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A Method for the Identification of Critical Interstop Sections in Terms of Introducing Electric Buses in Public Transport

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Abstract: Among the activities that cities are taking to reduce the emissions of harmful substances emitted by conventional engine-powered vehicles is replacing the fleet with electric vehicles in public transport that can operate in urban areas. Fleet conversion is a process in which one of the decisions that must be made is the choice of lines that should be served in the first place by electric buses. Due to the specificity of the battery charging process, the routes of lines serviced by electric vehicles should run through sections that are as little exposed to disruptions as possible, which can adversely affect the travel time of these sections. The main goal of the article was to develop a method that supports the search for bus lines that are characterized by the highest level of reliability and punctuality and therefore also by the stability of the travel time between stops. The proposed method makes it possible to indicate critical interstop sections that have the greatest impact on the sensitivity of the line to disturbances. It was assumed that the more critical sections of the route, the greater the risk of bus delay, which may be disadvantageous in the case of electric vehicles due to the need to reach the battery charging station in time. The method was implemented on the example of selected lines in the Upper Silesian region (Poland) for data covering four years (2016–2019). The proposed approach allowed for the development of the ranking of lines, corresponding to the order in which the conventional fleet should be changed to electric.

Keywords: electric bus; public transport; road and street network; critical interstop section; sustainable development; traffic congestion; bus route; GTFS; GIS; bus stop

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1. Introduction

Currently, cities are experiencing an increasing motorization rate, defined as the ratio of the number of vehicles to the number of residents in a given area [1,2]. The growing number of vehicles generates the number of trips made [3]. This is the result of changes in people's lifestyles, the habits created, and the increased convenience associated with personal transport [4]. However, the development of individual transport contributes to the worsening of road conditions, causing congestion, which affects delays in both the private and public transport systems [5]. It also has a negative impact on the environment due to air pollution, noise, and energy consumption, which in turn can lead to deterioration in the health of the inhabitants [6]. Therefore, it is necessary to take actions to minimize these unfavourable phenomena.

Activities that reduce the level of negative impact of transport on the natural environment are included in the idea of sustainable development, which distinguishes three main factors: environmental, social, and economic [7–9]. An important action in this regard is to encourage people who use private vehicles to use public transport. This problem is particularly important in a post-pandemic situation where a decrease in the share of public transport trips is observed in cities [10–13]. To effectively compete with individual transport, public transport must be attractive and meet a number of passengers' expectations expressed in transport postulates, including directness, frequency, accessibility, low cost, punctuality, regularity, reliable information, and comfort [14,15]. A modern bus fleet is one of the main factors that increase the share of public transport [16]. Currently, to decarbonize public transport, public transport is moving towards the use of electric vehicles [17]. Such solutions make public transport attractive for mobility in urban areas, thus reducing the negative impact of individual transport [18].

For financial, technical, and organizational reasons, it is often not possible to completely convert a conventional fleet to an electric one. Then it is necessary to decide which lines should be serviced by electric vehicles in the first place. The main goal of the research is to develop a method to select bus lines intended for servicing by electric vehicles in a situation in which it is not possible to provide all lines with such types of vehicles. This means that from the set of existing or planned lines analysed, one should select those for which the value of the assessment measure in terms of the adopted criterion is the most favourable. Due to the specificity of the battery charging process, the lines operated by electric vehicles should be characterized by high reliability and punctuality, as well as by the stability of travel time between stops. Therefore, these factors were adopted as the main determinants of the selection of the lines to be serviced by electric buses. They are closely related to the occurrence of disturbances on sections of the road and street network.

This article focuses on the role of punctuality, which can increase the demand for public transport services, and is also an important factor when using electric buses. The risk of delays on the road and street section makes it necessary to use batteries with a higher capacity when powering electric buses to prevent the vehicle from stopping due to battery discharge.

The article proposes a method to identify critical interstop sections on bus routes that make these lines unsuitable for electric bus service. Depending on the needs, the method can be applied to the entire set of lines that serve the area studied or to selected bus lines. The presented research aims to look for bottlenecks in the road and street network based on time deviations from planned departures in public bus transport and on a spatial analysis considering the structure of the transport network. The proposed method makes it possible to search for critical elements that have the most significant impact on vulnerability of the network. The more critical elements there are, the greater the risk of delaying the bus.

The approach was developed following a literature review which showed that many researchers neglect spatial analysis and focus solely on temporal aspects. Therefore, there is a lack of information on the relationship between time deviations and spatial considerations. The questions addressed in this article are:

- Which bus routes may be affected by only minor delays, making them suitable for electric buses?
- Which sections of the road and street network cause the most delays in public transport?

Including spatial analysis in the research makes it possible to study the influence of the structure and parameters of the elements of the transport network on delays. Spatial mapping of bus routes in a city is possible using a Geographic Information System (GIS) [19,20]. Data on the road and street network layout are available, for example, from OpenStreetMap [21]. Many bus operators provide standard data on the General Transit Feed Specification (GTFS), which contains specific information on bus routes, for example, distances and bus stop sequences [22].

The first step of the method is to designate the area and the bus routes to be analysed. This article presents a case study of selected bus routes in the city of Katowice in southern Poland. The proposed method shows which bus routes are the most suitable for electric buses. This information can help transport planners ensure the efficient operation of the transport network. The results obtained make it possible to identify places that require changes in the organization of traffic or reconstruction of road facilities to improve traffic conditions, at least for public transport vehicles. In the transition period, based on the experience collected, the timetable can be adjusted to improve the punctuality of the travel time of a given section.

The article is structured in six sections. In the following section, a discussion is provided, based on existing studies related to the issues of introducing electric vehicles in public transport and identifying critical sections in terms of traffic problems in the transport network. In Section 3 the assumptions and outline of the adopted research method are described. Section 4 covers the characteristics of the research area, the method for preparing the data for analysis, and the presentation of the research results. Section 5 presents a broad and multifaceted discussion of the results in the context of the current state of the issue. The last part of the article contains conclusions and directions for further research.

2. Related Literature

As the conventional engine-powered fleet changes to modern electric propulsion, it is essential to consider where and how this fleet can be introduced safely and effectively [23]. Is it better to change the entire fleet in the area being studied or just the fleet that serves selected routes?

Electric buses have range limitations, which are related to battery capacity [24]. To use this type of fleet on existing bus routes, it is necessary to know the specifications of the buses [25]. An important aspect is how these vehicles are charged, which can be performed in depots by cable charging, at bus stop stations by pantograph charging, or on roads by inductive charging. In terms of cost, the most efficient option is to charge vehicles in the depots [24].

The fundamental parameter for the introduction of electric buses is the length of the entire route, including additional sections such as from the depot to the first stop and from the last stop to the depot [26]. Other parameters related to the local landform (elevation and depression), the road network, the availability of charging infrastructure, and the weather, the level of energy required is influenced by the need to use heating and air conditioning [27]. Existing bottlenecks on public transport routes may preclude the introduction of electric buses due to the longer time required to cover a relatively short route due to traffic congestion in these places [24].

Therefore, delays that occur along the bus route affect the ability of the vehicle to perform its scheduled work. This article proposes a method to analyse bus delays and the resulting delays on operational bus routes. The impact of infrastructure on delays is also considered, particularly regarding individual interstop sections.

Passengers want a reliable bus service "to arrive on time" [28]. Punctuality is one of the basic parameters of public transport that bus operators monitor, and a large sample of data collected from different periods (weekdays, weekends, public holidays, rush hour, and off-peak periods) enables a comprehensive analysis of the situation for a given bus line. Three methodological problems can be distinguished in published studies that analyse delays. The first problem is the way punctuality data are collected and analysed [29]. Modern methods allow the collection of a wide range of data (big data) on buses using a variety of tools, and disturbances on the network are studied in different ways depending on the tool used: prediction of traffic volume using GPS transmitters, radar sensor data for traffic flow measures, or Bluetooth sensors for travel time [30]. Furthermore, to determine the travel time of buses, GPS transmitters connected to a computer on board are used (automatic vehicle location [28]) and the moment the door opens at a bus stop is analysed. Another problem is to find a reliable measure to assess delays, and a third is related to the need to collect data from several different periods to avoid skewing the results due to atypical delays [28].

Research on delays is carried out in a variety of ways. A study [31] showed the use of data collection from GPS sensors and interviewers to estimate travel time by car and public transport (bus and metro). Average travel times were compared. The most stable results were obtained for the metro due to minor network-related disruption. In another study [32], the authors indicated three measures of travel time costs. The first is related to the analysis of the schedule by subtracting departure times from arrival times. The second concerns Bernoulli cost measures. The third is related to the analysis of a model of average deviations, where the proposed models are theoretically described without presenting a case study. Another team of authors [28] proposed to perform a percentage analysis for the entire journey by subtracting the usable schedules from the timetables and dividing them by the travel time according to the timetable. The measure divides the shortest and longest trips into two sets. A study of delays was also presented in [33] by analysing the average travel time and its variability. The models presented are based on marginal cost functions of departure and arrival times.

In addition to delay analysis, methods based on traffic volume analysis, such as annual daily traffic or volume-to-capacity ratio, are also used in the literature to find critical sections. However, the authors of these studies point to the erroneous results of this approach and the implementation of network robustness index analysis [34]. This approach allows for a general analysis without a specific analysis of public transport. A similar analysis was presented in [35], indicating that the results may improve the infrastructure through a change in traffic control. Another way to analyse delays was presented in [36,37], where the data used were obtained from questionnaires. The preference of the travellers and their acceptance of delays in relation to the price of the trip was determined. Another example of delay analysis for the whole metro system was presented in another study [38] using a Bayesian network model.

In the literature, several studies present have routed optimization algorithms to reduce delays [39,40]. A paper [41] provided a theoretical outline of the delay analysis associated with rerouting bus lines. Hierarchical routing using a genetic algorithm was presented in [42]. The proposed solution makes it possible to determine new routes using the existing road network. The authors of another study [43] showed how to optimize travel times for the task of mapping the route between start and end stops using a shifted log-normal distribution. A disadvantage of the method is that intermediate stop stations are not considered. Such solutions are not always suitable for decision-makers, as there may be a need to omit key stop stations on a particular bus route network. In another article [44], the authors used a global approach to find critical sections using the Hansen essential accessibility index. This method does not allow for an accurate estimate of local problem areas in public transport. The use of delay times is also used to optimize the public transport network. A method was proposed that considers the use of travel time to satisfy the demand of passengers and provide a reliable public transport service [45]. Another optimization approach was presented in [46], where the objective of the proposed method is to maximize the destinations that passengers can reach. Network optimization was achieved using a measure of arrivals of vehicles in public transport [47]. Regularity was defined by the mean percentage deviation.

In another study [48], the results of the delay analysis were found to be essential for the development of infrastructure and connections between newly planned bus lines. For such analyses, the distance between stop stations, the number of passengers likely to be carried, and the infrastructure are critical parameters [49,50]. The re-routing planner should be able to answer questions about the number of people who cannot reach their destinations using only one bus and identify critical sections [51]. Another article [52], presented the positive features of developing a new bus route to minimize delays. This study shows that the least-delay-prone structure is a straight line without any central stop stations, whereas the most-delay-prone structure is a circular line with many stop stations near the beginning and end of the route. Network analysis can provide recommendations for three different levels: strategic (e.g., extension of the existing network, introduction of new bus routes), tactical (e.g., change in bus frequencies, addition of bus lanes), and operational (e.g., changes in the way traffic lights operate) [48].

The review of the literature showed that the problem of assessing sections of the road and street network from the point of view of their usefulness for the electric bus service is a new issue. No publications have been found that consider disturbances that occur in the sections as determinants of the possibility of introducing electric vehicles in these parts of the infrastructure. Therefore, the problem has been carefully investigated.

The aim of this article is to develop a method to identify critical interstop sections on bus routes. The interstop sections have been determined on the basis of a measure capturing the degree of variability of deviations in the travel times of these sections, determined on the basis of real and scheduled departures from neighbouring stop stations. Sections with too high levels of disruptions make bus lines that run on these sections unsuitable for operation by electric buses.

3. Research Method

3.1. The Main Assumptions of the Method

Various types of disruption can occur in the interstop sections of the public transport network, which adversely affect the battery charging process, and in critical situations, with large and unusual delays, can even lead to the need to stop the vehicle. As a result, electric vehicle-operated bus lines should be characterized by a high level of invariability of travel time in individual sections of the route. Therefore, the deviation of the differences between the actual and scheduled departures of public transport vehicles from successive bus stations was adopted as a measure of the disturbance assessment. On this basis, the critical interstop sections with the highest level of interference were determined. Lines with the lowest share of critical interstop sections, assuming other criteria related to the introduction of electric vehicles at a similar level, should be recommended for service by this type of vehicles.

The method considers the conditions and assumptions concerning both the characteristics of the analysed lines and the time range of the analysis and the structure of the data set. When selecting lines that can potentially be serviced by electrically powered rolling stock, one should first consider technical, technological, and organizational factors relating to the battery charging process itself, including, e.g., the method of charging and the associated location of chargers or battery replacement points. In this regard, spatial conditions (e.g., road inclination, geometric parameters of the road and street infrastructure, and line length) and traffic conditions (i.e., volume of traffic, traffic structure, and the possibility of separating bus traffic from other infrastructure users) are also important. Financial, political, and environmental factors also play an essential role in the selection of the lines for analysis.

The travel times of individual sections of the road and street network may be subject to greater or smaller deviations depending on the time of day and traffic volume. Therefore, the method assumes that the analysis is performed separately for the morning and afternoon rush hours, with a distinction between holidays and school days, and it only concerns working days.

It was assumed that the global analysis covers a set of partial analyses (marked as R) conducted in periods with homogeneous characteristics. Therefore, four independent periods of analysis were distinguished:

- School days morning rush hours (*SM*);
- Holidays (all days off from school) morning rush hours (*HM*);
- School days afternoon rush hours (*SA*);
- Holidays (all days off from school) afternoon rush hours (*HA*).

This can be described as follows:

$$R = \{SM,\ HM,\ SA,\ HA\} \tag{1}$$

Moreover, due to the representativeness of the conducted analyses, it was assumed that the values of the adopted measures for the assessment of the level of disturbances on the interstop sections would be determined based on large data sets covering at least a two-year period.

The analyses were performed at the stop station level. Data on all scheduled and actual departures from the station in a specific period (that is, during the morning and afternoon rush hours on holidays and school days) were included. If the station is served by more than one line, the analyses were carried out separately for each of the lines. To eliminate incidental situations resulting from atypical traffic disturbances on the road and street network, only departures from a stop station for which deviations from the scheduled departure time are within the specified tolerance range were considered.

3.2. The Outline of the Method

The general scheme of the method is presented in Figure 1.

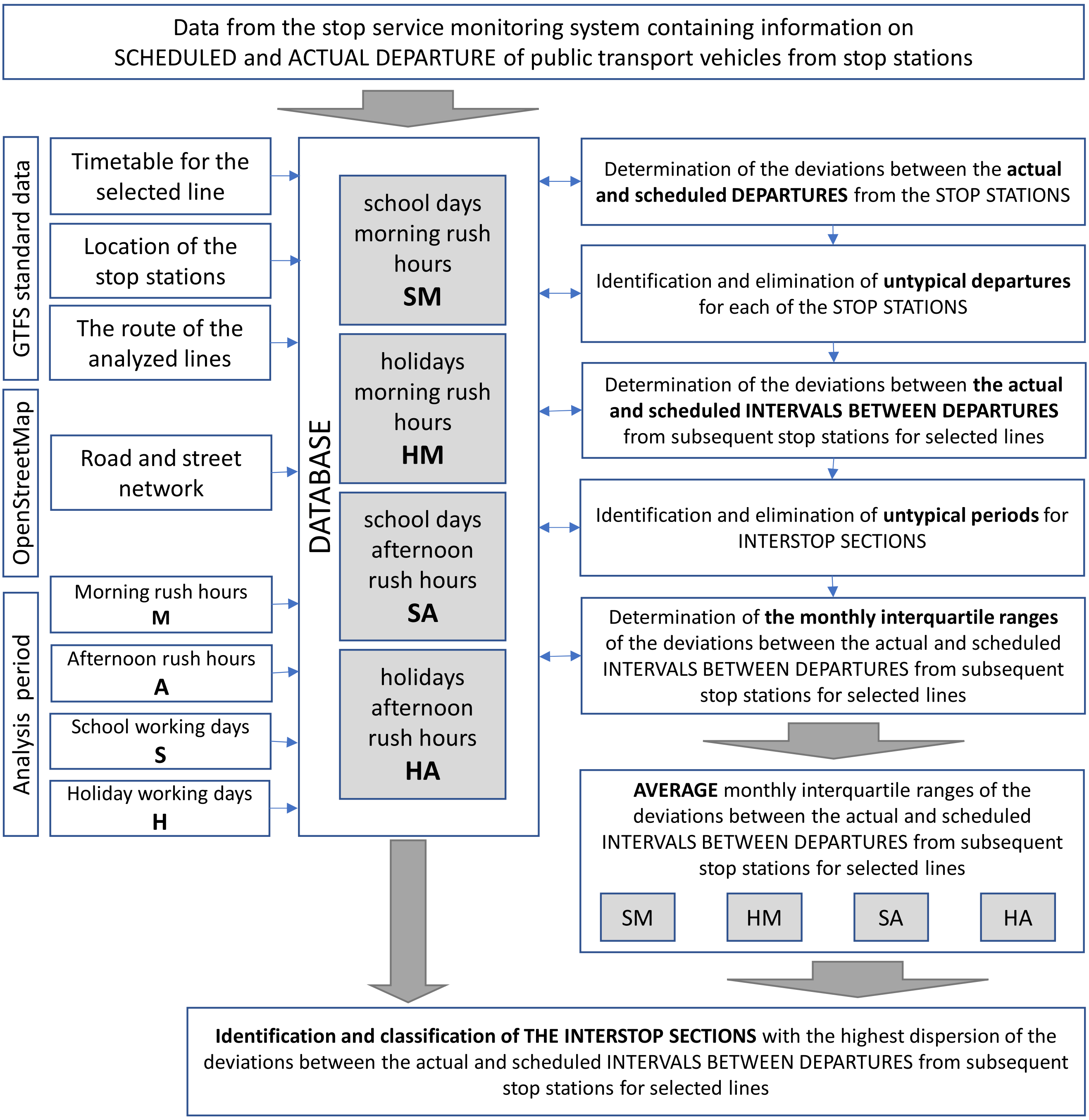


Figure 1. The scheme of the research method.

