



Traffic Flow Research – Application of the Roundabout Investigation Model (MIKR)

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ABSTRACT

Monitoring vehicle movements at roundabouts and determining their operational throughput traditionally relies on tracking individual turning movements, a process that is technically demanding, labour-intensive and often impractical for complex multi-leg roundabouts. This study proposes a simplified approach to data collection and the determination of roundabout flow parameters. Two data collection techniques were examined: simplified manual counting of vehicles at entry legs and automated licence plate recognition. For roundabout flow parameters, determining the key methodological contribution is applying the roundabout investigation model (MIKR). Model MIKR enables capacity and turning-movement estimation using only entry and exit counts, thereby substantially reducing the scope of required field observations compared with conventional trajectory-based methods. The results show that licence plate recognition can determine turning flows with an accuracy of approximately 90%. The MIKR model reliably estimates roundabout capacity without requiring vehicle trajectory tracking. These findings confirm the practical value of the MIKR approach and highlight its potential for more efficient and cost-effective traffic-flow analysis at roundabouts.

KEYWORDS

capacity analysis; turning movement counts; data collection methods.

1. INTRODUCTION

Roundabouts represent an effective traffic solution implemented in many countries, such as the United Kingdom, Germany and France, particularly at complex intersections with a high risk of traffic accidents. Their advantages are in reducing the number of conflict points, lowering vehicle speeds and improving visibility. Furthermore, up to a certain level of traffic demand, they enable higher throughput (traffic volumes), shorter delays, lower construction and maintenance costs, reduced fuel consumption and emissions, and better integration into the surrounding environment.

However, roundabouts also present certain drawbacks, including drivers' initial unfamiliarity, difficulties in accessibility for special vehicles, and discomfort experienced by pedestrians and cyclists due to longer crossing paths. At some locations, construction costs and the need for enhanced lighting may be significant. Although signalised intersections may perform better under specific conditions, roundabouts generally offer greater efficiency and safety.

Their application is not universal, and each case requires individual planning, including analysis of traffic demand, safety and economic factors. Roundabouts make a significant contribution to the modernisation and improvement of the transportation system. Clear limitations are evident in existing methods for determining roundabout capacity [4], such as:

- Most existing methods rely on static models that do not account for dynamic changes in traffic flows and driver behaviour,
- Conventional approaches often fail to consider specific local factors, such as driver habits or unpredictable entry flows,
- Current methodologies inadequately address congestion and phenomena such as spillback,
- Limited use of modern data collection techniques (e.g. cameras, sensors) reduces analytical accuracy,
- Capacity estimation becomes difficult under changing priority rules or emergency situations.

The reasons and need for improving traffic flow investigation methods stem from broader trends in shaping sustainable urban mobility strategies.

Vehicle flow analysis at roundabouts, based on turning movement counts, is significantly more complex and challenging compared to standard four-leg intersections or at T and Y-type junctions. Manual turning movement counts at roundabouts require tracking each vehicle from the entry leg to the exit leg of the roundabout. In roundabouts, particularly those with a higher number of legs, larger radius or more than one circulating lane, each vehicle must be followed from a specific entry leg to its corresponding exit leg to assign it to a particular movement. For a four-leg roundabout, a minimum of 12 observers is required simultaneously, each of whom must track every vehicle from entry to exit, which becomes unfeasible under high traffic volumes. In addition, each observer must also account for vehicle classification, further increasing the workload. Advanced data collection technologies, including video analytics and AI-based trajectory extraction, have significantly improved the accuracy of turning-movement estimation, but their application remains limited. Many cities lack the financial and technical capacity to implement such systems.

The proposed model for roundabout traffic flow investigation, abbreviated as MIKR [2, 3], is based on vehicle counts at the entry and exit legs of the roundabout, without requiring turning movement data. The model outlines a method for determining vehicle flows along a roundabout section and roundabout capacity. This model represents an alternative approach that avoids tracking individual vehicle trajectories. Earlier publications of this model demonstrated the theoretical foundation of the model and its potential to simplify turning-movement estimation; however, they provided limited empirical validation and did not incorporate modern data collection techniques that could extend the model's practical applicability for roundabout capacity calculation. In particular, previous studies did not explore the integration of automated licence-plate recognition (LPR) systems as a complementary data source for validating turning movement patterns and evaluating time-dependent parameters of vehicle circulation.

The motivation for reapplying the MIKR model in this study arises from the need to develop a method that can deliver reliable flow parameters with minimal field effort, while remaining applicable in environments where advanced sensing technologies may be unavailable. By introducing LPR data for the first time in combination with the MIKR framework, this study enables a more detailed assessment of time-dependent characteristics of roundabout circulation.

The contribution of this research is threefold. First, it provides the first empirical evaluation of the MIKR model using both manual and LPR-based data, thereby extending previous theoretical work on roundabout capacity calculation. Second, it demonstrates that roundabout capacity can be estimated reliably using only entry and exit counts, substantially reducing personnel requirements compared with trajectory-based observation. Third, it positions the MIKR model as a practical and cost-effective alternative for traffic flow analysis in contexts where AI-based methods are either infeasible or unnecessary.

2. LITERATURE REVIEW

Methods for traffic flow analysis at roundabouts have been employed in developing models to determine roundabout capacity. The most recent approaches include methodologies based on the Highway Capacity Manual (HCM) [1,4–6], as well as advanced software tools such as SIDRA (the SIDRA software combines the HCM approach with additional simulation capabilities, enabling analysis of various roundabout configurations, including multi-lane and signalised roundabouts, while optimising capacity based on actual traffic flows) [7], also TRL (Transport Research Laboratory) models [8] which apply linear relationships to estimate capacity. HCM provide structured procedures for analysing roundabout performance; it relies heavily on obtaining detailed information about vehicle trajectories, data that are often challenging to collect reliably in real-world conditions. The HCM provides guidelines for collecting traffic data and defines traffic flow in the context of roundabout capacity. Its methodology utilises data on traffic volumes, vehicle types, delay times and operating conditions to determine the capacity of roundabouts. Based on these inputs, HCM offers

expressions and parameters for calculating traffic flow and estimating capacity under various conditions. More accurate and comprehensive data on traffic flows have continuously improved the accuracy and flexibility of roundabout modelling, enabling better adaptation to local conditions.

