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Urban mobility efficiency resulting from interdependencies between elements of road infrastructure: the city of Turin example

Abstract

In this study, an attempt was made to determine the interdependencies between individual parameters of urban logistic networks. As a result of the literature review, a research gap was identified indicating the lack of precise reference to the dependencies between selected road infrastructure elements. The collected information is of key importance for IT systems supporting the management of urban infrastructure in the area of Intelligent Traffic Systems (ITS). The impact of the number of lanes on average travel speeds broken down into rush hours and off-peak hours has been analysed. The conducted research allowed the authors to determine the degree of influence of the number of lanes on the road capacity and the average speed of vehicles. The results of the analyses can be used to power integrated systems for city traffic management and affect the shape of the new road infrastructure design.

Keywords: mutual dependence between elements of urban infrastructure, urban mobility, traffic capacity, intelligent urban network
JEL Classification: R410, R420

Introduction

Providing the expected capacity of the existing urban infrastructure is becoming a major challenge for local authorities that manage urban space [Mouronte-López, Luz, 2021]. This challenge is becoming difficult due to several factors: the growing number of cars, the development of economies determining the increase in workforce demand, which translates into an increase in pedestrian flows, individual vehicles, and public transport [Caramihai, Dumitrache, 2013]. Due to numerous limitations in the existing cities, based on European experience, it can be assumed that the factor limiting the possible growth of road and rail infrastructure is limited by the existing residential buildings, public utility buildings, private or industrial areas. Therefore, it seems reasonable to focus on determining the optimal parameters of the existing elements of urban infrastructure. For this purpose, it is necessary to indicate precisely the system of interdependencies that occur between individual parameters determining the capacity of intersections. In our research, we will only refer to urban-vehicular traffic except bicycles and pedestrians. Data from the UTD19 programme accumulating basic data on urban traffic in 41 selected European cities provides an excellent database for further research regarding network efficiency.

Literature review

Numerous studies in the area of urban mobility aimed at improving the quality of the urban logistic network indicate the importance of the issue. Various researchers are searching for the key parameters that determine the quality and capacity of the logistic network [Mouronte-López, Luz, 2021; Zhuravleva et al., 2019; Buch et al., 2011]. The relationship between the parameters and the effectiveness of the network is also important, the same as identifying potential influencing parameters. Accurate parameterisation and effectiveness assessment of the analysed solution are crucial for further optimisation [Robertson, Dennis, 2021]. Some researchers point to the importance of the historical foundation in the process of planning the shape of the city street network [Giuliani et al., 2020]. One of the parameters they indicate is the availability of playgrounds and the need to ensure the safety of city infrastructure for its youngest users [Hart, 2002]. There is also a trend in planning urban infrastructure in the Mediterranean region based on lessons learned from other European agglomerations. Among others, in Spain, the ASCIMER (Assessing Smart Cities in the Mediterranean Region) project is carried out, relating to Smart Cities projects conducted in other parts of Europe. The result of the researchers' work is a tool for planning effective urban spaces in terms of capacity, security, and sustainable development [Monzon, 2015]. Other researchers point to the dynamic development of urban agglomerations, which is often associated with the lack of adequate planning of transport infrastructure to support the flow of private vehicles, public transport, and pedestrian flows. The lack of proper planning results in an increase in the anthropogenic impact on the environment, which is reflected in the health condition of the inhabitants [Monzon, 2015; Keller, 2019]. As a remedy for this condition, the proposed solution indicates a potentially new area to be settled, which could be the underground areas below the current cities. This would require a precise definition of the development plan, but it would allow for the design of the shape of city infrastructure from scratch, eliminating in advance the risks associated with waste management, minimising pollution, and designing the optimal capacity of road and transmission infrastructure. However, the proposed idea seems to be somewhat innovative but difficult to implement in European conditions [Xie et al., 2017]. An interesting view is presented by some Romanian researchers, who try to identify the behavioural factors of humans that determine the effectiveness of using the existing urban infrastructure. Thanks to the proposed division into active and passive infrastructure elements and the creation of a dynamic intersection management model, it is possible to propose an optimal solution to prevent the formation of congestions. However, the researchers point out that the final traffic management system has to operate both on-line and off-line [Caramihai, Dumitrache, 2013]. In reference to the assumptions of the Model-Based Systems Engineering for Networked CPS Research and Education project implemented as part of the CPS Summit supported by the European Commission, the HORIZON programme points to the important role of sensors implemented within urban infrastructure. In this case, the WSN (Wireless Sensor Networks) are used to monitor infrastructure in terms of environmental, health, project design, and energy consumption at various stages of the process [Baras, 2015]. The conclusions resulting from this project give a practical dimension to the remaining research and allow for a partial validation of the assumptions made by various scientists. Another important approach to improve urban mobility within the existing infrastructure networks is supported by Intelligent Transport Systems (ITS). This solution is gaining importance in controlling the traffic of the largest metropolises. As a result of the development of a system of cameras at intersections, originally designed to be operated by people, today it is possible to collect autonomously data defining traffic parameters such as congestion, as well as cases of breaking traffic rules. The availability of technology and hardware allows for increasing the popularity of this type of solution [Buch et al., 2011]. However, proper forecasting of traffic flow is essential for further urban infrastructure development that will be sourced from actual concept model calculations [Kamarianakis, Prastacos, 2021]. Forecasting traffic changes tends to play an important role in determining the final shape of deigned changes within urban infrastructure. An adequate solution can be proposed based on accurate forecasts related to traffic changes understood as traffic density, vehicles flow peaks, city infrastructure user behaviours in the next years [Zhao et al., 2020]. Supporting the overall assessment of the quality of the municipal network has a positive effect on maintaining traceability within it. This allows for a complementary way to track the passage of vehicles on the road infrastructure on the example of one vehicle. This helps to identify the behavioural patterns of infrastructure users and adequately model their proper shape [Zhuravleva, 2019]. Summarising the literature review, it was shown that the main areas that require in-depth research and identification of the mutual interdependencies that affect its flow efficiency can be presented in the following points:

- a dynamic increase in the number of vehicles that does not correspond to the development of urban infrastructure;
- the need to create a complex solution for urban traffic management integrated with the existing sensor infrastructure and designed for future implementation;
- a large number of factors determining the capacity of urban infrastructure elements and high flow dynamics, variable in daily cycles;
- the need to propose a comprehensive solution to increase the capacity of the existing municipal infrastructure.

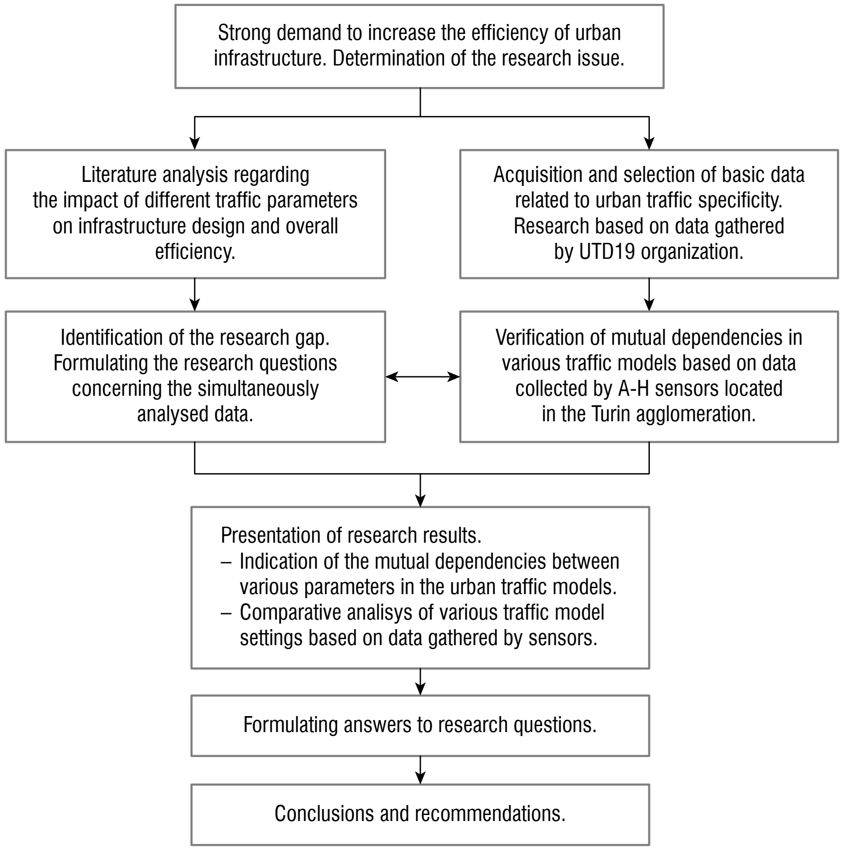
Research method

The applied research method was based on a review of the literature focused on the analysis of research aimed at identifying the relationship between the parameters of the urban network and its effectiveness. For this purpose, it was also necessary to define appropriate criteria that were noticed by other researchers during the literature review. The crucial factor taken into account was the relationship between the efficiency of the infrastructure and the quality of its management based on extensive sensor networks managing urban infrastructure (Intelligent Traffic Systems). Simultaneously, the basic data defining the parameters of road traffic was analysed. Thanks to the database provided by UTD19 containing detailed data referring to the traffic characteristics of a selected communication node in Turin, Italy was used for the analyses.

As a result of the data analyses and literature review, a research gap was identified. Research questions appeared for which an attempt was made to find answers. The following research questions are stated in this paper:
RQ1: Which of the factors that regulate the capacity of urban infrastructure are interdependent and how do they affect the overall efficiency of the urban network?
RQ2: Does the increase in vehicle speed directly increase the throughput of junctions?
RQ3: How does the number of road lanes affect the capacity of a road section at night and during the day?

The logical diagram of the research conducted is presented in Figure 1.

Figure 1. Research methodology implemented within this research



Source: own elaboration.

Research assumptions

The research began with selecting the intersection in a database containing data on infrastructure parameters necessary for further calculations. The focus was put on the data completeness of various parameters: the number of road lanes in one direction, average speed, the possibility of calculating the average speed of vehicles, the number of vehicles registered by each sensor in a specified time, determining the speed limit for the road section and a possibility of indicating the road class on which the sensor was placed. On this basis, an intersection in the city of Turin, Italy was selected. The location of the sensors and the road system are shown in Figure 2.

On the basis of the source data, an attempt was made to parameterise the characteristics determining the measured traffic parameters, appropriate for the relevant road sections. Firstly, the class of roads, the number of lanes in each direction, the average daily speed, and the speed limit were determined. In the next step, the overall hourly average capacity of the road section was indicated, and the distance (expressed in meters) from the nearest traffic lights. In this case, the road sections without traffic lights were not identified, which is positive information, as it is possible to model city traffic using the settings of traffic lights. Collected parameters are presented in Table 1.