The essential stage of the method is the proper preparation of the data collected in the database to facilitate the formulation of conclusions and to make the correct decisions. Public transport operators usually have raw data obtained directly from devices that monitor the service of stop stations. For these data to be useful for the conducted analyses, they should be properly processed and adjusted. Therefore, the most important information from the point of view of the research objective is the scheduled and actual bus departures from a single stop station served by the line. To develop a database with a structure that allows for the implementation of the assumed analyses, it is also necessary to obtain information about the timetable and route of the analysed lines with the exact locations of the stop sections.

Data for spatial analysis were collected in the QGIS software. This requires geospatial baseline data on the public transport network in GTFS file format provided by the public transport operator or organizer. For the purposes of the analysis, the period of the morning and afternoon rush hours, as well as the specification of school and holiday working days, should also be precisely defined. It depends on local conditions and should be preceded by detailed traffic analyses.

The data provided by the operator may be incomplete or may contain errors. Therefore, only data that included information on public transport punctuality for representative days were accepted for analysis and then divided into school–working days and school-free working days. Furthermore, trips with missing data on actual or scheduled departures from the stop station were excluded from further analysis. At this stage, the analysis was carried out independently for a single stop station. Therefore, it covered only trips for which the scheduled departure from the station is within the assumed traffic rush hours.

Identification and elimination of atypical trips were carried out for each stop station separately and consisted of the removal of those whose actual delay or acceleration regarding departures from the station is not within the accepted tolerance range.

Based on the information about the route in the d-th direction, the analysed i-th bus line was divided into a specific number of interstop sections forming the following ordered set:

$$\boldsymbol{IS}_{id} = \left\langle is_{id1}, is_{id2}, \ldots,\ is_{idj}, \ldots, is_{idn_{id}} \right\rangle \tag{2}$$

where is_{idj} denotes the j-th route segment (that is, interstop section) for the i-th line for the d-th direction, and n_{id} is the number of all interstop sections for the i-th line in the d-th direction. The number of interstop sections may be different for each of the directions of the analysed bus lines.

Each interstop section is located between two stop stations, one of which for a given direction is the start–stop station marked as ss_{idj1}, and the other is the end stop station marked as ss_{idj2}.

Due to the assumption that analysis was made only in the previously defined peak periods, a set of trips for each stop station was determined, for which the scheduled departure is within these periods. However, such assumptions may generate situations in which the sets of trips for subsequent stop stations on the route are different, which make it impossible to determine the intervals between departures from subsequent stop stations. Then the departure, which is not present in both sets for subsequent stop stations on the route of the tested line, should be removed from the analysis for the interstop section connecting these stop stations.

In this way, the sets of departures of trips from subsequent stop stations considered during the analyses were assigned to interstop sections and not to individual stations. These sets are marked generally as $\mathbf{P}^{\mathrm{R}}\left(is_{idj}\right)$ and for each of the independent period as $\mathbf{P}^{\mathrm{SM}}\left(is_{idj}\right)$, $\mathbf{P}^{\mathrm{HM}}\left(is_{idj}\right)$, $\mathbf{P}^{\mathrm{SA}}\left(is_{idj}\right)$, and $\mathbf{P}^{\mathrm{HA}}\left(is_{idj}\right)$.

A single trip is marked as p. In the next stage of analyses for specific departures from subsequent stop stations on the route served during p-th, trip the differences between the scheduled departures from the following station, i.e., $t^{sched}\left(ss_{idj2}, p\right)$ and the preceding station $t^{sched}\left(ss_{idj1}, p\right)$, were determined. Then, in a similar way, the deviations between the actual departures from the following station, i.e., $t^{act}\left(ss_{idj2}, p\right)$ and the preceding station $t^{act}\left(ss_{idj1}, p\right)$, were determined. At this stage, trips for which it is not possible to estimate the values of the intervals between departures from the stop stations for the single interstop section, or if the values were incorrect, were removed independently for each stop station.

The result of the research carried out at this stage is that the determination of the difference between the actual and scheduled intervals between departures from the stop stations for the single interstop sections is_{idj}. For the set of p-th trips from subsequent stop stations, this difference is determined as:

$$DAS\left(is_{idj}, p\right) = \left(t^{act}\left(ss_{idj2}, p\right) - t^{act}\left(ss_{idj1}, p\right)\right) - \left(t^{sched}\left(ss_{idj2}, p\right) - t^{sched}\left(ss_{idj1}, p\right)\right) \quad (3)$$

The analysis at this stage is performed independently for each interstop section, considering individual lines and their directions. This means designating for each interstop section is_{idj} four independent sets containing the values of differences between departures from the subsequent stop stations, i.e., $DAS\left(is_{idj}, p\right)$, for individual months, considering peak period and the type of day. These sets are marked generally as $\mathbf{DAS}^{\mathrm{R}}\left(is_{idj}, m\right)$ and for each of the independent period as $\mathbf{DAS}^{\mathrm{SM}}\left(is_{idj}, m\right)$, $\mathbf{DAS}^{\mathrm{HM}}\left(is_{idj}, m\right)$, $\mathbf{DAS}^{\mathrm{SA}}\left(is_{idj}, m\right)$, and $\mathbf{DAS}^{\mathrm{HA}}\left(is_{idj}, m\right)$, where m is the number of the month.

At this stage, another identification and elimination of atypical periods for interstop sections takes place. It consists of removing from the database the set of $DAS\left(is_{idj}, p\right)$ in defined time period for which the dispersion was considered significantly different from the dispersion of deviations in the reference period for the studied interstop section. This process is carried out in two stages. First, with the use of statistical tools, the identification of months in which atypical deviations in time intervals were observed was performed, and then, for the identified month an in-depth analysis was carried out for the weekly periods. The periods for which the data significantly deviate from the distribution of deviations in the reference period are considered atypical and removed from the database.

For the database prepared in this way, for each month, independently for each interstop section served by a given line, the interquartile ranges of deviations between the actual and scheduled departures from the subsequent stop stations were estimated. The dispersion measures are determined for the traffic peak period in specific types of days, which can generally be written as:

$$IQR_m^{\mathrm{R}}\left(DAS\left(is_{idj}, p\right)\right) \ : DAS\left(is_{idj}, p\right) \in \mathbf{DAS}^{\mathrm{R}}\left(is_{idj}, m\right) \quad (4)$$

and for each of the independent periods as:

$$IQR_m^{SM}\left(DAS\left(is_{idj}, p\right)\right) \ : DAS\left(is_{idj}, p\right) \in \boldsymbol{DAS}^{SM}\left(is_{idj}, m\right) \quad (5)$$

$$IQR_m^{\mathrm{HM}}\left(DAS\left(is_{idj}, p\right)\right) \ : DAS\left(is_{idj}, p\right) \in \mathbf{DAS}^{\mathrm{HM}}\left(is_{idj}, m\right) \quad (6)$$

$$IQR_m^{\mathrm{SA}}\left(DAS\left(is_{idj}, p\right)\right) \ : DAS\left(is_{idj}, p\right) \in \mathbf{DAS}^{\mathrm{SA}}\left(is_{idj}, m\right) \quad (7)$$

$$IQR_m^{\mathrm{HA}}\left(DAS\left(is_{idj}, p\right)\right) \ : DAS\left(is_{idj}, p\right) \in \mathbf{DAS}^{\mathrm{HA}}\left(is_{idj}, m\right) \quad (8)$$

Then, independently for each interstop section, average values of the monthly values of interquartile ranges are estimated. Thus, for each segment is_{idj}, four average values are determined $IQR_{\mathrm{avg}}^{\mathrm{SM}}\left(is_{idj}\right)$, $IQR_{\mathrm{avg}}^{\mathrm{HM}}\left(is_{idj}\right)$, $IQR_{\mathrm{avg}}^{\mathrm{SA}}\left(is_{idj}\right)$ and $IQR_{\mathrm{avg}}^{\mathrm{HA}}\left(is_{idj}\right)$, which constitute the basis for the identification of interstop sections with the highest dispersion of deviations between the actual and scheduled intervals between departures from subsequent stop stations for selected lines.

The last stage is the classification of interstop sections based on the level of disturbance, measured by the average interquartile range, according to the k-means clustering method. In this way, the critical sections in the road and street network were determined by the largest deviations from the differences in time intervals. The average interquartile ranges $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ are entered simultaneously into the analysis in the form of four independent variables corresponding to the collected sets of data for four peak periods. Three levels of disturbances were distinguished, that is, $k = 3$. Separately for each peak period R the mean values of $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ were determined based on set of sections assigned to a given level. This assignment of interstop sections to the levels of disturbances was carried out in such a way that the deviations within the groups were as small as possible, while between the groups were as large as possible.

Let the q variable take three values corresponding to the three levels of disturbance, 1 is the lowest disturbance, and 3 is the highest disturbance. Each interstop section is classified separately for each line that serves that section. Information about the assigned level of disturbance is stored for each section in the $LoV\left(is_{idj}\right)$ attribute that depends on the average interquartile ranges of deviations $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$, i.e.:

$$LoV\left(is_{idj}\right) = f\left(IQR^{SM}_{avg}\left(is_{idj}\right), IQR^{HM}_{avg}\left(is_{idj}\right), IQR^{SA}_{avg}\left(is_{idj}\right), IQR^{HA}_{avg}\left(is_{idj}\right)\right) \tag{9}$$

Next, for each bus line, the average weighted level of disturbance is estimated, considering the lengths of interstop sections with particular disturbance levels. For this, it is necessary for each line to determine three sets of sections (for three levels of disturbance) defined as follows:

$$\boldsymbol{V}_i^q = \left\{is_{idj} : LoV\left(is_{idj}\right) = q\right\} \tag{10}$$

The approach assumes determination of two key sets of parameters used to identify the critical interstop sections. The first one is the share of the total length of the sections with a specific level of disturbance in the total length of the examined line, which is estimated as:

$$SD_i^q = \frac{\sum_{is_{idj} \in V_i^q} D\left(is_{idj}\right)}{\sum_q \sum_{is_{idj} \in V_i^q} D\left(is_{idj}\right)} \tag{11}$$

where $D\left(is_{idj}\right)$ is the length of the interstop section is_{idj}.

$$IQR^{i,q}_{\mathrm{avg}} = \frac{\sum_R \sum_{is_{idj} \in V_i^q} IQR^R_{avg}\left(is_{idj}\right)}{n(R)\cdot n\left(\boldsymbol{V}_i^q\right)} \tag{12}$$

where $n(R)$ stands for the number of periods of analysis considered and $n\left(\boldsymbol{V}_i^q\right)$ is the number of sections of a given line with the q-th level of disturbances.

The average weighted level of disturbance is estimated as:

$$MV_i = \sum_q IQR^{i,q}_{\mathrm{avg}} \cdot SD_i^q \tag{13}$$

The values of MV_i determine the average size of the disturbance for individual lines and allow to indicate the critical lines for electrification.

Identification of interstop sections with the highest dispersion of $DAS\left(is_{idj}, p\right)$ is an activity closely related to the achievement of the assumed strategic goals, including the implementation of the fleet conversion process into electric rolling stock. Conducting a systemic assessment of interstop sections allows to concentrate activities improving the regularity of $DAS\left(is_{idj}, p\right)$ on links that most need infrastructure changes, prioritizing bus traffic or modifying the timetable. The ability to precisely select critical interstop sections contribute to reducing expenditure and increasing the legitimacy of incurring them. The assessment of the impact of the route and the type of the line allows to determine the causes of non-punctuality and the degree to which it is possible to stabilize the set of $DAS\left(is_{idj}, p\right)$. Preceded by the analysis of variability, a reliable selection of time interval between departures from successive stop stations in the timetable improves the punctuality of journeys and increase the reliability of transfer connections. These are important elements that influence the quality and attractiveness of public transport.

To distinguish sets of interstop sections with similar homogeneous attributes, they were clustered using the k-mean method based simultaneously on data from four periods of analysis R. They contained the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values. The most favourable division of sections was obtained by distinguishing three clusters. Let $\boldsymbol{IQR}^{\mathbf{R,q}}_{\mathbf{avg}}$ stands for set defined as:

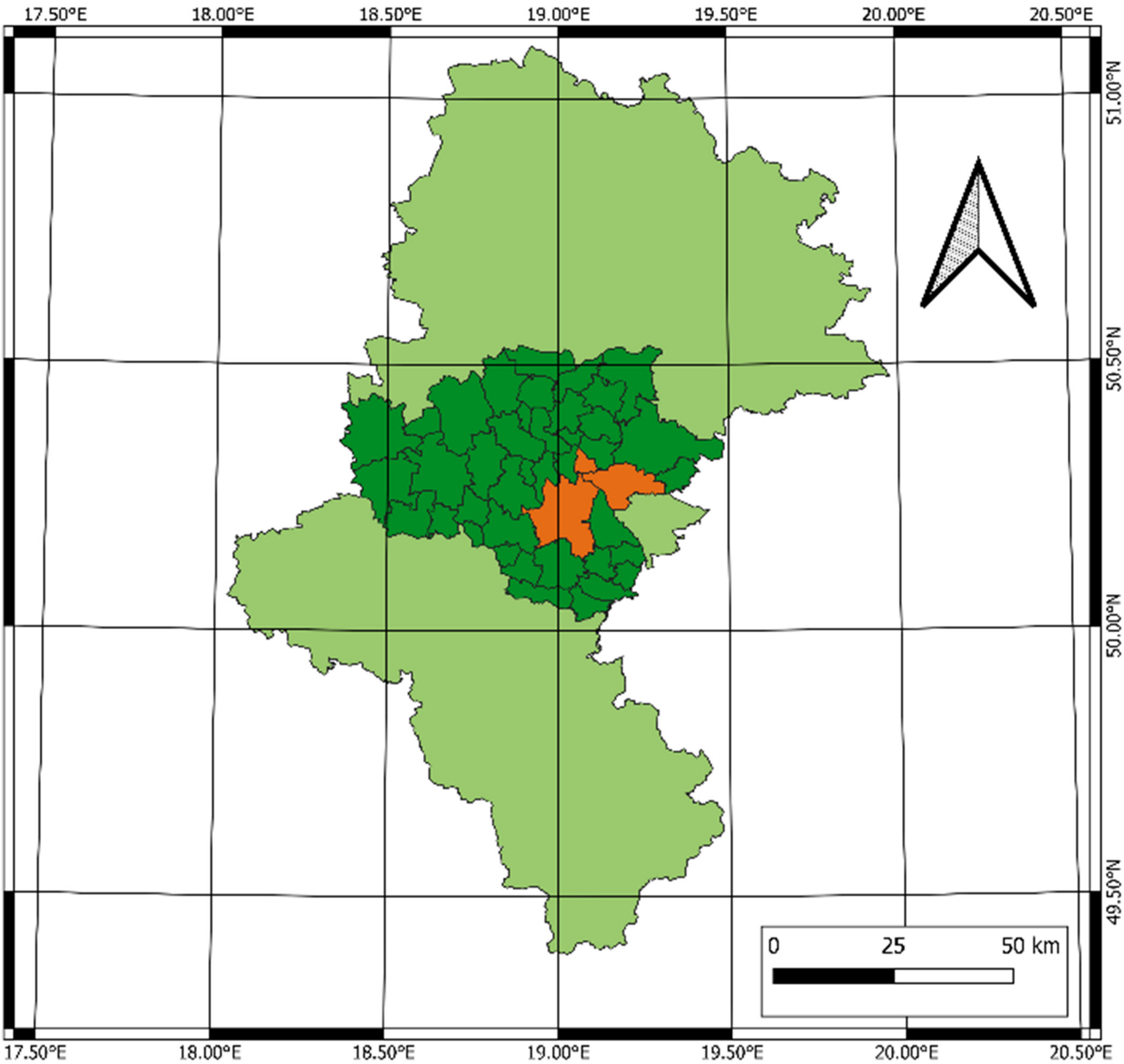
$$\boldsymbol{IQR}^{\mathbf{R,q}}_{\mathbf{avg}} = \left\{IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right) : LoV\left(is_{idj}\right) = q\right\}\boldsymbol{IQR}^{\mathbf{R}}_{\mathbf{avg}} = \bigcup_{q=1}^{3}\boldsymbol{IQR}^{\mathbf{R,q}}_{\mathbf{avg}} \tag{14}$$

The dispersion of $DAS\left(is_{idj}, p\right)$ values may be one of the criteria for assessing the bus lines in terms of introducing electric buses onto it. Here, three categories of bus lines can be distinguished. The first group consists of bus lines with regular time intervals that can be electrified immediately. The second group includes bus lines with irregular time intervals, for which it is possible to reduce dispersion through changes in the infrastructure or schedule, and the introduction of electric buses to them are justified only after these modifications have been made. The last group consists of bus lines with irregular time intervals, for which it is not possible to improve punctuality by significantly reducing the dispersion of the $DAS\left(is_{idj}, p\right)$ values. The bus lines of this group should be electrified at a later stage, when electric buses already operate in the system on other bus lines. The proposed approach is all the more correct because due to the high costs of converting the fleet into electric rolling stock, vehicle purchases and line electrification are carried out in stages. Electric buses are just being implemented by Polish public transport operators looking for the optimal sequence of line electrification. Increasing the repeatability of the time intervals allows a better prediction of the energy consumption of electric buses. This affects the reduction or adjustment of battery capacity and the necessary supply of electricity to ensure the completion of the entire routes, the precise determination of the time and places of charging of the vehicle on the route, and the construction of transport tasks. Therefore, the implementation of these activities contributes to optimizing the costs of the implementation of electric buses, as well as the costs of organization and operation of the electrified public transport system.

