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Development of the transport network considering the specifics of Lviv's planning structure (compared to Leipzig and Krakow)

Abstract. The relevance of this study is determined by the need to adapt the transport network of Lviv to the requirements of modern urban traffic. The planning structure of Lviv was formed based on radial roads, later developing ring connections, which is typical for most European cities, but eventually acquired its own characteristics. The purpose of this study was to analyse the specific features of the current planning structure of Lviv, which affect the development of urban transport infrastructure and mobility of each mode of transport. The methodology of this study involves analysing the modern street and road network as the formative basis of the planning structure of the city of Lviv and assessing transport mobility based on geospatial data from open sources. Comparison with similar European cities, such as Leipzig and Krakow, helps to highlight the specific features and rational ways of developing Lviv's transport network. The results of the study point to the main feature of Lviv's planning structure, which is its compactness and high population density – twice as high as in comparable cities. This makes it impossible to adapt the transport infrastructure for car travel and highlights the need to improve public transport networks and cycling infrastructure as more efficient and environmentally friendly ways of urban transport. However, the study of urban transport mobility found that the means of limiting the use of private cars in Lviv are inferior to those implemented in comparable cities, and the public transport network and bicycle infrastructure are underdeveloped and do not provide a quality alternative to car travel as of 2023. The practical value of the study lies in highlighting the most problematic aspects of Lviv's transport infrastructure that require urgent decisions to function in the context of the specific planning structure of the city

Keywords: urban mobility; sustainable urban transport; development of urban transport; transport system of European cities; historically formed cities

INTRODUCTION

The planning structure of Lviv was historically formed based on radial roads that were not designed for the intensity of modern traffic (Petryshyn & Liubytskyi, 2018). The same path was followed by most European cities, which were formed from the early Middle Ages based on a radial-ring planning structure. With the growth of cities and the emergence of new ways of moving around them, the planning structure, which is based on the street and road network, has undergone appropriate transformations to meet the requirements of modern traffic.

The specific feature of Lviv, compared to Western European cities, is that the development of modern transport infrastructure in post-Soviet cities began only in 1990, along with the rapid growth of motorisation as a result of the transition to a market economy (Cavoli, 2021). At the same time, processes of rapid urban densification began

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and are still ongoing due to the rapid construction that became possible in market conditions (Habrel *et al.*, 2020). For example, in the Ukrainian SSR in 1981, the level of motorisation was 31 cars per 1,000 residents (for comparison, in Germany it was about 300 cars per 1,000 residents). The small number of cars in the Soviet period led to stagnation in the development of transport infrastructure, the state of which still affects traffic today. On the other hand, it minimised radical interventions in the historical planning structure of Lviv. For comparison, as early as the 1950s, the scientific literature of developed countries considered the idea of introducing fees for private cars entering the central zones of cities (Lehe, 2019).

To limit the presence of vehicles in the city, especially in narrow historic streets with limited capacity, it is advisable to apply a strategy of intercepting cars at the entrances to the city, including the median zone and the city centre itself. These measures are aimed at excluding transit vehicles through the urban space, as well as at intercepting vehicles travelling from nearby settlements to the agglomeration centre and for movement within the city itself. Measures to restrict the use of private cars are aimed at improving the functioning of other means of transport in the city. It has been proven that in more developed countries with higher incomes, citizens prefer sustainable modes of transport to car travel, and that cars have a negative impact on stress levels (Avila-Palencia *et al.,* 2018).

In cities that have inherited historically dense development, it is important to give preference to public transport as the main means of urban mobility, given its ability to carry many passengers compared to cars, while taking up less space on the road. In historic European cities, trams and light rail are the main public transport modes, achieving high passenger and speed performance (De Las Heras-Rosas & Herrera, 2019). Providing priority to public transport on roads and designating dedicated lanes are strategically important measures to avoid traffic congestion. The comfort of public transport, which includes coverage of all urban areas by a network, precise timetables, maintenance of vehicles, etc., makes it more attractive for citizens to use it, which at the same time helps to reduce the frequency of private car use.

A well-developed network of bicycle paths and a well-developed public transport system have a positive impact on reducing the use of private cars in the urban environment. Historic cities with dense, compact development have significant potential for the development of cycling and walking infrastructure. Recent studies indicate that the old neighbourhoods of historic cities are much more attractive for these modes of travel than new urban areas (Telega *et al.,* 2021). By avoiding busy main streets, walking, or cycling is often faster and more comfortable than using public transport or a private car, and a typical cycle lane has 5 times the capacity (per person) and one parking space can be replaced by a parking space for 10 bicycles (Gehl, 2018).

The purpose of this study was to identify the specifics of the current planning structure of Lviv, which has an impact on the development of urban transport infrastructure and mobility of each mode of transport. A common modern trend in the development of a sustainable transport system in the planning structure of a historic city is the simultaneous implementation of two sets of measures – restrictions on private cars and the development of alternative urban transport – public, cycling, and walking. This article sets the following objectives:

- Analysis of the planning structure of the city, the formative basis of which is the historically formed street and road network;
- Assessment of urban transport mobility – private cars, public transport, cycling;
- Identification of rational approaches to the development of Lviv's transport network and individual modes of transport, considering the unique features of the planning structure, which is a scientific originality of this study.

MATERIALS AND METHODS

The study was conducted in two stages: firstly, an analysis of the city's planning structure was used, and then, based on this, urban mobility was assessed for each mode of transport. For the comparative study, the cities of Leipzig and Krakow were chosen, which are similar to Lviv in terms of their historically formed radial-ring planning structure, historical development, and population (Lviv – 758,500, Leipzig – 575,000, Krakow – 744,230). The comparison with similar cities helped to identify approaches to the development of the transport network that are appropriate for Lviv, as well as to identify those that are irrational due to the differences in the city's planning structure.

By analysing the planning structure of the city, the key elements of the planning structure of cities were identified, such as different categories of motorways (international, national, regional, etc.) that pass through the city and the intra-city street network. The presence and level of development of the system of ring streets and roads of various categories used for transit and intra-city movement to bypass the historic core was assessed. It was also planned to determine the length of the street and road network to assess the potential of urban mobility.

The assessment of urban transport mobility included an analysis of the mobility (efficiency of use) of private cars, urban public transport, and cycling. The analysis of private car mobility was carried out in the context of restrictions on movement within the city. The research phase included the identification of the main ring streets and roads, the location of transfer hubs ("Park&Ride" car parks), and the identification of areas where the presence of cars is restricted. The stage of public transport mobility analysis involved identifying the areas of the city covered by different types of public transport services and conducting calculations to determine the extent of coverage of the city (line lengths) by each of these types of transport. Furthermore, the study considered the convenience of use – compliance with timetables, the condition of the rolling stock fleet, etc. At the stage of analysing cycling mobility, the study identified the areas covered by the bicycle route network and calculated the extent of this coverage. Moreover, the quality of the cycling infrastructure was analysed, including the logic of cycling connections, routing (via motorways or quiet streets), characteristics of cycle tracks and their location (on carriageways or dedicated lanes), and the availability and number of cycle parking spaces.

