Research Article

Simulation-based optimization approach for effective corridor management: A case study of Denizli

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Abstract: This study examines effective urban management models and simulation-based optimization approaches to help cities adapt to socio-economic changes and support sustainable development. The research focuses on the effectiveness of simulation-based optimization for intersections on an artery in Denizli. Synchro traffic simulation software was used for modeling, with different scenario models created based on existing intersection geometry and signal plans. A system was developed to provide coordination using automatically adjusted offset times via Synchro. Analyses evaluated the proposed models' performance in terms of bandwidth, average intersection delay, and volume-to-capacity (v/c) ratios during peak traffic hours. The models' contributions to reducing fuel consumption and emissions were also assessed. Results demonstrated that the simulation-based optimization approach significantly improved traffic flow and minimized delays compared to current conditions. Moreover, the proposed models positively reduced fuel consumption and emissions. The findings suggest that this approach can make significant contributions to urban planning and traffic engineering, supporting sustainable development goals.

Keywords: Signalized Intersections, Coordination, Delay, Offset, Bandwidth, Synchro

Etkin koridor yönetimi için simülasyon esaslı optimizasyon yaklaşımı: Denizli alan çalışması

Özet: Bu çalışma, şehirlerin sosyo-ekonomik değişimlere uyum sağlamasını ve sürdürülebilir kalkınmayı desteklemek amacıyla kentsel yönetim modelleri ve simülasyon tabanlı optimizasyon yaklaşımlarını incelemektedir. Araştırma, Denizli şehrindeki yoğun trafik arterlerindeki kavşaklar için simülasyon tabanlı optimizasyonun etkinliğine odaklanmaktadır. Modelleme ve analiz için Synchro trafik simülasyon yazılımı kullanılmaktadır. Bu bağlamda, mevcut kavşak geometrisi ve sinyal zaman planlarını yansıtan çeşitli senaryo modelleri geliştirilmiştir. Trafik akışını iyileştirmek için Synchro kullanılarak dinamik olarak ayarlanan ofset zamanları ile koordinasyon sağlayan bir sistem uygulanmıştır.

Analizlerde, önerilen modellerin bant genişliği, ortalama kavşak gecikmesi ve kapasite kullanım oranları (v/c) bakımından sabah ve akşam yoğun saatlerde performansları değerlendirilmiştir. Ayrıca, modellerin yakıt tüketimi ve emisyon seviyelerindeki olası azaltıcı etkileri incelenmiştir. Bulgular, simülasyon tabanlı optimizasyon yaklaşımının trafik akışını etkin bir şekilde düzenleyebildiğini ve mevcut duruma kıyasla gecikmeleri azaltabildiğini göstermektedir. Sonuçlar ayrıca, önerilen modellerin yakıt tüketimi ve emisyonlar üzerinde olumlu etkiler yarattığını ortaya koymaktadır.

Genel olarak, elde edilen sonuçlar bu simülasyon tabanlı optimizasyon yaklaşımının kentsel planlama ve trafik mühendisliği alanında önemli katkılar sağlayabileceğini ve sürdürülebilir kalkınma hedeflerine ulaşmak için değerli bir potansiyele sahip olduğunu vurgulamaktadır.

Anahtar Kelimeler: Sinyalize kavşaklar, Koordinasyon, Gecikme, Ofset Süresi, Bant Genişliği, Synchro

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1. Introduction

In the context of today's fast-paced socio-economic changes, cities must consistently adapt to fulfill the requirements of sustainable development. Efficient urban management models and simulation-based optimization approaches are vital tools for addressing the complex challenges faced by urban areas. This study focuses on employing a simulation-based optimization approach for effective corridor management in urban traffic systems.

The aim of this study is to develop and implement time-adaptive control strategies and a real-time signal coordination system within urban transport networks. The selected study area includes the intersections called Tiyatro, Havuzlu Köşk, Bursa, and Tokat Streets along the Ulus artery, a high-traffic corridor. Initially, key components of the existing signaling systems at these intersections—such as traffic volumes, phase durations, phase plans, and cycle lengths—were analyzed. Based on these parameters, the intersections were modeled using Synchro traffic simulation and analysis software. Subsequently, alternative models were created, incorporating different intersection geometries, phase plans, and cycle times to explore various scenarios. In these models, offset times were automatically adjusted using Synchro to achieve effective coordination between intersections.

In this study, the Synchro/SimTraffic microsimulation software package was utilized due to its robust capabilities in modeling coordinated signalized intersections and arterial corridors. One of the primary reasons for selecting this software is its integrated environment, which allows for both deterministic signal timing analysis (via Synchro) and stochastic traffic simulation (via SimTraffic). This dual functionality provides a comprehensive framework for evaluating signal coordination strategies under both idealized and real-world traffic conditions.

Synchro is particularly effective for optimizing signal timings and evaluating progression quality along arterials, which is crucial when assessing the performance of coordinated signalized intersections. Additionally, SimTraffic enables the detailed simulation of individual vehicle movements, incorporating driver behavior, queuing, and randomness in arrival patterns, thereby enhancing the realism and reliability of the results.

To facilitate automatic offset adjustments, Synchro's built-in algorithms and optimization techniques were utilized. Through these methods, the software analyzes traffic flow to calculate optimal offset times and autonomously adjusts the signal plans at each intersection.

Scenario models were developed and evaluated using Synchro to determine the most effective offset times, with the goal of achieving coordinated intersection operations and optimizing overall traffic flow. The scenario models yielding the lowest delays were then compared to baseline models.

Upon evaluating the scenario models, proposed configurations were established to facilitate coordinated operations across intersections along the artery. These configurations, which feature cycle and offset times optimized to minimize intersection delays while maximizing bandwidth, are compared with baseline models for both morning and evening peak periods in the results section.

1.1. Previous Studies

The literature contains extensive research on traffic signaling and coordination systems, with several studies focusing on optimizing signalized intersections to alleviate congestion and enhance traffic flow. Some relevant studies are summarized as follows:

Çakıcı and Murat (2016) examined isolated and coordinated management of signalized intersections, highlighting signal management techniques aimed at reducing traffic congestion, with particular emphasis on green wave coordination systems. Karaoğlan (2021) investigated coordinated signal control across various scenarios, emphasizing the importance of effective corridor management on traffic outcomes. Tian et al. (2008) analyzed the impact of left-turn phases on signal coordination, underscoring the significance of phase sequence and number in achieving optimal flow. Ioannou and Chien (2018) explored artificial intelligence applications in traffic engineering, evaluating AI-driven approaches for managing coordinated signalized intersections. Arslan and Bhouri (2019) assessed different coordination strategies for signalized intersections, providing recommendations for enhancing traffic flow.

Wang et al. (2019) focused on coordination between connected vehicles and isolated intersections, studying how communication-based data exchange between vehicles and intersections can improve traffic performance. Guo and Wang (2020) used driver cooperation and communication-based methods to address real-time signal control within dense urban networks. Lin et al. (2020) investigated various optimization methods, traffic flow models, and signal planning strategies, concentrating on optimal coordination of signalized intersections. Yang et al. (2020) examined the use of connected vehicle data for coordinated signalized intersections, evaluating its impact on improving intersection performance. Qi et al. (2020) proposed a model and optimization method for traffic signal settings, addressing coordinated signal design for mixed traffic consisting of Human-Driven Vehicles (HDVs) and Connected Autonomous Vehicles (CAVs). Yue et al. (2021) introduced a signal retiming approach to assess and optimize the operation of existing coordinated corridors. Kart et al. (2021) demonstrated a 20% reduction in vehicle wait times and a 20% increase in average speed using SUMO software compared to conventional green wave systems. Finally, Duman et al. (2024) employed Vissim micro-simulation software for analyses at intersections in Elâzığ, observing that coordinated intersection operation often achieved 100% efficiency and offered significant advantages.

Most of the studies referred to above illustrate the effectiveness of coordinated intersection operations in corridor management. In contrast to previous research, this study elaborates on a simulation-based optimization method to identify the main parameters involved in signal coordination, aiming for improved corridor management efficiency.

1.2. Bandwidth and Delay-based design approaches

Coordinated control systems are those in which various approaches and strategies can be applied to manage successive signalized intersections. Depending on their operating principles, these systems can be categorized into synchronized systems, alternating systems, progressive systems, and areal traffic control systems.