4. Case Study

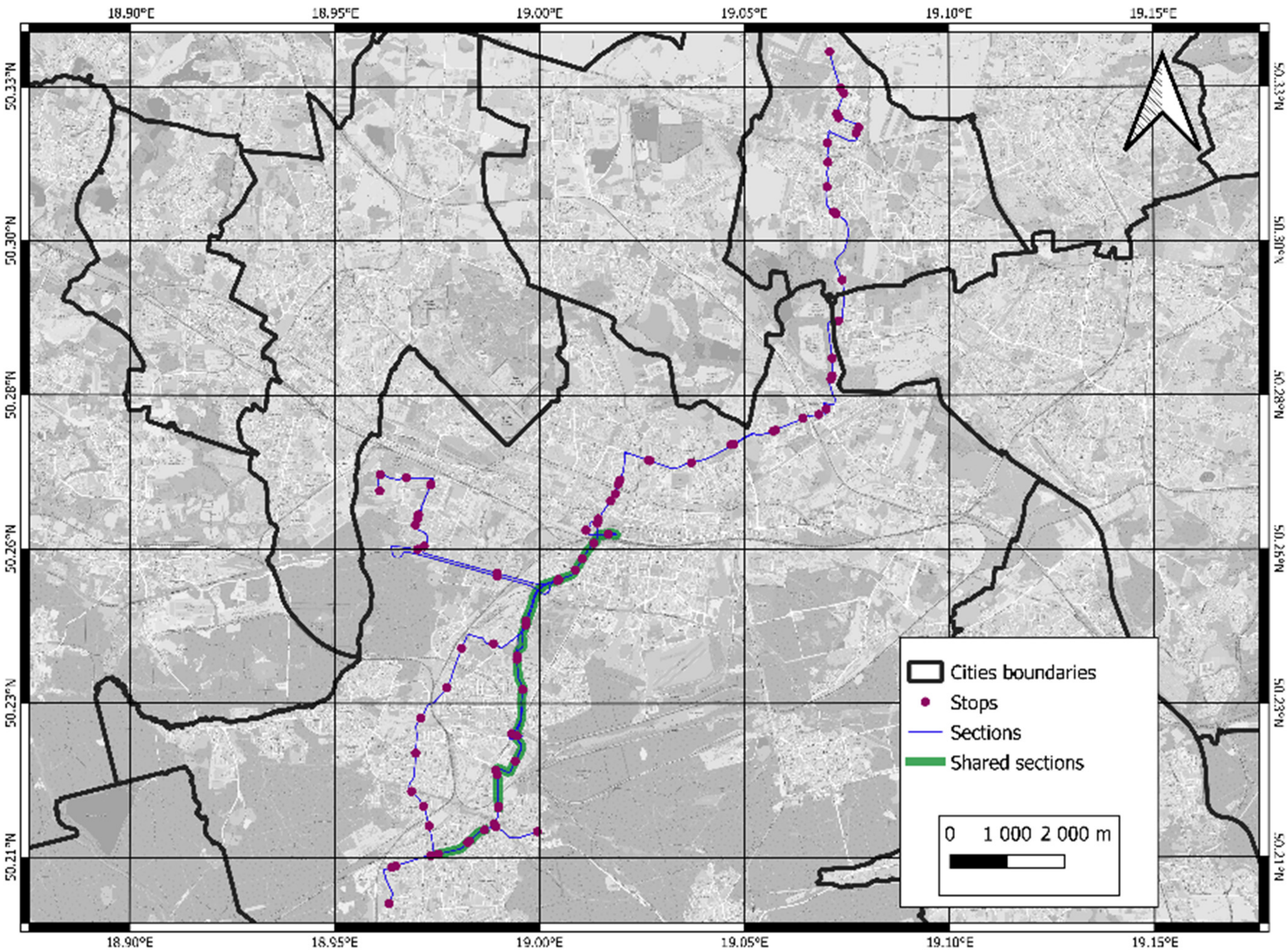
4.1. Study Area and Bus Routes

The method developed to identify critical interstop sections in the public transport network for the implementation of electric buses was applied in the Upper Silesian agglomeration, Poland. The study covered selected bus lines in the area of one of the most important bottlenecks in the transport network of the city of Katowice [53]. Figure 2 shows the location of three cities served by the analysed lines, that is, Katowice, Czeladź, and Sosnowiec, against the background of the Silesian Voivodeship (Figure 2a) and the routes of the tested lines in relation to the boundaries of the cities (Figure 2b). The area of Górnośląsko-Zagłębiowska Metropolis (GZM), i.e., a union of cities and communes in the Silesian Voivodeship established on 1 January 2018, is marked in dark green on the map.



(**a**)

Figure 2. *Cont*.



(**b**)

Figure 2. The area served by the tested lines: (**a**) the cities against the background of the Silesian Voivodeship and GZM; (**b**) the routes of the examined lines.

The area of Czeladź and Sosnowiec is served only by one of the lines examined in the article. It runs through the western outskirts of Sosnowiec and practically does not play any role in this city. However, it connects the suburbs with the centre of Czeladź and connects the two cities analysed. Czeladź is a smaller city than the two mentioned and occupies the 18th position in terms of population in GZM. Several major companies have their branches here and due to its location, it is an important logistic centre in the region. Katowice plays a key role in the analysed example. About 71% of the sections are in this city, and the routes of the three lines run along a few common sections. The selected lines are of various types and serve various parts of Katowice, downtown, the transition zone, and the suburbs, so the results obtained may indicate a wider picture of the implementation of the method in the area analysis than in the case of two other cities analysed. Therefore, it is necessary to characterize a bit more the specificity of the functioning of public transport in Katowice.

Katowice is the capital of the Silesian Voivodeship, an important industrial, commercial, service, educational, administrative, and cultural centre. Katowice is also the capital of the GZM, the only metropolis in Poland. The centres that create it, despite strong functional connections and a uniform and coherent area of activity of residents, have not been associated so far. Only now do they focus on joint implementation of strategic goals, including sustainable socio-economic development, shaping spatial order, and promotion, becoming a strong partner for centres in the country and abroad. Today, the metropolis comprises 41 cities and municipalities with a total area of 2500 square kilometres, inhabited by 2.3 million inhabitants. There are 240,000 companies and enterprises that produce approximately 8% of Polish GDP. To implement one of the most important tasks, which is the organization of public transport, a separate institution was established within the association, the Metropolitan Transport Authority (MTA). It took over the functions of several previous public transport authorities operating in the area and became the largest public transport authority in Poland. It undertakes activities in the field of restructuring and supplementing the connection system, changes in the direction of adapting the offer to the needs of users and unifying the system. There are 460 public transport lines operating in the metropolis, including 420 bus lines, 32 tram lines, and 7 trolleybus lines. Accessibility and transport connectivity are ensured by 7000 stop stations and 1500 vehicles (as of 1 January 2021).

Changes in socioeconomic structure, growing transport problems (related to the enrichment of society, common access to cars, and the constant increase in the number of individual transport journeys [53]), and environmental problems have made the activities and strategic plans of the authorities at various levels focus on achieving the goals of sustainable mobility in agglomerations. This is consistent with the directions of the activities indicated and implemented throughout the European Union [54]. The developed Polish national strategy for the development of transport requires the improvement of traffic conditions in cities and reducing the negative impact on the natural environment. This should be achieved by reducing the number of journeys by individual transport and increasing the use of other forms of urban travel. It requires improving their attractiveness and encouraging residents to use them [55].

The response of MTA and Katowice city (which also struggles with the congestion of the city centre [53]) to the identified problems is to ensure an efficient network of internal transport connections by creating a sustainable transport system in the city. Activities also aim to convert the vehicle fleet to zero-emission rolling stock to improve the condition of the natural environment, the quality of life and the perception of the city by investors and tourists. This is even more important, as the Act on electromobility and alternative fuels adopted in Poland in 2018 imposes the obligation to gradually increase the share of electric buses in the fleet. The imposed pace of their implementation poses a significant technical and economic challenge to municipal authorities. Therefore, at the stage of implementing electric buses, the key is to choose the order of electrification of the lines, which allows one to optimize costs and spread them evenly over time. Adopted strategic goals include improving the quality of public transport, particularly reducing travel time, increasing integration, improving accessibility and reliability, increasing the interest of residents in using of public transport and, as a result, reducing congestion in the city of Katowice [56].

Achieving these goals is now even more difficult as a result of historical conditions. There are four stages of agglomeration development. Each of them had a completely different specificity and left a clear mark. Traces of each of them are visible in today's spatial development structure and in the layout of the transport network. The first stage took place during the industrial revolution and included the emergence and uncoordinated development of independent cities in the region concentrated around heavy industry and mining plants. In the second stage, after the nationalization of industry, there was rapid urbanization and spatial expansion of urban areas. Large housing estates with high buildings were built in the suburbs, in the outer districts, and in neighbouring areas. The significant increase in the number of people was related to greater concentration around large industrial plants. The political transformation began with the third stage, which included the restructuring of the economy, the liquidation of companies, the dispersion of origins and destinations, and the practical suspension of investment and development. Stage four, which is currently underway, is characterized by an intensive development of residential construction spread throughout the agglomeration, infrastructure investments, and a revival in the production and services industry. When selecting the location of the diverse buildings, no plans were developed to meet the future transportation needs of the residents. At all stages, the lack of central management, dense development, and high population density meant that for years, investments were local in adapting the transport network to the changing spatial development and population needs. During economic changes, some infrastructure projects were abandoned during their implementation. Many projects have not been implemented to date. All this has made the current transport network very heterogeneous, and the existing connections are insufficient [53].

The immediate functional area includes the centre of Katowice and its transition zone in relation to the surrounding southern districts. An analysis was performed for three bus lines. In addition, much attention was paid to the selected sections, which run along the common road sections. There are only four road connections between the southern districts of Katowice and the city centre. Only two of them lead directly to the central business district (CBD) and connect to the downtown street network. The first has a tram connection, while the second one (the subject of the research) has only bus lines, including the analysed lines. Due to the significant urban density in the district of their operation, which is a significant traffic generator, bus lines ensure access to the area and support significant passenger flows.

All-day lines operating from 4:00 AM to 11:00 PM on all days of the week were analysed. Despite this, the functional range of the selected lines is varied. Their routes are of a different type.

Line 115 is a shuttle line. It only serves the city centre and its immediate surroundings. In rush hours, the running interval is 10 or 20 min and in off-peak hours, 30 min. This ensures a high frequency of running, considering the conditions of the Upper Silesian agglomeration, especially considering the large number of bus lines running along the same route by line 115 under study. There are 12 stop stations on the 7.7 km long route, covered in 23 min toward the city centre (115A). On the other hand, 10 stop stations were in the direction of the zone surrounding the city centre (115B), on a 6.5 km long route with a travel time of 20 min. Four vehicles are assigned to carry out the transportation tasks of a given line, making 136 departures from each stop station in total during the working day, covering a total of over 1000 km. About 4000 passengers use the line daily.

Line 10 is a circular line (with one direction designated as 10A) connecting the city centre with four districts, meeting the transport needs of residents in relation to and from the centre, but also between districts excluding the centre. There are 28 stop stations on the 18.05 km route, covered in 66 min. For the implementation of this line, five vehicles are assigned to perform a total of 95 departures from each stop station on working days, providing 570 km. The running interval throughout the day is 30 min. The line serves approximately 2400 passengers per day.

Line 11 is a shuttle line and a cross-city line, serving 36 stop stations in both directions (11A from south to north and 11B in opposite direction), located in three neighbouring cities. In the section of the route connecting the terminus located in the southern district of Katowice with the city centre, the line runs on the same routes as line 10. The 22.8 km long route takes 71 min. For the implementation of line 11, 7 vehicles are assigned to a total of 32 departures from each stop station in each direction, which provides 1550.4 km. The running time on working days is 30 min. About 31,700 passengers use the line daily.

4.2. Data Filtering

The analysis was carried out according to the method presented in Section 3. The characteristics of the interstop sections in terms of $DAS\left(is_{idj}, p\right)$ were made based on data on the departures of public transport vehicles collected by the public transport authority in the GZM agglomeration. The vehicle traffic monitoring and supervision system records the actual departure time of all buses from each stop station on an on-board GPS receiver, as well as additional information related to the implementation of transport tasks, important in the process of settlements with operators. The period from 1 January 2016, that is, from the start of full implementation of the system to 31 December 2019, was analysed. After this date, the pandemic affected traffic flows and bus delays. This made it impossible to perform one common analysis for these two different periods, forcing the authors to adopt a defined caesura.

For the analysis, carried out independently for each stop station, only data collected during representative working days were selected. Data from public holidays and days off, as defined in Polish law, and the associated longer period (a whole week) if a public holiday occurs during the working week, were omitted, since residents were then engaged in other non-professional activities. Only data for which the scheduled departure from a given stop station was within the assumed morning and afternoon peaks were selected for the next stages of data processing. Based on the research of other authors, who analysed traffic conditions in Poland, we chose the period between 6:00 AM and 8:00 AM as morning rush and the period between 3:00 PM and 5:00 PM as afternoon rush.

At each stage of data processing, records were removed in the case of revealing data gaps or errors and outliers that prevented the correct estimation of $DAS\left(is_{idj}, p\right)$. The basis for assessing the correctness of the data and their further processing was the calculation of the punctuality deviation from a given stop station for each departure. As the subjects of the research are typical regular traffic conditions, it was required to remove 15% of the largest delays and accelerations treated as the effects of irregular traffic disturbances from the database. The next step was to determine the actual and scheduled difference between departure from two consecutive stop stations.

Due to the adopted analysis period of four years, the public transport network and the road network were subject to changes and modifications. The reconstruction of parts of the transport network and the temporary organization of traffic influenced the changes in the distribution of traffic flows over the transport network, as well as the change in traffic conditions. Additionally, the placement of new stop stations, their relocation or liquidation, and changes in the route of the line and changes in the availability and number of connections resulted in the creation of new and deletion of existing interstop sections, as well as a change in traffic conditions. The dynamics of changes in the elements of the transport system makes it impossible to examine some interstop sections in accordance with the developed method in light of the adopted time horizon and requires individual analysis. In interstop sections where the described changes occurred, the difference between actual and scheduled departure time from two consecutive interstop sections was very diverse, resulted from the overlapping of very different phenomena, and characterized different sections of the transport network.

The last stage of data processing and preparation for analysis included the estimation of the dispersion of the set of $DAS\left(is_{idj}, p\right)$. The collected data set was subjected to statistical analysis to determine the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$. Size of the collected data set is presented in Table 1.

Table 1. Summary of the data sets collected for the individual directions of the lines and for each period R.

