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Sustainability and Operational Performance of Fixed-Time and Fully Traffic-Actuated Signal Control Across Different Intersection Types

Tolga Yaman [1], Metin Mutlu Aydin [1], Edgar Sokolovskij [2,*], Jonas Matijošius [3] and Eren Dağlı [4]

[1] Civil Engineering Department, Engineering Faculty, Ondokuz Mayıs University, 55270 Samsun, Türkiye; tolgayaman7400@gmail.com (T.Y.); metinmutlu.aydin@omu.edu.tr (M.M.A.)
[2] Department of Automobile Engineering, Faculty of Transport Engineering, Vilnius Gediminas Technical University, Plytinės g. 25, LT-10105 Vilnius, Lithuania
[3] Mechanical Science Institute, Vilnius Gediminas Technical University, Plytinės g. 25, LT-10105 Vilnius, Lithuania; jonas.matijosius@vilniustech.lt
[4] Transportation Service Department, Doganhisar Vocational School, Selcuk University, 42930 Konya, Türkiye; e.dagli6607@gmail.com
* Correspondence: edgar.sokolovskij@vilniustech.lt

Abstract

Traffic signal-controlled intersections are important elements of urban transport systems, where inappropriate signal control strategies can increase traffic congestion, energy consumption, and pollutant emissions. Increasing and time-varying traffic intensity reduces the efficiency of traditional fixed-cycle traffic signal control; therefore, fully traffic-actuated control solutions are increasingly being applied. This study compares the efficiency of fixed-cycle and fully traffic-actuated signal control at eight traffic signal-controlled intersections in Bursa (Turkey), including four-way intersections and signalized three-way and four-way roundabouts with different geometric characteristics. The analysis was performed using a microsimulation method and PTV Vissim software, incorporating actual peak hour traffic flows, detailed intersection geometry, and camera-based vehicle detection logic implemented through the VisVAP module. Particular attention was given to the sustainability implications of signal control by jointly considering traffic performance, fuel consumption, and traffic-related pollutant emissions. The efficiency of intersections was assessed based on average vehicle delays, the number of stops, queue length, average speed, fuel consumption, and emissions (CO, NOx, and VOC). The results show that fully traffic-actuated traffic control usually improves both operational and environmental performance, but the magnitude of the effect depends on the intersection geometry and traffic flow distribution. At four-way intersections, average delays decreased by up to 47% and queue length by up to 67%, while fuel consumption and emissions decreased by around 20–39% in some cases. These findings indicate that fully traffic-actuated control can contribute to more sustainable urban mobility by reducing congestion-related inefficiencies, unnecessary fuel use, and local pollutant emissions, although the magnitude of these benefits depends strongly on intersection geometry and traffic flow characteristics.

Keywords: fully traffic-actuated traffic signal control; sustainable urban mobility; traffic emissions; energy efficiency; signalized intersections; traffic microsimulation

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1. Introduction

Transport can be defined as the process of moving people, animals, and goods from one place to another for a specific purpose [1]. Along with the demands of population

growth and urbanization, the form and scope of transport change over time. Different modes of transport, such as road, sea, air, and rail, are used to move people and goods. These modes, each with its own advantages and disadvantages, are central to the economic and social development of societies. Transport is the totality of movements and interactions that occur during the use of these modes of transport [2]. However, transport has become much more complex with urbanization and population growth. Unplanned urbanization and inadequate road networks are among the main parameters contributing to traffic problems [3]. Transport is not only a part of daily life but also an important issue in terms of environmental impact and use of energy resources. Therefore, not only should transport be managed carefully considering its impact on the environment and resources, but the need for transport in daily life should also be met in a safe and comfortable way. For all these reasons, traffic management and planning has become an important issue for a sustainable future.

From a sustainability perspective, the performance of urban intersections should not be evaluated solely in terms of traffic capacity and travel efficiency. Repeated stops, prolonged idling, queue formation, and frequent acceleration and deceleration increase fuel consumption and traffic-related emissions. Consequently, signal control strategies capable of reducing these inefficient operating conditions can contribute simultaneously to operational efficiency, energy conservation, and improved local environmental quality.

Global population growth brings with it a number of problems, including road accidents, environmental damage, and noise pollution, as the number of motorized and non-motorized vehicles increases [4]. This increase leads to traffic congestion, especially on urban roads, and various methods are being investigated to solve these problems. For this reason, studies in transport science have focused on intersections and traffic management techniques to reduce traffic accidents and provide safer transport [5], especially in the last three decades. As a concrete indicator of this trend, statistical data on the distribution of the number of motorized land vehicles in Turkey according to TÜİK [6] and in the world according to Aydin and Aydoğdu [4] are shown in Figure 1, which was prepared by the authors based on these sources. Especially in the last 20 years, it can be seen that the demand for transport in the world, as well as in Turkey, has increased continuously. These statistics clearly show the extent of the increase in the number of vehicles and the corresponding increase in the demand for transport.

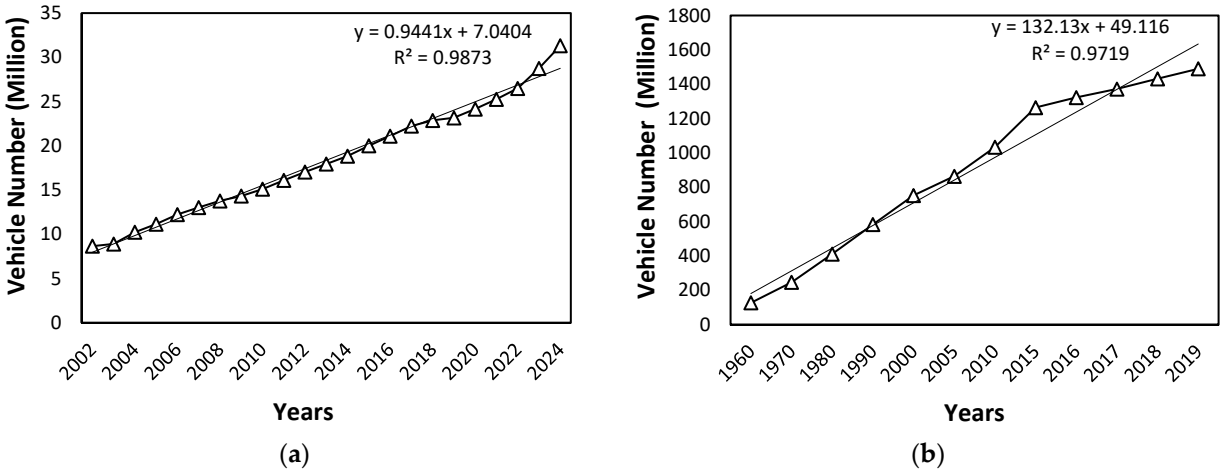


Figure 1. (**a**) Number of motor vehicles in Türkiye between 2002 and 2024 and (**b**) in the world between 1960 and 2019.

As shown in Figure 1, while the global vehicle fleet has grown steadily since the 1960s, the rate of increase in Türkiye has been notably steeper, with the number of registered

motor vehicles nearly tripling between 2002 and 2024. This divergence suggests that rapidly developing countries such as Türkiye are experiencing accelerated motorization compared to the global average, placing disproportionate pressure on existing urban road infrastructure and intersection capacity. The sharp upward trend observed in Türkiye underscores the urgency of implementing more efficient traffic signal control strategies to manage growing demand without proportional expansion of road infrastructure. Intersections stand out as points where conflicts and confusion in traffic flow on urban and intercity road sections are most intense due to the increasing number of vehicles [7]. Traffic demand at intersections and urban traffic are constantly increasing with population growth and urbanization [8]. This growth leads to problems such as delays, vehicle queues, and congestion at intersections, and finding a solution to these problems has become one of the most important tasks of urban planning and transport engineering today. For this reason, traffic management studies usually aim to solve problems by focusing on these critical points of the transport network [9,10]. Traffic flow regulation at intersections, selection of the appropriate intersection type, and effective setting of traffic light signal durations are essential factors that allow improving traffic throughput as the number of vehicles and transport needs increase. Delays and queues at intersections not only increase traffic congestion but also negatively affect fuel consumption and pollutant emissions. This causes environmental problems, increases air pollution, and reduces the quality of urban life [11,12]. The growing number of vehicles and traffic intensity, in particular, encourage the development of innovative solutions in the fields of intelligent transport systems and traffic management [13]. As motorways are the main transport network for urban and intercity journeys, technological solutions are being developed to increase the capacity of this network and to regulate traffic flow. These solutions focus on areas such as intersection analysis, traffic simulation, and signaling improvements. In recent years, fully traffic-actuated signalized intersections, equipped with camera/sensor detectors capable of detecting traffic density, which are an important component of intelligent transport systems (ITSs), have been increasingly preferred to solve or optimize and reduce the problems encountered at intersections. A traffic-actuated signalized intersection is an intersection where the timing of traffic signals is dynamically adjusted based on real-time traffic demand, rather than operating on fixed cycles. These intersections are equipped with vehicle detection sensors (such as inductive loops, video cameras, or radar sensors) embedded in the roadway or mounted on poles. The system continuously monitors traffic flow and adjusts green light durations, phase sequences, and cycle lengths to optimize efficiency, reduce delays, and minimize congestion [7].

This study compared the performance of fixed-time operated intersections and fully traffic-actuated intersections for identified four-leg signalized, three-leg roundabout signalized, and four-leg roundabout signalized intersections, and thoroughly examines the effects of these two different traffic-actuated intersection operation methods on traffic flow. Although the literature frequently includes comparisons between fully traffic-actuated intersections and fixed-time intersections, it has been observed that these studies do not sufficiently address differences in geometric measurements or intersection types. In this study, intersections of different types and geometric characteristics were modeled for both operational methods (fixed-time and traffic-actuated) using simulation software. Performance criteria such as the level of service, delay per vehicle, the number of stops per vehicle, average speed, fuel consumption, and emission values were evaluated at the modeled pilot intersections for both intersection management methods. Thus, intersections with operational differences were compared in terms of performance based on identical structural features. The results revealed that traffic-actuated intersections play a critical role in managing urban traffic flow and enhancing road safety, especially at intersections with varying geometric and structural characteristics.

In addition to operational performance, the present study considers the environmental sustainability implications of intersection control. Accordingly, this study aims to compare fixed-time and fully traffic-actuated signal control across different intersection geometries by jointly evaluating vehicle delay, the number of stops, queue length, average speed, fuel consumption, and pollutant emissions. Particular emphasis is placed on identifying whether the environmental benefits of fully traffic-actuated control vary with intersection geometry and traffic flow characteristics. In this way, this study evaluates fully traffic-actuated signal control not only as a traffic efficiency measure but also as a potential instrument for sustainable urban mobility.