These systems have various objectives, such as minimizing vehicle delays, reducing fuel consumption and emissions, ensuring efficient arterial flow, increasing intersection and network capacity, reducing vehicle queues at intersections, controlling vehicle speeds, enabling vehicles to move in clusters, and maximizing bandwidth along a route. Various coordination systems and strategies are implemented to achieve these goals.

Traffic signals can be coordinated so that a group of vehicles starting from one end of a main artery and travelling at predetermined speeds can get to the other end without stopping at a red light. Bandwidth refers to the time difference, in seconds, between the first and last vehicles in a group that can pass through all intersections on an arterial without stopping. It can be defined as the width, in seconds, between two parallel speed lines on a time-distance diagram, representing the duration that traffic can flow uninterrupted.

Delay, defined as the time lost by a vehicle at a signalized intersection due to other vehicles, geometric features and control systems, is a key parameter used to measure the level of service. Effective management is provided by reducing delay at urban intersections with high traffic volumes (Murat, 2002, 2016). To avoid congestion at signalized intersections and to improve the performance of the transport system, the value of vehicle delay should be measured as accurately as possible. Figure 1 shows vehicle delay at signalized intersections and delays due to stopping, acceleration and deceleration.

The parameter that influences the increase or decrease in delay time at coordinated signalized intersections is the offset time. The offset represents the time between the start of green light signals for traffic moving in the same direction at two consecutive coordinated signalized intersections. When the offset values assigned to the intersections are configured to best achieve the desired objective, it is known as the ideal offset. For instance, the goal might be to minimize delay based on the average speed of a cluster of vehicles.

However, the ideal offset alone is not sufficient to minimize delay. Variations in the speed of vehicles traveling along the artery compared to the designated operating speed also impact delay times.

Additionally, factors such as intersection capacity, intersection geometry, cycle length, signal cycle times, phase plans, and phase sequences contribute to the delay time and overall operational performance of a signal coordination system. By optimizing these factors, junction delay can be minimized at the optimum bandwidth.

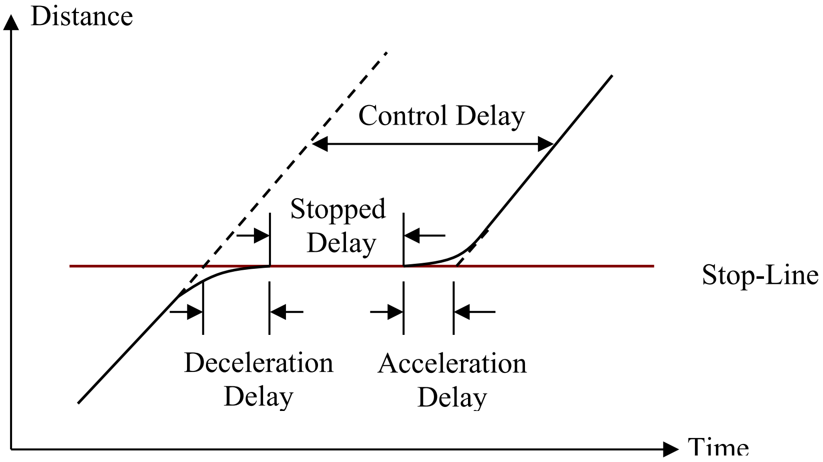


Figure 1. Definition of Signal Control Delay Components.

2. Materials and Methods

The workflow diagram for this study is presented in Figure 2, illustrating the step-by-step process of optimizing intersection traffic flow through a simulation-based optimization. This diagram outlines the approach to managing traffic during morning and evening peak hours and the sequence of analysis steps.

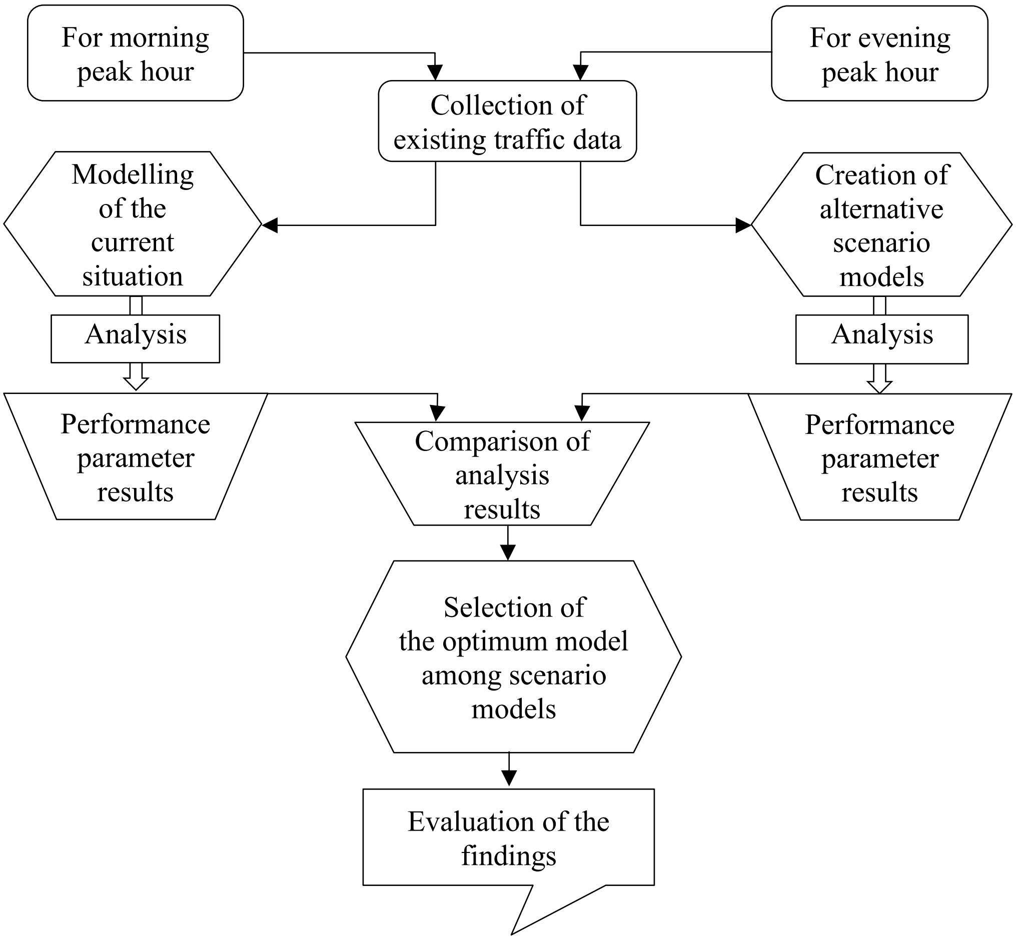


Figure 2. Flow chart of the study

The first step in the process is to gather existing traffic data related to intersection geometries. Traffic data collection encompasses both morning and evening peak periods, forming the basis for subsequent modeling efforts. To determine traffic volume values, vehicle counts at intersection approaches were recorded using piezometric electrical sensors (loop sensors) installed at the approaches, with data logged at the Traffic Control Center (TCC), where intersections are continuously monitored. This data collection was further supplemented by 1-hour drone footage to enhance the accuracy of the traffic counts.

Table 1 presents the resulting traffic volumes for each coordinated intersection during peak hours.

Table 1: Sample Traffic volumes at intersections

Traffic Volumes for the Morning Peak Hour(veh/hr)					
Direction	Intersection	Tiyatro	H.Köşk	Bursa	Tokat
East	Left	111	96	71	9
	Through	675	471	435	418
	Right	202	55	27	328
West	Left	580	140	43	69
	Through	879	675	669	543
	Right	505	296	77	167
North	Left	216	65	67	120
	Through	243	353	220	90
	Right	181	41	37	60
South	Left	163	247	150	55
	Through	296	258	235	100
	Right	16	49	43	6
Number of Cars		4067	2746	2074	1965
Sum		10852 (veh/hr)			

Traffic Volumes for the Evening Peak Hour (veh/hr)					
Direction	Intersection	Tiyatro	H.Köşk	Bursa	Tokat
East	Left	124	149	154	217
	Through	662	735	709	934
	Right	455	38	75	135
West	Left	115	58	211	326
	Through	420	500	550	669
	Right	211	111	99	200
North	Left	117	180	79	184
	Through	60	258	419	226
	Right	130	27	77	251
South	Left	130	176	382	244
	Through	100	319	374	196
	Right	20	66	40	7
Number of Cars		2544	2617	3169	3589
Sum		11919 (veh/hr)			

The arterial considered, along with geometries of intersections and traffic volumes by direction, are shown in Figure 3.

