transit. A confirmation of three hypotheses was sought:

H1: There are relations among: (1) the number of connections in the region; (2) the lengths of regional transportation lines; (3) the regional GNP; (4) the population of the region; (5) the population of the region's cities; (6) the number of passenger transport services.

H2: There are no confirmations of the significance of the relationship between the regional GNP and the number of passenger transport services. In the majority of regions examined, the regional GNP has been growing, while the number of passenger transport services has been decreasing (with the calculated correlation coefficient, one that has not indicated any significance). The share of the number of mass transit transport services is higher in regions with a high GNP, but this is mainly determined by the region's employment rate and urban development.

H3: Optimization of a network with respect to a single branch of mass transit and synchromodal planning in the ITS are the expectations of the residents of the region.

H4: Synchronization of transportation networks from various branches will convince the region's residents to switch to public communication—thus increasing the share of passenger transport services in total transit.

Figure 4 illustrates the research model developed.

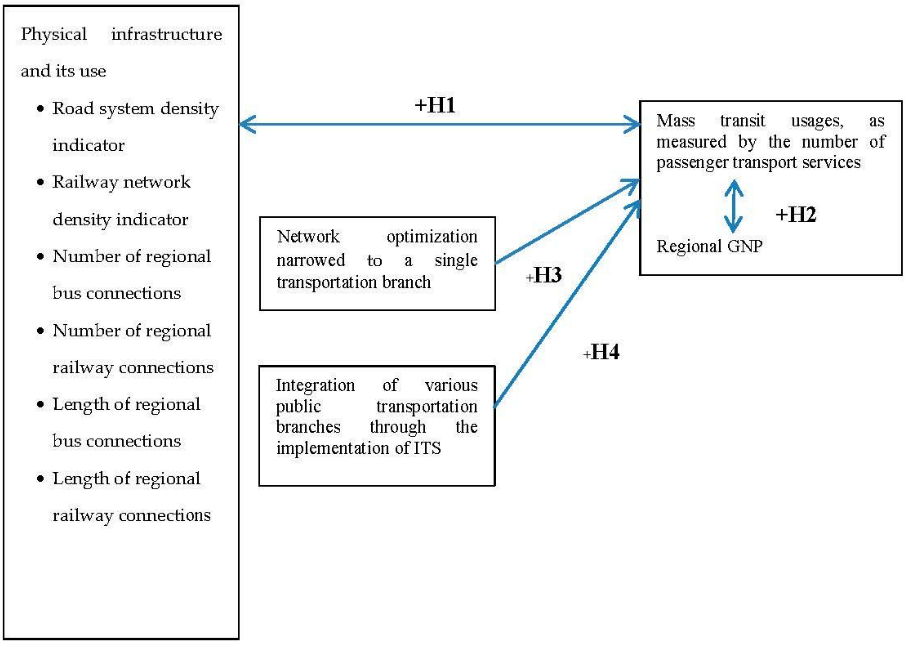

Figure 4. Research model. Source: Own study.

The first stage of the research process consisted in a statistical analysis of the secondary data obtained (applying the correlation coefficient). Then, an analysis of the railway network was carried out, applying the aforementioned graph theory, using the secondary data obtained as well as own data in the simulation. The purpose of quantitative analyses is to identify practical tips for decision-makers who oversee the development and maintenance of infrastructure and who manage public transportation networks (with emphasis on railway transportation). The last stage consisted in a qualitative and direct poll carried out among 500 passengers and concerning the development of ITS. The results of the survey provide an answer the following question: which of the ITS functions change the prevalent traveling patterns. The goals, methods and measures of this study could be used in each EU region. The data used in calculations is sourced from Polish regions. Hypotheses 2 and 3 were confirmed using data from Silesia (a region in southern Poland). On 1 July 2017, a metropolis of 41 municipalities referred to as Górnośląsko-Zagłębiowska Metropolia was established in the Śląskie Voivodeship. The government of the metropolis set the goals, the budget and the financial forecasts for the area. An important goal of the metropolis was to generate economic benefits for the region, among others, by reforming the transportation system (promoting a switch to mass transit) and implementing new investments in the transportation infrastructure.

Tables 2 and 3 presents source data, Table 4 presents correlation variables for which the coefficients were calculated, Table 5 presents the results of an analysis of correlations among secondary quantitative data, Tables 6 and 7 also present source data. Tables 8–15 present the results obtained, describing the parameters of the analyzed network of railway connections, and Table 16 presents the results of qualitative polls carried out among passengers and concerning their needs in terms of the most desired ITS from the passenger support group. Figures 5–16 illustrate a modeling of the Silesian Railway (Koleje Śląskie) connection networks from particular analyzed periods, and their proposed modification.

3. The Use of Transportation Infrastructure and ITS in the Context of the Economic Development of Polish Regions (Stage One of the Study)

3.1. Source Data Describing the Transportation Infrastructure and Its Use in Polish Regions

In the past few years, Polish regions have made significant endeavors in investing in their transportation infrastructures and connecting various branches of public transportation by means of ITS implementations. The rate of public investments (i.e., their GNP ratio) has increased from an average level of 3.4% in 1995–2006 to 5.2% in the following years. Counting both the last five years and the last decade, Poland was consistently top-ranked among countries with the highest rate of public investments in Europe, mainly owing to EU financing. However, achieving significant progress in the extension and improvement of infrastructure will require maintaining a successful investment rate at a high level for many years.

Poland has recorded an economic growth of approx. 1.8% GNP in 2016. Mazowsze, Śląsk, Wielkopolska, Dolny Śląsk, Małopolska and Łódzkie are the regions that particularly contributed to this growth, as illustrated in Table 2. These regions are very industrialized, and have the best transportation infrastructures in the countries. They also focus on the development of connections and on the computerization of mass transit (both public and private). They accumulate data related to transportation, preparing for the management of their transportation systems with the use of ITS based on Big Data and 4.0 solutions.

Table 3 presents the regional balance of passenger transport services in the railway system (published data) and using other means of transport (estimated data—calculated on the basis of published data).

3.2. The Use of Transportation Infrastructure and ITS in the Context of the Economic Development of Polish Regions—Results of the First Stage of the Study

Testing hypothesis H1, an analysis of correlations among variables selected from Tables 2 and 3 was conducted. As mentioned earlier, Table 4 presents correlation variables for which the coefficients were calculated. Table 5 presents the calculated coefficients of variable correlations for the Śląskie Region. For other regions, correlation calculations were completed, but were left out due to the limited volume of the article, focusing further studies on the Śląskie Region.

Completed calculations produced cognitive conclusions for the first stage of the study. There is a straightforward correlation between particular variable couples: 1. number of connections in the region, 2. length of regional connection lines, 3. regional GNP, 4. population of the region, 5. population of the region's cities, 6. number of passenger transport services. The highest correlation indicator was calculated for:

The number of regional bus connections and the number of passenger transport services using buses traveling among the region's cities (0.78).

The number of regional railway connections and the number of passenger transport services carried out by the regional railway system (0.81).

The indicators calculated have confirmed hypotheses 1 and 2. The results of the correlation analysis were similar for other Polish regions.

Table 2. Economic results for Polish regions, data on transportation infrastructures in regions (data for 2016, for the purposes of consecutive calculations, data was also gathered for 2015 and estimated for 2017). Sources: [46–52].

Poland/Regions	GNP (B USD)	GNP (B PLN)	%	Road Density/Length of National Roads and Motorways Ratio (km/100 km^2)	Network Density/Length of Railway Lines Ratio (km/100 km^2)	Number of Regional Bus Connections in Mass Transit (Both Public and Private)	Length of Regional Bus Connections (km)	Number of Regional Railway Routes/Connections (Secondary)	Length of Regional Railway Connections (km)
Poland	524	1888	100%	0.97	6.2	2702	202,360		19,386.13954
Dolnośląskie	44.6	160.48	8.5%	1.1–1.5	8.8	2545	191,483	29	1755.31312
Kujawsko-pomorskie	23.1	83.1	4.4%	1.1–1.5	6.7	163	10,518	23	1204.07978
Lubelskie	20.5	73.6	3.9%	0.0–0.5	4.1	141	9272	22	1030.02086
Lubuskie	11.5	41.5	2.2%	1.6–2.0	6.6	372	25,684	15	923.20074
Łódzkie	32	115.1	6.1%	<2.0	5.9	394	26,568	25	1074.91805
Małopolskie	40.9	147.2	7.8%	1.1–1.51	7.2	266	17,150	34	1093.16088
Mazowieckie	116.4	419.1	22.2%	0.6–1.0	4.7	263	17,814	28	1671.24809
Opolskie	11	39.6	2.1%	0.6–1.0	8.1	151	10,666	16	762.36147
Podkarpackie	20.5	73.6	3.9%	0.0–0.5	5.5	93	6238	11	981.5168
Podlaskie	11.5	41.5	2.2%	>0.5	3.2	144	13,225	23	645.98464
Pomorskie	29.9	107.6	5.7%	0.6–1.0	6.7	138	12,600	13	1226.79278
Śląskie	65	234.1	12.4%	<2.0	16	42	4178	30	1973.2944
Świętokrzyskie	12.6	45.3	2.4%	>0.5	6.2	34	3023	16	726.051
Warmińsko-mazurskie	14.2	50.9	2.7%	0.6–1.0	4.6	376	31,553	16	1111.97962
Wielkopolskie	50.9	183.1	9.7%	1.1–1.5	6.3	361	30,436	32	1879.0695
Zachodnio-pomorskie	19.9	71.7	3.8%	1.1–1.5	5.2	49	2814	13	1190.40896

Table 3. Regional balance of passenger transport services carried out by the regional railway system (published data) and using other means of transport (estimated data—calculated on the basis of primary studies) [53–56].

