

Navigating the future: Evaluating two-level transport solutions for sustainable urban development

Mykola Stashkiv *, Oleg Tson *, Marta Łakomy-Zinowik**,
Michał Basta ***

* Department of Automobiles, Ternopil Ivan Puluj National Technical University,
56, Rus'ka Str., 46001 Ternopil, Ukraine
stam77@ukr.net; tson_oleg_@ukr.net

** University of Szczecin,
Aleja Papieża Jana Pawła II 22A, 70-453 Szczecin, Poland
marta.lakomy-zinowik@usz.edu.pl

*** Polish Chamber of Work Safety at Height,
Jana Matejki 17, 33-300 Nowy Sącz, Poland
mbasta@tgls.pl



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Abstract: *Purpose:* The purpose of this paper is to propose and evaluate two options for two-level transport solutions at the intersection of the bypass road and the Pidvolochyske Highway in Ternopil, Ukraine. The aim is to address the issues associated with the current road network passing through residential zones and present an optimal resolution for the intersection. *Methodology:* The methodology involves using the PTV Vissim software to conduct simulation modelling. The transport and operational indicators of the two options for two-level transport solutions, an elongated loop and two interconnected rings, are compared across different traffic intensities. *Results:* The results show that the transport solution with two roundabouts exhibits superior characteristics, particularly under high traffic flow conditions. The strengths and limitations of each solution are comprehensively delineated, encompassing factors like efficiency, cost-effectiveness, safety measures, and ecological impacts. *Theoretical contribution:* The paper contributes to advancing knowledge and practice in two-level transport solutions. It provides valuable insights for developing the transportation system in Ternopil and other post-conflict cities. The advantages and disadvantages of public-private partnerships (PPP) as a tool for attracting investments and innovations in transportation infrastructure are also discussed. *Practical implications:* The findings of this research can be used by professionals in transportation, urban planning, and ecology for infrastructure development. It also serves as a valuable resource for residents of Ternopil interested in fostering improvements to their city's quality of life.

Corresponding author: *Mykola Stashkiv*
E-mail: stam77@ukr.net

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1. Introduction

Transportation infrastructure development is crucial for any city's economic and social well-being. However, many cities face challenges such as traffic congestion, road safety, environmental pollution, and insufficient funding for infrastructure projects. One of the possible solutions to these challenges is the use of public-private partnerships (PPP), which involve the collaboration of public and private entities to design, finance, construct, operate, and maintain public infrastructure and services (Zagozdzon, 2016; 2020). PPP can offer benefits such as attracting private capital, enhancing innovation, improving efficiency, and sharing risks and responsibilities (European PPP Expertise Centre, 2018).

One of the areas where PPP can be applied is the restoration and modernisation of transportation infrastructure, especially in regions affected by military actions. Such regions often suffer from damaged or outdated facilities, which require significant investments and innovations to meet the current and future needs of the population and the economy. PPP can provide a viable option for restoring and modernising transportation infrastructure in such regions, as it can leverage the resources and expertise of both the public and private sectors.

This article focuses on the case of Ternopil, a city in western Ukraine that has experienced several military conflicts, such as the Polish-Ukrainian War, the Second World War, and the recent Russian aggression. The article aims to analyse the role of PPP in the reconstruction of the transportation infrastructure of Ternopil, particularly the bypass road around the city, which is an essential element of the city's transportation system. The article consists of three main parts. The first part describes the problems associated with the existing bypass road, which passes through residential areas and causes negative impacts on the city's transportation, safety, and ecology. The second part proposes two options for two-level transport solutions at the intersection of the bypass road and the Pidvolochyske Highway, an international highway connecting Ternopil with other regional centres. The article uses the PTV Vissim software to conduct simulation modelling and compare the transport and operational indicators of the two options. The third part concludes that the transport solution with two roundabouts has better characteristics than the one with an elongated loop, especially at high traffic flow intensities. The article also discusses the advantages and disadvantages of each option in terms of efficiency, cost, safety, and ecology. The article is relevant and valuable for specialists in transport, urban planning, and ecology, as well as for Ternopil residents interested in improving the quality of life in their city.

2. Literature review

The literature review provides an overview of the existing research on two-level transport solutions, focusing on their advantages, disadvantages, and applications in different contexts. The literature review also identifies the gaps and limitations in the current knowledge and suggests directions for future research.