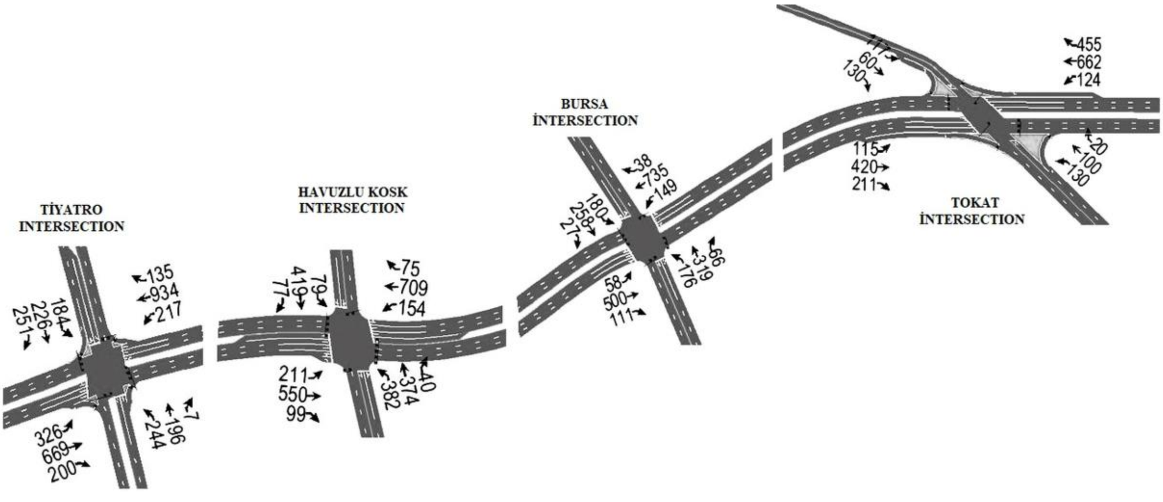


Figure 3. Traffic volumes for the arterial.

After collecting the necessary data, separate modeling for the morning and evening peak hours was conducted to gain a comprehensive understanding of existing traffic operations. These models provided valuable insights that informed the development of alternative scenarios tailored for both peak periods, allowing for the evaluation of different phase plans and geometric layouts. Simulation and analytical tools were employed to assess key performance metrics for each scenario, such as delay times, corridor efficiency, and per-vehicle fuel consumption.

The results of these analyses were then compared to identify the most effective scenario. Performance parameters were systematically evaluated to determine which model offered the best improvements. The selected model incorporated strategic geometric modifications, including optimized phase plans and the addition of left-turn bays, to significantly reduce delay times and improve overall traffic flow.

Finally, a thorough evaluation of the chosen model's performance results was conducted. This assessment confirmed improvements in traffic flow along the corridor, reduced delay times, and enhanced system efficiency. Furthermore, the study highlighted important sustainability outcomes, such as decreased fuel consumption and a reduced environmental footprint, reinforcing the value of implementing environmentally conscious traffic management solutions.

2.1. Study Area

In this study, Ulus Street, a major traffic artery in the city of Denizli, was chosen as the application area. Traffic coordination efforts were carried out along this street, progressing from west to east, specifically at the intersections of "Tiyatro," "H. Köşk," "Bursa," and "Tokat," in sequential order. A bird's-eye view of these intersections is provided in Figure 4.

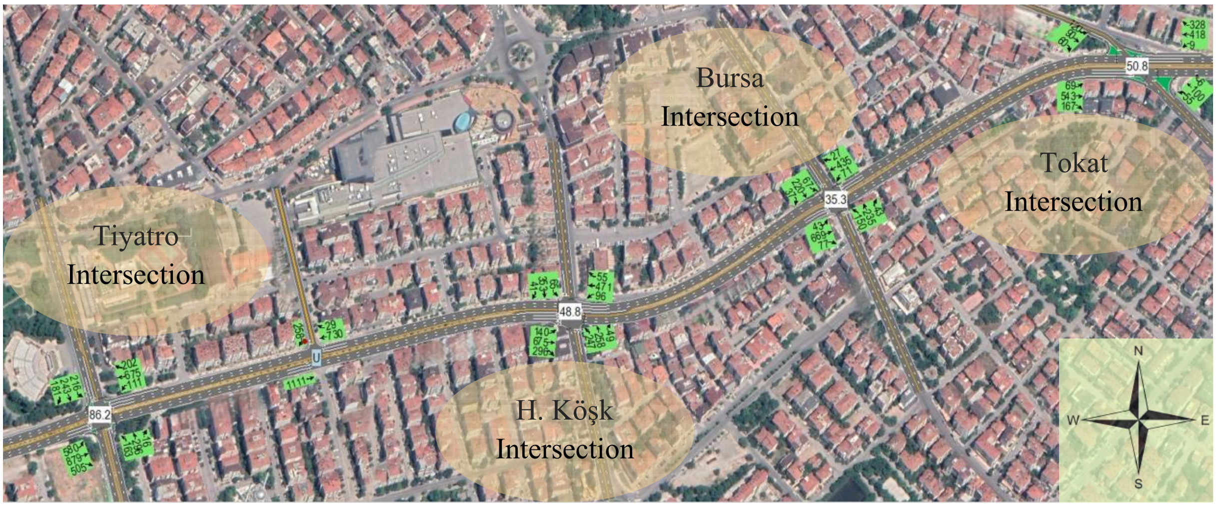


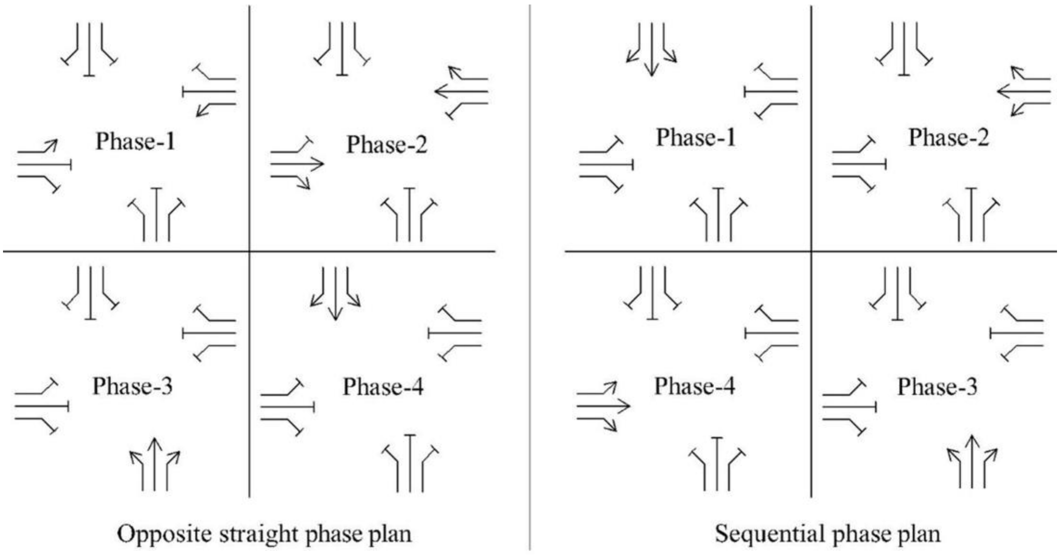
Figure 4. Bird's-eye view of intersections.

2.2. Phase plan and intersection geometry used in the scenario models

In this study, scenario models were developed for two intersection geometries, each with different phase plans. The first intersection type represents the existing intersection geometry, while the second introduces a left-turn bay on the coordinated approach arm. For these intersection geometries, three distinct phase plans—Opposite Through, Sequential, and Mixed—were considered in the scenarios.

