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SIMHEURISTIC FRAMEWORK FOR OPTIMIZING URBAN MOBILITY AT SIGNALIZED ROUNDABOUTS

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Abstract
Managing high traffic volumes and traffic congestion at signalized intersections remains a critical urban challenge. Appropriate traffic signal timing (TST) and phase sequencing are essential for ensuring smooth traffic flow. This study presents a microscopic simulation-based heuristic optimization (Simheuristic) framework using the Genetic Algorithm (GA) for optimizing the TST of Four-Legged Two-stops Signalized Roundabouts (FLTSR). The framework is tested using the actual traffic flow through a microscopic simulation model developed in Simulation for Urban Mobility (SUMO). Within this framework, the integrated GA searches for the green TSTs to minimize vehicular queue lengths, while SUMO is used to evaluate those timings. Additionally, four different phase sequence settings are evaluated to find the efficient configuration. The proposed approach is benchmarked against Webster's method and the existing TST plan. In the best-case scenario, the proposed framework improves vehicular flow by mitigating the average time loss, average waiting time, and the average number of vehicles in a queue at the FLTSR up to 35.83 %, 51.91 %, and 50.97 %, respectively, compared to the current setting.
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Key Words: Signalized Roundabout, Phase Sequence Settings, Simulation-Optimization, Traffic Signal Timing, Genetic Algorithm, SUMO

1. INTRODUCTION

Urban traffic congestion remains a major challenge, particularly in areas where infrastructure expansion is limited [1]. Although large-scale public transport interventions can influence overall congestion patterns, they are often insufficient to address localized operational inefficiencies at intersections [2]. Consequently, operational traffic management strategies, especially adaptive signal control at intersections and roundabouts, have gained increasing attention as effective and implementable solutions for mitigating congestion, reducing delays, and enhancing overall network performance. Although conventional intersections are well-studied, Four-Legged Two-Stops Signalized Roundabouts (FLTSRs) pose unique control challenges due to asymmetric traffic and staged stopping yet offer environmental benefits through reduced fuel consumption and emissions [3].

FLTSRs are commonly deployed across many countries, including the UK, France, Türkiye, etc., for balancing approach volumes and ensuring vehicular safety. However, determining optimal Traffic Signal Timing (TST) for these junctions remains a computationally intensive task, particularly under heterogeneous traffic conditions. Traditional analytical models, such as Webster [4] and Modified Webster's method [5], TRANSYT (TRAffic Network StudY Tool) [6], and the Highway Capacity Manual (HCM) [7], provide baseline timings but fail to address stochastic arrival patterns and real-time variability in traffic behaviour.

Although initially developing mathematical models was preferred by researchers for improving TST, getting realistic solutions to these models for real-life cases is practically impossible. To overcome this difficulty and analyse the responses of traffic systems under various conditions, the use of microscopic simulation tools becomes essential. Teo et al. [8] studied the effects of queue length, cycle time, and green and amber phase timing on the traffic

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system through simulation. Taking the current queue length as input, a GA-based mathematical optimization approach has also been proposed for determining the optimal green signal timing at an urban intersection to minimize queue lengths. Sanchez Medina et al. [9] also employed GA to solve a model proposed to obtain the optimum TST setting. The cellular automata-based simulators also assessed all the feasible solutions. Li and Schonfeld [10] applied simulated annealing (SA) and GA individually and in hybrid form to compare their performance and optimize the arterial TST. It was found that the hybrid of SA-GA exhibited some strengths compared to the SA and GA when applied independently. A hybrid chaotic quantum evolutionary approach was implemented by Cai and Cai [11] for the model developed to schedule traffic lights. Benhamza and Seridi [12] proposed a framework for the adaptive TST scheme. A microsimulation tool, SUMO, was also used to evaluate the results. Gökçe et al. [13], Dabiri and Abbas [14], and Jintamuttha et al. [15] integrated different simulation tools with metaheuristic algorithms to solve the TST problem through various performance measures. A simulation-based investigation using PTV VISSIM was conducted by Murat et al. [16] and Zhang et al. [17] to examine the relationship between left-turn traffic volume and capacity in the urban transportation network. A Flexsim-based simulation study on pre-emptive transportation control demonstrated that dynamic task reassignment can significantly enhance system responsiveness and efficiency, resulting in a 13 % increase in transport volume and a 13 % reduction in vehicle travel distance [18]. This finding conceptually supports the current work, which likewise seeks to minimize idle times and improve overall traffic flow efficiency at signalized roundabouts through adaptive TST optimization. Under different scenarios, the calculation procedure for TST was also made through the SIDRA Intersection [19] software. A traffic signal control (TSC) model for the three-leg signalized intersection is developed by Cakici and Murat [20]. The model was able to optimize TST and phase sequence settings simultaneously. The population-based meta-heuristic search algorithm, i.e., differential evolution (DE), was employed as a solution methodology. The model's effectiveness was also evaluated using a simulation model developed using PTV VISSIM. The results showed that the proposed model reduced the average vehicular delay by up to 42 % compared to the current fixed TST of the testbed. Continuous technological advancement has seen the TSC system undergo endless improvements, including adopting simulation tools and mathematical models to optimize TST. Showcasing the potential of machine learning techniques in traffic management, Jamil et al [21] proposed an adaptive TSC system that employs a composite reward architecture based on deep reinforcement learning. Further enhancements were observed as Huang and Qu [22] explored TSC operations improvements through proximal policy optimization, offering a refined approach to handling dynamic traffic conditions. Moreover, a substantial advancement in flexibility and control was introduced by Sun et al. [23] through a two-stage robust optimal TSC system that utilizes a reversible lane approach for isolated intersections, thus enhancing traffic management at complex urban intersections. Simultaneously, Lee et al. [24] developed a two-stage algorithm for optimizing TST settings, complemented by creating a web service system. This approach refines the optimization process and enhances integration with existing traffic management systems, marking a notable advancement in TSC technology. Recent studies have also addressed real-time traffic control using fog-enabled Vehicular ad hoc network (VANET) architectures for optimized resource management [25].