Poland/Regions	Number of Passenger Transport Services Carried out by the Regional Railway System (M Passengers)			Estimated Number of Passenger Transport Services Carried out in Busses Traveling Among the Region's Cities (M Passengers)			Estimated Number of Car Travels among the Region's Cities (M Passengers)			Population of the Region (M People)			Populations of the Region's Cities (M People)		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
POLAND	300.53	291.67	257.90	512.53	495.84	438.43	NDA	NDA	NDA	38.461	38.419	38.411	23.202	23.129	22.716
Dolnośląskie	9.04	7.18	6.45	15.36	12.20	10.97	80.37	63.84	57.39	2.905	2.899	2.899	2.011	2.002	1.956
Kujawsko-Pomorskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	2.089	2.086	2.086	1.250	1.244	1.212
Lubuskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	2.148	2.139	2.138	0.993	0.988	0.962
Lubuskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	1.020	1.019	1.001	0.643	0.641	0.629
Łódzkie	3.67	2.42	2.06	6.24	4.11	3.50	28.34	18.61	15.85	2.502	2.491	2.412	1.582	1.570	1.513
Małopolskie	5.68	4.70	4.23	9.66	7.99	7.19	28.83	23.85	21.47	3.367	3.373	3.365	1.635	1.633	1.620
Mazowieckie	61.43	59.82	53.66	104.43	101.69	91.22	288.71	281.14	252.19	5.329	5.341	5.245	3.422.9	3.430	3.456
Opolskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	0.999	0.994	0.964	0.520	0.516	0.498
Podkarpackie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	2.128	2.126	2.121	0.879	0.876	0.862
Podlaskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	1.191	1.187	1.178	0.720	0.718	0.709
Pomorskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	2.300	2.305	2.314	1.492	1.490	1.476
Śląskie	15.20	15.33	13.51	25.84	25.87	22.97	132.24	132.40	117.55	4.584	4.569	4.457	3.542	3.524	3.425
Świętokrzyskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	1.262	1.256	1.226	0.563	0.559	0.535
Warmińsko-Mazurskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	1.443	1.440	1.431	0.854	0.851	0.834
Wielkopolskie	8.17	8.19	7.27	13.88	13.92	12.36	108.55	108.85	96.64	3.472	3.476	3.480	1.911	1.905	1.873
Zachodnio-pomorskie	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	1.716	1.712	1.692	1.178	1.173	1.151

Table 4. Correlation variables.

Symbol	Correlated Variables
S1	Number of regional bus connections
S2	Length of regional bus connection lines (km)
S3	Number of regional *secondary* railway routes/connections
S4	Length of regional railway connections (km)
S5	Number of passenger transport services carried out by the railway system (M passengers)
S6	Estimated number of passenger transport services carried out in busses traveling among the region's cities (M passengers)
S7	Estimated number of car travels among the region's cities (M passengers)
S8	Population of the region (M people)
S9	Populations of the region's cities (M people)
S10	Regional GNP

Table 5. Variable correlation indicators.

Variables	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
S1	1									
S2	0.66	1								
S3	0.41	0.17	1							
S4	0.38	0.41	0.71	1						
S5	0.52	0.19	0.81	0.68	1					
S6	0.78	0.55	0.36	0.21	0.14	1				
S7	−0.32	−0.21	−0.25	−0.13	−0.12	−0.23	1			
S8	0.45	0.23	0.34	0.38	0.54	0.64	0.76	1		
S9	0.23	0.34	0.27	0.23	0.41	0.48	0.87	0.63	1	
S10	0.21	0.29	0.34	0.31	0.32	0.35	0.54	0.47	0.48	1

Source: Own study on the basis of announced and estimated data from the Main Statistical Office.

Comparing the correlation results for various regions, a conclusion was drawn that the regional GNP was strongly correlated with the population of the region and, above all, with the populations of the region's cities, and was higher in the most populated areas and cities in the region. The results have also displayed a strong correlation, i.e., of approx. 0.5, between the number of passenger transport services (carried out by both the railway and the bus system) and the city populations in the Mazowieckie and Małopolska Regions. The number of passenger transport services was the higher the more people lived in the region's cities. Referring these studies to the road density indicator provided in Table 1, a conclusion is drawn that the lower the road density in the region the higher the number of passenger transport services carried out with the railway and the bus system. Another conclusion from the study has indicated that the higher the density of railway connections the higher the number of passenger transport services carried out with the railway system. A similar relationship was recorded for this transportation branch between the number of connections and the number of passenger transport services.

Statistical analyses produce an important practical conclusion, and namely that the optimization of railway connections is the most important factor in increasing the number of passenger transport services in the region. This conclusion is confirmed by other studies as well [57,58].

4. Analysis of the Structure of Railway Connections—Course of Analyses, Results Obtained and Conclusions Drawn (Stage II of the Study)

4.1. Source Data and Diagrams Illustrating the Railway System in the Śląskie Region

At the second stage of the study, a research hypothesis was formulated, which claimed that an analysis and optimization of the network within a single transportation branch in a selected region (applying the ITS: the graph theory) would stimulate an increase in the number of mass transit transport services. The optimization criterion consisted in so modifying the network of connections that the parameters of the network as a whole are improved. To verify the hypothesis, a set of data concerning the number of passengers in regional transit (considering municipal transportation systems—bus, tram and trolley bus transport) and in railway transit (carried out by Koleje Śląskie) was presented for the Śląskie Region. Data from 2011–2017 was used to increase the accuracy of results.

Table 6. Number of passengers in the Śląskie Region in 2014–2016 [52,53].

Year	2011	2012	2013	2014	2015	2016	2017
Number of passenger transport services in the region, including by municipal transportation (busses, trams, trolley busses) (M passengers)	NDA	NDA	NDA	436	417	414	NDA
Passenger transport service by Koleje Śląskie	1.786	9.130	16.327	16.032	15.906	15.334	15.730
In total:	NDA	NDA	NDA	452.032	432.906	429.334	NDA

Source: Own study on the basis of data from the Main Statistical Office and the Office of Rail Transport.

As illustrated in Table 6, the number of passengers has been gradually decreasing in the Śląskie Region in the recent years. The most noticeable causes of this trend included the absence of measures to coordinate individual carriers in the region and a raise in ticket prices set by the region's largest carrier, KZK GOP. Despite their large populations, the region and the voivodeship, as well as the Śląsko-Zagłębiowska Metropolis established in its central part, problems related to road bottlenecks or road paralyses are rare. Plus, if we considered the large area of the region and the distances made during the daily commute, we will find that a large number of the region's residents still prefer individual transportation. This is very strongly affected by the poor synchronization of bus and modal connections, and long travel times, as the author has already indicated in [59–62]. These may discourage commuters from using means of mass transit.

Decreasing passenger numbers have been recorded by Koleje Śląskie. However, data for 2017 have indicated a slight increase.

Table 7 presents a breakdown of the number of Koleje Śląskie passengers in successive years.

Table 7. Number of passengers carried by Koleje Śląskie in 2011–2016 [52].

Year	2011	2012	2013	2014	2015	2016	2017
Number of passengers carried (M people)	1.786	9.130	16.327	16.032	15.906197	15.334056	15.730040

Source: Statistical data from the Office of Rail Transport.

As illustrated above, Koleje Śląskie went through a dynamic increase in the number of passengers in 2011–2013. This is due to the fact that the company was established in 2011 and took over the majority of regional connections from Przewozy Regionalne in 2012. A gradual decrease in the number of passenger transport services has been recorded since 2013. What is important, in 2013–2017, the network of connections for Koleje Śląskie was slightly modified, as illustrated in the network analysis carried out with the use of the graph theory.

A preliminary study of the network of connections for Koleje Śląskie is presented in [63]. The modeled network, as presented in [63], does not account for the distribution of the carrier's individual lines, and refers to a single year instead of several years, as referred to in this article.

The following figures illustrate the network of connections for Koleje Śląskie from particular periods.

