RT&A, No 4 (89)
Volume 20, December 2025

OPTIMIZING TRAFFIC SIGNAL TIMING FOR EFFICIENT FLOW THROUGH URBAN CROSSROADS

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Abstract

This paper presents an intelligent traffic signal control system aimed at optimizing vehicle flow at a two-lane crossroads intersection using a network flow-based framework. Rapid urbanization and the corresponding rise in vehicle usage have exacerbated congestion issues, especially at intersections where traditional fixed-time signal controls often result in inefficiencies and increased vehicle delays. The proposed system addresses these limitations by integrating real-time traffic data with principles of network flow theory to coordinate signal timing and vehicle movement dynamically. The intersection is modeled as a directed graph, where nodes represent entry and exit points, and edges signify possible vehicle paths. The system utilizes a weighted signal control algorithm that incorporates traffic volume, direction, and flow density to determine optimal signal phases. These weighted parameters guide the adaptive timing of traffic lights, allowing for parallel vehicle movement while preventing collisions. Specific constraints are applied to eliminate conflicting movements and maintain safety, thereby enhancing throughput and reducing total waiting times. A key objective of the model is to minimize total waiting time across all directions by identifying and enforcing necessary conditions for optimal traffic flow. To evaluate the performance of the proposed system, a simulation environment was developed to mimic real-world traffic conditions under various scenarios. Performance metrics such as average delay, queue length, and throughput were used for comparison against traditional signal control methods. Simulation results indicate significant performance improvements. The proposed system achieves a vehicle flow time of 804 seconds compared to 400 seconds in the existing system, with an optimized objective function value of 972. A numerical case study further illustrates the implementation, signal phase structuring, and resulting efficiency gains. In conclusion, the intelligent traffic signal control model demonstrates strong potential for reducing congestion and improving traffic management at urban intersections. Its adaptive, data-driven approach not only enhances current traffic flow but also allows for forecasting future patterns. The model is scalable, flexible, and suitable for integration with intelligent transportation systems, offering a proactive solution to modern traffic challenges.

Keywords: Traffic data, Signal distribution, Linear Programming Model, Flow Direction, Statistical Interference, XLSTAT Software

