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Criterion for reducing traffic delays at a roundabout exit in the presence of a public transport stop

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Abstract. The efficiency of roundabout intersections largely depends on traffic conditions at their exit sections, in particular the location of public transport stops immediately after the exit or in its vicinity, which reduces capacity and increases delays due to forced lane-changing manoeuvres and a shortage of acceptable gaps in the traffic stream. The aim of the study was to develop criteria for reducing traffic delays at the exit of a roundabout in the presence of a public transport stop, taking into account vehicle lane-changing processes and the critical gap in the adjacent traffic lane. The study was conducted using principles of traffic flow theory, methods for evaluating intersection capacity, and approaches for determining critical gaps; it was also shown that delays at roundabout exits are caused by right-lane blockage by public transport, demand for lane changing, and insufficient acceptable gaps in the adjacent stream within a local critical zone. A system of delay-reduction criteria is proposed, based on minimising total delay in the local critical zone, ensuring consistency between traffic demand and effective exit capacity, and matching lane-changing demand with the possibility of its execution under existing traffic conditions. Conditions for the transition of the traffic stream to a critical operating regime were also defined in terms of speed, density, and capacity indicators. To validate the proposed methodological approach, a computational scenario of a two-lane roundabout exit was considered. With an exit traffic flow of 1,000 veh/h, adjacent lane flow of 900 veh/h, and an average right-lane blocking time by public transport of 25 s, a lane occupancy coefficient of $\varphi = 0.125$ was obtained, resulting in a reduction of effective capacity to 1,575 veh/h. Under these conditions, traffic demand does not exceed the effective exit capacity, ensuring stable traffic operation and enabling lane-changing manoeuvres without the formation of critical delays. The obtained results may be used to justify the location of urban public transport stops, determine the length of weaving sections, and select organisational and technical measures aimed at improving the efficiency of roundabout operation and reducing traffic delays

Keywords: traffic management; lane-changing manoeuvres; critical gap; lane blockage; bottlenecks

Introduction

Roundabouts are widely recognised as one of the most effective traffic control solutions in urban transportation systems due to their ability to improve road safety, reduce the number of conflict points, and maintain continuous traffic movement. However, the operational efficiency of roundabouts is strongly influenced by traffic conditions at their exit sections, particularly when public transport stops are located directly at or immediately downstream of the exit area. Under such conditions, traffic delays may increase significantly due to the combined effects of lane

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blockage, lane-changing manoeuvres, and limited availability of acceptable gaps in adjacent traffic streams. Recent research has increasingly focused on the operational performance of roundabouts under varying traffic conditions. M. Guerrieri (2024) proposed a methodology for assessing sustainable traffic levels at urban roundabouts using a macroscopic fundamental diagram approach. The study demonstrated the importance of traffic density and speed relationships in determining operational efficiency and identifying the transition from stable to congested traffic conditions. H. Jiang *et al.* (2024) conducted a comprehensive review of traffic behaviour and intelligent driving at roundabouts from a microscopic perspective. The authors emphasised that traffic delays and travel times are strongly affected by lane-selection behaviour, lane-changing decisions, traffic demand, and geometric characteristics of roundabouts. E. Campi *et al.* (2024) analysed the application of traffic simulation models for evaluating the operation of connected and automated vehicles at roundabouts. Their findings confirmed the importance of microscopic modelling approaches for investigating vehicle interactions and traffic flow dynamics within roundabout influence areas. F. Abu Hamad *et al.* (2024) investigated driver behaviour at roundabouts operating under mixed traffic conditions using machine learning techniques. The study demonstrated that lane selection, gap acceptance behaviour, and driver decision-making processes significantly influence traffic performance and the occurrence of conflicts within roundabout influence areas. The authors emphasised the importance of considering vehicle interactions and lane-changing behaviour when assessing operational efficiency at roundabouts.

Y. Liang *et al.* (2024) developed a three-stage cellular automata model for analysing traffic operations at complex multilane roundabouts. Their findings showed that vehicle interactions occurring during entering, circulating, and exiting manoeuvres substantially affect traffic stability, delay formation, and overall operational performance. The study confirmed the importance of considering localised traffic disturbances and lane-changing processes when evaluating roundabout efficiency. K. Čulík *et al.* (2025) compared the operational performance of conventional and turbo roundabouts using field observations and calibrated simulation models. The results demonstrated that traffic delays and capacity utilisation are highly sensitive to lane allocation and vehicle weaving processes. E. Zadobrischi (2025) investigated intelligent traffic management systems for roundabouts based on advanced vehicle communication technologies. The study highlighted the significance of traffic flow organisation and conflict reduction measures for improving operational efficiency and reducing vehicle delays. The influence of public transport stops on traffic performance has also attracted considerable attention. I. Medvediev & S. Soroka (2020) proposed a methodology for evaluating the impact of public transport stop placement on the capacity of urban road networks. Their results confirmed that stop location may substantially affect traffic performance and capacity utilisation. E.B. Lieberthal *et al.* (2024) examined traffic conditions on urban road sections with reduced capacity and demonstrated the necessity of considering localised bottlenecks when assessing traffic performance and delay formation processes.

