# Approach Methodology for Comprehensive Assessing the Public Passenger Transport Timetable Performances at a Regional Scale

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**Abstract:** The paper is focused on the issue of assessing the quality of transport connectivity on a predesignated transport network in regular public passenger transport at a regional scale. Comprehensively, using the defined key qualitative indicators, it assesses the performance of passenger transport timetables, in both ways of ex ante, as well as ex post. Existing methodologies in a given issue have only dealt with a partial assessment of the transport connectivity quality on specific transport network. However, unlike them, the objective of this manuscript was to propose a new unified methodology to assess the passenger transport timetables in terms of transport connectivity, and subsequently to complexly evaluate the whole predesignated regional transport network from a qualitative point of view. In this paper, the proposed methodology is demonstrated on a particular regional transport network, specifically an existing railway network in the Slovak Republic, whereby the data related to regional passenger transport timetables for a certain day is an input factor. The purpose of this study was to design and verify a draft methodological procedure to assess the quality of transport connectivity on a certain transport network, thus moving towards more effective evaluation of integrated transport systems. Its practical applicability consists in comparison of existing and proposed timetables, which is considered one of the crucial factors in terms of public passenger transport quality.

**Keywords:** public passenger transport; transport connectivity; timetable performance; quality assessment; quality indicators

## 1. Introduction

The role of the European Union's (EU's) transport system is to provide a high degree of mobility, while increasing its performance in terms of speed, comfort, and safety. At present, achieving a uniform, sustainable, integrated, and efficient transport system requires creation of transfer links and interconnections across all modes of transport. The availability of destinations and the frequency of connections are the most important criteria in terms of passengers' interest in public transport [1–3].

The transport infrastructure function is to comprehensively serve the state territory or selected geographic agglomeration. Transport infrastructure is one of the basic conditions for the functioning the national economy. It can be stated that, from a spatial point of view, the transport network intended to serve as regular passenger transport is rather well developed and sufficiently covers transport areas of public interest. Compared to the EU average, however, the quality of examined transport network

in the Slovak Republic is poor, in particular in regard to demands placed on it. Regional differences in the quality of transport network, which has far-reaching consequences in terms of increasing economic and social disparities among individual parts of the country, are also apparent [4–7]. Previous research studies [8–12] have confirmed that the quality of transport infrastructure is considered a crucial element which makes decisions about the foreign investment allocation very often. The offered quality of transport network connectivity is considerably related to services provided within transport sector [4].

The main task of transport is to satisfy the customers' requirements for quality, flexible, fast, and safe transportation of passengers and cargo [1,3]. Quality is differently perceived from the transport user [12], transport services provider, or transport organizer point of view, but also from the society-wide point of view. This is caused due to the fact that assessing the quality of transport network connectivity is performed in a non-systematic manner, regardless of the interaction of carried passengers with traffic or transport system [12,13]. Customers' needs and expectations are monitored by establishing procedures in accordance with the Regulation (EC) No 1371/2007 of the European Parliament and of the Council of 23 October 2007 on rail passengers' rights and obligations [14–16].

Based on the previous research studies [17–21], it can be declared that one of the fundamentals of providing transport services is to offer travel opportunities by designing transport network connectivity among individual transport lines, i.e., assessing the transport connectivity and travel opportunities themselves. Often, after implementing the new timetable in rail transport, particularly the train schedule diagram, discussions are going on about whether it is better or worse than in the previous period, while assessing is approached solely subjectively [3,4,17].

The availability of destinations and the frequency of connections are also important criteria for passengers in relation to public transport [3,13]. The key task of transport services is, therefore, to provide ample travel opportunities accordingly, whilst that of the infrastructure is to create the opportunity to provide a comprehensive service within a given state, specific geographical agglomeration, or area of interest [22–24]. The difference in quality standards within regional transport networks is also of significance because it can result in widening economic and social differences between individual areas [24].

At present, there is no comprehensive methodology for assessing the quality of a compiled timetable from the transport network aspects as a whole. Only specific transport lines and connections in passenger transport terminals are taken into consideration; nevertheless, the quality of transport connectivity from point A to point B is not assessed. The objective of this study was to fill the mentioned gap within assessment and set up an innovative and comprehensive view of assessing the quality of transport network connectivity, thus supporting operation of high-quality passenger transport connections, which represent meaningful and attractive alternative to private car transport. Outcomes of the proposed methodology may serve as a fundamental for ministries, carriers and customers in regard to public passenger transport [3,6].

The purpose of the paper is to create and verify a methodological procedure to evaluate the quality of connectivity on a particular transport network, thus generally contributing to the formation of an efficient evaluation method of integrated transport system in the regional territory. The proposed procedure is also intended to support the creation of high-quality transport connections in public passenger transport at a regional scale with a fixed timetable, which will represent a meaningful and attractive alternative to private car transport. Many studies have dealt only with partial indicators regarding the evaluation of public passenger transport quality, whereby this manuscript synergizes all the indicators into a single approach methodology.

## 2. Literature Review

The issue of public passenger transport quality assessment, to a certain extent, has already been addressed in several publications [1–11]. Nevertheless, results of these studies point only to partial evaluations of the quality of individual transport sections, while there is lack of reference and link to the individual timetable evaluations as a whole. Some research studies are particularly focused on an

effect of the transport network utilization on optimization algorithms [1–3,12], whilst others deal with periodic transport modes on transport networks and their optimization [6,7]. For instance, authors in [13,14] present a particular transport network, specifically railway transport infrastructure in regard to the quality evaluation. The application of empirical models in transport and traffic planning in terms of travel time impact on transport operation is addressed in publications [15–17], and the empirical studies [18,19] highlight the identification of key qualitative factors for the selected city. Relations between transport infrastructure and economic growth in India, and China's foreign capital issues are addressed in articles [8,20,21]. Temporal and spatial accuracy represents one of the most important attributes regarding the quality of public passenger transport. Time deviations from the planned schedule diminish the level of transport service provided, which is examined in research study in detail [22].

