Research Article

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Long-term urban traffic monitoring based on wireless multi-sensor network

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Abstract: Increasing the number of vehicles on the road network and the growing popularity of sustainable development of urban areas have resulted in the need for implementing efficient and cost-effective traffic measurement methods. From the perspective of traffic management, up-to-date information about vehicle density and access to historical data are the key components of traffic variability analyses. Rapid technological development based on Intelligent Transport Systems (ITS) has popularised the wireless sensor networks (WSN) application. The solution enables continuous monitoring of selected area using multiple wireless and low-cost sensors connected within a network. Those systems are dynamically evolving tools for solving an effective traffic management issues in city centres and urban environments. In the study, authors have performed a traffic variability and its dynamics analysis in a selected area using a multi-sensor network for traffic volume monitoring. The article presents the results of research conducted between years 2015 - 2018 throughout the city of Bielsko-Biala with the support of OnDynamic multimodal system. Within the context of the analyses, basic traffic parameters have been determined and variability trends have been identified on selected road sections. Long-term research indicated the minor variation in a number of vehicle detections and relatively stable traffic volume in the city centre during the analysis period.

Keywords: wireless sensor networks, data collection, traffic volume, traffic flow

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1 Introduction

As road traffic increases, effective traffic management becomes a priority for infrastructure managers. An essential tool for traffic management is up-to-date and high-quality data from the road network. Their analysis and characteristics allow for precise planning of future investments. Due to the specificities of urban traffic characterized by increased traffic, transport congestion, bottlenecks and growing expectations of citizens, the demand for this information becomes particularly important. Traffic engineering tries to meet these requirements by creating traffic models based on accurate traffic data including real-time information on the traffic volume of vehicles and pedestrians. In urban areas, traffic detection and supervision are also a basic elements of the implementation and use of Intelligent Transport Systems, and thus the development of the Smart City concept. In the mentioned concept transportation is considered to be a key resource and critical sector in modern cities development [1, 2]. Smart city definitions consider communications and sensor capabilities sewn into the cities' infrastructures for transportation optimization purposes [3]. This trend is based on digital information and communication networks to integrate urban systems in order to improve their efficiency and interactivity [4, 5]. The use of these elements makes it possible to meet the requirements of the residents and satisfy their transport needs.

Due to the growing demand for vehicle detection systems, this market has been developing very dynamically over the last few years. The popularity of these solutions is influenced by the fact that modern systems, apart from the detection itself, allow obtaining data on the distribution of motion, speed, headway measurement, classification, weight and dimensions of individual vehicles [6]. Today's solutions are based on detection of phenomena accompanying a passing vehicle, and the technologies used are divided into two main groups: based on invasive and non-invasive sensors.

Classical systems use inductive loops, magnetometers, microloop probes, pneumatic road tubes, piezoelectric cables or other alternative weigh-in-motion sensors [6] and require a single surface intervention. This group, although characterized by high measurement accuracy, has a negative impact on the durability of the surface and requires periodic replacement and calibration of sensors. The consequences of this are interruptions in road traffic continuity, high costs of system implementation and maintenance. Striving to eliminate these inconveniences has resulted in the development of unconventional systems based on non-invasive and low-cost detection technologies.

This group includes *e.g.* video image processing, microwave and laser radars, passive infrared, ultrasonic, passive acoustic array, sets of diverse sensing technologies such as passive infrared Doppler radar. The sensors are usually located at the side of the road or above the lane. Some of them are characterized by mobility, and most of them achieve a measured accuracy comparable to classical solutions. On account of the fact that, one of the main WSN's challenges is size and cost minimalization, most of mentioned solution is built according to this philosophy [7–9]. Cost-effectivness of this technology is the result of reletively low implementation (*e.g.* avoidance of infrastructure interference) and service costs. Additionally, in harmony with mention philisophy most WSN solutions are based on simple modules that are decisively more cost-effective than conventional measurement methods. Systems using non-invasive measuring methods are gaining more and more market share [10, 11].

In this paper authors would like to present WSN application and its usefullness for real-time traffic data monitoring in urban areas.

2 Research testing ground

The research was carried out in the Bielsko-Biala city, where an innovative OnDynamic system based on low-cost detectors was implemented in 2015. In the initial phase of implementation, calibration and start-up works were carried out, then the system was used for research on traffic characteristics. The system covers almost all major communication arteries connecting the eastern and western as well as the northern and southern ends of the city.

2.1 Technology used

Wireless sensor networks (WSNs) are a collection of any number of devices (nodes) that are characterized by the small size and communicate wirelessly with each other. Their task is to detect the event and estimate its parameters. Network nodes exchange information with a central node called sink node. It is used for data collection and processing and serves as an interface between the detection area and the user.

Wireless sensor networks are becoming increasingly popular due to their flexibility in solving problems in different applications and have the potential to be implemented in many sectors of people's live. Examples of mentioned application domains may be [12]:

- military applications – as a part of military command, control, communications and targeting systems;
- area monitoring – as a tool for selected phenomenon or event monitoring and reporting;
- health applications – as a support for patient monitoring, diagnostics, drug administration and tracking;
- environmental sensing – as Environmental Sensor Networks for air pollution monitoring, forest fire detection, greenhouse monitoring, volcano sensing etc.

Another example of wireless sensor network application is transportation sector. WSN-based traffic detection has shown a great usefulness in real-time traffic monitoring, work zone and incident management and transportation planning. By providing up-to-date vehicle or traffic information captured by an in-vehicle GPS module or smart mobile devices it is possible to receive real-time travel information to support roadway users and traffic management authorities [13].

A typical WSN architecture is shown in Figure 1. An example of such implementation is the OnDynamic system.