Recent studies addressing public transport stop operations and lane-changing processes indicate that the interaction between temporary lane blockage, lane-changing demand, and traffic flow characteristics plays a significant role in determining local traffic conditions. Nevertheless, existing studies primarily investigate these factors separately. The combined influence of public transport stop operations, lane-changing demand, and the availability of acceptable gaps within the roundabout exit area remains insufficiently explored. The aim of this study was to establish criteria for reducing traffic delays at roundabout exits where a public transport stop is present, considering vehicle lane-changing behaviour and the critical gap in the adjacent traffic stream.

Literature Review

The issue of determining capacity and traffic delays at roundabouts is predominantly addressed in the scientific literature through gap-acceptance models, critical gap estimation, and analyses of traffic flow interactions within roundabout entry and exit areas. A. Polus *et al.* (2003) found that the critical gap is dependent on drivers' waiting time, which directly affects roundabout capacity. O. Hagring (2001) proposed an approach for estimating roundabout entry capacity while accounting for mixed circulating and exiting traffic flows. O. Giuffrè *et al.* (2016) systematised the gap-acceptance parameters commonly applied in the evaluation of roundabout performance. K. Shaaban & H. Hamad (2020) investigated variations in critical gap values for single-, two-, and three-lane roundabouts. A separate group of studies focuses on the impact of public transport stops on traffic conditions. D. Cvitanić (2017) demonstrated that the location and configuration of a public transport stop significantly affect vehicle delays and the operational performance of intersections. X. Yang *et al.* (2013) developed a model for evaluating vehicle delays in the vicinity of public transport stops under mixed traffic conditions. H. Jin *et al.* (2019) found that curbside stops cause periodic lane blockages, aggressive lane-changing manoeuvres, reduced roadway capacity, and increased traffic delays. In recent studies, increasing attention has been devoted to microscopic traffic flow modelling, driver behaviour in lane-selection decisions, and the evaluation of traffic management measures. H. Jiang *et al.* (2024) noted that travel time and delays at roundabouts depend on drivers' lane-changing behaviour, the geometric characteristics of the intersection, traffic demand, and local traffic control regulations. K. Čulík *et al.* (2025), in a comparison of conventional and turbo roundabouts, employed field observations, origin-destination traffic matrices, and a calibrated microscopic simulation model. E. Zadobrischi (2025) investigated opportunities for improving traffic flow efficiency at roundabouts, particularly through the implementation of public transport priority measures. M. Riaz *et al.* (2023) highlighted the effectiveness of microscopic traffic simulation techniques for evaluating traffic management strategies in urban transportation systems. The authors demonstrated that microsimulation models can successfully reproduce lane-changing behaviour, traffic delays, and congestion formation, providing valuable support for the assessment of traffic control measures and infrastructure design alternatives.

Despite the considerable progress achieved in the fields of roundabout capacity assessment, lane-changing behaviour analysis, traffic microsimulation, and public transport stop evaluation, the combined influence of temporary lane blockage, lane-changing demand, and acceptable gap availability at roundabout exits remains insufficiently investigated. Existing studies primarily address these factors separately, whereas their simultaneous interaction may significantly affect traffic delays and traffic flow stability within the exit influence area. Recent studies have increasingly focused on the behavioural and operational aspects of traffic flow at roundabouts. F. Abu Hamad *et al.* (2024) and Y. Liang *et al.* (2024) demonstrated the importance of lane-changing processes and vehicle interactions for traffic performance, whereas M. Riaz *et al.* (2023) confirmed the usefulness of microscopic simulation approaches for evaluating traffic management strategies. However, the integration of these factors into a unified analytical framework for assessing traffic delays at roundabout exits has received limited attention in previous research. At the same time, the literature review indicates that most studies examine either roundabout capacity, the impact of public transport stops, or vehicle lane-changing processes as separate components. Their combined effect at roundabout exits remains insufficiently explored, despite the fact that three interrelated factors occur simultaneously in this area: temporary blockage of the outer lane by public transport vehicles, increased lane-changing demand, and a shortage of acceptable gaps in the adjacent traffic stream. This research gap justifies the need to develop criteria for reducing traffic delays within the critical exit zone of a roundabout. Although numerous studies have addressed roundabout capacity, the effects of public transport stops on traffic conditions, and vehicle lane-changing processes separately, their combined impact within the roundabout exit area has received limited attention. In particular, the mechanism of traffic delay formation under the simultaneous influence of outer-lane blockage, lane-changing demand, and the limited availability of acceptable gaps in the adjacent traffic stream requires further investigation (Yang *et al.*, 2013; Cvitanić, 2017; Jin *et al.*, 2019). An analysis of the current regulatory framework indicates that the requirements governing the location and design of public transport stops in Ukraine are primarily established by GBN V.2.3-37641918-550:2018 (2018) and DBN V.2.3-5:2018 (2018). GBN V.2.3-37641918-550:2018 defines the general requirements for the design of public transport stops, while DBN V.2.3-5:2018 serves as the principal regulatory document governing the design and construction of urban streets and roads in populated areas. When addressing traffic control devices and traffic management measures, reference should also be made to DSTU 4100:2021 (2021) and DSTU 2587:2021 (2021).