Nevertheless, the presented paper is based on the combination of several publications dealing with dynamic models of the transport service quality [23], as well as approaches to measure and evaluate the quality of services in passenger transport [24,25]. The authors have concluded that the assessing the transport connectivity is to be considered as a whole, resulting in a synergistic effect when evaluating the identified quality indicators. Therefore, it is necessary to come out on the quality standards of services provided in regional railway passenger transport [26–28]. An important aspect of this research study is also to rapidly relocate (move) among tariff points on the predesignated network; the following publications point to these qualitative attributes, whereby the effect of high-speed rails is addressed in [5,29], as well as in [30–32]. In publication [33], the methodology for examining the connectivity on a transport infrastructure, where the transport policy is applied to the specific case study regarding the high-speed rail, is the research topic in regard to transport infrastructure. In [34,35], a stability simulation analysis for intercity railways is presented, and in [36–38], new technologies for intelligent transport systems improving the transport connection quality on a certain network are described and analyzed.

This study is also focused on time-based synchronization in transfer points, as discussed in transport related studies in publications as well [39–44], where the effects of travel times on cost savings in terms of commuting on public transport routes and passengers' behavior under regional conditions in Eastern Europe are sequentially being discussed. Support for individual transport mode connections to the railway network is examined in [45,46], and a variety of case studies to increase the share of railway transport within the limitations of existing railway network are addressed in [47–51].

As for this manuscript, applying the methodology itself to the case study is performed using a particular web application [52], on a specific day and utilizing the search engine for train connections [53]. Implementing the regular timetable into particular studies is also, for example, carried out in publications [54–56], which needs to be assessed on the basis of the transport connectivity accessibility, as referred to in several transport research procedures [57–59].

Examples of economic impacts and financial compensation in regard to regional passenger transport are discussed in publications [60,61]; pricing, as well as optimal taxation of transport networks in [62]; and integration of tariffs in public transport is addressed in literature sources as follows [63,64]. Research in terms of specific transport networks and options for their assessment within regional conditions is executed in detail in [19,65]. In the context of transport service quality assessment, as well as internalization of external costs, the articles, as follows, have been published [66–69].

## 3. Materials and Methods Used to Compile Final Methodology

As a consequence of increasing competition in passenger transport [2], it is necessary to look for ways of making public transport more attractive to passengers. The leading indicator is the overall time spent traveling between two points. Reduction of the overall travel time (hereinafter as start-stop achieving time) can be achieved by optimum coordination of the participating transport subsystems. In this case, public regional passenger transport modes having assigned a timetable are considered the participating transport subsystems. This requires an integrated offer [25], which means that timetables,

driving times and transfer times are coordinated in order to minimize the start-stop achieving time between two points on a given transport network.

The superstructure for regular services is represented by the Integrated Public Transport Timetable (IPTT) [26]. This timetable not only provides an overview of regular services, but also of network interconnectivity in terms of individual lines operating during a particular period and transfer times at selected locations. The general aim is to minimize a passenger's start-stop achieving time from point A to B. This kind of service provision requires high precision planning and also needs to take into consideration marginal condition. Essential requirements are also imposed on the amount of marginal time (see below) between two subsequent hubs where two-way transfers can take place. Applying marginal times enables a combination of appropriate measures to be implemented in regard to infrastructure, vehicles and, last but not least, connections [27].

The basic principle of the IPTT underpins the regular timetable for the superordinate transport network [24]. Optimal transfer conditions are achieved when all means of transport intercept during the same time period at a given transfer hub [28]. During this time period, it is necessary to provide passengers with supplementary means of transport at the transfer point so that they can travel onwards to particular transfer hubs within the transport area at minimum cost. Analogically, passengers may also travel in the opposite direction [27].

The timetable that is drawn up of the connections at a transfer hub within a given transport area is called the 'transfer tree' [28]. The timetable indicates the intervals for transfers, i.e., marginal times at the transfer hub. The situation as represented by a transfer tree is often reproduced after the expiration of a particular period of time [25,27].

Connections in the opposite direction for a particular line should intercept due to the symmetry of the timetables [16], whereby time-distances are equal to half the period. As a transfer hub is situated at a time-distance equal to the integer multiple of half the period, the connections in the opposite direction, therefore, intercept at these transfer hubs [27].

The time-distance between the symmetrical transfer trees of two sequential transfer hubs is called 'marginal time' [24]. A one-hour period amounts to marginal times of 30, 60, and 90 min, etc. [18].

In a given systematized transport network [26], it should be possible to go from one point to another in the suggested way without a substantial loss of time due to waiting for a connection. This must also apply vice-versa, thereby creating transfer tree symmetry. As a result, the time needed for the return journey is equal to the integer multiple of the period [28].

For these reasons, timetables of this kind between hubs must be extremely precise [25]. Within this context, it is not necessary to take into consideration the maximum value for line speed because the transport time (see below), and therefore line speed, depends on these timetables.

This way of systematizing timetables enables railway transport to become part of an integrated base for comprehensive systematized integrated timetables [27]. By implementing the suggested requirements, the quality of transport network connectivity considerably increases [15].

During the addressing this issue, it was necessary to examine certain methods of Operations Research that are inevitably related to the forming and optimizing the transport network itself. In practice, there are a number of methods regarding the topics of transport network optimization, e.g., the nearest neighbor method, Chinese postman method (route inspection problem), traveling salesman problem, etc.