DOI: https://doi.org/10.24412/1932-2321-2025-489-642-650

I. Introduction

Mathematical modeling involves the representation of real-world phenomena using mathematical symbols and relationships to account for observable parameters. This process helps identify and generate decision-making parameters relevant to the problem. As parameters are developed, the existing system can be adapted and improved. During the evaluation process, additional insights often emerge and are incorporated into the solution algorithms. However, the success of the model is not solely determined by its accuracy, but also by how easily it can be applied and how effectively it predicts future outcomes. Mathematical models provide valuable tools for analyzing system performance and addressing real-world challenges. Traffic congestion, a common experience for most people, demands timely and efficient solutions. Unfortunately, current systems often fall short in delivering such performance. The growth of vehicle numbers is influenced by various factors such as road infrastructure, time, speed, and vehicle capacity. In this context, traffic signals become a critical element, significantly affecting traffic flow. Poor arrangement or optimization of traffic signal parameters can lead to increased congestion and a higher risk of accidents. The placement of traffic lights at crossroads is strategically planned to ensure smooth vehicle flow and prevent obstruction. Ideally, vehicles should move without hindering the available traffic stream. However, it has been observed that the volume of traffic on congested roads is often significantly higher than that on specific crossroad segments, leading to inefficiencies in the traffic control system. In this study, we examine the direction and behavior of vehicle flow at a crossroads junction. The intersection allows vehicles to move efficiently along two main directions in a straight path. When traffic volume increases beyond a manageable threshold, the situation can be analyzed using mathematical modeling. Such models provide feasible solutions to optimize traffic flow. In recent research, various models have been proposed. Ruikang Luo and Rong Su [6] Investigated crossroads traffic using a stochastic process model, incorporating variable vehicle speeds and distribution times based on real-time data collected during peak hours in Singapore. The Nonlinear Programming (NLP) model was developed using data collected on the characteristics and capabilities of various vehicle types. The duration of traffic signal phases was estimated using statistical methods. Bo Lin et al. [1] presented dynamic traffic flow model for both urban and freeway networks, examining different methodologies along with their computational benefits and impacts on system performance. Rajendra et al. [4] presented a high-precision transport model, dynamic signal control algorithm aimed to distribute vehicle flow based on population density while minimizing congestion and stagnation. The model incorporated variables such as road length, quality, and vehicle speed to evaluate road capacity. Furthermore, Manigandan et al. [8] published foundational work on Traffic Management Systems (TMS), while Robertson and Transit [5] developed the TRANSYT software tool to optimize traffic signal timing and assess system performance. Lee et al. [2] proposed a Traffic Control System (TCS) to manage traffic flow and identify the most efficient signal path through a TCS junction area. The Intelligent Traffic Signal Control Problem (ITSCP) was addressed by Mckenney and White et al. [3] using a Multi-Dominant approach, which modeled vehicle flow considering human behavior, network structures, risk factors, and traffic demand. Geetha and Srividhya [7] analyzed a complexity of the ITSCP model is influenced not only by the number of arriving vehicles at a junction but also by the number of intersections, vehicle types, and user preferences within the network. Seyit Alperen Celtek [13] introduced a self-adaptive signal control algorithm that presents an innovative solution to mitigate urban traffic congestion. This approach dynamically adjusts signal timing parameters according to seasonal traffic demand variations, thereby enhancing operational efficiency within urban traffic networks. Myungeun Eom and Byung Kim [9] provided a comprehensive review of the scope of survey issues, assessment procedures, and methodologies related to the Intelligent Traffic Signal Control Problem (ITSCP), summarizing the key control parameters involved. Geetha et al. [10] proposed a novel algorithm aimed at optimizing crossroad traffic light coordination to effectively reduce vehicle delay times during transit. The traditional fixed-time control system, as highlighted Balamurugan et al. [11], considered outdated. As a response, an ITS-based method known as ratio-monotonic scheduling has been proposed to determine the optimal signal timing, with its outcomes compared to alternative scheduling methods. Kavitha and Rayalu [12] Explored real-time signal control improvements, revealing that delays and vehicle queue lengths can be significantly minimized compared to those under static signal timing systems. Uddin et al. [14] Enhanced traffic signal control strategies using swarm intelligence techniques and assessed computational efficiency. The outcomes indicate a strong correlation between accurate traffic data usage and the effectiveness of the proposed method. Current eco-traffic systems adjust signal durations (green/red), yet inefficiencies arise when vehicle arrivals do not match the allocated green time, resulting in wasted time and increased costs. Pachiyappan et al. [15] Noted that traffic signal control systems have evolved considerably in recent years, especially with the implementation of the Advanced Traffic Signal Control System (ATSC), where timing adapts through RTC (Real-Time Control). A genetic algorithm is applied within this system for parameter optimization. Furthermore, a new lane bypass strategy was developed to reroute traffic, thereby improving flow in metropolitan traffic grids. Premila et al.[16] Contributed to this area by developing a traffic optimization model based on a genetic algorithm, implemented in MATLAB. In this study, we adopt a network flow model to address the traffic signal control problem. The goal is to enable smooth vehicle movement across intersections, especially in horizontal directions, without the risk of collision. The traffic signal pattern at the intersection is modeled to accommodate bi-directional lane flows effectively. Vehicle flow at the intersection can proceed in parallel directions without resulting in collisions. This model considers key constraints such as traffic volume and the weight or influence of the traffic signal system. The proposed design aims to minimize total waiting time across all directions by first identifying the necessary conditions for optimal flow. Ultimately, the system's performance is analyzed, and vehicle flow patterns are forecasted to enhance traffic network management. The rest of the paper summarized as follows: In chapter 2 proposed the mathematical model and methodology of this work. In chapter 3 discussed the traffic signal parameter assignments. In chapter 4 discussed the numerical example and conclusion.

II. Methods and Methodology

The objective of this paper is to develop a mathematical model for managing traffic flow at intersections and to determine the optimal green light duration for vehicle movement in each direction. Traffic flow is not uniformly distributed across the network, making efficient signal timing critical. The proposed model focuses on the intersection point where two traffic streams converge. It takes into account key constraints, such as traffic volume and the relative influence (or weight) of the traffic signal system, to ensure smooth and balanced vehicle flow.

I. Signal light distribution

This model predicts that the labelled points are controlled by traffic signal lights, a, b, c, d, e, f, g and h each of which is colored green, yellow and red In traffic networks, paths are typically represented as flows between nodes, with the connections referred to as edges. These edges indicate the movement of traffic between two points without intersecting other flows. The first step is to identify the permissible directions of vehicle movement at the intersection. Begin by defining distinct initial flows. Establish basic assumptions, such as identifying flows involving left-turning signals. Determine whether the current left-turn signal flow shares the same end nodes as a previously established flow. For example, flows such as A1 and D1 may not operate in parallel due to conflict, while D2 and B1 or B2 and C1 might function in parallel safely. (iv) Represent each traffic flow using its associated nodes in the network. (v) Define an edge between two nodes in the traffic signal network if and only if the sequential flows represented by these nodes are compatible and part of a continuous movement from one intersection to another. These relationships help define the connectivity and coordination within the traffic management system, particularly for multi-road intersections.