Characteristics of Bus Lines	Direction of Bus Line				
	11A	11B	115A	115B	10A
Number of interstop sections	31	33	11	8	22
Number of recorded departures	164,927	176,992	92,366	84,231	107,458
2016	37,811	41,568	17,017	19,649	23,271
School days morning rush hours SM	13,918	16,091	6642	7793	9104
School days afternoon rush hours SA	14,036	14,204	6199	7204	7692
Holidays morning rush hours HM	4928	6076	2323	2567	3364
Holidays afternoon rush hours HA	4929	5197	1853	2085	3111

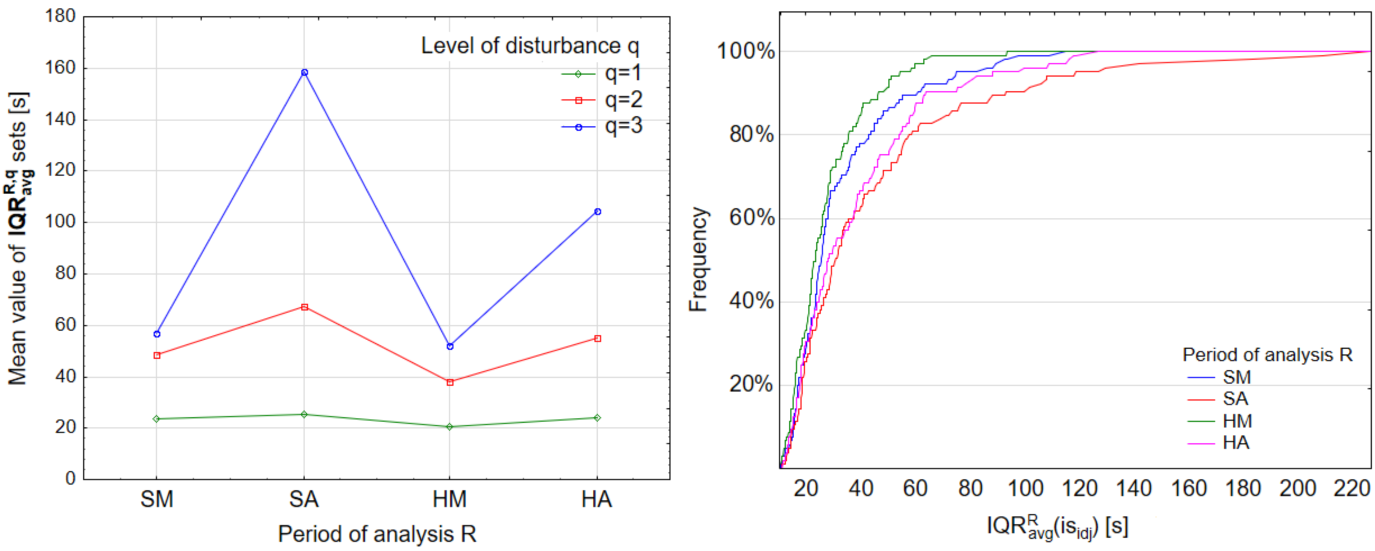
Table 1. *Cont.*

Characteristics of Bus Lines	Direction of Bus Line				
	11A	**11B**	**115A**	**115B**	**10A**
2017	41,518	43,268	21,309	21,359	28639
School days morning rush hours SM	15,496	16,723	8239	8440	10,975
School days afternoon rush hours SA	14,596	14,651	7762	7981	9594
Holidays morning rush hours HM	5715	6388	2867	2510	4170
Holidays afternoon rush hours HA	5711	5506	2441	2428	3900
2018	41,668	43,702	26,446	20,833	23,732
School days morning rush hours SM	16,687	18,351	11,109	8422	11,355
School days afternoon rush hours SA	15,971	15,435	9350	8064	10,827
Holidays morning rush hours HM	4528	5318	3311	2300	801
Holidays afternoon rush hours HA	4482	4598	2676	2047	749
2019	43,930	48,454	27,594	22,390	31,816
School days morning rush hours SM	16,569	18,772	10,962	8504	12,129
School days afternoon rush hours SA	16,102	17,240	9247	8111	11,135
Holidays morning rush hours HM	5706	6479	4035	2918	4379
Holidays afternoon rush hours HA	5553	5963	3350	2857	4173

4.3. Results

The analysis of vehicle departure data for three selected lines operating in the GZM, carried out in accordance with the procedure described in Section 3, allowed to obtain results characterizing the values of dispersion $DAS\left(is_{idj}, p\right)$. The results of the work are discussed in this section.

The average values for each set $\boldsymbol{IQR}^{\mathbf{R,q}}_{\mathbf{avg}}$, i.e., for each cluster in the four analysis periods as well as the dispersion of elements of sets $\boldsymbol{IQR}^{\mathbf{R}}_{\mathbf{avg}}$ separately in each period of analysis are shown in Figure 3.



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

Figure 3. Results of the analysis of dispersion of $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values: (**a**) Means of sets $\boldsymbol{IQR}^{\mathbf{R,q}}_{\mathbf{avg}}$ separately in each period of analysis and each level of dispersion; (**b**) cumulative histograms of elements of sets $\boldsymbol{IQR}^{\mathbf{R}}_{\mathbf{avg}}$ separately in each period of analysis.

Two types of interstop sections can be distinguished: undisturbed, i.e., with a high repeatability of the travel time, and disrupted. Among the disturbed interstop sections, two types should be distinguished due to the different values between the morning and afternoon peaks, visualized in the average values of the $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{R,q}}$ sets. Regardless of the division into levels of dispersion, the results of the analysis show that the afternoon rush is a much bigger problem in the construction of vehicle cycles, generating higher dispersion of the $DAS\left(is_{idj}, p\right)$ values in most interstop sections than during the morning rush. This effect is even more clearly visible when comparing the distribution of cumulative values of the $IQR_{\mathrm{avg}}^{\mathrm{R}}\left(is_{idj}\right)$ values prepared independently for each of the four analyses (Figure 3b). Among the 10% of interstop sections with the highest dispersion of the $DAS\left(is_{idj}, p\right)$ values, almost three quarters are interstop sections analysed during the afternoon peak. The most predictable and repeatable is the time interval of the interstop sections in the morning peak during the holidays. $IQR_{\mathrm{avg}}^{\mathrm{HM}}\left(is_{idj}\right)$ values do not exceed 60 s. In the case of school days, only 90% of the sections meet this condition. The morning rush is dominated by sections with dispersion not exceeding 40 s, and in the afternoon rush hours not exceeding 60 s. However, the worst and most variable traffic conditions occur on school days during the afternoon rush hour.

The distances between clusters measured on the basis of values belonging to a set $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{R,q}}$ and the number of interstop sections classified to each level of disturbance are presented in Table 2.

Table 2. Distances between clusters and number of included interstop sections.

Level of Disturbance q	Linear and Square Euclidean Distance between Clusters			Number of Interstop Sections
	1	2	3	
1	-	30.09 [s]	80.98 [s]	73
2	905.70 [s^2]	-	52.52 [s]	25
3	6557.78 [s^2]	2759.01 [s^2]	-	7

The distances determined between the three levels of disturbance adopted constitute a measure normalized in the k-means method, determining the degree of differentiation of the values between the objects included in different clusters. It is determined independently between each pair of disturbance levels on the basis of the mean values of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{R,q}}$. Despite distinguishing the disturbed and undisturbed interstop sections, level 2 is closer to level 1 than to level 3. This is due to the very high values assumed by the elements of sets $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA},3}$ and $IQR_{\mathbf{avg}}^{\mathbf{HA},3}$ for level 3. The values of selected summary statistics measures in each of the analysis periods R characterizing the structure of the $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{R,q}}$ sets are presented in Table 3.

There is a clear difference in the mean values of the interquartile range between the levels of disturbance. The interstop sections classified as level 1 are characterized by the lowest dispersion of $DAS\left(is_{idj}, p\right)$ values. In each of the periods, the mean value of the interquartile range for this group is about 23 s, and other measures have similar values. This group is the most numerous. It covers almost 70% of all analysed interstop sections. Traffic conditions are regular and predictable here. It is not a problem to develop a schedule and keep drivers on time. Sections classified to level 1 do not need to be subject to further detailed analysis at the stage of planning vehicle cycles due to the high regularity of time intervals in typical road conditions.

Table 3. Statistics for the set of sections assigned to the clusters in each of the analysis periods.

Period of Analysis R	Selected Measures of Summary Statistics	Level of Disturbance q		
		1	2	3
SM	Mean of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SM,q}}$	23.4	48.5	56.8
	Standard deviation of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SM,q}}$	11.4	23.8	25.0
	Maximum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SM,q}}$	86.0	114.6	97.4
	Minimum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SM,q}}$	10.4	16.6	26.6
SA	Mean of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA,q}}$	25.6	67.3	158.5
	Standard deviation of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA,q}}$	10.0	21.4	47.9
	Maximum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA,q}}$	54.7	108.0	226.5
	Minimum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA,q}}$	10.8	23.4	101.4
HM	Mean of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HM,q}}$	20.5	37.9	52.1
	Standard deviation of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HM,q}}$	7.0	11.9	23.4
	Maximum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HM,q}}$	50.7	65.9	93.5
	Minimum value in $IQR_{\mathbf{avg}}^{\mathbf{HM,q}}$	10.2	16.0	26.7
HA	Mean of $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HA,q}}$	24.3	55.1	104.6
	Standard deviation of	9.7	13.4	18.2
	Maximum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HA,q}}$	51.5	82.2	127.0
	Minimum value in $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HA,q}}$	11.1	19.1	75.0

The remaining two levels of disturbance contain interstop sections that are much more susceptible to traffic disturbances, which generate $DAS\left(is_{idj}, p\right)$ values irregularity at least twice as large as for the level 1 interstop sections. The second level includes sections that are exposed to a relatively constant size of dispersion of $DAS\left(is_{idj}, p\right)$ in each R. The mean value of the interquartile range for level 1 is approximately 53 s. However, the last, third, highest level of disturbance covers several interstop sections most exposed to irregular time intervals. Definitely the highest dispersion is observed for them in the afternoon peak. The mean value of sets $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SA,q}}$ and $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HA,q}}$ are then about two times higher than mean values in the morning rush, i.e., $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{SM,q}}$ and $\boldsymbol{IQR}_{\mathbf{avg}}^{\mathbf{HM,q}}$, respectively, for which the interstop sections included in level 2 and 3 assume similar values of the $IQR_{\mathrm{avg}}^{\mathrm{SM}}\left(is_{idj}\right)$ values. The greatest differentiation between the levels of disturbance is visible for the mean and maximum values. On the other hand, the standard deviation and the minimum value have more similar values both between the periods of analysis and levels of disturbance.

The general characteristics of the phenomenon of the variability of the $DAS\left(is_{idj}, p\right)$ values, broken down into traffic peak periods and types of traffic days, and the identification of the dispersion size on individual interstop sections, is a reference point for conducting a detailed analysis independently for individual lines and directions. The values $IQR_{\mathrm{avg}}^{\mathrm{R}}\left(is_{idj}\right)$ were presented in a graphical form in relation to the course of the line route described by the sequence of interstop sections on the map (Appendix A).

Taking into account the dispersion of the $DAS\left(is_{idj}, p\right)$ values along the route of the 115A line, five separate groups of interstop sections can be distinguished, including three independent groups more exposed to higher values of the dispersion of the time intervals: the first group of interstop sections is related to running the line route along the collector road of the residential district, the second is related to the road junction and the southern entry to the centre of Katowice city, and the third one with the road running through the very centre of the city. They are subject to high variability of traffic conditions. Between the three identified groups of interstop sections, there are interstop sections in which, for all periods of the analysis R, the dispersion of the $DAS\left(is_{idj}, p\right)$ values are consistently low.

In the morning rush hours on school days, high values of $IQR^{\mathrm{SM}}_{\mathrm{avg}}\left(is_{idj}\right)$ are caused by high traffic volumes generated largely by commuting. There is one interstop section of the entire route with an interquartile range with a value almost four times greater than in the other interstop sections. On holiday working days, the problems of increased $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ for interstop sections, which is similar on all interstop sections, disappear along the entire route. In each of the three groups of interstop sections identified on the route with a greater dispersion of the $DAS\left(is_{idj}, p\right)$ during the holidays, the greatest variation is recorded on the adjacent interstop section following the interstop section indicated as the one with the greatest dispersion on working days. It is probably related to the reduction in the length of the queues of vehicles at the entrances of intersections located on the line route. It can be hypothesized that the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values are greater in the interstop sections preceding bottlenecks in the transport network and decreases with increasing distance from them, measured in the opposite direction to the traffic on the route. This is due to the variable length of the queues. It can be observed in the morning rush that in two interstop sections the dispersion on holiday days increases compared with school–working days. The analysis of the regularity values of the $DAS\left(is_{idj}, p\right)$ for the entire route in the afternoon rush hour showed that it is deteriorating compared with the morning peak. This is clearly visible in two parts of the route: the initial interstop sections leading to the residential area, for which the trends are identical during school and holiday working days, and the final interstop sections on the road leading to the CBD. On school days, on this road, a markedly greater dispersion of the differences occurs on one interstop section (it is four times greater than on the other sections), while during the holidays the time interval dispersion is distributed more evenly between several adjacent interstop sections. Only two interstop sections on the route were included in level 2 of the disturbances, both near the entrance to the CBD, one due to the high variability of the $DAS\left(is_{idj}, p\right)$ values in the morning rush and the other one in the afternoon rush.

In the case of the 115B line, as for the previously described opposite direction, that is, 115A, three independent consecutive sets of interstop sections with a different levels of disturbance can be distinguished: the first one with the greatest variability of $DAS\left(is_{idj}, p\right)$ covers the interstop sections by the road leading out of the CBD and downtown Katowice towards the entire southern part of the city; the second runs along the motorway, connecting with the district in the inner city with a very regular, predictable $DAS\left(is_{idj}, p\right)$ values; and the third runs through the residential district, which is characterized by the average, compared with the previous fragments, values of $DAS\left(is_{idj}, p\right)$. It is visible mainly on the interstop section located on the road leading traffic to the centre of the residential district. In all periods of the analysis R, the tendencies and the relative difference in the variability of the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values are the same, only mean values in each period R is different. At the same time, the adjacent interstop sections are related to each other, showing the same trends in value changes. The periods of analysis R in order of increasing variation the $DAS\left(is_{idj}, p\right)$ values are morning rush on holiday days, morning rush on school days, afternoon rush on holiday days, and afternoon rush on school days. There are several interstop sections along the route where the dispersion of $DAS\left(is_{idj}, p\right)$ values is the greatest in each period. In the interstop section with the highest $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values, the variability of time intervals is over three times greater than in the remaining interstop sections of the route. This point in the street network is a key point, located in the CBD, close to the main train and bus stations, and it connects the northern and southern parts of the city. As the only one on the route, it was included in the level 3 sections and the section following it on the route to level 2.

The analysis of line 11A in the morning peak allowed to identify six interstop sections along the entire route (that is, less than 20% of the examined), which are exposed to irregular $DAS\left(is_{idj}, p\right)$ values at a level almost twice as high as in the rest of the route. In this period, even though the line has a cross-diameter character and runs through the entire CBD of Katowice, it can generally be described as fairly predictable and regular in terms of estimating $DAS\left(is_{idj}, p\right)$ values. Detailed analysis showed that the greatest dispersion occurs at points in the network where they concentrate and connect different traffic flows to a common destination in the city centre. These are interstop sections located on a collector road that runs through a large residential district, where other local roads that lead to the centre from individual housing estates converge. The irregularity of the $DAS\left(is_{idj}, p\right)$ values may also result from the handling of large passenger flows heading to the centre and the coexistence of several different lines on this interstop section providing connections in the same relations, which allows passengers to choose from among the available offer and random events affect the actual order of arrival of individual buses at stop stations, and thus the size of passenger flows using a given line. The second group of interstop sections that is important from the point of view of the subject of the article is in the CBD, due to the route of the line. It is the most important urban arterial in the city centre with a high access to local buildings, where the roads that lead to many neighbouring districts converge. There is a lot of passenger exchange in this area of the city. In the further part of the route, the line serves the inner city and the inner suburbs, crosses the border of the city of Katowice, and provides a connection with the centre of the city of Czeladź. The $DAS\left(is_{idj}, p\right)$ values are here very regular throughout the entire interstop sections of this part of the route. The only place, outside Katowice city, where there is an almost twofold higher $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values in relation to the neighbouring interstop sections, is one of the routes in inner city of Czeladź. The $DAS\left(is_{idj}, p\right)$ values on school and holiday working days are very similar and comparable in most parts of the line route, there is no clear reduction in the dispersion of the $DAS\left(is_{idj}, p\right)$ values as a result of a decrease in traffic during the holiday period. Only two interstop sections for which such an improvement of the values of the difference occurs should be indicated. These are interstop sections on the initial part of the route; that is, in the central part of the residential district in the suburbs and in the transition zone, on the road leading traffic to the centre of Katowice city. The analysis of the afternoon rush confirms that a large dispersion of $DAS\left(is_{idj}, p\right)$ values occur on the same interstop sections that were identified as critical in the morning rush, while its values are higher than 50% to 100%. There are other additional interstop sections other than in the morning, which are exposed to large irregularities in $DAS\left(is_{idj}, p\right)$ values. First, these are the interstop sections in the inner city leading directly to the BCD, where an over two or even fourfold increase in the value of the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ compared with the morning peak was recorded, in the inner suburbs. On the remaining interstop sections of the line route, not listed here, the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values of the remains at a constant low level in all periods of analysis R. The exception is one interstop section in the suburban district at the initial part of the route, where a decrease in the dispersion of the $DAS\left(is_{idj}, p\right)$ values in relation to the morning peak is observed, which is associated with a reduction in traffic and the impact of conflict streams at intersections at local road approaches. Summarizing the detailed analysis of the interstop sections, it is possible to distinguish sections of the route that are prone to significant dispersion of the $DAS\left(is_{idj}, p\right)$ values but determined by different factors. These are three groups of interstop sections where the values of the difference can be significantly more dispersed: in the morning rush, only in the afternoon rush, or in each of the analysed periods, which means that these interstop sections are constantly exposed to the occurrence of large dispersion of the $DAS\left(is_{idj}, p\right)$ values. For a given line, interstop sections with smaller $DAS\left(is_{idj}, p\right)$ values were classified as level 1, and disturbed sections as level 2 of disturbance.

The $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values along the entire route of line 11 direction B are very similar to line 11 direction A. In the vast majority of the interstop sections it ranges from 20 to 40 s. However, in the morning rush, five interstop sections are clearly distinguished from the others by a much greater value. Two of them are in downtown, on the key urban arterial of Katowice, near bottlenecks in the city's road network and in the area of impact of various traffic flows focusing on common parts of routes. Therefore, it can be concluded that high traffic volume not only causes deterioration of traffic conditions, but also significantly influences the irregularity and the high variability of the $DAS\left(is_{idj}, p\right)$ values. Additionally, these are interstop sections that are characterized by a large passenger exchange. Traffic conditions are clearly influenced by road traffic by commuters, since there is a decrease in dispersion of the $DAS\left(is_{idj}, p\right)$ vaues during the holidays. In the interstop section in the inner suburbs between cities: Czeladź and Katowice, the influence of the railway crossing is responsible for the high dispersion of the time intervals. The two remaining interstop sections are located in the initial and final part of the route, that is, the centre of Czeladź and the central part of the suburban southern residential district in Katowice, respectively. There, the dispersion is influenced by traffic lights, significant traffic volumes in various movements, the impact of traffic flows with different motivations, as well as the routing of the bus line via a collector road, key to the functioning of the adjacent areas and ensuring high accessibility. However, for the interstop sections discussed, no significant decrease in the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ value was observed during holiday working days compared with the of school–working days. In addition to the interstop sections discussed above, the analysis of the entire route of direction 11B distinguishes a set of subsequent interstop sections located in the inner suburbs leading traffic from the CBD towards the southern districts. The size of the dispersion of the $DAS\left(is_{idj}, p\right)$ values is not the highest, it remains on the average value of about 33 s with respect to the entire line, regardless of the type of days. Based on the analysis of the afternoon peak, it can be indicated that the same interstop sections as in the morning rush are exposed to the highest dispersion, but the impact of traffic flow and the length of the queues created causes the dispersion to spread also to adjacent interstop sections. It is particularly visible downtown, where the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ value reaches the maximal value of about 100 s or even 180 s on the interstop section which is one of the two along the direction's route that was classified as level 3 of disturbances. Traffic conditions in relation to the morning peak also deteriorate in the indicated interstop section of the route that leads traffic from the city centre to the southern districts, in the inner suburbs, to obtain an $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ value of over 220 s at its final interstop section, which made it a part of level 3 of disturbances. Apart from the two interstop sections indicated, only the sections susceptible to dispersion described above were included in level 2.