## 4. Developing Methodology for Assessing Network Connectivity

Any new methodology for the comprehensive assessment of the quality of network connectivity should be based on predetermined and well-defined steps [15,23]. The interconnection of individual indicators must enable the assessment of connectivity [12], and therefore the quality of transport, on equal terms [18]. This implies that all connections within a selected network must be taken into consideration [24,29]. The assessment procedure itself includes individual steps as follows: 1. Determining a transport network; 2. Identifying a set of transport connections; 3. Defining the relevant

tariff points on a defined transport network; 4. Selecting search engines for transport connections; 5. Specifying the assessment qualitative indicators; 6. Assessment of individual connections; 7. Assessment of average indicators within a specific route; and 8. Comprehensive assessment of a particular indicator within a transport network.

The suggested methodology is also vividly presented in the following flowchart (see Figure 1).
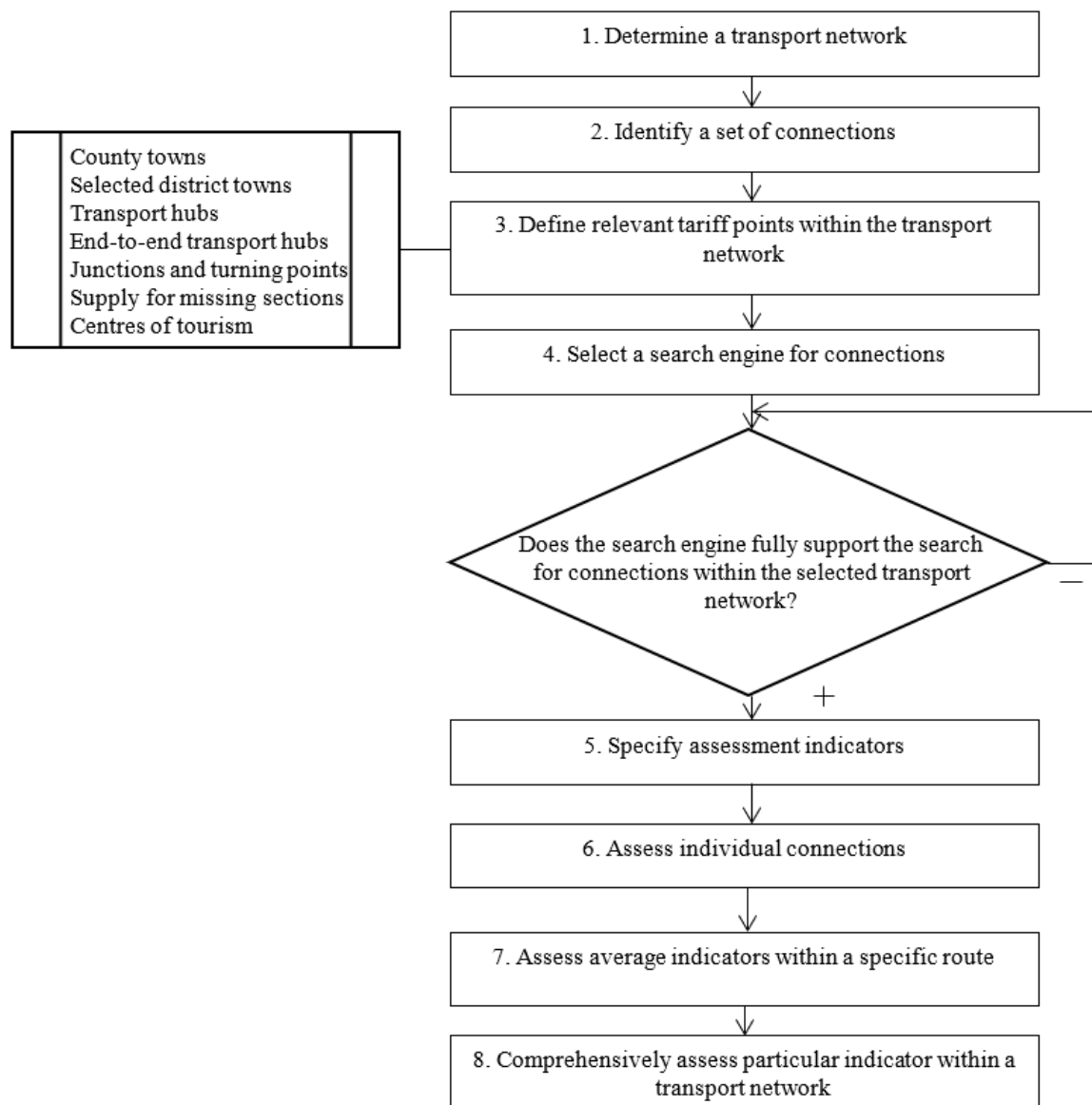
**Figure 1.** Flowchart for assessing the quality of transport network connectivity.

## 4.1. Determining a Transport Network

In this step, the passenger transport network (railway, road, air, water, integrated transport systems, etc.) is selected which will be the subject of the quality assessment. The specific choice may be defined in terms of mode of transport, operator, transport network or other criteria, and possibly also including ITS lines [30,31].

### 4.2. Identifying a Set of Transport Connections

In this step, specific connections should be selected. The choice depends either on the particular operator who provides transport services on the selected network [32], or on the kind of transport. Alternatively, all available connections as provided by all the operators are analyzed [33].

### 4.3. Defining the Relevant Tariff Points on the Defined Transport Network

Relevant qualitative indicators that serve as performance indicators for a particular connection between tariff points should be included in a comprehensive assessment of the connections incorporated in a timetable [34,35].