Properly resolving intersection behavior reduces driver conflict, enhances safety, and supports uninterrupted vehicle movement. The traffic management system incorporates multiple parameters essential for analyzing and modeling signal systems. The following section discusses key parameters relevant to the mathematical modeling of such systems. Flow Volume: This refers to the total number of vehicles that arrive and pass through a specified intersection node over a given time period. Flow Density: It denotes the number of vehicles occupying a certain length of road within a specified node, usually expressed in vehicle units per kilometer (v/km). To optimize the performance of an intersection junction, one must consider scenarios such as flooded flow traffic, which occurs when the number of vehicles at a node reaches or exceeds its capacity. The maximum vehicle capacity depends on the design and limitations of the intersection and is typically measured in vehicles per hour. However, traffic flow may vary across different intersections due to several influencing factors: Traffic layout and signal arrangements. Frequency of vehicle arrivals at the junction. The curvature or radius of the road. Right-turning movements, especially those conflicting with oncoming traffic from the opposite direction Phase: A phase represents a segment of the complete traffic signal cycle, assigned to specific traffic movement patterns. Each phase ensures a controlled movement for certain vehicle flows and may be subdivided into sub-flows to manage different traffic directions within the same signal cycle.

II. Possible Flow Directions

Traffic Flow Directions and Hypotheses of Intersection Behavior. The direction of traffic flow must be followed according to the labeled points outlined below:

- Flow A1 = (A2, D2, B2, C1, C2)
- Flow A2 = (A1, D2, B2)
- Flow D2 = (A1, A2, D1, D2, B1, C1, C2)
- Flow D1 = (D2, C1, C2)
- Flow B2 = (A1, A2, D2, B1, C1)
- Flow B1 = (D2, B2, C1)
- Flow C1 = (A1, D2, D1, C1)

Intersection Hypotheses: Right-turn movements do not intersect with left-turn flows, as the waiting time for such transitions is assumed to be zero. The remaining left-turn flows—specifically from nodes A1 and C1—are governed by traffic signal timing. In this configuration, A2, D1, B2, and C2 represent straight-through movements, while A1, D2, and C1 are left-turn flows. There is a single right-turn movement, represented by B1. Two nodes are considered connected if the flow between them is parallel and aligns consecutively, allowing smooth transition from one point to the next. The primary goal of the optimized traffic signal control system at the intersection is to prevent collisions and minimize overall vehicle waiting time. The timing for each directional flow must correspond to the vehicle's current position; otherwise, it is excluded from the signal schedule.

Table 1: *The total number of vehicles arriving from the each direction*

Date	Time	Red Signal Duration	Green Signal Duration	N-S	W-E	S-N	E-W	Total No of Vehicles
02-02-2025	7am to 8 am	450	600	112	196	151	113	572
				151	226	172	122	671
				182	244	202	154	782
				196	241	202	166	805
				184	222	191	157	754
				179	208	183	149	719
02-03-2025	7am to 8 am	450	600	279	302	247	221	1049
				282	302	254	221	1059
				277	289	245	219	1030
				281	299	256	211	1047
				278	299	245	213	1035
				249	278	202	177	906
02-04-2025	7am to 8 am	450	600	116	179	129	111	535
				191	162	177	141	480
				189	202	166	133	501
				188	221	166	142	529
				187	211	203	167	581
				195	233	181	176	590
02-05-2025	7am to 8 am	450	600	189	241	123	159	593
				141	155	123	100	519
				129	145	110	91	475
				123	139	119	89	470
				131	165	129	88	513
				133	166	98	88	485
02-06-2025	7am to 8 am	450	600	124	109	89	81	403
				129	187	154	97	547
				146	171	123	95	581
				134	167	112	91	568
				136	166	111	84	592
				129	141	134	111	597
				133	129	113	86	537
				123	131	104	92	526

Real-time traffic data was collected at the Solinganallur junction between 7:00 a.m. and 8:00 a.m. over the course of a week. This data was segmented into 10-minute intervals, with each cycle defined as 600 seconds in length. It is assumed that 2 vehicles are served per second, and vehicle arrivals are not limited. The objective is to compute the total waiting time and compare the results between the existing and proposed signal control methods.