The route of the direction of the bus line 10A consists of interstop sections with very different $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values. Here, in decreasing order, we should point out interstop sections with irregularities to the bottleneck in the middle of the CBD classified as level 3, the collector roads of suburban districts belonging mainly to the interstop sections of level 2, sometimes 3, and the inner city. The greatest regularity of $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values is the main (radial) arterial on the border of the CBD, the interstop sections located there are classified as level 1. Traffic conditions on the line are greatly influenced by the professional activity of the inhabitants. In the morning rush hours, greater $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values are observed on the interstop sections leading to the city centre, while in the afternoon they are observed on the interstop sections leading to the suburbs. The size of this dispersion to a small extent depends on the type of days; however, each interstop section should be analysed separately in this respect, as the reasons for the dispersion of $DAS\left(is_{idj}, p\right)$

values on individual interstop sections may be differential. The most important factor along the entire route is the impact of intersections, including traffic lights. On all their approaches there is high traffic volume, and the capacity of the line and point infrastructure is insufficient during peak hours. This causes congestion, queues of vehicles of variable length and, as a result, also an increase in the dispersion of $DAS\left(is_{idj}, p\right)$ values on the adjacent, i.e., preceding interstop sections. This is clear in the afternoon rush hour. In the interstop sections in the downtown area, a large dispersion of the $DAS\left(is_{idj}, p\right)$ values in both directions are observed, regardless of the analysed peak period. In the afternoon peak, most of the interstop sections prone to high dispersion show a twofold increase in the size of the $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values compared with the morning peak.

5. Discussion

A detailed analysis of the $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values allowed to identify places in the network where these values are clearly bigger than the others. Interstop sections with the small values were separated from those that required searching for the causes of high values and taking actions to improve traffic conditions. However, to indicate the lines correctly and precisely to which electric buses are allocated at the stage of a successive process of fleet conversion into 100% electric rolling stock, it is necessary to consider the implementation of vehicle cycles as a whole.

In the case of bus line 115 in both traffic peak periods, the A direction leading to the downtown is more susceptible to greater $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values along the entire length of the route than the direction from the centre. On school days in the morning peak, one of the interstop sections clearly differs from the others in terms of $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values, while in the initial interstop section near the main bus and railway stations, large values occur regardless of the type of day and the type of peak period. This value increases even more during the afternoon peak, also in the adjacent interstop sections. This means that for the line under study, the most difficult part of the route to plan the scheduled travel time is the set of successive interstop sections along the main arterial in the city centre that leads to and from the CBD.

In the case of bus line 11 in the morning rush hour, the greatest $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values occur on the key interstop sections shown in the previous section, at a similar level in both directions in the case of the analysis of a section of the route in the CBD. In both peak periods, the same tendencies are visible. In the morning there is a slight dominance towards the city centre and in the afternoon toward the suburbs.

The summary of the results of the analysis of the tested bus lines in terms of the number of interstop sections assigned to individual levels of disturbances and the $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values for sections of each level are presented in Table 4 and graphically in Figure 4.

The results obtained indicate that bus line 115 should be electrified first because it has the smallest number of both interstop sections assigned to levels 3 and 2. These lines have the lowest weighted mean MV_i value and the smallest share of the length of interstop sections included to level 2 and 3 in total length of the route. In the next stage, bus line 11 should be electrified because it has up to two interstop sections included in level 3 and the share of the length of interstop sections of this level is only about 5% of the total length. The line has a higher share of the interstop sections of level 1. Bus line 10 has four interstop sections included in level 3 which represents more than 18% of the total length of the route and five sections classified as level 2, which is another 20% of the length of the route. The range of values obtained indicates that according to the criterion of dispersion of $DAS\left(is_{idj}, p\right)$ values on bus line 10, electric buses should be introduced last.

Segments of the routes of the bus lines studied are running along common road sections. However, the research focused, due to the subject of the article, on an independent analysis of the $IQR^{R}_{\text{avg}}\left(is_{idj}\right)$ values in the route through individual bus lines. This approach resulted in the fact that each physical interstop section describes the $IQR^{R}_{avg}\left(is_{idj}\right)$ value of the given bus line. It means that the interstop sections included in the route of more than one bus line are described simultaneously by more than one $IQR^{R}_{avg}\left(is_{idj}\right)$ value. This allowed a comparative analysis to be carried out by checking the degree of similarity of the assessment of individual interstop sections fabricated independently for individual bus lines. It can validate the conducting analyses of $IQR^{R}_{avg}\left(is_{idj}\right)$ values separately through the prism of individual bus lines. The results obtained in this respect are inconclusive.

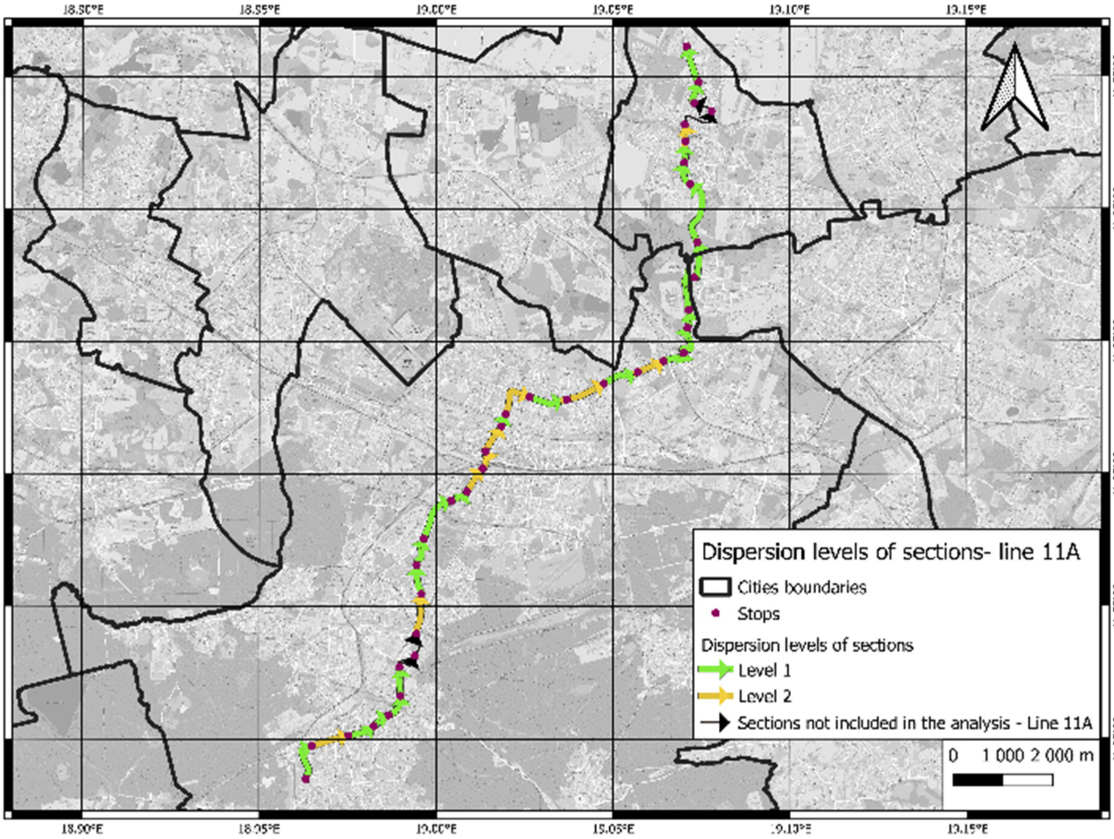
In the area of analysis, 13 interstop sections were identified, along which vehicles of at least two of the tested bus lines travelled. In 85% of the cases, the interstop sections were classified to the same level of disturbances. In this case, there are slight differences in the numerical $IQR^{R}_{avg}\left(is_{idj}\right)$ values determined based on the examination of individual bus lines. Usually, the discrepancies do not exceed 8 s, the mean value for the test is 2.6 s, and the variation index is 73%. There is no discrepancy between the bus lines here, and there is no clear trend to conclude that a certain line consistently describes a segment with higher values than other bus lines. The observations made above are common to all periods of analysis, no differences were found in this respect between each pair of the analysed periods. It can be presumed that the method of classification of sections to levels of disturbances is resistant to a certain extent from the influence of the interstop section description with the $IQR^{R}_{avg}\left(is_{idj}\right)$ value.

In three cases (each in a different period), the difference in the $IQR^{R}_{avg}\left(is_{idj}\right)$ value characterizing the interstop section determined on the basis of the analysis of different bus lines was: 25, 27, and 90 s (these values were omitted when determining the above-mentioned statistics), respectively, and yet in each case the interstop section was classified to the same category regardless of the line that was used to describe the time intervals dispersion. However, two interstop sections were identified for which the $IQR^{R}_{avg}\left(is_{idj}\right)$ has clearly different values depending on the bus line. For one of them, the difference varies from 60 to 70 s, depending on the period.

Table 4. Characteristics of the lines in term of $IQR^{R}_{avg}\left(is_{idj}\right)$ values.

Attribute of Bus Line	Level of Disturbances q	Bus Line		
		115	**11**	**10**
Number of interstop sections allocated to level of dispersion	Level 1	15	45	13
	Level 2	3	17	5
	Level 3	1	2	4
Mean value of $IQR^{R}_{avg}\left(is_{idj}\right)$ values characterising interstop sections in each level of dispersion	Level 1	22.29	22.1	29.39
	Level 2	46.45	52.77	53.68
	Level 3	82.15	105.4	89.49
Total length of interstop sections allocated to level of dispersion [km]	Level 1	11.3	28.7	9
	Level 2	2.4	11.7	2.9
	Level 3	0.7	2.3	2.7
MV_i value		29.23	34.99	45.33

Bus line 11A



Bus line 11B

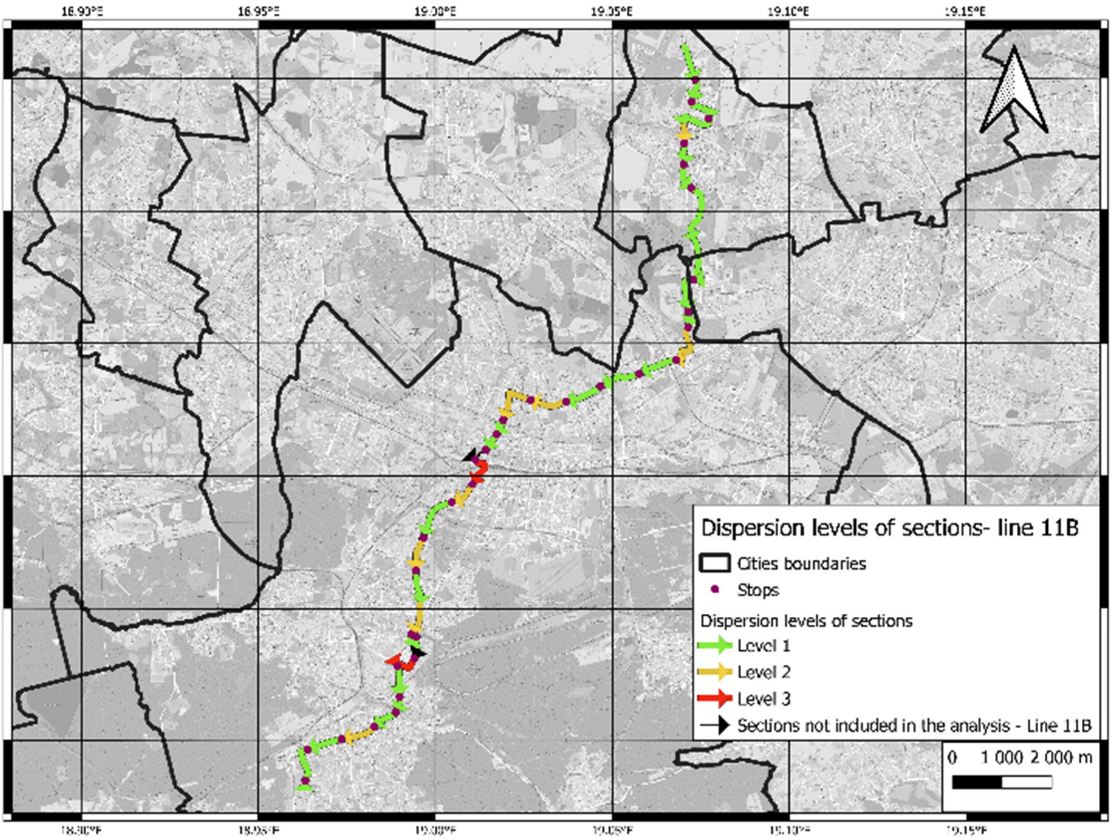
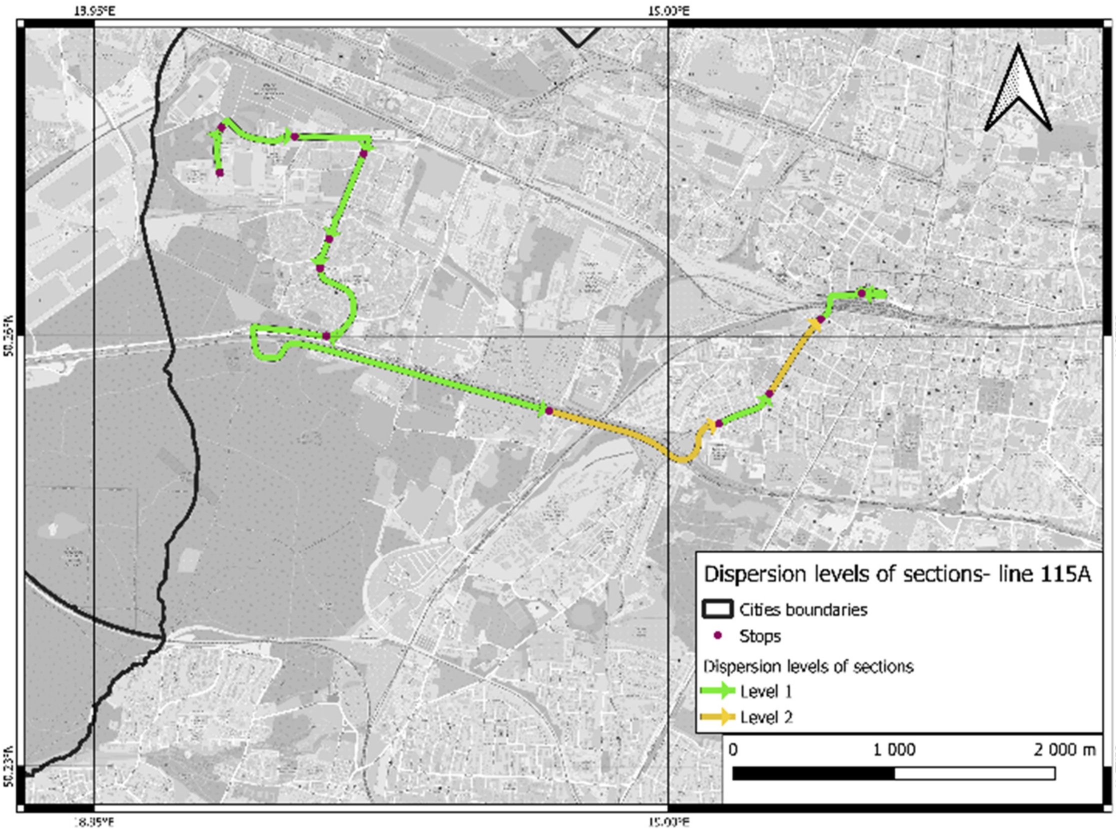


Figure 4. *Cont*.

