PROBLEM OF THE ROAD NETWORK CAPACITY

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Abstract

The perception of a typical user of the road network in a large Polish city is determined by the time he spends in queues and congestion every day. In the opinion of many users of this network, it is too long. This time ranges from several to several dozen minutes. In order to explain the dysfunction in question, the concept of physical and transportation capacity of the road network has been described. Then, the basic numerical characteristics of the Polish road network in selected small and voivodship cities have been presented. The analysis used basic data on the length of the road network, the number of inhabitants and the "motorization" indicator for the cities analysed in the article. In this context, reference was also made to commonly used ways to improve the functioning of the road network, from traffic lights, through roundabouts, to ITS (Intelligent transport systems). The summary presents, in the context of new technical solutions in the field of transport systems, the perspective of the functioning of road networks for the next 20-30 years.

Keywords:

road network, congestion, road network capacity, road network dysfunction

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Introduction

This article was inspired by the author's experiences related to participation in scientific conferences, trade fairs, science festivals in the last dozen or so years [1,2]. This inspiration was mainly due to industry exhibitions and educational events. During these events, meetings take place at the exhibition stands, during which visitors are asking questions. Questions are asked by both younger and older participants. Older people have in their minds different pictures of how the road network has been functioning in the last few decades. Many still remember relatively small traffic on the Polish roads in the 1960s and 1970s. Many guests ask about the basic problem of the functioning of the road network in Poland. The questions are asked in the context of numerous undertkings currently being carried out in the road infrastructure. The context of these questions is related to the conditions of travel on the Polish road network, or rather their subjective perception.

In the past, these questions had a different context due to the then (poor) condition of the Polish road network, which was underdeveloped compared to other European countries. However, now, after 30 years of system transformation and intensive development of not only the road network, but also the transport network, these questions are more difficult to explain. Visitors to the fair ask exhibitors why the road network is dysfunctional, supporting this question with numerous contextual examples. The questions concern the problems observed on a daily basis in the road network of a specific city in the context of completed or currently implemented undertakings in its area. People enquiring often quote specific investment amounts (in the order of tens of millions of zlotys or more), and then provide examples of old or new problems with navigating the network. The discussion in this field cannot concern spatial development plans, national development strategies, transport, etc. The observations of the enquirers have a local, often individual context. The answers should refer to the source of the existing state of affairs.

The society expects that undertakings and related costs, especially of the integrated systems, should have an immediate impact on the quality of operation of the entire road networks [3,4,5]. Although this is wishful thinking, more questions are asked in response to the answers provided by representatives of the transport community. This initiates a discussion, which in turn is reduced to discussing technical details, e.g. optimization of traffic parameters in ITS systems, which does not bring the enquirers closer to understanding the heart of the problem, as this is located somewhere else, and concerns relatively simple issues, such as road network capacity.

Road network capacity

The road network, like any spatial system, has (is characterized by) a specific capacity. Any road network can be characterized by a capacity expressed in road vehicles. This characteristic determines how many vehicles of a certain type can be introduced into a given road network due to its limited physical dimensions. This limitation is a deterministic factor, unlike many other factors accompanying the development of the road network, such as expenditure on network development, often dependent on a subjective decision, availability of funds and temporary economic situation. This parameter results directly from the length of all roads and streets located in a given road network. Those roads that have more than one lane increase the length of the entire road network accordingly, in proportion to the number of lanes.

Unlike capacity, throughput (or traffic density) is a road network parameter referring to its point elements, cross-sections, lanes, nodes, etc. Capacity is a characteristic related to the network space, not its point elements. In addition, capacity is not, unlike throughput, closely related to time, it is similar in the longer term due to the time of implementation of line undertakings in the road infrastructure. Moreover, studies in many Polish cities indicate that intersections often operate beyond throughput thresholds (load degree greater than 1). Therefore, although the parameters of capacity or density are well recognized, it is worth taking an interest in the capacity of the road network.

The capacity of the road network consists of public roads of all categories: national, regional, sub-regional and municipal (Act of 21 March 1985 on public roads, Journal of Laws of 2022, item 1693, as amended). However, it is problematic to include non-public roads in the capacity of the road network. This is due to the fact that a certain part of non-public roads is generally accessible to road vehicles, but they have not been given the status of a public road. Another part of non-public roads is located only in areas closed to public traffic, and sometimes these are large areas with a developed road network (e.g. military areas, industrial areas, etc.). Nevertheless, both types of non-public roads listed above increase the transport capacity, although to a different extent. Due to suburbanization, more and more areas with such closed roads are being created.