III. Data Collection:

Traffic data was gathered from a high-density urban intersection during peak hours over a onemonth period. The key parameters recorded include:

- Vehicle count
- Timestamp
- Signal phase
- Day of the week
- Signal cycle time

These variables form the basis for in-depth analysis of the intersection's performance and effectiveness of signal timing strategies.

Table 2: *Maximum significant vehicle flow level for each direction*

Marginal	Information for Sub Flow	Waiting Time	Moving Time	Total Time
Before Divider	Total Flow	450	150	600
	Flow P = (A1,A2,D2) Q = (D2,D1,C1,C2) R = (B1,C1,D2)	250	350	600
After Divider	Flow P = (A1,A2,D2) Q = (B1,B2,,D2) R = (D2,D1,C1,C2)	250	350	600
	Flow P = (A1,A2,D2,D1) Q = (B2,B1,C1,D2) R = (D2,D1,C1,C2)	300	300	600

The above flow considers only the straight-through direction. However, the traffic management system must account for the possibility of left or right turns during this time period. Therefore, the actual vehicle flow volume at the intersection should be determined by considering various possible path combinations. Assumptions can be made that the number of vehicles passing through each path within the given time intervals are uniformly distributed. To minimize the waiting time for all arriving vehicles, the system must be optimized by assigning different weights to each path, reflecting the varying flow volumes.

III. TRAFFIC SIGNAL PARAMETERS ASSIGNMENT

The traffic flow time at an intersection junction is initially set with equal length and weight for each flow. However, the existing flow times may be longer for more congested flows, such as those involving right or left turns where vehicle density is higher. In the traffic network, the four straight-through roads connect to C2, while the other flows are designated for left or right turns. The time intervals for each direction are assigned accordingly based on the flow characteristics.

$$A2 \rightarrow x_1,\ D1 \rightarrow x_3,\ B2 \rightarrow (x_1 \,\&\, x_2),\ C2 \rightarrow (x_3),\ A1 \rightarrow x_1,\ D2 \rightarrow (x_1, x_2, x_3)$$

The objective function of the mathematical representation for the above traffic network model is defined as follows:

$$Z=\delta_1\left(2x_1+x_2+2x_3\right)+\delta_2\left(2x_1+3x_2+2x_3\right)$$

Subject to the constraint as follows:

$$x_1+x_2+x_3=600,\ \ x_1\geq 150,\ \ x_1+x_2\geq 150,\ \ x_2\geq 150,\ \ x_3\geq 150,\ x_1+x_2+x_3\geq 150$$

Table 3: *Initial flow time*

Marginal	Red Light	Green Light	Total
(A1,A2)	145	205	350
(B2)	133	217	350
(C1)	218	132	350
(D1)	225	125	350
(D2,B1)	225	125	350
Total	946	804	

Now, split the actual vehicle at each intersection junction table as follows:

Table 4: *Flow index*

S.No	Flow Index	Actual Traffic Flow for Certain Time
1	A1	112
2	A2	151
3	B1	112
4	B2	252
5	C1	196
6	C2	271
7	D1	113
8	D2	252
Total		1459

The calculated traffic flow for each direction is as follows: SNS = (263/1459) = 0.18 x 100 = 18, SWE = (309/1459) = 0.2117 x 100 = 21.11, TLR = (748/1459) = 0.5125 x 100 = 51.26.

By the data, the current minimal flow is 400 second. The total flow of green light is 80seconds. The construed new model for the above problem is as follows:

$$z=18S_{NS}+21.11\ S_{WE}+51.26T_{LR}$$

Subject to the constraints:

$$S_{NS}+S_{WE}+T_{LR}=804,\ S_{NS}\geq 120,\ \ S_{NS}+S_{WE}\geq 120, S_{WE}\geq 120,\ \ S_{WE}+T_{LR}\geq 120,\ \ T_{LR}\geq 120,\ \ S_{Ns}+S_{WE}+T_{LR}\geq 120$$

Using Tora Software, we can get the optimal value of the traffic flow direction is

$$x_1=19,\ x_2=8,\ x_3=9$$

The objective function value is 972.22 ≈ 972. Using M/M/1 infinite queuing model to using XLStat, calculate the predicate number of passing vehicle and calculate total waiting time of the traffic length.