In the Opposite Through phase plan, intersection control is achieved by simultaneously activating Phase 2 for through and right-turn flows, Phase 1 for left-turn flows, and Phases 3 and 4 for flows from the side approach arms. This approach prioritizes flows traveling along the eastbound (EB) and westbound (WB) arteries, where coordination is established. In the Sequential phase plan, traffic flows from each approach arm can proceed sequentially at different times, ensuring controlled passage through the intersection. The Mixed phase plan combines the Opposite Through (O) and Sequential (S) phase plans, coordinating operation across intersections along the artery.

Figure 5 illustrates the phase plans applied when managing the signalized intersection using the Opposite Through and Sequential phase plans.



Opposite straight phase plan

Sequential phase plan

Figure 5. Phase plans used in the study.

3. Analysis

In the analyses carried out, the current situation was first modeled and compared with the scenario cases. Table 2 presents the level of service, volume-to-capacity (v/c) ratio, and delay values derived from analyses based on green phase times calculated for the existing intersection geometry and traffic volumes at the coordinated intersections.

Table 2: Performance parameter results for existing signal timings

Morning	Tiyatro	H.Köşk	Bursa	Tokat
Number of Vehicles	4067	2746	2074	1965
Phase-1	30	30	29	24
Phase-2	31	28	31	47
Phase-3	56	36	36	22
Phase-4	23	46	44	47
C	140	140	140	140
LOS	F	D	D	D
V/C	1.31	0.95	0.73	1.09
Int. Delay	86.2	48.8	35.3	50.8

Evening	Tokat	Bursa	H.Köşk	Tiyatro
Number of Vehicles	2544	2617	3169	3589
Phase-1	24	27	45	27
Phase-2	50	43	34	44
Phase-3	29	41	32	33
Phase-4	37	29	29	36
C	140	140	140	140
LOS	D	E	F	E
V/C	0.95	1.1	1.53	1.15
Int. Delay	44.5	58.8	107.7	78.3

In Tables 3 and 4, the offset times, phase sequence, and signal times were optimized using Synchro software to maintain a cycle length of 140 seconds. The resulting bandwidths from delay optimization at the intersections are also shown in Tables 3 and 4.

Table 3: The results of the analysis for the optimized model by Synchro in the morning peak hour

Current Situation at Morning Peak Hour									
Intersection	Cycle Length (sec)	Max. v/c Ratio	Intersection LOS	Offset	min. green EB/WB (sec)		Intersection Delay (sec/veh)	Direction of Coordination BW (sec) BWUP (%)	
Tiyatro	140	1.11	F	0	52	31	88.4	EB 33 100	WB 4 14.81
H.Köşk	140	0.85	D	53	41	27	41.1		
Bursa	140	0.74	D	78	43	31	34.2		
Tokat	140	0.86	D	114	33	53	40.3		
Average corridor delay(sec/veh) :							57.36		

During the morning peak hour, a bandwidth of 33 seconds was achieved along the eastbound (EB) artery, from Tiyatro to Tokat intersection (the coordinated direction), and 4 seconds in the westbound (WB) direction. The average corridor delay was calculated as 57.36 seconds per vehicle.

Table 4: The results of the analysis for the optimized model by Synchro in the evening peak hour

Current Situation at Evening Peak Hour									
Intersection	Cycle Length (sec)	Max. v/c Ratio	Intersection LOS	Offset	min. green EB/WB (sec)		Intersection Delay (sec/veh)	Direction of Coordination BW (sec) BWUP (%)	
Tokat	140	0.86	E	0	39	52	50.8	EB	WB
Bursa	140	0.94	E	22	26	42	65.4	0	33
H.Köşk	140	1.03	E	55	31	34	63.2	0.00	97.06
Tiyatro	140	1.04	D	85	27	45	67.3		
					Average corridor delay(sec/veh) :		62.27		

For the evening peak hour, a bandwidth of 33 seconds was established along the westbound artery, from Tokat to Tiyatro (the coordinated direction). In the eastbound direction (EB), no bandwidth was achieved. The average intersection delay for these bandwidths was calculated as 62.27 seconds per vehicle.

3.1. Scenario models where intersection geometry (with or without bay) and phase effect are analyzed

To analyze the effects of changes in phase plan (Opposite, Sequential, and Mixed phase plans) and intersection geometry (with or without a left-turn bay), scenario models were developed with coordinated cycle lengths of 120, 124, 128, 132, 136, 140, 144, and 148 seconds for the morning peak hour, and 130, 132, 134, 136, 138, and 140 seconds for the evening peak hour.

The scenario models created are detailed in Table 5:

- **Scenario Model-1:** Morning Peak Hour - Current Intersection Geometry - Opposite Through Plan (M.P.H - C.I.G - O)
- **Scenario Model-2:** Morning Peak Hour - Current Intersection Geometry - Sequential Phase Plan (M.P.H - C.I.G - S)
- **Scenario Model-3:** Morning Peak Hour - Current Intersection Geometry -Mixed Phase Plan (M.P.H - C.I.G - M)
- **Scenario Model-4:** Morning Peak Hour - Left Turn Bay Intersection Geometry - Opposite Through Phase Plan (M.P.H - L.T.P.G - O)
- **Scenario Model-5:** Morning Peak Hour - Left Turn Bay Intersection Geometry - Sequential Phase Plan (M.P.H - L.T.P.G - S)
- **Scenario Model-6:** Morning Peak Hour - Left Turn Bay Intersection Geometry - Mixed Phase Plan (M.P.H - L.T.P.G - M)
- **Scenario Model-7:** Evening Peak Hour - Current Intersection Geometry - Opposite Through Phase Plan (E.P.H - C.I.G - O)
- **Scenario Model-8:** Evening Peak Hour - Current Intersection Geometry - Sequential Phase Plan (E.P.H - C.I.G - S)
- **Scenario Model-9:** Evening Peak Hour - Current Intersection Geometry -Mixed Phase Plan (E.P.H - C.I.G - M)
- **Scenario Model-10:** Evening Peak Hour - Left Turn Bay Intersection Geometry - Opposite Through Phase Plan (E.P.H - L.T.P.G - O)

- **Scenario Model-11:** Evening Peak Hour - Left Turn Bay Intersection Geometry - Sequential Phase Plan (E.P.H - L.T.P.G - S)
- **Scenario Model-12:** Evening Peak Hour - Left Turn Bay Intersection Geometry - Mixed Phase Plan (E.P.H - L.T.P.G - M)

Twelve distinct scenario models were developed, with six representing the morning peak hour and six for the evening peak hour. These models were analyzed by considering both the current intersection geometry and an alternative geometry incorporating a left-turn bay, assessed across combinations of opposing, sequential, and mixed-phase plans.

The performance metrics derived from the analysis of both the existing model and the scenario models were compared and interpreted. Based on the traffic volumes recorded during the morning and evening peak hours, the current model and scenario models were evaluated accordingly.

3.2. Analysis results applied to scenario models for morning peak hour

For the morning peak hour, the analysis of scenario models with varying phase plans and cycle lengths applied to the current intersection geometry yielded the following results for scenarios achieving the minimum Average Corridor Delay (ACD):

• For 120, 124, and 128-second cycle lengths, the lowest ACD was observed in the phase-planned scenario model (S-S-S-O). Compared to the existing configuration, ACD decreased by 9.29%, 8.80%, and 8.19% at each respective cycle length.

• For 132, 136, 140, 144, and 148-second cycle lengths, the minimum ACD occurred in the phase-planned scenario model (S-O-S-O). ACD reductions relative to the existing setup were 7.58%, 9.73%, 10.84%, 9.82%, and 9.48%, respectively.

• Using the (S-S-S-S-S) phase plan in the existing intersection geometry with a 20-second reduction in cycle length from the existing value led to an 11.19% decrease in ACD.

For the morning peak hour using the left-turn bay intersection geometry, the results of the minimum ACD for each phase-planned scenario were as follows:

• For cycle lengths of 120, 124, 128, 132, 136, and 140 seconds, the lowest ACD was found in the phase-planned scenario model (S-O-S-O). ACD reductions compared to the current setup were 13.56%, 13.84%, 12.48%, 13.48%, 13.23%, and 10.88%, respectively.

• For 144 and 148-second cycle lengths, the minimum ACD occurred with the (S-O-S-S) phase plan. ACD reductions from the existing configuration were 10.39% and 13.11%, respectively.