The main source of source data used for the study was the OpenStreetMap geospatial platform (n.d.), data from which was obtained using the QGIS geographic information system through the “QuickOSM” plug-in. The study of geospatial data of urban transport network elements using a geographic information system allows for the analysis and further processing of a large array of data, which as a result objectively reflects the quantitative and qualitative indicators of the elements under study. Some of the thematic layers of OpenStreetMap geospatial data may contain minor inaccuracies and be incomplete, but for the scale of the entire city and the formulation of fundamental patterns, the use of this data is of great value.

The original geospatial data, which was extracted from the list of OpenStreetMap layers (n.d.) and used in the study:

• planning structure of cities – a layer of the street and road network (“key=highway”), which contains data on streets and roads of all hierarchical levels (“key=highway, value=primary”; (“key=highway, value=secondary”, etc.);

• private car mobility – a layer of the road network (“key=highway”) with further selection of ring roads; layers of car parks (“key=amenity, value=parking” etc.) with selection of interceptors (“Park and Ride”); a layer of boundaries (“key=boundary”), which may contain data on restricted parking zones;

• public transport mobility – a layer of routes (“key=route”), which contains data on public transport routes of all types (“key=route, value=tram”; (“key=route, value=bus” etc.); taxi stands (“key=amenity, value=taxi”);

• bicycle mobility – a layer of bicycle paths (“key=cycleway”; “key=highway, value=cycleway”); a layer of routes with dedicated bicycle routes (“key=route, value=bicycle”) of different hierarchical levels – international, national, regional, local (“network=icn/ncn/rcn/lcn”); location of bicycle rental points (“key=amenity, value=bicycle_rental”); bicycle parking (“key=amenity, value=bicycle_parking”).

Furthermore, to the OpenStreetMap geospatial platform, the study used additional sources for each city under study, which complement the OpenStreetMap data and contain specific information, including data on ring roads; location of interceptor car parks (“Park&Ride”); parking restriction zones, etc. In the end, the quantitative and qualitative results of the study were formulated based on the generalisation of data, the density of the city’s street and road network, the length of the public transport network, the presence of bypass rings, etc. Based on the data obtained, thematic diagrams were developed and the results were compared, followed by the formulation of conclusions: establishing the interdependence of mobility of different modes of urban transport on the existing planning structure of cities; comparing the characteristics of the planning structure and transport mobility of Lviv, Leipzig, and Krakow; substantiating the feasibility of future development of each mode of transport in the planning structure of Lviv.

RESULTS AND DISCUSSION

The planning structure of the cities of Leipzig, Krakow, and Lviv. The cities under study – Lviv, Leipzig, and Krakow – used a system of radial paths in their historical planning of their structure, which were directed to the central part of the city. After the dismantling of the medieval walls (in Lviv in 1777 (Krypiakevych, 1991); Leipzig in 1777 (Franz, 2004); Krakow in 1806 (Swiszczowski, 1955)) that ran around the historic core, circular “streets around the city” were formed, which at the present stage perform both transport and walking functions. Subsequently, the development of the planning structures of these cities continued based on radial paths, while creating connecting ring links between them.

Leipzig. Leipzig’s main motorway network covers various road categories, including motorways of European importance, autobahns, federal motorways, and state motorways. Other types of roads in Germany, such as district and local roads (kreisstraße, gemeindestraße), are designed to provide local communications. Transit motorways of European significance and motorways bypass the city of Leipzig, unlike federal and state roads, which run through the inner-city planning structure. This is conditioned by the fact that even within the historic centre of the city, these roads are wide. For example, the federal road “87”, which runs right up to the city centre on the north side, has 6 lanes for car traffic and 2 separate lanes exclusively for tram traffic (Fig. 1).

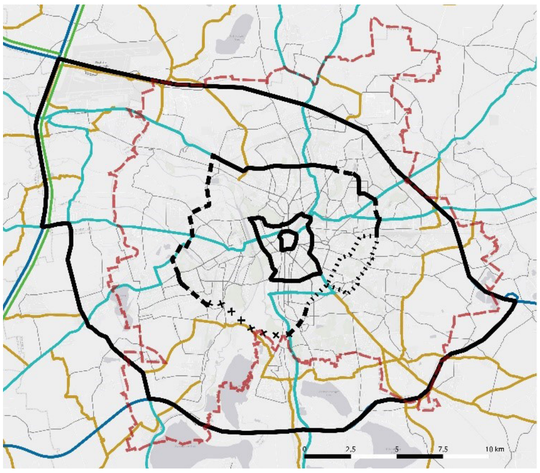

Figure 1. Street and road network as the basis of the planning framework of Leipzig

Notes: city limits are marked with a red dashed line; existing bypasses are shown with black lines, projected bypasses with a long-dashed line, suspended bypasses with a short-dashed line, and blocked bypasses with crosses; European motorways (“E”) are shown in green, Autobahns in dark blue, federal roads (“B”) in light blue, state roads (“L”) in yellow, streets and local roads in thin grey lines

Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

The wide width of the streets in Leipzig ensures a high capacity for traffic moving within the city. This situation can be explained by the consequences of the post-war reconstruction of Leipzig, which led to the expansion of historically established neighbourhoods and the construction of new streets through the city centre. Nevertheless, Leipzig is marked by a distinctive historical radial-ring planning structure, in which four bypass rings stand out. The first ring ("Innenstadtring") runs through the former medieval walls (Franz, 2004). The second ring is called the "Tangentenviereck" (Department of Urban Development and Construction, 2004) and runs between 0.50 and 1.5 km from the first ring, roughly bypassing the boundaries of the area built up until the end of the 19th century (Busch, 1891). As of 2023, the third bypass ring ("Mittlerer Ring") is not completed and bypasses the core of the historic city at 3 to 6 km, roughly on the border of the interwar period (City of Leipzig, n.d.-b). Due to insufficiently substantiated transport feasibility and crossing of city parks, the development of incomplete southern and eastern segments of the third ring caused protests among residents, which in turn stopped the design process. Implementation of measures to build the northern and western sections of the third transport ring is envisaged in the medium and long term (Department of Urban Development and Construction, 2011). The fourth transport ring does not have clearly defined official boundaries, but its contours are clearly recognisable in the planning structure. This network coincides with the motorways and federal roads that bypass the city, functioning for transit traffic at 7-15 km from the centre of Leipzig (Fig. 1).

Based on the analysis of geospatial data from OpenStreetMap (n.d.), the total length of the street and road network was calculated to be 2,314.47 km. It is estimated that there are 4.02 m of street length per resident (population 575,000). With an area of 297.36 km^2, Leipzig has a street and road network density of 7.78 km/km^2.