The minimum quality standards for the comprehensive assessment of an individual connection within a selected transport network (within a geographical area) are determined on the basis of the following indicators [15,36–39]:

- average travel speed;
- average speed until the final stop; and
- average waiting time.

For a comprehensive assessment, the quality of the connections at all tariff points within the selected transport network should be analyzed [15].

Alternatively, a set of tariff points may be selected for the quality assessment which are representative for the selected transport network as a whole [40].

### 4.4. Selecting Search Engines for Transport Connections

In this step, a search engine for connections needs to be selected according to input criteria [41]. Manual searching in timetables is the primary search method. However, websites, applications to search the transport connections, or offline mobile applications are also currently used for this purpose [52,53]. The individual parameters for searching for suitable connections (i.e., setting the date of departure, time of departure, maximum number of transfers, etc.) must be set correctly [43–45].

### 4.5. Specifying the Assessment Qualitative Indicators

Under the proposed methodology, the following indicators are used to assess the quality of the connections on a particular route [69]:

**Number of connections** $N_s$ for the assessed day includes both direct lines and transfer lines. This indicates the number of alternatives divided over time that passengers have to travel from point A to B. The higher the number of transport connections between the selected locations (tariff points) A and B exist, the better the choice by the customer arises, and thus the greater potential of meeting the customer's expectations occurs. As a rule, the need of a passenger to move from point A to point B arises at different time sequences throughout the day, however it is the most numerous in the early, as well as late afternoon rush hours. The necessary number of peak-to-peak (rush hour) connections must meet transportation requirements of passengers and, in particular, take into account the transport travel frequency for passengers.

**Average waiting time** $W_i$ refers to the amount of time spent by passengers waiting for a particular connection at the place of departure, or starting point. In regard to average waiting time of a passenger, there are two cases. First, a case when a passenger arrives at the point of departure just after the vehicle (train) departure, so he misses the transport connection, and thus is forced to wait for the next connection. The opposite case is when a passenger arrives at the point of departure just before the vehicle (train) departure, and is not forced to wait for the next connection. It is defined as half the time between the departure of two sequential connections:

$$W_i = \frac{(T_{odX+1} - T_{odXi})}{2} [h], \tag{1}$$

where: $T_{odXi}$ time of departure of the assessed connection from a tariffed starting point; and $T_{odXi+1}$ time of departure of the following connection from a tariffed starting point.

**Connection distance** $L_i$ refers to the distance traveled in kilometers (mostly tariff) by the mode of transport used for a particular connection. This does not always mean that the shortest possible route for the connection is used. As a result, this criterion, together with that of transport time, is classified as less important.

**Kind and number of modes of transport** that comprise a connection. This factor defines the quality of transport service connectivity.

**Transport time** $T_{pi}$ is calculated from the moment a passenger departs from their first starting point on the route to the moment of arrival at the final destination (tariff point). It is calculated as follows:

$$T_{pi} = T_{pr} - T_{od}[h], \tag{2}$$

where: $T_{pi}$ transport time [h]; $T_{pr}$ time of arrival at the final tariff point [h]; and $T_{od}$ time of departure from the starting tariff point[h].

**Number of transfers** $N_{pi}$ refers to the total number of transfers until the passenger reaches their final destination. This is the main criterion taken into account by passengers. Under ideal circumstances, the connection should be directly provided.

**Transfer time** $T_{wi}$ refers to the aggregate time that passengers spend waiting for the *i-th* connection at transfer points while traveling on a particular connection.

$$T_{wi} = \sum \left( t_{i2dep} - t_{i1arr} \right)[min], \tag{3}$$

where: $t_{i2dep}$ time of departure of the connecting train at the stop of *i-th* transfer; and $t_{i1arr}$ time of arrival of the connecting train at the stop of *i-th* transfer.

**Start-stop achieving time** $T_{Di}$ is calculated from the moment a passenger's arrives at the stop at the tariff starting point from which they are due to begin their journey to the moment of arrival of the last taken connection at the final stop at the output tariff point. This amounts to the sum of the average waiting time and transport time.

$$T_{Di} = W_i + T_{pi}[h], \tag{4}$$

where: $W_i$ average waiting time between two successive connections [h]; and $T_{pi}$ transport time [h].

**Travel speed** $V_{Pi}$ is calculated as the ratio of the traveled distance to the transport time.

$$V_{pi} = \frac{L_i}{T_{pi}} \left[ km \cdot h^{-1} \right], \tag{5}$$

where: $L_i$ traveled distance of the connection [km]; and $T_{Pi}$ transport time [h].

**Start-stop achieving speed** $V_{Di}$ is calculated as the ratio of the traveled distance to the start-stop achieving time.

$$V_{Di} = \frac{L_i}{T_{Di}} \left[ km \cdot h^{-1} \right], \tag{6}$$

where: $L_i$ traveled distance of the connection [km]; and $T_{Di}$ start-stop achieving time [h].

## 5. Assessment of Individual Connections

In order for the devised methodology to be applied successfully, more ways of assessing the quality of individual connections in a passenger transport network need to be considered [14]. For this research study, the quality of a connection was assessed according to the following [18,47]:

*Option 1*—Number of transfers;
*Option 2*—Start-stop achieving time;

*Option 3*—Travel speed; and

*Option 4*—Start-stop achieving speed.

After processing the assessment of the connectivity of one transport route, particular routes between tariff points on the transport network should be assessed [12]. This requires the careful selection of tariff points [48].