A number of recent studies have attempted to address the complexity of collecting reliable roundabout flow data by introducing mathematical formulations, reconstruction algorithms or sensor-based detection systems aimed at reducing the number of required counters or simplifying the observation process. In this context, a range of relevant studies can be highlighted:

- The paper by Al-Sobky and Hashim [9] presents a generalised mathematical model for determining the number of traffic turns at roundabouts. The conclusions of the study highlight that the model allows for more accurate traffic predictions and the optimisation of roundabout design, which can improve traffic safety and efficiency in urban areas. The model is flexible and can be adapted to various traffic conditions. In this paper, a simplified model is also developed and presented for calculating the most complex turning movements based on measurements of exit flows, circulating flows and the easiest turns. The validation example confirmed that the proposed model can significantly reduce labour costs required in the field or office. In conclusion, further research is recommended to examine the model using comprehensive field data for roundabouts with varying numbers of legs. The data for the research were collected at roundabouts through field measurements. This includes recording the number of vehicles passing through specific points, particularly for different types of turns and directions of travel. The data were collected using both manual and automated traffic monitoring methods.
- Europarc Intersection Dataset [10]: Data collected via video cameras; includes large multi-lane signalised roundabouts in France and is characterised by inefficient manual counting.
- Vehicle delay and queue length models are important indicators for optimising signal timing plans at signalised roundabouts. However, significant attention is currently being directed toward unsignalised roundabouts. In the work by Bie Y, Mao C. and Yang M. [11], a model was developed to estimate vehicle delays and queue lengths for the purpose of adaptive traffic control at signalised roundabouts. The conclusions of the study highlight that the application of these models can significantly improve traffic efficiency at roundabouts through adaptive signal management, reducing delays and increasing vehicle throughput. The results show that all deviations from accuracy were below 15%, with average deviations below 10%. The data were collected in the field through manual counting at a real roundabout.
- Authors [12] collected data from five roundabouts, data were collected using LiDAR and webcams, and the classification includes cars, trucks, motorcycles and buses. It covers five small single-lane unsignalised roundabouts. The conclusions of the study highlight that the collected dataset is a valuable resource for research in the field of intelligent transportation systems and naturalistic driving conditions. The data enable a better understanding of driver behaviour, safety and traffic efficiency at unsignalised roundabouts. The authors emphasise the importance of such datasets for the development and testing of new traffic management systems and safety technologies.
- Authors [13] classified data that includes cars, bicycles and trucks. It covers five different roundabouts in three countries (Germany, the USA and China). The work includes different roundabout types, including HD maps in Lanelet2 format, vehicle acceleration and data accuracy not specified, limited trajectory diversity and only one type of road user. The data were collected from the Interaction Dataset using UAV and traffic cameras.
- The authors [14] collected movement data for vehicles and other road users at roundabouts recorded via drone-mounted cameras within the RounD Dataset. Entity categories have been cars, vans, trucks, buses, pedestrians, trailers, motorcycles and bicycles. Includes three different roundabouts in Germany. Contains 6 hours of recordings and 13,746 trajectories. The authors emphasise that this dataset contributes to a better understanding of complex dynamics in traffic and aids in the development of safer and more efficient autonomous driving systems. They also highlight the importance of this type of data for testing and training models in realistic driving conditions.
- The paper [15] compares a traditional iterative algorithm (the Biproportional Procedure) with state-based methods previously unused for estimating turn ratios at roundabouts, and validates and compares them using real-world traffic data. The main contribution of the study is the validated comparison of different methods based on real data obtained by drone and subsequently manually counted. Additionally, historical traffic data could easily be integrated into the proposed state estimation procedure, serving as additional constraints (e.g. with reasonable upper/lower bounds) within the estimation algorithm. The data were collected through field measurements in real roundabouts. Drivers drove through the roundabouts while

their movement data, including turning rate and vehicle position, were recorded using advanced sensors and technologies such as GPS and accelerometers.

- A group of authors in the paper [16] propose a methodology for using CV (connected vehicle) data with a three-second reporting interval to estimate delay, level of service, queue length and origin-destination characteristics for roundabouts. The advantage of this technique is that it can be applied without the extensive and costly field data collection procedures typically required for evaluating roundabout efficiency. The model for estimating delay and level of service uses the Purdue Probe Diagram, which is commonly used in signal analytics. The model presented in this study can be used to assess the systemic efficiency of roundabouts.
- The paper [17] utilised visual data collected through video cameras, allowing such information to be extracted via computational methods. The paper proposes a method for vehicle detection, counting and tracking based on roundabout video recordings. The method offers two main contributions: (i) only moving vehicles are considered for tracking (moving vehicle detection), and (ii) the trajectories generated by object tracking algorithms are post-processed to reduce the rate of false trajectories (trajectory union). Vehicle detection is performed using YOLOv4, while tracking during the video is implemented using either the Kalman filter or the DeepSORT algorithm. The output of the proposed method is compared to the results of manual counting and reference tracking data, where the entry/exit matrix was generated using YOLOv4 and a basic object tracker. The results show that for a 20-minute video containing 297 vehicles, the absolute error of the proposed method is 14 vehicles, corresponding to a normalised absolute error of 1.571%. In the same video, the error metrics obtained by the reference method were 33 vehicles or 3.704%.
- In work [18], virtual zones are used where various vehicle counting methods at intersections are based on image processing techniques. Data on vehicle counts were obtained from four methods, including manual counting and three image-processing-based approaches. The study improves the accuracy of counting results by incorporating transportation engineering parameters such as traffic density and volume. The results showed that the “New Type of Virtual Zone” method achieved 95% accuracy in vehicle count estimation. The data were collected from image processing techniques.
- The study [19] aims to evaluate the capacity of both single-lane and multilane roundabouts in handling different levels of heterogeneous traffic flow. Four different models (linear regression model, non-linear regression model, VISSIM simulated model and calibrated Highway Capacity Manual [HCM] model) were developed for each roundabout, and results were compared with the field capacity values. Careful consideration was given to the statistical characteristics of the data, and different statistical tests were conducted to evaluate the reliability of these models. A separate set of roundabouts was used to test and validate the models. Results reveal that a non-linear regression model, based on both the geometrical and traffic flow characteristics, outperforms all other models. Additionally, sensitivity analysis was performed to check the effect of various parameters on the roundabout capacity. Data were collected at 10 roundabouts spread across three Indian cities.
- The paper [20] introduces a novel approach combining modern roundabout capacity models with the old rotary ones. Mixed data collection model. In particular, the present study proposes a mixed approach based on an iterative process that combines the English TRRL model, which is suited for the old rotaries and based on short weaving sections capacity, with the features of the HCM-7th entry capacity model of the modern roundabouts, which is based on the circulating-traffic priority rule. Such an approach is rooted in the total capacity criteria and traffic conditions where all roundabout entrances reach congestion simultaneously. Compared to the past, this new approach makes entry performance estimation, such as average delay and queue length, bridging the gap between outdated and current methodologies in the field of rotary intersection design and assessment.
- The paper [21] compares different types of roundabouts by estimating the deterministic fundamental diagram (MFD) and using microscopic traffic simulations. The data were collected through traffic recordings, sensors or other forms of traffic monitoring that enable the analysis of overall flow and traffic conditions at roundabouts. The deduction of MFD for different roundabout types (single and double-lane, flower and turbo-roundabout) is based on reasonably simplified traffic and boundary conditions. MFDs are estimated through several OD traffic matrices, considering as outputs the values of the macroscopic traffic variable deduced in time intervals of 5 min and 1 h. The findings from this research, in terms of total capacity, travel times and level of service (LOS) estimation, may be useful for traffic and highway engineers in many realistic applications to partially face congestion phenomena in urban areas. MFDs