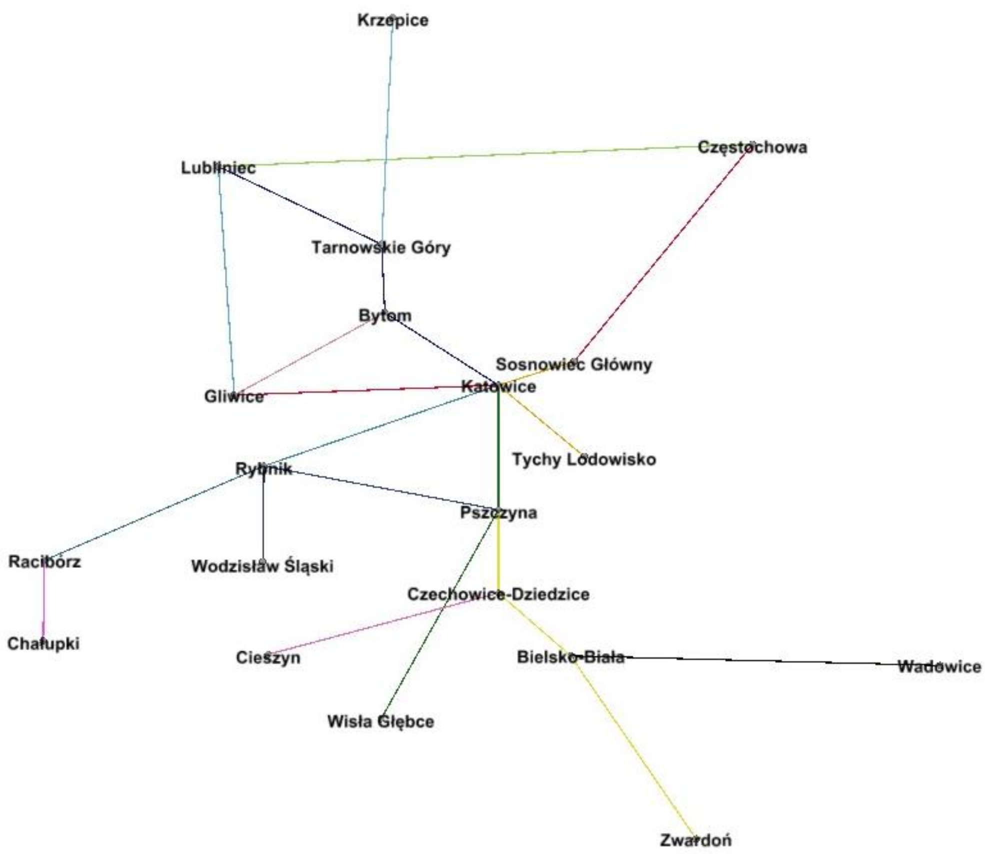

Figure 5. Network of connections for Koleje Śląskie from IX 2013 to X 2013. Source: Own study.

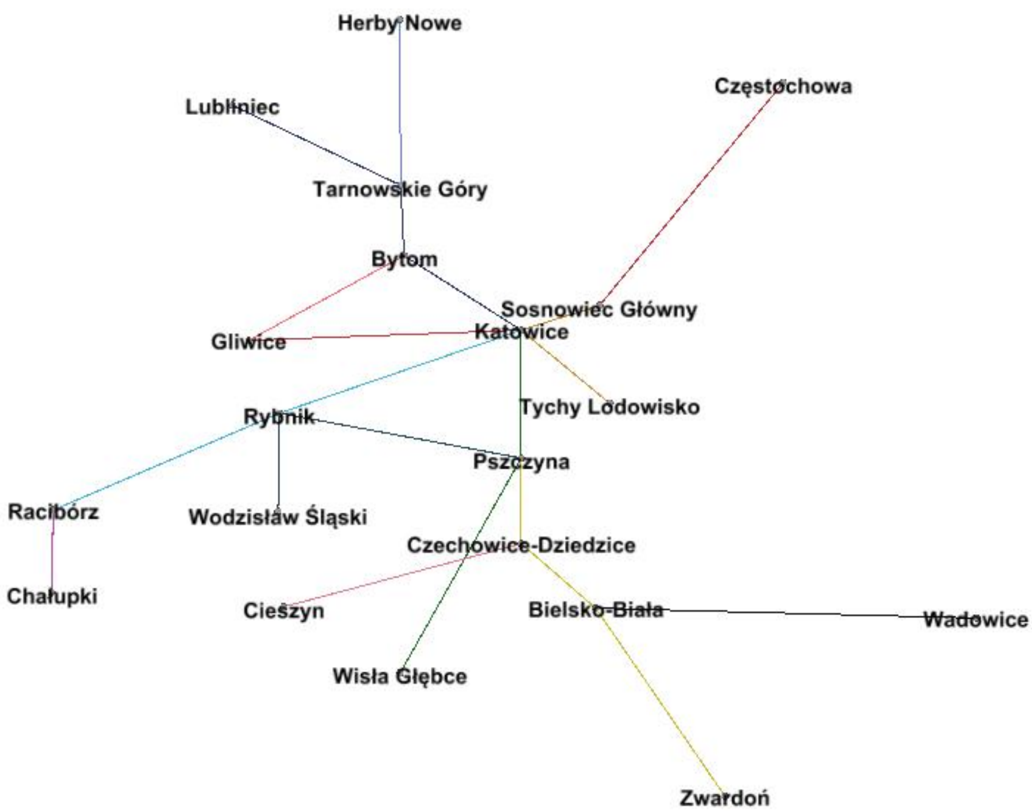

Figure 6. Network of connections for Koleje Śląskie from XII 2013 to III 2014. Source: Own study.

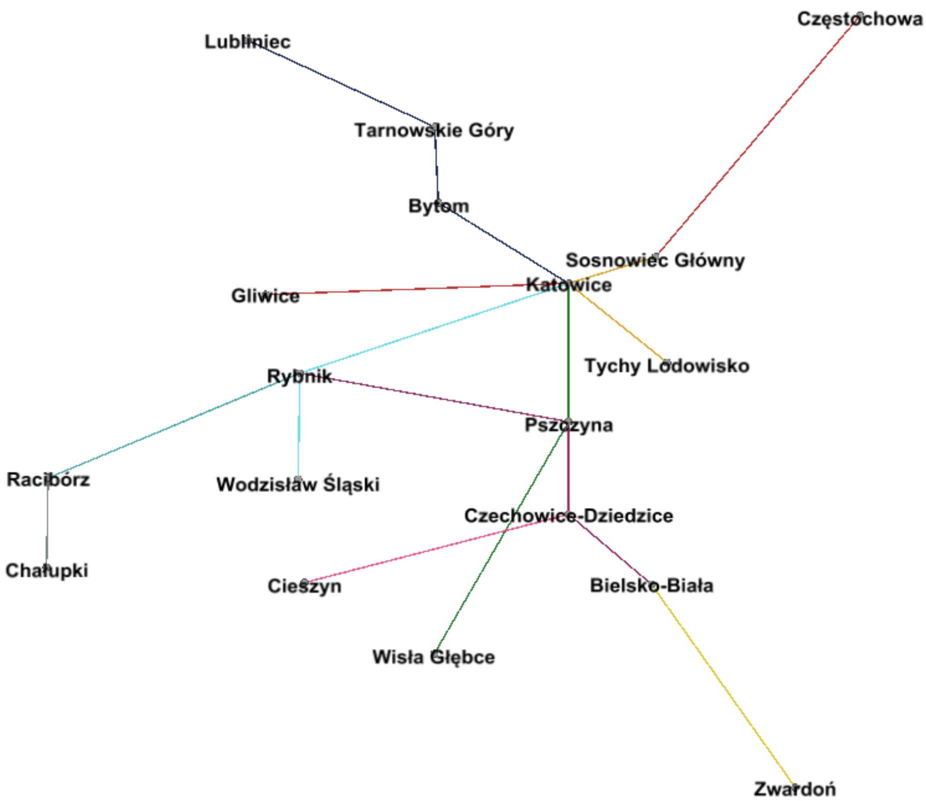

Figure 7. Network of connections for Koleje Śląskie from XII 2014 to VI 2015 Source: Own study.