However, the aforementioned regulatory documents do not provide an analytical framework for assessing the impact of a public transport stop on traffic delays specifically within the exit area of a roundabout. Furthermore, they do not account for the process of forced lane-changing manoeuvres undertaken by vehicles, nor do they relate the feasibility of such manoeuvres to the critical gap available in the adjacent traffic stream. This constitutes the principal distinction and scientific value of the proposed study. The conducted review demonstrates that previous studies have significantly contributed to the understanding of roundabout capacity, critical gap acceptance, traffic flow dynamics, and the operational effects of public transport stops. However, the majority of existing research examines these factors independently. Insufficient attention has been paid to the combined influence of temporary lane blockage caused by public transport stops, lane-changing demand, and the availability of acceptable gaps within adjacent traffic streams at roundabout exits. Consequently, there remains a need for a comprehensive methodological approach capable of simultaneously accounting for these interacting factors when assessing delay formation and developing traffic management measures at urban roundabouts.

Materials and Methods

The study was conducted based on the principles of traffic flow theory, methods for assessing the capacity of transportation facilities, and approaches to determining the critical gap required for vehicle lane-changing manoeuvres. The object of the study was the process of traffic delay formation at a roundabout exit in the presence of a public transport stop. The subject of the study comprised the interaction patterns of traffic flows within the roundabout exit area, which were determined by the influence of the public transport stop, traffic demand, lane-changing demand, and the availability of acceptable gaps in the adjacent traffic stream. A schematic representation of vehicle lane-changing manoeuvres within the influence area of the public transport stop is shown in Figure 1. The dynamics of vehicle departures from a roundabout are characterised by pronounced traffic flow heterogeneity in terms of speed profiles, headways, and the spatial distribution of vehicles across roadway lanes. The operation of a public transport stop located in close proximity to the roundabout exit creates conditions for temporary lane blockage, which not only directly reduces roadway capacity but also generates additional conflict areas associated with vehicle lane-changing manoeuvres. For the subsequent analysis of traffic delay formation, it was proposed to distinguish functional zones representing the influence of a public transport stop on traffic flow, as illustrated in

Figure 2. As vehicles move away from the roundabout, the traffic stream naturally disperses both longitudinally along the roadway segment and laterally across its width. However, the presence of a public transport stop modifies this process. In particular, it shifts the traffic stabilisation zone further downstream while simultaneously affecting key traffic performance measures, including average travel speed, the distribution of vehicles across lanes due to overtaking and lane-changing manoeuvres, and the overall travel time along the roadway segment.

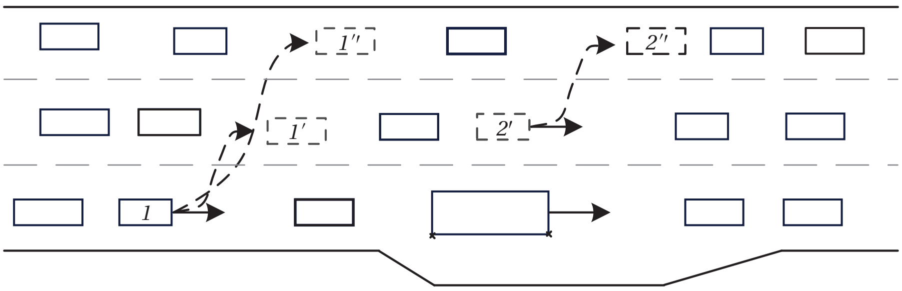

Figure 1. Schematic representation of a vehicle lane-changing manoeuvre
Source: developed by the authors

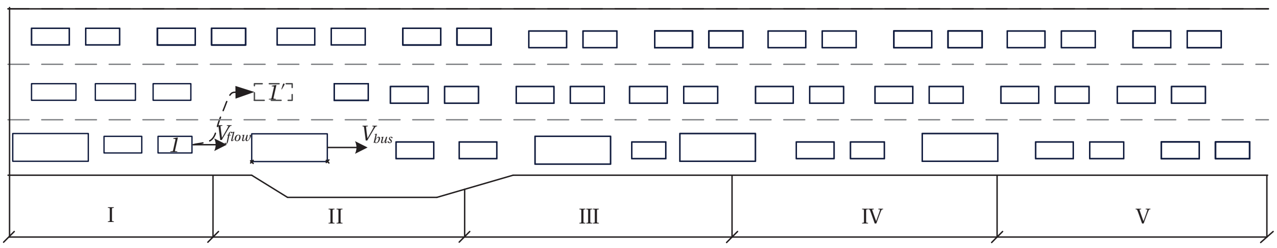

Figure 2. Functional zones of public transport stop influence on traffic flow
Source: developed by the authors