OnDynamic is a combination of multiple sensors and specialized software that collects and processes large amounts of data from the road network. The system detects active Bluetooth (BT) devices within the sensing

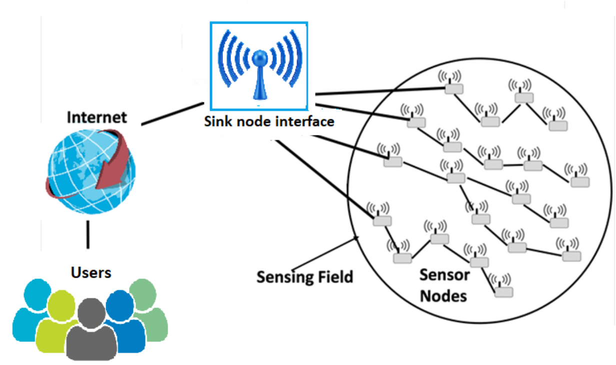

Figure 1: WSN architecture [6]

field. Devices detected by the system include hands-free kit, loudspeakers, smartphones and other mobile devices equipped with Bluetooth. The detection uses a unique MAC (Media Access Control) address for each device. It allows for clear identification of the device data. In order to clear the data from disturbances (*e.g.* pedestrians) and eliminate duplicate notifications of individual devices, a dedicated filtering algorithm was applied. The result is real-time data concerning among others:

- vehicle average speed measurement,
- measurement of time spent in congestions,
- travel time measurement,
- traffic flow measurement.

This allows to reconstruct the route of the vehicle in the examined area together with its characteristics.

The idea of the system is based on 3 stages: collecting data from the road network (using MCU- Microcontroller Unit), processing and presenting them in a user-friendly visual form (Figure 2).

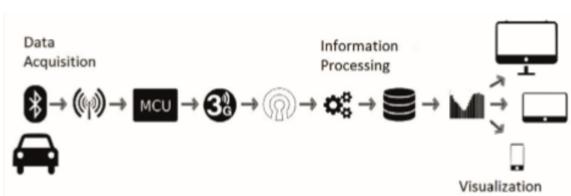

Figure 2: OnDynamic system diagram [14]

Detectors located on the supporting structure send data about registered objects and their location on the road network. The information is recorded in a central database where it is processed. Data from the whole network of sensors are divided according to the location of individual nodes and are used to determine average travel times, intensity and other traffic parameters. The developed information is presented to the end-user on a map. It visualizes momentary traffic parameters on defined segments and enables comparative analysis and viewing of historical data using figures. The visualization facilitates the detection of possible obstructions, traffic incidents and the freedom level determination of movement and changes thereto.

The system meets the requirements for WSN networks, *e.g.* it is characterized by [12, 15]:

- scalability – ability for a network to grow in terms of the number of nodes attached to the wireless sensor network,
- receptiveness – ability to cooperate with other subsystems,
- responsiveness – ability of the network to quickly adapt itself to change in the topology,
- reliability – probability that a system will perform satisfactorily during *e.g.* node failure, as long as there are other nodes that collect similar data in the same area,
- cost-effectiveness – solution is based on low-cost and easy maintenance devices,
- extended range – many wireless sensors can replace one wired sensor to cover a larger region,
- mobility – ability to handle mobile nodes and changeable data paths.

It should be added that in order to fulfil previously discussed functionalities, the system requires periodical calibration. The calibration process may be conducted using inductive loops, ANPR cameras or radar sensors. Calibration is performed in order to determine the coefficients converting the number of BT detections into estimated traffic volume. In case of traffic conditions analysis the detailed information about real traffic volume in not necessary as the OnDynamic travel time parameter is satisfactory. The effectiveness of objects detection depends on the range of the selected area and is estimated to be 10 – 35% [16].

2.2 Characteristics of the research area

The city of Bielsko-Biala is administratively located in the Silesian Voivodship. It is the historical industrial centre of the region, which was called “the city of 100 industries” years ago. According to the data of the Central Statistical Office, 171,505 people were living in the city in 2017 on the area of 459 km^2. The length of public roads with hard surfaces (county and municipal) per 100 km^2 was 412.9 km in 2015, 410.6 km in 2016 and 511 km in 2017. The number of passenger cars registered per 1000 inhabitants in 2015 amounted to 555 vehicles, in 2016 to 590 vehicles and in 2017 to 619 [17]. There was also an increase in the congestion index, which in 2018 rised by 3% compared to the previous year and reached the average daily value of 20% [18]. This result places the city as the 11th most crowded city in Poland and 264th city in the world. Bielsko-Biala is an important centre of cross-border development. This is due to the close location of the largest agglomerations in southern Poland (Upper Silesian and Zaglebie Metropolis and Cracow Agglomeration) and the proximity of industrial centres in the Czech Republic (Ostrava) and Slovakia (Zylina).