allow us to determine the best roundabout type based on the traffic demand and represent a parsimonious method for monitoring and controlling traditional and unconventional or smart roundabouts, even in the presence of connected and automated vehicles (CAVs).

- In the paper [8], the authors use direct capacity measurement and testing of the three selected most commonly used roundabout capacity models (HCM 2010, Akcelik and Brilon-Wu) was performed. All three models have different theoretical backgrounds. Based on the directly measured capacity, it was established that the application of the Brilon-Wu model gives the results closest to the directly measured capacity in the analysed local conditions in Bosnia and Herzegovina (small urban roundabout). The model is reliable with respect to overall volume ranges and has a good theoretical background based on conflict theory and queuing theory. In addition, this model provides the opportunity to analyse pedestrians and cyclists, which is especially important in urban environments.
- The study [22] aims to examine the efficiency of dedicated lanes for AVs in a roundabout with an unbalanced traffic flow pattern. Four factors of travel time, delay time, speed of vehicles and queue of vehicles have been selected as variables of traffic performance at the roundabout. Two microscopic traffic simulation software, AIMSUN and SIDRA Intersection, were used to examine the impact of the AV dedicated lanes at the roundabout. This study shows that the effects of an imbalanced traffic pattern in a roundabout are higher when the penetration rate of AVs is lower, and also, dedicated lanes in a roundabout's legs may improve traffic performance indicators when the penetration rate of AVs is higher, but this improvement is not significant.

Collectively, these studies illustrate the ongoing evolution of roundabout capacity analysis toward hybrid frameworks that combine analytical transparency with modern data acquisition and estimation techniques, within which the MIKR model can be positioned as a complementary approach that emphasises simplified yet robust input requirements for practical capacity and flow assessment.

3. METHODOLOGY

3.1 Data collection methods

The traffic flow observation at the subject roundabout was conducted on 24 April 2024. The input values for traffic flow analysis using the MIKR model include the number of vehicle entries U_i and vehicle exits I_i at each roundabout leg.

The vehicle flow data were collected using two methods:

- Method 1: A custom-developed software tool created by the authors, enabling manual registration of vehicle entry/exit events at each roundabout leg. The exact time of each vehicle's movement is recorded with one-second precision, along with its classification. Observers count all vehicles entering the roundabout regardless of their exit leg, and likewise, all vehicles exiting the roundabout regardless of their entry leg, and
- Method 2: Automated licence plate recognition based on camera footage. A dedicated software tool identifies licence plates at both the entry and exit points of the roundabout and registers the corresponding entry/exit times for each vehicle.

Method 1

Data collected using the dedicated software tool developed by the authors were obtained by processing video recordings from the field. The process involves starting the video and manually selecting a vehicle (based on predefined vehicle categories) in the software interface as it enters through a designated leg (e.g. leg C). The software automatically records the entry time (T_{entry}). The vehicle is then tracked until it exits through another leg (e.g. leg B), at which point the exit time (T_{exit}) is recorded with a single click on the corresponding leg.

The structure of input data is presented in tabular format below (*Table 1*). The number of vehicles in the Velešići roundabout intersection is presented in *Table 2*.

Table 1 – Entries and exits vehicle data (one part of the table) for the Velešići roundabout intersection

Time	Cumulative vehicle entries by leg			Cumulative vehicle exits by leg		
	Au	Bu	Cu	Ai	Bi	Ci
07:47:13		1				
07:47:14	1					
07:47:18	2	2				
07:47:36	4	6		1	2	
07:47:38		7	1		2	

Table 2 – Number of vehicles in the Velešići roundabout intersection (one part of the table)

Time	Cumulative entries – All legs $U = A_u + B_u + C_u$	Cumulative exits – All legs $I = A_i + B_i + C_i$	Entries – Exits $U - I$	Number of vehicles in the intersection
07:47:13	1	0	1	1
07:47:14	2	0	2	2
07:47:18	4	0	4	4
07:47:20	5	0	5	5

Method 2

Data collected via licence plate recognition of each vehicle entering or exiting the roundabout. The data are based on camera footage and use the DTK Licence Plate Recognition Solution [23]. Licence plates of vehicles were identified at all roundabout legs (entry and exit) along predefined lines marking roundabout entry/exit points in real time. A portion of the collected data is presented in Table 3.

Table 3 – Licence plate identifiers captured by OCR cameras by leg and movement direction

Leg B		Leg C		Leg A		Entries in B from			Entries in A from			Entries in C from		
Entries	Exits	Entries	Exits	Exits	Entries	A	B	C	A	B	C	A	B	C
LPi	LPi	LPi	LPi	LPi	LPi	0	1	0	0	1	0	0	1	0
LPi	LPi	LPi	LPi	LPi	LPi	0	1	0	0	1	0	1	0	0
LPi	LPi	LPi	LPi	LPi	LPi	0	0	0	0	1	0	0	0	0

LPi – Recorded licence plate

The accuracy of data obtained using this method exceeds 90%, which should be taken into consideration when using the dataset. In addition, this method does not allow identification of vehicle category, meaning that each vehicle is treated as an individual unit, with no distinction made between, for example, a bus and a passenger car.