Despite advances in TSC, limited research has addressed the specific structure and control complexities of FLTSRs. Prior studies often overlook phase sequence design under varying cycle length (CL) and typically rely on hypothetical data rather than field-calibrated traffic flows.

Original Contribution: Building upon earlier methodological foundations [26], this study presents a GA-based simheuristic framework specifically tailored to the operational characteristics of isolated FLTSRs, a configuration that has received limited attention in the modelling and simulation literature. Using real traffic data from Izmir, Türkiye, the framework jointly optimizes TST and phase sequences across multiple congestion levels, and benchmarks the results against existing signal settings and the Modified Webster's method [5], providing new operational insights specific to FLTSRs.

Practical Significance: By combining GA optimization with SUMO simulation, the framework provides a scalable, data-driven tool for reducing congestion and improving signal efficiency. It offers a cost-effective solution for municipal engineers without the need for infrastructure expansion.

Impact and Reusability: This method is adaptable for network-level optimization or integration with multi-agent systems, and aligns with research priorities identified by Qadri et al. [27], promoting further studies on heuristic-simulation hybrids for complex intersections.

2. OPERATIONAL LOGIC OF FOUR-LEGGED TWO-STOPS SIGNALIZED ROUNDABOUT

A configuration of TST is defined by the sequence and the duration of its signal phases, typically, red (stop), amber (prepare to go), green (go), and amber again (prepare to stop). One complete sequence of these signal phases is termed as *CL*. This study evaluates different phase sequence settings within a proposed Simheuristic framework, with the aim of minimizing (i) average queue length (number of vehicles), (ii) average time loss (s), and (iii) average waiting time in queue (s), defined as:

- **Average queue length** (vehicles): Average number of vehicles queued during evaluation.
- **Average time loss** (s): Delay due to travel below ideal free-flow speed (13.89 m/s).
- **Average waiting time** (s): Mean time spent in a stopped queue.

The modelled FLTSR includes eight signal heads: four on inbounds (EI, WI, NI, SI) and four along the circulatory lanes (R1, R2, R3, and R4). The outbound directions are EO, WO, NO, and SO. The geometric layout of a typical FLTSR is illustrated in Fig. 1.

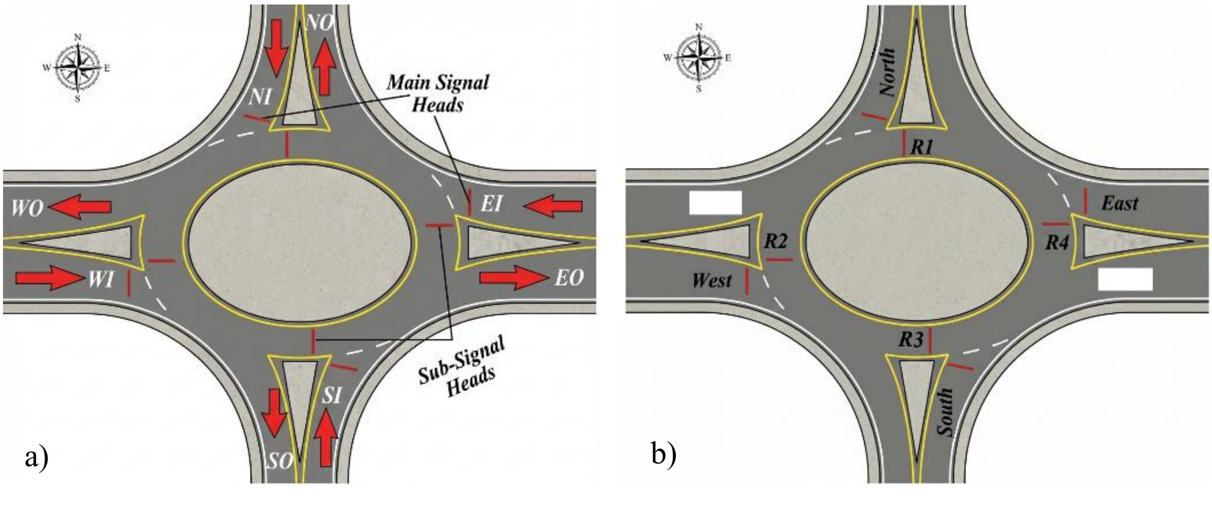

Figure 1: Typical geometry layout of FLTSR, a) geometric layout of approaches and roundabout circulation, b) signal heads' nomenclature.

2.1 Phase sequence settings under evaluation

A phase setting is a part of the traffic signal cycle in which one or more non-conflicting movements are allowed to move forward. These settings reduce potential conflicts and improve traffic safety. Figs. 2 a to d display the phase sequence settings evaluated in this study.

- Fig. 2 a: Standard 2-phase, with opposite inbounds operating concurrently.

- Figs. 2 b and c: 3-phase settings where two inbounds operate together, and the others independently. Right turns are permitted concurrently. The main difference between 2 b and 2 c lies in the pairing of simultaneous and independent inbounds.
- Fig. 2 d: 4-phase, where each inbound operates independently, allowing all movements, including U-turns.

2.2 GA-based simheuristic

Optimizing green TSTs for multiple signal heads at FLTSRs poses a complex combinatorial problem, which traditional analytical methods struggle to solve efficiently. To address this, a GA-simheuristic framework is proposed to determine optimal green timings across four distinct phase sequence settings as illustrating in Figs. 2 a to d.