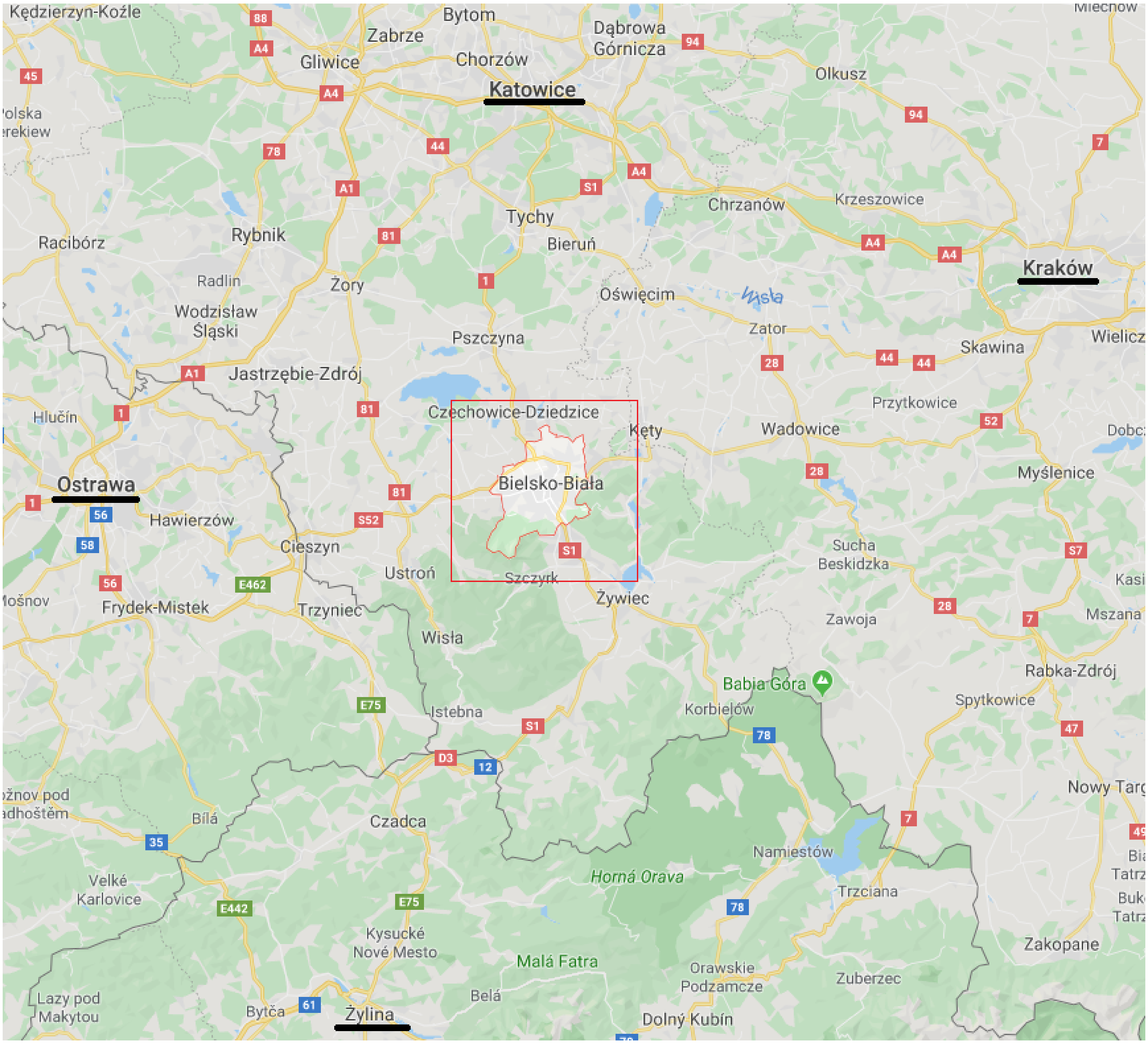

Figure 3: Location of Bielsko-Biala City [source: Google Maps]

Bielsko-Biala is located at the crossroads of international transport routes (Figure 3). The roads within the city are, among others:

- express roads:
  - S1 express road (Bielsko-Biala – Zwardon),
  - S52 express road (Cieszyn – Bielsko-Biala);
- national roads:
  - national road no. 1 (Gdansk - Zwardon),
  - national road no. 52 (Bielsko-Biala – Glogoczow);
- voivodship roads:
  - voivodship road no. 940 (Bielsko-Biala),
  - voivodship road no. 942 (Bielsko-Biala – Wisla);
- about 80 streets with the status of county roads.

In order to approximate the volume of road traffic, Table 1 presents the number of registered vehicles in Bielsko-Biala county in the years 2015-2018. As can be seen, the number of registered vehicles is steadily increasing, with an increase of more than 15% over the analysed period.

Bluetooth detectors operating within the OnDynamic system used in the study were provided by APM PRO company [14]. 27 detectors have been implemented in the area of the road network. Bluetooth detectors are additionally

Figure 4: Location of Bluetooth WSN nodes in the Bielsko-Biala City road network (source: [14], graphic: https://www.openstreetmap.org, https://pl.freepik.com)

Table 1: Vehicle in Bielsko-Biala county [17]

Years	2015	2016	2017	2018
Total vehicle	118,435	125,099	130,876	137,351

equipped with a GPS module, 3G modem working in a secured VPN and a controller for aggregation and preprocessing of acquired data. The device uses 12 dBi antenna operating within the range of 2.4GHz, which is a standard Bluetooth frequency. The location of Bluetooth WSN nodes is presented in Figure 4.

Obtained data set contained information about: average link volume, average link travel time, average link speed. All values were averaged into 15-minute intervals. An exemplary heat map presenting traffic conditions in morning and afternoon peak for selected day is shown in Figure 5. Data set description is presented in Table 2.

Table 2: Descriptive statistics of data set

Parameter	Average value	Standard deviation	Median	Percentile 75
No. of detection [veh./h]	54	41	55	82
Speed [km/h]	40.17	18.98	36.00	50.00
Travel time [s]	134.08	192.93	98.00	124.00