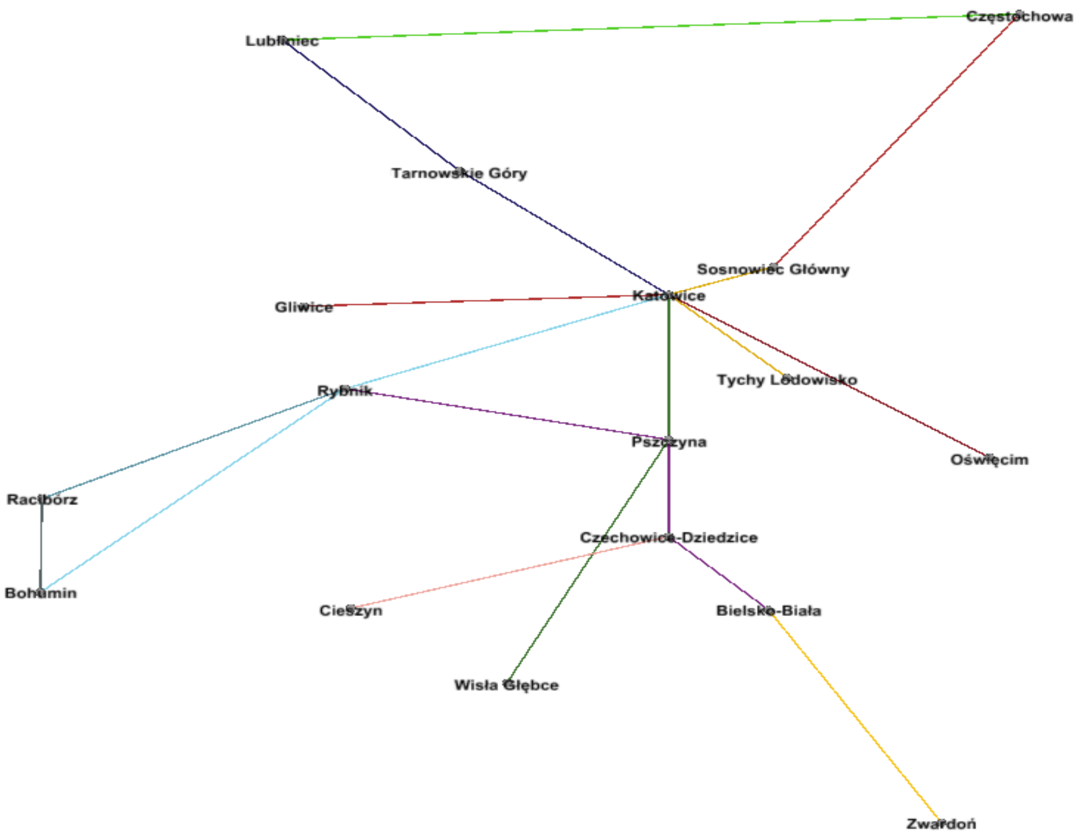

Figure 8. Network of connections for Koleje Śląskie from XII 2015 to XII 2017 Source: Own study.

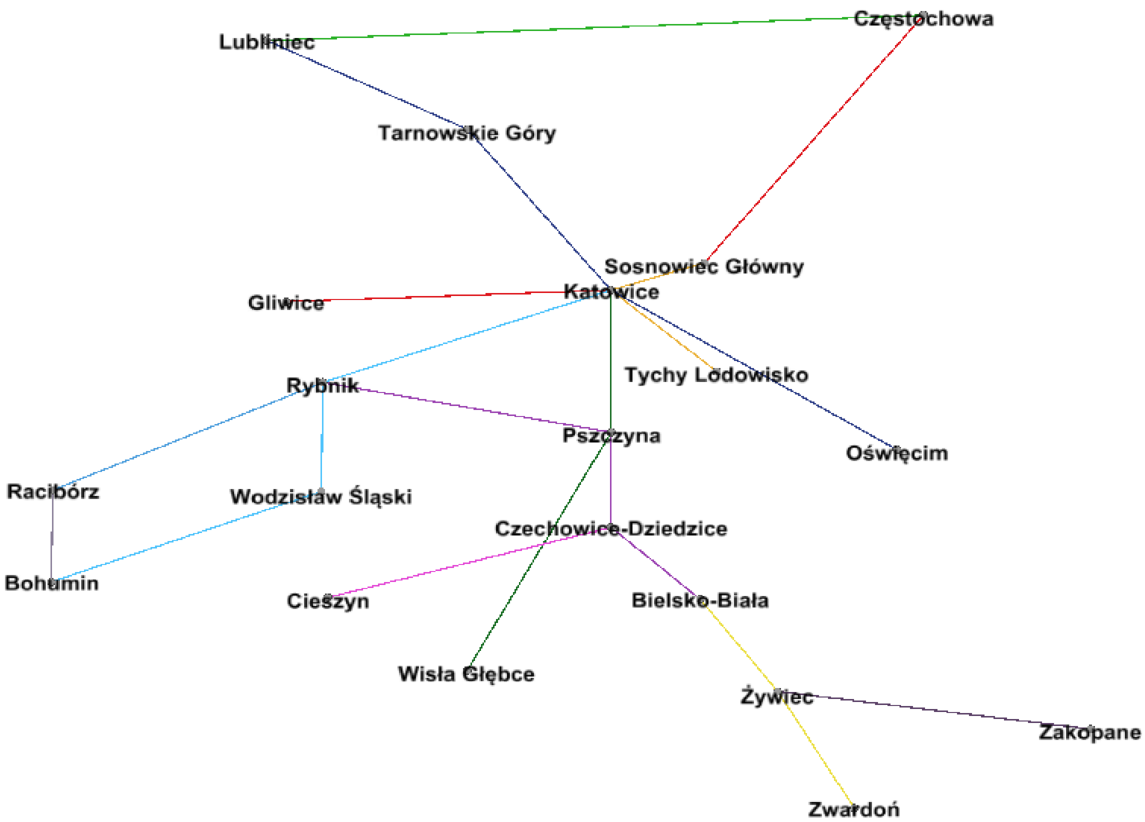

Figure 9. Network of connections for Koleje Śląskie from XII 2017 to III 2018 Source: Own study.

Calculations of parameters according to the network theory were carried out for the connection systems (network of connections), as illustrated in Figures 8–12. The parameters obtained are presented in Tables 8–12.

Table 8. Indicators for individual network nodes from IX 2013 to X 2013.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.526	3	0.333	0.543	0.639	0.143	1.000
Sosnowiec Główny	0.158	4	0.250	0.380	0.080	0.000	0.459
Częstochowa	0.105	5	0.200	0.311	0.008	0.000	0.136
Bytom	0.211	4	0.250	0.404	0.167	0.333	0.547
Tarnowskie Góry	0.158	5	0.200	0.322	0.109	0.000	0.168
Lubliniec	0.158	5	0.200	0.328	0.028	0.000	0.153
Gliwice	0.158	4	0.250	0.404	0.080	0.333	0.368
Krzepice	0.053	6	0.167	0.247	0.000	0.000	0.041
Tychy Lodowisko	0.053	4	0.250	0.358	0.000	0.000	0.213
Pszczyna	0.263	4	0.250	0.452	0.164	0.333	0.631
Czechowice-Dziedzice	0.211	4	0.250	0.442	0.368	0.167	0.399
Bielsko-Biała	0.158	5	0.200	0.333	0.205	0.000	0.109
Wadowice	0.053	6	0.167	0.253	0.000	0.000	0.030
Zwardoń	0.053	6	0.167	0.253	0.000	0.000	0.030
Wisła Głębce	0.053	5	0.200	0.317	0.000	0.000	0.135
Cieszyn	0.053	5	0.200	0.311	0.000	0.000	0.088
Rybnik	0.211	4	0.250	0.422	0.292	0.167	0.394
Wodzisław Śląski	0.053	5	0.200	0.302	0.000	0.000	0.087
Racibórz	0.105	5	0.200	0.311	0.105	0.000	0.096
Chałupki	0.053	6	0.167	0.241	0.000	0.000	0.025

Source: own calculations performed using the Gephi software.

Table 9. Indicators for individual network nodes from XII 2013 to III 2014.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.526	3	0.333	0.528	0.673	0.143	1.000
Sosnowiec Główny	0.158	4	0.250	0.365	0.105	0.000	0.453
Częstochowa	0.053	5	0.200	0.271	0.000	0.000	0.097
Bytom	0.211	4	0.250	0.404	0.281	0.333	0.536
Tarnowskie Góry	0.158	5	0.200	0.311	0.205	0.000	0.139
Lubliniec	0.053	6	0.167	0.241	0.000	0.000	0.035
Gliwice	0.105	4	0.250	0.380	0.000	1.000	0.331
Herby Nowe	0.053	6	0.167	0.241	0.000	0.000	0.035
Tychy Lodowisko	0.053	4	0.250	0.352	0.000	0.000	0.215
Pszczyna	0.263	4	0.250	0.442	0.164	0.333	0.640
Czechowice-Dziedzice	0.211	4	0.250	0.432	0.368	0.167	0.406
Bielsko-Biała	0.158	5	0.200	0.328	0.205	0.000	0.112
Wadowice	0.053	6	0.167	0.250	0.000	0.000	0.031
Zwardoń	0.053	6	0.167	0.250	0.000	0.000	0.031
Wisła Głębce	0.053	5	0.200	0.311	0.000	0.000	0.138
Cieszyn	0.053	5	0.200	0.306	0.000	0.000	0.090
Rybnik	0.211	4	0.250	0.413	0.292	0.167	0.401
Wodzisław Śląski	0.053	5	0.200	0.297	0.000	0.000	0.089
Racibórz	0.105	5	0.200	0.306	0.105	0.000	0.098
Chałupki	0.053	6	0.167	0.238	0.000	0.000	0.026

Source: own calculations performed using the Gephi software.