• In the left-turn bay geometry, when the (S-S-S-S-S) phase plan was applied with a 20-second reduction in cycle length from the current setting, ACD improved by 13.01%. However, with the (O-O-O-O) phase plan, ACD increased by 30.23% compared to the existing configuration.

A comparison of Bandwidth (BW) and Average Corridor Delay (ACD) across cycle lengths for the six scenario models analyzed for the morning peak hour is presented in Figure 6. For the existing intersection geometry, the scenario model with all intersections operating in a sequential phase plan achieved the minimum ACD.

For the intersection geometry with a left-turn bay, the minimum Average Corridor Delay (ACD) was achieved at a 124-second cycle length in the scenario model with the (S-O-S-O) phase plan, where offset times were optimized using Synchro.

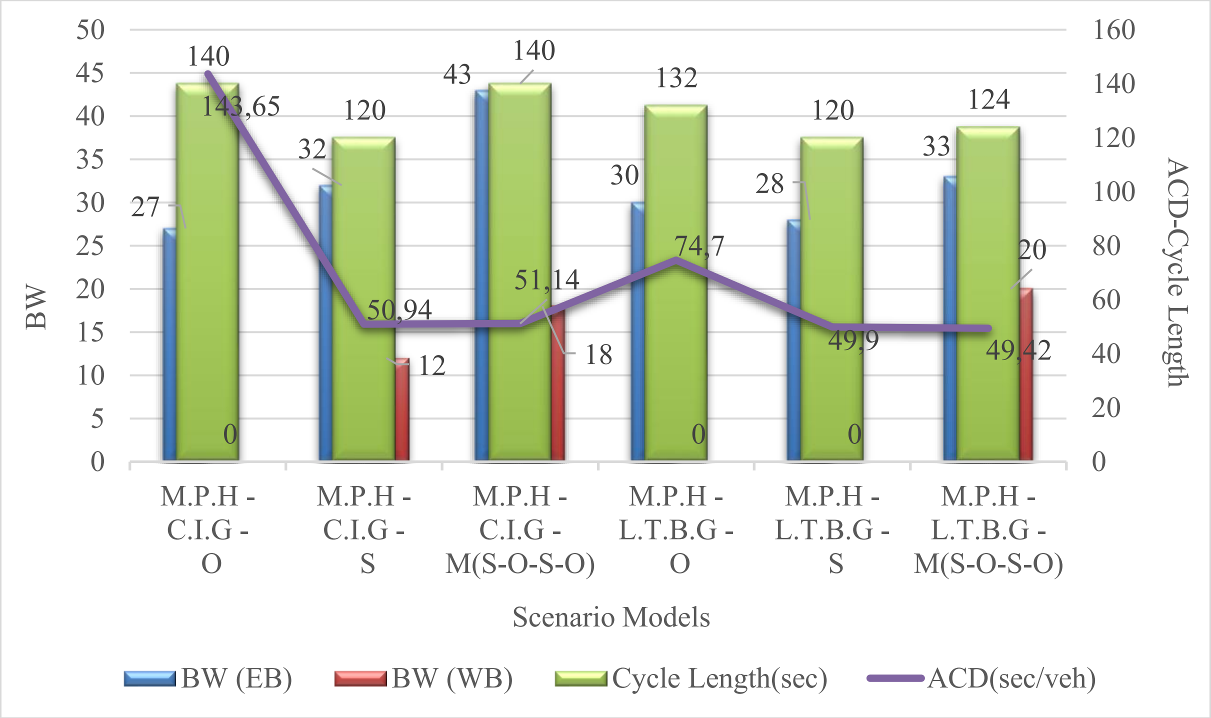


Figure 6. Comparison of scenario models for the morning peak hour.

The objective of this analysis is to develop a proposed model that minimizes delay while achieving optimal bandwidth. In line with this objective, a model was created for the morning peak hour to minimize delay using the (S-O-S-O) phase plan at intersections with a left-turn bay geometry. Synchro's analysis results for this model are presented in Table 5.

Table 5: Results of the analysis for the proposed model in the morning peak hour

Proposed Model (S-O-S-O)									
Intersection	Cycle Length (sec)	Max. v/c Ratio	Intersection LOS	Offset	min. green EB/WB (sec)		Intersection Delay (sec/veh)	Direction of Coordination BW (sec) BWUP (%)	
Tiyatro	150	1.15	E	0	62.7	29	69.2	EB 22 95.65	WB 11 68.75
H. Köşk	150	0.86	D	41	49	49	45.4		
Bursa	75	0.82	C	68	23	16	32.9		
Tokat	75	0.85	C	12	32	32	25.9		
Average corridor delay(sec/veh) :							48.40		

In the eastbound (EB) direction, which is designated as the coordinated direction, the minimum green time at the Bursa Street intersection was calculated as 23 seconds. According to the offset values determined by Synchro, a bandwidth of 22 seconds was achieved in the eastbound direction and 11 seconds in the westbound (WB) direction. Of this bandwidth, 95.65% is utilized in the eastbound direction, and 68.75% is utilized in the westbound direction. The corresponding time-distance diagram is shown in Figure 7. Under these coordinated conditions, an ACD of 48.40 seconds was calculated for the system. Compared to the current analysis results shown in Table 3, this represents an 18.51% improvement (8.96 sec/veh) in ACD, despite a 4-second reduction in the total two-way bandwidth. Furthermore, although the volume-to-capacity (v/c) ratio remained relatively stable, the level of service at the Tiyatro, Bursa, and Tokat intersections improved by one grade.

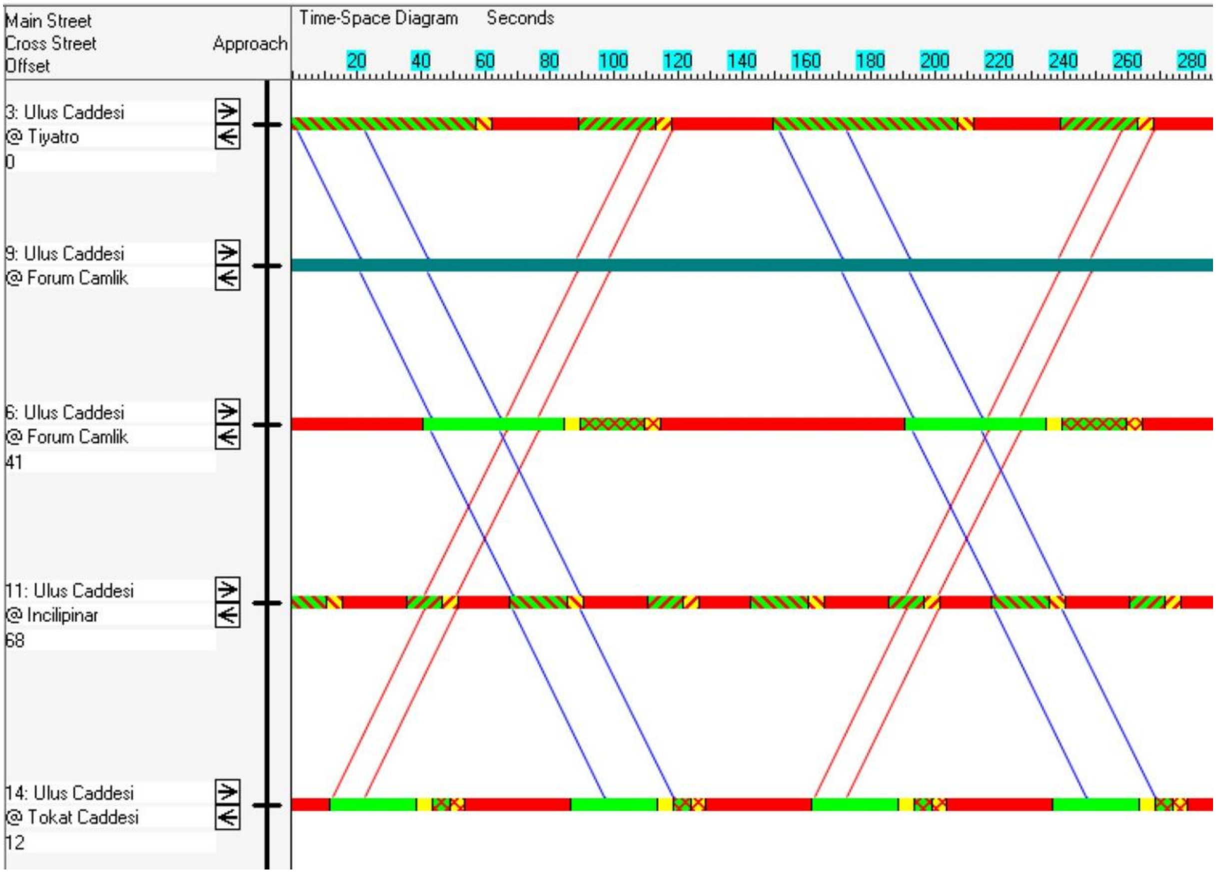


Figure 7. Distance-time diagram of the proposed model for the morning peak hour.