## 6. Assessment of Average Indicators within a Specific Route

During the assessments of the connections on a route, selected indicators are translated into average values [49]. This is done for the purposes of conducting the final comprehensive quality assessment of the whole route within the selected transport network [12].

For each route, average criterion values for all the assessed connections within a selected transport network must be calculated, i.e., average number of transfers (ø $N_p$); average transfer time (ø $T_w$); average start-stop achieving time (ø $T_d$); average travel speed (ø $V_P$); and average start-stop achieving speed (ø $V_D$) [69].

## 7. Comprehensive Assessment of a Particular Indicator Within a Transport Network

All the assessed routes within the network can then be evaluated on the basis of either the monitored indicators [17], or the weighted arithmetic mean of the number of passengers. As a result, the quality of a connection and that of the timetable for a selected transport network can be evaluated [12].

After determining the average values for all the monitored indicators, the average number of transfers for the whole transport network can be calculated. For the assessment of the quality of transport network´s connectivity, the following aspects should be taken into consideration:

*Arithmetic mean*

Average number of transfers, thereby taking into account the actual connections in the timetable:

$$\varnothing N_{ps} = \frac{\sum \varnothing N_p}{n} [transfer], \tag{7}$$

where:

$\varnothing N_{ps}$　average number of transfers in the whole transport network;

$\sum \varnothing N_p$　total of average transfers of *i-th* route on the examined route; and

$n$　number of examined routes in the network.

Average start-stop achieving time:

$$\varnothing T_{ds} = \frac{\sum \varnothing T_p}{n} [hod], \tag{8}$$

where:

$\varnothing T_{ds}$　average start-stop achieving time for the whole transport network;

$\sum \varnothing T_p$　sum of average transport time of *i-th* route on the examined route; and

$n$　number of examined routes in the network.

Average travel speed:

$$\varnothing V_{Ps} = \frac{\sum \varnothing V_P}{n} [km \cdot h^{-1}], \tag{9}$$

where:

$\varnothing$　$V_{Ps}$ average travel speed across the whole transport network;

$\sum \varnothing V_P$　total of average speeds of *i-th* route during the test period; and

*n*　number of examined routes in the network.

Average start-stop achieving speed:

$$\varnothing V_{Ds} = \frac{\sum \varnothing V_P}{n} \left[ km \cdot h^{-1} \right], \tag{10}$$

where:

$\varnothing \, V_{Ds}$　average start-stop achieving speed across the whole transport network;
$\sum \varnothing V_p$　total of average speeds of *i-th* route within the examined period; and
*n*　number of examined routes in the network.

***Average start-stop achieving speed using weighted arithmetic mean of the number of passengers***

In this case, the start-stop achieving speed is regarded as the most relevant indicator for assessing the quality of the selected transport network´s connectivity. In order to make the quality assessment of the network more objective, the balance of the number of passengers between individual tariff points is used.

$$\varnothing V_{Dos} = \frac{\varnothing V_{D1} \cdot n_{os1} + \varnothing V_{D2} \cdot n_{os2} + \ldots + \varnothing V_{Dn} \cdot n_{osn}}{n_{os}} \left[ km \cdot h^{-1} \right], \tag{11}$$

where:

$\varnothing V_{D1}$　average start-stop achieving speed for the 1st examined route;
$n_{os1}$　number of transported passengers on the 1st route during the examined period;
$\varnothing V_{D2}$　average start-stop achieving speed for the 2nd examined route;
$n_{os2}$　number of transported passengers on the 2nd route during the examined period;
$\varnothing V_{Dn}$　average start-stop achieving speed for the *i-th* examined route;
$n_{osn}$　number of transported passengers on the *i-th* route during the examined period; and
$n_{os}$　total of number of transported passengers.

## 8. Obtained Results: Application of a Case Study

The following example illustrates the use of the developed methodology for assessing the quality of a selected transport network´s connectivity.

### Step 1—Selection of a transport network

The case study focuses on the ŽSR (Railways of the Slovak Republic) rail network and covers all carriers that provide railway services within this network on a particular day.

### Step 2—Selection of a set of connections

The selected set of connections includes the county towns of self-governing regions, district towns with ŽSR or a stop, railway hubs, end-to-end route points, junctions and turns on the route, route sections, and centers of tourism.

### Step 3—Selection of relevant tariff points within the transport network

In total, 61 tariff points within the ŽSR rail network were examined. According to the methodology, county and district towns were selected that have populations of over 20,000 inhabitants; after that, railway hubs and stations subject to criteria determined by railway geography; and, subsequently, center of tourism, all subject to the presence of at least one tariff point [58,63].