Krakow. In the transport system of Krakow, road categories are represented by motorways of European importance, motorways, and expressways, national roads and voivodeship roads. These categories, except for voivodeship roads, provide interconnection between the largest cities in Poland or are intended for international transit. Voivodeship roads serve to connect the main cities of the voivodeships. The remaining categories of roads in Poland – county and municipal roads (droga powiatowa, droga gminna) – are used to provide local communication (Announcement of the Sejm of the Republic of Poland..., 2017). The network of major roads in Krakow, except for the voivodeship roads, goes around the city along the administrative boundary. The voivodeship roads that run radially from the second bypass ring are key routes to national and international transit roads (Fig. 2).

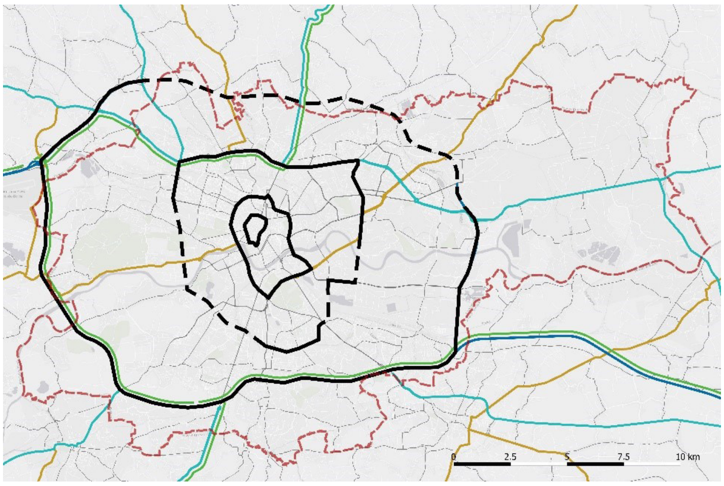

Figure 2. Street and road network as the basis of the planning framework of Krakow
Notes: The city limits are indicated by a red dashed line; existing bypasses are shown as black lines, and projected bypasses are shown as dashed lines; motorways of European importance ("E") are marked in green, motorways ("A") and expressways ("S") in dark blue, national roads (drogi krajowe) in light blue, voivodeship roads (drogi wojewodzkie) in yellow, streets and roads of local importance in thin grey lines
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

There are four bypass rings in Krakow, the development plan of which is prescribed in the City Development Strategy until 2030 (Resolution of the Krakow City Council No. XCIV/2449/18, 2018). The first bypass ring runs through the areas where the medieval city walls were located. The second ring, which bypasses the historic core outside its boundaries, is located at a distance of 0.5 to 2 km from the first ring, roughly along the contour of the territory built up until the end of the 19th century. The third ring is in implementation and covers the territory that was built up during the interwar period (except for the part adjacent to the east) (Zaremba, 1930). As of 2023, the western and eastern segments are still unfinished. Once completed, the third bypass ring will bypass the historic city centre at

3 to 5 kilometres. The fourth bypass ring in the southern and western parts of the city coincides with the A4 international motorway, and the northern segment of this ring is being implemented. Upon completion, the fourth ring will run close to the administrative city boundary of Krakow, at 6 to 10 kilometres from the historic centre (Fig. 2). The implementation of a network of bypass ring roads is of great strategic importance for Krakow, specifically because most of the streets in the historic part of the city have one-way traffic due to the small width of the streets, which causes considerable difficulties for transit travel.

Based on the analysis of geospatial data from OpenStreetMap (n.d.), the total length of the street and road network of Krakow was found to be 2,666.51 km. It is estimated that there are 3.58 m of street length per resident (population 744,230). With an area of 326.85 km^2, Krakow has a street and road network density of 8.16 km/km^2.

Lviv. The network of key roads in Lviv consists of roads of European importance, international roads of state importance, national roads of state importance and regional roads of state importance. Roads of European significance and international roads are used for transit traffic across the country's borders, national roads play the role of connecting administrative centres of oblasts, and regional roads provide connections between cities of oblast and rayon levels (Law of Ukraine No. 2862-IV, 2001). The main motorways, including international and European ones, are integrated into the internal transport system of Lviv and pass through the central part of the city, which contributes to the congestion of the central part with transit vehicles (Fig. 3).

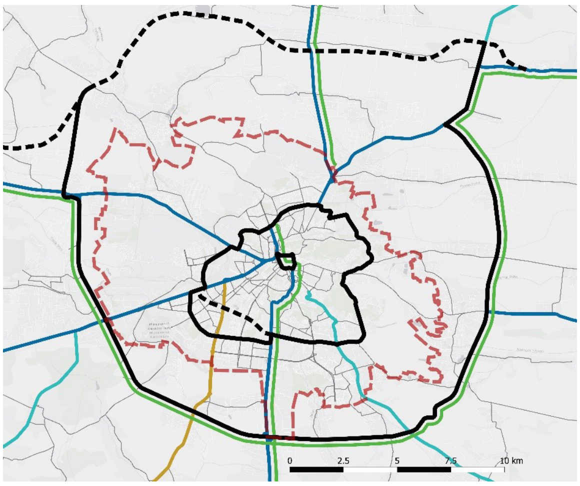

Figure 3. Street and road network as the basis of the planning framework of Lviv

Notes: the city limits are marked with a red dashed line; existing bypasses are shown with black lines, projected bypasses with a dashed line; European motorways ("E") are shown in green, international motorways ("M") in dark blue, national motorways ("N") in light blue, territorial motorways ("T") in yellow, streets and roads of local importance are shown with thin grey lines

Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Lviv's bypass roads include three traffic rings. The first ring runs along the territory where the medieval city defensive walls used to be located, which were completely dismantled in 1825. The second bypass ring was formed roughly along the contour of the city territory built up during the interwar period and as of 2023 is located at a distance of 1.5 to 4.5 kilometres from the first bypass ring. The current alignment of the ring is different from the plans for its development that were laid down in the Soviet period but never came to fruition. In the post-Soviet period, the city experienced and continues to experience rapid construction, the location of which is determined by commercial interests rather than urban development requirements (Habrel *et al.,* 2020). The number of traffic lanes on the second bypass ring varies, affecting the change in capacity on different segments. The third ring is a city bypass road laid at 8 to 10 km from the outline of the historic centre of Lviv. The lack of the northern ring segment causes transit traffic to pass through the historic part of the city, and the large distance of the second bypass ring from the central core of Lviv excludes the possibility of intra-city traffic bypassing the historic part of the city. Furthermore, the historic core of the city still performs its original functions today, with 4 administrative offices, 45 service establishments, and 8 cultural institutions located on Rynok Square itself, adding to the traffic load on the historic centre (Cherkes & Linda, 2019). The planning structure of Lviv does not have a bypass ring that would bypass the central part of the city, which is typical for other similar historic cities (the second Leipzig and Krakow bypass ring) (Fig. 3).

Based on the analysis of OpenStreetMap geospatial data, the total length of Lviv's street and road network was found to be 1,360.85 km. It is estimated that there is 1.79 m of street length per resident (population 758,500). With a city area of 150.09 km^2, the density of the street and road network is 9.07 km/km^2.