Another problem is the issue of including (or not) traffic collector in the capacity of the road network (so-called curbside, separate, small, medium and large, multi-level, recently popular pocket/cradle car parks). Vehicles are not in motion all the time, so these facilities affect the capacity utilization of the road network. Here, as in the case of streets, we can distinguish public and private car parks. In the case of car parks, determining their capacity is quite problematic due to the organization and the actual (and not planned) way of parking. The difficulty in determining the capacity is especially in relation to non-public car parks.

It should be noted that it is reasonable to express the capacity of the road network in one specific type of vehicle, which is usually in the form of the so-called a contractual vehicle (acronym – PDV, passenger-delivery vehicle). In this procedure, each vehicle involved in traffic, proportionally to its physical and traction parameters, is reduced to one conventional vehicle (by reference it is PDV). For example, a bus corresponds to 2.2 passenger cars in road traffic. This number is equivalent in the movement of a bus vehicle (for a truck it is 1.6). This means that a bus-type vehicle behaves in road traffic like a 2.2 of a passenger vehicle. In this way, a uniform description of the traffic structure is obtained, expressed in conventional vehicles, depending on the actual generic structure of traffic streams and flows.

The procedures for converting individual types of vehicles have been established and known since the mid-twentieth century [6]. These coefficients were verified in practice at the TRRI test grounds in England in the 1950s and 1960s [7]. Appropriate national instructions are published in this regard [8].

It should be noted that in selected countries, due to the specificity of various (untypical for other locations) types of vehicles used in road traffic, certain modifications may be applied in this respect. In the USA, these will be strongly represented in traffic SUVs, and in Asia popular three--wheelers. Such specificity of the traffic structure must be taken into account in the calculation of the capacity of the road network.

A conventional vehicle is related to the dimensions of a passenger car, but the length of this type of vehicle has been systematically increasing in the last few decades [9]. The dimension of this type of vehicle up to ca. 4.5 meters in length was assumed in the calculations (dimensioning of traffic and road systems). The vehicle standing in the queue must have free space in the back and front of the vehicle. In many traffic models, a minimum distance of 0.5 meters is assumed as a safe distance (although, in various microsimulation models, significant deviations in this range are observed).

In road traffic, the distances between vehicles are defined by relevant regulations, e.g. Art. 19 of the Road Traffic Act [8]. Pursuant to the provisions of this article: *"when driving on a motorway and an expressway, the driver is obliged to keep a minimum distance between the vehicle he is driving and the vehicle ahead of him on the same lane. This distance, expressed in meters, is defined as not less than half of the number specifying the speed of the vehicle in which the driver is moving, expressed in kilometres per hour. This provision does not apply during an overtaking manoeuvre…"* (Article 19(3a) of the Road Traffic Act).

Therefore, road vehicles at rest, taking into account the homogeneous traffic structure, occupy on average not less than about 5 metres. When road vehicles are moving at a certain speed, they occupy 4.5 meters plus the distance resulting from the current speed and depending on the distance to the vehicle ahead.

It should be noted that the definitions of safe distances in road traffic gradually penetrate into Polish law, following the example of codes in force for many years in Western European countries, e.g. French one. However, control of this type of parameters, without advanced driver assistance systems, is, to put it mildly, conventional.

Taking into account the above-mentioned data, two capacities of the road network can be defined: physical and transportation one, the first of which being larger [11]. Physical capacity is the length of the road network divided by the assumed length of a passenger vehicle with a safety buffer – and it corresponds to the positioning of vehicles one after another along the entire length of the network, in a fixed place, without the possibility of any manoeuvre. The transportation capacity is the length of this network divided by the assumed length of the vehicle and the distance between the vehicles resulting from the speed of the vehicle and the distance from the vehicle ahead. This capacity depends on many random variables, but is a static value over longer time horizons. Due to the heterogeneous speeds of traffic streams in different areas of the road network, it is difficult to estimate this type of parameter for a given city. Certain estimates of the transportation capacity for the road networks can be indicated using traffic models prepared in microsimulation software [12, 13]. For this purpose, in the selected traffic microsimulation program, after entering data on the infrastructure, places of traffic aggregation and absorption and after describing the method of its organization, a simulation is performed by measuring the number of vehicles in the road network on an ongoing basis. The procedure is performed until the network is saturated with traffic (increasing the amount of vehicles in the model), which results in the spreading traffic congestion, blocking almost the entire network or its large areas [14]. Colloquially speaking, the road network "clogs up", and more precisely, the vast majority of vehicles are stopped in traffic jams, and the introduction of new vehicles to the network from appropriately located traffic generators is strongly limited. All popular microsimulation programs provide the total number of vehicles present in the entire modelled road network at a given moment as a model operating parameter [14]. Based on this it is possible to roughly estimate the instantaneous value of the transport capacity for the road network of a given city. Unfortunately, this is a stochastic value, highly variable during the simulation. It is more reasonable to classify these capacities at certain levels by analogy with Freedom of Movement Levels (FML). The issue of the functioning of road networks in conditions of traffic congestion is well described in the works [15, 16, 17].