To the best of the authors' knowledge, no previous study has assessed performance, fuel consumption, and emissions (CO, NOx, and VOC) simultaneously within a single microsimulation range across three different intersection geometries (four-leg signalized, three-leg signalized roundabout, and four-leg signalized roundabout) with fixed-time and continuous traffic signals. Unlike previous processes that addressed fully traffic-actuated signal control or intersection geometry separately, the integrated multi-geometry, multi-criteria sustainability assessment presented here constitutes the fundamental novelty of this work. In addition, the use of camera-based VisVAP logic more accurately simulates real-time traffic control applications than the continuous cyclical spectrum-based or segmented scenarios commonly found in the literature.

2. Literature Review

There are many studies in the literature attempting to improve intersection performance. These studies focus on solving the problem by studying and optimizing one or more parameters, as there are many different parameters (driver characteristics, lane width, the number of arms, signal type, heavy vehicle ratio, the number of lanes, intersection type, traffic volume, etc.) that are effective in improving intersection performance. When these parameters are evaluated together, sub-parameters that may have an impact on intersection performance can be grouped into parameter categories of geometric modifications, signal time optimization, and operation properties, as explained below.

2.1. Geometric Modifications

The geometry of signalized intersections plays a critical role in urban transport networks, significantly influencing traffic flow, safety, and overall system efficiency. The geometric design or modification of these intersections has great importance in determining their operational performance. In the literature, numerous studies have evaluated different geometric modifications to determine their impact on intersection efficiency. Empirical studies show that adjusting the geometric elements of intersections can have a significant impact on traffic throughput and vehicle delays. The current analysis provides strong evidence that the arrangement of intersections has a considerable impact on both operational efficiency and safety. Nonetheless, a careful investigation reveals significant limits that prevent the widespread application of several proposed solutions. A substantial body of research concentrates on geometric approaches to lane management, specifically lane reallocation and enhancements to turning radii. Many sources [14–17] demonstrate that modifying lane configurations and applying targeted channelization strategies can enhance service capacity, decrease delays, and lower the incidence of accidents. The evidence provided is corroborated by many studies [18–22], demonstrating significant decreases in congestion and delays following the implementation of dedicated turning lanes. The majority of these studies focus on changes in the geometry of individual objects in theoretical traffic scenarios. They typically fail to acknowledge the significance of long-term operational uncertainty and its relationship to signal control approaches.

The existing body of research demonstrates a major gap in understanding the trade-offs between vehicle efficiency and pedestrian safety. Wang et al. [17] found that geometric extensions, while often enhancing vehicle throughput, frequently result in longer pedestrian crossing distances and higher implementation costs. In view of these findings, it is essential to acknowledge that the impact on pedestrians is often considered a secondary performance metric or, in certain instances, entirely overlooked. Many authors [23–28] documented notable enhancements in operational efficiency, attaining reductions of up to 60% in vehicle delays through the expansion of left-turn lanes. Nonetheless, the evaluation of these modifications primarily concentrated on vehicular characteristics, leaving unresolved questions regarding their impact on non-motorized users and areas with mixed traffic conditions. Ahmed and Wang [29] elucidated the benefits of right-turn channelization in reducing conflict points. Nevertheless, they did not explicitly assess the effectiveness of these designs in settings characterized by dense pedestrian activity or limited urban spatial configurations.

The existing literature does not provide a comprehensive review of geometric aspects, including intersection angles and median design, nor does it thoroughly analyze lane configurations. Many authors [30–33] consistently demonstrated that near-orthogonal crossing angles, in conjunction with median interventions, substantially enhance visibility and pedestrian safety. Many authors [34–37] elucidated the relationship between asymmetrical junctions, increased accident rates, and inadequate signal phase utilization. Many authors [38–43] conducted quantitative analyses and determined that employing more fluid vehicle trajectories led to throughput improvements of up to 20%. Nevertheless, most of these studies evaluated geometric elements independently, without explicitly examining their combined effects when integrated with adaptive signal control or real-time traffic management systems. This restriction diminishes their significance in contemporary, innovative intersection design.

Advanced geometric arrangements, such as continuous-flow intersections (CFIs) and median U-turns (MUTs), have been identified as viable solutions to significantly reduce delays and conflict points [44–49]. The existing body of research indicates that, while these systems have both theoretical and practical benefits, their efficacy is heavily influenced by driver behavior, familiarity, and adherence to established standards. Many authors [50–53] underscore the importance of conducting comprehensive site-specific assessments prior to implementation. Nevertheless, a significant gap remains in the development of structured frameworks for these evaluations. The discrepancy is particularly evident in rapidly expanding urban areas. Aydin and Aydoğdu [4] identified significant geometric irregularities, operational challenges, and unregulated lane utilization within these systems. The findings suggest that the adoption of sophisticated designs may be unfeasible unless both institutional and infrastructure systems are simultaneously enhanced.

Many authors [54–59] observed reductions in crashes spanning from 30% to 50% subsequent to the implementation of exclusive turning lanes and approach reconfiguration. It is essential to highlight that these findings are predominantly derived from pre- and post-intervention studies, which may not precisely represent the behavioral changes that develop over time. Furthermore, the current corpus of research often emphasizes crash frequency over exposure-based risk metrics, leading to an incomplete evaluation of safety performance, especially for vulnerable road users. Many authors [59–63] highlighted the importance of implementing enhanced pedestrian-oriented strategies at prolonged or grade-separated intersections. Nonetheless, there remains a notable lack of comprehensive frameworks that effectively reconcile vehicular efficiency with the accessibility needs of pedestrians and cyclists.

In summary, although geometric design is acknowledged as a valuable tool for enhancing intersection performance, the literature underscores the existence of several unresolved

challenges. The current challenges include limited integration of geometric modifications with adaptive signal control, inadequate consideration of mixed traffic conditions, and the lack of comprehensive evaluation frameworks that concurrently address operational efficiency, safety, cost, and environmental impacts. Kwon et al. [64] posited that intersections featuring excessively intricate design elements may unintentionally promote increased vehicle velocities and expanded land development, underscoring the importance of context-sensitive design. Consequently, there is a substantial need for thorough investigations that assess the combined effects of geometric design and signal control systems under real-world traffic conditions, taking into account multiple performance metrics—a topic that has been insufficiently examined in the existing research.

2.2. Signal Time and Phase Optimization

Signal timing optimization is recognized as a profoundly influential and frequently employed approach for improving the operational efficiency of signalized intersections. Over the course of many decades, this topic has been examined in diverse geographic and traffic contexts, highlighting its fundamental importance in the field of traffic engineering practice. The careful selection of signal timing parameters is essential in determining the allocation of green time, which in turn affects traffic flow distribution, patterns of vehicle delay, fuel consumption, and safety outcomes. Consequently, the refinement of signal timing has become a crucial focus of investigation in the broad field of intersection performance analysis.

Preliminary investigations revealed the effectiveness of adaptive signal control methodologies in addressing variable traffic scenarios. Abbas et al. [65] and Wong and Wong [66] presented compelling evidence that the implementation of adaptive signal timing can markedly reduce vehicle delays and improve the efficiency of intersection throughput. The research conducted by Skabardonis and Geroliminis [67] was further validated, demonstrating that traffic-responsive signal control offers considerable benefits during peak periods, a phase when fixed-time strategies often falter in accommodating short-term fluctuations in demand. Nonetheless, a considerable segment of this preliminary investigation focused on isolated intersections or simplified traffic scenarios, thus limiting the relevance of the identified benefits.

As research progressed, a varied spectrum of methodological approaches to signal timing optimization became apparent. Heuristic algorithms and model-based optimization techniques have consistently emerged as widely utilized solutions across various applications. Many authors [68–74] demonstrated that combining microscopic traffic simulation with optimization algorithms facilitates the systematic identification of effective signal timing strategies in complex traffic environments. In a comparable context, many authors [75–81] emphasized the potential of genetic algorithms, particularly in non-linear and highly variable traffic scenarios. Although these approaches exhibit significant efficacy, they often demand considerable computational resources and are particularly sensitive to calibration assumptions. This sensitivity could limit their applicability in the realm of real-time traffic management.

A substantial body of research has investigated the importance of signal coordination and synchronization in mitigating congestion at the network level. Tian and Urbanik [82] recorded significant reductions in travel time and fuel consumption due to the implementation of coordinated signal operation. Comparable findings were obtained by Calle-Laguna et al. [83], who demonstrated that well-coordinated signal plans can significantly reduce the number of stops, emissions, and delays, particularly in densely populated urban corridors. Chen et al. [84] observed that many coordination strategies are inherently predicated on the assumption of consistent traffic patterns. When traffic demand exhibits considerable fluctu-

ations, neglecting this variability can undermine coordination advantages and threaten the system's robustness.

Recent research has concentrated on integrating real-time data into frameworks developed to enhance signal timing optimization. Many authors [85–89] demonstrated that real-time adaptive control systems surpass traditional fixed-time approaches by continuously adjusting to changing traffic conditions. Complementary studies conducted in [90–96] elucidated the benefits of integrating connected car technologies with real-time data analytics to improve operational efficiency, safety, and environmental sustainability. Given these advancements, it is evident that the existing literature lacks comprehensive assessments that simultaneously address signal timing optimization, real-time data integration, and the diverse geometries of intersections within a cohesive analytical framework.

In conclusion, the optimization of signal timing and phases is acknowledged as a crucial element affecting the efficiency of intersections; however, contemporary research reveals considerable shortcomings in this domain. The issues under examination encompass a narrow perspective on the fluctuations of traffic conditions in real-world scenarios, an absence of synergy with adaptive detection technologies, and a propensity to evaluate operational metrics without considering their implications for safety and environmental factors. Addressing these issues is crucial for developing signal control systems that are both technically robust and effective in managing traffic in contemporary urban environments.

2.3. Traffic-Actuated Signal Control

The implementation of adaptive traffic signal control has emerged as a significant component of contemporary traffic management strategies in recent years. This is primarily due to the potential fluctuations in transportation demand. Adaptive control systems diverge from fixed-time signal systems, which operate on predetermined schedules and presuppose a uniform flow of traffic. In contrast, adaptive control employs real-time data on the movements of pedestrians and vehicles to adjust the timing of traffic signals. A significant number of individuals claim that this major change has resulted in enhanced safety and increased efficiency at crossings. Empirical studies demonstrate that adaptive systems optimize the allocation of green time according to real-time demand, resulting in reduced delays and increased intersection throughput [97–102]. Nonetheless, the aforementioned benefits often originate from controlled experimental environments or limited case studies, thereby raising questions regarding their applicability and reliability in diverse urban settings.

The advancement of adaptive traffic management systems has been intricately associated with the rapid expansion of vehicle detection technologies. Inductive loop detectors have traditionally served as the core components of traffic sensing systems. Nevertheless, issues related to maintenance, adaptability, and spatial coverage have led to the investigation of alternative sensing methods. Image-based detection systems, microwave radar, and infrared sensors are increasingly employed to enhance detection accuracy and system responsiveness [103–107]. While these technologies offer enhanced and more dependable data streams, the existing literature frequently neglects the intricacies related to sensor calibration, environmental sensitivity, and data integration. Research that integrates multiple detection sources demonstrates enhanced predictive capabilities, enabling adaptive systems to anticipate variations in traffic flow rather than simply responding to them [108–113]. Nevertheless, there continues to be a lack of comprehensive evaluations concerning the efficacy of predictive control in the context of diverse traffic compositions and varying geometric constraints.