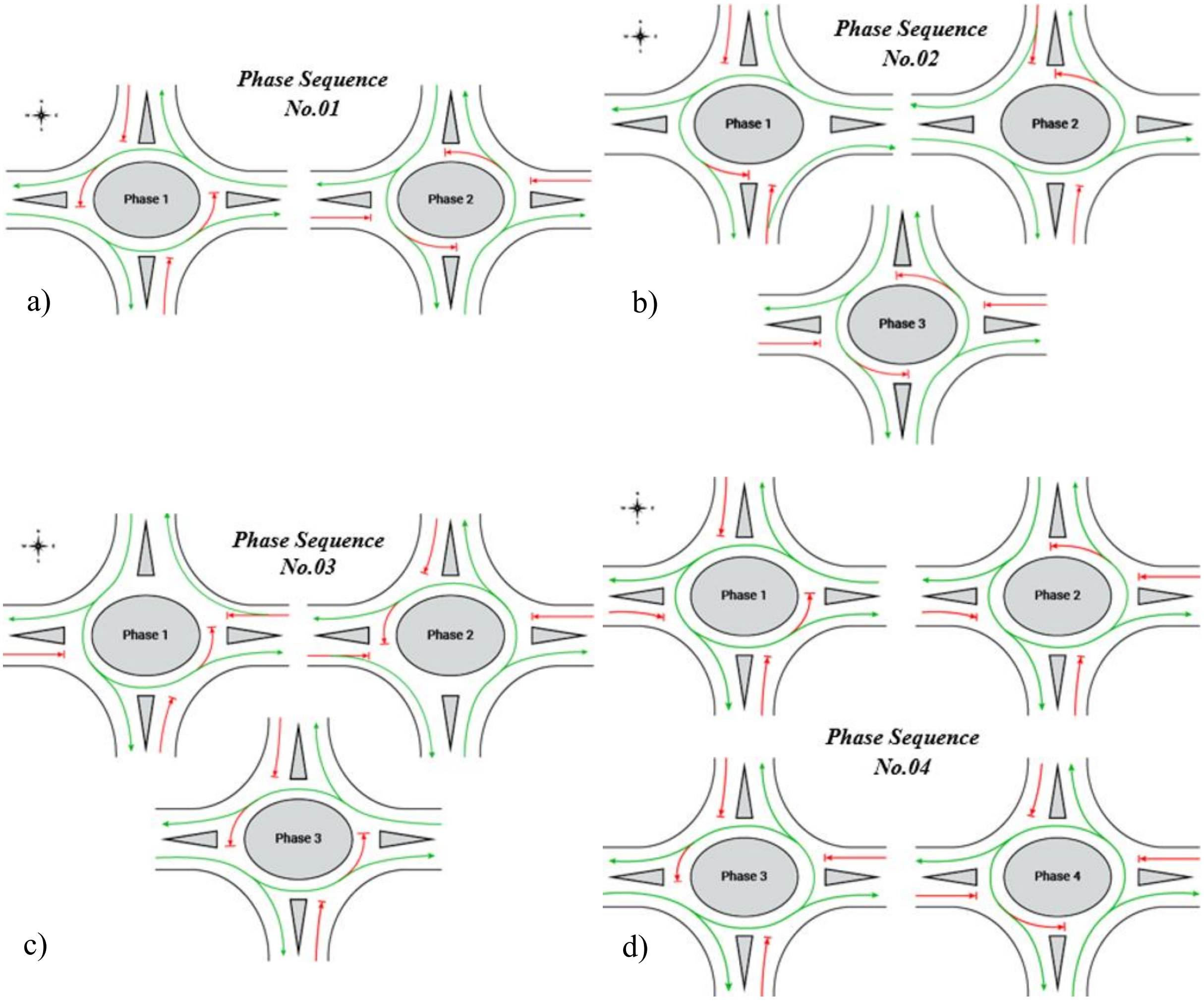

Figure 2: a) Typical 2-phase sequence setting, b) 3-phase sequence setting (i) (currently in use), c) 3-phase sequence setting (ii), d) Typical 4-phase sequence setting.

Similar to the approach used by Wang and Zhang [28], which involved optimization and simulation to enhance supply chain coordination, this study integrates heuristic optimization with microscopic simulation to improve traffic flow efficiency at signalized roundabouts. In the proposed framework, GA explores green TST combinations, while a microscopic simulation model evaluates the viability of each solution. Simulation results are iteratively fed back into the GA to refine the optimization process. This closed-loop evaluation is applied across all phase sequence scenarios. Fig. 3 illustrates the framework’s structure in detail.

Microscopic simulation is essential for modelling the randomness and complexity of traffic flow, including unbalanced demand and pedestrian interaction. It effectively captures the impact of small signal changes, outperforming purely mathematical models in realism [13]. Microscopic simulation, on the other hand, is capable of reflecting the effect of a small change that involves stochasticity [13, 29]. SUMO serves as the simulation engine integrated with a Python-based GA to assess metrics such as queue length, time loss, and waiting time for performance evaluation. Each simulation run involves counting vehicles within the roundabout, facilitating a comparative analysis between the current system and the GA-optimized outcomes.

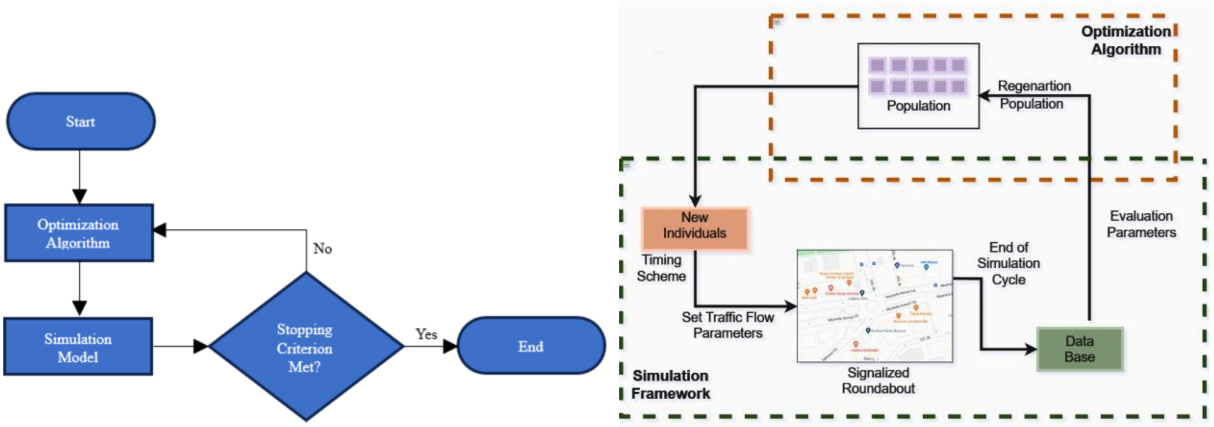

Figure 3: Standard simheuristic strategy.