The structural decomposition of the public transport stop influence area (Fig. 2) made it possible to identify five consecutive sections whose characteristics are variable parameters: the approach zone (I), the manoeuvring zone during entry into the bus bay (II), the exit zone from the bus bay (III), the zone of direct merging of public transport vehicles into the main traffic stream (IV), and the traffic stabilisation zone (V). For the purposes of this study, the local critical zone is defined as the road section extending from the roundabout exit line to the point where traffic flow parameters return to stable operating conditions. The upstream boundary of the zone coincides with the beginning of the exit section, whereas the downstream boundary was determined by the completion of lane-changing manoeuvres and the stabilisation of traffic flow speed, density, and headway distribution. Consequently, the length of the local critical zone is not constant and depends on traffic demand, public transport stop operation characteristics, and the geometric parameters of the road section. The length of the approach section is determined by the time required to reach the lower speed threshold, which is constrained by the dynamic envelope characteristics of the specific vehicle type. In turn, the parameters of the entry section are governed by the geometric characteristics of the bus bay and the presence of a queue of public transport vehicles. To evaluate the operating conditions of the local critical zone, the following indicators are employed: traffic flow rate, vehicle speed, traffic density, effective lane capacity, and the critical gap available in the adjacent lane.

The critical gap represents one of the key parameters governing the feasibility of lane-changing manoeuvres. In practical applications, its value may be estimated from accepted and rejected gaps obtained through field observations within the influence area of a public transport stop. The performance criterion for the local critical zone is defined as the minimisation of total vehicle delay while ensuring the required exit capacity and maintaining the feasibility of lane-changing manoeuvres without causing the traffic stream to enter a critical operating state. The study was based on a theoretical and analytical framework developed using the principles of traffic flow theory and capacity analysis. Illustrative traffic scenarios with representative parameters of urban roundabout exits were used to demonstrate the application of the proposed criteria. The illustrative scenarios were developed using parameter ranges reported in previous studies on roundabout capacity, gap acceptance, and public transport stop impacts, such as K. Shaaban & H. Hamad (2020), H. Jin *et al.* (2019) and National Academies of Sciences, Engineering, and Medicine (2010). Field observations are considered as a future stage of research intended for model calibration and validation. Based on the proposed methodological framework, functional relationships were established among traffic flow rate, effective lane capacity, lane-changing demand, and the number of acceptable gaps in the adjacent traffic stream. These relationships provided the basis for developing a system of criteria aimed at reducing traffic delays at roundabout exits.

Results and Discussion

To investigate traffic conditions at roundabout exits, it is proposed to define a local critical zone comprising the following components: the immediate roundabout exit zone, the influence area of the public transport stop, the lane-changing section where vehicles merge into the adjacent lane, and the traffic stabilisation zone located downstream of the stop. It is within this zone that the most significant reductions in vehicle speed, changes in traffic density, and the formation of additional travel delays occur. The proposed analytical framework is based on several simplifying assumptions. Traffic arrivals in the adjacent lane are assumed to follow a Poisson process. Traffic flow characteristics within the local critical zone are considered homogeneous over short observation intervals. Public transport vehicles are assumed to occupy the curb lane for the average dwell time at the stop. Lane-changing demand is represented by the proportion of vehicles affected by temporary lane blockage. These assumptions allow the derivation of analytical relationships suitable for preliminary traffic engineering assessments. The total traffic delay within the local critical zone can be determined as the difference between the actual and normative travel times required to traverse the individual exit segments:

$$T_{\text{delay}} = \sum_{r=1}^{m} q_r \left(\frac{L_r}{v_r} - \frac{L_r}{v_{0r}}\right), \quad (1)$$

where q_r – traffic flow rate in the r-th zone, veh/h; L_r – length of the r-th zone, m; v_r – actual average travel speed, m/s; v_{0r} – average travel speed under normal operating conditions, m/s.

The obtained relationship makes it possible to quantify the contribution of each functional zone within the local critical area to the formation of total traffic delay and provides a basis for the subsequent development of performance criteria for roundabout exit operations. The performance criterion for roundabout exit operations is defined by the equation:

$$T_{\text{delay}} \longrightarrow min. \quad (2)$$

The presence of a public transport stop at a roundabout exit reduces the capacity of the outer lane due to its periodic occupation by public transport vehicles. The magnitude of this effect is proposed to be assessed using the lane occupancy factor given by the equation:

$$\varphi_{ps} = \frac{q_b \cdot t_d}{3600}, \quad (3)$$

where q_b – arrival rate of public transport vehicles at the stop, veh/h; t_d – average dwell time of a public transport vehicle at the stop, s.