Two-level transport solutions are road interchanges that allow traffic to cross at different levels, reducing the number of conflict points and improving the traffic flow efficiency. Two-level transport solutions, such as cloverleaf, diamond, trumpet, and roundabout interchanges, can be classified according to their geometry.

The advantages of two-level transport solutions include minimizing traffic crossings at one level, reducing vehicle delays and stops, and enabling higher travel speeds (Kumar & Rao, 2013; Garbarinina & Fedorchak, 2022). Two-level transport solutions can also enhance road safety and improve the ecological situation in adjacent areas by reducing noise, vibrations, and air pollution from exhaust gases (Garbarinina & Fedorchak, 2022).

The disadvantages of two-level transport solutions include high construction costs, increased area requirements, and extended vehicle travel distances (Kumar & Rao, 2013; Garbarinina & Fedorchak, 2022). Two-level transport solutions may also pose maintenance, operation, and management

challenges, especially in accidents, congestion, or adverse weather conditions (Garbarinina & Fedorchak, 2022).

Two-level transport solutions have been applied in various contexts, such as urban, suburban, and rural areas, and for different types of roads, such as highways, arterial roads, and bypass roads (Kumar & Rao, 2013; Garbarinina & Fedorchak, 2022). The choice of the optimal type of two-level transport solution depends on several factors, such as traffic volume, composition and direction, road geometry and alignment, land use and availability, environmental and social impacts, and economic feasibility (Kumar & Rao, 2013; Garbarinina & Fedorchak, 2022).

The literature review reveals that there is a lack of comprehensive and comparative studies on the performance and evaluation of different types of two-level transport solutions, especially in the context of post-conflict countries, where the transportation infrastructure is often damaged or outdated (Garbarinina & Fedorchak, 2022). Moreover, there is a need for more innovative and sustainable approaches to the design and implementation of two-level transport solutions, such as using public-private partnerships, incorporating smart technologies, and applying simulation modelling and optimisation techniques (Garbarinina & Fedorchak, 2022).

Therefore, this study aims to fill these gaps by proposing and analysing two options for two-level transport solutions for the bypass road of Ternopil, an essential element of the city's infrastructure. The study uses the PTV Vissim software to conduct simulation modelling and compare the transport and operational indicators of the two options at different intensities of traffic flow. The study also discusses the advantages and disadvantages of each option in terms of efficiency, cost, safety, and ecology. The study contributes to advancing knowledge and practice in two-level transport solutions and provides valuable insights for developing the transportation system in Ternopil and other post-conflict cities.

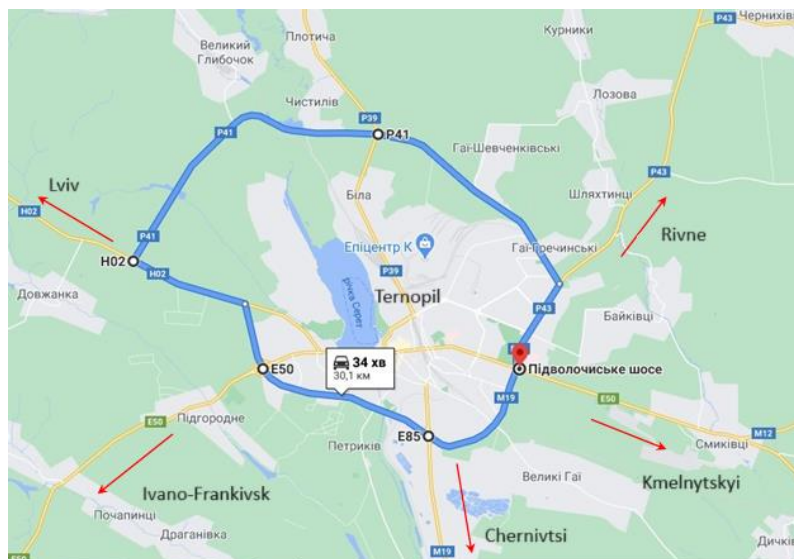
3. Methodology and results

Its bypass road is an essential element of the transportation system in any sufficiently large city. The circumferential road around a city enables the redirection of transit traffic beyond the city streets, significantly enhancing the transportation and operational characteristics of the city's road network. This redirection elevates street safety and stabilizes the ecological situation within residential areas.