Fig. 1. An exemplary model of the road network with the estimated transport capacity, on the example of Katowice.

Source: own study.

Fig. 1 shows a model of the road network for a fragment of the city of Katowice (downtown and important communication routes). The model was made in the VISSIM program. In the area of the road network defined in this way, it was possible to introduce to the road network, (depending on the model settings and temporary traffic conditions), from 35,000 to 55,000. vehicles simultaneously. Attempts to introduce more vehicles caused traffic congestion to spread over large areas of the city, creating congestion blocking subsequent road intersections (one queue covering many entrances at subsequent intersections). By the way – there are currently over 300,000 vehicles registered in Katowice with a maximum capacity of approx. 55 thousand vehicles. In addition, tens of thousands of vehicles transit daily (these fill the main arteries: DTŚ, A4, DK 86, DK 81). The network is therefore overloaded with traffic.

The transportation capacity is modified not only by the speeds of individual traffic streams (average), but also, and perhaps above all, by the mutual interaction of vehicles. This is clearly visible in a situation where congestion is observed on one section of the street, and a few hundred meters "earlier" the street is completely empty. These impacts can be particularly strong with a large share of heavy vehicles in traffic, a large number of intersections and pedestrian crossings [14].

Due to the difficulty in determining the transportation capacity and its variability over time, the further description of the problem will only include the physical capacity. Especially since the transportation capacity is not particularly useful when comparing different road networks. This topic will be addressed in other publications using a traffic model dedicated to a given city.

It is worth noting that capacities can be defined for smaller, selected or defined fragments of the road network. Such a procedure can be used for spatial areas (e.g. transport areas) created as a result of deliberate delimitation of the entire network area, or for individual sections of roads and streets [14]. This is an approach known from area traffic control systems, where the logic of reconfiguration of the control area is used, the so-called marriage&divorce (e.g. ATMS Los Angeles).

It should also be noted that such capacities are characteristic of networks with the so-called unregulated (traffic). In the case of regulated, fully autonomous, rail and air traffic, the capacities are closely related to the way of organizing traffic in relation to fragments of the infrastructure of the route/network/controlled area.

Selected statistics

In the further discussion on the physical capacity of the road network, public statistics of the road network in Poland will be quoted [18]. When citing such data, attention should be paid to the entity managing a given road and its type: public and internal (these statistics are given for different periods and categories of road). The largest management body in Poland, GDDKiA (General Directorate for National Roads and Motorways), manages a network of roads with a total length of approx. 18,000 km. Out of this number, GDDKiA manages 3,804 km of expressways. Including 1247 km of motorways and 2557 km of expressways [18]. These numbers are important in the context of determining the global physical capacity in the Polish road network, which will be referred to in the summary. Vehicles leaving the home road network (where registered) are omitted from the data cited in this article. Besides, it should be noted that to some extent these migrations compensate each other, especially for administrative units located close to each other, as is the case, for example, in the Upper Silesian-Zagłębie conurbation [14]. There are 4-5 such areas in Poland, depending on the search criteria (Silesian conurbation, Warsaw agglomeration, Tri-City, Toruń-Bydgoszcz, Rybnik district).

In this context, more interesting figures concern the length of road networks administered in individual sub-regional/regional cities. This data can be obtained from various sources, including websites of road authorities, city services, statistical databases, etc. [19-25]. Sometimes, the authority managing a given network provides this information only approximately. Often a network has several governing bodies. In this type of analysis, it is good to use official lists of public roads and internal data of local government units – these are provided very precisely. These lists all roads, often with their exact length.

Table 1. Selected cities, length of the road network, number of inhabitants and registered vehicles

City	Total length of roads [km]*	Number of inhabitants approx. [thousand]**	Number of registered vehicles approx. [thousand][24]
Katowice	1120	283	328
Warszawa	2837	1862	2139
Kraków	686	803	550
Gdańsk	284	486	323
Poznań	700	541	517
Rzeszów	552	197	123
Bielsko-Biała	306	168	123
Opole	566	127	140
Wrocław	1066	674	492
Kielce	682	185	118
Toruń	303	196	155
Grudziądz	392	89	46
Olkusz	429	35	74

**- in different years, values are rounded*
***- due to ongoing migrations, values are rounded*

Source: [19-25].

The physical capacity, calculated on the basis of the assumed length of the vehicle and the safety distance, is as follows (Table 2).