Accordingly, the effective lane capacity within the stop influence area can be expressed by the equation:

$$C_{ps} = C_0(1 - \varphi_{ps}), \quad (4)$$

where C_0 – lane capacity in the absence of a public transport stop, veh/h.

Based on the equation (4), the first condition for reducing traffic delays is expressed by the equation:

$$q_{ex} \leq C_{ps}, \quad (5)$$

where q_{ex} – traffic flow rate at the roundabout exit, veh/h.

If this condition is not satisfied, a portion of vehicles is forced to merge into the adjacent lane. The lane-changing demand can then be determined according to the equation:

$$q_{lc} = p_{lc} \cdot q_{ex}, \quad (6)$$

where q_{lc} – flow rate of vehicles requiring a lane change, veh/h; p_{lc} – proportion of vehicles compelled to change lanes.

However, the existence of lane-changing demand alone does not guarantee the feasibility of executing the manoeuvre. For a lane change to occur, sufficiently large temporal gaps must be available in the adjacent lane. Such a gap may be characterised by the critical gap t_{cr}, which may be estimated from field observations according to the equation:

$$t_{cr} = \frac{\bar{h}_{\text{rej}} + \bar{h}_{\text{acc}}}{2}, \quad (7)$$

where $\bar{h}_{\text{rej}}$ – mean value of the gaps rejected by drivers; $\bar{h}_{\text{acc}}$ – mean value of the gaps accepted for performing the lane-changing manoeuvre.

The critical gap is considered as one of the key parameters affecting lane-changing feasibility. In practical applications, it may be estimated using established approaches such as the Raff method based on accepted and rejected gap observations. For the illustrative scenario presented in this study, a representative critical gap value of $t_c = 4.0$ s was adopted. This value lies within the range of critical gap values reported in the literature and applied in roundabout capacity assessment and traffic operations analysis and was selected to demonstrate the application of the proposed methodology (National Academies of Sciences, Engineering, and Medicine, 2010; Austroads, 2017). According to the Raff method, the critical gap corresponds to the intersection point of the cumulative distribution functions of accepted and rejected gaps. This approach enables the identification of the minimum acceptable time interval required for a driver to perform a lane-changing manoeuvre under prevailing traffic conditions. Future studies should estimate the critical gap using field observations collected at urban roundabout exits. Assuming a Poisson arrival process of vehicles in the adjacent lane, the probability of observing a gap not smaller than t_{cr} is determined by the equation:

$$P_{\text{cr}} = exp\left(-\frac{q_{adj} \cdot t_{\text{cr}}}{3600}\right), \quad (8)$$

where q_{adj} – traffic flow rate in the adjacent lane, veh/h.

Accordingly, the number of gaps suitable for lane-changing manoeuvres per unit time can be calculated using the equation:

$$n_{\text{cr}} = q_{adj} \cdot exp\left(-\frac{q_{adj} \cdot t_{\text{cr}}}{3600}\right). \tag{9}$$

The second principal condition for reducing traffic delays is represented by the equation:

$$q_{lc} \leq n_{cr}. \tag{10}$$

To demonstrate the application of the proposed criteria, a hypothetical urban roundabout exit with a two-lane downstream section was considered. The following input parameters were adopted: exit flow rate $q_{ex} = 1{,}000$ veh/h, adjacent lane flow rate $q_{adj} = 900$ veh/h, base lane capacity C_0 = 1,800 veh/h, public transport arrival rate $\lambda_{bus} = 18$ veh/h, average dwell time $t_d = 25$ s, and critical gap $t_c = 4.0$ s, and weaving section length $Lr = 120$ m. The calculated lane occupancy factor was $\varphi = 0.125$, resulting in an effective lane capacity of $C_{ps} = 1{,}575$ veh/h. Since $q_{ex} < C_{ps}$, the capacity criterion was satisfied. The probability of observing an acceptable gap was P = 0.368, corresponding to approximately 331 acceptable gaps per hour. Under these conditions, the traffic stream remains within a stable operating regime and no critical congestion effects are expected. The scenarios summarised in Table 1 represent generalised operating conditions developed for comparative assessment of public transport stop placement alternatives, whereas the numerical example presented in the text corresponds to a specific illustrative calculation scenario.