With the development of Ternopil city, a section of its bypass road found itself within residential districts (the "Soniachny" and "Skhidny" micro-districts). The public infrastructure in these areas is continuously evolving, witnessing the emergence of new commercial complexes, eateries, sports facilities, offices, kindergartens, schools, and large residential micro-districts, such as the "Varshavsky" micro-district, stretching along the Pidvolochyske Highway.

The operation of the bypass road within these districts poses numerous inconveniences for the residents and the municipal authorities. The city administration is continually tasked with addressing various issues associated with the functioning of this section of the bypass road, such as low road safety levels, high accident rates, increased congestion and duration during peak hours, a sudden decline in the ecological situation in adjacent residential areas (elevated noise levels, vibrations, and air pollution from exhaust gases), the necessity to organize additional measures for transporting oversized cargo within the city, and extra expenses for periodic maintenance of the bypass road within the city limits.

The general layout of the existing bypass road around Ternopil and the directions toward the regional centres are depicted in Figure 1.

Figure 1: Diagram of the existing bypass road around Ternopil

In the city's master plan for development (see Appendix A), the relocation of this section of the bypass road around Ternopil is envisaged, aiming to reduce the intensity and density of transit traffic flow.

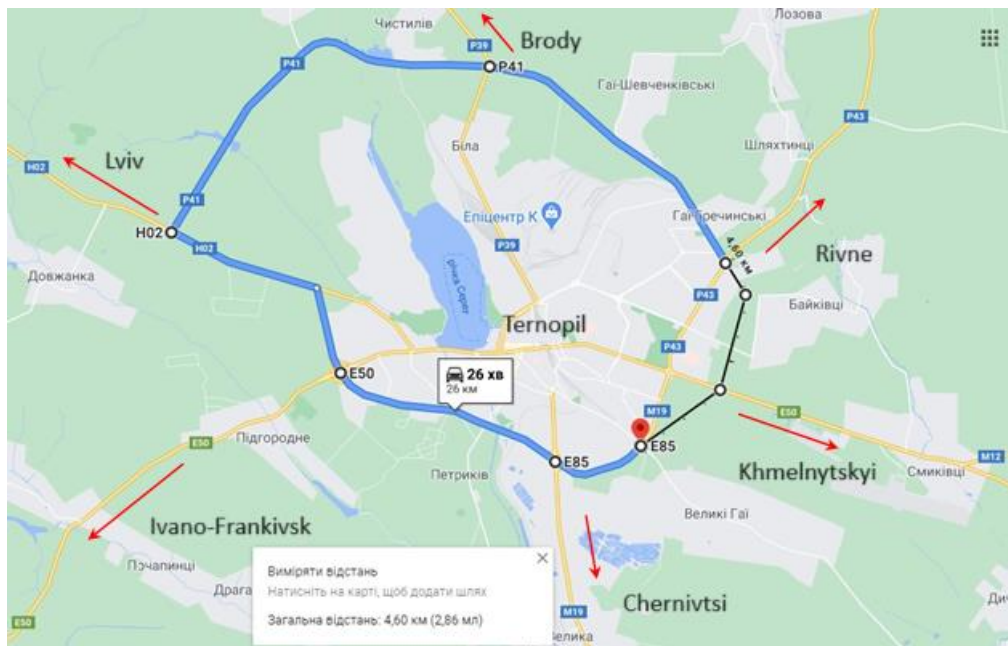
The plan involves relocating a segment of the bypass road within the city limits along T. Protasevycha Street and 15 Kvitnia Street outside the city - from the bridge near the Haiivske intersection through the field between the village of Velyki Hai and Ternopil to the Pidvolochyske Highway, further through the field between the village of Baikivtsi and Ternopil to an unregulated roundabout at the entrance to Ternopil from the Zbarazh side.

A component of the city's development plan featuring the relocated section of the bypass road around Ternopil is illustrated in Figure 2.

Figure 2: Diagram of the bypass road section around Ternopil

The overall layout of the planned bypass road around the city is depicted in Figure 3.

Figure 3: Diagram of the proposed bypass road around Ternopil



The relocated section of the bypass road around Ternopil will intersect with the Pidvolochyske Highway – an international highway M12 (Stryi – Ternopil – Kropyvnytskyi – Znamianka) (see Figure 2.4).