Mobility of private cars in Leipzig, Krakow, and Lviv. *Leipzig.* Roads that provide international and domestic transit are represented by motorways that bypass the city. Federal (Bundesstraße) and state (Landesstraße) roads are woven into the city's structure and even adjoin its historic centre. This is explained by the extensive network of German high-speed motorways, which began to develop in 1920 (Schiller *et al.,* 2010). Most transit traffic passes through motorways, while other roads have a lower priority and play a secondary role in providing intra-agglomeration and intra-city connections. The main transit flow through the city is intercepted by two bypass rings: the "Tangentenviereck" (second) and the "Mittlerer Ring" (third), the latter of which has unfinished sections that are being completed in stages to reduce the importance of the federal motorways within the second bypass ring (Department of Urban Development and Construction, 2011).

To intercept private cars that are regularly used by residents to commute to the city centre, Leipzig has a well-developed network of interceptor "Park&Ride" facilities, which includes 14 sites with a total capacity of 3,208 parking spaces (City of Leipzig, n.d.-b). The "Park&Ride" network is built on the existing infrastructure of the "S-Bahn" urban high-speed railway and is often also adjacent to tram services. Parking in these interceptor car parks is free of charge and the operating hours are around the clock.

Since 2011, Leipzig has had an "Ecological Zone" ("Umweltzone"), which covers 62% of the city (City of Leipzig, n.d.-a). Private cars are only allowed within the "Ecological Zone" if they are compliant with the established emission standards and have a green sticker. This restriction applies to all types of vehicles, including those owned by foreign drivers. Furthermore, to improving the environmental situation in the city, the "Ecological Zone" also regulates the access and transit of cars through the city.

To reduce the parking pressure on the historic centre of Leipzig, 12 multi-level or underground car parks with a total of 7,124 spaces are located around the historic core. These car parks are owned by different companies and set different prices for their services and opening hours (City of Leipzig, n.d.-b). The operation of a paid parking zone covering an area of 8.97 km² in the central part of the city helps to reduce the attractiveness of using private cars for trips to the city centre (City of Leipzig, 2020) (Fig. 4).

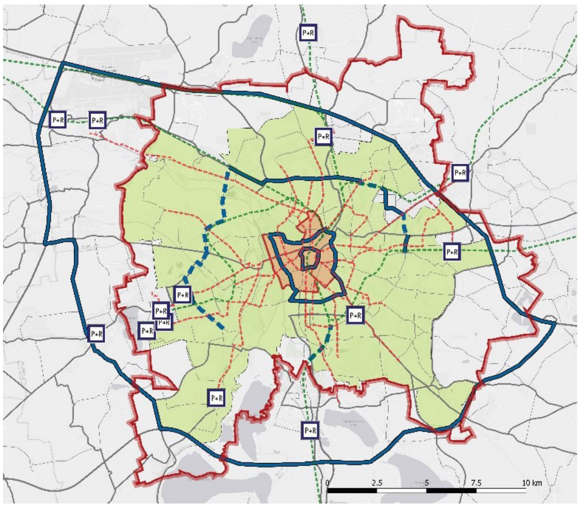

Figure 4. Means of intercepting private vehicles in Leipzig
Notes: city limits are indicated by a red line; existing bypasses are shown by blue lines, planned bypasses are shown by a dash; intercepting "Park&Ride" facilities are shown by the "P+R" icons; paid parking zones in the city centre are shown with a red fill, the "Ecological Zone" ("Umweltzone") with a green fill; the "S-Bahn" network is shown with green dashed lines, the tram network with red dashed lines
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Krakow. Unlike Leipzig, Krakow does not have any international motorways in its internal planning structure. International and domestic transit trips are carried out via the outer ring road (the fourth ring), but the northern section of this ring is still unfinished as of 2023. This leads to the fact that traffic from the northern direction of the city passes through the northern fragment of the third ring, which is included in the inner-city structure. In turn, intra-agglomeration and intra-city transit traffic mainly passes through the second ring, as fragments of the third ring are currently missing. The city authorities of Krakow note that the second bypass ring does not meet the required capacity, so the completion of the third ring, which is envisaged in the development strategy, is essential to avoid local transit traffic through the central area of the city (Resolution of Krakow City Council No. XCIV/2449/18, 2018).

To control the entry of cars regularly travelling to the city from the Krakow agglomeration (daily labour migration), interceptor "Park&Ride" car parks located at the tram terminals are used. Currently, there are five such car parks in the city with a capacity of 843 cars, and two more are under construction (Road Administration of the city of Krakow, n.d.). Interceptor car parks are available from 4.30 am to 2.30 am, with a daily parking fee of PLN 10. During the day, the use of public transport is free for parking users. If one buys a public transport pass, the use of interceptor parking is free of charge (Resolution of Krakow City Council No. LIII/723/12, 2012). By the year 2030, according to the city's parking programme, it is planned to implement 17 interceptor car parks in the city, which will provide parking for 3570 cars (Public Information Bulletin of the City of Krakow, 2012).

To limit the excessive number of cars in the historic part of Krakow and reduce the so-called "cruising for parking" phenomenon (Barter, 2016), Krakow has a paid parking zone covering 12.78 km² of the historic part of the city (Resolution of Krakow City Council No. LXXXIX/2177/17, 2017) (Fig. 5). Furthermore, 30 parking garages are planned to be built on the territories within the second ring, four of which have already been constructed.

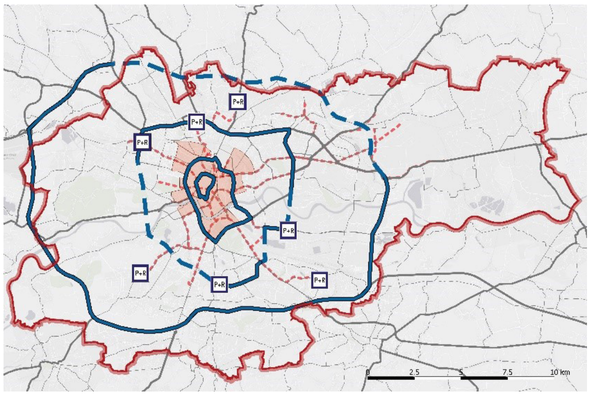

Figure 5. Means of interception of private vehicles in Krakow
Notes: city limits are shown as red lines; existing bypasses are shown as blue lines, projected bypasses are shown as dashed lines; "Park&Ride" intercepts are shown as "P+R" icons; paid parking zones in the city centre are shown as red fills; tram network is shown as red dashed lines
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Lviv. The restriction of private cars in the central part of Lviv is partially implemented by traffic rings that redirect transit trips. Although the second ring is formally present on the city plan, its imperfections are explained by its brokenness, partial overlap with radial roads, and variable width of the cross-sectional profile and, accordingly, the number of lanes. The missing segment of the bypass road (the third ring) causes international and intercity transit trips through the historic centre of Lviv. The long distance from the first to the second bypass ring causes excessive traffic on the I ring for intra-city travel. The situation is further complicated by the fact that Lviv is the centre of a monocentric agglomeration that "attracts" a significant amount of traffic from the surrounding settlements (Rusanova, 2015). A study was conducted on the impact of traffic congestion (5 km/h) on the environment (on the example of the Bandera Street), which indicates an 8-fold increase in emissions compared to a 50 km/h traffic flow (Kachmar & Lanets, 2020).