3.3. Analysis results applied to scenario models for evening peak hour

For the evening peak hour, analysis of scenario models with varying cycle lengths and phase plans applied to the existing intersection geometry revealed the following minimum Average Corridor Delay (ACD) scenarios:

• At cycle lengths of 120, 124, 128, 132, 136, 140, 144, and 148 seconds, the minimum ACD was achieved in the (S-O-S-S) phase-planned scenario model. Compared to the current situation, ACD reductions ranged from 6% to 7.18% across these cycle lengths.

• A 3.60% reduction in ACD was observed when the current phase plan (S-S-S-S) was applied in the existing intersection geometry, with the cycle length shortened by 16 seconds from the current setting.

For the evening peak hour in the intersection geometry with a left-turn bay, the minimum ACD scenarios for various phase plans and cycle lengths were as follows:

• At cycle lengths of 130, 132, 134, 135, 136, and 138 seconds, the minimum ACD was achieved in the (S-S-O-S) phase-planned scenario model. ACD reductions compared to the current setup were 20.35%, 20.3%, 19.56%, 19.56%, 19.29%, 18.72%, and 18.52%, respectively.

• At a 140-second cycle length, the minimum ACD was observed with the (S-O-S-S) phase plan, showing a reduction of 17.83% compared to the current configuration.

• In the left-turn bay intersection geometry, using the (S-S-S-S) phase plan with a 20-second reduction in cycle length resulted in a 14.10% decrease in ACD compared to the existing situation. When the phase plan was applied as (O-O-O-O), a 5.83% decrease in ACD was observed relative to the existing setup.

A comparison of Bandwidth (BW) and Average Corridor Delay (ACD) across cycle lengths for the six scenario models developed for the evening peak hour is presented in Figure 8.

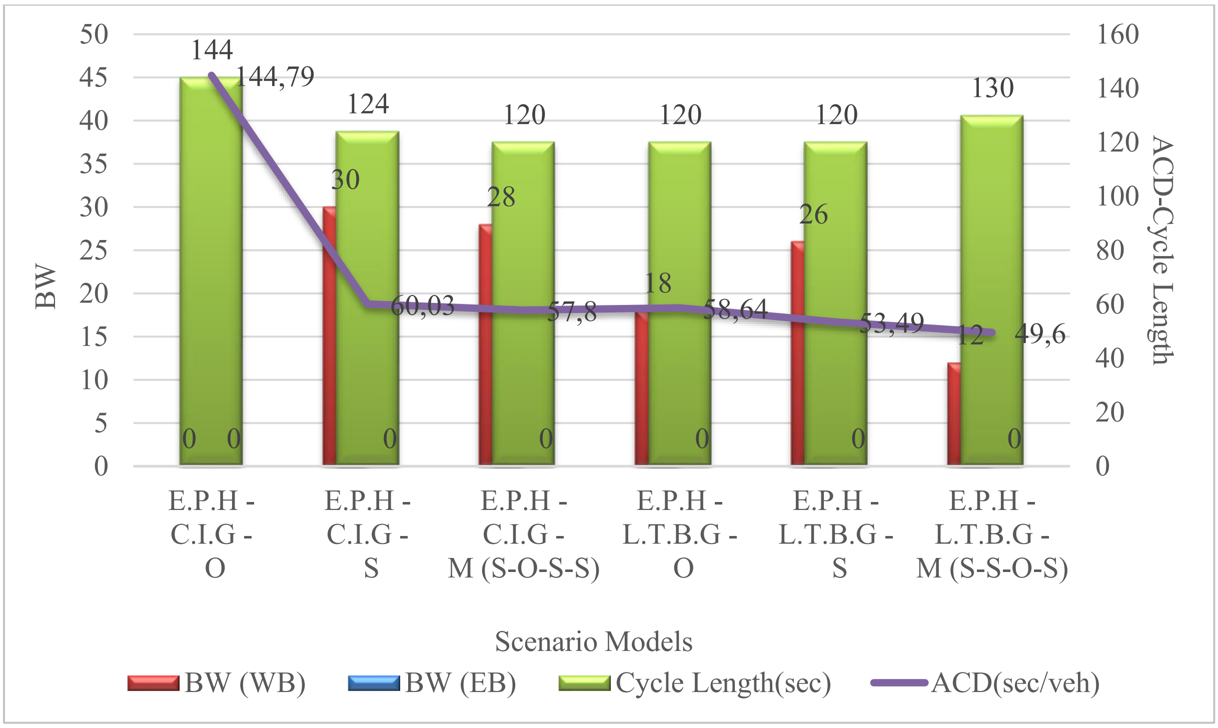


Figure 8. Comparison of scenario models for the evening peak hour.

In the existing intersection geometry, the minimum Average Corridor Delay (ACD) was achieved with a 120-second cycle length in the (S-O-S-S) phase-planned scenario model, optimized for offset times using Synchro. For the left-turn bay intersection geometry, the minimum ACD was achieved with a 130-second cycle length in the (S-S-O-S) phase-planned scenario model, also optimized by Synchro for offset timing.

Based on these analyses, a proposed model for the evening peak hour has been developed, utilizing the scenario model that produced minimum delay at the optimal bandwidth. In this proposed model, designed specifically for the evening peak hour, the optimal bandwidth and minimum delay are presented using a (S-S-O-S) phase plan in the left-turn bay intersection geometry.

Following Synchro's optimization of cycle lengths, the Tiyatro, H. Köşk, and Bursa intersections operate with a 124-second cycle length, while the Tokat intersection operates with a 62-second cycle length. Table 6 presents the analysis results for this model.

Table 6: Results of the analysis for the proposed model in the evening peak hour

Proposed Model (S-S-O-S)

Intersection	Cycle Length (sec)	Max. v/c Ratio	Intersection LOS	Offset	min. green EB/WB (sec)		Intersection Delay (sec/veh)	Direction of Coordination BW (sec) BWUP (%)	
								EB	WB
Tokat	62	1	C	0	12	19	33.6	1 8.33	19 100
Bursa	124	0.84	D	76	34	34	42.1		
H. Köşk	124	1.05	E	106	23	30	66.7		
Tiyatro	124	0.97	D	18	35	35.6	47.8		
Average corridor delay(sec/veh) :							48.54		

In the eastbound (EB) direction, the minimum green time was calculated as 19 seconds at the Bursa intersection. According to the offsets determined by Synchro, a bandwidth of 19 seconds has been provided in the westbound (WB) direction, with a bandwidth of 1 second in the EB direction. Of this bandwidth, 100% is utilized in the WB direction, while 8.33% is utilized in the EB direction.

In the coordinated system, Synchro's offset optimization yielded an ACD of 48.54 seconds. As shown in Table 4, a reduction in total bandwidth is observed due to the Tokat intersection's cycle length being half that of the other intersections. Nevertheless, an improvement of 29.08% (13.73 sec/veh) in ACD was achieved. Compared to the current situation, the volume-to-capacity (v/c) ratio in the system improved, with a one-level service improvement (E→D) at the Bursa intersection and a two-level improvement (E→C) at the Tokat intersection.

4. Results

This study conducted coordination analyses on four consecutive four-leg signalized intersections under various scenario models. These scenario models were analyzed using Synchro optimization software to ensure realistic simulation conditions.

The performance metrics obtained from the analysis of both the existing model and scenario models were compared and interpreted. The current intersection model was evaluated against scenario models based on observed traffic volumes for morning and evening peak hours.