Figure 2. Location of sensors used in this research. Turin, Italy

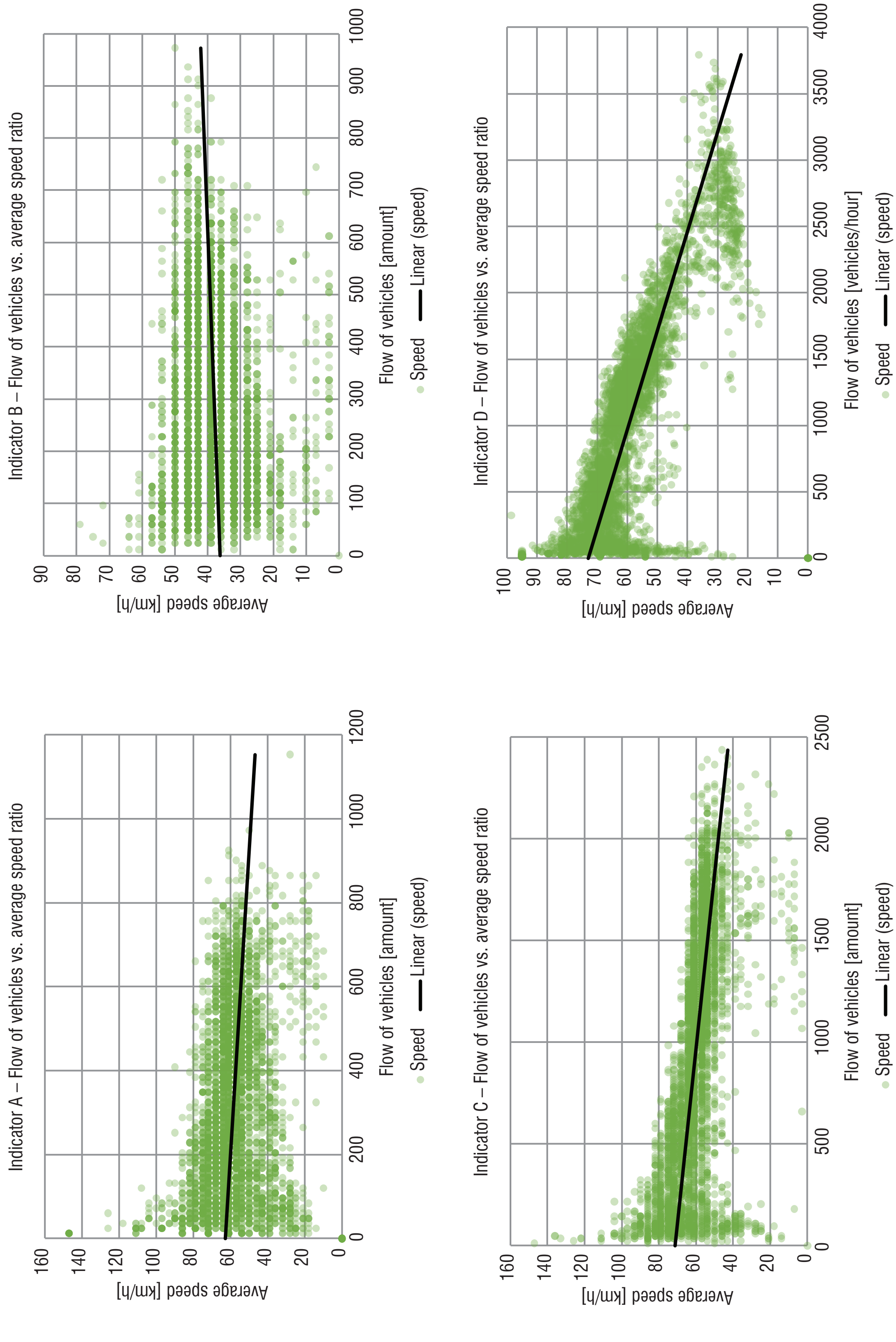
Source: own elaboration based on UTD19 basic data.