The restriction of the presence of cars in the historic part of Lviv is implemented through a pedestrian zone in the historic core of the city, which today runs roughly along the border of the medieval city walls, as well as five paid parking zones. Parking zones I-III with a total area of 7.2 km^2 have clearly defined boundaries (Fig. 6), while zone IV formally covers the rest of the city. V zone – special paid parking areas near the airport and railway station. Paid parking zones apply only to designated on-street parking spaces within their boundaries, so even in the central part of the city there is still a significant number of "free" parking spaces – especially in the third parking zone. The progress and problems of on-street parking in the central part of Lviv are discussed separately in the publication C. Zhou *et al.* (2022).

There are no transport hubs with intercepting car parks ("Park&Ride") on the boundary of the historic area in Lviv. Also, no garages have been built in the central part of the city, which would be aimed at short-term "daytime" visitors ("Park&Walk"). Such garages should replace on-street parking spaces to expand pedestrian areas and improve the conditions for other modes of public transport.

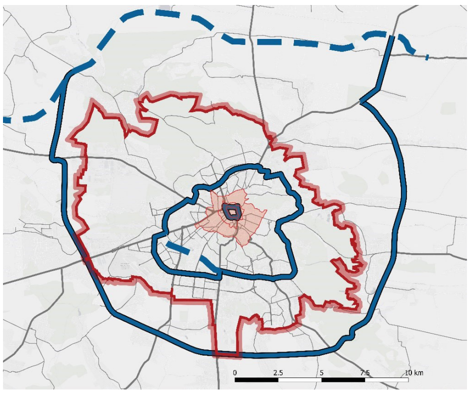

Figure 6. Means of interception of private vehicles in Lviv
Notes: the city boundary is marked by a red line; existing bypass rings are shown by blue lines, projected ones – by a stroke; I-III paid parking zones in the central part of the city are marked with a red fill
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Mobility of public transport in Leipzig, Krakow, and Lviv. *Leipzig.* The geospatial data analysis revealed that Leipzig's urban public transport system consists of a network of tram, bus, and rail routes with a total length of 514 km (with a city area of 297.36 km² and a density of 1.73 km/km²). Tram lines are 146 km long, bus lines are 302 km long, and rail lines are 66 km long. There is a well-developed network of interceptor "Park&Ride" facilities at tram and rail ("S-Bahn") terminals, as well as on the city's outskirts outside the third ring, which are free of charge (Leipzig transport company, 2023). The tram lines run close to the city limits and the IV bypass ring. In 2013, the construction of a 3.6-kilometre long (5.3 km including portals and ramps) "S-Bahn" tunnel under the city centre was completed, with 4 railway stations. Tickets for public transport are unified, which makes it possible to transfer between diverse types of transport. There are one-day, three-day, weekly, and monthly passes that enable travel within the city or agglomeration, as well as tickets for groups (Leipzig transport company, n.d.). The density of the public transport network in Leipzig, including the passenger-capacity and highly mobile tram and rail networks, is 0.71 km/km² (Fig. 7).

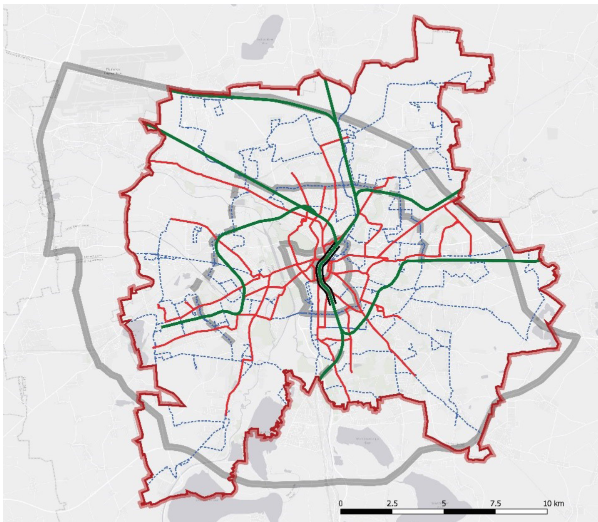

Figure 7. Public transport network in Leipzig
Notes: city limits are shown as red lines; the "S-Bahn" network is shown as green lines, the tram network as red lines, and the bus network as blue dashed lines; existing bypasses are shown as light grey lines, and the projected bypasses are shown as dashed lines
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Krakow. The city's public transport is represented by tram and light rail systems, a bus system, and a railway network with a total length of 498 km. Given the city's area of 326.85 km², the density of public transport lines is 1.52 km/km². Analysis of geospatial data showed that the tram network has a length of 97 km, including a high-speed tram with a network length of 32 km. The specific feature of Krakow's tram network is the presence of an underground tunnel that runs under the city centre. Its construction was completed in 2008. The tunnel is 1,538 metres long and has 2 underground stations. Most of the tram lines are directed to the peripheral districts of Krakow outside the third ring. There is also an extensive network of free "Park&Ride" car parks at the tram terminals (Road Administration of the city of Krakow, n.d.). The tram network is complemented by bus routes that cover areas of the city not covered by the tram network. The total length of the bus lines is 327 km. Furthermore, the 74 km long railway network in Krakow is used for both intra-city and agglomeration passenger transport (TOR Economic Advisory Team, 2011). The density of the network of highly mobile and passenger-capacious public transport modes in Krakow, such as tram, light rail, and rail, is 0.52 km/km^2 (Fig. 8). The public transport network in Krakow is divided into two zones: inner-city and agglomeration, with ticket prices depending on the zone chosen. Tickets (hourly, daily, monthly, and group tickets) are standardised for travel by any type of public transport, including rail, and allow transfers between diverse types of transport (Municipal Communication Company in Krakow, 2021).