Bus line 115A



Bus line 115B

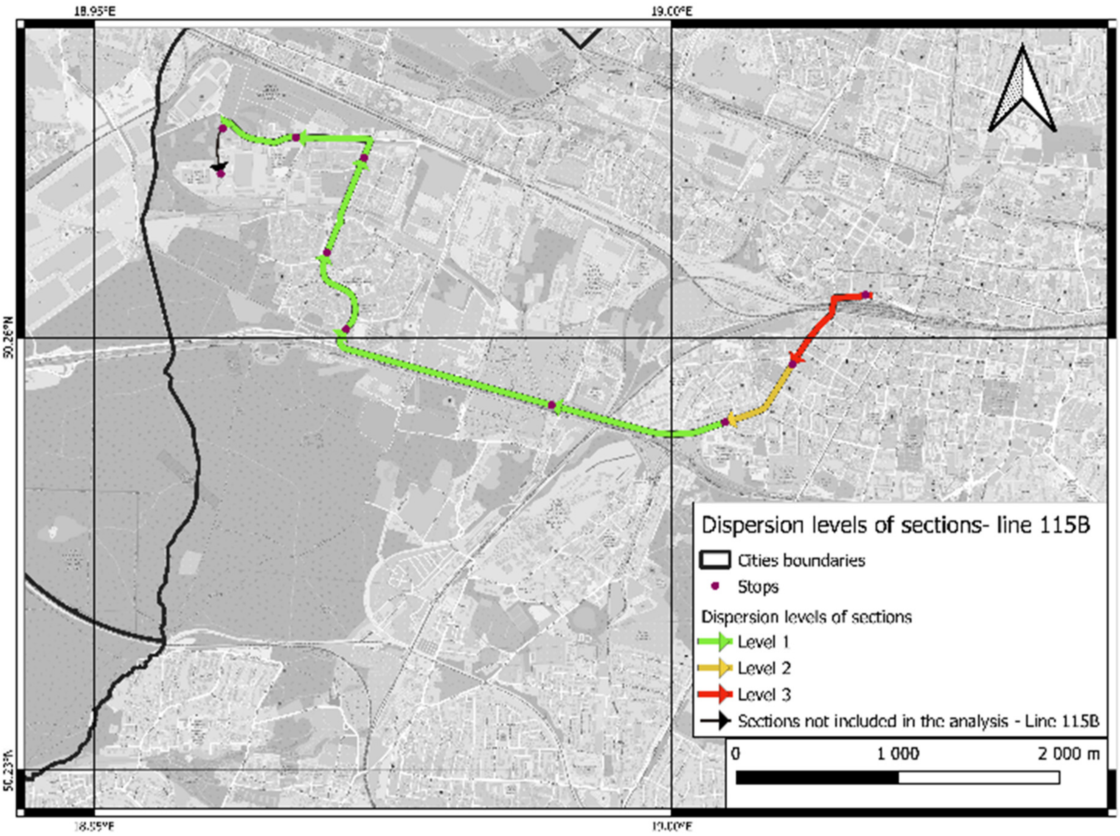


Figure 4. *Cont.*

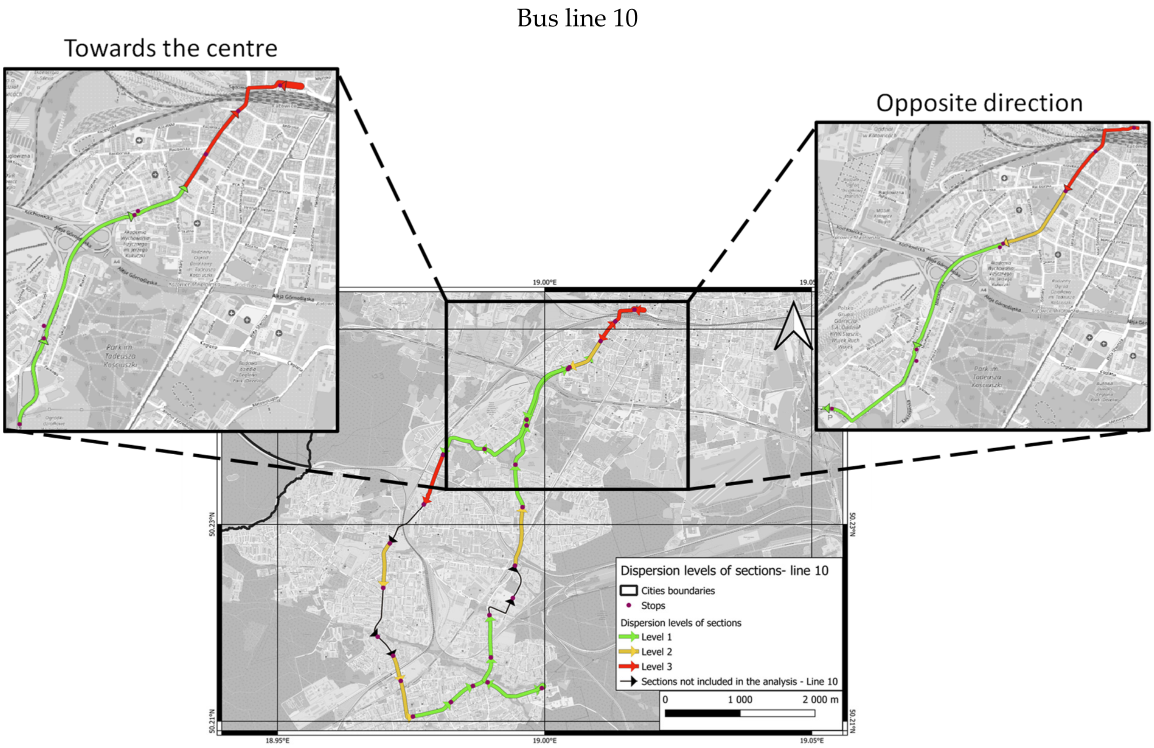


Figure 4. Graphical presentation of interstop sections corresponding to specific levels of disturbance.

This results in classification of this section based on testing one bus line to level 3, and the second line to level 1. In the second of the detected cases the difference is in level 2, allocated based on two lines, and level 3, allocated based on data from the third of the tested bus lines. Differences were detected only in the afternoon rush, and it is 12 and 20 s, respectively. The analysis of the number of passengers in vehicles and the number of passengers entering and exiting these sections did not show any differences between the lines, and it cannot be said that this factor was responsible for the different assessment of the interstop section and different $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values. The noticed differentiation must be the subject of further detailed studies of bus traffic on the identified interstop sections to be able to determine the causes of this discrepancy. The previous analysis was carried out independently for each of the bus lines tested because the aim was to describe the dispersion on the interstop sections on the route of a given line. In the event of focusing on examining interstop sections using the $DAS\left(is_{idj}, p\right)$ values, omitting the information about the bus line on which the departure was provided, it would be necessary to supplement the proposed procedure with the stage of linking the interstop sections to the routes of individual lines.

Although the authors made every effort to develop the method and implement it in practice for real bus lines, this issue has not yet been exhaustively examined in the literature. Therefore, there is no possibility of independent verification and confrontation of the obtained results. At each stage of data development and processing, various possibilities of analysis and verification of its accuracy were applied, selecting the most appropriate procedure. All this had a positive effect on the result obtained. However, the authors are aware of some limitations of the analysis carried out and see potential areas for further work.

The very definition of the time frame for the duration of the rush hours remains a problematic issue. In the research, they were selected based on a review of the literature, in which traffic conditions in the region were characterized. They were compared with data from other similar agglomerations in the country of the analysis. A common time span for the three tested lines was chosen so that the results can be comparable, and a two-hour period was chosen to ensure many trips carried out by individual lines. Of course, this has an impact on the results obtained. It is potentially possible that, during such a long period, the traffic conditions on individual interstop sections may be subject to rapid changes. On the other hand, the shorter the assumed duration of the analysis period, the fewer departures are tested, this is particularly important in the case of lines with a lower frequency of running, while the smaller number of departures tested can potentially, after carrying out the process of data preparation, processing, and elimination, be insufficient and too small for the needs of inference.

The obtained $DAS\left(is_{idj}, p\right)$ values are burdened with additional inaccuracy resulting from the recording by the on-board GPS receiver of the vehicle traffic monitoring and supervision system only the actual time of departure of the vehicle from the stop station. Due to this approach, the time of passenger exchange is included in the travel time of an interstop section, which also varies in individual rates, which was not distinguished in the analysis. The adopted procedure resulted from the lack of historical data from the transport organizer on the load and the time of passenger exchange for the tested bus lines in the adopted time horizon. On the other hand, the aim of the authors was to develop a method that is as simple as possible for practical use in industrial conditions, so that the results can be widely used in optimizing the functioning of public transport.

Currently, public transport organizers are much less likely to continuously and automatically register the number of passengers that enter and exit than the parameters of the vehicle. The integration of data from both independent systems would require additional coordination at the stage of data processing, and this would generate additional errors and data gaps. However, determining the variability of the actual travel time of the section, i.e., extracting the stopping time at a stop, is a very valuable contribution to achieving a precise and complete characteristic of the actual operation of public transport. Additionally, it is not possible to link the results of the analysis with the traffic volume, as there are no sufficiently accurate historical data in the time horizon corresponding to the analysis. The information on the averaged values from websites is not as precise and may not correspond to the actual momentary conditions. The analysis also ignored the impact of bus drivers on the travel time of the route and individual interstop sections, especially as a function of compliance with the implementation of individual routes with the schedule. To some extent, the dispersion of the values $DAS\left(is_{idj}, p\right)$ depends on the individual characteristics of the drivers, especially when there is low traffic, and on the framework adopted in each area for assessing the implementation of the departure as punctual. Perhaps a certain way to solve this problem in future analyses to be carried out will be to conduct an analysis in off-peak periods. The results can be a reference to the results presented in this article. On the other hand, each period is certainly characterized by a different specificity: traffic conditions, which means that determining the scope in which it is possible to compare different periods is a separate research problem. The current schedule may, to a varying extent, also consider the actual time needed to change passengers and interstop section travel time.

At this point, it is important to indicate the directions for further research to obtain a broad and multidimensional view of the whole issue of irregular bus running and the impact on the possibility of replacing the fleet with electric rolling stock. The method proposed in the article should constitute only one of the set of partial criteria in the integrated multi-criteria decision making, taking into account various parameters of line routes, timetable, the size of demand in individual OD matrix and its variability over time, delays and disruptions in vehicle journeys, information on vehicle circles, fleet size, and location of charging points in order to minimize fleet conversion costs, spread them over time and maximize the benefits obtained. It is necessary to determine the real relationship between the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values and the traffic conditions prevailing on it and the range of their variability. It is very important to identify the factors that influence the variability of travel time and to determine the strength of their impact. The result of the method is to indicate the set of interstop sections assigned to individual levels of disturbances and as a result to indicate preferences regarding the line, which is more advantageous to electrify according to the adopted criterion. On the other hand, the method of assessing the interstop sections lacks the possibility and legitimacy of introducing infrastructural and organizational changes on the interstop sections in order to reduce the dispersion. A valuable and very practical result would be the empirical determination of the functional dependence between the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values and the necessary level of energy reserve to ensure uninterrupted route passage between successive charging points and its impact on operating costs. For a broader description of the phenomenon, it would be beneficial to analyse the travel time of the entire route between the terminus based on individual departures so as to be able to determine the interactions between adjacent interstop sections and the impact of the $IQR^{\mathrm{R}}_{\mathrm{avg}}\left(is_{idj}\right)$ values and punctuality at all stop stations on the route. Obtaining the results of the above-mentioned conceptual analysis would allow to determine the full impact of the dispersion of the $DAS\left(is_{idj}, p\right)$ values on the implementation of the fleet conversion process into fully electric rolling stock. The authors were not able to determine whether the route where all sections are exposed to the same dispersion size with a high mean value is more favourable for electrification, or a route where only a few interstop sections are characterized by a very large variation in $DAS\left(is_{idj}, p\right)$ values and the remaining interstop sections are under this very regular and predictable terms. The research carried out included an analysis of the dispersion in four periods of analysis, i.e., two rushes and two types of days (school and holiday working days). The occurrence of large dispersion differences between the four analysis periods was revealed. However, the impact of this variability between analyses on the actual possibility of electrification and the resulting recommendations for the construction of vehicle cycles has not been established. In the future, it should be checked whether the implementation of four independent single-criterion interstop section classifications would be more useful in planning the fleet conversion.

6. Conclusions

As part of the problem of converting the bus fleet into fully electric rolling stock, the subject of the analysis is the criterion of $DAS\left(is_{idj}, p\right)$ values along the line's route. It is an important component from the point of view of the possibility of proper forecasting of energy demand, its consumption and variability, and the necessary battery capacity. This affects the possibility of exploiting cost optimization by supporting the planning of infrastructure investments, the selection of the location of the charging station, and the selection of rolling stock for the implementation of individual vehicle cycles.

The result of the article is the development of a method to identify bus lines on which, due to the slight $DAS\left(is_{idj}, p\right)$ values, electric buses can be introduced without any problems. On the other hand, it indicates places in the public transport network, where this introduction must be preceded by infrastructural and organizational changes that improve the regularity of $DAS\left(is_{idj}, p\right)$ values. Detecting the impossibility of making changes is an important premise to exclude the bus lines on the route on which these sections are located from the fleet conversion process until a high level of electrification of other, more advantageous bus lines. Proper planning of tasks and the feasibility assessment of using the technical infrastructure can optimize the cost of the fleet's electricity. A precise assessment of the energy consumption along the route allows you to properly determine the charging needs and select the most advantageous points for the location of the charging points. Due to this, it will be possible to rationalize the costs of the fleet conversion process, its better distribution over time, and a more justified investment in the charging infrastructure. The analysis carried out is important not only from the perspective of planning vehicle cycles by organizers and transport companies, but also from the perspective of users. Reducing the diversification of the values $DAS\left(is_{idj}, p\right)$ improves the quality of the transport offer by increasing the repeatability, predictability of travel time, and thus also the reliability and punctuality. This allows users to better plan their travel time and reduces the likelihood of inconvenience associated with extended travel or waiting times.

Future research directions should consider infrastructure problems. Spatial analysis can focus on the attributes of sections and nodes of the transport network. The aim of future research will be to find critical elements of transport infrastructure and their attributes that have the greatest impact on the vulnerability of the bus lines to disruptions. The higher the level of disruptions (e.g., due to delay) on these components, the more significant their loss in the system.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Morning rush hours

115A School days

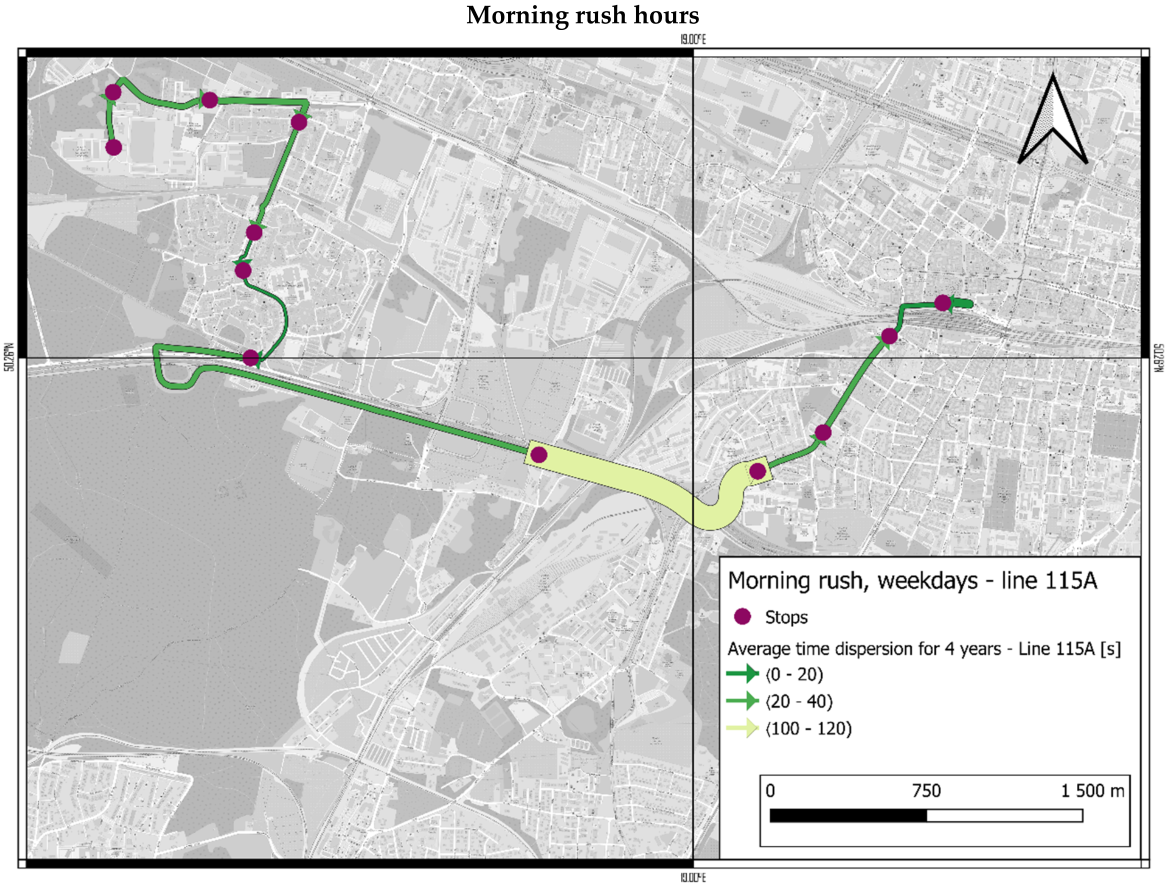
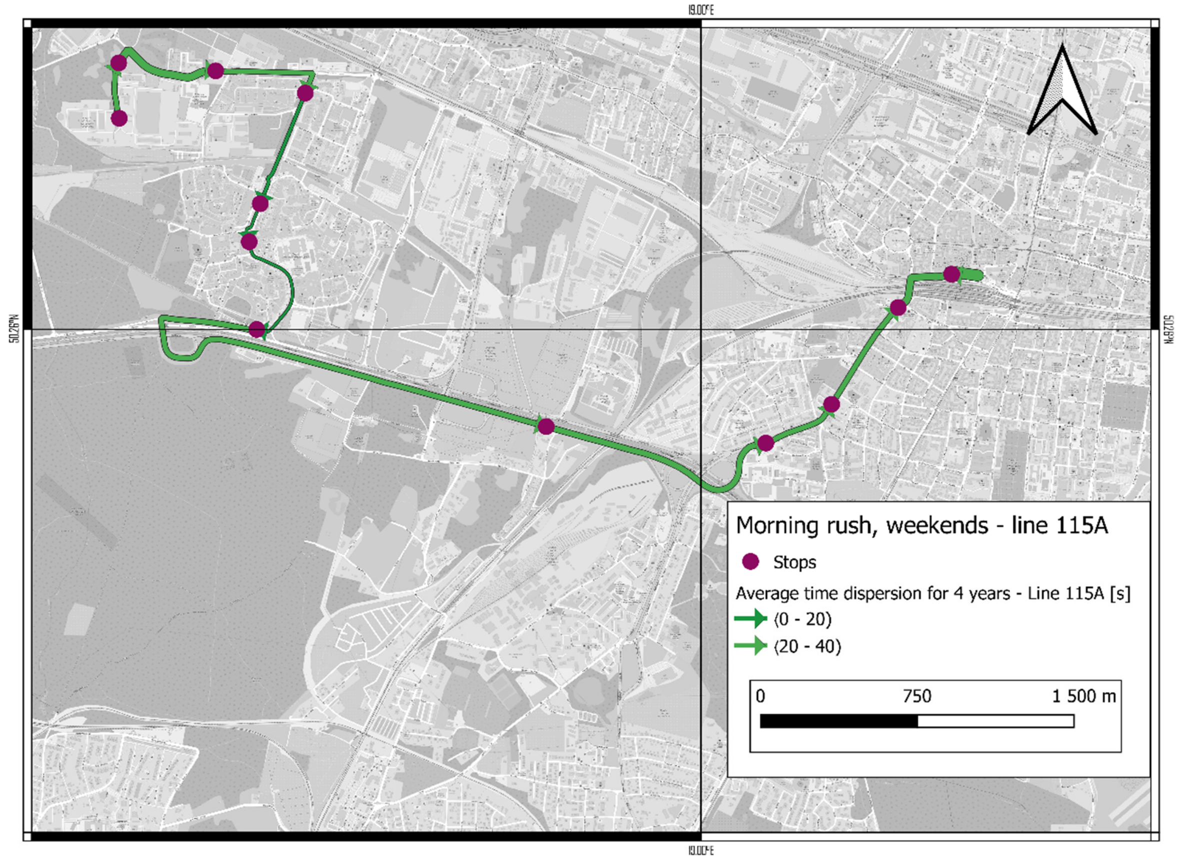