Table 10. Indicators for individual network nodes from XII 2014 to VI 2015.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.588	3	0.333	0.567	0.699	0.095	1.000
Sosnowiec Główny	0.176	4	0.250	0.386	0.118	0.000	0.417
Częstochowa	0.059	5	0.200	0.283	0.000	0.000	0.084
Bytom	0.118	4	0.250	0.405	0.221	0.000	0.214
Tarnowskie Góry	0.118	5	0.200	0.304	0.118	0.000	0.052
Lubliniec	0.059	6	0.167	0.236	0.000	0.000	0.015
Gliwice	0.059	4	0.250	0.370	0.000	0.000	0.199
Tychy Lodowisko	0.059	4	0.250	0.370	0.000	0.000	0.199
Pszczyna	0.353	4	0.250	0.472	0.176	0.333	0.823
Czechowice-Dziedzice	0.353	4	0.250	0.447	0.324	0.167	0.670
Bielsko-Biała	0.176	5	0.200	0.327	0.118	0.000	0.283
Zwardoń	0.059	6	0.167	0.250	0.000	0.000	0.059
Wisła Głębce	0.059	5	0.200	0.327	0.000	0.000	0.163
Cieszyn	0.059	5	0.200	0.315	0.000	0.000	0.134
Rybnik	0.294	4	0.250	0.447	0.324	0.167	0.617
Wodzisław Śląski	0.059	5	0.200	0.315	0.000	0.000	0.123
Racibórz	0.118	5	0.200	0.327	0.118	0.000	0.133
Chałupki	0.059	6	0.167	0.250	0.000	0.000	0.030

Source: own calculations performed using the Gephi software.

Table 11. Indicators for individual network nodes from XII 2015 to XII 2017.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.625	4	0.250	0.552	0.658	0.048	1.000
Sosnowiec Główny	0.188	5	0.200	0.390	0.108	0.000	0.450
Częstochowa	0.125	6	0.167	0.302	0.008	0.000	0.117
Oświęcim	0.063	5	0.200	0.364	0.000	0.000	0.211
Tarnowskie Góry	0.125	5	0.200	0.390	0.108	0.000	0.232
Lubliniec	0.125	6	0.167	0.302	0.008	0.000	0.080
Gliwice	0.063	5	0.200	0.364	0.000	0.000	0.211
Tychy Lodowisko	0.063	5	0.200	0.364	0.000	0.000	0.211
Pszczyna	0.375	3	0.333	0.516	0.492	0.167	0.803
Czechowice-Dziedzice	0.313	4	0.250	0.400	0.342	0.000	0.464
Bielsko-Biała	0.188	5	0.200	0.302	0.125	0.000	0.218
Zwardoń	0.063	6	0.167	0.235	0.000	0.000	0.051
Wisła Głębce	0.063	4	0.250	0.348	0.000	0.000	0.169
Cieszyn	0.063	5	0.200	0.291	0.000	0.000	0.102
Rybnik	0.313	4	0.250	0.471	0.233	0.333	0.672
Racibórz	0.125	5	0.200	0.333	0.000	1.000	0.183
Bohumin	0.125	5	0.200	0.333	0.000	1.000	0.183

Source: own calculations performed using the Gephi software.

Table 12. Indicators for individual network nodes from XII 2017 to III 2018.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.526	5	0.200	0.452	0.585	0.048	1.000
Sosnowiec Główny	0.158	6	0.167	0.333	0.094	0.000	0.450
Częstochowa	0.105	7	0.143	0.264	0.006	0.000	0.117
Oświęcim	0.053	6	0.167	0.317	0.000	0.000	0.211
Tarnowskie Góry	0.105	6	0.167	0.333	0.094	0.000	0.232
Lubliniec	0.105	7	0.143	0.264	0.006	0.000	0.080
Gliwice	0.053	6	0.167	0.317	0.000	0.000	0.211
Tychy Lodowisko	0.053	6	0.167	0.317	0.000	0.000	0.211
Pszczyna	0.316	4	0.250	0.452	0.526	0.167	0.806
Czechowice-Dziedzice	0.263	4	0.250	0.380	0.433	0.000	0.473
Bielsko-Biała	0.158	5	0.200	0.306	0.281	0.000	0.230
Zwardoń	0.053	7	0.143	0.202	0.000	0.000	0.023
Wisła Głębce	0.053	5	0.200	0.317	0.000	0.000	0.170
Cieszyn	0.053	5	0.200	0.279	0.000	0.000	0.103
Rybnik	0.263	5	0.200	0.413	0.284	0.167	0.666
Wodzisław Śląski	0.105	6	0.167	0.306	0.050	0.000	0.161
Racibórz	0.105	6	0.167	0.306	0.050	0.000	0.161
Bohumin	0.105	7	0.143	0.244	0.003	0.000	0.075
Żywiec	0.158	6	0.167	0.250	0.205	0.000	0.073
Zakopane	0.053	7	0.143	0.202	0.000	0.000	0.023

Source: own calculations performed using the Gephi software.

As illustrated in Figures 5–9 and presented in Tables 8–12, the network of connections for Koleje Śląskie has been slightly modified throughout the years. According to the information in Tables 8–12, the most important modifications were implemented between 2015 and 2016. In this period, the network was significantly remodeled basing on the importance of its individual nodes. The Katowice node is still the dominant one, however the 2015–2016 network modification gave rise to the Pszczyna node at the expense of the Czechowice-Dziedzice node. What is important, the Pszczyna node is closely tied with the Rybnik node, and is situated closer to the newly established Śląsko-Zagłębiowska Metropolis, compared to the Czechowice-Dziedzice node. This points to a gradual strengthening of this area (the Metropolis) in the carrier's network of connections. These changes are clearly illustrated in Figures 10–14, which present one of the calculated indicators for the network in question.

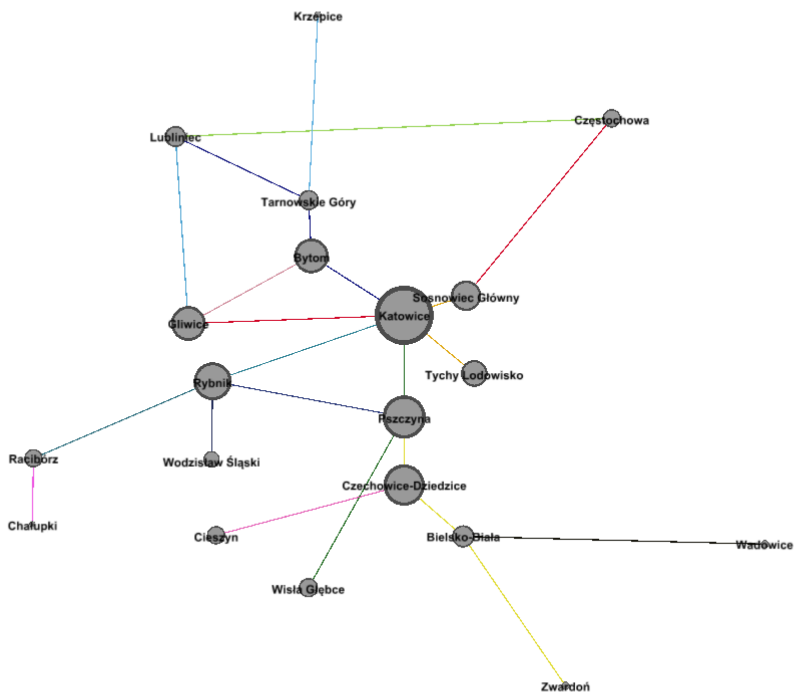

Figure 10. The closeness coefficient to the network of connections from IX 2013 to X 2013. Source: own study performed using the Gephi software.

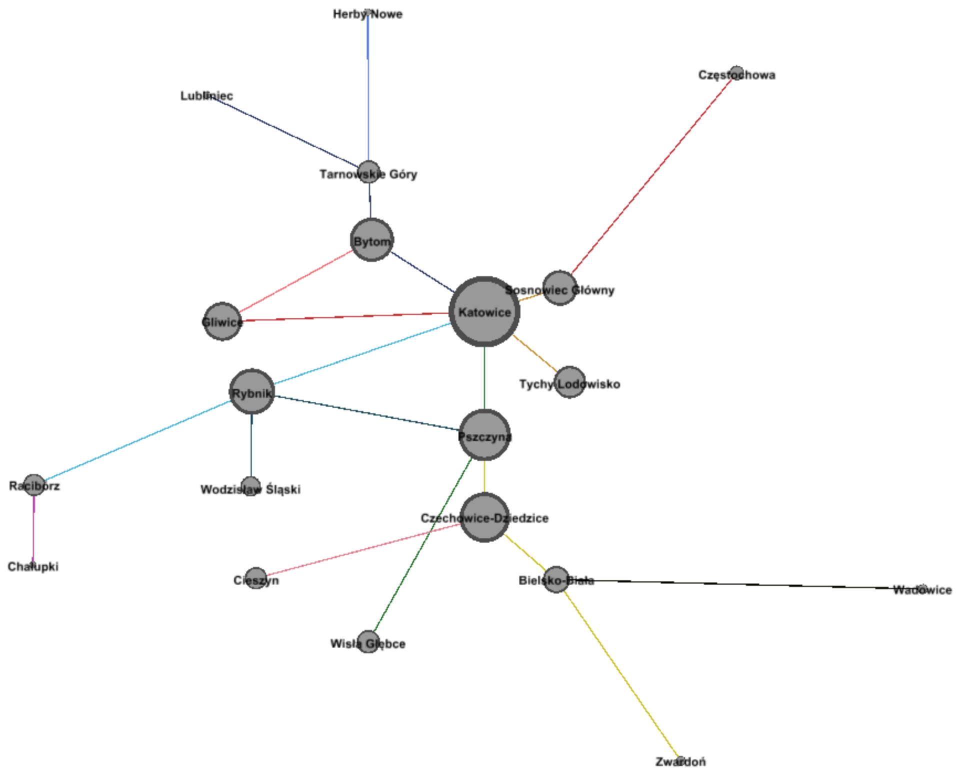

Figure 11. The closeness coefficient to the network of connections from XII 2013 to III 2014. Source: own study performed using the Gephi software.