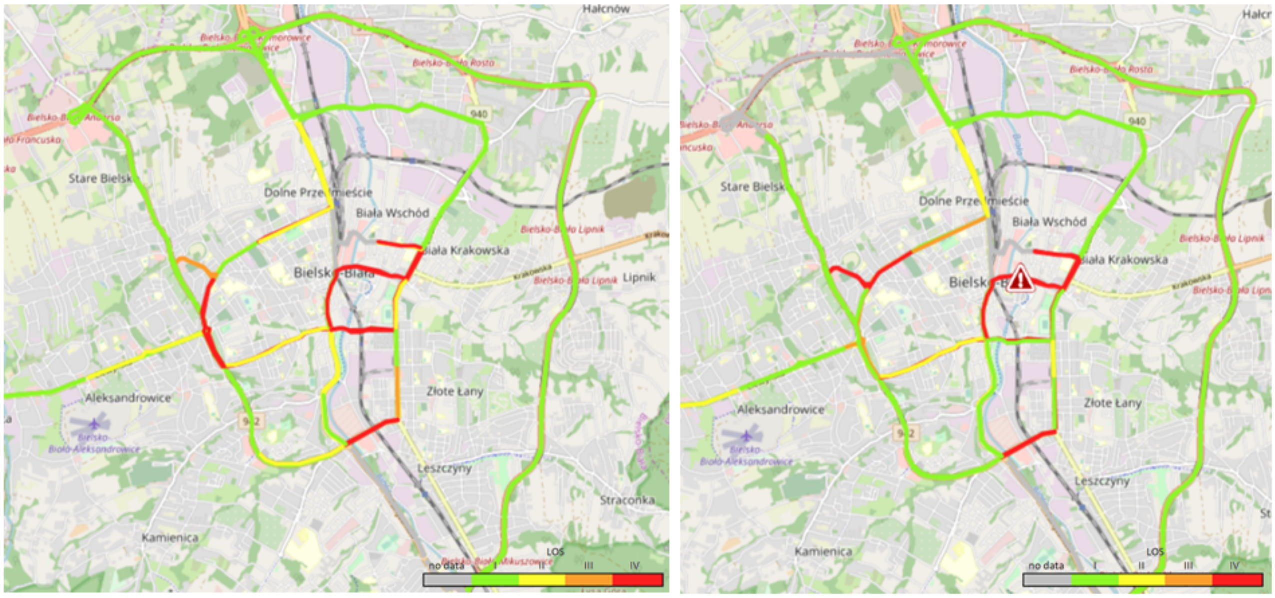

Figure 5: Traffic conditions in morning (left) and afternoon (right) peak – example for day 2017-08-01 (map source: OpenStreetMap)

Figure 6: Example of OnDynamic device implemented in the road infrastructure [source: Google Maps]

3 Results

The analyses presented in the paper were performed only for sections between base stations of the OnDynamic system, excluding urban road network outside of system detection range. This approach eliminates, among other things, the detection of objects at intersections, which do not participate in road traffic (*e.g.* pedestrians, public transport passengers, office devices etc.), and narrows down the analysed data set for vehicle streams. The example of OnDynamic device implemented in Bielsko-Biala is presented in Figure 6.

The first step was determining the number of links where the travels of vehicles equipped with BT active modules were registered. Monthly distribution of active BT modules detection is presented in Figure 7.

The values presented in Figure 7 indicate limited availability of link data in the period up to July 2015, which is a result of the OnDynamic calibration period. Also in the period from March 2018, a decrease in the number of available links was observed due to road works in the city of Bielsko-Biala and the necessity to disassemble some of the transmitters. Therefore, the time interval between July 2015 and March 2018 has been chosen as the representative period in this part of the analysis.

The total number of BT modules registered and the average number of detections in 15-minute periods (Figure 8) were determined during the analysis. Such period was chosen due to highest accuracy among typical traffic measurement intervals.

The obtained results prove a gradual reduction of the total number of registered objects in the analysed periods with significant fluctuations in the summer months of 2016. However, in relation to the average number of detections in 15-minute intervals, these values remain at a constant level and range from 10 to 15 recorded travels.

For long-term analyses of traffic conditions in the city, the average speed of traffic streams is an important parameter. Figure 9 shows the recorded average speed for the morning (7-9 a.m.) and afternoon peak (3-5 p.m.).

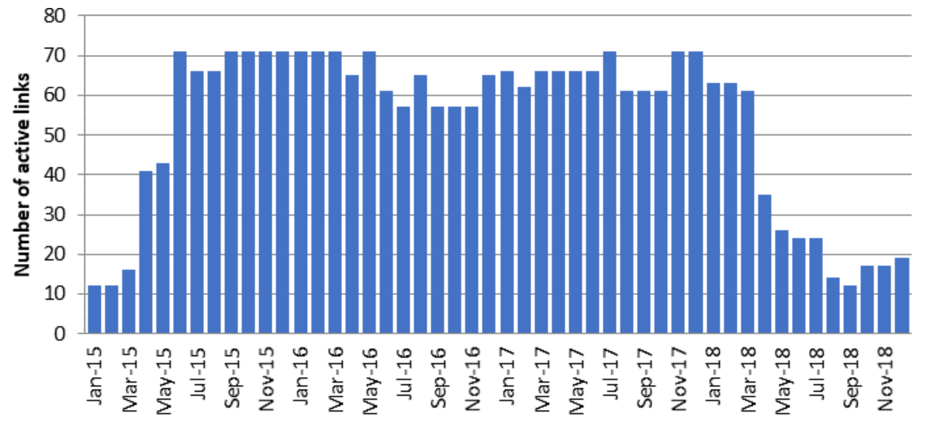

Figure 7: Number of active links in the area of Bielsko-Biala

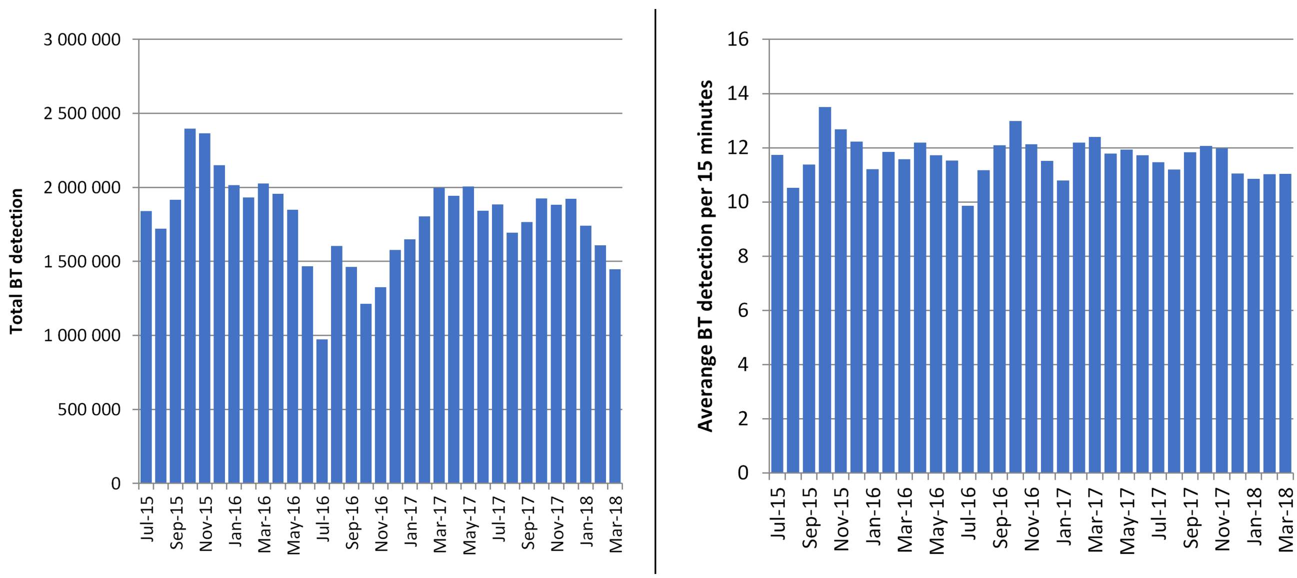

Figure 8: Total BT detection and average BT detection per 15 minutes in the area of Bielsko-Biala