In conjunction with advancements in sensor technologies, considerable scholarly effort has been directed toward enhancing adaptive signal control algorithms. Methodological

techniques include the integration of vehicle license plate recognition data with advanced optimization and machine learning algorithms. Many authors [114–117] demonstrated that improved traffic state information can reduce unnecessary pauses and delays by enabling a more precise characterization of flow. Concurrently, simulation platforms like VISSIM, TRANSYT-7F, and DTALite have emerged as essential instruments for evaluating adaptive strategies within controlled environments [118–122]. Although these instruments yield significant insights, their substantial dependence on calibration assumptions and scenario-specific configurations constrains the applicability of the results to practical implementations, especially in intricate urban networks.

While the operational benefits of adaptive systems are evident, their deployment presents a series of complex challenges that remain inadequately explored in the existing literature. A persistent issue pertains to the equilibrium among various categories of road users. Many authors [123–133] emphasized that adaptive control strategies may inadvertently prioritize motorized traffic, potentially resulting in adverse conditions for pedestrians and cyclists unless equity considerations are intentionally incorporated into the control framework. Furthermore, adaptive systems necessitate reliably accurate detectors and control algorithms that are subjected to periodic recalibration to ensure their continued effectiveness. In performance assessments, the critical elements of maintenance needs and the limitations of institutional capacity are often overlooked, despite their considerable importance in practical implementation. A recent study highlights the potential of utilizing data from connected and autonomous vehicles to tackle specific limitations, thereby fostering opportunities for enhanced safety and traffic flow management [74]. Nevertheless, there exists a notable lack of thorough empirical validation.

A multitude of studies presents practical examples of adaptive control implementation; nonetheless, the majority are constrained in their breadth. Many authors [134–136] presented a system that employs a programmable logic controller (PLC) to dynamically adjust signal timing based on traffic volume, thus enhancing traffic flow at intersections. Some authors [137,138] documented notable reductions in travel time and delays when utilizing the adaptive SCATS system compared to fixed-time control. Approaches employing artificial intelligence have attracted significant attention; Şimşir et al. [139] demonstrated that optimization via learning-based methodologies can substantially reduce queuing times at intersections. A study conducted by Çakıçı [140] on sensor-monitored signalized roundabouts demonstrated that the adoption of adaptive control improves the effectiveness of traffic management. Such investigations typically concentrate on specific intersections and limited observation periods, thus restricting our understanding of the wider network effects and the sustainability of performance over the long term.

Adaptive traffic control systems (ATCSs) have been deployed in numerous urban environments, underpinned by intelligent transport system (ITS) infrastructure. The implementation of real-time monitoring and dynamic signal adjustment has resulted in a significant reduction in delays, fuel consumption, and pollutant emissions. Some authors [140–143] demonstrated positive effects on traffic safety, emissions, and fuel efficiency while also noting that current implementations do not completely exploit the potential of adaptive control. The studies performed in [144–146] in Bursa indicated that dynamic signal optimization is superior to fixed-time operation in enhancing traffic throughput and improving environmental metrics. The predominant focus of applied research remains on specific contexts, underscoring the need for thorough evaluation frameworks that simultaneously consider adaptive control strategies, detection technologies, intersection geometry, and multi-dimensional performance indicators.

Adaptive traffic signal control is increasingly relevant not only from an operational perspective but also in the context of sustainable urban mobility. At signalized intersections,

delays, queues, repeated stopping, and acceleration events contribute to unnecessary fuel consumption and local pollutant emissions. Therefore, improvements in traffic flow stability may generate environmental benefits, alongside conventional mobility benefits.

Previous studies have shown that traffic-responsive and coordinated signal control strategies can reduce travel time, fuel use, and emissions [147–150]. However, the magnitude of these effects varies considerably among traffic environments. Intersection geometry, traffic demand distribution, pedestrian activity, turning movements, and lane configuration can influence the extent to which operational improvements are translated into environmental benefits.

This issue is particularly important from a sustainability perspective because a control strategy that reduces delays does not necessarily provide the same proportional reduction in fuel consumption or pollutant emissions at all intersection types [151,152]. Consequently, sustainability-oriented evaluation should combine operational indicators with environmental indicators rather than relying on traffic efficiency alone.

Despite the growing literature on adaptive signal control, comparative studies evaluating the sustainability effects of the same control strategy across multiple intersection geometries remain limited. Therefore, the present study addresses this gap by jointly assessing operational performance, fuel consumption, and traffic-related emissions under fixed-time and fully traffic-actuated control for eight intersections with different geometric configurations. Specifically, the following research gaps have been identified in the existing literature:

(i) Comparative studies rarely include signalized roundabouts in the same evaluation as conventional four-way intersections;
(ii) Sustainable consumption (fuel consumption and emissions) is often treated as an aggregate outcome rather than a primary design objective;
(iii) Camera-based fully traffic-actuated control logic (VisVAP) has not been systematically tested with constant-time operation in various geometries under real-world conditions.

This study directly addresses these three gaps.

3. Materials and Methods

3.1. Study Site

Eight signalized intersections located on the main arterials of Bursa city were chosen for this pilot study in Türkiye to compare the performance of different fully traffic-actuated signalized intersections. Figure 2 shows the locations of the selected intersections. The selection of intersections was based on the following main criteria:

- Representative of most major urban road types, with a straight and low-gradient segment;
- The presence of various vehicle types and flow densities;
- The presence of visible road lane line markings and clear sight distances for drivers;
- No pavement surface deformation effects that can adversely affect lane utilization of vehicles;
- The presence of various vehicle types and flow characteristics (hourly volumes);
- No fluctuations in traffic flow for unexpected reasons such as football matches, concerts, and activity-based organizations.

In this study, the characteristics of the examined intersections were obtained from field surveys and geometric measurements. All of the structural characteristics of the traffic-actuated signalized intersections with different geometric features are provided in Table 1. Additionally, real site images of these intersections and their approach legs are shown in Figure 3.

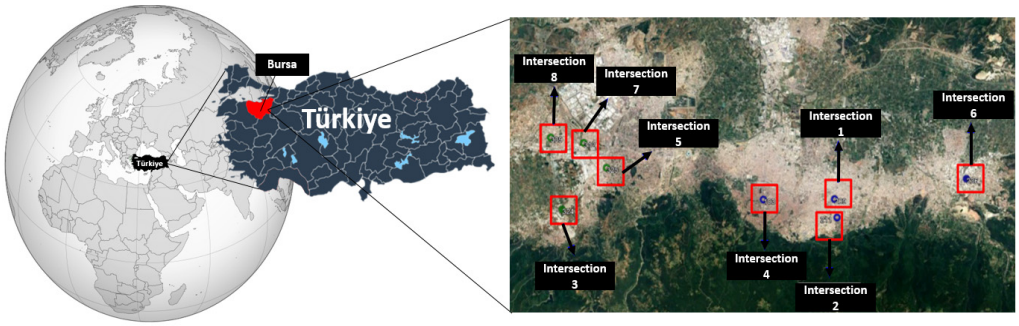


Figure 2. Locations of the eight examined traffic-actuated signalized intersections.

Table 1. The characteristics of the selected traffic-actuated signalized intersections.

Intersection No.	Intersection Name	Intersection Type	Lane Width (m)	Circle Diameter (m)
I-1	Eğitim Caddesi	4-Legged	3	-
I-2	Mesken	4-Legged	3	-
I-3	Çalı Alaaddinbey H.A.	4-Legged	2.75	-
I-4	Şehreküstü	3-Legged Circle	3	20
I-5	Çalı Yolu Beşevler Girişi	3-Legged Circle	3.5	23
I-6	Kestel	4-Legged Circle	3.25	28
I-7	Altınşehir Mah. Hipodrom	4-Legged Circle	3.5	45
I-8	Bursaspor Tesisleri	4-Legged Circle	3.25	21

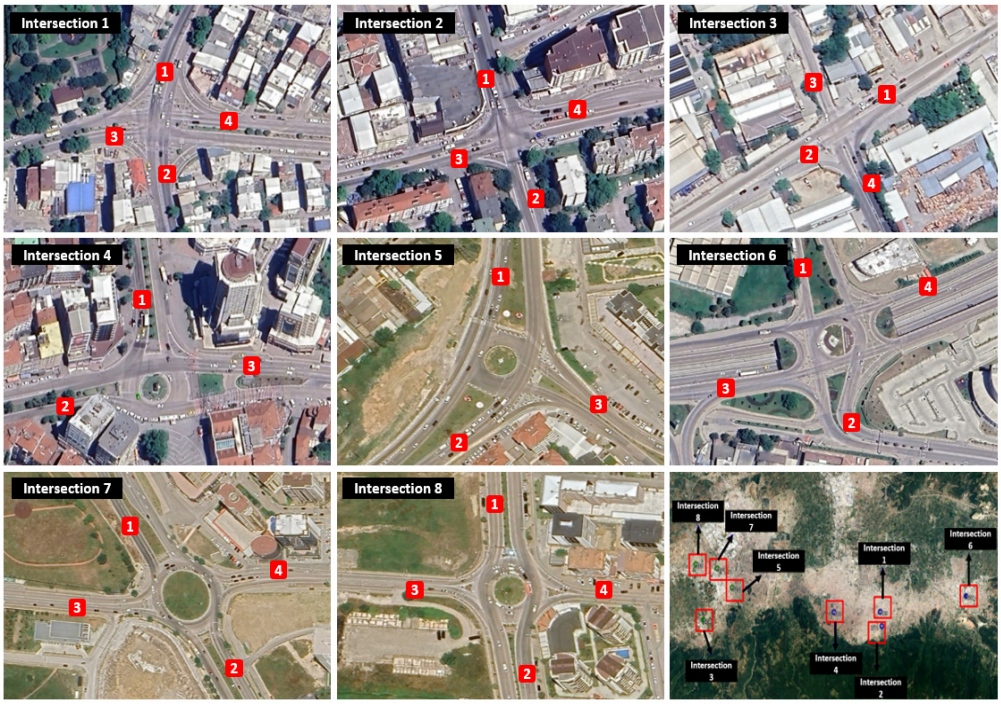


Figure 3. Real site images, locations, and leg numbers of examined signalized intersections.

3.2. Flow Data

Data collection at the real site focused specifically on the peak traffic flow conditions. Thus, vehicle counts and measurements were conducted to determine the traffic flow

characteristics of the examined signalized intersections during peak hours. Video recordings were taken from installed cameras during morning, noon, and evening hours for the vehicle counting process. A special software program was used to convert the obtained video recording images into numerical data for the analysis. The recorded videos were decoded into two different vehicle types, namely, Type 1 (cars and minibuses) and Type 2 (buses, trucks, and trailers (heavy vehicles)), and peak traffic flow hours were identified as given in Table 2. Real site images of Intersection 1 (I-1) and Intersection 8 (I-8) are presented in Figure 4 as examples of the examined intersections.

Table 2. Intersection-based observed traffic volumes (veh/h).