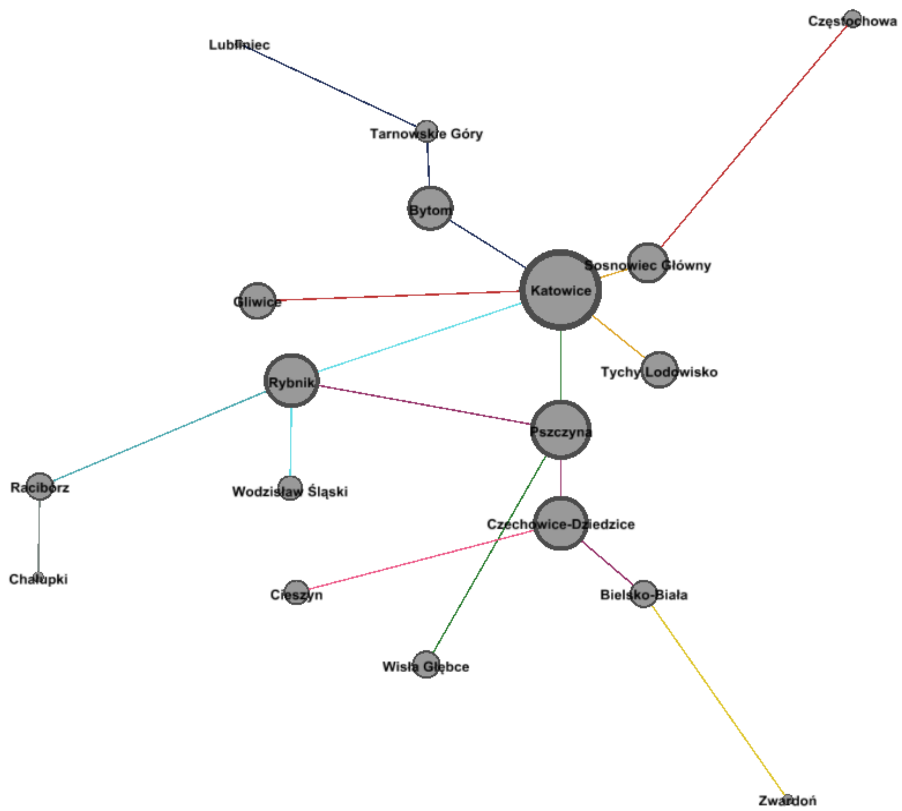

Figure 12. The closeness coefficient to the network of connections from XII 2014 to VI 2015. Source: own study performed using the Gephi software

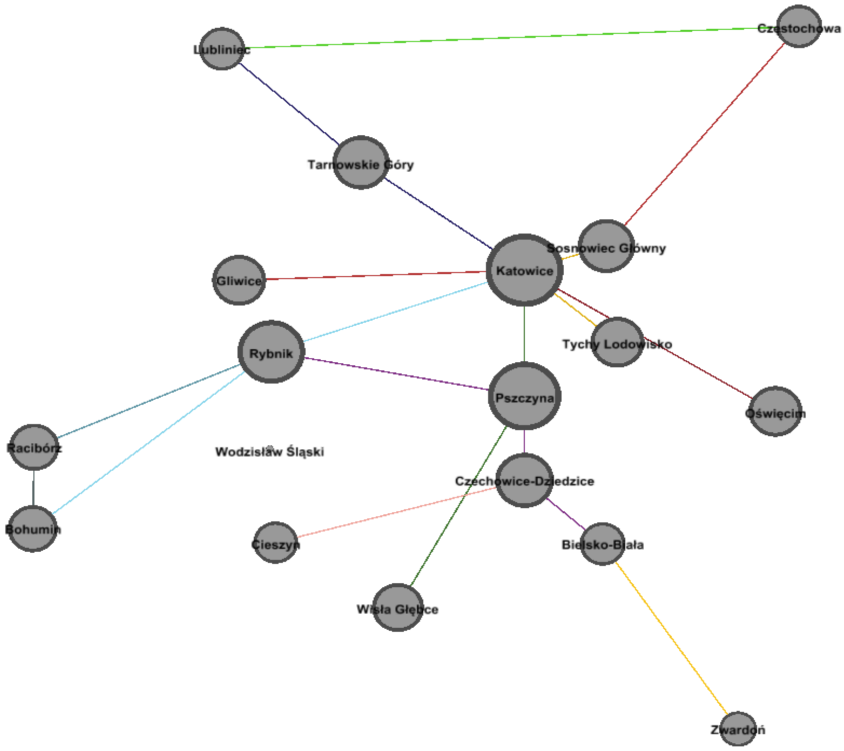

Figure 13. The closeness coefficient to the network of connections from XII 2015 to XII 2017. Source: own study performed using the Gephi software.

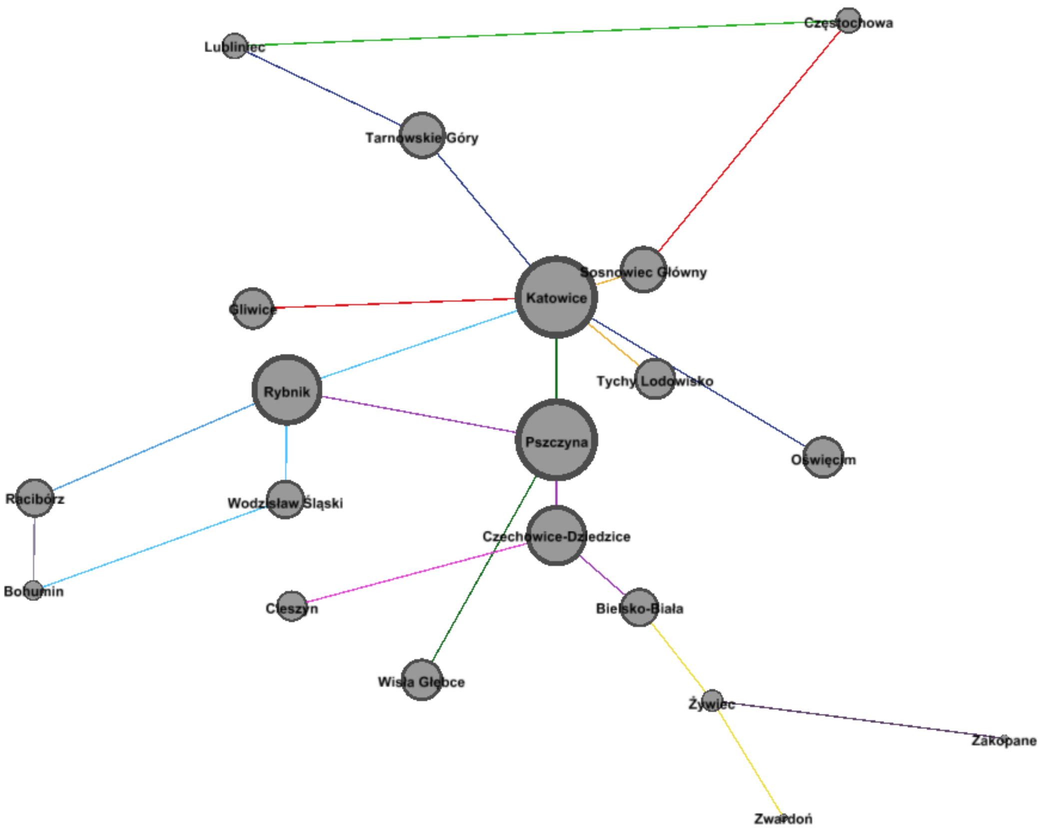

Figure 14. The closeness coefficient to the network of connections from XII 2017 to III 2018. Source: own study performed using the Gephi software.

The indicator illustrated in the figures (the closeness coefficient) displays a clear growth in the importance of nodes situated closer to the center of the region, and this change is also related to the establishment of the Śląsko-Zagłębiowska Metropolis. This can point to the fact that the railway carrier has been focusing on the structure of the network of offered connections, aiming to increase accessibility of the central area of the network. What is important, is that the network of Koleje Śląskie is a Free-scale network, characterized by relatively high immunity to random disturbances, such as rolling stock failures, which contributes to its high reliability, which, in turn, can be an important parameter that will encourage passengers to using this means of transport.