The obtained results show the relative stability of average speed during the morning peak. Significant disturbances were observed in July 2015, it may be result of calibration of the OnDynamic system, and in October-December 2016, when there is a significant reduction in average speed. In the case of the afternoon peak, a clear increase in the average speed in the summer periods of 2016 was also observed.

During the works, the number of sections with significant restrictions on the level of service (LOS) was also examined. According to work [19] LOS is a quality measure which is used to describe traffic conditions. In [19] there are defined six levels (A-F), where A are the best operating conditions and F the worst. The OnDynamic has also built-in mechanism for assessing the LOS, however with gradations from 1 to 4, where 1 is full freedom and 4 is a breakdown. Figure 10 shows the percentage of sections with LOS levels 3 and 4 for all sections of the network. As can be seen in the analysed area of the road network, in about 20% of the sections there are significant reduction in flow rates. These values were significantly lower at the system start-up stage and slightly lower during the holiday periods.

In the next part of the paper, detailed analysis of traffic conditions in relation to three defined traffic routes was performed (Figure 11):

- Route 1: running through the very centre of the city, on the route of which there are the city's Main Railway Station, Main Market Square with a historic castle and many service points,
- Route 2: running at one of the city's hospitals, the main city stadium and traffic to the city's eastern residential districts,

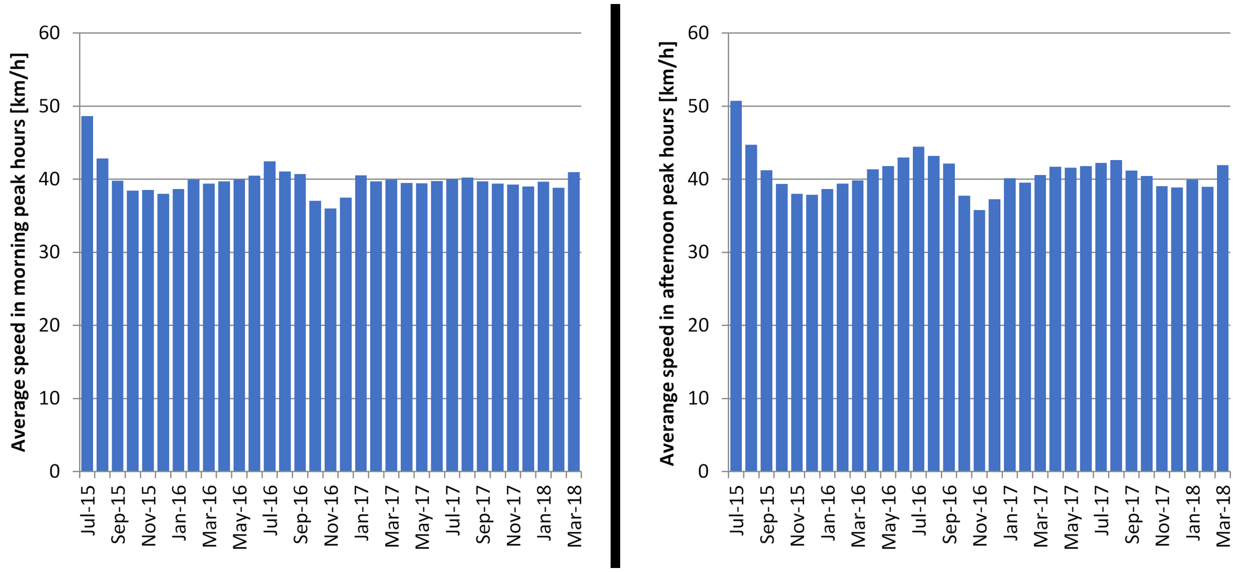

Figure 9: The average speed at links in the area of Bielsko-Biala for the morning (left fig.) and afternoon (right fig.) peak hours

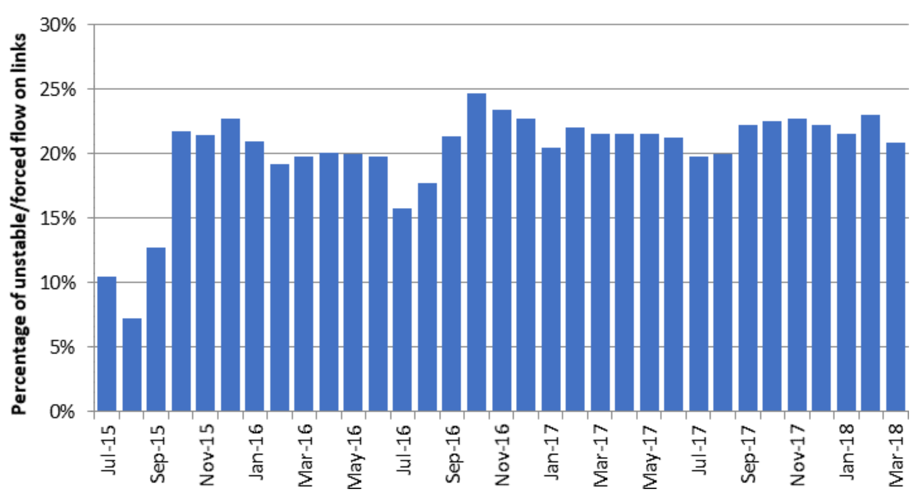

Figure 10: Percentage of unstable/forced flow on links

– Route 3: covers a part of the S1 road which is a ring road of the city, serving both urban and transit traffic towards the neighbouring cities (Zywiec and Cieszyn) and the surrounding towns.