Intersection No.	Morning		Afternoon		Evening	
	Peak Hours	Flow (veh/h)	Peak Hours	Flow (veh/h)	Peak Hours	Flow (veh/h)
I-1	07:45–08:45	3325	13:00–14:00	2979	18:00–19:00	3250 *
I-2	07:15–08:15	1736	12:30–13:30	1652	18:45–19:45	1894 *
I-3	07:30–08:30	2235	13:00–14:00	1885	17:30–18:30	2329 *
I-4	08:15–09:15	2921	13:00–14:00	3046	18:15–19:15	3444 *
I-5	08:00–09:00	4104 *	13:00–14:00	2909	18:00–19:00	3888
I-6	08:15–09:15	3628 *	13:00–14:00	2509	16:15–17:15	3276
I-7	08:15–09:15	4190	12:45–13:45	3586	17:45–18:45	4745 *
I-8	08:15–09:15	4042 *	12:45–13:45	3069	16:15–17:15	3802

Note: * shows the observed maximum traffic volumes.

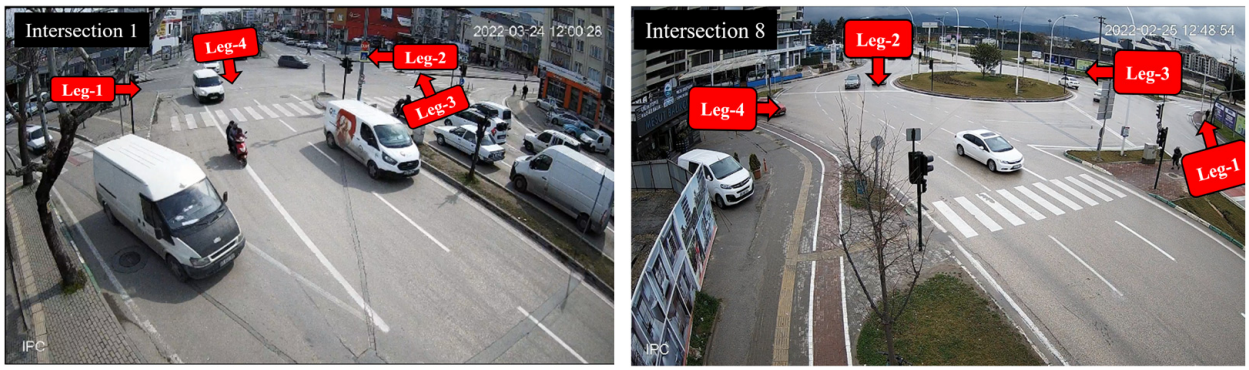


Figure 4. Data collected from video recordings of I-1 and I-8 as examples.

In the analyses, the obtained peak hour traffic counts were used to represent the highest observed traffic volumes; specifically, the evening peak hour counts were used for Intersections 1 (I-1), 2 (I-2), 3 (I-3), 4 (I-4), and 7 (I-7), and the morning peak hour counts were used for Intersections 5 (I-5), 6 (I-6), and 8 (I-8). Field observations were made during these identified peak hours, and the traffic counts obtained are summarized in Table 2.

Table 3 also shows the peak hour traffic volumes obtained from counts conducted during either morning or evening peak periods, depending on the specific intersection, detailed on a leg-by-leg basis. In the table, the columns indicate the directions from which vehicles approach the intersection, while the rows show the directions in which vehicles depart. The table also shows the vehicle-type-based volumes obtained for all intersections and their legs.

Table 3. Entry and exit leg distributions of vehicles at intersections by vehicle type (veh/h).

Inters. No.	Time	Leg No.	Type 1 (Passenger Car and Minibus)					Type 2 (Bus, Truck, and Lorry)					Total (∑)				
			1	**2**	**3**	**4**	∑	**1**	**2**	**3**	**4**	∑	**1**	**2**	**3**	**4**	∑
I-1	E	1	14	669	316	220	1219	14	669	316	220	1219	14	677	322	222	1235
		2	472	0	88	75	635	472	0	88	75	635	489	0	99	76	664
		3	340	50	21	298	709	340	50	21	298	709	344	56	21	305	726
		4	181	83	316	33	613	181	83	316	33	613	185	84	323	33	625
		∑	1007	802	741	626	3176	1007	802	741	626	3176	1032	817	765	636	3250
I-2	E	1	0	205	234	133	572	0	6	3	11	20	0	211	237	144	592
		2	175	0	39	41	255	1	1	3	0	5	176	1	42	41	260
		3	232	50	2	257	541	3	5	0	7	15	235	55	2	264	556
		4	109	41	300	1	451	27	0	8	0	35	136	41	308	1	486
		∑	516	296	575	432	1819	31	12	14	18	75	547	308	589	450	1894
I-3	E	1	1	461	32	346	840	0	15	0	14	29	1	476	32	360	869
		2	581	0	4	80	665	30	0	3	3	36	611	0	7	83	701
		3	21	18	0	148	187	0	2	0	5	7	21	20	0	153	194
		4	336	48	157	4	545	12	2	6	0	20	348	50	163	4	565
		∑	939	527	193	578	2237	42	19	9	22	92	981	546	202	600	2329
I-4	E	1	51	794	186	-	1031	2	62	1	-	65	53	856	187	-	1096
		2	196	112	443	-	751	2	0	2	-	4	198	112	445	-	755
		3	130	1377	1	-	1508	14	71	0	-	85	144	1448	1	-	1593
		∑	377	2283	630	-	3290	18	133	3	-	154	395	2416	633	-	3444
I-5	M	1	6	840	396	-	1242	5	50	10	-	65	11	890	406	-	1307
		2	1139	1	325	-	1465	39	0	10	-	49	1178	1	335	-	1514
		3	665	595	3	-	1263	14	6	0	-	20	679	601	3	-	1283
		∑	1810	1436	724		3970	58	56	20		134	1868	1492	744		4104
I-6	M	1	0	238	47	112	397	0	7	1	2	10	0	245	48	114	407
		2	174	5	894	17	1090	1	0	20	8	29	175	5	914	25	1119
		3	375	440	815	143	1773	12	10	48	9	79	387	450	863	152	1852
		4	37	49	44	101	231	0	5	1	13	19	37	54	45	114	250
		∑	586	732	1800	373	3491	13	22	70	32	137	599	754	1870	405	3628
I-7	E	1	3	570	90	15	678	0	51	2	1	54	3	621	92	16	732
		2	793	49	487	108	1437	62	4	6	3	75	855	53	493	111	1512
		3	321	812	6	637	1776	4	20	0	13	37	325	832	6	650	1813
		4	67	312	292	1	672	1	4	11	0	16	68	316	303	1	688
		∑	1184	1743	875	761	4563	67	79	19	17	182	1251	1822	894	778	4745
I-8	M	1	4	1597	112	150	1863	0	20	1	3	24	4	1617	113	153	1887
		2	952	156	90	72	1270	56	19	0	3	78	1008	175	90	75	1348
		3	104	320	0	117	541	0	0	0	0	0	104	320	0	117	541
		4	166	70	30	0	266	0	0	0	0	0	166	70	30	0	266
		∑	1226	2143	232	339	3940	56	39	1	6	102	1282	2182	233	345	4042

Note: M: morning; E: evening.

When traffic volumes are examined, it is observed that the car utilization rate at the examined intersections varies between 96% and 98%, while heavy vehicles account for only 2% to 4%. Certain legs of each intersection show higher density. For example:

- The busiest leg is Leg-1 at Intersection 1, which directs traffic to residential areas, while at Intersection 2, all legs, except for the southern leg, have a similar density.
- At Intersection 3, Leg-1 stands out with through and left-turn movements, whereas at Intersection 4, Leg-3 (east) is prominent for through movements, and Leg-1 (north) is notable for right turns.
- At Intersection 5 and Intersection 6, the morning peak is more intense, with through and U-turn movements generally directed toward the city center.
- At Intersection 7, the western leg is prominent for through and right-turn movements, while at Intersection 8, the northern leg stands out for through movements.

3.3. Signal Phase Data

Signal phase data for a controlled intersection are obtained by consistently and methodically collecting information about the operation of traffic lights. In the initial stage, using traffic management software, the total lap time of the intersection is identified; the sequence of phases is determined; and the durations of individual signals are calculated, covering the green, yellow, and red signal intervals. Later, more detailed local observations and video recordings are obtained, which allow checking the accuracy of the collected data and ensuring their mutual compatibility. The movement of vehicles in each direction of the intersection is recorded separately, clearly identifying permitted and reserved maneuvers in specific signal phases. Finally, all the collected information is systematized and presented in the form of phase diagrams, which allows for a clear visualization of the intersection signaling structure and the control scheme used in the analysis. An example of the structure and signal phase diagram of Intersection 1 (I-1) is presented in Figure 5, and the data of the phase plans of all analyzed intersections are summarized in Table 4.

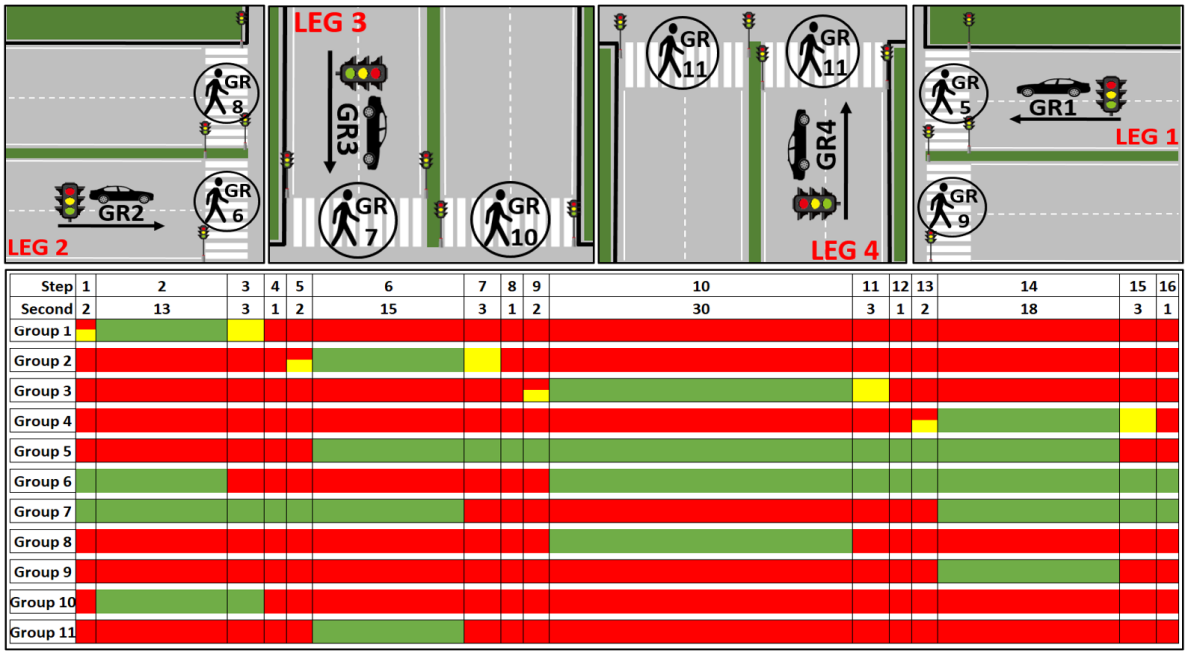
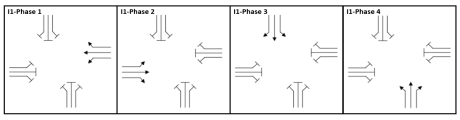
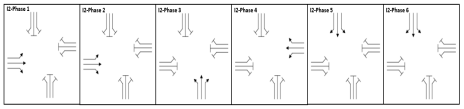
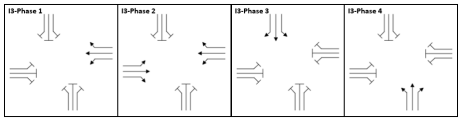
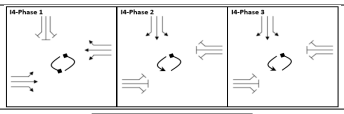
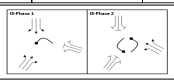
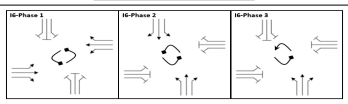
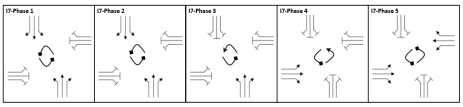
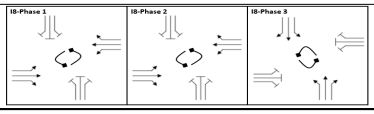