4.2. Diagrams Describing the Railway Transport Network Simulation for the Śląskie Region. Conclusions from the Second Stage of the Study

A simulation of modifications of the network of connections by adding new connections among the main hubs incorporated in the metropolis was carried out as part of the analyses presented herein. The purpose of this optimization was to increase the attractiveness of the network of connections for the commuters by improving its network parameters, and, ultimately, to increase the number of passengers carried in the future. A two-staged modification was simulated:

Stage 1: direct connections were added between Sosnowiec and Tychy, between Tychy and Rybnik and between Rybnik and Gliwice (Figure 15).

Stage 2: a connection between Gliwice and Tarnowskie Góry was added to stage 1 of the modification—this connection had been offered by the carrier in the past (Figure 16).

What is noteworthy, the existing railway infrastructure in the region supported all of these modified connections.

The indicators obtained are presented in Tables 13 and 14.

Figure 15. Railway network, taking the stage 1 modification into account (the proposed connections are marked with black lines). Source: own study performed using the Gephi software.

Table 13. Network indicators including stage 1 modifications.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.526	5	0.200	0.452	0.480	0.190	1.000
Sosnowiec Główny	0.211	6	0.167	0.339	0.096	0.333	0.498
Częstochowa	0.105	7	0.143	0.268	0.009	0.000	0.115
Oświęcim	0.053	6	0.167	0.317	0.000	0.000	0.194
Tarnowskie Góry	0.105	6	0.167	0.333	0.091	0.000	0.211
Lubliniec	0.105	7	0.143	0.264	0.006	0.000	0.069
Gliwice	0.105	6	0.167	0.339	0.000	1.000	0.340
Tychy Lodowisko	0.158	6	0.167	0.352	0.009	0.667	0.437
Pszczyna	0.316	4	0.250	0.452	0.526	0.167	0.720
Czechowice-Dziedzice	0.263	4	0.250	0.380	0.433	0.000	0.381
Bielsko-Biała	0.158	5	0.200	0.306	0.281	0.000	0.176
Zwardoń	0.053	7	0.143	0.202	0.000	0.000	0.018
Wisła Głębce	0.053	5	0.200	0.317	0.000	0.000	0.141
Cieszyn	0.053	5	0.200	0.279	0.000	0.000	0.079
Rybnik	0.368	5	0.200	0.432	0.318	0.200	0.749
Wodzisław Śląski	0.105	6	0.167	0.317	0.050	0.000	0.163
Racibórz	0.105	6	0.167	0.317	0.050	0.000	0.163
Bohumin	0.105	7	0.143	0.250	0.003	0.000	0.069
Żywiec	0.158	6	0.167	0.250	0.205	0.000	0.055
Zakopane	0.053	7	0.143	0.202	0.000	0.000	0.018

Source: own study performed using the Gephi software.

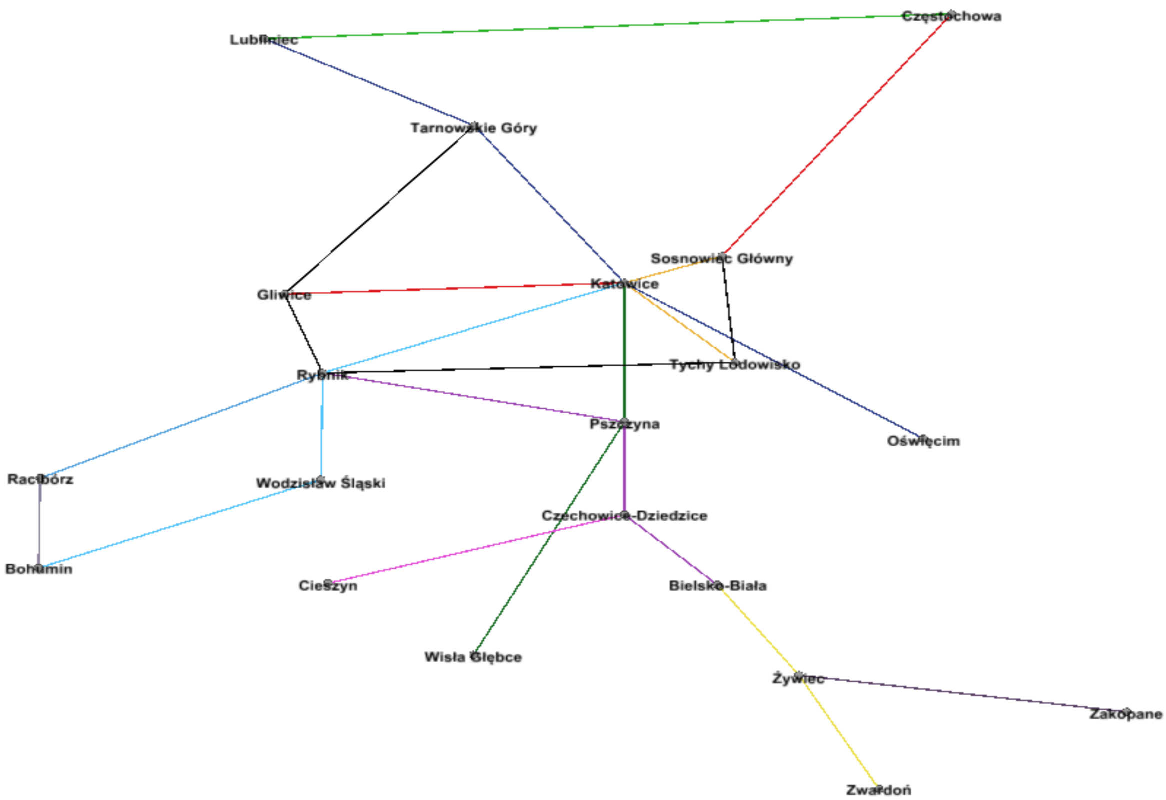

Figure 16. Railway network, taking the stage 2 modification into account (the proposed connections are marked with black lines). Source: own study performed using the Gephi software.

Then, indicators were calculated for all of the analyzed and proposed networks to determine the condition of the network as a whole. The coefficients obtained are presented in Table 15.

Table 14. Network indicators including stage 2 modifications.

City (Node)	Normalized Degree	Eccentricity	Radius	Closness Centrality	Betweeness Centrality	Clustering	Eigencentrality
Katowice	0.526	5	0.200	0.452	77.067	0.238	1.000
Sosnowiec Główny	0.211	6	0.167	0.339	16.167	0.333	0.490
Częstochowa	0.105	7	0.143	0.268	1.500	0.000	0.114
Oświęcim	0.053	6	0.167	0.317	0.000	0.000	0.192
Tarnowskie Góry	0.158	6	0.167	0.339	15.833	0.333	0.287
Lubliniec	0.105	7	0.143	0.268	1.333	0.000	0.082
Gliwice	0.158	6	0.167	0.352	2.667	0.667	0.392
Tychy Lodowisko	0.158	6	0.167	0.352	1.600	0.667	0.429
Pszczyna	0.316	4	0.250	0.452	90.000	0.167	0.705
Czechowice-Dziedzice	0.263	4	0.250	0.380	74.000	0.000	0.367
Bielsko-Biała	0.158	5	0.200	0.306	48.000	0.000	0.168
Zwardoń	0.053	7	0.143	0.202	0.000	0.000	0.017
Wisła Głębce	0.053	5	0.200	0.317	0.000	0.000	0.136
Cieszyn	0.053	5	0.200	0.279	0.000	0.000	0.075
Rybnik	0.368	5	0.200	0.432	54.333	0.200	0.744
Wodzisław Śląski	0.105	6	0.167	0.317	8.500	0.000	0.160
Racibórz	0.105	6	0.167	0.317	8.500	0.000	0.160
Bohumin	0.105	7	0.143	0.250	0.500	0.000	0.067
Żywiec	0.158	6	0.167	0.250	35.000	0.000	0.053
Zakopane	0.053	7	0.143	0.202	0.000	0.000	0.017

Source: own study performed using the Gephi software.

Table 15. Coefficients obtained for the network, in individual variants.

Network Coefficient	Network Application System							Effect of Changes
	From IX 2013 to X 2013	From XII 2013 to III 2014	From XII 2014 to VI 2015	From XII 2015 to XII 2017	From XII 2017 to III 2018	From XII 2017 to III 2018 Modification 1	From XII 2017 to III 2018 Modification 2	
Avg. Clustering Coefficient	0.123	0.214	0.085	0.232	0.029	0.17	0.174	Improvement
Average path length	3.021	3.158	2.967	2.838	3.353	3.3	3.289	Improvement
Diameter	6	6	6	6	7	7	7	Slight deterioration
Radius	3	3	3	3	4	4	4	Slight deterioration
Average nodes degree	2.7	2.5	2.667	2.823	2.7	3	3.1	Improvement

Source: Own study.

As presented in Table 15, compared to previous periods, coefficients the current network (functioning up to III 2018) were improved (Avg. Clustering Coefficient, Average path length and Average nodes degree). This indicates that the carrier has attempted to optimize the network (improve its parameters as a whole) which translates into an increase in the number of passenger transport services carried out by the railway system (M passengers)—as confirmed by the data in Table 6.