3.2 Description of the MIKR model

The mathematical foundations of the MIKR model, including determination of traffic flow on roundabout segments based on vehicle entries and exits, determination of traffic flow on roundabout segments based on vehicle turning movements and determination of roundabout service volume, have been extensively described in earlier publications [2,3]. In this study, those formulations are applied without modification. While previous studies applied MIKR primarily to reconstruct flow distributions along roundabout segments, the present work extends its practical use by introducing the estimation of roundabout capacity.

Capacity is defined as the maximum possible vehicle flow rate per unit of time (h), expressed as $C = q_{\max_possible}$ (veh/h). The traffic flow density g represents the number of vehicles along the length of the circulating lane within the roundabout, and can be calculated by dividing the number of vehicles in the roundabout N (veh) by the circumference of the centreline of the circulating lane L_o (m) (Equation 1):

$$g = 1,000 * N/L_o = 1,000 * N/81.64 \text{ (veh/km)} \tag{1}$$

The maximum number of vehicles in the roundabout depends on the safety gap between vehicles, determined by drivers, and is therefore stochastic in nature. The total length of roadway occupied by a single vehicle, including the safe stopping distance, is equal to the sum of the vehicle length L_v and the gap L_{ras} between the front of one vehicle and the rear of the one in front of it (Figure 1). From a safety perspective, this gap L_{ras} varies within the range (Equation 2):

$$L_{rasmin} < L_{ras} < L_{rasmax} \tag{2}$$

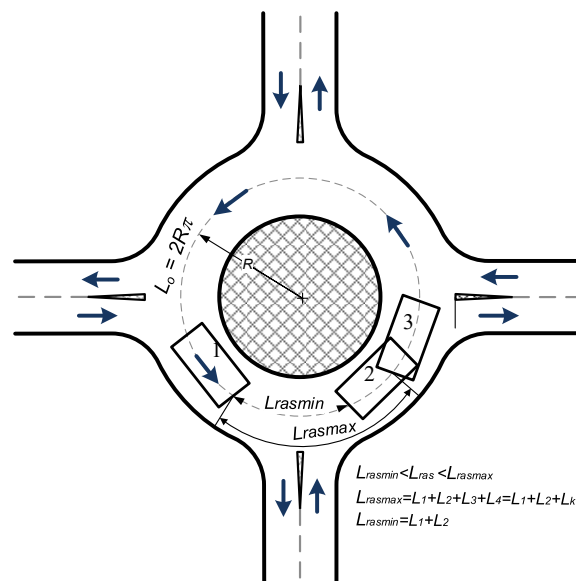


Figure 1 – Distance between vehicles in the traffic flow within a roundabout

Assuming that the maximum deceleration of both vehicles is the same (b_{max}), the minimum headway L_{rasmin} is equal to the distance travelled during the driver’s reaction time L_1 , the distance for mechanical brake response time of the vehicle L_2 , and the stopping gap in a stationary position $L_{z0} = 1.00$ (m) (typically ranging from 1 to 2 metres) [24] (Equation 3):

$$L_{rasmin} = L_1 + L_2 + L_{z0} \text{ (m)} \tag{3}$$

The maximum headway L_{rasmax} is the sum of the distances traveled during the driver’s reaction time L_1 , the distance for mechanical brake response time of the vehicle L_2 , the braking distance L_k and the stopping gap in a stationary position $L_{z0} = 1.00$ (m) (Equation 4):

$$L_{rasmax} = L_1 + L_2 + L_k + L_{z0} \text{ (m)} \tag{4}$$

The maximum number of vehicles in the roundabout is calculated as (Equation 5):

$$N_{max} = \frac{L_o}{L_v + L_{ras}} \tag{5}$$

Since vehicle lengths vary within the traffic stream, it is necessary to determine the average vehicle length $\overline{L_v}$ for each observation interval. To estimate the maximum headway $L_{rasmax} = L_z + L_{z0}$ the total stopping distance L_z was used, which consists of (Equation 6):

$$L_z = L_1 + L_2 + L_k \text{ (m)} \tag{6}$$

where: L_1 (m) – distance travelled during driver reaction time, L_2 (m) – distance during braking system response delay, L_k (m) – braking distance during deceleration.

The capacity of the roundabout C is determined as the product of the space speed of the traffic flow v_s (km/h) and the traffic flow density q (veh/km).

4. RESULTS: TRAFFIC FLOW ANALYSIS AT A ROUNDABOUT USING THE MIKR MODEL

The application of the MIKR model is presented through the example of a three-leg roundabout, including a real-life case study of a roundabout located in Sarajevo. This paper presents the results of the analysis for the roundabout located in the urban area of Velešići - Sarajevo (Figure 2). The intersection is T-type (three-leg), situated on roads connecting relatively densely populated parts of the city of Sarajevo. It consists of key elements such as legs (arms), entry and exit lanes on each leg, segments between adjacent legs, and the centreline radius of the circulating lane. Leg A leads from the Ciglane neighbourhood, Leg B from the railway station, following the route of the First Transversal, and Leg C from the Velešići neighbourhood. All legs are single-lane. The roundabout has one circulating lane approximately 5 metres wide. The radius of the centreline of the circulating lane is 13 metres. The positions where vehicle entries and exits were recorded are marked by transverse lines and GPS coordinates, as shown in Figure 2. A three-leg roundabout was selected for model application due to its simplicity and the ability to observe specific dependencies among the modelled variables. Basic roundabout elements and traffic observation setup are:

- $n = 3$ – number of legs of the roundabout
- $R_1 = 16$ (m) – radius of the outer edge of the circulating lane
- $r = 10$ (m) – radius of the inner edge of the circulating lane
- $R = 13$ (m) – radius of the centreline of the circulating lane
- $L_0 = 2 * R * \pi = 8164$ (m) – circumference of the circulating lane at the centreline
- T_c (min) – cycle time (calculated as the average value \bar{T}_c over the observation period)
- $v_s = 15$ (km/h) – assumed average vehicle speed in the circulating lane
- $Tc \approx tc = 0.3769 * R/vs = 0.327$ (min) = 19.6 (s) – cycle duration
- $T_{sn} = 08:50:49 - 07:47:13 = 01:03:36 = 3,816$ (s) – total observation time
- $n_c = 194.69$, INT (194.69) = 194 – number of cycles during the observation
- $\bar{T}_c = 3,816/194 = 19.67$ (s) – corrected cycle time (adjusted due to rounding of the number of cycles)

The final values for cycle duration and average speed during the cycle will be determined after observation.