Table 2. Physical capacity of cities from Tab. 1

City	Capacity	Number of registered vehicles approx. [thousand][24]	Proportion
Katowice	224000	328	1,464286
Warszawa	567400	2139	3,769827
Kraków	137200	550	4,008746
Gdańsk	56800	323	5,68662
Poznań	140000	517	3,692857
Rzeszów	110400	123	1,11413
Bielsko-Biała	61200	123	2,009804
Opole	113200	140	1,236749
Wrocław	213200	492	2,307692
Kielce	136400	118	0,865103
Toruń	60600	155	2,557756
Grudziądz	78400	46	0,586735
Olkusz	85800	74	0,862471

Source: own study

The data presented in Table 2 clearly shows that there are too many cars in relation to the available length of the road network (except for Grudziądz). It should be noted that these figures refer to the use of each running meter of the road network when cars are in a congestion/queue. Some of the vehicles are on other roads at any time (outside the place of registration), and therefore they do not use the transportation capacity calculated in this way on a regular basis. Nevertheless, these "vehicle migrations" are compensated between neighboring territorial units, the closer they are to each other, a good example of which is the Upper Silesian-Zagłębie conurbation, the Warsaw agglomeration, the Tri-City (in fact, these areas have different specificity of communication systems). However, it is known that there are relatively strong asymmetries between neighboring cities (Tax Office data on local taxes: Katowice--Sosnowiec). In addition, these asymmetries are distributed not only to the road network, but also to the railway network (discussion of this issue exceeds the scope of this article).

Is it possible to critically assess the usefulness of this data? The basic question in this context is what proportion of vehicles are used simultaneously? Is it questionable to use only registration data (CEP, Central Register of Vehicles)? Indeed, not every vehicle is in motion all the time, and often it is not at all in "its" administrative area at a given moment. In this respect, one can try to use traffic model data, especially data on the mobility of residents. In the Upper Silesian-Zagłębie conurbation, it is from 1 to 16 movements per day, depending on the motivation (data obtained in the 2009 project to modernize the rail traction in the agglomeration). However, it is the random increases in the access to the road network that cause its dysfunctions. These reports are random in time and space. Therefore, taking into account the theoretical number of vehicles registered in given administrative units is reasonable as an upper limit for the capacity of the road network. At the most, this data can be made more realistic with data on mobility from traffic models, if available. This is a broader horizon of perceiving the road network and analyses of its stability, which the reader can follow in the publications of B.Kerner [13-15].

Contrary to the popular opinion based on media reports, Poland has not been able to restore the potential of rail passenger transport in agglomeration traffic, which in the 1970s amounted to over a dozen percent of total transport, which also has a negative impact on the use of the transportation capacity of the road network .

It is interesting that the physical capacity of the network is strongly correlated with the number of cars registered in its area (0.906), nevertheless not as strong as the number of inhabitants of a given local government unit (0.997), which seems obvious, but it is not. More and more often, one driving license holder registers several vehicles for himself, and yet he or someone related to him usually does not use them simultaneously.

The study should also take into account the number of people with a driving license (which is difficult to estimate after February 2022). In addition, the indicated random data shows that in larger cities the situation is much worse, even assuming that the trucks and delivery vehicles registered there, to a large extent and for longer periods, operate outside the area of the home road network. Perhaps the development of road networks should be planned taking into account traffic model data, which are currently difficult to obtain for each city, because they are expensive. Moreover, it should take into account more closely socio-demographic data as well as transport behaviour. Such a methodology, however, is a distant prospect, as it means fully dynamic design and management of the road network, which is possible not earlier than after the introduction of C-ITS (Cooperative Intelligent Transport System).