Figure 4: Photo of the section of the M12 highway where the interchange is planned



The M12 highway is part of the European route E50 and is among the longest in Ukraine, with a total length of 746.7 km, including access roads, extending to 756.1 km.

The road consists of two lanes, although within Ternopil, there are several sections with four lanes.

The length of the new section of the bypass highway around Ternopil will be approximately 5 km (see Fig. 3). At the intersection of this road section with the Pidvolochyske Highway, it is necessary to

construct a two-level interchange to minimize traffic crossings, reduce the number of conflict points, and consequently increase road capacity.

Advantages of a two-level transport interchange include minimizing traffic crossings at one level, reducing vehicle delays and stops, and enabling higher travel speeds. Disadvantages encompass high construction costs, increased area requirements, and extended vehicle travel distances.

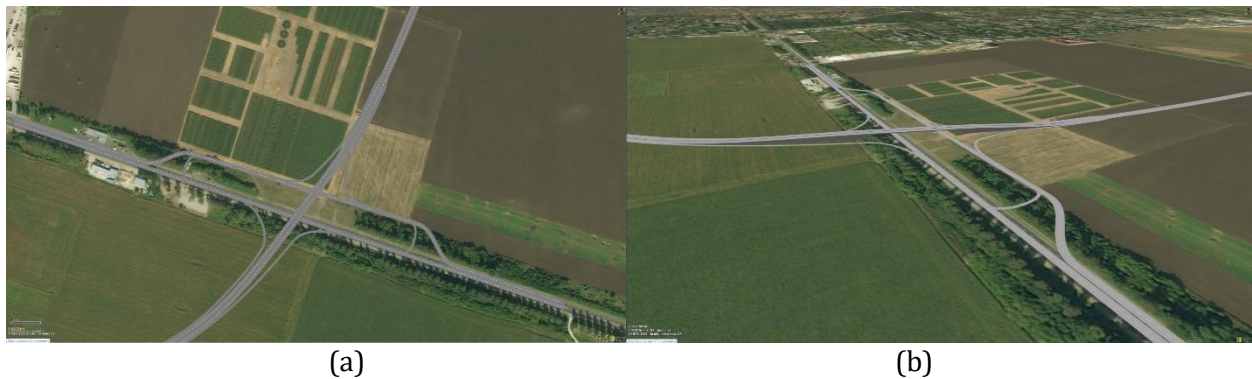
Implementing such organizational solutions will necessitate substantial budget allocation from the city but will significantly enhance the operational efficiency of the road network in the southern and southeastern parts of the city. It will also elevate road safety and improve the city's ecological conditions.

3.1. Simulation of a two-level interchange with an extended loop

Simulating the two-level road interchange is conducted to determine the parameters and characteristics of the designed system before its creation, aiming to ensure the correspondence of the solution to the specified initial parameters. The investigational tool employed is the PTV Vissim software, which enables the creation of a fully functional model of the road network segment.

The overall layout of the proposed transport interchange at the intersection of the Pidvolochyske Highway and the bypass road around Ternopil is depicted in Figure 5.

Figure 5: Perspective of the transportation interchange in plan (a) and volume (b)



The choice of this transportation interchange scheme is influenced by its relatively low cost, minimal area requirement, and a slight increase in vehicle travel distances. The limitation on the length of the displayed roads in the transportation interchange model is because the student version of PTV Vissim only allows the construction of road segments up to a length of 1000 meters.

Four traffic flows have been added to the constructed road network of the transportation interchange, each representing directions from Ternopil, Lviv, Rivne, and Khmelnytskyi. For each flow, four vehicle routes were designated: right turn, straight, left turn, and U-turn (see Fig. 6).

Figure 6: Vehicle routes according to traffic directions
Direction I (from Ternopil)



Direction II (from Ternopil)



Direction III (from Khmelnytskyi)



Direction IV (from Rivne)



For the trial run, the traffic intensity for each route was set uniformly at 1500 vehicles per hour. Within each traffic flow, there is a distribution of 33% for cars, buses, and trucks and 1% for cyclists. The distribution of traffic across routes is uniform.

Figure 7 displays the resolution of conflict zones within the transportation interchange roads. The planned road network scheme involves 12 conflict points.