Although microscopic simulations provide a detailed and realistic view of traffic systems, they demand extensive computational resources. Therefore, it is essential to achieve optimal or near-optimal solutions with minimal simulation runs and an efficient framework design. GA is effective in continuous domains, explores solution spaces efficiently, and often converges to optimal solutions faster.

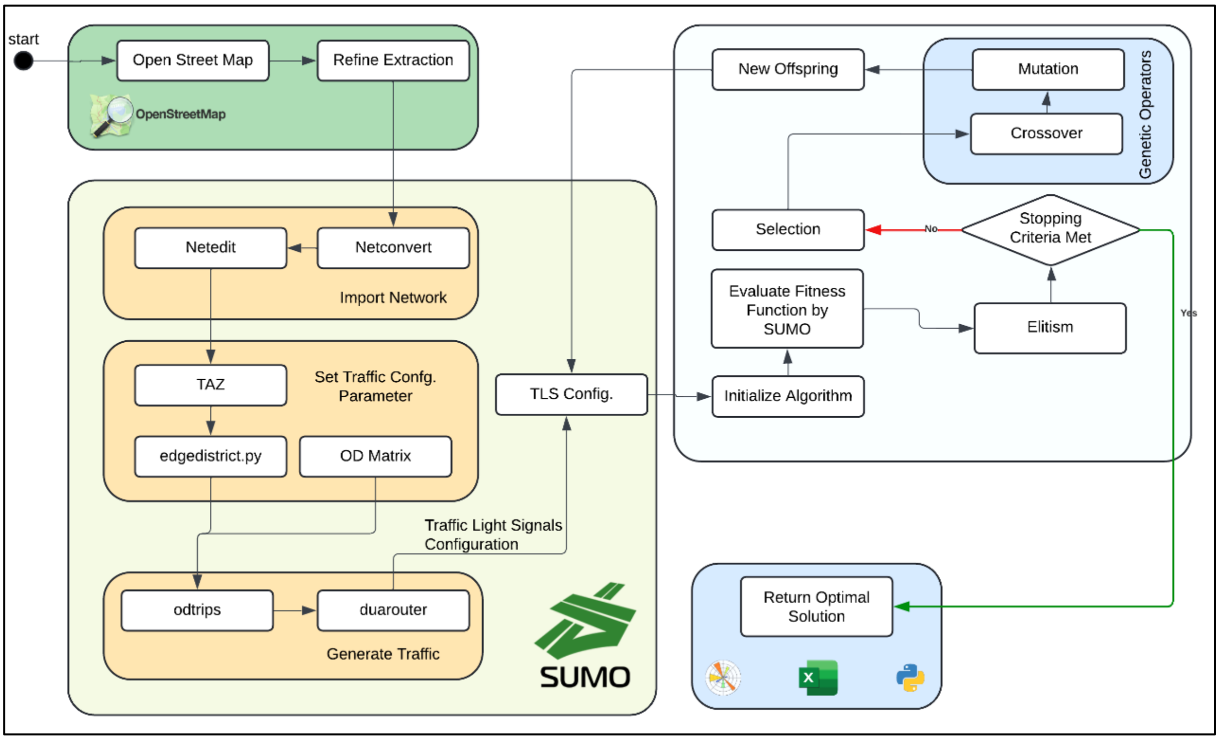

Figure 4: Flowchart of proposed GA-simheuristic framework.

As a metaheuristic approach, GA provides the intelligent exploitation of the random search with historical data to move the search to a better-performing region in the solution space. GA starts by initializing the population of individuals' chromosomes randomly. The search for these possible solutions is stochastic, enabling simultaneous exploration of the search space, which increases the chance of finding the global optimum solution in the search space instead of trapping it in a local one [30]. Finding the best solution in GA relies on creating new individuals from the existing ones. This is primarily achieved through crossover operators, which ensure the exchange of genetic material from parents to offspring during the reproduction process. Throughout the GA process, the operator performs its operation based on a specified probability (*cross_prob*). Subsequently, mutation introduces variability with a given probability (*mu_prob*) to maintain diversity and prevent premature convergence. In this study, three different crossover operators (single-point crossover operator, arithmetic operator, and average crossover operator), along with a swap mutation operator, are employed to enhance solution quality.

Elitism is applied after fitness evaluation: if a new offspring outperforms the worst in the population, it replaces it. The stopping condition is defined as a maximum of 10 consecutive iterations without improvement. This is selected as a practical convergence indicator, as further iterations were observed to yield negligible performance gains. A complete flowchart of the proposed GA-simheuristic methodology is shown in Fig. 4.

3. EXPERIMENTATION

This section presents the implementation of the proposed Simheuristic framework for the TST problem at an FLTSR in Izmir, Türkiye. Fig. 5 shows the Google image of the roundabout under study and a screenshot of the corresponding simulation model. This roundabout consists of 8 links, all of which going towards the roundabout are controlled by traffic lights. Additionally, four traffic signal heads are positioned at different locations around the roundabout.