Fundamental changes in the road network

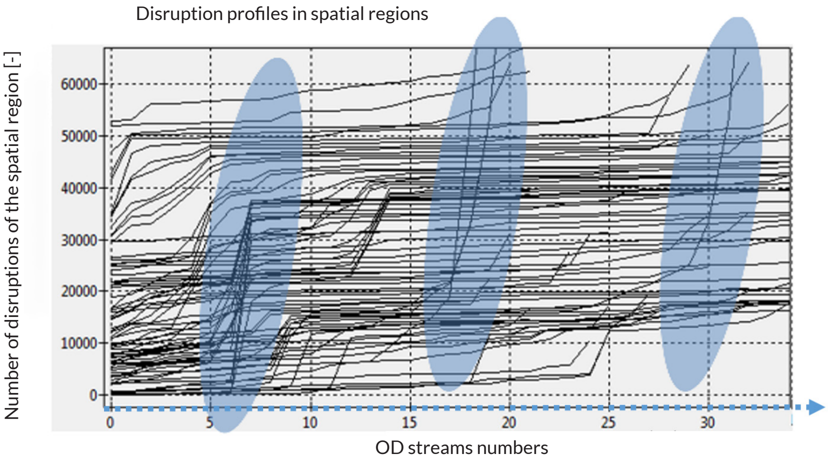
In public discussions on problems in the road network, the issues of the advisability of introducing new traffic organization, traffic lights, roundabouts, changes in traffic management and then ITS (Intelligent Transport System) are usually clarified. For this purpose, undertakings are justified by the effects measured in the form of e.g. reduction of: travel time, length of queues, number of road events and accidents, etc. Traffic lights are designed to separate traffic flows in time, roundabouts are responsible for separating collision points of traffic flows in space. Nevertheless, these solutions function locally, influencing better management, but only of fragments of the road network ("local", regional capacities, calculated for small areas of the road network, including these intersections), and this effect is achieved somewhat apart from other aspects of their use, such as e.g. improvement of traffic safety, traffic synchronization. The effects of traffic lights, which de facto increase the local use of the capacity of the road network by rationing access to its fragments in time, fade away as the distance from the intersection increases, due to the dispersion of traffic flows. This dispersion, in consequence, causes local capacity limitations of the network after the vehicles left the intersection.

Therefore, the capacity parameters of the road network can be modified by the number and type of organizational solutions related to the use of intersections with traffic lights and roundabouts, as well as reasonable changes in the organization and management of the road network. However, these are all actions carried out in small steps, generally changing traffic conditions more or less, but locally and to a limited extent. They do not significantly affect the traffic parameters and capacity of the road network. Only the introduction of ITS systems results in synergy of various types of technical and organizational solutions. Nevertheless, also in this case the "quality profit" is limited and ranges from a few to over a dozen percent, depending on the parameter/measure adopted for the analysis [27, 28]. The potential of ITS systems in this respect often raises consternation in the public perception, due to the weighing of profit with expenses and often unnoticed fixed costs of operating the ITS system, which may also reach several percent of the base value of the investment per year. The conclusion is that both, small changes and large ones, such as the implementation of ITS systems, sooner or later become ineffective against the road network capacity barrier, which requires its significant expansion in terms of infrastructure. Capacity is therefore more important in analyses than cross-sectional (point) parameters such as throughput or traffic density. So maybe it's worth taking a closer look at the configuration of the road network and its capacity, moving away from old organizational patterns based, for example, on throughput? The more so that C-ITS systems appear on the horizon, whose V2X (vehicle to everything) transportation functionalities will be conducive to this type of analysis: total analyses conducted in relation to the entire space-time of the road network.

Segmentation of the road network in terms of its capacity

The research carried out as part of the work [12] indicates that the interactions between vehicles affecting the possibility of using the communication capacity are not homogeneous in the space of the road network. This is presented in Fig. 2.

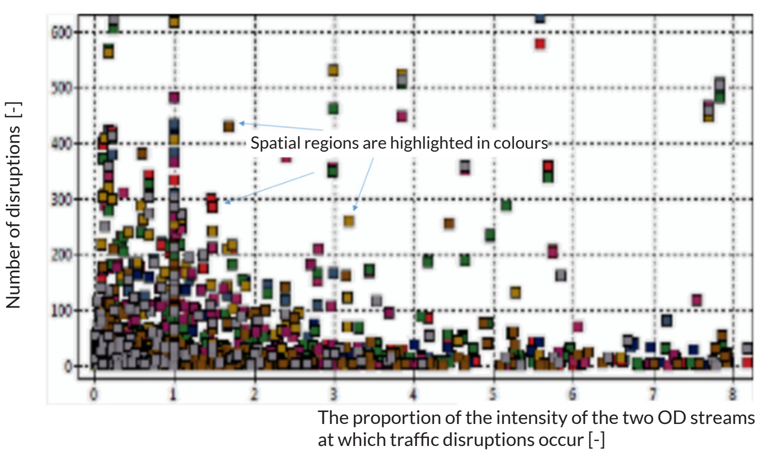
Fig. 2. Interaction profiles in various spatial regions of the Katowice road network (OD, origin – destination).



Source: own study.

Fig. 2 shows the number of interactions that occur between vehicles in the spatial regions into which the area of the road network presented in Fig. 1 was divided, counting them in relation to OD (origin-destination) flows. In each of these homogeneous (in terms of area) regions, there is a different number of interactions. This stems, for example, from the density of the road network in a given area and traffic parameters, the distribution of absorbers and traffic generators. In the context of the article, this illustrates the fact that large changes in the use of the transport capacity of the road network can be achieved by reconfiguring road connections between individual spatial regions (changes in traffic organization). Thus, segmentation can be introduced in the road network in order to better use the capacity in particular spatial regions of the network. There is a similarity to the well-known motion control logic used in mariage&divorce (Los Angeles) area control systems.