Figure 7: Resolution of conflict zones in the transportation interchange



The results of the trial run of the simulation model of the transportation interchange are depicted in Figure 8.

Figure 8: 3D view of the simulation launches of the transportation interchange model



Based on the simulation results, it has been determined that overall, the considered transportation interchange scheme provides the necessary capacity given the designated composition and traffic intensity. For a more detailed analysis of the transportation operational characteristics of the interchange with the extended loop, isolines of the following traffic parameters have been constructed: average speed (Fig. 9), average density (Fig. 10), delay time (Fig. 11), and network load (Fig. 12).

Figure 9: Distribution of average speed (km/h)

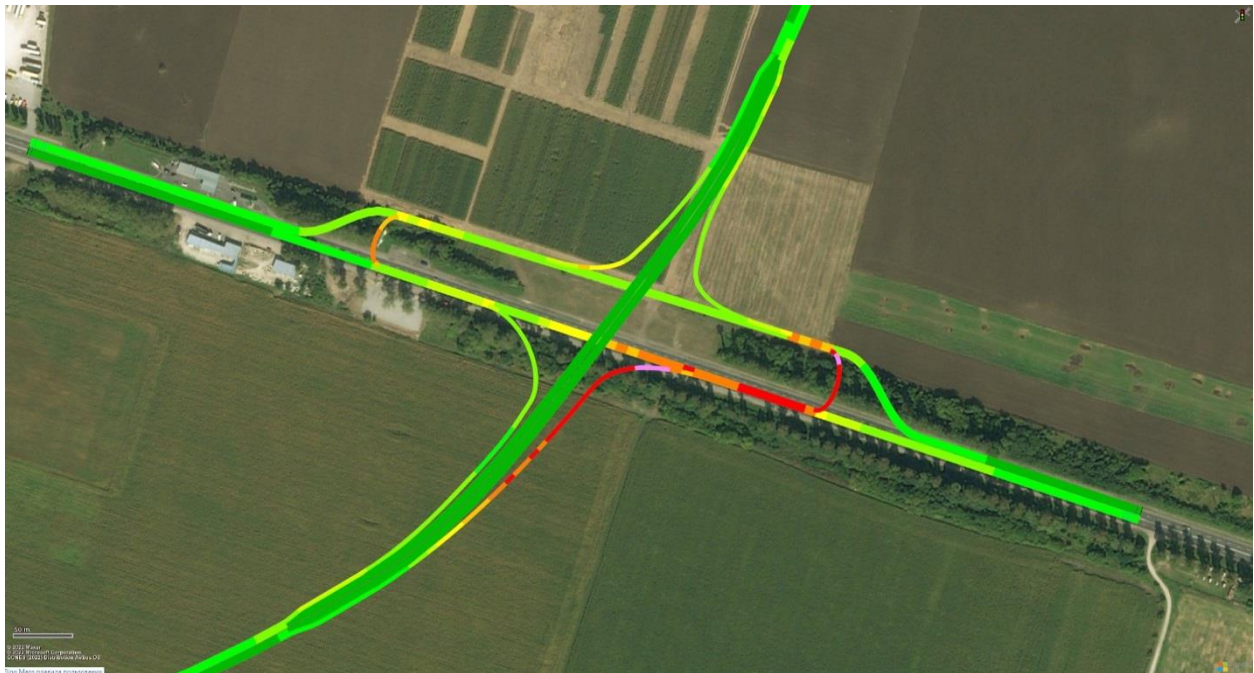


Figure 10: Distribution of average density (vehicles/km)



Figure 11: Distribution of average relative delay time (seconds)**Figure 12: Distribution of the average network load (vehicles/hour)**

From the obtained isolines, it can be concluded that the worst transportation operational indicators are present in the turning lanes and the sections of the road network near them. This is evidently due to the limited distance between secondary roads, complicating lane change manoeuvres for left and right turns.

3.2. Simulation of a two-level interchange with two roundabouts

To enhance the transportation operational indicators of the considered scheme of the bypass road around Ternopil, it is necessary to increase the distances between the junction points of secondary roads with the main thoroughfare. This would allow more space and time to execute lane change manoeuvres for left and right turns. This can only be achieved by increasing the radii of the turning lanes.