Figure 5: Microscopic simulation model and Google image of the roundabout.

The site experiences significant daily commuter traffic, often resulting in congestion due to suboptimal TST, leading to extensive waiting times and backlogs on arterial roads. Pedestrian traffic is also considerable, and it is presumed that the TST settings for vehicles sufficiently accommodate pedestrians. Additionally, it is assumed there are no parking lanes on any approach or departure routes associated with this FLTSR.

3.1 Traffic demand data

Traffic volume data were recorded during weekday morning peak hours (8:30–9:30 AM) in September 2024, excluding heavy commercial vehicles. Averaged data were used in the simulation, detailed in Table I. All four phase sequence settings (Figs. 2 a to d) were evaluated under five *CLs* (30 s to 90 s, at 15 s intervals), with the current setup operating at 60 s using Fig. 2 b. Table II outlines the existing TST. Simulations were run on a system with Intel i7-4700MQ CPU @ 2.40 GHz and 3.0 GB RAM (Windows 10 v21H2).

Table I: Details of vehicle flow per hour.

		Destination				
		Mustafa Kemal Cd. (EB)	243. Sk. (NB-Out)	Mustafa Kemal Cd. (WB-Out)	Sakarya Cd. (SB-Out)	**Total**
Source	Mustafa Kemal Caddesi (EB)	87	205	381	185	**858**
	243. Sk. (NB)	146	68	189	106	**509**
	Mustafa Kemal Caddesi (WB)	283	126	107	166	**682**
	Sakarya Caddesi (SB)	195	97	205	68	**565**
Total		**711**	**496**	**882**	**525**	**2614**

*CL*s were varied from 30 s to 90 s in increments of 15 s, and the optimal green phase timing for these cycles was also examined across all phase sequence settings. Currently, the FLTSR operates with a 60 s *CL* as per the phase sequence depicted in Fig. 2 b. Table II outlines the existing TST configuration implemented at the roundabout. All performance metrics considered under this study were obtained for the roundabout through the simulation model.

Table II: TST setting currently implemented at the FLTSR.

	EI	**WI**	**NI**	**Right turn (N to W)**	**SI**	**Right turn (S to E)**	**Average time loss** (s)	**Average waiting time** (s)	**Average jam length** (# vehicles)
Green Phase Timing (s)	35	34	16	34	15	35	28.180	17.38	11.034

3.2 Parameter tuning

Optimizing GA parameters is a complex task in itself. For each *CL* (30 s–90 s), parameter tuning was conducted across all phase settings. To address stochasticity, each configuration was simulated 10 times, and averages were used. Table III summarizes the tested GA configurations, with optimal ones highlighted.

Table III: Best parameter setting of every phase sequence for an isolated signalized roundabout.

Population size	**Crossover operators**	α	**Mutation operators**	**Crossover probability**	**Mutation probability**	**Working best with**
125	Arithmetic	0.3	Single Point Swap Operator	0.8	0.3	Phase Sequence 1 & 4
	Average	NA			0.2	Phase Sequence 3
	1 Point					Phase Sequence 2

4. COMPUTATIONAL RESULTS

The warm-up period for the model is set to 1200 s, i.e., 20 minutes, to ensure steady-state traffic conditions. For each *CL*, the model is run 10 times (10 replications) with each setting of the green TST values to find the most efficient setting for each phase sequence. The solution that provides the minimum results of all the performance measures is selected as the optimal green signal timing, and its corresponding *CL* is considered optimal.

To evaluate the current TST settings (Table II), the simulation model is run with the existing configuration and traffic flow data from Table I. With this setting, 10 replications of the simulation model are performed, and the averages of different performance measures are used to compare the current setup against the optimal solution obtained via the GA-simheuristic framework.

Detailed results for all four-phase sequence settings under different *CLs* are presented in Table IV. The percentage differences of performance measures are also calculated relative to the best result under each *CL*.

Table IV: Results obtained according to each *CL* and phase sequence.

Phase sequence setting	***CL***	**Average time loss** (s)	**Average waiting time** (s)	**Average jam length** (# vehicles)	**Percentage difference in average time loss**	**Percentage difference in average waiting time**	**Percentage difference in average jam length**
1	30 s	18.082	8.358	5.41	0.00 %	0.00 %	0.00 %
2	30 s	26.927	15.1	8.0901	32.85 %	44.65 %	33.13 %
3	30 s	23.975	12.256	8.813	24.58 %	31.80 %	38.61 %
4	30 s	19.231	8.928	5.673	5.97 %	6.38 %	4.64 %
1	45 s	23.069	12.91	7.4602	0.00 %	0.00 %	0.00 %
2	45 s	25.515	14.774	8.8755	9.59 %	12.62 %	15.95 %
3	45 s	29.648	17.659	11.224	22.19 %	26.89 %	33.53 %
4	45 s	24.759	14.168	8.072	6.83 %	8.88 %	7.58 %
1	60 s	25.406	15.399	9.8247	5.09 %	3.52 %	1.10 %
2	60 s	28.06	17.316	10.963	14.06 %	14.20 %	11.37 %
3	60 s	32.892	20.99	12.886	26.69 %	29.22 %	24.59 %
4	60 s	24.114	14.857	9.717	0.00 %	0.00 %	0.00 %
1	75 s	30.554	20.044	12.543	11.05 %	10.02 %	2.24 %
2	75 s	33.851	22.366	13.448	19.71 %	19.36 %	8.82 %
3	75 s	41.365	28.77	17.235	34.29 %	37.31 %	28.85 %
4	75 s	27.179	18.035	12.262	0.00 %	0.00 %	0.00 %
1	90 s	37.789	26.953	14.954	20.22 %	18.81 %	0.70 %
2	90 s	37.048	25.708	16.056	18.62 %	14.87 %	7.52 %
3	90 s	39.782	28.093	18.002	24.21 %	22.10 %	17.51 %
4	90 s	30.149	21.884	14.849	0.00 %	0.00 %	0.00 %

Fig. 6 presents violin plots illustrating the distribution of performance metrics across different *CLs*, based on the best parameter settings highlighted in Table IV. The plots highlight the variability and concentration of congestion, delay, and waiting time, offering insights into how signal durations influence traffic flow.