Figure A1. *Cont.*

115A Holidays



115B School days

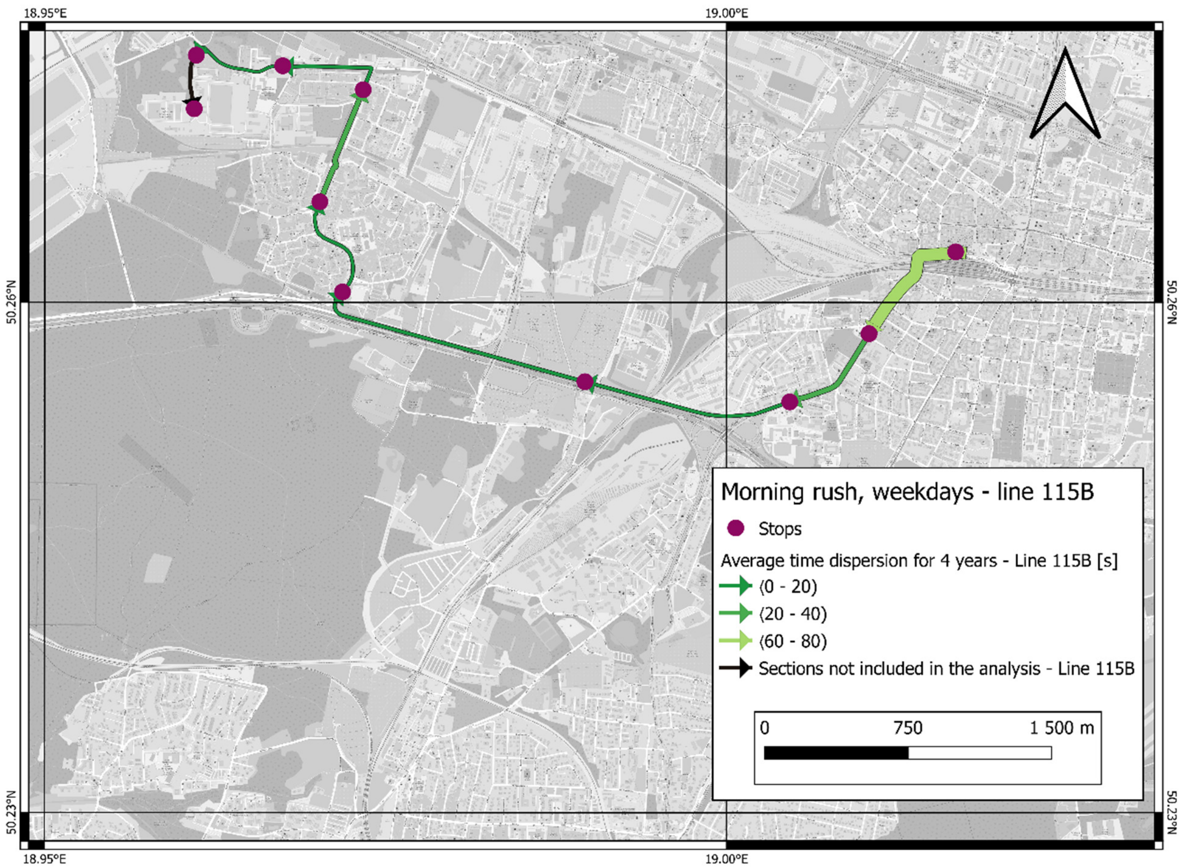
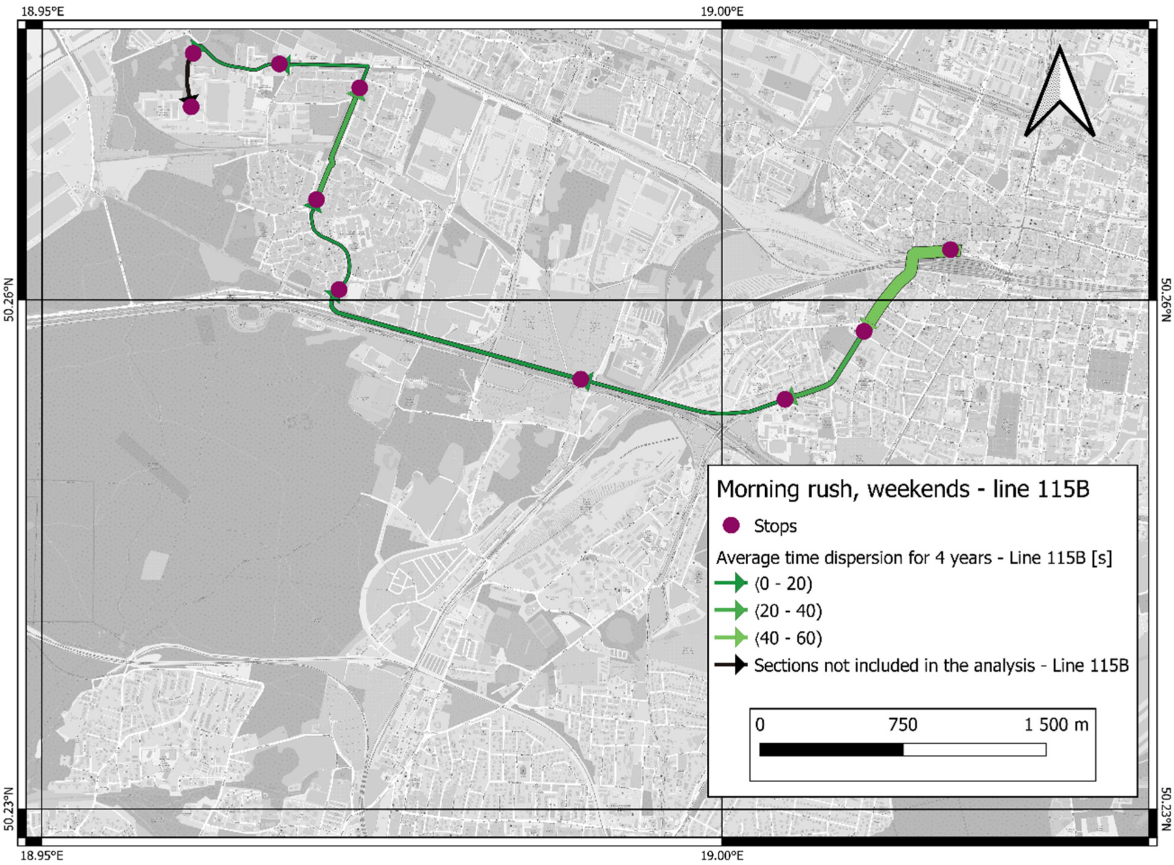


Figure A1. *Cont.*

115B Holidays



11A School days

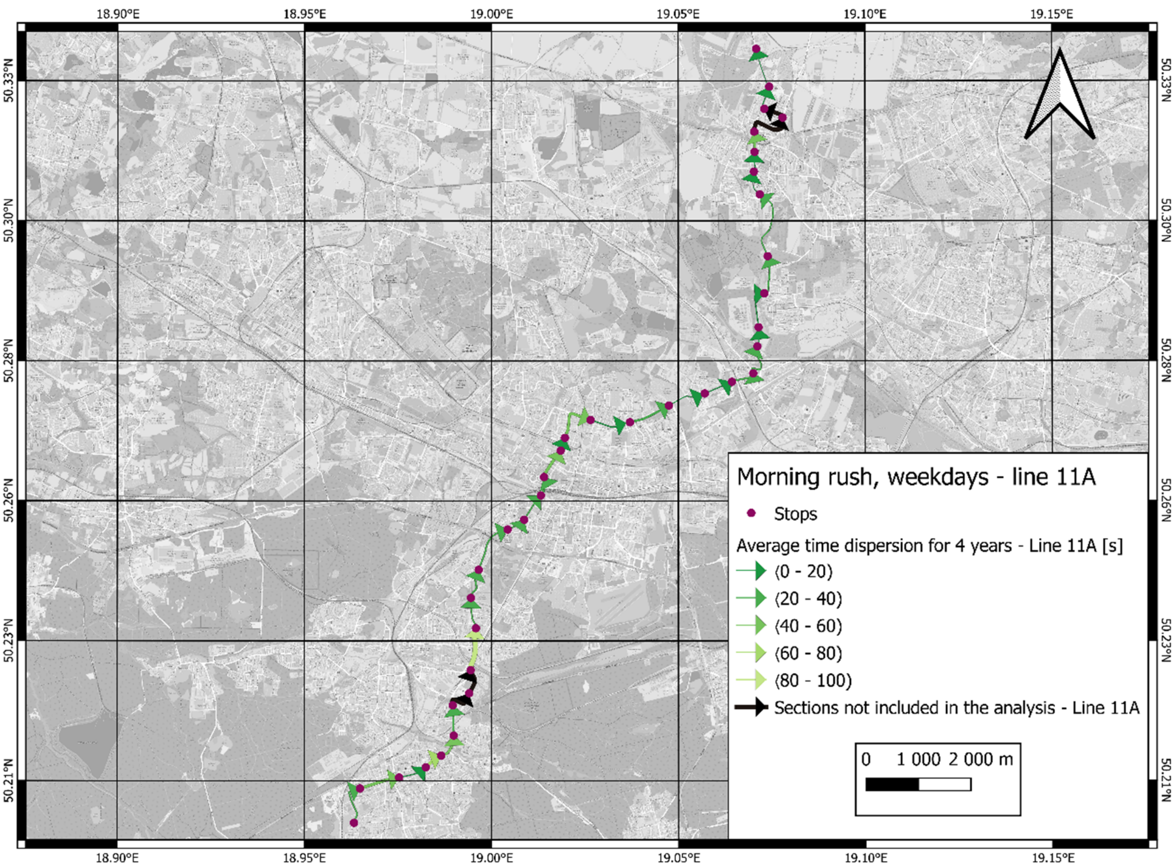
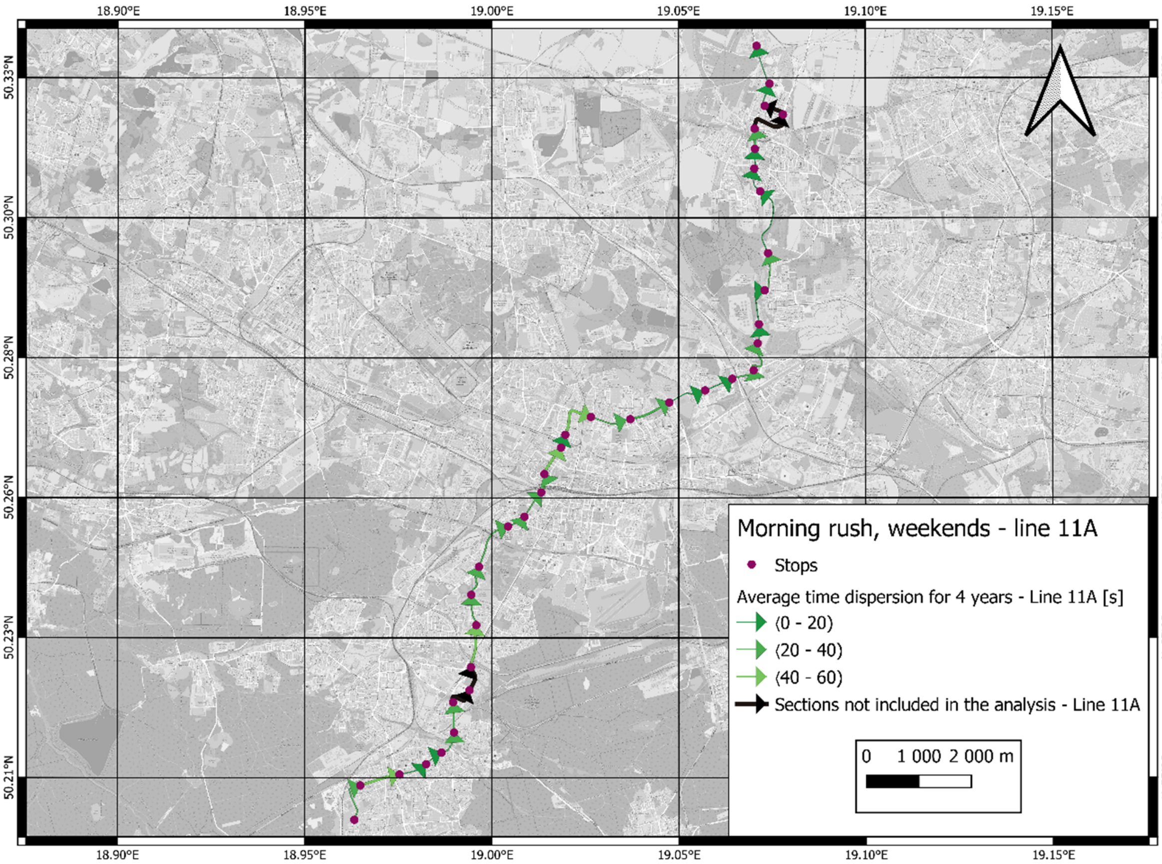


Figure A1. *Cont*.