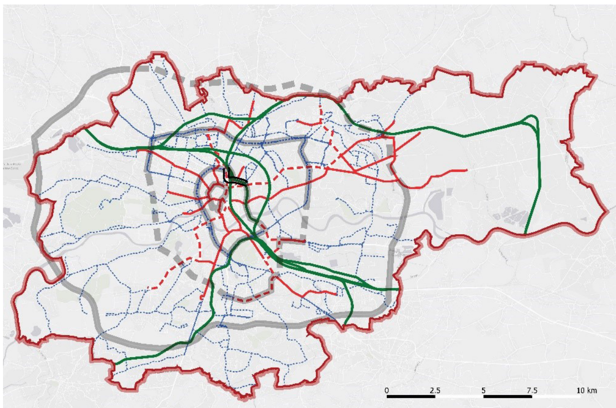

Figure 8. Public transport network in Krakow
Notes: city limits are marked with a red line; railway network is shown with green lines, tram network with red lines, BRT routes with red dashed lines, bus network with blue dashed lines; existing bypasses are shown with light grey lines, projected bypasses are shown with a dash
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Lviv. Lviv's public transport system consists of a network of tram, trolleybus, and bus routes. According to OpenStreetMap (n.d.), the total length of the lines is 257 km, and the total density of the network of all public transport modes is 1.71 km/km^2 with a city area of 150.09 km^2. The tram network is 34 km long. Lviv's tram lines were laid in the city's interwar period (Kotlobulatov, 1931) and run only up to the boundaries of the modern second bypass ring. The exception is the newly built line to the Sykhiv district. Transport links in the new areas of typical Soviet-era housing construction were provided by a trolleybus network, which today has a total length of 52 km. The rest of the city is served by a 170 km long bus network. The network of highly mobile and passenger-intensive urban transport (including only tram lines) has a density of 0.23 km/km^2 (Fig. 9).

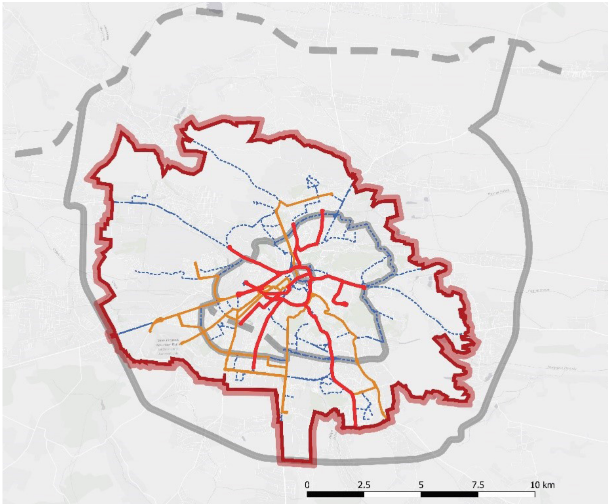

Figure 9. Public transport network in Lviv
Notes: city limits are marked with a red line; tram network is shown with red lines, trolleybus network with orange lines, bus network with a blue dashed line; existing bypass rings are shown with light grey lines, projected ones with a dash
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

The planning and development of the Lviv light rail network, which began in Soviet times, has not received a boost in the modern period either. As of 2023, only designated tram lanes on Horodotska, Chernivetska, Vakhnyanyna, Sakharova, Lychakivska, Knyahyni Olhy Streets and a new line on Chervonoi Kalyny Avenue, which was also planned to be implemented in the Soviet period, are operational (Novakovskij *et al.,* 1983). Due to the fact that tram traffic mostly runs on shared carriageways with cars, strict adherence to timetables is not possible. The concept of a high-speed tram with underground tunnels, which was developed in the Soviet period, was not implemented due to difficult geological conditions.

As the tram network is underdeveloped, the peripheral areas are served only by buses and partially by trolleybuses. The bus network is mainly provided with small-sized rolling stock with low passenger capacity, and modern large-sized buses mostly serve radial routes with the highest demand (EasyWay, n.d.). Most existing trolleybuses have already suffered wear and tear and obsolescence – as of 2017, 59 out of 78 trolleybuses are models or modifications of developments of the 1970s and 1980s (Škoda 14TR, 15TR, LAZ-52522) (Ukrelectrotrans, n.d.). One of the most significant problems that hinders the smooth operation of bus and trolleybus routes is the movement of these vehicles along with private vehicles on common carriageways.

Despite the presence of railway lines and stops in the central part of Lviv, the existing railway infrastructure is not used for regular city and intra-agglomeration passenger transport. An unsuccessful six-month experiment in 2009 to introduce a "rail bus" from the Sykhiv district to the central part of Lviv was stopped due to unprofitability, which was caused by a bad schedule and long travel times (From Sykhiv to Pidzamche…, 2021).

As of 2023, there is no single ticket in Lviv public transport that would allow transfers between different modes of transport and routes. The use of the electronic fare collection system is limited and available only for tram and trolleybus routes. Even though most buses have already been equipped with validators for cashless payment, only privileged passengers can use them, while others pay for travel only in cash.

Cycling mobility in Leipzig, Krakow, and Lviv. *Leipzig.* The total length of bicycle routes in Leipzig is 904 kilometres, including 193 kilometres of nationally important bicycle roads and 711 kilometres of city bicycle routes. The number of bicycles for every thousand Leipzig residents is 905 (City of Leipzig Transport and Civil Engineering Department, 2018). The network covers areas of Leipzig that do not have adequate tram connections and connects the main recreational facilities that form the city's waterfront. The total density of bicycle routes in Leipzig is 3.04 kilometres per square kilometre (Fig. 10). The network of bicycle infrastructure is formed by "Nextbike" bicycle rental stations, which serve 32 stations, as well as 927 bicycle parking spaces (OpenStreetMap, n.d.).

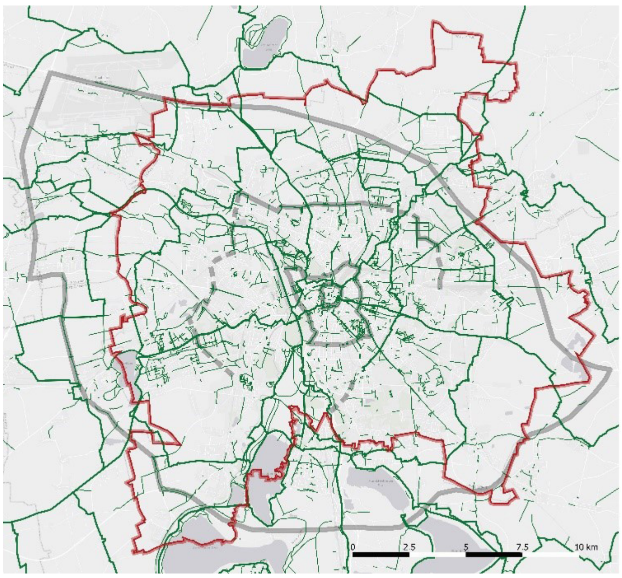

Figure 10. Leipzig cycle network

Notes: the city limits are marked with a red line; the network of main bicycle routes is shown with thick green lines, secondary bicycle routes with thin green lines; existing bypass rings are shown with light grey lines, projected ones with a dash

Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Krakow. Krakow's cycling network is 658 km long, of which 169 km are national cycle routes and 489 km are city cycle paths. A denser system of bicycle routes is developed in the west-east direction, which compensates for the lack of tram lines in these areas. Krakow has a well-developed infrastructure for cyclists, which is mainly concentrated in the historic city centre (within the third bypass ring). It is estimated that the density of Krakow's cycling network is 2.02 km/km^2 (Fig. 11). Within the third bypass ring, rental stations are located at a distance of 500 to 1,000 m. According to OpenStreetMap (n.d.), there are 1,406 bicycle parking spaces in the city.