In Figure 2, the tariff points for the selected network are marked in red. The selected date was a working day, namely, Thursday, 14 April 2017, with the assessment conducted on the basis of the train timetable of the Slovak Republic 2016/2017 [53].
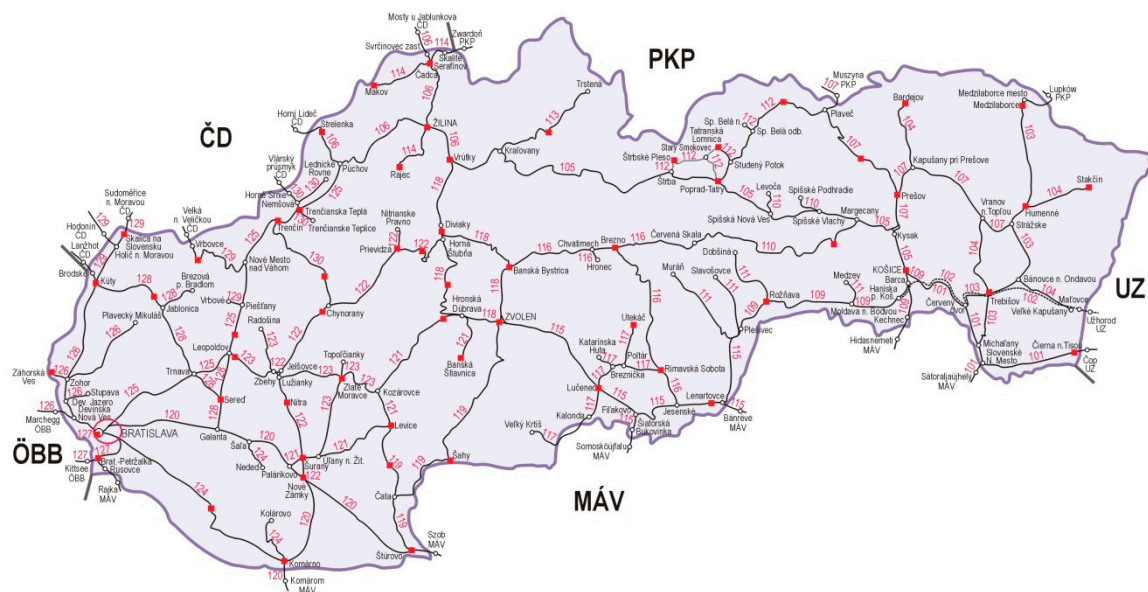
**Figure 2.** Map of the Railways of the Slovak Republic (ŽSR) rail network with the selected tariff points.

All connections between all the tariff points included in the 2016–2017 timetable were assessed. This involved the assessment of 3721 routes and all connections over a 24-h period.

### Step 4—Selection of a search engine for connections

Internet searches for all the connections were conducted via www.cp.sk [52] and search engine of timetables in Slovakia ELIS [53].

### Step 5—Assessment of an individual connection

Table 1 provides a good example of the assessment of a selected route between two points within the ŽSR rail network [52,53]. The data presented is for the Žilina–Bardejov route. In total, 10 connections were examined over the predetermined 24-h period. According to the 'transport time' criterion [64], number 6, which departs from Žilina at 11:20 am and arrives in Bardejov at 3:31 pm, can be regarded as the best connection. The journey of 288 km is covered in 4 h and 20 min with an average waiting time of 48 min in Žilina for this connection. This connection required two transfers, one from an intercity train to a local train, and the second between two local trains (Os) or train SC (Super City) and Os [45]. The average transfer time between trains was 10 min, which is highly satisfactory when waiting for a connecting passenger train [47]. The qualitative indicators regarding the transport connection are as follows [24,69]: start-stop achieving time $T_{d6}$ = 4:50; travel speed $V_{P6}$ = 68.84 km.h$^{-1}$; and start-stop achieving speed $V_{D6}$ = 58.88 km.h$^{-1}$.

### Step 6—Assessment of all connections on the route

Further assessment of the entire transport network requires the determination of the average indicators for each route. According to the proposed methodology, the values of the indicators for the Žilina–Bardejov route are as follows: average number of transfers $øN_p$ = 1.9; minimum average transfer time $øT_w$ = 46; average start-stop achieving time $øT_d$ = 6:20 h; travel speed $øV_P$ = 58.70 km.h$^{-1}$; and start-stop achieving speed $øV_D$ = 47.83 km.h$^{-1}$.

### Step 7—Assessment of connections within the selected network

All routes on the network and all the connections between the selected points within the ŽSR rail network need to be subsequently assessed in the same way. This amounted to the testing of all existing connections on 3721 routes during the predetermined 24-h period.

**Table 1.** Assessment of the Žilina–Bardejov route (Timetable 2017).

| Serial connection Number | Departure [hh:min] | Arrival [hh:min] | Average Waiting Time $W_i$ [h] | Connection Distance $L_i$ [km] | Transport Means (types) | Transport Time $T_P$ [h] | Number of Transfers $N_p$ | Transfer Time $T_w$ [h] | Start-Stop Achieving Time $T_d$ [h] | Travel Speed $V_P$ [km.h$^{-1}$] | Start-Stop Achieving Speed $V_D$ [km.h$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0:26 | 5:32 | 0.00 | 288 | EC, Os, Os | 5.10 | 2 | 1.03 | 5.10 | 56.47 | 56.47 |
| 2 | 0:26 | 7:10 | 2.08 | 288 | EC, Os | 6.73 | 1 | 2.65 | 8.81 | 42.77 | 32.70 |
| 3 | 4:35 | 9:31 | 1.08 | 288 | EN, R, Os | 4.93 | 2 | 0.80 | 6.02 | 58.38 | 47.87 |
| 4 | 6:45 | 11:31 | 1.00 | 288 | R, Os, Os | 4.77 | 2 | 0.40 | 5.77 | 60.42 | 49.94 |
| 5 | 8:45 | 13:31 | 1.29 | 288 | R, Os, Os | 4.77 | 2 | 0.40 | 6.06 | 60.42 | 47.54 |
| 6 | 11:20 | 15:31 | 0.71 | 288 | SC, Os, Os | 4.18 | 2 | 1.17 | 4.89 | 68.84 | 58.88 |
| 7 | 12:45 | 17:31 | 1.00 | 288 | R, Os, Os | 4.77 | 2 | 0.40 | 5.77 | 60.42 | 49.94 |
| 8 | 14:45 | 19:31 | 1.00 | 288 | R, Os, Os | 4.77 | 2 | 0.40 | 5.77 | 60.42 | 49.94 |
| 9 | 16:45 | 21:55 | 1.36 | 288 | R, Os, Os, Os | 5.17 | 3 | 0.88 | 6.53 | 55.74 | 44.14 |
| 10 | 19:28 | 0:02 | 2.48 | 288 | EC, Os | 4.57 | 1 | 0.58 | 7.05 | 63.07 | 40.85 |
| Average route values | | | | | | | 1.9 | 0.77 | 6.18 | 58.70 | 47.83 |