11A Holidays



Afternoon rush hours

115A School days

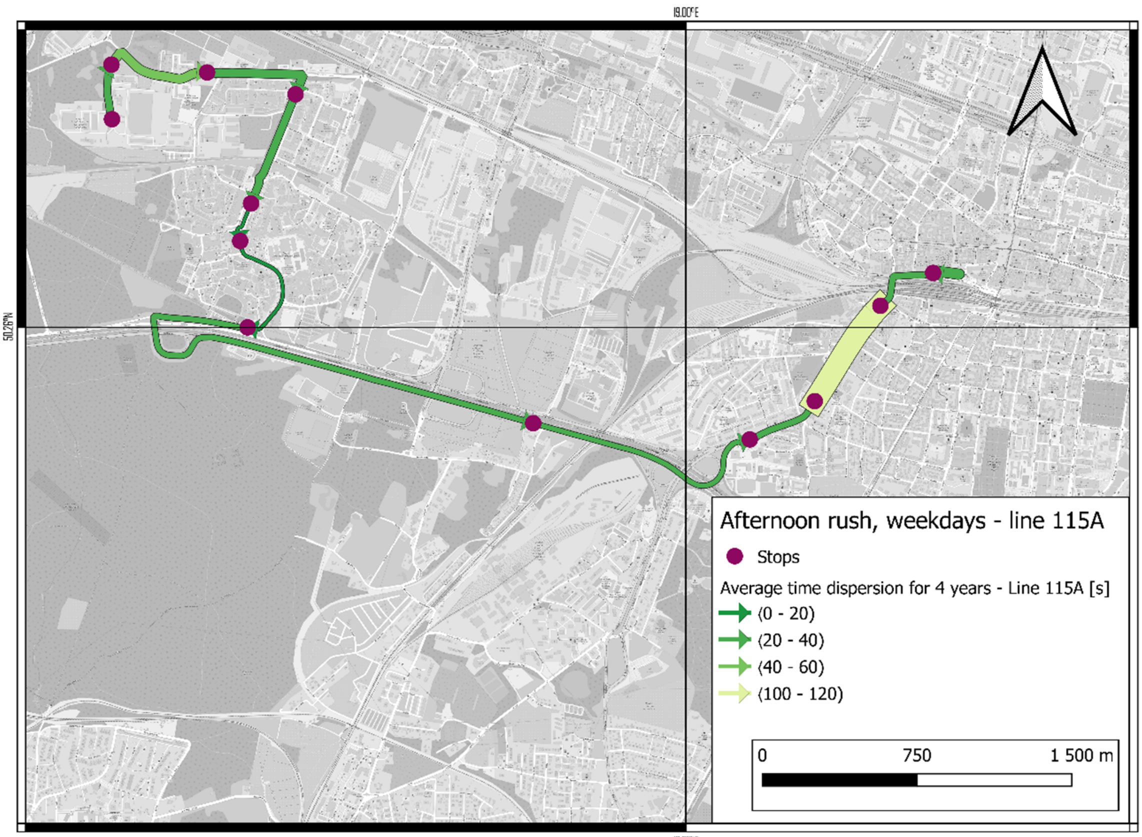
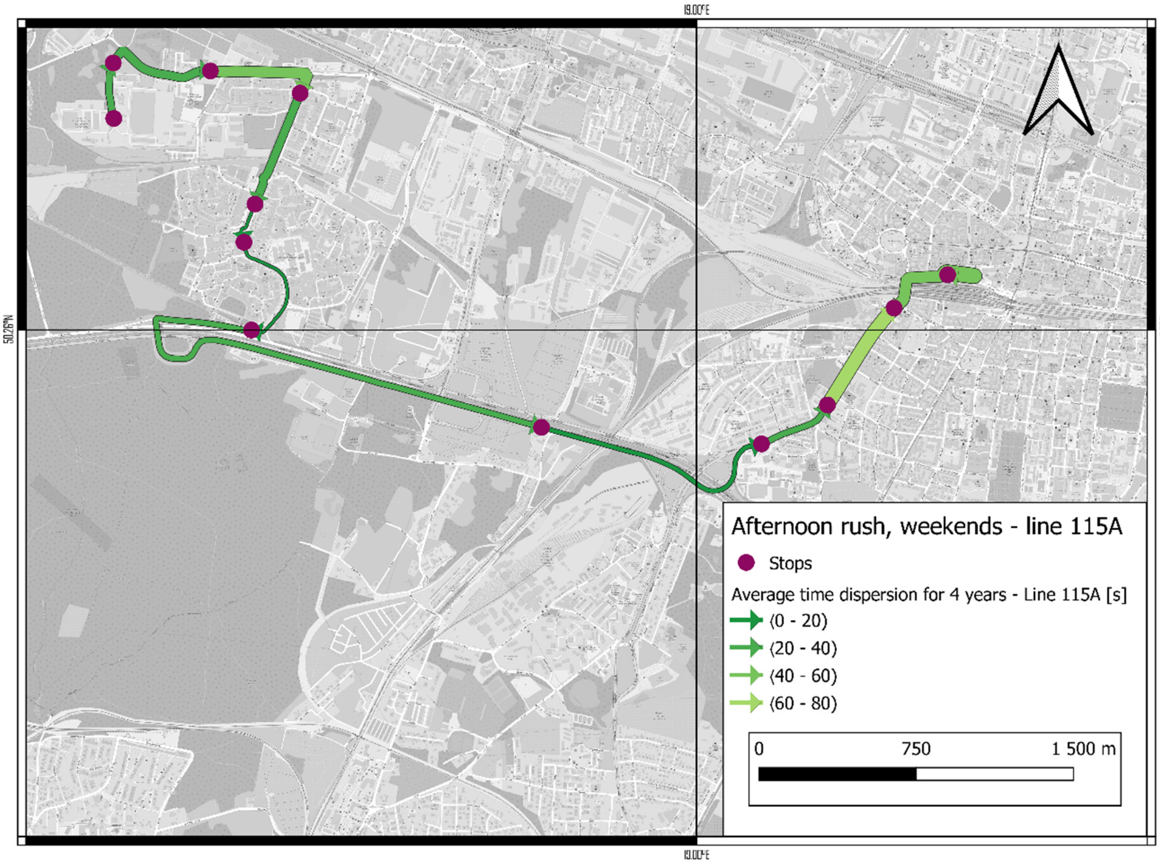


Figure A1. *Cont*.

115A Holidays



115B School days

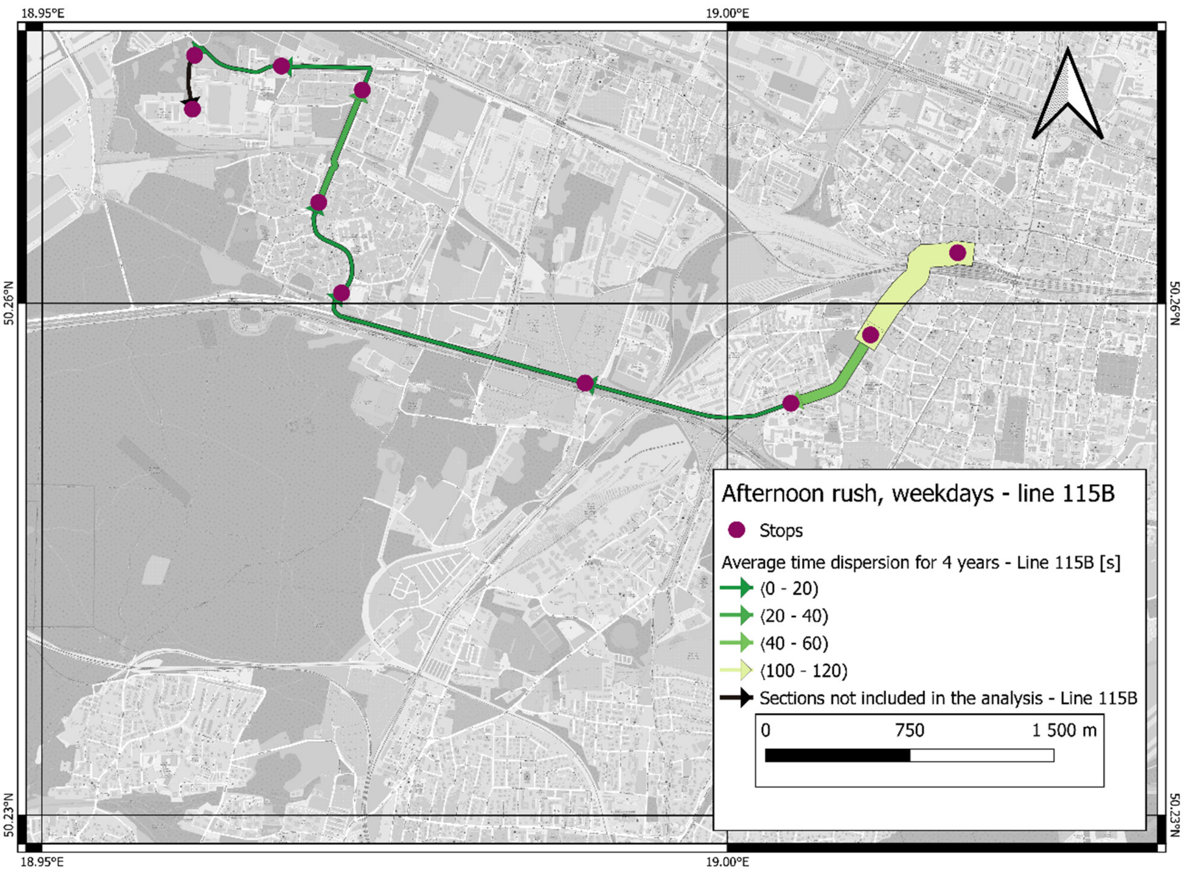
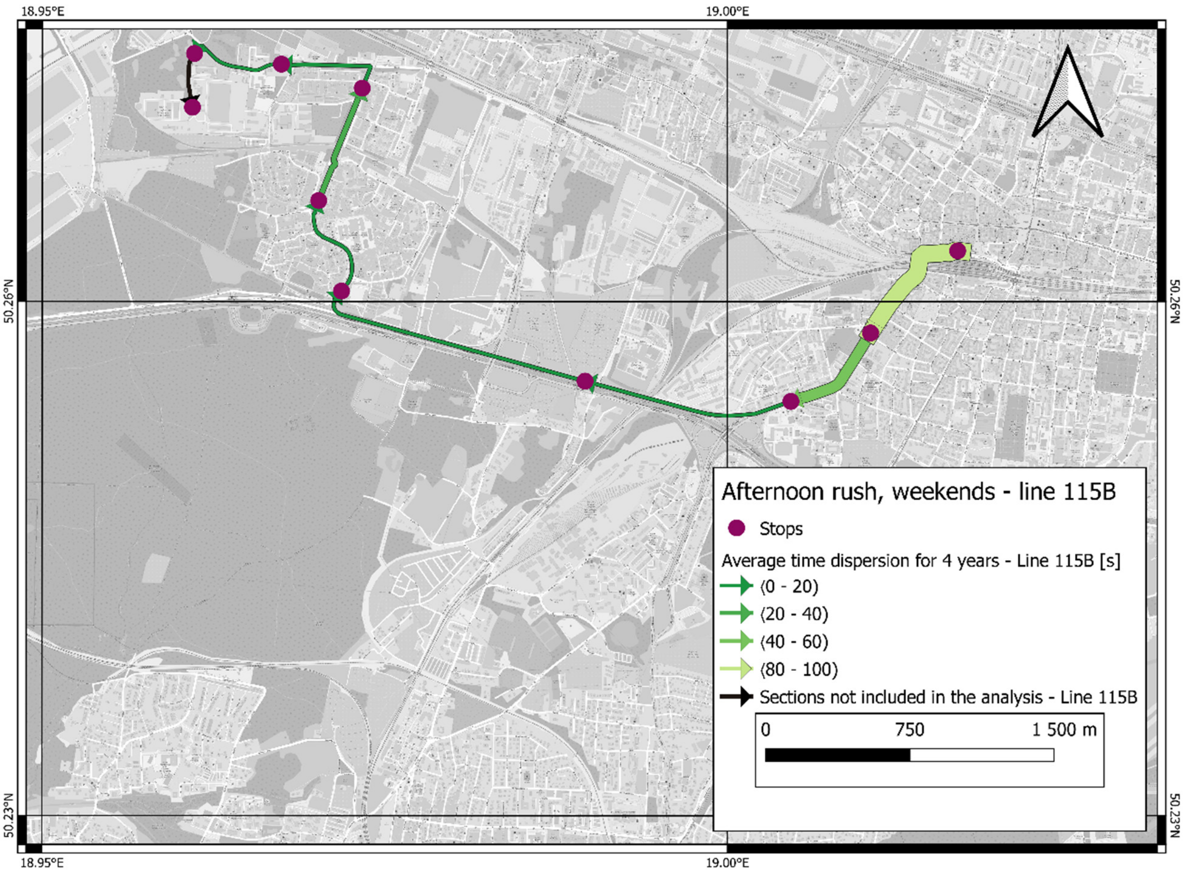


Figure A1. *Cont*.

115B Holidays



11A School days

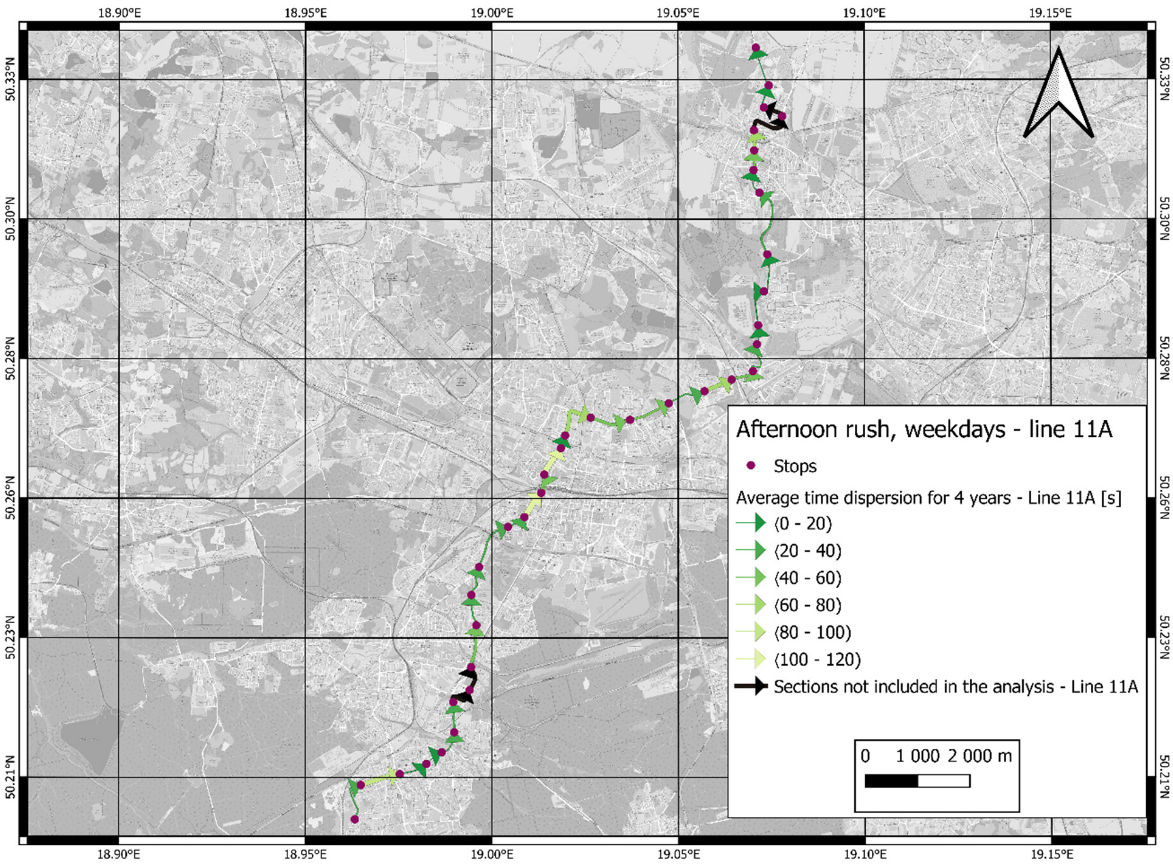


Figure A1. *Cont.*

11A Holidays

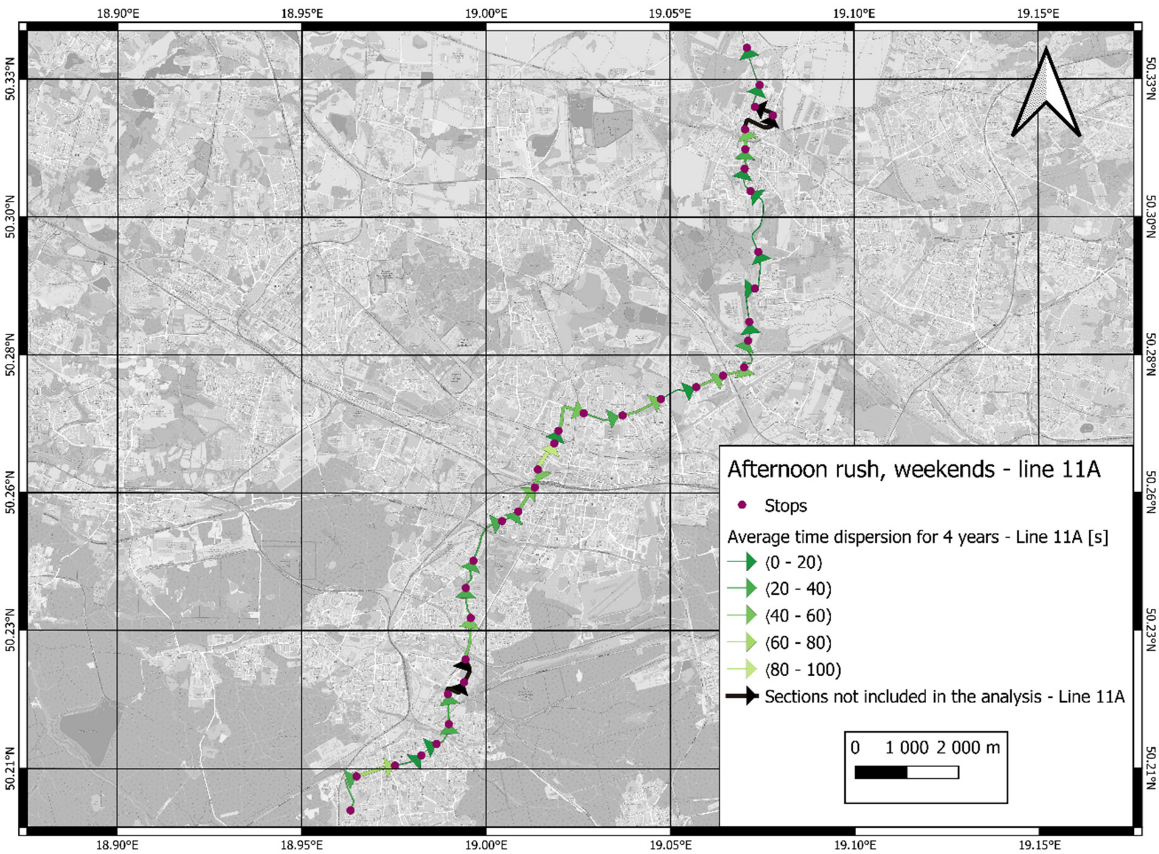


Figure A1. Spatial temporal analysis of $IQR^{R}_{avg}\left(is_{idj}\right)$ values broken down into line directions, traffic peak periods and types of traffic days.

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