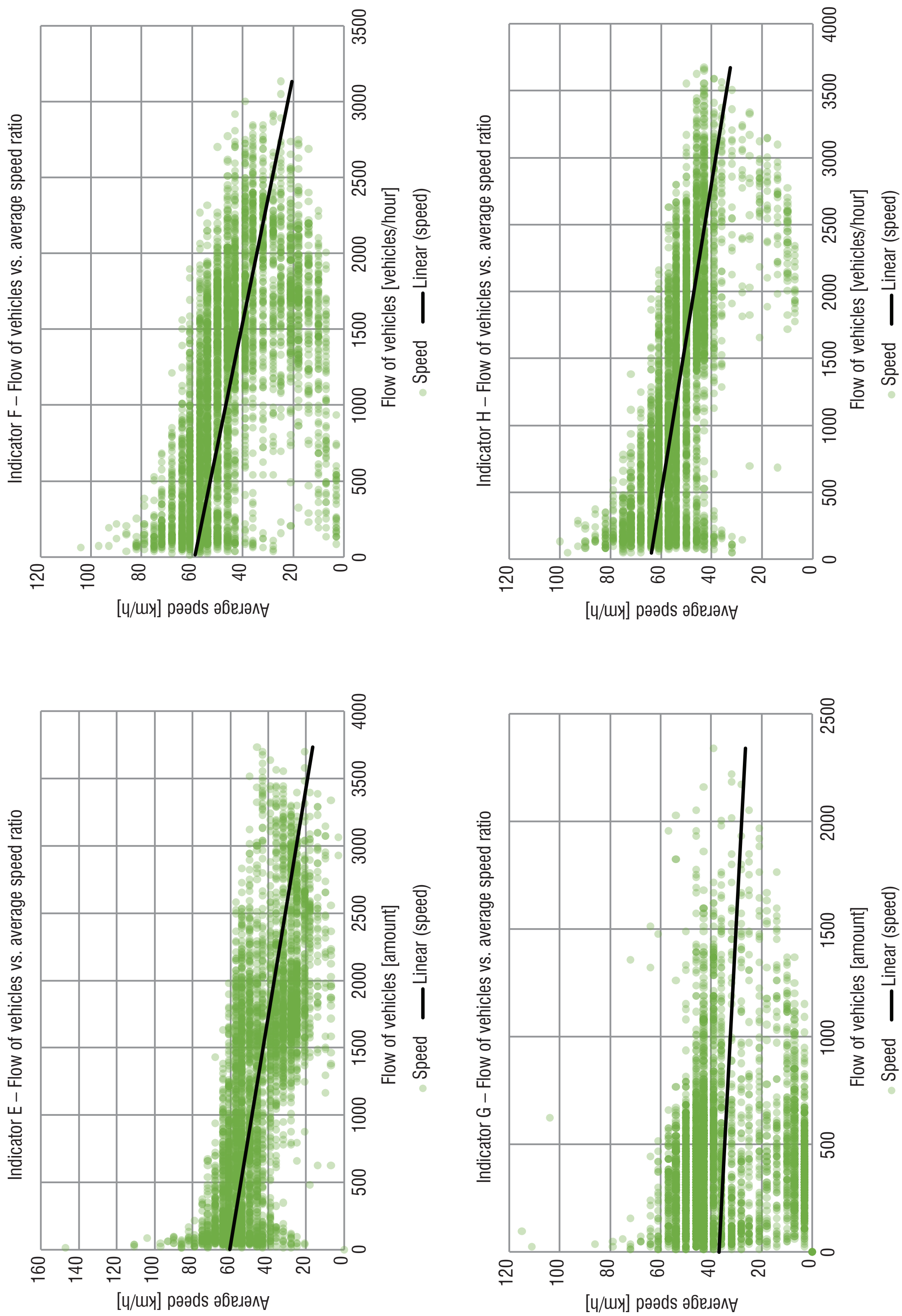
Table 1. Comparison matrix of the analysed sensors, infrastructure type within Turin agglomeration

Sensor ID	Road class	Road strips in one direction	Average speed recorded by sensors [km/h]	Speed limit [km/h]	Average number of vehicles [vehicles/hour]	Location	Traffic lights
A	Tertiary, local	2	58.3	50	321	200 meters before the traffic lights	Yes
B	Tertiary, local	3	38.0	50	287	70 metres past the traffic lights	Yes
C	Primary, main road	3	60.5	50	923	120 metres past the traffic lights	Yes
D	Primary, main road	3	58.7	50	1,075	200 metres before the traffic lights	Yes
E	Primary, main road	4	44.9	50	1,275	95 metres before the traffic lights	Yes
F	Primary, main road	3	44.4	50	1,154	100 metres before the traffic lights	Yes
G	Primary, main road	2	34.8	50	463	90 metres past the traffic lights	Yes
H	Primary, main road	3	51.1	50	1,367	35 metres past the traffic lights	Yes

Source: own elaboration based on UTD19 basic data.

Figure 3. Correlation between the average speed and number of vehicles per each sensor





Source: own elaboration based on UTD19 basic data.

The collected data was visualised in graphs showing the ratio of the increase in the number of cars to the changes in the average speed of vehicles. In order to capture any differences, the data was compared for all eight sensors. It can be observed that in seven cases, the average speed of vehicles decreased with the increase in the number of cars. In only one case of the data from sensor B, the average speed did not decrease with the increase in the number of vehicles. This is due to the road class marked as local, a relatively large number of lanes (3), and the lowest average number of vehicles that travelled through the tested road sections within an hour. The outcome of this comparison has been visualised in Figure 3.

Correlation between the number of vehicles and the average speed records

On the basis of the analysed data, it was found that in most cases the increase in the number of vehicles contributed to a decrease in the average speed. The exception is the road section measured by sensor B, for which the trend line shows an increasing character of the speed average along with the number of vehicles. The trendline for sensor A shows a slight decrease in the speed compared to the other sensors (C to H). The key parameter in those two examples (Sensor A and B) is a type of the road (local road class), which is related with a relatively low level of vehicles passing through in comparison to the other main roads. Therefore, it can be concluded that in the case of local roads, the decrease in the average speed is not that significant or does not occur at all due to a relatively small number of vehicles.