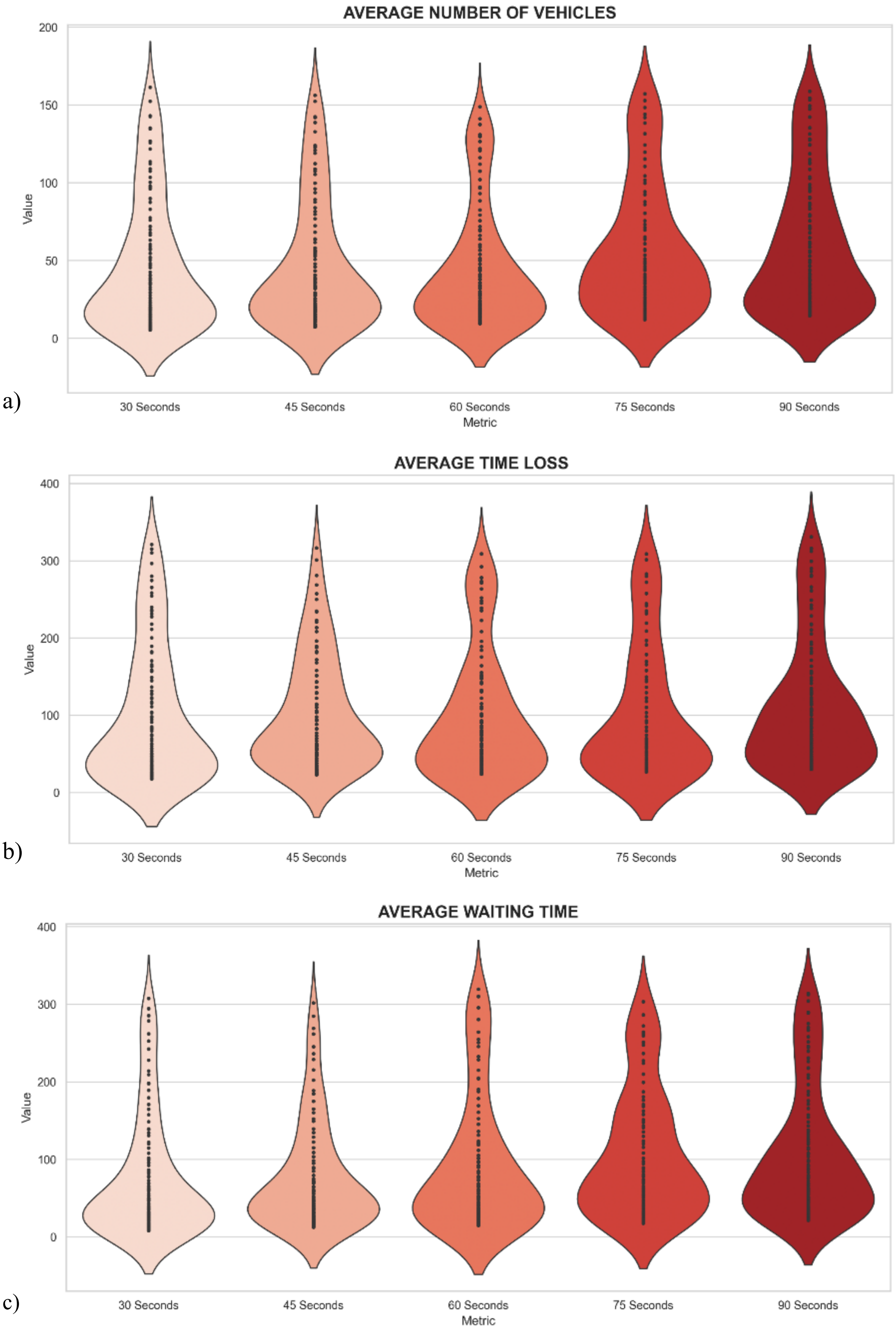

Figure 6: Comparison of traffic performance metrics across varying signal cycle times (30 s–90 s) at a Four-Legged Two-Stops Signalized Roundabout; a) average number of vehicles, b) average time loss, c) average waiting time.

Fig. 7 illustrates a comparison between the outcomes of the optimal configuration (phase sequence 1 at a 30 s *CL*) and the simulation outcomes under the existing TST settings. The bar graph demonstrates that the GA-simheuristic framework significantly enhances performance, achieving reductions in average time loss (s), average jam length (number of vehicles in a queue), and average waiting time (s) by 35.83 %, 50.97 %, and 51.9 % respectively, compared to the current TST settings. Additionally, the results obtained from the proposed framework also exceed those of Webster's model, as depicted in Fig. 8.

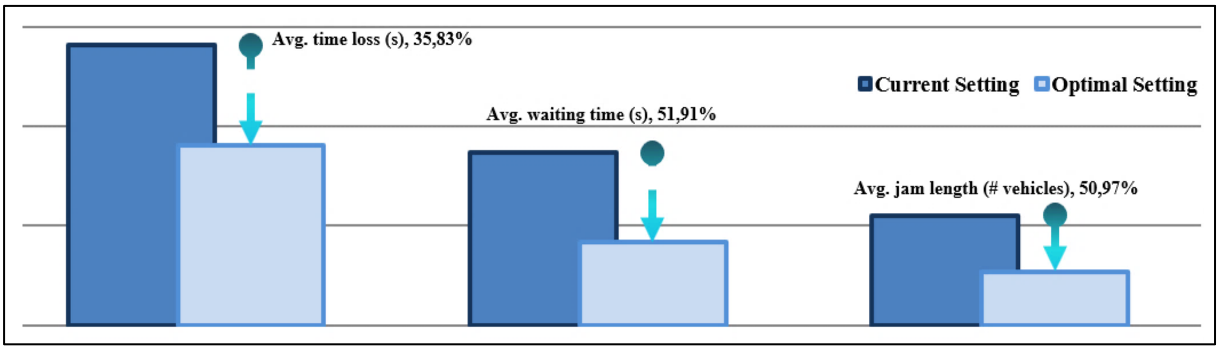

Figure 7: Reduction of different parameters in optimal and current TST results.