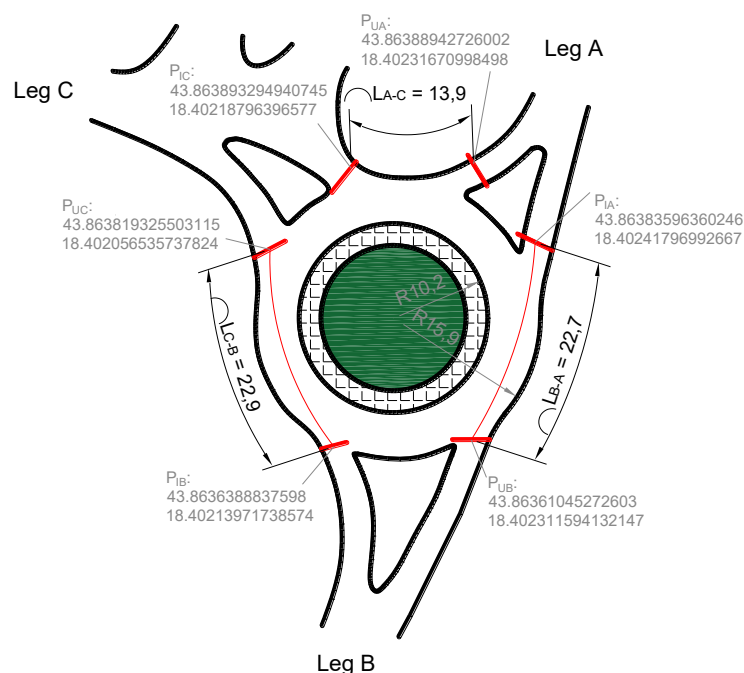


Figure 2 – Roundabout intersection in Velešići, Sarajevo

The data collected using the two previously described methods (see Section 3.1) were statistically processed, and the most relevant results of the analysis are presented below.

Table 4 presents the statistical analysis of vehicle travel times across roundabout segments during the observation period from 07:47 to 08:47, based on data collected using the dedicated software. The table includes data for various turning movements, showing the number of observed vehicles (N), minimum and maximum travel times, total travel time, as well as average travel time (t_{sr}), standard deviation (S_{tDev}) and variance (V_{ar}) for each direction.

Table 4 – Statistical analysis of vehicle travel time on roundabout segments during the observation period 07:47–08:47

Approach	Vehicle number - N		Travel time - t_{sr} (s)					
			Min	Max	Sum	t_{sr}	S_{tDev}	V_{ar}
A-A	2	311	4	7	11	5.50	2.12	4.50
A-B	266		4	55	2,178	8.19	6.71	45.05
A-C	43		4	65	296	6.88	9.20	84.68
B-A	485	681	4	9	2,723	5.61	1.36	1.84
B-B	25		4	83	536	21.44	23.90	571.09
B-C	171		4	9	1,266	7.40	1.38	1.91
C-A	40	242	5	56	396	9.90	9.11	83.02
C-B	202		4	83	1,362	6.74	6.79	46.06
C-C	0							

Based on the data presented in Table 5, the average cycle time (\bar{T}_c) can be calculated as the sum of average travel times along adjacent segments of the roundabout (Equation 7):

$$\bar{T}_c = t_{srAC} + t_{srCB} + t_{srBA} = 6.88 + 6.74 + 5.61 = 19.23 \text{ (s)} \tag{7}$$

Table 5 – Statistical analysis of cycle time based on segment travel time

Segment	t_{sr} (s) – Travel time per segment	Segment	t_{sr} (s)	Segment	t_{sr} (s)
A-A	5.50	B-A	5.61	C-A	9.90
A-B	8.19	B-B	21.44	C-B	6.74
A-C	6.88	B-C	7.40	C-C	

The average traffic flow speed during the period 07:47–08:47 can be determined based on the average cycle time (\bar{T}_c) and the circumference of the centreline of the circulating lane $L_0 = 81,64$ (m) (Equation 8):

$$\bar{v}_s = L_0/\bar{T}_c = 81.64/19.23 = 4.245 \text{ (m/s)} = 12.28 \text{ (km/h)} \tag{8}$$

The average headway \bar{l}_s between vehicles during the observed period with N vehicles is (Equation 9):

$$\bar{l}_s = 3,600/N = 3,600/1,234 = 2.92 \text{ (s)} \tag{9}$$

The average spacing \bar{L} between vehicles (front-to-front distance) is (Equation 10):

$$\bar{L} = \bar{v}_s * \bar{l}_s = 4.245 * 2.92 = 12.4 \text{ (m)} \tag{10}$$

Note: The accuracy of the average speed calculation improves when the segment lengths are defined such that their total sum equals the circumference of the centreline of the circulating lane. It is evident that the average traffic speed within the roundabout varies even within shorter time intervals of the observation period. A 5-minute interval is sufficient for analysis and should not be shorter than the average cycle time (\bar{T}_c). By applying a 5-minute interval, statistical parameters of traffic speed can be determined for each cycle, allowing for analysis based on the theory of stochastic processes, as presented in *Table 6*.

Table 6 – Average speed per segment and cycle v_{sr} (km/h) based on segment travel time

Intervals (excluding upper bound)	A-A	A-B	A-C	B-A	B-B	B-C	C-A	C-B	C-C
07:45:00-07:50:00	13.04	14.47	8.05	13.47	25.34	12.19	11.46	9.56	
07:50:00-07:55:00		8.92	7.74	16.03	12.76	16.34	9.97	7.68	
07:55:00-08:00:00		12.84	8.19	14.29	14.05	12.69	12.52	10.28	16.24
08:00:00-08:05:00		14.09	11.68	14.86	27.47	15.44	14.45	8.30	
08:05:00-08:10:00		16.72	5.78	14.46	20.90	17.12	19.15	16.86	
08:10:00-08:15:00	21.00	20.63	7.62	14.60	20.65	17.38	15.08	14.41	
08:15:00-08:20:00		22.41	9.28	17.13	19.84	19.08	17.68	16.91	
08:20:00-08:25:00	22.50	23.53	11.95	13.00	19.36	16.67	14.25	15.28	
08:25:00-08:30:00		24.50	11.51	16.24	21.39	17.82	18.35	16.83	
08:30:00-08:35:00	18.00	21.76	11.39	16.26	19.82	19.30	14.47	13.96	
08:35:00-08:40:00		20.04	12.63	16.49	21.58	19.75	18.52	17.35	12.27
08:40:00-08:45:00		18.87	8.34	18.68	19.32	20.57	22.66	19.93	
08:45:00-08:50:00		22.13	10.01	16.91	26.85	21.96	17.62	13.27	
08:50:00-08:55:00							12.53	11.22	

The average cycle speed values can be determined based on the data for the most heavily loaded direction that forms a closed cycle – in this case, direction B–B (*Table 7*). It is particularly important that the number of observations within each interval is sufficiently large and that their values are relatively uniform. The calculated average speed and average cycle time are: $\bar{v}_s = 20.72$ (km/h) and $\bar{T}_c = 17.08$ (s).