Fig. 3. Interactions between different traffic flows in Katowice's road network.



Source: own study.

Figure 3 presents an example of measuring interactions between OD traffic flows in the Katowice road network [12]. Data aggregated to streams in the OD matrix describing traffic in a given area was used. These flows can essentially be organized in a different way in principle, minimizing the number of interactions between vehicles of each traffic flow. In principle, this should lead to a better use of the transportation capacity of the road network. Therefore, the capacity can be used better by reorganizing the OD flows, which requires fundamental changes in the organization of traffic in a given road network (these changes are in fact imposed historically, conditioned by the path of development of the socio-economic system of the city). Some cities in Poland still function based on the distribution of traffic generators and absorbers historically set in the 20th century (e.g. Katowice). This requires a change of paradigms in the organization of a given road network, which implies carrying out costly linear investments, and consequently also point investments (and those in Katowice are gradually being implemented).

Thus, the transportation capacity is affected by: the existing linear and point infrastructure, traffic organization, signalling control systems, delimitation of the road network into spatial regions and reconfiguration of connections between them, reorganization of OD streams in the area of the entire road network. A departure from the way of perceiving reality in a given road network, adopted for years, may be of key importance, which implies large investment outlays, but not necessarily for line investments.

Conclusions and summary

From the point of view of a road network analyst, these types of problems should also include an introduction to the issues of road network planning, explaining the goals and assumptions that accompany it. First of all, it should be clarified that the current methods of conduct are, on the one hand, the result of certain resource constraints, and on the other hand, they are outdated in the face of the upcoming changes in the field of Big Data analyses using C-ITS, and in particular the methods in the field of artificial intelligence being introduced. However, the description of this issue in such a broad context exceeds the scope of this article.

Therefore, the main conclusion is that the observed dysfunctionality of road networks is mainly related to limited physical capacity of the network in relation to the number of road vehicles travelling in this network (and registered there). Another reason is the archaic approach, historically conditioned, to the organization of traffic in a given road network. The author, pointing to the basic cause of the existing state of affairs: the limited capacity of the road network, is at the same time of the opinion that its intensive increase is not the right (economically reasonable) course of action. It is proposed to include in the analyses – in addition to throughput – also data on the capacity of the road network.

It should also be noted that Poland is not a country with a high population density, (apart from metropolitan areas), such as the Netherlands, northern Italy, central England or some federal states of Germany. Similarly, in terms of total road network density, Poland occupies an average position in the EU. All the more so, the problem of the road network capacity is of great importance for the territory of Poland. This is because in these dense road networks (such as the Dutch one), the local capacity of the road network, which is exhausted, can be compensated to some extent by the neighbouring parts of the road network. In Poland, this is limited by bottlenecks between parts of the network with higher density. This is despite the developed backbone of national roads and motorways in Poland.

It is difficult to analyse the issue of network capacity without analysing the intensity of its use. However, this is a difficult topic in this context, i.e. the capacity of the road network. In this regard, it is worth quoting, for example, the data of GDDKiA and NIK on the condition of roads in Poland [35]. According to reports, about 20% of roads, especially local ones, require general renovation. Moreover, the mobility within the professional groups in Poland is different according to movement models. The organization of traffic in a stream system in most cities is historically imposed. All these are problems that require recognition in the context of analyses of the capacity of the road network and its intensity of use. However, this issue is very broad.

Another problem is the ineffective use of parts of the new infrastructure. Research confirms that expenditure on its expansion sometimes does not bring benefits if the efficiency of using the existing infrastructure is low. Nevertheless, in the author's opinion, this is a problem related to the so-called "sleeper effect" (borrowed from psychological terms). This means that the study of the effectiveness of use should take into account the dormant effect, i.e. the delay effect associated with changes in users' perception in the road environment.

The data presented above in this article simplified the problem by replacing the actual number of vehicles filling the road network with the number of vehicles registered in a given territorial unit. Unfortunately, this is a significant simplification of the problem, which can be eliminated in the analyses of areas for which traffic models have been prepared.

The use of the most advanced solutions in the field of road traffic control and organization allows to achieve effects ranging from several to 20 percent, e.g. in the form of shortening driving time on selected routes, reducing the length of queues, etc. This is due to the fact that there are simply too many registered vehicles, in relation to the physical parameters of the road network and the possibility of its reorganization (which in many cases can be called "covering the problem", not an organizational innovation). The network should therefore be developed in terms of road infrastructure in a way that not only increases capacity, but also adapts traffic organization to the specific nature of the network. This is where microsimulation models and research related to traffic modelling can be helpful.