Figure 5. Evening peak hour signal schedule for signalized Intersection 1. Red: Stop time, Yellow (Amber): Clearance time and Green: Pass time (permitted movement time).

Table 4. Phase design of all signalized intersections.

Intersect. No.	Phase No.	Phase Name	Green Light (s)	Protection Period (s)	Cycle Period (s)	Phase Design
I-1	1	E	13	6	100	
	2	W	15	6		
	3	N	30	6		
	4	S	18	6		
I-2	1	W	13	7	105	
	2	W	5	3		
	3	S	11	7		
	4	E	16	7		
	5	N	6	7		
	6	N	17	6		
I-3	1	E	20	8	85	
	2	E and W	17	10		
	3	N	6	10		
	4	S	6	8		
I-4	1	E-W	34	15	113	
	2	N	9	20		
	3	N-Uturn	28	7		
I-5	1	N-SW	20	11	64	
	2	SE	20	13		
I-6	1	E-W	7	10	43	
	2	N-S	3	12		
	3	S	5	6		
I-7	1	N-S	13	20	116	
	2	N-S	7	5		
	3	S	5	6		
	4	W	28	6		
	5	E-W	14	12		
I-8	1	E-W	30	25	91	
	2	E-W	5	14		
	3	N-S	12	5		

Notes: E: east, W: west, N: north, S: south, SW: southwest.

3.4. Simulation Methodology

During the study, the main analysis stages were formulated and clearly defined, the sequence of which is presented in Figure 6 in a schematic flow diagram. This scheme describes the methodological basis of the microsimulation analyses of the fully traffic-actuated controlled intersections. The first stage focuses on collecting the initial data—recording traffic intensities, determining the geometric solutions of intersections, and identifying the time parameters of traffic light signals. Later, the collected information is prepared for the modeling process and transferred to the selected microsimulation software.

In the next stage, model calibration and validation are performed, during which the simulation parameters are systematically adjusted in order for the modeling results to replicate real, observed traffic conditions as accurately as possible. Only after achieving sufficient model compliance is the modeling of different traffic scenarios performed. Analysis of these scenarios allows for the assessment of the main indicators of intersection performance, such as vehicle delays, queue formation, and intersection throughput. In the final stage, the simulation results obtained are used to optimize the traffic light signal settings in order to improve the functioning of the intersections and ensure more efficient traffic flow management.

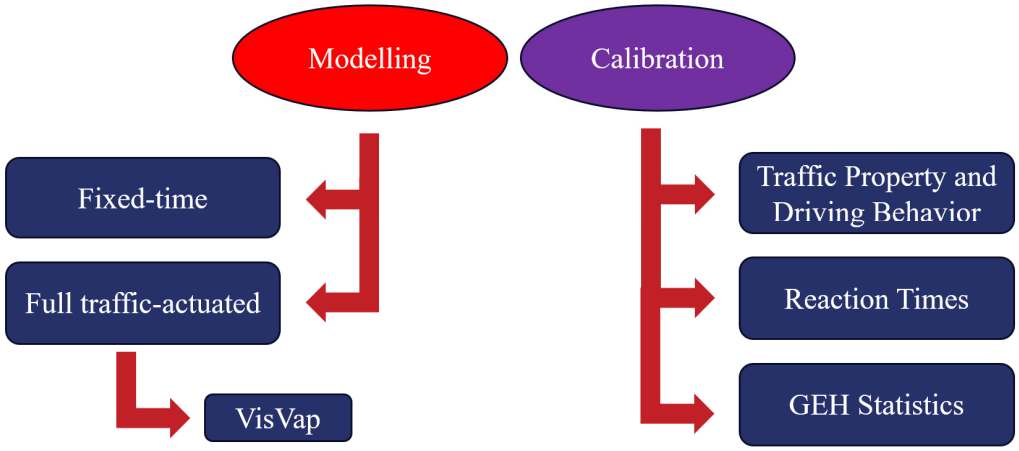


Figure 6. Flowchart of the simulation methodology.

In this study, the performance of fully traffic-actuated controlled intersections was analyzed using the microsimulation software "PTV Vissim v22". The total simulation duration was set to 5400 s for each scenario, inclusive of a warm-up period to allow the network to reach steady-state conditions prior to the evaluation period. Before starting the simulation, the intersection simulation environment was built by selecting parameters that correspond to the real conditions of the objects under study. First, the simulation duration was set, and all parameters that were not included in the default base data were individually defined. This included vehicle speeds, travel times, vehicle types and classes, and road categories and levels. Signaling schemes for the controlled intersections were created using the VISSIG module.

In order for the simulation results to reflect actual traffic conditions as accurately as possible, real environmental elements were integrated into the model. On-street parking lots and parking maneuver trajectories, public transport stops and routes, and horizontal and vertical road markings were recreated. All other environmental solutions that affect the formation of traffic flows at intersections were additionally defined. Specific evaluation parameters were determined for the analysis, and observation zones and points were selected, which were later used for the interpretation of the results. After preparing the modeling environment, test calculations were performed, which allowed for a visual assessment of the movement of traffic flows and identification of possible design or flow modeling inaccuracies. If discrepancies between real field conditions and the simulation results were identified, a calibration process was applied, the course of which is described in the next section.

Unlike in the case of fixed-time signaling, additional detector configuration was necessary to model intersections that fully respond to traffic. During the modeling stage, vehicle detectors were installed at the intersections, as shown in Figure 7, allowing for the implementation of fully traffic-actuated signal control logic. Specific port numbers were assigned to each detector, their operating lengths were determined, and the corresponding signal controllers were linked. After the installation of the detectors was completed and the VAP control program was created, the signal control mode in the signal controller was changed from fixed-time to VAP mode via the VISSIG environment. In this way, the intersection signaling began to operate as a fully traffic-actuated system, the duration of the signal phases of which varies depending on the traffic flows recorded by the detectors in real time.

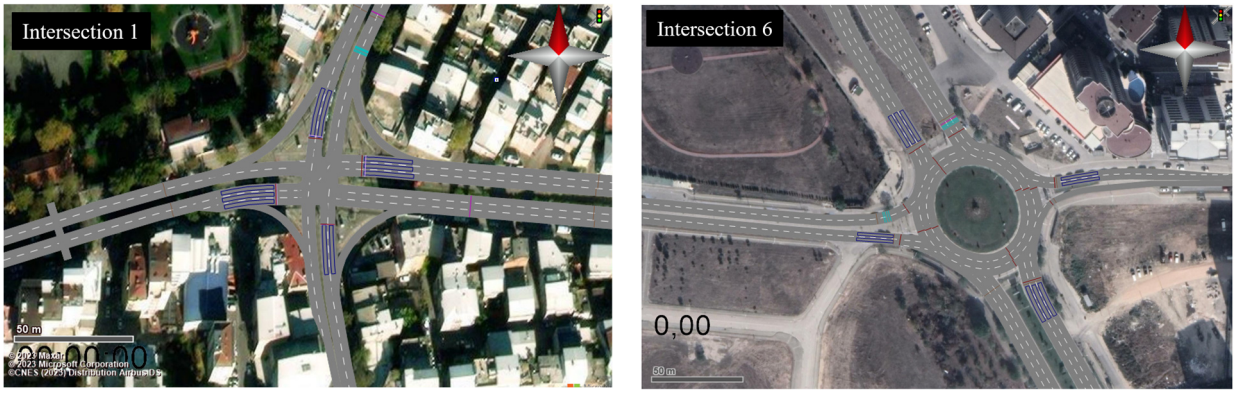


Figure 7. Detectors used on intersection leg entries.

In the literature, various traffic parameters are used to determine the performance of intersections, measure their efficiency, and assess their adequacy [4]. These parameters, which can be referred to as intersection performance parameters, include the level of service, average delay per vehicle, average number of stops per vehicle, average speed, fuel consumption, emission levels, and queue length. In this study, the values provided in Table 5, as recommended by the Highway Capacity Manual (HCM) 2010, were used to determine the level of service, while the values obtained from Vissim were used for the other intersection performance parameters.

Table 5. Levels of service based on delay times (LOSs) (HCM, 2010).

LOS	Delay (s/veh.)
A	<10
B	>10–20
C	>20–35
D	>35–55
E	>55–80
F	>80

For the sustainability assessment, fuel consumption and traffic-related emissions were treated as direct environmental indicators. Fuel consumption and pollutant emissions (CO, NOx, and VOC) were estimated using the HBEFA (Handbook Emission Factors for Road Transport) emission model integrated within PTV Vissim. Vehicle delay, the number of stops, queue length, and average speed were considered complementary operational indicators because they characterize traffic conditions associated with idling and repeated acceleration–deceleration cycles, which influence energy use and emissions. The combined assessment therefore enables the operational and environmental effects of the two signal control strategies to be evaluated within a common sustainability framework.

With the acceleration of the development of smart infrastructures and intelligent transport systems (ITSs), more and more attention is being paid to video-based traffic data collection solutions. The application of camera technologies in traffic management is considered promising due to the possibility of continuous and real-time monitoring of traffic flows, without physical interventions in the road surface and with relatively lower operating costs. Using advanced image analysis algorithms, such systems make it possible to determine the intensity of vehicle traffic and their speeds, perform vehicle classification, and assess the characteristics of intersection functioning. For these reasons, camera-based detection allows for greater accuracy in traffic modeling and ensures that the modeling results better reflect real traffic conditions.