Table 7 – Statistical analysis of average speed v_{sr} (km/h) in 5-minute intervals for direction B–B – by cycle

Segment	Intervals (excluding upper bound)	<i>N</i>	<i>Min</i>	<i>Max</i>	<i>Sum</i>	v_{sr} (km/h)	S_{tDev}
B-B	07:45:00-07:50:00	11	3.25	67.50	278.78	25.34	25.26
B-B	07:50:00-07:55:00	15	6.00	33.75	191.43	12.76	7.28
B-B	07:55:00-08:00:00	9	7.30	18.00	126.44	14.05	4.17
B-B	08:00:00-08:05:00	15	5.09	90.00	412.00	27.47	27.81
B-B	08:05:00-08:10:00	14	12.86	38.57	292.62	20.90	7.36
B-B	08:10:00-08:15:00	10	15.88	30.00	206.47	20.65	4.63
B-B	08:15:00-08:20:00	14	11.74	33.75	277.70	19.84	5.00

Segment	Intervals (excluding upper bound)	<i>N</i>	<i>Min</i>	<i>Max</i>	<i>Sum</i>	<i>v_{sr}</i> (km/h)	<i>S_{tDev}</i>
B-B	08:20:00-08:25:00	9	14.21	30.00	174.25	19.36	4.98
B-B	08:25:00-08:30:00	8	14.21	33.75	171.10	21.39	6.33
B-B	08:30:00-08:35:00	11	13.50	30.00	218.02	19.82	4.04
B-B	08:35:00-08:40:00	11	14.21	45.00	237.41	21.58	8.57
B-B	08:40:00-08:45:00	9	14.21	24.55	173.84	19.32	3.74
B-B	08:45:00-08:50:00	10	18.00	67.50	268.47	26.85	15.46

Vehicle entries and exits by leg are illustrated in *Figure 3a*, and the number of vehicles within the roundabout is shown in *Figure 3b*. (Note: Cumulative vehicle entries and exits for all legs – number of vehicles ($N = U - I$) within the roundabout over time *t*.)

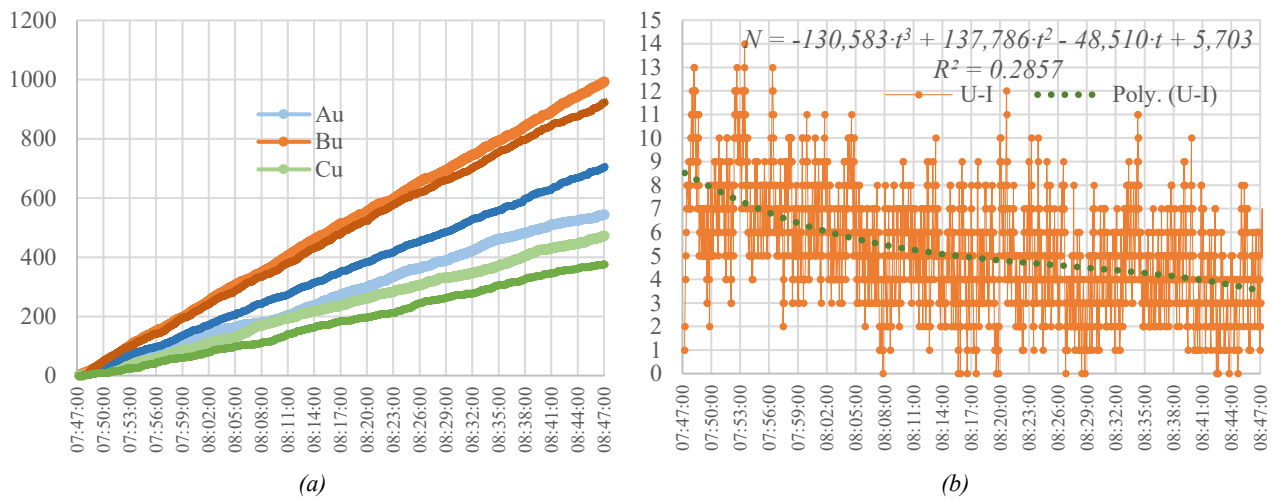


Figure 3 – A figure with two subplots: a) Cumulative number of vehicles entering and exiting the roundabout by leg; b) Number of vehicles within the roundabout

Based on the statistical analysis of the number of vehicles within the roundabout during the observation period, the following parameters were determined: Mean: 5.250691; Standard Error: 0.046467; Median: 5; Mode: 5; Standard Deviation: 2.338615; Sample Variance: 5.46912; Kurtosis: 0.075133; Skewness: 0.34607; Range: 14; Minimum: 0; Maximum: 14; Sum: 13300; Count: 2533.

The results indicate that:

- The average number of vehicles within the roundabout during the observation period was 5.25, confirming that slightly more than 5 vehicles were present in the roundabout at any given time,
- The low standard error value (0.046) indicates that the estimate of the mean is precise,
- The median is 5, meaning that half of the observations recorded 5 or fewer vehicles, while the other half recorded 5 or more, suggesting a symmetrical distribution,
- The mode is also 5, indicating that this was the most frequently occurring value in the dataset, consistent with both the mean and the median, which suggests a relatively even distribution,
- The standard deviation of 2.34 shows that the data are moderately dispersed around the mean, implying a moderate variation in the number of vehicles in the roundabout,
- The variance, calculated as 5.47, is the square of the standard deviation and confirms the presence of moderate variability in vehicle counts,
- The kurtosis value of 0.075 suggests that the distribution is approximately normal, with no pronounced tails, as the value is close to the kurtosis of a standard normal distribution (which is 0),
- A skewness of 0.346 indicates a slightly positive skew, meaning there are slightly more values above the mean; however, this asymmetry is not significant,

- The range, defined as the difference between the maximum and minimum values, is 14 (from 0 to 14), showing that the number of vehicles in the roundabout varied considerably during the observation period,
- A total of 2,533 observations were recorded, which is a sufficiently large sample size to ensure reliable statistical analysis.