By increasing the radii of the turning lanes and reducing the distance between the lanes of oncoming traffic, we obtain a scheme of a transportation interchange with two roundabouts (see Fig. 13).

Figure 13: Model of a two-level interchange with two roundabouts



Advantages of the two-level interchange scheme with two roundabouts:

- Increased distance for executing lane change manoeuvres for left turns.
- Shorter elevated road sections, simplifying construction and reducing costs.
- In case of an obstruction of the overpass, such as in an accident, an alternative route is available (via the roundabouts).

For the constructed topological model of the interchange with two roundabouts, traffic flows and vehicle routes were set similarly to section 2.2 (see Fig. 14).

Figure 14: Vehicle routes according to traffic directions
Direction I (from Ternopil)



Direction II (from Lviv)



Direction III (from Khmelnytskyi)



Direction IV (from Rivne)



For the trial run, the traffic intensity for each route was set uniformly at 1500 vehicles per hour. Each traffic flow comprises 33% cars, buses, trucks, and 1% cyclists. The distribution of traffic across routes is uniform.

Figure 15 displays the resolution of conflict zones within the transportation interchange roads. Such a road network scheme involves 16 conflict points.

Figure 15: Resolution of conflict zones within the transportation interchange



The results of the trial run of the simulation model of the transportation interchange are depicted in Figure 16.

Figure 16: 3D view of the simulation launches of the transportation interchange with two roundabouts



According to the modelling results, the proposed transportation interchange scheme ensures the necessary capacity given the designated composition and traffic intensity. For a more detailed analysis of the transportation operational characteristics of the interchange with two roundabouts, isolines of the following traffic parameters have been constructed: average speed (Fig. 17), average density (Fig. 2.18), delay time (Fig. 19), and network load (Fig. 20).

Figure 17: Distribution of average speed (km/h)



Figure 18: Distribution of average density (vehicles/km)



Figure 19: Distribution of average relative delay time (seconds)



Figure 20: Distribution of average network load (vehicles/hour)



The obtained isolines visually assess the transportation operational metrics for the interchange with two roundabouts.

3.3. Comparative analysis of the transportation operational indicators of modelled road interchanges bypassing Ternopil

Seven simulation variants were conducted to compare the transportation operational indicators of the modelled road interchanges, varying the traffic flow intensity from 500 to 3500 vehicles per hour in increments of 500 vehicles per hour. The simulation results for the road interchanges are presented in Table 1 and Table 2.

Table 1: Simulation results for the interchange with an elongated loop							
Traffic intensity	500	1000	1500	2000	2500	3000	3500
Vehicle parameter							
Average delay time per vehicle	5.96	29.53	141.19	237.00	287.03	310.02	334.58
Average number of stops per vehicle	0.00	0.71	4.27	6.29	7.03	7.46	7.55
Average speed	92.17	59.05	15.12	8.53	6.73	5.98	5.45
Average idle time per vehicle	0.00	6.97	94.60	175.93	226.53	237.86	263.99
Total distance of all vehicles							
Total travel time of all vehicles	339.63	706.24	572.19	457.82	402.06	375.51	355.12
Total delay time of all vehicles	13264.90	43054.30	136268.50	193132.10	214995.70	225898.10	234735.80
Total number of stops of all vehicles	1782.40	19399.37	117048.48	177746.92	201494.29	213292.37	222827.18
Total stop time of all vehicles	0	464	3541	4714	4932	5134	5031
Total number of vehicles in the network at the end of the simulation	0	4577.27	78425.44	131944.45	159023.52	163644.47	175818.11
Total number of vehicles that	20	97	444	457	454	466	459

reached their destination by the end of the simulation							
Total delay time of vehicles that were not used	279	560	385	293	248	222	207
Total number of vehicles that were not used by the end of the simulation	0	5.80	20132.90	94363.20	186158.20	279368.50	375835.40
Average number of stops per vehicle	0	0	175.00	609.00	964.00	1291.00	1664.00