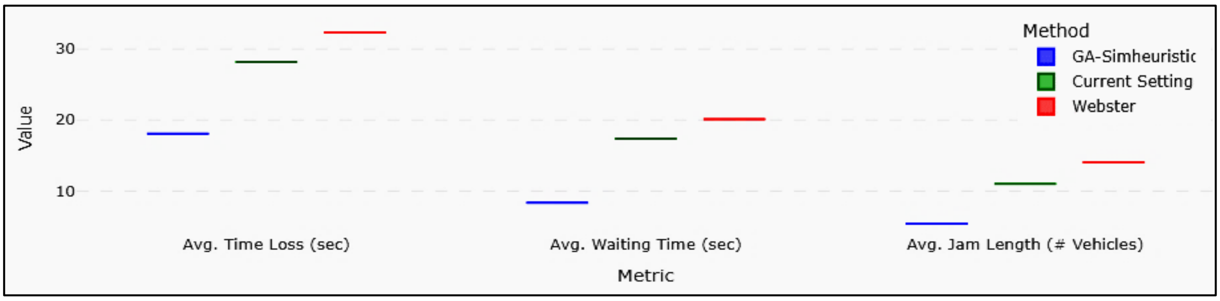

Figure 8: Comparison of traffic metrics by methods.

5. CONCLUSION

This study proposes a GA-based Simheuristic optimization model to determine optimal TST for an FLTSR, applied to a real-world case in İzmir, Türkiye. Given the widespread use of FLTSRs in Türkiye, the proposed approach addresses a pressing urban traffic challenge by reducing delays, congestion, and queue lengths. The model uniquely integrates GA with the SUMO simulation platform to evaluate the performance of multiple TST and phase sequence configurations under varying *CLs*. To minimize conflict movements, four distinct phase sequences were assessed. Among them, Phase Sequence 1 with a 30-second *CL* emerged as the most effective, achieving improvements of up to 35.83 % in average time loss, 51.91 % in average waiting time, and 50.97 % in average queue length over the current settings. The primary advantage of this framework lies in its ability to search large solution spaces efficiently using metaheuristics, while maintaining simulation-based realism. This integration allows decision-makers to derive optimal timing plans without relying on oversimplified analytical approximations. However, the current study is limited to an isolated roundabout and assumes static vehicle demand and predefined routing. In practical deployment, dynamic demand and network-wide interdependencies must also be addressed. Future work will focus on extending the methodology to signalized roundabout networks, where increased complexity, inter-roundabout coordination, and larger chromosome structures will require advanced tuning and scalability strategies. Such enhancements could support adaptive, real-time traffic control solutions for smart cities.

REFERENCES

[1] Huang, J. H.; Sun, M. G.; Cheng, Q. (2021). Congestion risk propagation model based on multi-layer time-varying network, *International Journal of Simulation Modelling*, Vol. 20, No. 4, 730-741, doi:10.2507/IJSIMM20-4-585

[2] Tang, M.; Buchmeister, B.; Gong, D.; Xue, G.; Khoa, B. T. (2025). Subway expansion and traffic flow: a spatiotemporal analysis of urban congestion dynamics, *Technical Gazette*, Vol. 32, No. 1, 44-53, doi:10.17559/TV-20241015002063

[3] Demir, H. G.; Demir, Y. K. (2020). A comparison of traffic flow performance of roundabouts and signalized intersections: a case study in Nigde, *The Open Transportation Journal*, Vol. 14, 120-132, doi:10.2174/1874447802014010120

[4] Webster, F. V. (1958). *Traffic Signal Setting*, Road research technical paper N° 39, Road Research Laboratory, Department of Scientific and Industrial Research, London

[5] Verma, A.; Nagaraja, G.; Anusha, C. S.; Mayakuntla, S. K. (2018). Traffic signal timing optimization for heterogeneous traffic conditions using modified Webster's delay model, *Transportation in Developing Economies*, Vol. 4, No. 2, Paper 13, 13 pages, doi:10.1007/s40890-018-0064-2

[6] Robertson, D. I. (1969). TRANSYT: a traffic network study tool, RRL Report LR 253, Road Research Laboratory, Crowthorne

[7] Akçelik, R. (2012). An improved method for estimating sign-controlled intersection capacity, *New Zealand Modelling User Group NZMUGS 2012 Conference*, 11 pages

[8] Teo, K. T. K.; Kow, W. Y.; Chin, Y. K. (2010). Optimization of traffic flow within an urban traffic light intersection with genetic algorithm, *Proceedings of the 2nd International Conference on Computational Intelligence, Modelling and Simulation (CIMSim 2010)*, 172-177, doi:10.1109/CIMSiM.2010.95

[9] Sánchez-Medina, J. J.; Galán-Moreno, M. J.; Rubio-Royo, E. (2010). Traffic signal optimization in "La Almozara" district in Saragossa under congestion conditions, using genetic algorithms, traffic microsimulation, and cluster computing, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 11, No. 1, 132-141, doi:10.1109/TITS.2009.2034383

[10] Li, Z.; Schonfeld, P. (2015). Hybrid simulated annealing and genetic algorithm for optimizing arterial signal timings under oversaturated traffic conditions, *Journal of Advanced Transportation*, Vol. 49, No. 1, 153-170, doi:10.1002/atr.1274