Improvements in average intersection delay were identified in the scenario models compared to the existing model. Results indicate that scenario models incorporating left-turn bays lead to enhancements in the volume-to-capacity (v/c) ratio in the most effective phase plans, resulting in increased capacity. Consequently, improvements in service levels were observed in these intersections.

In scenarios applying the opposing through-phase plan, increased volumes of left-turning vehicles were associated with higher average vehicle delays at intersections. This delay was more pronounced at intersections lacking storage lanes for left-turning vehicles.

Table 7 presents a comparison of fuel consumption and emissions (CO, NOX, and VOC) between the existing conditions and proposed models for both morning and evening peak hours. The analysis, based on offset times optimized by Synchro, showed a reduction of approximately 7% in fuel consumption and emissions during the morning peak hour and approximately 11% during the evening peak hour.

In the coordinated intersection models, improvements achieved through new cycle lengths and phase plans—considering both existing intersection geometry and left-turn bay configurations—are illustrated by the analysis results. The changes in conditions from the existing model (before) to the proposed scenario-based models (after) during morning and evening peak hours are shown in Table 7.

Table 7. Comparisons of existing conditions and proposed models for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Phase Plan		Max. v/c Ratio			Intersection LOS		Intersection Delay (sec)		
		B*	A**	B*	A**	I.R***(%)	B*	A**	B*	A**	I.R***(%)
Morning	Tiyatro	S	S	1.11	1.15	3.48	F →	E	88.4	69.2	-27.75
	H. Köşk	S	O	0.85	0.86	1.16	D	D	41.1	45.4	9.47
	Bursa	S	S	0.74	0.82	9.76	D →	C	34.2	32.9	-3.95
	Tokat	S	O	0.86	0.85	-1.18	D →	C	40.3	25.9	-55.60
Evening	Tokat	S	S	0.86	1	14.00	E →	C	50.8	33.6	-51.19
	Bursa	S	O	0.94	0.84	-11.90	E →	D	65.4	42.1	-55.34
	H. Köşk	S	S	1.03	1.05	1.90	E	E	63.2	66.7	5.25
	Tiyatro	S	O	1.04	0.97	-7.22	D	D	67.3	47.8	-40.79

Table 7(continued). Comparisons of existing conditions and proposed models for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Cycle Length (sec)		Average Corridor Delay (sec/veh)			BW (sec)	
		B*	A**	B*	A**	I.R***(%)	B*	A**
Morning	Tiyatro	140	150	57.36	48.4	-18.51	33(EB)	22(EB)
	H. Köşk		150					
	Bursa		75				4(WB)	11(WB)
	Tokat		75					
Evening	Tokat	140	62	62.27	48.54	-28.29	0(EB)	1(EB)
	Bursa		124					
	H. Köşk		124				33(WB)	19(WB)
	Tiyatro		124					

* Before, ** After, ***Improvement Rate

During the morning peak hour, utilizing the offset determined by Synchro, the (S-S-S-S) phase plan applied from the Tiyatro intersection to the Tokat intersection at a 140-second cycle length produced a total bandwidth of 37 seconds in both directions. Transitioning to the (S-O-S-O) phase plan with adjusted cycle lengths of (150-150-75-75) seconds reduced this bandwidth to 33 seconds. Although the total bandwidth decreased by 4 seconds in both directions compared to the current model, the Average Corridor Delay (ACD) showed an improvement of 18.51% (8.96 seconds/vehicle). While there was no significant change in the v/c ratio, improvements in the level of service were observed at the Tiyatro (F→E), Bursa, and Tokat (D→C) intersections. The Havuzlu Köşk intersection, however, exhibited no change in its service level.

For the evening peak hour, under the offset configuration determined by Synchro, the (S-S-S-S) phase plan with a 140-second cycle length from Tokat to Tiyatro intersection produced a total bandwidth (BW) of 33 seconds in both directions. Subsequently, applying the (S-S-O-S) phase plan with cycle lengths of 62, 124, 124, and 124 seconds led to a reduced BW of 20 seconds. Despite the 13-second decrease in total BW in both directions compared to the existing model, the Average Corridor Delay (ACD) improved by 28.29% (13.73 seconds/vehicle). Although no significant change was observed in the v/c ratio relative to the prior scenario, the level of service at the Tokat intersection improved by two levels (E→C), while the service level at Bursa improved by one level (E→D). There was no observed change in the service levels at the Havuzlu Köşk and Tiyatro intersections.

Comparisons of the delay values for the intersections are depicted in Figure 9. In this figure, morning and evening peak hours are considered and the delay values given in Table 7 are compared.

The impact of the left-turn bay was also analyzed for the proposed models during both morning and evening peak hours. This analysis re-evaluated the models by removing the left-turn bay and compared the outcomes with the analysis results from the original scenario that included the left-turn bay. A comparison of these results is provided in Table 8.

In the proposed model for the morning peak hour, removing the left-turn bay led to a 2-second reduction in bandwidth for the eastbound direction. In contrast, previously absent 11-second bandwidth emerged in the westbound direction. Additionally, the average corridor delay improved by 8.53% (4.13 seconds/vehicle). The service levels at the Tiyatro, Havuzlu Köşk, and Tokat intersections remained unchanged, while the service level at the Bursa intersection improved by one level (D→C).

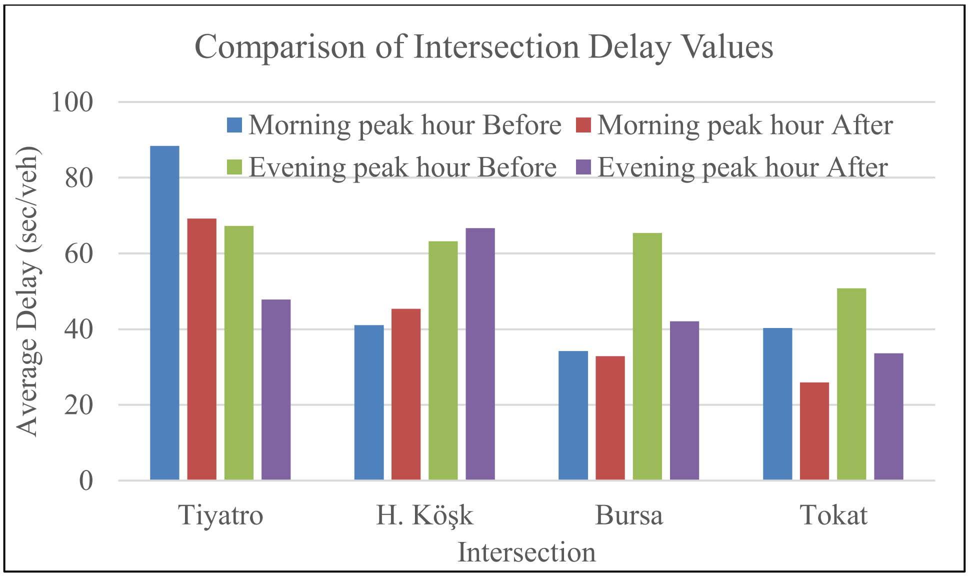


Figure 9. Comparisons of delay values for the intersections.

In the proposed model for the evening peak hour, removing the left-turn bay resulted in a total reduction of 10 seconds in two-way bandwidth (BW), while the average corridor delay (ACD) improved by 43.33% (4.13 seconds/vehicle). Service level improvements were observed at the Tokat (D→C) and Tiyatro (E→D) intersections, with a two-level improvement at the Bursa intersection (F→D). No change in service level was observed at the Havuzlu Köşk intersection.

The comparative analysis of fuel consumption and emissions (CO, NOX, and VOC) between existing conditions (baseline) and the proposed models during morning and evening peak hours is summarized in Table 9. According to the offsets determined by Synchro, the proposed models show a reduction of approximately 7% in fuel consumption and emissions during the morning peak hour, and a reduction of approximately 11% during the evening peak hour.

In conclusion, the analysis results reveal that the proposed models yield significant improvements in intersection performance parameters, fuel consumption, and emission outputs at the studied intersections for both morning and evening peak hours.