Simulations/successive modifications of the network signal even higher improvements of the network coefficients, which can contribute to an increase in the number of passenger transport services.

The results obtained confirm an assumption that the graph theory can be an effective tool to be used when making investment decisions related to the extension or upgrading of transport networks. Analyses carried out with the use of the graph theory and the results obtained provide information on the parameters of the modeled network and can be used to assess it in terms of a possible increase in the number of passengers. It is therefore recommended that ITS based on algorithms derived from the graph theory be implemented and used in decisions concerning future network modifications.

In this respect, other ITS solutions contributing to a gradual increase in the number of passenger transport services carried out with the railway system in the Śląskie Region are also noteworthy. Apart from the question of taking over connections operated by Przewozy Regionalne, the increase in the number of passengers recorded in 2013–2017 is probably related to improved quality of the rolling stock used. In November 2013, Koleje Śląskie decommissioned their classic railway cars [64] in favor of modern cars equipped with ITS solutions—electric multiple units which provide a traveling comfort and access to important traveling data (information on the current station, the next station, possible delays, switches to other means of transport, etc.). measures to apply ITS solutions were commenced in 2016 in order to promote access to information on the services offered by Koleje Śląskie, and to gradually integrate them with the services provided by other carriers, such as KZK GOP. Some model measures in ITS implementation included:

- In August 2016, the company entered into cooperation with Google to make its connections visible in the browsing mechanism and in the browsers of all portals integrated with Google [65];
- The sales of a joint daily ticket with KZK GOP and MZK Tychy was commenced in October 2016, allowing passengers to switch between their means of transport on a single ticket [66];
- The sales of Koleje Śląskie tickets via the SkyCash app, which is very popular among the youth and people up to the age of 40 (people in the productive age, using innovative mobile solutions and ICT on a regular basis) was commenced in January 2017 [67];
- The joint ticket offer held with KZK GOP and MZK Tychy was extended to include another carrier, MZKP Tarnowskie Góry in February 2017, thus increasing the number of ticket sales locations [68];
- In October 2017, the connections offered by the company were displayed on e-podroznik (online browser of connections offered by different carriers and operators) [69].

Considering the statistical data concerning the number of passengers for 2016 and 2017, we are witnessing a slow but gradual increase in their numbers (in 2017, the number of passengers was 400 thousand, which is a 2.58% increase in comparison to the preceding year). This growth probably results from an extension of ITS services and an integration of services offered by Koleje Śląskie with the services of other carriers, as well as the discussed optimization of the carrier's network of connections.

A conclusion is therefore drawn that the proposed network optimization and the past ITS implementations will stimulate further growth in the number of regional railway passengers.

5. ITS Solutions Promoting Changes in Commute Habits—Poll Results

Stage three of the study consisted in a poll (carried out with the use of a questionnaire prepared according to [70,71]) carried out among the commuting residents of the region. The size of the research sample was 500 people. The purpose of the poll was to answer the question: "Which of the ITS solutions listed will contribute to increasing the number of regional passenger transport services?". The poll sought to extract solutions which could possibly affect the commute decisions of the local population, i.e., convince them to switch from their own means of transport to mass transit. The poll also asked for a grade of the solution (10 pts.—highest-graded solution, 1 pt.—lowest-graded solution). The results of the third stage are presented in Table 16.

As illustrated in Table 16, easy and comfortable access to travel parameter information both during and before the commute (planning the commute) is the most important factor in changing commute habits. These results are confirmed by other studies as well, for instance by [72].

The respondents pointed to the need of implementing ITS solutions to integrate information from different carriers. In their opinion, an IT platform integrating various transportation branches and different carriers was necessary (available on mobile devices in real time), one they could personalize to receive individualized information. In the opinion of the respondents, the development of such platforms would contribute to changing their commute habits, i.e., would stimulate an increase in the share of passenger transport services in total transit. The results of this poll confirm the fourth hypothesis H4.

Table 16. Grading (an average of the grades given in a scale from 1 to 10), illustrating the impact of the proposed solution on the ITS and on a change in commute patterns towards mass transit).

Description of Solution	Grade
Information provided before and during the commute (allowing the passenger to choose the most suitable means of transport, transfer stations and to determine the travel time), prepared for the individual passenger	10
Information provided before the commute (calculation of the travel cost using different means of transport)	9.5
Information on the travel time using different means of transport (including delays, substitute means of transport, etc.)	9.1
Electronic payment for travel in different means of transport	8.7
Payment during the travel	7.1
Display of the route and information on arriving in the destination	6.7
Safety in mass transit (information on the technical condition of vehicles displayed during the travel)	6.2
Guaranteed care for weak and/or immobilized passengers	4.0
Free use of all means of transport during a smog alert, also for passengers	5.8
Free parking lots in the suburbs and free use of municipal transport	5.6
Free WiFi in means of transport	4.9
Remote call center for people unskilled in the use of mobile devices or without mobile devices/support to foreigners	4

Source: Own study on the basis of primary studies.

6. The Impact of Innovative ITS Solutions on the Number of Passengers—Conclusions

The studies and analyses conducted herein have legitimized the research hypotheses formulated (both the first and the second one), as they indicated that there is a strong relationship between the number of railway connections in the region and the number of passenger transport services. The relationship between the regional GNP and the number of passenger transport services was not confirmed (the calculated correlation coefficient was irrelevant, although it was noticeable that, in the majority of studies regions, the regional GNP was growing while the number of regional passenger transport services was decreasing). According to calculations, the share of passenger transport services carried out by mass transit was higher relative to total transit in regions: with a high GNP, with a large population and a high urban development rate. For further analyses, it is necessary to implement an ITS (service category Traffic management, service name: Infrastructure maintenance management). The effectiveness of ITS in supporting infrastructure maintenance management depends on successively accumulated statistical data.

In verifying the third hypothesis, data from a single region Śląskie was examined. The hypothesis claiming that network optimization in terms of a single transportation branch would cause a slight increase in mass transit transport services was confirmed. For this study, data was obtained from a regional carrier. It is necessary to implement ITS (service category: Railway traffic management, service name: Transport planning support). The effectiveness of ITS in supporting future and successively repeated conditioning optimizations depends on the accumulation of data required by the graph theory. For other branches, a similar study was impossible to conduct, as there was no compatible statistical data available from the road, tram, trolley bus carriers operating in the region. In the Śląskie Region, ITS implementation is necessary (service category Traffic management, service name: Transport planning support). The effectiveness of ITS in supporting transportation planning depends on the quality and amount of successively accumulated statistical data from other transportation branches, provided in standard formats.

Obtaining and analyzing data from primary studies, the fourth hypothesis claiming that the integration of different branches of public transport and implementing synchromodal ITS planning was the ultimate expectation of the region's residents was explicitly confirmed. Synchronizing the networks for various means of transport will encourage commuters to switch to mass transit, which will ultimately increase the number of passenger transport services in total transit. Synchronizing transportation networks for various means of transport is possible using ITS (service category Traffic management, service name: Traffic control and service category Traffic management, service name: Information provided before and during commute using a means of public transport). However, the effectiveness of ITS is determined by the need to successively accumulate statistical data from all branches of regional transport, provided in standard formats. A conclusion can be drawn basing on the results of the study, that the number of mass transit passenger transport services will increase when information on travel times using different means of transport (in combined passenger transport) is available online. The studies have also indicated that sustainable development of transport (i.e., an increase in the number of passenger transport services) will take place if a single ticket can be used for different carriers, and if railway connections are integrated with bus connections.

In conclusion, what is necessary is a partnership dialogue among all parties interested in investing in regional transport, and for the voice of the commuters to be heard in developing operational ITS. The Management of the Śląsko-Zagłębiowska Metropolis has taken certain steps towards achieving the said dialogue and standardization of public transport, utilizing operative ITS. In the future, the authors of the article plan to study the dependence between the standards adopted in public transport and the development of the region. Studies devoted to modal changes resulting from the implementation of a single ticket for means of transport from different sectors will be a priority.

Author Contributions: Ewa Stawiarska has developed a comprehensive research model, collected and conducted secondary data analysis related to the use of transportation infrastructure and ITS in the context of the economic development of Polish regions. Prepared and conducted primary research for the development of ITS in the selected region (showing passenger requirements), as well as analyzed the data obtained from the conducted research. Paweł Sobczak developed and conducted experiments related to analysis of the structure of railway connections using the graph theory, as well as analyzed the data obtained from the conducted research. He also analyzed the impact of modern ITS solutions on the growth of passenger numbers on the example of the Koleje Śląskie. Authors Ewa Stawiarska and Paweł Sobczak have jointly developed and prepared the introduction and impact of innovative ITS solutions on the number of passengers (conclusions).

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Terms and Abbreviations

IT	Information Technology
GNP	Gross National Product
ITS	Intelligent Transport Systems
GUS	Polish Main Statistical Office
UTK	Polish Office of Rail Transport
KZK GOP	Upper Silesian Industrial Area Communication Association
MZK	Polish Municipal Transport Company
Poviat	second-level local government unit, a part of the Polish voivodeship

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