This part of the analysis compares the variability of the average number of detections per consecutive days of the week in the period from July 2015 to March 2018 in individual routes. Analysing the variability in Route 1 and Route 2 (Figure 12), clear repeatability of indications can be observed, including an increase in the average number of detections at the beginning and end of working days and a clear decrease in the number of detections at weekends. During the analysed period, the number of detections remained at a similar level in the years 2015-2017, a slight decrease in the number of detections was observed in 2018.

The analysis of the average number of detections variability in the following days of the week carried out for the Route 3 (Figure 13) showed an upward trend, which is noticeable in the years 2017-2018. As in the case of Route 1 and Route 2, the highest mean detection values were observed on Mondays and Fridays, while weekends were characterized by a lower level of detection.

The above analyses showed relative stability of the system's operation over the analysed years. This demonstrates that the multi-sensor wireless networks in the cities can be used in urban ITS systems.

The analyses of road traffic on selected routes took into account the data from the OnDynamic system on the average number of detections and their average speed on the

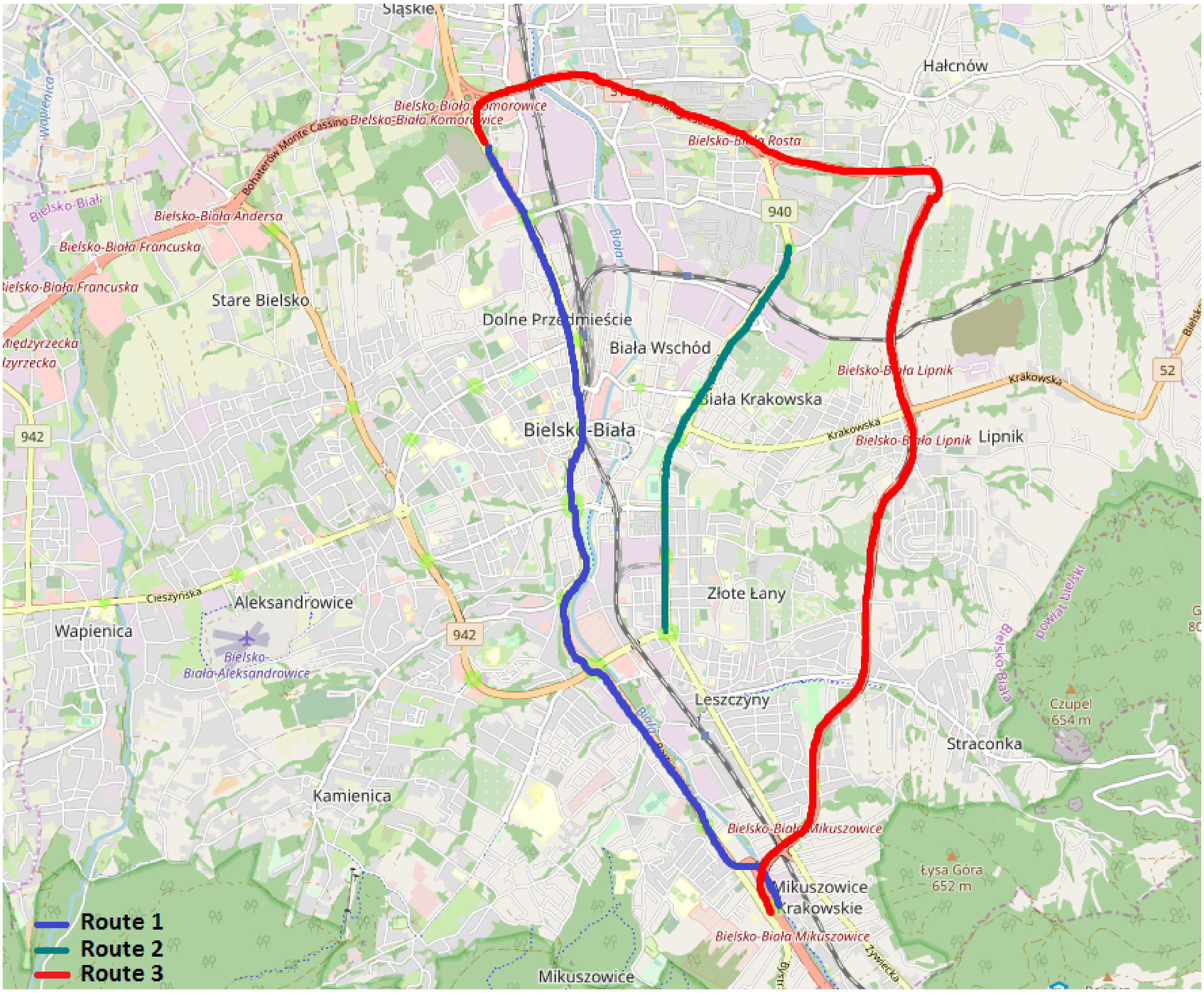

Figure 11: Selected routes of OnDynamic system in the area of Bielsko-Biala

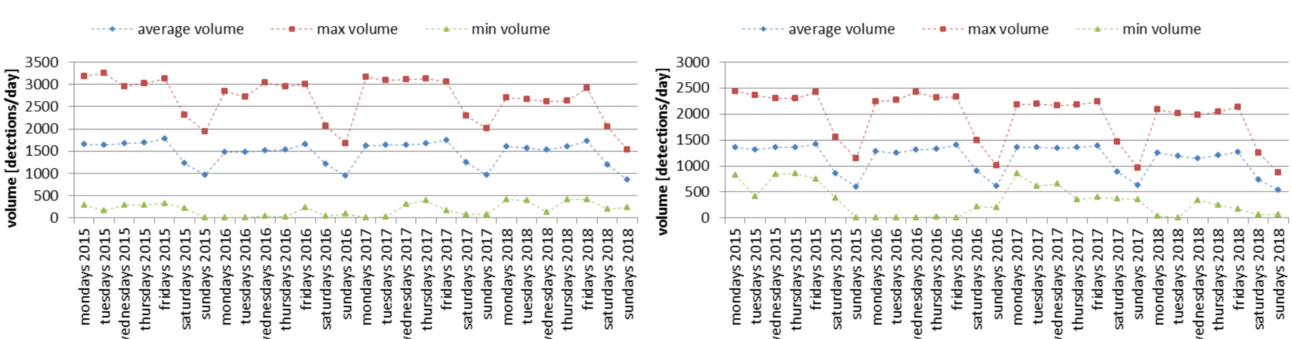

Figure 12: Number of detections per consecutive days of the week of 2015-2018 period for Route 1 and Route 2