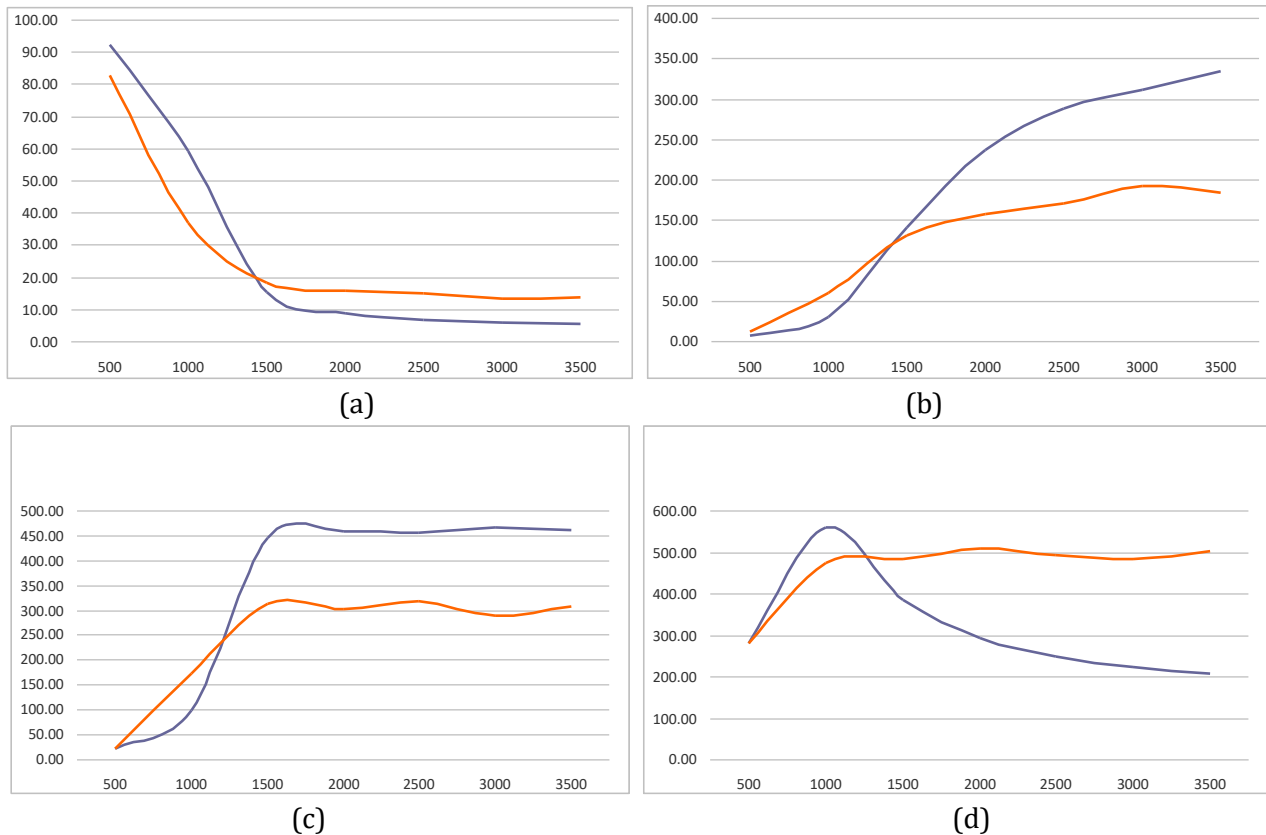
Table 2: Results of modelling the transport junction with two rings

Traffic intensity	500	1000	1500	2000	2500	3000	3500
Average delay time per vehicle	10.86	60.32	130.2	156.59	169.91	192.33	183.08
Average number of stops per vehicle	0.03	1.7	4.41	6.9	7.96	7.35	7.7
Average speed							
Average idle time per vehicle	82.67	36.71	18.22	15.82	14.75	13.18	13.77
Total distance of all vehicles	0.24	29.06	69.86	72.89	74.39	96.82	87.3
Total travel time of all vehicles	333.86	603.69	630.23	652.88	652.05	619.03	650.02
Total delay time of all vehicles	14537.7	59203	124501.9	148592.5	159151	169045.8	169909.4
Total number of stops of all vehicles	3247.92	38965.81	103377.24	126685.06	137286.84	148285.52	148110.19
Total stop time of all vehicles	10	1101	3501	5583	6430	5663	6233
Total number of vehicles in the network at the end of the simulation	72.71	18771.77	55470.73	58969.27	60105.9	74652.04	70623.36
Total number of vehicles that reached their destination by the end of the simulation	21	173	312	301	317	289	307
Total delay time of vehicles that were not used	278	473	482	508	491	482	502
Total number of vehicles that were not used by the end of the simulation	0	251.6	28367.8	99955.9	192259.9	281943.4	376357.2
Average delay time per vehicle	0	11	210	550	858	1208	1521