Overall, the data suggest that the distribution of the number of vehicles in the roundabout during the observation period is relatively symmetrical, with both the mean and median at 5 vehicles. Although there is moderate variation, the distribution is close to normal.

Data analysis collected using the DTK software

The data processed using the DTK licence plate OCR software yielded the results presented in *Table 8*.

Table 8 – Data processed using DTK licence plate OCR software during the period 07:47–08:47

Entry leg	Vehicles entered	Vehicles exited	Turning movements	
A	292	521	A-A	4
			A-B	253
			A-C	35
B	671	493	B-A	464
			B-B	28
			B-C	179
C	268	217	C-A	53
			C-B	212
			C-C	3
Total	1,231	1,231		1,231

Table 9 – Statistical analysis of segment travel times within the roundabout

Segment	t_{sr} (s) – Travel time per segment	Segment	t_{sr} (s)	Segment	t_{sr} (s)
A-A	5.80	B-A	5.52	C-A	9.10
A-B	8.54	B-B	20.64	C-B	6.55
A-C	6.11	B-C	6.81	C-C	7.21

According to the data from *Table 9*, the average cycle time (\bar{T}_c) is calculated as (*Equation 11*):

$$\bar{T}_c = t_{srAC} + t_{srCB} + t_{srBA} = 6.11 + 6.55 + 5.52 = 18.18 \text{ (s)} \tag{11}$$

The average traffic flow speed within the roundabout is (*Equation 12*):

$$\bar{v}_s = L_0/\bar{T}_c = 81.64/18.18 = 4.249 \text{ (m/s)} = 16.17 \text{ (km/h)} \tag{12}$$

Traffic flow on roundabout segments

In *Table 10* traffic flow on roundabout segments was determined using *Equation 13*, with identical results obtained via *Equation 14* [2, 3].

$$q_i^{(k)} = US^{(k-1)} - IS^{(k-1)} + \sum_{j=1}^i U_j^{(k)} - \sum_{j=1}^i I_j^{(k)} \tag{13}$$

where: $q_i^{(k)}$ – traffic flow on the roundabout segment from leg i to leg j during cycle k , $U_j^{(k)}$ and $I_j^{(k)}$ - observed vehicle entries and exits at leg i and leg j , during cycle k .

$$q_i^{(k)} = \sum_{l=0}^{k-1} \sum_{j=1}^n \sum_{l=1}^n u_{ji}^{l1} - \sum_{l=0}^{k-1} \sum_{j=1}^n \sum_{l=1}^n u_{ij}^{l1} + \sum_{j=1}^i \sum_{l=1}^n u_{ji}^k - \left(\sum_{l=j}^n u_{jl}^{k-1} + \sum_{l=1}^{i-1} u_{li}^k \right) \tag{14}$$

Table 10 – Traffic flow q_i (veh/h) by roundabout segment during the period 07:47–08:47

Segment	A-C	C-B	B-A
using the model	507	535	723
using the DTK software	502	553	731

Approximately the same results were obtained using both MIKR model estimation and OCR camera-based vehicle detection. The highest traffic flow was recorded on the roundabout segment between leg B and leg A with a value of 723 (veh/h). The highest number of vehicle entries during the observation period occurred at leg B, with a total of 681 vehicles.

Roundabout service volume

The service volume (W_o) of the roundabout was determined based on Equation 15. It reflects the total number of vehicles that entered the roundabout at all legs during the period 07:47–08:47:

$$W_o^{(k)} = \sum_{j=1}^n U_j^k = 292 + 671 + 268 = 1,231 \text{ (veh/h)} \tag{15}$$

The roundabout service volume varies depending on several influencing factors, such as the geometric characteristics of the intersection, traffic flow composition, driving behaviour and other parameters. These factors were not analysed in this study; instead, a service-based approach was applied.

Roundabout capacity

The capacity of the roundabout was determined using both the MIKR model and the HCM methodology, and the results were compared.

1. According to the HCM methodology for roundabout capacity analysis, it is possible to estimate the entry leg and overall roundabout capacity utilisation with acceptable accuracy for single-lane roundabouts.

The capacity (throughput) of the roundabout (C), defined as the number of vehicles that can pass through the intersection per unit of time, is calculated as the sum of the entry capacities (Q_{Ei}) of all roundabout legs (Equation 16):

$$C = \sum_{i=1}^c Q_{Ei} \text{ (veh/h)} \tag{16}$$

where: Q_{Ei} (veh/h) – entry capacity of a leg and $Q_E = f(Q_C, \text{ geometry parameters})$

Several models exist for estimating capacity. For the conditions in Bosnia and Herzegovina, the Austrian–Swiss model [25] can be applied with appropriate adjustments. The entry capacity for small and medium-sized roundabouts (linear relationship) is given by Equation 17:

$$L = 1,500 - [8 * (b * M_K + a * M_A)/9] \text{ (veh/h)} \tag{17}$$

where: L – entry capacity (veh/h), M_K – circulating flow at the conflict point (veh/h), M_A – exiting flow (veh/h), a – entry geometry factor, b – factor for the number of circulating lanes.

The parameter values used for the Velešići roundabout, following HCM methodology with adjustments for local conditions, are presented in *Table 11*.

Table 11 – Roundabout parameters – Velešići, Sarajevo (date of observation)

Parameter	Segment		
	A	B	C
M_e	292	671	268
M_A	521	493	217
M_K	507	723	535
a	0.3	0.3	0.3
b	0.95	0.95	0.95
c	1	1	1
L	933	758	990
A	31.30	88.52	27.06

According to the HCM methodology roundabout capacity is $C = 2,681$ (veh/h), and service volume is $W_0 = 1,231$ (veh/h).

2. According to the MIKR method, the capacity of a roundabout is calculated based on the principle of minimum service time (see Section 3.2). The service time of the roundabout is a variable of random nature and depends on the speed of the circulating flow.