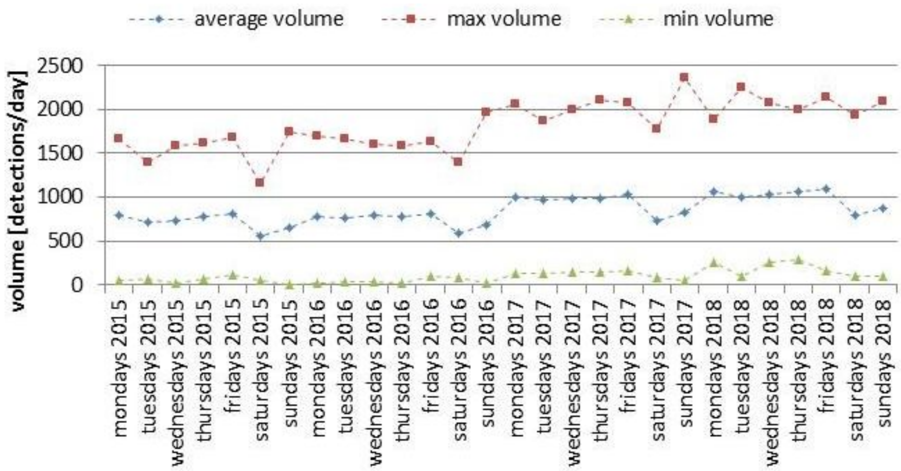

Figure 13: Number of detections per consecutive days of the week of 2015-2018 period for Route 3

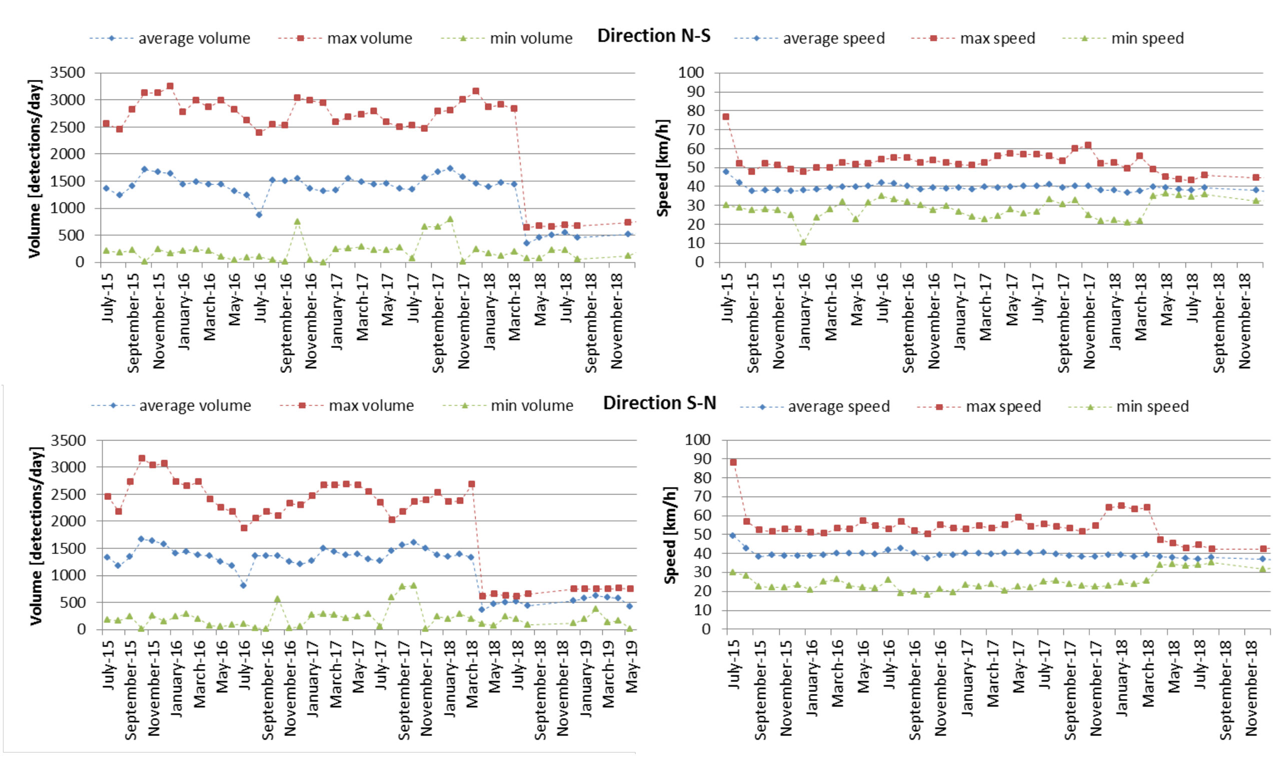

Figure 14: Number of detections and average speed for Route 1 in both directions

tested sections. In this part of the work, the analysis period was extended to December 2018 to investigate the impact of the road network reconstruction in the city centre area and the reduction of the detection points number on the overall performance system. For the discussed parameters, basic statistical values were calculated, presenting the characteristics of traffic variability over the studied period. Further part of the work presents only the results of the research for the traffic running from the north to the south of the city. It is dictated by very similar characteristics of average changes of parameters in the period considered, regardless of the direction of movement along the route as it may me be seen in Figure 14.