Table 8. Effect of left turn bay on proposed models for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Phase plan		Max. v/c Ratio			Intersection LOS		Intersection Delay (sec)		
		B*	A**	B*	A**	I.R***(%)	B*	A**	B*	A**	I.R***(%)
Morning	Tiyatro	S	S	1.1	1.15	4.35	E	E	78.9	69.2	-14.02
	H. Köşk	O	O	0.86	0.86	0.00	D	D	40.9	45.4	9.91
	Bursa	S	S	0.92	0.82	-12.20	D	→ C	40.8	32.9	-24.01
	Tokat	O	O	0.92	0.85	-8.24	C	C	26.6	25.9	-2.70
Evening	Tokat	S	S	1.05	1	-5.00	D	→ C	45.1	33.6	-34.23
	Bursa	S	S	1.31	0.84	-55.95	F	→ D	103.6	42.1	-146.0
	H. Köşk	O	O	1.05	1.05	0.00	E	E	61.4	66.7	7.95
	Tiyatro	S	S	1.08	0.97	-11.34	E	→ D	69.3	47.8	-44.98

Table 8 (continued). Effect of left turn bay on proposed models for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Phase Plan		Average Corridor Delay (sec/ta)			Cycle Length (sec)		BW (sec)	
		B*	A**	B*	A**	I.R*** (%)	B*	A**	B*	A**
Morning	Tiyatro	S	S	52.53	48.4	-8.53	150	150	24(EB)	22(EB)
	H. Köşk	O	O				150	150		
	Bursa	S	S				75	75	0(WB)	11(WB)
	Tokat	O	O				75	75		
Evening	Tokat	S	S	69.57	48.54	-43.3	62	62	12(EB)	1(EB)
	Bursa	S	S				124	124		
	H. Köşk	O	O				124	124	18(WB)	19(WB)
	Tiyatro	S	S				124	124		

* Before, ** After, ***Improvement Rate

The effect of left turn bay on delay values is shown in Figure 10. In this figure, the delay values defined in the Table 8 are used regarding morning and evening peak hours.

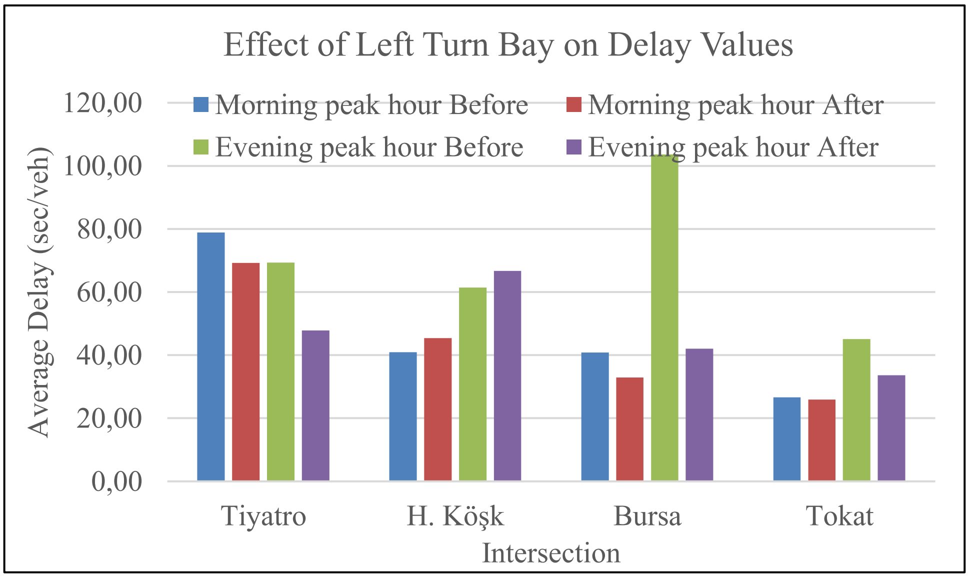


Figure 10. The effect of left turn bay on delay values of the intersections

Table 9. Comparison of performance parameters for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Phase Plan		Cycle Length (sec)		Total Delay (hr)			Total Delay/Vehicle (sec/veh)		
		B*	A**	B*	A**	B*	A**	I.R*** (%)	B*	A**	I.R*** (%)
Morning	Tiyatro	S	S	140	150	174	147	-18.37	48	41	-17.07
	H. Köşk	S	O		150						
	Bursa	S	S		75						
	Tokat	S	O		75						
Evening	Tokat	S	S	140	62	207	162	-27.78	52	41	-26.83
	Bursa	S	S		124						
	H. Köşk	S	O		124						
	Tiyatro	S	S		124						

Table 9(continued). Comparison of performance parameters for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Cycle Length (sec)		Number of Stops			Number of Stops/Vehicle			Average Speed (km/hr)		
		B*	A**	B*	A**	I.R*** (%)	B*	A**	I.R*** (%)	B*	A**	I.R*** (%)
Morning	Tiyatro	140	150	8530	8135	-4.86	0.66	0.63	-4.76	16	18	11.1
	H. Köşk		150									
	Bursa		75									
	Tokat		75									
Evening	Tokat	140	62	10021	9916	-1.06	0.7	0.7	0.00	16	18	11.1
	Bursa		124									
	H. Köşk		124									
	Tiyatro		124									

* Before, ** After, ***Improvement Rate

Table 10. Comparison of fuel consumption and emission levels for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Phase Plan		Work	Total Travel Time (hr)	Distance Traveled (km)	Fuel Consumed (l)
		B*	A**				
Morning	Tiyatro	S	S	Before	255	4083	1060
	H. Köşk	S	O	After	231	4212	989
	Bursa	S	S	Difference	-24	129	-71
	Tokat	S	O	Advance(%)	-10.39	3.06	-7.18
Evening	Tokat	S	S	Before	301	4698	1245
	Bursa	S	S	After	256	4698	1116
	H. Köşk	S	O	Difference	-45	0	-129
	Tiyatro	S	S	Advance(%)	-17.58	0.00	-11.56

Table 10(continued). Comparison of fuel consumption and emission levels for the morning and evening peak hours (Before/After)

Peak Hour	Intersection	Work	Fuel Economy (km/l)	CO Emissions (kg)	NOx Emissions (kg)	VOC Emissions (kg)
Morning	Tiyatro	Before	3.9	19.72	3.81	4.55
	H. Köşk	After	4.3	18.4	3.55	4.24
	Bursa	Difference	0.4	-1.32	-0.26	-0.31
	Tokat	Advance (%)	9.30	-7.17	-7.32	-7.31
Evening	Tokat	Before	3.8	23.15	4.47	5.34
	Bursa	After	4.2	20.76	4.01	4.79
	H. Köşk	Difference	0.4	-2.39	-0.46	-0.55
	Tiyatro	Advance (%)	9.52	-11.51	-11.47	-11.48

* Before, ** After

5. Discussion

This study investigates the optimization of phase plans, left-turn bays, and cycle lengths to improve corridor management using a simulation-based optimization approach. The findings highlight the importance of dynamically adapting phase plans based on traffic density by evaluating coordinated intersections with two distinct intersection geometries and testing various scenarios—including sequential, opposing, and mixed-phase plans. The results indicate that the coordinated direction's green bandwidth led to significant reductions in average delays during morning and evening peak periods, enhancing service levels at these intersections.

The integration of left-turn bays proved beneficial, allowing left-turning vehicles to proceed without impeding the main traffic flow, thus improving corridor efficiency and ensuring smoother overall operations. Specifically, scenarios incorporating left-turn bays experienced reductions in intersection delays ranging from 10% to 15%. Additionally, tailoring cycle lengths in response to traffic volumes was crucial in the optimization process. Through simulation-based assessments of various cycle lengths, optimal timing adjustments were identified, resulting in delay reductions of up to 18% during morning peak hours and 28% during evening peak hours.

Moreover, this coordinated approach, facilitated by simulation-based optimization, supports environmental sustainability by reducing fuel consumption and emissions. The combined implementation of optimal phase plans, left-turn bay configurations, and well-calibrated cycle lengths enables corridors to operate more efficiently and with a reduced environmental impact. Thus, the simulation-based optimization approach presented in this study constitutes an effective strategy for promoting sustainable development objectives within urban transportation systems.

Researchers' Contribution Rate Statement

All authors equally contributed to the study. This study was produced from master's thesis of the first author.

Acknowledgment and/or disclaimers

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Conflict of Interest Statement

There is no conflict of interest with any parties.

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