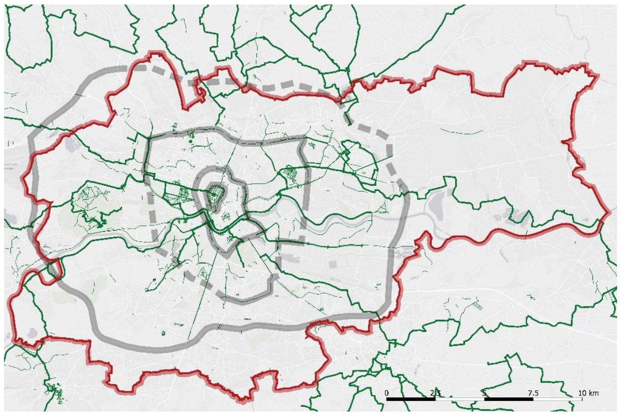

Figure 11. The network of bicycle paths in Krakow

Notes: the city limits are marked with a red line; the network of main bicycle routes is shown with thick green lines, secondary bicycle routes with thin green lines; existing bypass rings are shown with light grey lines, projected ones with a dash

Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

Lviv. The total length of urban bicycle routes in Lviv is 304 km, mostly concentrated within the second bypass ring. The main challenge for cycling infrastructure is the lack of systemic connections, which in many areas are interrupted and suddenly end. The total density of bicycle paths in Lviv is 2.03 km/km^2, although this figure also includes paths in parks, which are formally also suitable for cycling (Fig. 12). Lviv does not have a network of bicycle routes of national importance (as in Leipzig or Krakow), which would serve to connect the main urban areas, towns and villages of the agglomeration and tourist and recreational routes. The cycling infrastructure, according to OpenStreetMap (n.d.), consists of 24 "Nextbike" bicycle rental stations and 150 bicycle parking spaces. In recent years, there has been a growing interest in cycling, with the city launching the "Bolt" and "E-wings" electric scooter rental services and considering the creation of mobile applications for cyclists (Teslyuk *et al.,* 2019).

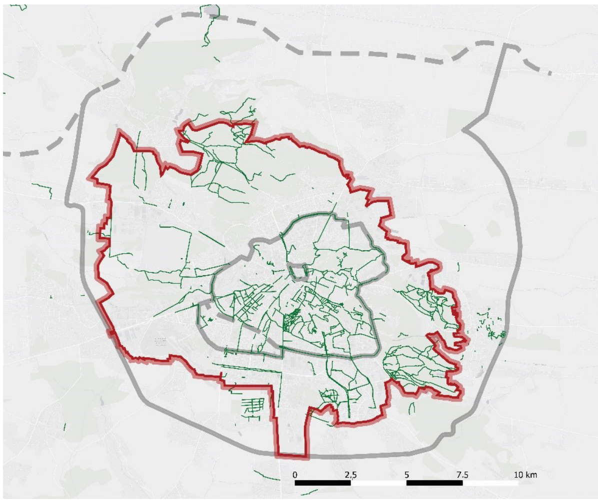

Figure 12. The network of bicycle routes in Lviv
Notes: city limits are marked with a red line; the bicycle network is shown with green lines; existing bypass rings are shown with light grey lines, projected ones are shown with a dash
Source: developed by the author of this study based on geospatial data from OpenStreetMap (n.d.)

The layout of bicycle lanes within the cross-sectional profiles of streets is imperfect, creating dangerous situations for pedestrians and cyclists. In the central part of the city, one can find bicycle lanes that are laid on sidewalks and marked only with a distinct colour paving type (e.g., on Kulisha, Sichovykh Striltsiv, Horodotska Streets) or on the roadways (Voronoho Street).

Specifics of the development of Lviv's transport network. The analysis of the parameters of the street and road network as the main formative element of the planning structure of the cities under study helps to highlight the specific features of Lviv. With the same population, Lviv has twice the population density, which is due to the city's twice smaller area. The length of Lviv's street and road network per capita is also half as long (Table 1). The above facts, as well as the fact that Lviv has not undergone major street reconstruction and widening in the past, prove that the city is unsuitable for intensive traffic development. Nevertheless, unlike Leipzig and Krakow, transit roads of international and European importance run through the historic part of Lviv, and the incomplete system of bypass traffic rings (especially the lack of a ring that would bypass the historic centre) provokes transit traffic through the historic core of the city.

Table 1. Generalised indicators of planning structure and urban transport mobility in Leipzig, Krakow, and Lviv

No.	Indicator	Leipzig (575,000 residents)	Krakow (744,230 residents)	Lviv (758,500 residents)
	Characteristics of the planning structure			
1	City area	297.36 km²	326.85 km²	150.09 km²
2	Length of the street and road network	2,314.47 km	2,666.51 km	1,360.85 km
3	Per 1 resident	4.02 m	3.58 m	1.79 m
4	Density of the street and road network	7.78 km/km²	8.16 km/km²	9.07 km/km²
5	Main roads through the historic city centre	no	no	yes
6	Bypass transport rings	4	4	3
	Urban transport mobility			
	Private motor transport			
7	Number of cars	253,575	292,492	153,217
8	Cars/1,000 residents	441	393	202
9	Cars/km² of the city	853	895	1021
10	Cars/km of street	110	110	113
11	Interceptor car parks ("Park&Ride")	14 (3,208 parking spaces)	5 (843 parking spaces) + 2 (under construction)	-
12	Controlled parking area	8.97 km² of paid parking area in the city centre (dedicated parking spaces) 62% of the city's area ("Umweltzone")	12.78 km² of paid parking zone in the city centre	7.2 km² of paid parking zones in the city centre (zones I-III, dedicated parking spaces)
	Public transport			
13	Length of public transport network	514 km	498 km	257 km
14	City railway	66 km	74 km	-
15	Tram	146 km	97 km	34 km
16	Bus	302 km	327 km	170 km

Table 1. Continued

No.	Indicator	Leipzig (575,000 residents)	Krakow (744,230 residents)	Lviv (758,500 residents)
17	Trolleybus	-	-	52 km
18	Network density (total)	1.73 km/km²	1.52 km/km²	1.71 km/km²
19	Network density (urban rail and tram)	0.71 km/km²	0.52 km/km²	0.23 km/km²
		Bicycle transport		
20	Length of the cycle network	904 km	658 km	304 km
21	Network density	3.04 km/km²	2.02 km/km²	2.03 km/km²
22	Bicycle parking	927	1,406	150

Notes: numerical indicators were calculated by the author using QGIS based on geospatial data from OpenStreetMap (n.d.), except for those specifically referenced in the text
Source: developed by the author of this study

The number of private cars in Lviv is half that of Leipzig and Krakow, despite the same population, but their pressure on the road network is more noticeable as of 2023. This is explained by the fact that the number of cars in Lviv per km² of city area is already 20% higher than in Leipzig, and 14% higher than in Krakow. Given the prospects for growth in car ownership to reach the European average of 560 cars/1,000 residents in 2020 (European Automobile Manufacturers' Association, 2022), and in the absence of new restrictive measures on the use of private cars, Lviv will face a transport collapse. G. Zantke (2015) substantiated the need to introduce restrictions on entry to the central part of Lviv. The feasibility of such restrictions for cars is substantiated by many studies on sustainable urban transport, namely, P. Schiller *et al*. (2010), V. Vuchic (2017) and L. Lehe (2019).