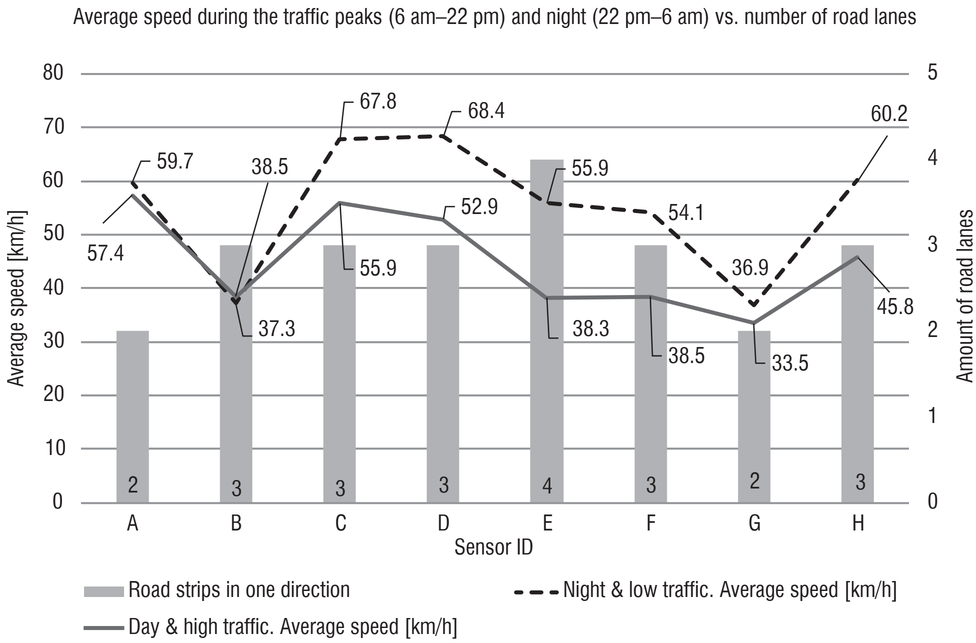
Traffic lights

In order to verify the impact of traffic lights, it would be necessary to expand the sensor network so that the sensors are located in front of and behind the signalling device. At the same time, the data should contain information for each reading and specify the light indication of the signalling device at the time of measurement for a passing vehicle. The influence of traffic lights is less important in the case of local roads, as these types of roads have been measured by sensors A and B. Based on the gathered data it is visible that local roads capacity depends on the average number of vehicles passing.

Number of road lanes and the average speed

On the basis of the collected data, it can be noticed that the increase in the number of lanes does not proportionally increase the overall average speed of vehicles. It was observed that in the case of main, primarily class roads with at least 3 lanes, there are significant differences in the dynamic of the increase in the average speed measured between 6 am to 10 pm and at night from 10 pm to 6 am. Main roads, built with a minimum of 3 lanes, are characterised by a much higher dynamic of speed increase of the passing vehicles in comparison with the day and night period. A road of the same main class with only two lanes shows almost no change in the average speed between the day and night. This corelation has been visualised in Figure 3. The detailed information used to prepare the figure is presented in Table 3.

Figure 4. Corelation between the number of lanes and the average speed during the day and at night for each sensor



Source: own elaboration.

Table 3. Detailed information regarding the average speed and the number of road lanes for each sensor between 6 am-10 pm and 10 pm and 6 am

Sensor ID	Average speed at night (10 pm–6 am) – low traffic density		Average speed during the day (6 am–10 pm) – increased traffic density
	Road strips in one direction	Average speed [km/h]	Average speed [km/h]
A	2	59.7	57.4
B	3	37.3	38.5
C	3	67.8	55.9
D	3	68.4	52.9
E	4	55.9	38.3
F	3	54.1	38.5
G	2	36.9	33.5
H	3	60.2	45.8
Total average speed [km/h]		55	45