Table 1. Scenario analysis of roundabout exit operation

Scenario	Stop position (m)	Lane occupancy factor φ	Effective capacity (veh/h)	Lane-changing demand	Traffic regime
No public transport stop	–	0.00	1,800	Low	Stable
Stop located at roundabout exit	0	0.125	1,575	High	Transitional
Stop relocated downstream	120	0.06	1,692	Moderate	Stable

Source: developed by the authors

Traffic regimes were classified according to the conceptual thresholds presented in Figure 3: stable operation (q < 1,100 veh/h), transitional operation (1,100 ≤ q ≤ 1,400 veh/h), and oversaturated operation (q > 1,400 veh/h). Lane-changing demand was qualitatively assessed based on the proportion of vehicles affected by temporary lane blockage and required to merge into the adjacent lane, where low, moderate, and high demand levels correspond to increasing proportions of affected vehicles. The scenario analysis demonstrates that the operational regime of the roundabout exit is highly sensitive to the location of the public transport stop. The most unfavourable conditions are observed when the stop is located directly within the exit influence area, resulting in reduced effective capacity and increased lane-changing demand. Relocating the stop further downstream improves operating conditions by reducing lane blockage duration and increasing the availability of acceptable gaps for lane-changing manoeuvres. The obtained results indicate that the location of a public transport stop relative to the roundabout exit constitutes one of the key factors affecting traffic performance. Stops located within the immediate influence area of the exit increase lane-changing demand and reduce the availability of acceptable gaps for manoeuvre execution. Consequently, the proposed criteria may serve as a practical tool for evaluating alternative stop locations and identifying configurations that minimise traffic delays while maintaining adequate operational conditions. If the condition defined by the equation is satisfied, a portion of vehicles is unable to complete the lane-changing manoeuvre within the available weaving section:

$$q_{lc} > n_{cr}. \tag{11}$$

A portion of vehicles is unable to complete the lane-changing manoeuvre within the available weaving section. As a result, localised vehicle accumulation occurs, traffic speed decreases, and delays increase.

To assess the transition of the roundabout exit into a critical operating state, it is also necessary to consider the critical speed v_{cr} and the critical traffic density λ_{cr}. The critical density may be determined according to the equation:

$$\lambda_{\text{cr}} = \frac{q_r}{v_{\text{cr}}}. \tag{12}$$

The local critical zone is considered to operate under critical conditions when at least one of the criteria expressed by the equations is satisfied:

$$v_r < v_{cr}; \tag{13}$$

$$\lambda_r > \lambda_{cr}; \tag{14}$$

$$q_{ex} > C_{ps}; \tag{15}$$

$$q_{lc} > n_{cr}. \tag{16}$$

Thus, traffic delay at a roundabout exit is not caused by a single factor but rather by the combined influence of three interrelated mechanisms: periodic blockage of the outer lane by public transport vehicles serving the stop, the forced redistribution of vehicles between lanes, and an insufficient number of acceptable gaps in the adjacent traffic stream. Considering the above, the proposed system of criteria for reducing traffic delays at roundabout exits includes the following conditions:

- the traffic flow rate at the exit should not exceed the effective lane capacity within the public transport stop influence area;

- lane-changing demand should not exceed the number of acceptable critical gaps available in the adjacent lane;
- traffic speed within the local critical zone should not fall below the critical speed;
- actual traffic density should not exceed the critical density;
- total delay within the local critical zone should be minimised.

Based on the proposed system of criteria, a conceptual relationship between traffic delay and traffic flow rate can be established. When both the capacity criterion and the lane-changing feasibility criterion are satisfied, the traffic stream operates under stable conditions. As traffic demand approaches the effective capacity of the local critical zone, the system gradually transitions to an unstable operating regime. Further increases in traffic flow rate result in system oversaturation, leading to a sharp increase in traffic delays (Fig. 3). Figure 3 illustrates the impact of a public transport stop on vehicle delays as a function of traffic flow rate, comparing scenarios with and without a public transport stop located at the exit of a roundabout. The threshold values shown in the figure are illustrative and intended to demonstrate the qualitative behaviour of the proposed criteria rather than represent a specific field case. Analysis of the graph indicates that under low and moderate traffic demand levels (up to 1,100 veh/h), the traffic stream operates in a stable regime. Within this range, traffic delay increases gradually, while the difference between scenarios with and without a public transport stop remains relatively small. This can be explained by the availability of a sufficient number of acceptable gaps for lane-changing manoeuvres and the absence of lane oversaturation. For traffic flow rates ranging from 1,100 to 1,400 veh/h, a transitional operating regime is observed. Traffic delays begin to increase more rapidly, particularly in the presence of a public transport stop. During this phase, lane-changing demand increases, whereas the number of acceptable gaps available in the adjacent lane gradually decreases. When traffic demand exceeds 1,400 veh/h, the traffic stream enters an oversaturated regime. Traffic conditions are characterised by a sharp increase in delays, with the presence of a public transport stop significantly amplifying the negative effect. This phenomenon is attributable to the simultaneous action of three factors: the reduction in effective lane capacity caused by periodic occupation of the outer lane by public transport vehicles, the increase in the number of forced lane-changing manoeuvres, and the shortage of acceptable gaps required for their execution.