The results of modelling the transport solutions for the road bypassing Ternopil concerning parameters like average speed, average delay time, the total number of vehicles in the network at the end of the simulation, and the total number of vehicles that reached their destination by the end of the simulation are presented graphically in Figure 21. Analysing these graphs, one can conclude that the transport junction with an elongated loop has better traffic-operational characteristics when the traffic

intensity is less than 1500 vehicles/hour. At a traffic intensity of approximately 1500 vehicles/hour, the characteristics of the two transport junctions are almost identical.

Figure 21: Comparison of indicators for the transportation solution with an elongated loop (blue line) and with two circles (orange line)*



* a - average vehicle speed (km/h), b - average vehicle delay time (s), c - total number of vehicles remaining in the network at the end of the simulation, d - total number of vehicles that reached their destination by the end of the simulation

4. Conclusion

The transportation solution with two circles demonstrates better transportation technological parameters with a further increase in traffic intensity. Notably, at a traffic intensity of 3000 vehicles per hour, the average vehicle speed increases by $\approx 55\%$, the average delay time decreases by $\approx 38\%$, the total number of vehicles in the network at the end of the simulation decreases by $\approx 38\%$, and the total number of vehicles reaching their destination by the end of the simulation increases by $\approx 54\%$.

Public-Private Partnership (PPP) is a cooperative arrangement between the public and private sectors, which is widely used in various countries, including Poland and other European countries, for infrastructure development. Here are a few examples:

1. Poland: In Poland, PPP is used to develop public infrastructure and provide related services (Zagozdzon, 2016). For instance, the city of Łódź launched the Resident Card service, and Kraków expanded and operated a car park through PPP. Another example is the Centrum PPP, a non-profit NGO launched in 2008 by public and private entities to create and develop the Polish PPP market (Zagozdzon, 2016; 2020).
2. Europe: In Europe, PPP projects attracted 14.4 billion euros in 2017 (European PPP Expertise Centre, 2018). These projects span various areas such as social (healthcare, education), transport (roads, ports, rail transport), and energy (power plant construction, energy facility management) (European PPP Expertise Centre, 2018). One of the successful PPP projects in Europe is the Active and Assisted Living Research and Development Programme (European Commission, 2018).

PPP can play a significant role in restoring and modernising transport infrastructure. It allows the state to attract private capital to implement important but costly projects, contributing to economic growth (Zagozdzon, 2016; 2020; European PPP Expertise Centre, 2018).

Public-private partnerships (PPP) can be an effective tool for attracting investments in transportation infrastructure, especially in restoring and modernising facilities damaged due to military actions (Garbarinina & Fedorchak, 2022). Here are several ways in which PPP can be applied in such projects:

Streamlining the preparation and implementation of PPP projects: This can incentivise the private sector to participate in projects to restore and modernise existing infrastructure (Garbarinina & Fedorchak, 2022).

Enhancing the innovation component in PPP projects: Innovations can enhance the efficiency and resilience of infrastructure projects, which, in turn, can attract more investments.

Establishing an appropriate institutional environment: Developing and implementing appropriate legislative and regulatory acts can create a conducive environment for PPP project realisation.

Regarding development directions, some key areas might include:

Efficiency in state management of the transportation sector: Improving management mechanisms can increase resource utilisation efficiency and enable better planning and project execution (Bondar, 2014).

Providing quality and efficient transport services: Enhancing the quality and efficiency of transport services can increase customer satisfaction and demand.

Ensuring sustainable transportation financing: Involving private investments through PPPs can ensure stable transportation infrastructure development and modernisation funding.

Public-private partnerships can play a significant role in restoring and modernising transportation infrastructure. However, to effectively utilise this tool, there's a need to improve legislative and institutional environments and devise mechanisms for attracting private investments and innovations.

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Conflicts of Interest

The authors declare no conflict of interest.

Data availability

Some or all data and models that support the findings of this study are available from the corresponding author upon reasonable request.

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