Analysing the variability of the average intensity in Route 1 (Figure 14), seasonal repeatability of the obtained values (August 2015 – July 2016 and August 2016 – July 2017) can be observed. A significant drop in traffic was recorded in April 2018, which may be caused by the commencement of reconstruction of the surface on the east-west subsidiary roads leading to traffic to the city centre.

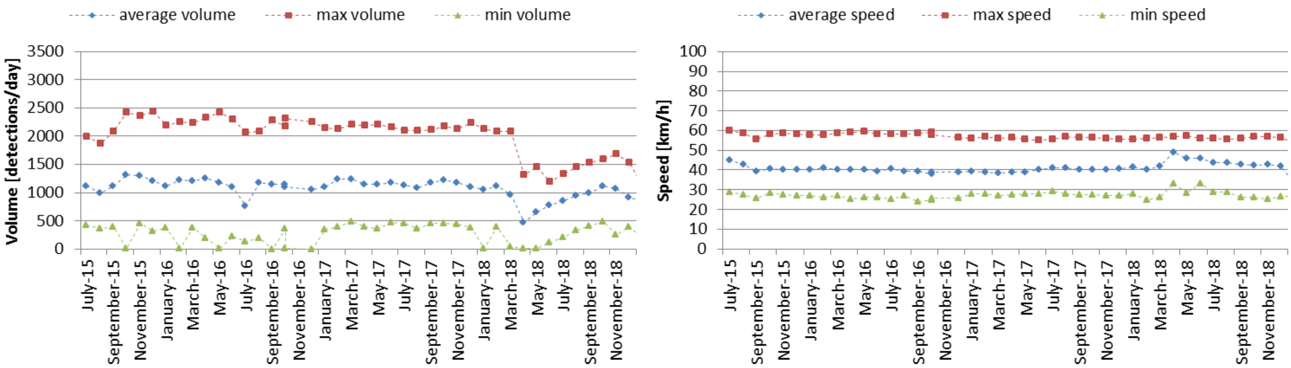

Figure 15: Number of detections and average speed for Route 2

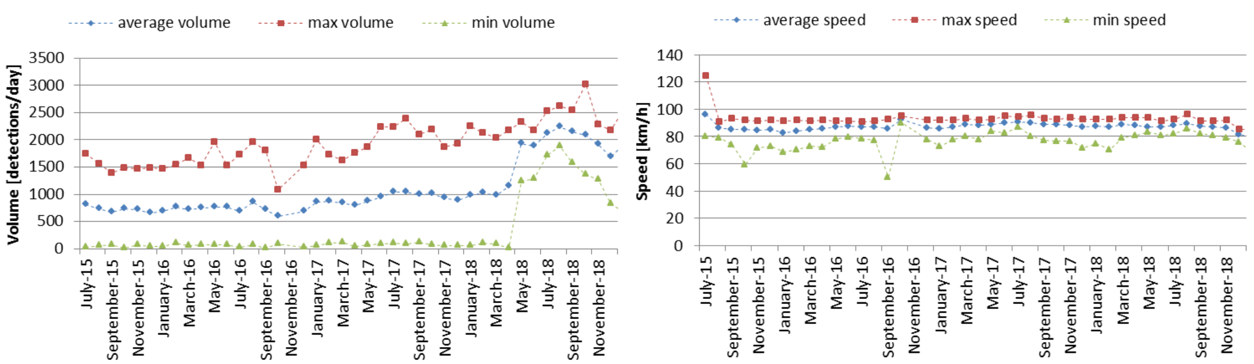

Figure 16: Number of detections and average speed for Route 3

The above hypothesis may be confirmed by the course of average speed, which maximum and minimum values in the period of the commencement of construction works significantly approached the average value.

Analysing the data recorded on Route 2 (Figure 15), one can observe slight fluctuations in the average daily traffic in the period from July 2015 to March 2018 and, similarly to Route 1 analyses, a clear decrease in the intensity of traffic in April 2018. It is also worth noting that the average speed on Route 2 decreased in December 2018, which it turns coincides with the start of reconstruction of one of the main crossroads of the described Route.

A section of the S1 express road, which serves as the city's eastern bypass, was also analysed. Figure 16 shows a significant increase in traffic volume from April 2018, which corresponds to the commencement of the aforementioned reconstruction of roads in the city centre. This may indicate that a large part of the traffic from Route 1 and Route 2 is being transferred to the ring road. Average speeds in Route 3 did not change significantly during the analysed period, which results from the fact that despite the additional traffic load, the sequence maintained a constant level of service.

4 Conclusions

The conducted research has shown that WSN multi-sensor wireless networks are useful tools for long-term variability analysis and monitoring of current traffic conditions. They provide information on trends and dynamics of changes in tested parameters over a freely chosen period. WSN can be an important support for traffic management systems in the city by providing real-time data on the estimated traffic load of the network. The measurements provided by the WSN network may also be used to assess the effectiveness of ITS systems in urban areas and the effectiveness of the applied strategy for controlling vehicle flows in the network.

Analysing the characteristics of the changes in the examined traffic parameters on 3 selected routes, constituting mainly city arteries, one can notice minor variations indicating relative stability of the obtained results. This is confirmed by long-term analyses of individual days of the week, characterized by high repeatability of indications (Figure 9). It should be borne in mind, however, that in the analysed period (2015-2018) there was a 15% increase in the number of vehicles in the urban network (Table 1), which did not translate into the indication of the detection system. The reason may be a decrease in the availability of active BT modules in the devices of road network users, compensating the aforementioned increase in traffic. The analyses showed a dynamic increase in the vehicle traffic in the Route 3 from April 2018. It may indicate that the works started in this period to rebuild the road network in the area of the city centre contributed to transferring a significant part of the traffic to the S1 road, which is the city's ring road.

In the future, the authors plan to expand the work by including the development of indicators and presentation of a method for evaluating the multi-sensor wireless networks functioning and effectiveness to monitor traffic conditions in urban areas.

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