Absolute numbers of transfers were identified for each existing connection, after which an average number was determined for each examined route. After identifying all the average transfers, an average number of transfers for the whole transport network were calculated on the basis of Equation (7).

$$\varnothing N_{ps} = \frac{\sum \varnothing N_{pr}}{n} = \frac{7815.25}{3721} = 2.10 \; transfers,$$

The number of transfers for the whole network was determined to be 2.10; this indicator is very important in regard to the number of direct connections within the network. The start-stop achieving time for the transport network is also regarded as a qualitative indicator for the transport process. After determining all the average start-stop achieving time, the average start-stop achieving time for the whole network was calculated on the basis of Equation (8).

$$\varnothing T_{ds} = \frac{\sum \varnothing T_{pr}}{n} = \frac{25022.35}{3721} = 6.72 \; hours,$$

The average start-stop achieving time for the whole network was determined to be 6.72 h; this indicator is very important in terms of available time at individual tariff points in the network.

The travel speed across the network is regarded as next indicator for the transport process. After determining all the average travel speeds, the average travel speed across the whole network was calculated on the basis of Equation (9).

$$\varnothing V_{ps} = \frac{\sum \varnothing V_{pr}}{n} = \frac{168549.42}{3721} = 45.30 \; km{\cdot}h^{-1}$$

The average travel speed across the whole network was determined to be 45.30 km.h$^{-1}$.

After determining all the average start-stop achieving speed, the average start-stop achieving speed across the whole network was calculated on the basis of Equation (10).

$$\varnothing V_{Ds} = \frac{\sum \varnothing V_{pr}}{n} = \frac{131069.81}{3721} = 35.22 \; km{\cdot}h^{-1},$$

The average start-stop achieving speed (correct according to the original text) across the whole network was determined to be 35.22 km.h$^{-1}$.

The quality of the transport network´s connectivity, as defined by the flows of passengers between the monitored points of the network during the predetermined 24-h period, was subsequently examined. The flows (numbers) of passengers were subjected to the requirements set out in this article. Table 2 presents the product of the start-stop achieving speeds and the numbers of passengers traveling between the tariff points of the selected transport network. After totaling these results, the arithmetic mean was determined according to the number of passengers by applying Equation (11).

In order to assess the quality of the transport network´s connectivity on the basis of the start-stop achieving speed, flows of passengers were used to objectivize the assessment. The weighted arithmetic mean of the number of passengers was used for the calculation (and the value of start-stop achieving speed across the whole network weighed by number of passengers was calculated):

$$\varnothing V_{Dos} = \frac{\varnothing V_{BN}{\cdot}n_{BB} + \varnothing V_{BN}{\cdot}n_{BS} + \ldots + \varnothing V_{ZA}{\cdot}n_{ZH}}{n_{os}} = \frac{29.98*129 + 17.96*52 + \ldots + 37.20*150}{157172} = 38.93 \; km{\cdot}h^{-1},$$

The results are presented below (Table 2).

After identifying all the average start-stop achieving speed and passenger flows for the individual routes of the selected transport network, the start-stop achieving speed was determined to be 38.93 km.h$^{-1}$.

**Table 2.** Start-stop achieving speed across the whole network weighed by number of passengers.

| Product of Number of Passengers and $V_D$ | Bánovce nad Bebravou | Banská Bystrica | Banská Štiavnica | Bardejov | … | Zvolen | Želiezovce | Žiar nad Hronom | Žilina |
|---|---|---|---|---|---|---|---|---|---|
| Bánovce nad Bebravou | 0.0 | 3867.8 | 933.7 | 0.0 | … | 1043.8 | 0.0 | 0.0 | 1524.5 |
| Banská Bystrica | 2741.2 | 0.0 | 1256.8 | 0.0 | … | 24928.3 | 0.0 | 3909.5 | 8846.3 |
| Banská Štiavnica | 0.0 | 345.9 | 0.0 | 0.0 | … | 3846.4 | 199.2 | 5864.2 | 1008.6 |
| Bardejov | 0.0 | 0.0 | 0.0 | 0.0 | … | 2651.1 | 0.0 | 0.0 | 3337.1 |
| … | … | … | … | … | … | … | … | … | … |
| Zvolen | 0.0 | 34816.6 | 1007.7 | 0.0 | … | 0.0 | 0.0 | 6550.3 | 3753.2 |
| Želiezovce | 2476.0 | 0.0 | 0.0 | 0.0 | … | 1008.6 | 0.0 | 0.0 | 4140.1 |
| Žiar nad Hronom | 0.0 | 1023.0 | 0.0 | 0.0 | … | 12463.7 | 0.0 | 0.0 | 2149.8 |
| Žilina | 3369.4 | 0.0 | 2260.2 | 0.0 | … | 33915.7 | 0.0 | 5579.5 | 0.0 |
| Sum of $V_D$ across the whole network | | | | | | 6118426.93 | | | |
| Start-stop achieving speed across the whole network weighed by number of passengers. | | | | | | 38.93 km.h$^{-1}$ | | | |

## 9. Discussion

In the case study elaborated in previous Chapter, as an example, the evaluation of one particular railway transport section (Žilina–Bardejov, located in the Slovak Republic) out of 3721 train lines was selected. The following results were calculated on the given transport route:

- average number of transfers $øN_p$ = 1.9;
- average transfer time $øT_w$ = 46 min;
- average start-stop achieving time $øT_d$ = 6:20 h;
- travel speed $øV_P$ = 58.70 km.h$^{-1}$; and
- start-stop achieving speed $øV_D$ = 47.83 km.h$^{-1}$.