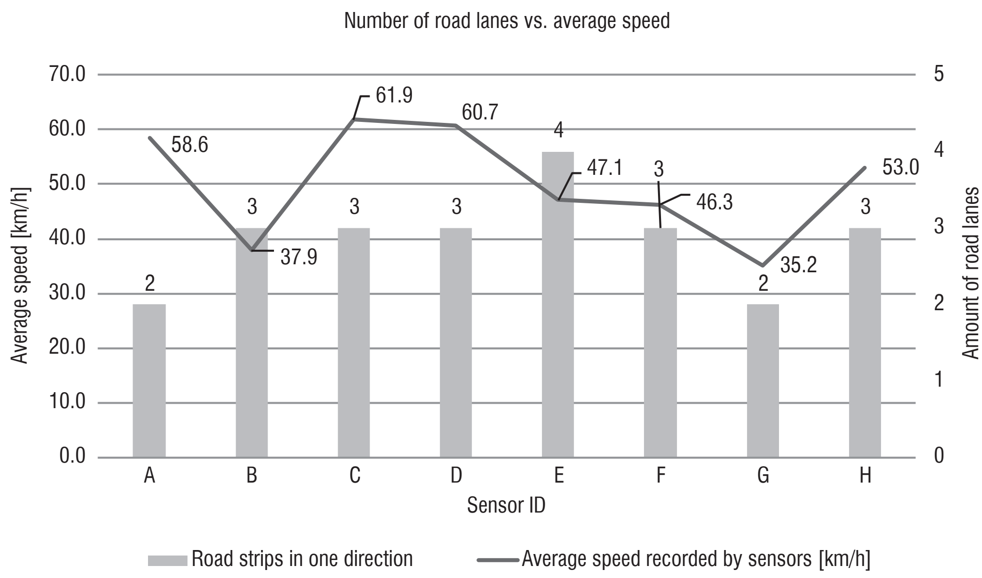
Source: own elaboration.

Based on the research, it was also noticed that the number of lanes does not proportionally increase the average speed from the whole day perspective. The readings from the E sensor describing the road section with as many as 4 lanes indicate that the passing vehicles did not reach the highest speed in comparison with the road sections with 3 lanes. At the same time, in the case where only 2 lanes were present, the speed was the lowest in the case of main roads. However, this relation does not apply to local roads (Sensors A and B), as the average number of vehicles crossing this road class is more important there.

The increased number of vehicles crossing the road sections monitored by sensors from C to H indicates a strong relationship between the average speed and road capacity. It is clearly visible that 3 lanes in one direction are the optimal value for roads of this class. The use of only 2 lanes in the case of the main road related to sensor G significantly reduces the average speed and may impact generation of traffic jams.

The overall relation between the number of road lanes presented in Figure 4 and the average speed presented has the same trend from the whole day perspective in comparison with the trend shown in Figure 3.

Figure 5. Correlation between the number of lanes and the average speed from the whole day perspective



Source: own elaboration.

Summary

Based on the research, it was possible to find answers to all three research questions. It has been proved that there is a certain capacity level of each road that does not affect the drop in the average speed under specified conditions such as the number of vehicles on the road per hour that is related to the road class, and a relatively high number of lanes. However, above a certain level of the flow of vehicles, different for each road class, the average speed drops along with an increase in the number of road lanes.

The interdependent factors regulating the efficiency of the urban logistic network include the shape of the road infrastructure expressed as the number of lanes. This value has a direct impact on the road capacity. The relation of the number of road lanes and the average speed of vehicles shows a higher increase dynamic, especially in the case of main roads between 10 pm and 6 am, for roads over 3 lanes.

On the basis of the conducted research it was indicated that it is important to develop software and tools to support dynamic traffic management in the area of intersections. Dynamic planning of urban infrastructure network settings plays a key role for ensuring the optimal capacity of the urban logistics model in complex urban networks. According to some research [D'Andrea, Marcelloni, 2017], modern IT tools and computing machines are able to model dynamically a logistic network and support it even in the online mode.

An important element that indicates the indirect impact on the quality of basic data determining the capacity of intersections is the location of sensors and the related traffic light mode. The recommended area for further research in terms of network capacity improvement is the appropriate standardisation of the location of sensors for measuring the quality of urban networks in order to provide excellent quality data. Conclusions from the article may be helpful for decision-makers who decide about the shape of public road infrastructure.

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