Table 5: *Queue length for each direction*

Lq1	Wq1	Lq2	Wq2	Lq3	Wq3	Lq4	Wq4	Lq	Wq
0.1651	0.3318	0.5058	0.5807	0.3002	0.4474	0.1681	0.3348	1.1394	1.6948
0.3002	0.4474	0.6726	0.6696	0.3895	0.5096	0.1960	0.3614	1.5584	1.9881
0.4362	0.5392	0.7840	0.7229	0.5373	0.5985	0.3123	0.4562	2.0698	2.3170
0.5058	0.5807	0.7648	0.7140	0.5373	0.5985	0.3268	0.4918	2.1709	2.3851
0.4458	0.5451	0.6490	0.6511	0.4804	0.5659	0.3245	0.4651	1.8998	2.2340
0.4219	0.5303	0.5697	0.6162	0.4410	0.5422	0.2923	0.4414	1.7250	2.1303
0.5918	0.6281	0.8765	0.7644	0.6607	0.6637	0.4804	0.5659	2.6095	2.6222
1.0250	0.8266	1.2010	0.8948	0.8034	0.7138	0.6417	0.6581	3.6769	3.1014
1.0472	0.8355	1.2010	0.8948	0.8945	0.7525	0.6431	0.6548	3.7410	3.1377
1.0104	0.8207	1.0998	0.8562	0.7045	0.7259	0.6315	0.6488	3.5323	3.0185
0.2435	0.4029	0.3687	0.4918	0.1622	03288	0.0929	0.2488	0.8616	1.4725
0.2191	0.3822	0.2618	0.4177	0.2364	0.3970	0.1622	0.3288	0.8796	1.5259
0.2329	0.3940	0.2191	0.3822	0.1681	0.3348	0.0973	0.2548	0.7176	1.3659
0.1992	0.3644	0.2259	0.3881	0.1424	0.3081	0.1114	0.2725	0.6791	1.3333
0.2736	0.4266	0.4362	0.5392	0.1864	0.3525	0.1290	0.2933	1.0248	1.6118
0.2730	0.4266	0.4654	0.5570	0.1960	0.	0.1114	0.2725	1.0459	0.6177
0.2544	0.4118	0.3850	0.5066	0.1833	0.3496	0.1507	0.3170	0.5736	1.5851
0.24	0.4	0.4219	0.5303	0.1802	0.3466	.01397	.03051	0.9819	1.5822
0.2618	0.4177	0.1992	0.3644	0.1593	0.3259	0.0801	0.2311	0.7004	1.3392
0.2435	0.4029	0.1864	0.3525	0.1163	0.2785	0..885	0.2429	0.6349	1.2770
0.1479	0.3140	0.2090	0.3733	0.1290	0.2933	0.0929	0.2488	0.5790	1.2296
0.1651	0.3318	0.2495	0.4029	0.1424	0.3081	0.1019	0.2607	0.6531	1.3037
0.1771	0.3437	0.2507	0.4088	0.1536	0.32	0.1043	0.2637	0.6858	1.336
0.1864	0.3525	0.2329	0.3940	0.1163	0.2785	0.0885	0.2429	0.6243	1.2681
0.1564	0.3229	0.1992	0.3644	0.0951	0.2518	0.0907	0.2459	0.5415	1.1854
0.1681	0.3348	0.2768	0.4296	0.1290	0.2933	0.1043	0.2637	0.6784	1.3214

Table 6: *Path flow Predictions*

Variable	Mini	Max	Mean	Std.Deviation
Lq = (N1^2)/(O1*(O1-N1))	-602.022	598.002	0.488	53.136
Wq = (N1)/(O1*(O1-N1))	-1.002	0.998	0.002	0.089

IV. Discussion

This study analyzes a network-based traffic signal control system and its associated model, which is applied at a crossroads junction. The connected roadway paths are segmented into multiple directional flows to manage and guide vehicle movement effectively. The proposed approach is evaluated against the existing system, showing a notable improvement—while the current model allows 400 seconds of vehicle flow time, the proposed algorithm achieves 804 seconds, with an objective function value of 972. The network flow model provides distinct signal control for specified flow directions. This model contributes to enhancing the overall efficiency of traffic signal operations. Results clearly indicate that the proposed system outperforms the existing traffic flow model. Furthermore, the benefits of the new signal control approach over conventional methods are thoroughly outlined. The construction of the proposed scheme is statistically validated, offering time savings, economic benefits, and equitable access for all traffic participants.

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