The same principle was applied across the whole transport network, and by implementing the same methodological procedure, the remaining 3720 transport routes were examined. After applying this procedure throughout the network, the following results were obtained:

- average number of transfers across the whole transport network $øN_p$ = 2.10 transfers;
- average transfer time across the whole transport network $øT_w$ = 6.72 h;
- average start-stop achieving time across the whole transport network $øT_d$ = 45.30 km.h$^{-1}$;
- start-stop achieving speed across the whole transport network $øV_D$ = 35.22 km.h$^{-1}$; and
- start-stop achieving speed across the whole network weighed by number of passengers $øV_{Dos}$ = 38.93 km.h$^{-1}$.

Thus, after identifying and calculating the individual indicators when taking into account passenger flows, start-stop achieving speed across the whole network was determined at 38.93 km.h$^{-1}$. Based on this value, it is possible to compare the upcoming timetables and objectify the quality of timetables based on the proposed procedures.

As mentioned, the major objective of the manuscript was to propose a universal and comprehensive methodology to assess the quality of transport connectivity on a predesignated transport network within regular passenger transport at a regional scale, specifically when using the public passenger transport timetable performance data. The main benefit of the performed research study lies in a draft of unified methodology that may be applicable on any regional transport network and on any regular public passenger transport mode, as well as integrated transport systems. Other benefits may include, e.g., specification of requirements of the public passenger transport orderer for better transport connectivity in timetables based on the proposed assessment qualitative indicators; and particular support of EU transport policy objectives in terms of public passenger transport with an emphasis on quantification of qualitative indicators assessing the relocation process on a transport network.

The proposed methodology can be used to compare parameters and indicators for different timetable variants, in both methods of ex ante, as well as ex post.

The approach procedure is directly applicable to the following modes in regular public passenger transport: railway passenger transport, bus passenger transport, air passenger transport, and integrated transport systems, due to their regularity in the context of passengers' carriage. The methodology cannot be applied to private car transport nor passenger transport, which do not have assigned a timetable.

## 10. Conclusions

As for the area of assessing the transport connectivity quality on a transport network, a number of standards, regulations and directives exist. They are implemented in national legislation; however, the quality of transport connectivity and availability is perceived subjectively by each passenger or potential passenger. No unified methodology for comprehensive assessing the quality of transport connectivity within regular passenger transport on a predesignated transport network at a regional scale has been designed yet. The stated suggestions and solutions to address the issue of assessing the quality of transport connectivity contribute to enforce the EU transport policy intentions and objectives, i.e., promoting the population mobility using more environmentally-friendly modes of transport.

Sequentially, according to the proposed approach methodology, the specific regional railway network was identified, as well as more important economic nodes and relevant tariff points on this railway network were specified. Subsequently, using the ELIS search engine of timetables and by analyzing individual transport sections between two tariff points, on a selected day and a given section, the calculated average values of each determined indicator per route were evaluated.

These indicators are as follows:

- average number of transfers $\text{øN}_\text{P}$;
- average transfer time $\text{øT}_\text{w}$;
- average start-stop achieving time $\text{øT}_\text{d}$;
- travel speed $\text{øV}_\text{P}$;
- start-stop achieving speed $\text{øV}_\text{D}$; and
- start-stop achieving speed weighed by number of passengers $\text{øV}_\text{Dos}$.

In the draft comprehensive methodology, a total of 3721 transport sections (routes) were processed, and in each section, all connections were taken into account for individual calculations. To objectify the outcomes depending on the start-stop achieving speed, passenger flows (number of passengers) were utilized. This indicator can be used to compare certain values among individual timetables in railway passenger transport, either ex post or ex ante.

As mentioned, the research study addressed is applied to assess the quality of transport connectivity at existing regional railway network in a given transport territory (located in the Slovak Republic); nevertheless, the proposed methodological procedure is applicable to all modes of regular public passenger transport and integrated transport systems. It is intended to serve as a fundamental for assessing, analyzing, or comparing the compiled public passenger transport timetables on a particular transport network when using specified assessment qualitative indicators.

Following the aforementioned, the approach methodology may serve as a basis for multiple purposes for ministries, operators, and orderers (customers) within public passenger transport. It should be noted that the draft assessment procedure makes it possible to compare different timetable variants on a defined transport network.

The methodology presented is primarily based on an ideal situation, i.e., times in timetables are adhered to and there are no significant delays in individual transport connections. However, for future investigations, the criteria related to the transport connection delays may be taken into account, thereby to compare current (existing) timetables with real (including delays) timetables. Such comparisons could subsequently serve as an evaluation of compliance (ideal) or non-compliance (including delays)

with timetables. In that case, the resulting monitored indicators would be changed, which could lead to optimization of timetables, thus minimizing transport connection delays for future time-periods. This could be considered another factor to assess the timetable reliability, thus helping to improve the quality of public passenger transport.

**Availability of data and material:** Not applicable. All relevant data is presented in the main manuscript.

**Author Contributions:** V.Ľ. and P.D. conceived and designed the manuscript; particularly, they elaborated the methodology, performed individual calculations and performed the experiments. O.S. and M.S. obtained and analysed the input data, processed literature review, verified the results, elaborated the discussion chapter and ensure the comprehensive English translation (even with final revisions). I.R. approved the final manuscript corrections and provided the supervising the final version of the manuscript.

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