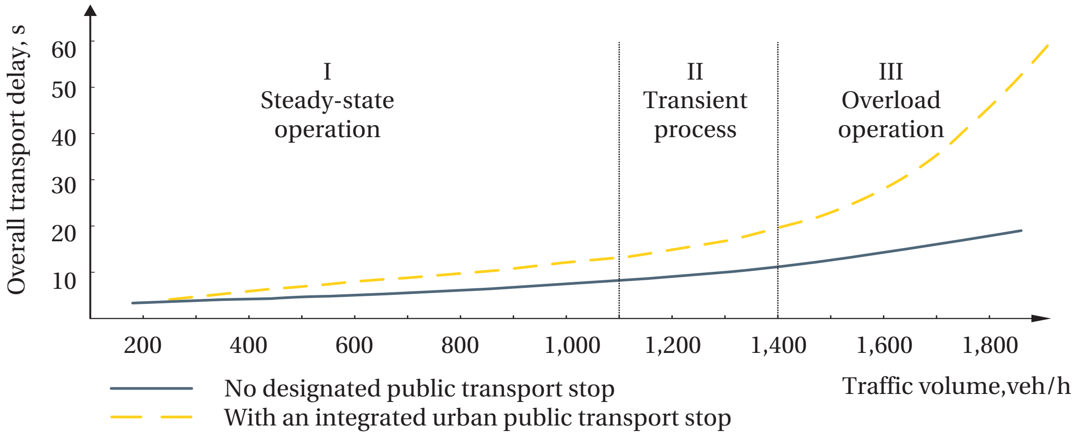

Figure 3. Conceptual relationship between traffic delays and traffic flow rate in the presence of a public transport stop
Source: developed by the authors

The obtained results demonstrate that the impact of a public transport stop on traffic delays is nonlinear and becomes particularly significant under high traffic demand conditions, when the system approaches a critical operating state. From a practical perspective, traffic delays may be reduced through the appropriate placement of public transport stops relative to the roundabout exit, increasing the length of the weaving section, reducing the duration of outer-lane blockage, and implementing traffic management measures aimed at decreasing forced lane-changing demand. The findings support previous studies emphasising the critical role of gap acceptance and lane-changing processes in determining roundabout capacity, such as K. Shaaban & H. Hamad (2020) and A. Polus *et al.* (2003). However, unlike existing approaches, the proposed system of criteria incorporates the combined effects of public transport stop operations, lane-changing demand, and the shortage of acceptable gaps in the adjacent traffic stream. This makes it possible to provide a more comprehensive description of the mechanisms responsible for traffic delay formation at roundabout exits and expands the opportunities for developing and justifying traffic management and engineering measures aimed at mitigating such delays. The proposed approach may be applied both to the evaluation of existing traffic management schemes at urban roundabouts and to the design of new transportation facilities. Its application enables the assessment of the suitability of locating a public transport stop within the roundabout exit area, the determination of the required weaving section length, and the justification of traffic management measures intended to reduce delays and improve the operational performance of the intersection. The proposed methodology consists of the following sequential stages:

1. Determination of traffic flow characteristics within the local critical zone.
2. Estimation of the lane occupancy factor caused by public transport stop operations.
3. Calculation of the effective lane capacity.
4. Assessment of lane-changing demand generated by temporary lane blockage.
5. Determination of the critical gap and the number of acceptable gaps available for manoeuvre execution.
6. Verification of the proposed delay-reduction criteria.
7. Identification of stable, transitional, or critical traffic operating conditions.

The obtained results indicate that traffic delays at roundabout exits are determined not only by traffic demand and available capacity but also by the interaction between lane-changing demand and the availability of acceptable gaps in the adjacent traffic stream. The analysis demonstrates that even when the effective lane capacity remains sufficient, traffic performance may deteriorate if the number of available gaps becomes inadequate for the execution of mandatory lane-changing manoeuvres. The obtained findings are generally consistent with previous studies addressing roundabout operations and public transport stop impacts. Similar conclusions regarding the influence of public transport stop placement on traffic performance were reported by I. Medvediev & S. Soroka (2020) and H. Jin *et al.* (2019). Furthermore, the importance of gap acceptance and driver decision-making processes identified in the present study is in agreement with the findings of K. Shaaban & H. Hamad (2020) and H. Jiang *et al.* (2024). However, unlike previous research, the proposed approach simultaneously considers effective lane capacity, lane-changing demand, and acceptable gap availability within a unified analytical framework. The principal contribution of the proposed methodology lies in the introduction of the concept of a local critical zone at roundabout exits affected by public transport stop operations. The developed criteria make it possible to identify traffic conditions under which the combined influence of lane blockage, lane-changing demand, and limited gap availability may result in unstable traffic operation and increased delays. From a practical perspective, the proposed criteria may assist traffic engineers in evaluating alternative locations of public transport stops, determining appropriate weaving section lengths, and identifying traffic conditions requiring operational improvements. The methodology may also support decision-making during the design and reconstruction of urban roundabouts by providing a simple analytical tool for preliminary traffic performance assessment. Several limitations of the proposed approach should be acknowledged. The presented methodology is based on simplified assumptions regarding traffic arrival distributions and average public transport dwell times. Furthermore, the proposed framework does not explicitly account for variations in driver behaviour, heavy vehicle composition, weather conditions, or traffic signal interactions. The threshold values presented in the illustrative example are scenario-specific and should not be interpreted as universal design values. Future research should focus on model calibration and validation using field observations collected at urban roundabouts with different geometric and traffic characteristics.