Despite the need for restrictions on cars, Lviv has not yet implemented any transport hubs with intercepting "Park&Ride" car parks that would restrict the entry of private vehicles into the city centre. For comparison, there are 14 such hubs in Leipzig, 7 in Krakow, and there is a consensus to increase their number. A positive trend is the expansion of the paid parking zone in Lviv, which since 2018 has increased from 0.95 to 7.2 km² (parking zones I-III, which have clearly defined street boundaries), but within the third zone there are still many streets with free parking spaces (Zhou *et al.,* 2022). The experience of Krakow, where the paid parking zone provides for payment for parking on all streets within its boundaries, and not only on separately defined streets, as in Lviv, seems appropriate.

Although the density of the public transport network in Lviv and comparable cities is identical, it is misleading. This is because, according to the study, 86% of the network in Lviv is bus and trolleybus transport, with most of it being small buses. This type of transport is inefficient in historic districts, as it is not possible to organise dedicated lanes on most of Lviv's narrow streets. The remaining 14% is covered by the tram network, which in historically established European cities is usually the basis of public transport due to its high passenger capacity and high mobility, as well as the priority of trams on the roadways. The railway will not be used for urban transport in 2023. In contrast, in Leipzig and Krakow, the total share of trams and urban rail in the public transport structure is 41 and 34%, respectively. According to modern works in the field of public transport development, specifically P. Daniels *et al*. (2013), J. Walker (2014) and E. Sclar *et al*. (2016), it should be the basis of urban transport, especially in dense historic cities, and its operation should be unhindered by dedicated traffic lanes.

According to OpenStreetMap (n.d.), the density of bicycle paths in Lviv is comparable to Krakow (Leipzig has half as many), which indicates the gradual development of this type of urban transport. Given the much smaller number of bicycle parking spaces in Lviv, it can be concluded that the popularity of using a bicycle for urban transport is low today. Nevertheless, the city's compactness (the distance from the centre to the bypass road is only 8-10 km) substantiates the relevance of developing and promoting cycling, which is also confirmed by the studies of E.J. Adams *et al*. (2016) and A. Telega *et al.* (2021), which emphasise that historic city districts are more attractive for cycling than new ones. A widely used measure in European cities is the conversion of individual on-street parking spaces into bicycle parking (Pucher & Buehler, 2012; Gehl, 2018), which is also rational for Lviv.

The generally accepted approaches to sustainable transport development mentioned in the above works are also necessary for implementation in Lviv. However, the results of this study highlight the city's distinctive characteristic – high population density combined with the compact historical planning structure of Lviv, which exacerbates the problem of transport infrastructure more than in similar cities.

CONCLUSIONS

The study covered the specific features of Lviv's planning structure, which include a high population density and a preserved compact network of narrow historic streets, which makes intensive car traffic impossible and requires solutions to improve highly mobile and passenger-capacious modes of urban transport. First and foremost, solutions are needed to optimise the planning structure – organising bypass routes for the central part and removing transit roads from it. The construction of new large-scale architectural and urban planning complexes should be carried out outside the historic area, which will reduce the additional traffic load on the historic centre of Lviv. Furthermore, it is advisable to reconsider the removal of city and regional administrative functions from the historic core.

The creation of missing interceptor "Park&Ride" lots and the improvement of strict paid parking zones in Lviv can motivate residents not to use cars without a justified need, without introducing a "ban", but by regulating the demand for parking spaces with high prices. These solutions are politically unpopular and will not gain the support of residents at first, but this is the path taken by all European cities that have experienced excessive traffic pressure on the road network. Reducing car traffic on the streets of Lviv will create the preconditions for the development of alternative modes of urban transport. For mass and fast movement, the most efficient way is the tram network, which is underdeveloped as of 2023. It should be expanded to densely populated areas outside the city's historical area. Small bus routes, which currently account for the largest share of urban transport, should only complement the network of highly mobile and passenger-capacious public transport in remote and sparsely populated areas of the city.

The generally accepted trends of "sustainable transport development in historic cities", such as limiting car use and developing public transport and cycling, are ideal for Lviv, but given the specific features of the planning structure identified in this study, measures should be more decisive, rigorous, and urgent. Given the specific features of Lviv mentioned in the article, further research on the decentralisation of the city centre and the formation of new sub-centres is relevant, which will reduce the traffic pressure on the historic part of the city. In addition, given the compactness of Lviv, special attention should be paid to the development of the cycling and pedestrian infrastructure network, which also deserves future research.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Розвиток транспортної мережі із врахуванням специфіки планувальної структури Львова (у порівнянні з Лейпцигом та Краковом)

Анотація. Актуальність статті зумовлена необхідністю адаптації транспортної мережі Львова вимогам сучасного міського руху. Планувальна структура Львова формувалася на базі радіальних доріг, згодом розвиваючи кільцеві зв'язки, що притаманно більшості європейських міст, проте із часом набула власних особливостей. Метою статті постає аналіз особливостей сучасної планувальної структури Львова, які впливають на розвиток міської транспортної інфраструктури та мобільності кожного виду транспорту. Методика даного дослідження передбачає аналіз сучасної вулично-дорожньої мережі, як формотворної основи планувальної структури міста Львова та оцінку мобільності транспорту, спираючись на геопросторові дані із відкритих джерел. Порівняння із схожими європейськими містами – Лейпцигом та Краковом, дозволяє виокремити особливості та раціональні шляхи розвитку транспортної мережі Львова. Результати дослідження вказують на основну особливість планувальної структури Львова, яка полягає у його компактності та високій щільності населення – вдвічі більшій за порівнювані міста. Це унеможливлює адаптацію транспортної інфраструктури для автомобільних поїздок та підкреслює необхідність вдосконалення мереж громадського транспорту і велоінфраструктури, як більш ефективних та екологічних способів міського пересування. Проте дослідження міської транспортної мобільності виявило, що засоби обмеження використання приватних автомобілів у Львові поступаються тим, які реалізовано в порівнюваних містах, а мережа громадського транспорту та велоінфраструктури розвинена недостатньо і станом на 2023 р. не складає якісної альтернативи автомобільним поїздкам. Практична цінність дослідження полягає у виокремленні найбільш проблемних аспектів транспортної інфраструктури Львова, які вимагають прийняття невідкладних рішень задля функціонування в умовах специфіки планувальної структури міста

Ключові слова: міська мобільність; сталий міський транспорт; розвиток міського транспорту; транспортна система європейських міст; історично сформовані міста