However, despite its obvious advantages, PTV Vissim software is not designed to directly and seamlessly integrate camera-based detectors into the modeling environment. This system mainly relies on traditional inductive loop detectors and internal intersection management algorithms. In order to solve the integration problem identified in this study, the "Occupancy Rate" parameter in the PTV Vissim program was used. This indicator is defined as the fraction of time that the detector was occupied during the previous second of the simulation. The occupancy indicator is exponentially smoothed every second of the simulation, and the smoothing factors are defined as attributes of the specific detector.

In this study, exponential smoothing was applied to adjust the detectors' occupancy rates. This adjustment was necessary because detectors are typically either fully occupied or completely empty, thus failing to provide sufficient data for signal control decisions. The exponentially smoothed occupancy rate was calculated using Equation (1). Additionally, the occupancy rate during the most recent time interval, determined based on the signal controller's frequency, was also taken into account for signal control optimization [153,154].

$$s(i) = \alpha \times x + (1 - \alpha) \times s(i - 1), \quad (1)$$

where $s(i)$ is the exponentially smoothed occupancy rate; $s(i-1)$ is the previous exponentially smoothed occupancy rate, determined based on the signal controller's frequency; x is the currently measured, unadjusted internal occupancy rate [0 and 1]; α is the smoothing factor that can be entered for Increase and Decrease [0 and 1]; and i is the internal indicator number.

After this point, the newly exponentially smoothed value becomes the weighted average of the currently measured unsmoothed occupancy rate and the occupancy rate corrected from the most recent signal control interval. The new detector occupancy rate is weighted by α, while the previous corrected value is weighted by $(1 - \alpha)$. The exponentially smoothed occupancy rate represents a kind of variable average of the detected values from all previous time steps, thereby giving the most recent values the strongest weight.

In this study, VisVAP provided a debugging function that allowed step-by-step execution of the control logic using the proposed control scheme during a simulation run in Vissim. Additionally, by showing the current values of all parameters used in the logic, it enabled the VAP signal control program logic to be easily represented as a flowchart. Specifically, to model the VisVAP algorithm for camera-based detector modeling, a camera-based detector system for intelligent transportation systems (ITSs) was used. Within this scope, "Stage_duration" parameters were used to define the minimum and maximum green durations for each approach, and the "Occup_rate" parameter was used for vehicle detection. If two different cameras were needed for a given direction, the "OR" expression was used to determine the signal timing. A representative image of the basic algorithm used is provided in Figure 8. "Stage_active (a)" indicates the active phase "a", while "Interstage (a, b)" denotes the transition from phase "a" to phase "b".

In the flowchart shown in Figure 8, the expressions in the first column are used to control transitions between phases, while those in the second and fourth columns are used to set the minimum and maximum durations of a given phase. The third column contains the section where the detectors used in the field are specified. The fifth column determines which phase transitions to execute. A detector with a smoothing factor increasing by 0.25 may take a long time to reach a 100% occupancy rate. Therefore, the occupancy rate parameter was set to 0.8, which was found to work effectively in simulating camera-like detector behavior. This value was selected through iterative trials during the calibration phase, in which thresholds of 0.6, 0.7, 0.8, and 0.9 were tested against field-observed queue lengths and phase utilization rates; the 0.8 threshold produced the closest agreement with observed traffic behavior. It is acknowledged that a formal sensitivity analysis was not conducted, and the transferability

of this threshold to intersections with significantly different traffic compositions may require further validation. Figure 9 shows a sample visual of the application of occupancy rates across different arms of signalized Intersection 1 (I-1).

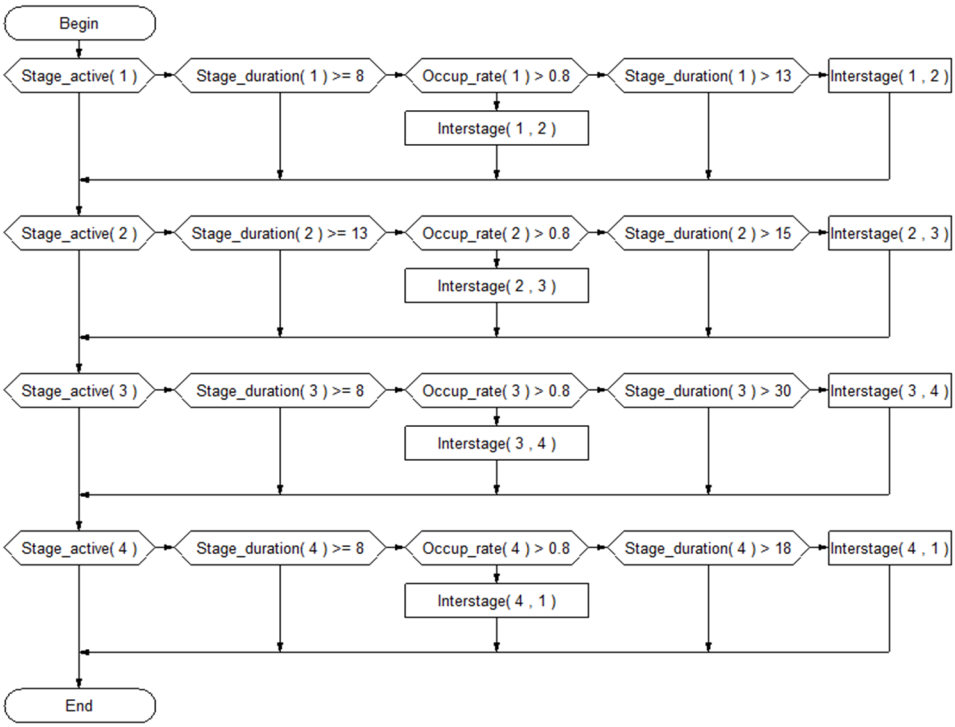


Figure 8. The VisVAP algorithm applied to camera-based detectors at Intersection 1 (I-1).

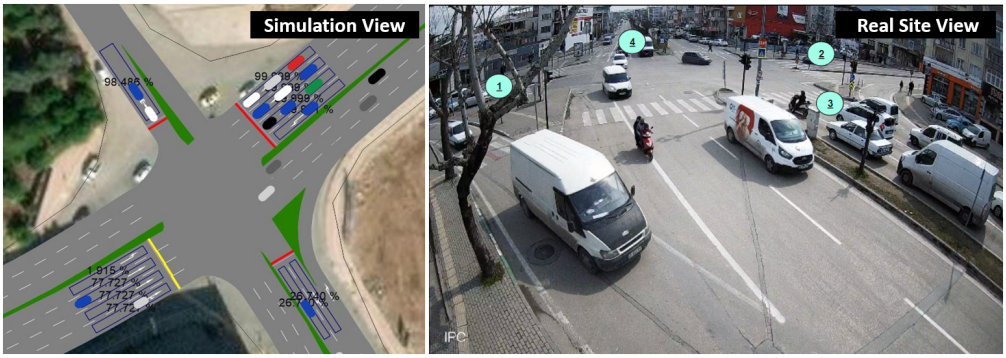


Figure 9. Occupancy rate values from different directions for I-1.

The minimum green durations assigned in the VisVAP flowchart were determined based on field measurements of pedestrian crossing distances at each intersection, calculated using a reference walking speed of 1.2 m/s in accordance with HCM guidelines, and verified against the minimum green times specified in the existing fixed-time signal plans. The maximum green durations were set equal to the corresponding phase durations in the existing fixed-time program so that the total cycle length remained consistent between the two control scenarios. In all cases, a minimum green time of no less than 7 s was maintained for pedestrian phases to ensure safe crossing opportunities. At I-2, Phase 2 and Phase 5 are short dedicated pedestrian phases. These were therefore kept at fixed durations and excluded from actuated control to prevent any unsafe reduction in pedestrian crossing time. At I-6, the cycle length was increased by 9 s because applying the pedestrian-based minimum green times within the original cycle structure would have resulted in an insufficient total green duration across all phases.

After modeling, a calibration process was conducted to reflect real-world traffic conditions at the intersections. The model was calibrated by considering traffic and driver behaviors, thereby aiming to produce results as close to reality as possible. During calibration, the following steps were applied sequentially:

- Queue lengths and driver behaviors were adjusted to match field observations.
- Lane change distances were set based on field observations.
- Reaction times of vehicles to those ahead and behind were adjusted.
- The accuracy of the data was verified using the GEH statistic.

The GEH statistic was used during the calibration process. It is designed to measure the degree of agreement between modeled traffic flow and observed traffic flow. The GEH statistic provides more reliable results than percentage calculations, especially for low traffic volumes [155–158]. The formula for the GEH statistic used in this study is given in Equation (2):

$$GEH = \sqrt{\frac{2 * (M - C)^2}{M + C}}, \quad (2)$$

where M is the number of vehicles obtained in the modeling, and C is the number of vehicles observed in the current situation.

According to analyses performed using the GEH statistic, if the resulting value is less than 5, the modeling results are considered consistent with real-world observation data and deemed usable. If the result falls between 5 and 10, the simulation data are considered unreliable and need to be reviewed. However, if the value is greater than 10, the simulation data are deemed inconsistent with real-world observation data and therefore unusable [159–164]. In this study, the GEH values obtained from the simulation results for each intersection were found to be less than 5, indicating that the modeled traffic volumes were consistent with field-observed counts. It should be noted that this volume-based calibration does not constitute validation of the modeled delay, queue length, or emission outputs.

4. Analysis and Model Results

The intersections considered in this study were modeled and analyzed in the microsimulation program (Figure 10). The performance parameters of the intersections were compared between fixed-time operation and fully traffic-actuated operation. At this stage, delay per vehicle, the number of stops per vehicle, average speed, fuel consumption, emission levels, and average queue lengths were the considered performance parameters.

As part of the analyses, the fixed-time state of all intersections was first modeled and analyzed in Vissim. For the case of fully traffic-actuated control, the model was analyzed again by placing camera detectors on all available legs (see Figure 7). The Visvap module was used to operate the camera detectors, and an example flowchart is shown in Figure 8. When creating the flowchart for the intersections, the minimum times given were adjusted to take into account the pedestrian crossings at the intersections. When determining the maximum times, the times in the fixed program were used so that the lap time did not change. It should be noted that this approach constitutes isolated fully traffic-actuated control rather than network-level fully traffic-actuated control. By obtaining the maximum green durations from the existing fixed-time plan, the total cycle length was intentionally kept constant to enable a fair and controlled comparison between the two strategies. While this constraint limits the full potential benefit of actuated control—particularly the ability to dynamically adjust the cycle length in response to real-time demand—it ensures that the observed performance differences are attributable solely to green time redistribution within phases rather than changes in the overall cycle structure. The camera detectors were designed to provide dynamic management at these specified intervals according to

density. As Phase 2 and Phase 5 at I-2 are short segmented phases created for pedestrians, it is preferable to keep their durations constant so that the trip duration does not change. At I-3, since Phase 2 opens in an east–west direction, two cameras were used for density control. At I-6, the lap time was increased by 9 s because the minimum times given when the flowchart was created would be too small. The analysis results obtained from the simulation model with all the adjustments made for each intersection are presented in Table 6, which compares the results of the fixed-time and fully traffic-actuated cases.