Conclusions

The rationale for treating the exit section of a roundabout located adjacent to a public transport stop as a local critical zone had been established, as this was the area where primary additional vehicle delays were formed. Theoretical analysis had shown that delay formation within this local critical zone was driven by the combined influence of three interrelated factors: a temporary decrease in the capacity of the right-hand lane caused by public transport stop operations, an increase in the intensity of mandatory lane-changing manoeuvres, and a lack of suitable gaps in the adjacent traffic stream. The research objective was achieved by developing a set of criteria for mitigating traffic delays at roundabout exits. The proposed framework was founded on three key principles: minimising total delay experienced by the traffic stream, maintaining consistency between traffic demand and effective lane capacity within the stop influence area, and balancing lane-changing demand with the availability of acceptable gaps in the adjacent traffic stream. The practical value of the findings lay in their applicability to the justification of public transport stop placement, the determination of the required length of weaving sections, and the selection of traffic management and engineering measures intended to enhance the operational performance of roundabouts. The obtained results confirmed that the location of a public transport stop within the roundabout exit influence area significantly affected traffic performance. Relocating the stop beyond the local critical zone could reduce lane-changing demand and improve traffic operating conditions. The illustrative scenario demonstrated the practical applicability of the proposed criteria. For an exit flow rate of 1,000 veh/h and a public transport stop occupancy factor of 0.125, the effective lane capacity was estimated at 1575 veh/h, while approximately 331 acceptable gaps per hour were available for lane-changing manoeuvres. Under these conditions, the traffic stream remained within a stable operating regime. Future research should focus on validating the proposed models through field observations and on identifying the threshold operating conditions of the local critical zone for various traffic control schemes, public transport stop configurations, and numbers of traffic lanes.

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Conflict of Interest

None.

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Критерій зменшення затримок руху на виїзді з кільцевого перехрестя за наявності зупинки міського транспорту

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Анотація. Ефективність кільцевих перехресть значною мірою залежить від умов руху на вихідних ділянках, зокрема розташування зупинок громадського транспорту одразу після виїзду з кільця або поблизу нього, що знижує пропускну здатність і підвищує затримки через вимушені маневри та дефіцит прийнятних інтервалів у потоці. Мета роботи полягала у розробленні критеріїв зменшення затримок руху на виїзді з кільцевого перехрестя за наявності зупинки міського транспорту з урахуванням процесів перешикування транспортних засобів та величини граничного інтервалу в суміжній смузі руху. Дослідження виконано з використанням положень теорії транспортних потоків, методів оцінювання пропускної здатності та визначення критичних інтервалів, а також показано, що затримки на виїзді з кільцевого перехрестя зумовлені блокуванням правої смуги громадським транспортом, попитом на перешикування та нестачею придатних інтервалів у суміжному потоці в межах локальної критичної зони. Запропоновано систему критеріїв зменшення затримок, що ґрунтується на мінімізації сумарної затримки в локальній критичній зоні, забезпеченні відповідності інтенсивності транспортного потоку ефективній пропускній здатності виїзду та узгодженні попиту на перешикування з можливістю його реалізації в наявних умовах руху. Також визначено умови переходу транспортного потоку в критичний режим функціонування за показниками швидкості, щільності та пропускної здатності. Для апробації запропонованого методичного підходу розглянуто розрахунковий сценарій функціонування двосмугового виїзду з кільцевого перехрестя. За інтенсивності транспортного потоку на виїзді 1000 авт/год, інтенсивності руху в суміжній смузі 900 авт/год та середній тривалості блокування правої смуги маршрутним транспортом 25 с отримано значення коефіцієнта зайнятості смуги $\varphi = 0{,}125$, що обумовлює зниження її ефективної пропускної здатності до 1575 авт/год. За цих умов інтенсивність руху не перевищує ефективної пропускної здатності виїзду, що забезпечує функціонування транспортного потоку у стабільному режимі та створює передумови для виконання маневрів перешикування без формування критичних затримок. Отримані результати можуть бути використані для обґрунтування розташування зупинок міського транспорту, визначення довжини ділянок перешикування та вибору організаційно-технічних заходів для підвищення ефективності функціонування кільцевих перехресть і зменшення затримок руху

Ключові слова: організація дорожнього руху; транспортний потік; перешикування транспортних засобів; граничний інтервал; пропускна здатність