According to the MIKR model, roundabout capacity is $C = 1,688$ (veh/h)

5. DISCUSSION

An important practical contribution of this study relates to the process of data collection. One of the key motivations for reapplying the MIKR model was the need to reduce the operational complexity associated with turning-movement observations at roundabouts. In this context, the introduction of licence-plate recognition (LPR) data proved particularly valuable. With an accuracy exceeding 90%, LPR detection enabled reliable identification of vehicle entries and exits, and consequently allowed the reconstruction of circulation flows within individual roundabout segments without the need for continuous trajectory tracking.

Traffic flow analysis at the roundabout was conducted using the MIKR model and LPR. The comparison of circulation flows obtained from the MIKR model with those derived from LPR data further demonstrates the robustness of the proposed approach. Segment-based flow rates calculated using the MIKR model (507, 535 and 723 (veh/h) for segments A–C, C–B and B–A, respectively) closely matched those obtained from the LPR system (502, 553 and 731 (veh/h) for the same segments). The relative deviations between the two methods were below 4% for all segments, confirming that the simplified MIKR input structure captures the essential dynamics of circulation flow with high consistency. These findings reinforce the practical advantage of using simplified input data for roundabout flow analysis and highlight the potential of combining MIKR with LPR-based observations as an effective strategy for reducing field effort while maintaining analytical accuracy.

The MIKR model clearly distinguishes between capacity and service volume. Capacity is considered the maximum number of possible service events at the roundabout within a given time period, allowing for any combination of input flows per leg. Service volume is represented by vehicle entries and exits, either by direction or by leg. In the context of roundabout capacity analysis, the model is based on the principle of minimum service time. The model takes into account: traffic flow (q) as a function of density (g) and flow speed (v), vehicle density (g), which depends on the number of vehicles in the roundabout (N) and the length of the circulating lane (L_0), and stopping distance (L_z) and the space occupied by a vehicle in the roundabout (L), which depend on driver reaction time, braking system response, and vehicle speed.

The capacity (C) of the roundabout is defined as the maximum possible flow rate. In the example of the roundabout in Velešići, Sarajevo, the maximum service volume, i.e. roundabout capacity, was calculated as 1,688 (veh/h), reached at a flow speed of 30 (km/h). This value was derived through analysis of vehicle density and safety gaps, highlighting the importance of dynamic traffic characteristics in capacity estimation.

The HCM methodology (Highway Capacity Manual) relies on empirical models for analysing roundabout capacity, especially for single-lane roundabouts. The main features of the HCM approach are: roundabout capacity (C) is defined as the sum of the entry capacities of all legs, and entry capacity (Q_E) depends on circulating flow (M_K), entry geometry (a), and number of lanes (b).

Using the HCM methodology and the Austrian-Swiss model for estimating roundabout capacity, the capacity at the Velešići roundabout was calculated as 2,681 (veh/h). A quantitative comparison of the capacity results reveals substantial differences between the analytical approaches. The MIKR model estimates the roundabout capacity at 1,688 (veh/h), while the HCM-based calculation yields 2,681 (veh/h), a value approximately 59% higher than the MIKR estimate. The magnitude of this deviation is not only methodological but also operationally significant. During the observed peak hour, the service volume at the roundabout intersection was 1,231 vehicles, and field conditions indicated that the circulating flow operated near saturation. Given these operational constraints, it is highly unlikely that the roundabout could accommodate an additional 1,400 vehicles, as HCM estimates. This discrepancy underscores an important limitation of empirical, correction factor-based models. In contrast, the MIKR model incorporates density-dependent interactions and safety gaps derived directly from observed traffic conditions, enabling capacity estimation that more closely aligns with real operational performance. The proximity between the observed service volume 1,231 (veh/h) and the MIKR-based capacity estimate 1,688 (veh/h) indicates that the MIKR result is substantially closer to the roundabout's actual operational performance than the HCM estimate. Therefore, while the HCM methodology yields higher capacity estimates (useful for planning), the MIKR model provides greater accuracy in scenarios where safety and dynamic conditions are prioritised.

6. CONCLUSION

The research conducted at the roundabout in Sarajevo demonstrated that the application of the MIKR model enables detailed monitoring of vehicle flows and capacity analysis based on recorded vehicle entries and exits. This method allows the determination of traffic flow along roundabout segments, assessment of the impact of individual flows on total capacity, and estimation of vehicle turning movements within the roundabout. The model proved to be practical due to its simplicity and adaptability to specific local traffic conditions, which is especially important in urban environments.

The MIKR model is particularly suitable as it enables efficient data collection, either manually or through the application of new technologies, enabling the acquisition of time-dependent inputs. Furthermore, the structure of the model allows analysis over short and long observation intervals, offering both static and dynamic insight into roundabout performance. Based on the results of the Sarajevo case study, the model identified an optimal traffic flow speed of approximately 30 km/h for maximum capacity utilisation, as well as the influence of geometric parameters such as the number of traffic lanes and vehicle spacing on traffic efficiency and safety.

The application of this model supports not only roundabout capacity assessment but also analysis of other at-grade intersection types, regardless of complexity or number of legs. Combining the MIKR model with the HCM methodology and the Austrian-Swiss model enables a comprehensive analysis of traffic flows and more precise planning of future intersections. The research conducted in Sarajevo serves as a good example of how such models can be used to optimise traffic flow in urban environments, while further testing could confirm their applicability under varying traffic and geometric conditions.

The findings are based on a single roundabout and do not include multilane or signalised roundabouts, where driver behaviour, gap acceptance and lane changing patterns may differ substantially. Furthermore, estimation was validated under one hour of peak demand, and broader temporal variability was not assessed. These limitations indicate that generalisation of the model requires further empirical testing.

Future research should therefore extend the application of the MIKR model to roundabouts of different geometries, traffic volumes and lane configurations, as well as to longer observation periods. Additional validation using datasets from alternative sensing technologies would support more robust calibration. The structural characteristics of the MIKR model make it a promising foundation for the development of hybrid analytical machine-learning approaches. Such methods could be used to enhance prediction accuracy, calibrate

dynamic flow parameters or simulate complex operational scenarios, thereby broadening the model's applicability in traffic engineering practice. Such approaches may support the development of predictive models capable of forecasting traffic states, identifying congestion patterns, or optimising operational performance under varying demand conditions. In addition, the increasing availability of IoT-based data streams offers opportunities for automated monitoring of MIKR input parameters, enabling seamless integration with machine-learning pipelines.

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