Figure 10. Models of intersections in the conducted simulation.

Table 6. Performance indicators for eight different signalized intersections under fixed-time and traffic-actuated conditions.

Intersect. No.	Signal Type	LOS	Delay (s/veh)	Number of Stops	Average Speed (km/h)	Fuel Cons. (US Gallon)	Emission		
							CO (g/km)	NOx (g/km)	VOC (g/km)
I-1	FT	E	60.5	1.5	25.0	98.3	6870.3	1336.7	1592.3
	FTA	D	38.8	0.9	27.0	74.4	5197.2	1011.2	1204.5
I-2	FT	D	43.0	0.9	31.0	62.0	4330.7	842.6	1003.7
	FTA	C	38.0	0.8	37.0	58.97	4122.3	802.1	955.4
I-3	FT	E	60.0	1.3	29.0	104.8	7328.8	1425.9	1698.5
	FTA	C	32.0	0.8	37.0	83.6	5840.6	1136.4	1353.6
I-4	FT	D	47.6	1.2	23.6	103.07	7204.9	1401.8	1669.8
	FTA	D	36.9	1.1	25.1	92.13	6440.1	1253.0	1492.5
I-5	FT	B	17.5	0.9	24.9	58.12	4062.7	790.5	941.6
	FTA	B	11.7	0.5	25.1	35.66	2492.9	485.0	577.7
I-6	FT	D	32.0	1.7	39.8	153.63	10,739.3	2089.5	2488.9
	FTA	C	26.3	1.1	41.1	125.61	8780.6	1708.4	2035.0
I-7	FT	D	44.0	1.0	24.9	128.3	8968.2	1744.9	2078.5
	FTA	D	38.0	0.9	36.3	125.14	8747.4	1701.9	2027.3
I-8	FT	D	40.0	1.6	32.8	93.75	6553.4	1275.1	1518.9
	FTA	D	35.0	1.5	34.7	87.05	6084.8	1183.9	1410.2

Note: LOS: level of service; FT: fixed-time signalized intersection; FTA: fully traffic-actuated signalized intersection. One American gallon is 3.7854 L. All emission values (CO, NOx, VOC) are modeled outputs obtained from PTV Vissim using the HBEFA emission model and do not represent field-measured emissions.

When the analysis results between the FT and FTA scenarios are compared, it is concluded that traffic-actuated signalized intersections provide significant performance

improvements. The reduction (improvement) results achieved under traffic-actuated signalized conditions compared to fixed-time conditions for the eight different intersections studied are presented in Table 7.

Table 7. Comparison of performance results between FT and FTA intersections.

Parameter	Signalized Intersection (SI) Number							
	I-1	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**I-8**
Delay (s)	36%	12%	47% *	22%	33%	18%	14%	12%
Number of Stops (N)	41% *	7%	40%	12%	41% *	38%	2%	10%
Fuel Consumpt. (US Gallon)	24%	5%	20%	11%	39% *	18%	2%	7%
Average Speed (km/h)	7%	16%	21%	6%	1%	3%	31% *	6%
Queue Length (m)	51%	8%	67% *	19%	48%	39%	63%	17%
CO Emissions (g/km)	24%	5%	20%	11%	39% *	18%	−2%	7%

Note: * shows the observed maximum decrease (−) values.

From a sustainability perspective, Table 7 shows that the operational advantages of FTA control are generally accompanied by reductions in fuel consumption and pollutant emissions. This relationship indicates that lower delays, fewer stops, and shorter queues can reduce inefficient vehicle operating conditions, thereby decreasing unnecessary energy use and environmental burden. However, the magnitude of the improvement differs substantially among intersections, suggesting that sustainability benefits are strongly dependent on local geometry, traffic distribution, and operating conditions.

A comparative analysis of delay times per vehicle at intersections is presented in Figure 11a. The modeled results suggest that fully traffic-actuated systems generally outperform fixed-time systems at four-legged signalized intersections. For example, at junction I-3, the application of a fully traffic-actuated system resulted in a significant delay reduction of as much as 47%, with the average delay time decreasing from 60 s to 32 s. Meanwhile, at junction I-2, the improvement was only 12% (from 43 s to 38 s), as more efficient signal control was limited by the narrow, single-lane roads. At junction I-1, a 36% delay reduction was recorded, as this junction is able to efficiently serve the traffic demand on routes 1–2, despite some problems with exit flows.

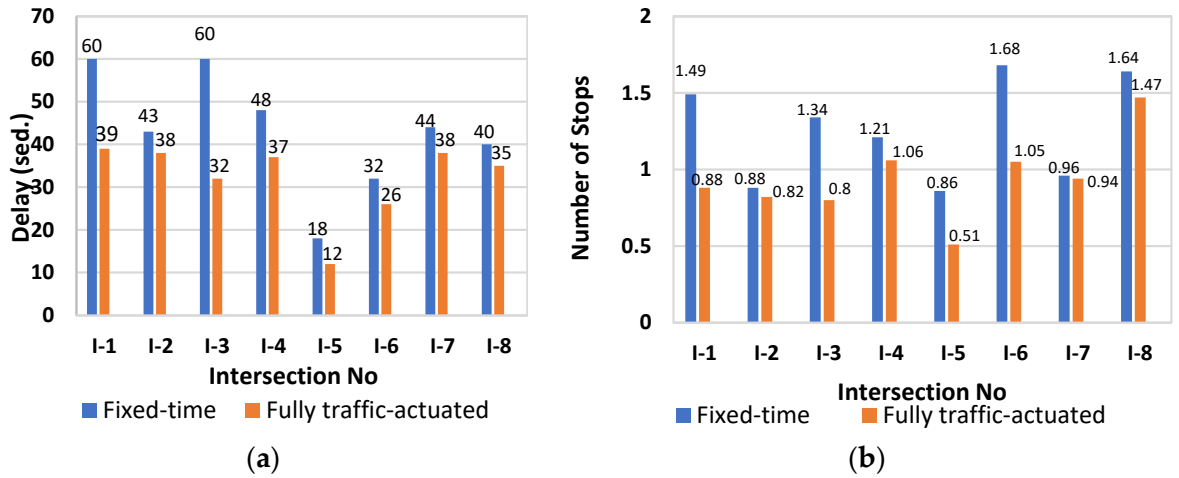


Figure 11. Number of (**a**) delays and (**b**) stops per vehicle at intersections.

At three-way roundabouts with islands, fully traffic-actuated systems also showed a noticeable advantage over fixed-time control. In particular, at junction I-4, delays decreased by 22%, from 48 s to 37 s, while at junction I-5, an even greater reduction of 33% was achieved, with the average delay time decreasing to 12 s. The smaller impact at junction I-4

than at I-3 is attributed to its location in a city square, where the high intensity of vehicle and pedestrian traffic limits the potential for efficiency improvements.

Relatively smaller improvements were observed at four-way roundabouts with islands. At junction I-6, delays decreased by 18%, from 32 s with fixed-time control to 26 s with a fully traffic-actuated system. At junction I-7, a 14% reduction was recorded (from 44 s to 38 s), and at junction I-8, a 12% reduction was recorded, with delays decreasing from 40 s to 35 s. The relatively better results at the I-6 intersection are associated with shorter turnaround times. The results obtained show that optimizing turnaround times at four-way roundabouts is one of the key factors determining the increase in operational efficiency.

Figure 11b shows a comparison of fully traffic-actuated systems and fixed-time control in terms of the number of stops per vehicle. The results of the analysis show that fully traffic-actuated systems were more effective in reducing the number of stops in most cases. The largest improvements were found at four-way controlled intersections. For example, at intersection I-3, the number of stops decreased by 41%, from 0.86 to 0.51. Meanwhile, at intersection I-2, the improvement was only 7%, which was mainly due to the unfavorable geometry of the intersection and parking restrictions in the entry zone. I-4, a three-legged roundabout island intersection, had a limited improvement of 12% due to high pedestrian traffic and bridge-related overlaps. At I-6, a four-legged roundabout, stops decreased by 37%, from 1.68 to 1.05. However, I-7 and I-8 showed minor improvements (2% and 10%, respectively), attributed to the large diameter of roundabout islands and simultaneous openings causing repeated stops by left-turning vehicles. Figure 12 illustrates a comparison of the fuel consumption and average queue length at the intersections. Figure 12a suggests that fully traffic-actuated systems reduced fuel consumption by 24.5% and 4.8% at I-1 and I-2, respectively, decreasing from 98 to 74 US gallons at I-1 and from 62 to 59 US gallons at I-2. At I-3, fuel consumption improved by 20%, from 105 to 83 US gallons.

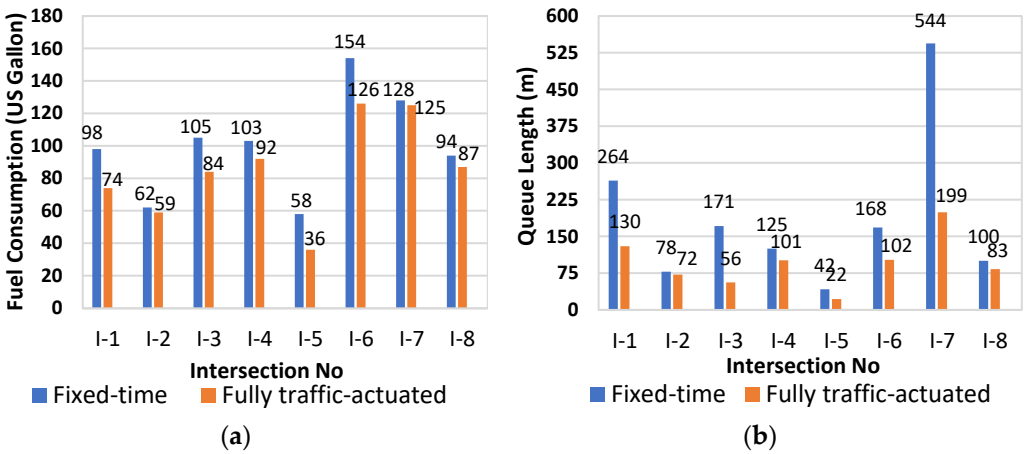


Figure 12. (**a**) Fuel consumption (US gallon) and (**b**) average queue length (m) at intersections.

Figure 12b compares the total queue lengths at the intersections under the fully traffic-actuated and fixed-time systems. The results indicate a significant reduction in the total queue lengths, especially at the four-legged signalized intersections. I-3 showed the most substantial improvement, with queue lengths decreasing by 67%, from 171 m to 56 m. Meanwhile, at the I-2 intersection, the improvement was only 8%—the queue length decreased from 78 m to 72 m. This limited effect was due to the single-lane roads, parking of vehicles close to the intersection, and problems with the unloading of flows in the exit directions. At the I-4 intersection, which is a three-way roundabout with islands, the queue length decreased by 19%, but the result was limited by the periodic interweaving of flows in the west direction. At the four-way roundabout I-6, an 18% decrease in queues was

recorded, which was associated with the fact that the initial queues at this intersection were small. It should be noted that, at the I-7 intersection, a very significant improvement was achieved—even reaching 63%—mainly due to optimized signal control, which allowed the redistribution of queue formation from the west direction. These results show that fully traffic-actuated systems are able to effectively manage queue lengths, regardless of the intersection type, by adapting the green signal duration to the actual traffic flows.