In the context of analysing the capacity of the road network, an interesting topic is the trend of developing autonomous vehicles, observed for over a decade. Due to the specificity of their control, these cars are predestined for optimal use of the road network area and, at the same time, its capacity. They enable precise control of the distance between vehicles at different driving speeds, which is impossible to achieve to the same extent for humans. This translates directly into better use of the road network's transport capacity. However, this depends largely on interactions with driver-driven vehicles. Most likely, due to existing problems with the systems (modules, perception, prediction and driving tactics) of autonomous vehicles, the next 20-30 years will be a period in which autonomous vehicles will develop mainly on isolated sections of public roads [28-30]. The author doubts quickly achieving a mixed traffic structure (autonomous and non-autonomous) on universal lanes for both types of road traffic. A similar opinion, broadly justified on several pages, regarding the implementation of autonomous vehicles was expressed in the book [36].

In fact, the usable capacity of the road network is strongly modified by the traffic structure and it is the interactions between different types of vehicles that influence the capacity of the road network. This impact requires further intensive research in the construction of micro-simulation models of road traffic for various cities. The key to this approach may be intermediate levels of vehicle automation (so-called levels 3 and 4).

As mentioned in the introduction, some vehicles leave their home road networks (places of vehicle registration) and move on public roads. This percentage of vehicles, or rather its estimation, requires to be taken into account in further research in this field. It should be noted that these vehicles travelling on national roads are able to use the capacity of the road network better than in the case of dense urban road networks. Especially in the case of the introduction of any forms of traffic automation on national roads, which in turn is realistic in the near future, in contrast to the free introduction of autonomous vehicles into areas of dense road networks.

Sustainable development and a reasonable modal division represent also an important research area in this field. It is possible to optimize the use of the transport capacity of road networks by means of a justified modal division of movements in the cities. Each bus trip represents from several dozen to several hundred meters of free road length in each network. In a study in Wrocław, the result was an average of 22 people per trip, which translates into 110 meters of free road or street [31,32]. Daily, these are values reaching, e.g. for GZM (*Górnośląsko-Zagłębiowska Metropolia)*, 223,600 meters, which corresponds to approx. 25% of the network capacity (without taking into account the dynamics of the phenomenon) [33]. For rail transport, this is over one kilometre of free space in the road network, including the train (only seated places, for the NEWAG 37WE traction unit) [34]. For example, 10 pairs of this type of EMUs on a line parallel to a road can free up approx. 26 km of the length of this road (when the vehicle is filled to 1.0). What is important, this may generally take place (capacity release) during periods of traffic peaks (some passengers may only travel by rail). The development of P&R systems located at railway stations in recent years, however, indicates that the proportions of modal division conducive to smoothing traffic in the road network can be further deepened.

To sum up, if a strong upward trend continues to be observed in the number of passenger vehicles being registered, congestion will continue to be a commonly observed phenomenon in the road network over the next two to three decades. Significant changes will be introduced only after C-ITS systems become popular, which will enable total control of the road network. On the other hand, these systems also pose many threats, especially in terms of cybersecurity. At the moment, however, it is difficult to estimate the impact of this threat on the capacity utilization of the road network. Dedicated cyber-attacks (not malicious ones, these are widely analysed in the literature) can paralyze entire networks.

Bibliography:

1. Śląski Festiwal Nauki, https://us.edu.pl/nauka-i-badania/popularyzacja--nauki/slaski-festiwal-nauki; odsłona: 23-06-2023
2. Konferencja Naukowo-Techniczna Systemy Transportowe, Teoria i praktyka, https://tstp.syskonf.pl; odsłona: 24-06-2023
3. ITS Wrocław, http://its.wroc.pl; odsłona: 23-06-2023
4. ITS, Trójmiasto, TRISTAR, https://www.gdansk.pl/inwestycje-miejskie/Tristar-inteligentny-system-sterowania-ruchem; odsłona: 23-06-2023
5. ITS Tychy, https://its.tychy.pl; odsłona: 22-06-2023
6. Transport Research Laboratory (Fundation), https://www.trl.co.uk/about-us/who-we-are/ odsłona: 23-06-2023
7. https://smallblogv8.blogspot.com/2020/06/the-transport-research--laboratorys-test.html, odsłona: 28.08.2023 r.
8. GDDKIA, Metoda obliczenia przepustowości skrzyżowań bez sygnalizacji świetlnej-instrukcja obliczania, Warszawa 2004.
9. Wybór kierowców, https://www.wyborkierowcow.pl/o-ile-urosly--samochody-zestawienie; odsłona: 22-06-2023
10. Ustawa z dnia 20 czerwca 1997 r., Prawo o ruchu drogowym Dz. U. 1997 Nr 98 poz. 602, https://isap.sejm.gov.pl/isap.nsf/download.xsp / WDU19970980602/U/D19970602Lj.pdf; odsłona: 22-06-2023
11. Celiński, I., Sierpiński, G.: Wybrane aspekty problematyki zakłóceń ruchu pojazdów w sieci drogowej, Przegląd Komunikacyjny 12/2012.
12. VISSIM, https://www.ptvgroup.com/pl/rozwiazania/produkty/ptv--vissim; odsłona: 23-06-2023
13. SUMO, https://sumo.dlr.de/docs/index.html; odsłona: 23-06-2023
14. Celiński, I.: Metoda oceny oddziaływania między ruchem drogowym wewnątrz i poza strefą sterowania obszarowego, OWPW, 2019 r.
15. Kerner, B. S.: Three-phase theory of city traffic: Moving synchronized flow patterns in under-saturated city traffic at signals, Physica A: Statistical Mechanics and its Applications 397, p. 76-110, 2014.
16. Kerner, B. S.: The maximization of the network throughput ensuring free flow conditions in traffic and transportation networks: Breakdown minimization (BM) principle versus Wardrop's equilibria, Eur. Phys. B J., 89, 199, 2016.
17. Kerner, B. S.,: Understanding Real Traffic: Paradigm Shift in Transportation Science, Springer, Berlin, Heidelberg, New York, 2021.
18. GDDKiA, https://www.gov.pl/web/gddkia/aktualna-statystyka-drogowa, odsłona: 23-06-2023
19. Mapa akustyczna, https://emapa.katowice.eu/mszkiip/geoportal--obslugi-obywatela/mapa-akustyczna ?start=3, odsłona: 23-06-2023
20. SISKOM, siskom.waw.pl; odsłona: 23-06-2023
21. BIP Kraków, bip.krakow.pl; odsłona: 24-06-2023
22. https://gzdiz.gda.pl/zalatw-sprawe/utrzymanie-drog,a,3131; odsłona: 23-06-2023
23. badam.pozan.pl; odsłona: 23-06-2023
24. https://mzd.erzeszow.pl; odsłona: 23-06-2023
25. https://beskidzka24.pl/w-bielsku-bialej-ruszylo-zimowe-utrzymanie--miasta-do-odsniezenia-jest-620-km-drog; odsłona: 23-06-2023
26. Polska w liczbach, https://www.polskawliczbach.pl/miasta_z_najwieksza_liczba_ samochodow_osobowych; odsłona: 23-06-2023
27. https://bydgoszcz.naszemiasto.pl/its-w-bydgoszczy-dziala-juz-od--roku-drogowcy-zadowoleni-a/ar/c4-3952046; odsłona: 23-06-2023
28. https://www.transport-publiczny.pl/wiadomosci/its-we-wroclawiu-przyspiesza-411.html; odsłona: 23-06-2023
29. Karoń, G., Janecki, R., Sobota, A., Celiński, I., Krawiec, S., Macioszek, E.: Program inwestycyjny rozwoju trakcji szynowej na lata 2008÷ 2011, Analiza ruchu. Praca naukowo-badawcza NB-67/RT5
30. Petrović, D., Mijailovic, R., Pešić, D.: Traffic Accidents with Autonomous Vehicles: Type of Collisions, Manoeuvres and Errors of Conventional Vehicles' Drivers. Transportation Research Procedia. 45. P. 161-168, 2020.
31. Filiz, C.: Can Autonomous Vehicles Prevent Traffic Accidents?. Intechopen, 93020, 2020.
32. Xue, C.: Liability Analysis of Autonomous Vehicles Accidents, Advances in Economics, Business and Management Research, v. 185, 2021.
33. Wskaźniki napełnienia pojazdów w wybranych liniach tramwajowych i autobusowych bip.um.wroclaw.pl; odsłona: 23-06-2023
34. Sierpiński G., Kowalska K., Sobczak P: Integracja łańcuchów przemieszczeń sposobem na kształtowanie postaw komunikacyjnych, TTS, 10/2013.
35. https://www.metropoliaztm.pl/pl/s/linie-metropolitalne; odsłona: 22-06-2023
36. https://www.newag.pl/oferta/impuls; odsłona: 22-06-2023
37. https://www.nik.gov.pl/aktualnosci/nik-o-niszczeniu-drog--lokalnych-przy-budowie-autostrad-i-drog-ekspresowych.html; odsłona: 22-06-2023
38. Bostrom, N.: Superintelligence, Paths, Dangers, Strategies, Oxford University Press: 2016

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