[11] Cai, Y.; Cai, H. (2012). A dynamic traffic signal timing model and its algorithm for junction of urban road, Zhang, Y. (Ed.), *Future Wireless Networks and Information Systems*, Lecture Notes in Electrical Engineering, Vol. 144, Springer, Berlin, 555-566, doi:10.1007/978-3-642-27326-1_71

[12] Benhamza, K.; Seridi, H. (2015). Adaptive traffic signal control in multiple intersections network, *Journal of Intelligent & Fuzzy Systems*, Vol. 28, No. 6, 2557-2567, doi:10.3233/IFS-151535

[13] Gökçe, M. A.; Öner, E.; Işık, G. (2015). Traffic signal optimization with Particle Swarm Optimization for signalized roundabouts, *Simulation*, Vol. 91, No. 5, 456-466, doi:10.1177/0037549715581473

[14] Dabiri, S.; Abbas, M. (2016). Arterial traffic signal optimization using Particle Swarm Optimization in an integrated VISSIM-MATLAB simulation environment, *Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, 766-771, doi:10.1109/ITSC.2016.7795641

[15] Jintamuttha, K.; Watanapa, B.; Charoenkitkarn, N. (2016). Dynamic traffic light timing optimization model using Bat algorithm, *Proceedings of the 2016 2nd International Conference on Control Science and Systems Engineering (ICCSSE)*, 181-185, doi:10.1109/CCSSE.2016.7784378

[16] Murat, Y. S.; Cakici, Z.; Tian, Z. (2019). A signal timing assignment proposal for urban multi lane signalised roundabouts, *Građevinar*, Vol. 71, No. 2, 113-124, doi:10.14256/JCE.2323.2018

[17] Zhang, L. Y.; Duan, X. K.; Ma, J.; Zhang, M.; Wen, Y.; Wang, Y. (2022). Mechanism of road capacity under different penetration scenarios of autonomous vehicles, *International Journal of Simulation Modelling*, Vol. 21, No. 1, 172-183, doi:10.2507/IJSIMM21-1-CO4

[18] Sun, P. F.; Zhang, Y.; Wu, X. J.; Du, J. Y.; Hou, R. R.; Liu, J. (2024). Simulation and analysis of a preemptive transportation model using Flexsim software, *International Journal of Simulation Modelling*, Vol. 23, No. 2, 335-346, doi:10.2507/IJSIMM23-2-CO7

[19] Akçelik, R. (2009). Evaluating roundabout capacity, level of service and performance, *Institute of Transportation Engineers 2009 Annual Meeting*, 22 pages

[20] Cakici, Z.; Murat, Y. S. (2019). A Differential Evolution algorithm-based traffic control model for signalized intersections, *Advances in Civil Engineering*, Vol. 2019, No. 1, Paper 7360939, 16 pages, doi:10.1155/2019/7360939

[21] Jamil, A. R. M.; Ganguly, K. K.; Nower, N. (2020). Adaptive traffic signal control system using composite reward architecture based deep reinforcement learning, *IET Intelligent Transport Systems*, Vol. 14, No. 14, 2030-2041, doi:10.1049/iet-its.2020.0443

[22] Huang, L.; Qu, X. (2023). Improving traffic signal control operations using proximal policy optimization, *IET Intelligent Transport Systems*, Vol. 17, No. 3, 592-605, doi:10.1049/itr2.12286

[23] Sun, Z.; Wang, Z.; Qi, X.; Wang, D.; Li, Y.; Lu, H. (2024). A two-stage robust optimal traffic signal control with reversible lane for isolated intersections, *IET Intelligent Transport Systems*, Vol. 18, No. 4, 723-742, doi:10.1049/itr2.12465

[24] Lee, S.; Eom, M.; Kim, B.-I. (2024). Two-stage algorithm for traffic signal optimization and web-service system development, *IET Intelligent Transport Systems*, Vol. 18, No. 9, 1697-1715, doi:10.1049/itr2.12542

[25] Atre, A.; Singh, K. K.; Chaurasia, B. K.; Sengar, S. S.; Srivastava, P. (2025). Optimized resource analysis in VANET cloud using fog enabled real-time traffic control system, *Proceedings on Engineering Sciences*, Vol. 7, No. 3, 1939-1954, doi:10.24874/pes07.03a.020

[26] Qadri, S. S. S. M.; Gökçe, M. A.; Öner, E. (2020). Traffic signal timing optimization for signalized roundabout using GA, *International Journal of Advanced Research in Engineering and Technology*, Vol. 11, No. 11, 1888-1897, doi:10.34218/IJARET.11.11.2020.176

[27] Qadri, S. S. S. M.; Gökçe, M. A.; Öner, E. (2020). State-of-art review of traffic signal control methods: challenges and opportunities, *European Transport Research Review*, Vol. 12, No. 1, Paper 55, 23 pages, doi:10.1186/s12544-020-00439-1

[28] Wang, S. L.; Zhang, X. (2024). Optimization strategies and simulation of integrated management in supply chains, *International Journal of Simulation Modelling*, Vol. 23, No. 3, 543-554, doi:10.2507/IJSIMM23-3-CO15

[29] Qadri, S. S. S. M.; Gökçe, M. A.; Öner, E.; Gökçe, E. G. (2019). Analysis of various scenarios to mitigate congestion at a signalized roundabout using microsimulation, *Proceedings of the 2019 Innovations in Intelligent Systems and Applications Conference (ASYU)*, 6 pages, doi:10.1109/ASYU48272.2019.8946339

[30] Araghi, S.; Khosravi, A.; Creighton, D.; Nahavandi, S. (2017). Influence of meta-heuristic optimization on the performance of adaptive interval type2-fuzzy traffic signal controllers, *Expert Systems with Applications*, Vol. 71, 493-503, doi:10.1016/j.eswa.2016.10.066