Figure 13 shows a comparison of the air pollution emissions between the fully traffic-actuated and fixed-time signal systems. The largest improvement was observed at intersection I-5: carbon monoxide (CO) emissions decreased by 39% (from 4063 to 2493 g/km), nitrogen oxide (NOx) emissions decreased by 39% (from 790 to 485 g/km), and volatile organic compound (VOC) emissions decreased by 39% (from 942 to 578 g/km). In contrast, the I-7 intersection recorded the smallest effect—CO, NOx, and VOC emissions decreased by only 3% each (from 8968 to 8747 g/km, from 1745 to 1702 g/km, and from 2078 to 2027 g/km, respectively).

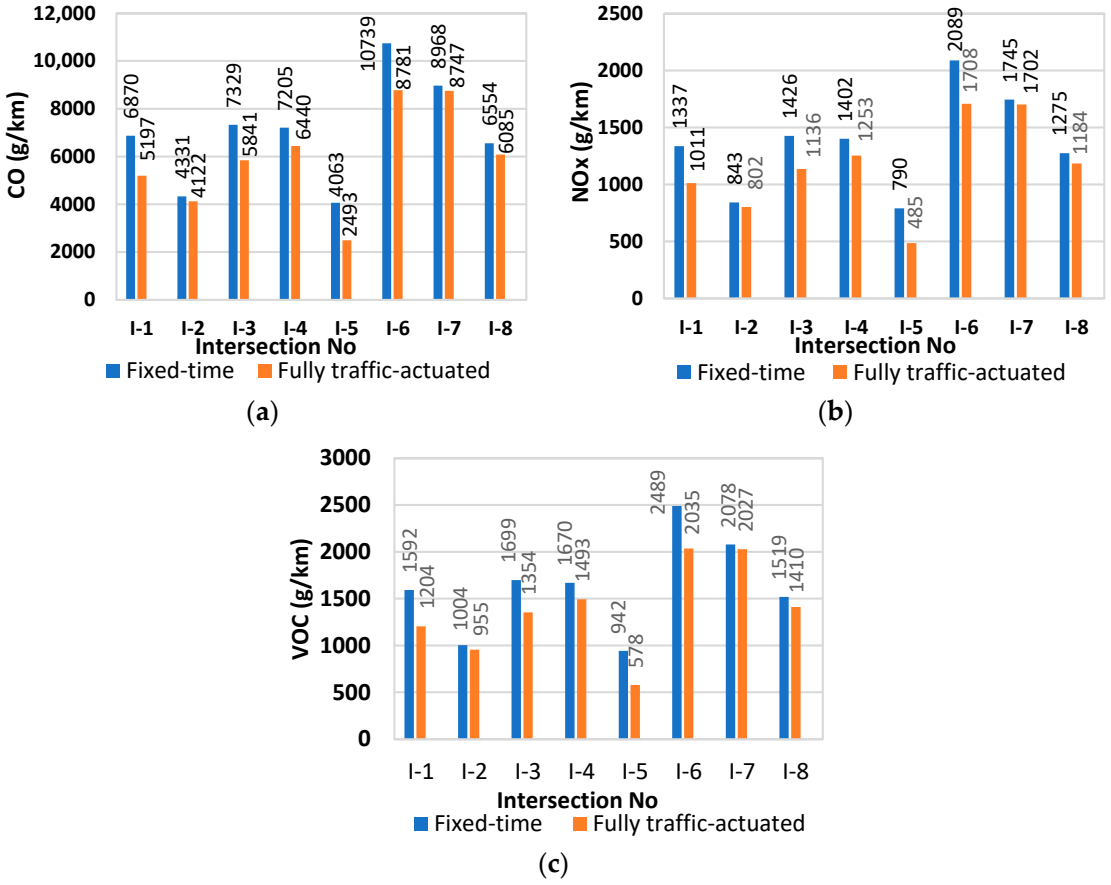


Figure 13. Air pollution performance comparison of (**a**) Co (g/km), (**b**) NOx (g/km), and (**c**) VOC (g/km).

The results demonstrate that the benefits of fully traffic-actuated control extend beyond conventional traffic performance improvement. Reduced delays, fewer stops, and shorter queues decrease the duration and frequency of inefficient vehicle operating conditions, particularly idling and repeated acceleration events. These operational improvements are accompanied by lower fuel consumption and reduced CO, NOx, and VOC emissions, establishing a direct connection between the intersection control strategy and the environmental performance of urban transport.

The results also indicate that these sustainability benefits are not uniform across all intersection types. The magnitude of the fuel and emission reductions varies among the

examined sites, demonstrating that intersection geometry, traffic demand distribution, and local operational constraints influence the environmental effectiveness of fully traffic-actuated signal control. Consequently, FTA control should not be treated as a universal sustainability solution, but rather as a context-dependent traffic management strategy whose environmental performance should be evaluated at the intersection level.

From an urban sustainability perspective, fully traffic-actuated signal control is particularly relevant because environmental improvements can be achieved by improving the use of the existing transport infrastructure without immediately increasing road capacity. This is important in dense urban environments, where infrastructure expansion may be constrained by land availability, implementation cost, pedestrian activity, and other competing urban functions.

The findings are also consistent with the objectives of sustainable urban mobility and SDG 11, as fully traffic-actuated signal control can contribute to more efficient and environmentally responsible urban transport systems. By reducing unnecessary fuel consumption and traffic-related emissions, such systems may also indirectly support broader energy efficiency and climate-related objectives.

5. Conclusions

The results of this study demonstrate that fully traffic-actuated traffic signal control systems typically surpass traditional fixed-time approaches across diverse intersection configurations. Performance metrics, such as vehicle delay, queue length, fuel efficiency, and exhaust emissions, exhibited notable improvements. At four-way signalized intersections, notable benefits were observed following the implementation of fully traffic-actuated control. This method successfully mitigated congestion-related inefficiencies, resulting in delay reductions of up to 47% and a significant decrease in queue lengths of as much as 67%. The findings show that fully traffic-actuated control demonstrates particular effectiveness in traffic conditions characterized by substantial temporal variability, such as during peak periods, where fixed signal timing proves insufficient in delivering appropriate responsiveness.

It should be noted that these findings are based on microsimulation of isolated intersections during peak hour conditions only. The limited improvements observed at I-2 and I-7—attributable to geometric constraints, high pedestrian activity, and restricted carriageways—indicate that the benefits of fully traffic-actuated control are site-specific rather than universally applicable. Generalization to off-peak periods, coordinated corridor operations, or network-level performance should be approached with caution.

The model analysis suggests that fully traffic-actuated signal control is not a universally applicable solution, as its efficacy depends on specific local conditions. The observed improvements in performance exhibited significant variability across the examined intersections, highlighting the impact of geometric constraints and operational limitations. Intersections impacted by restricted carriageways, on-street parking, or increased pedestrian activity demonstrated more refined improvements. Additionally, simulations were conducted with a fixed random seed; while formal multi-replication variance analysis was beyond the scope of this study, the observed differences at all intersections are considered meaningful within the context of peak hour operational assessment. A further limitation concerns the acquisition of the maximum green durations from the existing fixed-time signal plans, which constrained cycle length variability throughout the actuated control scenarios. This design choice, while necessary for a controlled comparison, restricts the actuated control benefit to intra-phase green time flexibility and does not capture the full performance potential achievable through network-level fully traffic-actuated systems that simultaneously optimize cycle length, split, and offset across multiple intersections. Future

research should investigate the additional sustainability benefits of unconstrained cycle length optimization across the intersection geometries examined here. The slight improvement in performance observed at Intersection I-2 suggests that sophisticated control systems alone are inadequate for fully resolving issues related to geometric design deficiencies or suboptimal traffic management. This discovery underscores the importance of integrating fully traffic-actuated signal control within a comprehensive intervention framework, rather than considering it as an isolated approach.

The findings emphasize the significance of adaptable traffic management strategies in addressing environmental challenges within urban transportation systems dedicated to promoting sustainability. A consistent decline was observed in the emissions of carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs), concomitant with a decrease in fuel consumption. Therefore, it appears that a more stable traffic flow and a reduction in stop-and-go conditions exert a direct, beneficial effect on the environment. The significance of these effects is particularly evident in densely populated urban areas, where even modest improvements in intersection performance can result in substantial gains in air quality and energy efficiency. Within this framework, fully traffic-actuated traffic management is essential for improving operational efficiency and furthering goals related to sustainable urban development.

More broadly, the results demonstrate that fully traffic-actuated signal control should be considered not only as an instrument for improving traffic efficiency but also as a potential urban sustainability measure. Its value lies in simultaneously reducing congestion-related inefficiencies, unnecessary fuel consumption, and local pollutant emissions while making more efficient use of the existing transport infrastructure. Nevertheless, the results confirm that sustainability benefits depend on local intersection characteristics and therefore require site-specific implementation rather than uniform application across the urban network.

The findings of this research indicate that the maximum effectiveness of fully traffic-actuated signal control can only be achieved through its integration with suitable infrastructure and management strategies. Geometric modifications, parking policies, and demand management approaches are essential for eliminating structural barriers that hinder the efficiency of fully traffic-actuated systems. Furthermore, future implementations are expected to leverage more extensive integration with advanced intelligent transportation technologies, such as real-time fully traffic-actuated algorithms and vehicle-to-infrastructure (V2I) communication, which can substantially improve control flexibility and system awareness.

Subsequent investigations should expand their focus beyond metrics related to vehicle performance and emphasize the incorporation of non-motorized road users into fully traffic-actuated control frameworks. The integration of pedestrian and cyclist movements into signal decision-making processes presents a significant challenge for attaining balanced and equitable operations at intersections. This study presents valuable insights that serve as a practical foundation for policymakers and urban planners. It underscores the significance of prioritizing investments in intelligent traffic management systems, which not only improve operational efficiency but also support long-term urban sustainability.

The findings of this study should be interpreted within the constraints of the study design, which is limited to isolated peak hour microsimulation at eight intersections. Broader generalization to off-peak conditions or network-level sustainability policy requires further empirical validation.

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administration, M.M.A.; funding acquisition, E.S. and J.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CO	Carbon monoxide
FTA	Fully traffic-actuated
GEH	Geoffrey E. Havers statistic used for traffic model calibration
FT	Fixed-time
HCM	Highway Capacity Manual
ITS	Intelligent transportation system
LOS	Level of service
NOx	Nitrogen oxide
PTV	Planung Transport Verkehr
VOC	Volatile organic compound
VAP	Vehicle Actuated Programming (used in the VISSIM environment)
VISSIG	Signal control module of PTV Vissim
Vissim	Microscopic traffic simulation software

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