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A Genetic Algorithm-Based Optimization Strategy for Traffic Signal Control in Multiple Intersections

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Abstract

With the continued development of urban areas, traffic congestion has become an increasingly significant issue. This problem is especially pronounced in dense city centers where population, commercial facilities, and public institutions are highly concentrated. This study focuses on how to effectively mitigate traffic congestion along busy corridors that contain multiple intersections.

Keywords : Traffic signal optimization, Multi-objective optimization, NSGA-II, Urban traffic congestion, SUMO simulation, Traffic flow management

1 Introduction

Traffic congestion is a familiar sight almost everywhere. In Japan, congestion contributes to more than 3.8 billion hours of lost time annually[1]. Many drivers consistently report dissatisfaction with current mobility conditions, and prolonged delays continue to impose significant economic, environmental, and social burdens on urban communities. The reasons why traffic congestion happened include traffic concentration, accidents, roadway construction, weather disturbances, and signal miscoordination, among others. Among these factors, congestion resulting from excessive traffic concentration and insufficient signal control remains one of the most dominant and persistent contributors.

With increasing urbanization, the challenge of congestion mitigation is particularly critical along major urban corridors composed of multiple closely spaced intersections. Along such corridors, traffic interactions become highly complex: queues may propagate upstream, local bottlenecks can disrupt progression bands, and even small fluctuations in traffic demand may trigger widespread delays. As a result, traditional single-intersection optimization approaches often fail to address corridor-wide performance holistically, while network-level measures may overlook severe localized congestion. These limitations highlight the need for optimization frameworks that can simultaneously consider both global efficiency and intersection-level congestion characteristics.

To address these challenges, this study examines how congestion can be more effectively mitigated along busy multi-intersection corridors through multi-objective optimization. Specifically, we aim to develop a signal control framework that captures not only overall network performance but also localized congestion severity at individual intersections. By incorporating both macroscopic and microscopic traffic behavior into the optimization process, the proposed method seeks to generate control strategies capable of improving travel efficiency while preventing the persistence of localized bottlenecks. This dual focus provides a more comprehensive approach to corridor-level signal optimization, enabling more equitable and effective congestion reduction across the entire roadway.

2 Background and Related Work

Previous research on signal optimization has largely focused on adjusting the offset, which determines how green intervals are temporally aligned across intersections. Many studies have applied Genetic Algorithms (GA) in combination with simulation platforms to optimize a single performance indicator, typically average travel time (ATT) [2]. While this single-objective approach can improve corridor-level travel time, it does not necessarily reduce congestion at individual bottlenecks.

Traffic signal control is governed primarily by three parameters [3]:

- Cycle: the total duration of one complete signal cycle.
- Split: the allocation of green time among competing movements.
- Offset: the relative timing of green signals between adjacent intersections.

Conventional studies emphasize offset optimization while assuming homogeneous traffic conditions across intersections. However, intersections in real networks often experience varying degrees of congestion, making uniform control strategies insufficient.

3 Preliminary Experiment and Problem Identification

In this study, a road network model (Fig. 1) was constructed, and an optimization method targeting average waiting time was applied to a real roadway. Because the model used a single lane per direction, manual traffic counts were performed to recalibrate the simulated demand. Two short observation periods recorded 123 and 116 vehicles over two signal cycles, and approximately 600 vehicles were generated for the 1800-second simulation.

The experimental results in Table 1 show that although average travel time (ATT) improved, average waiting time and maximum queue length did not, and in some cases worsened. This indicates that ATT alone cannot represent local congestion; corridor-level performance may improve while delays at specific intersections remain unresolved.

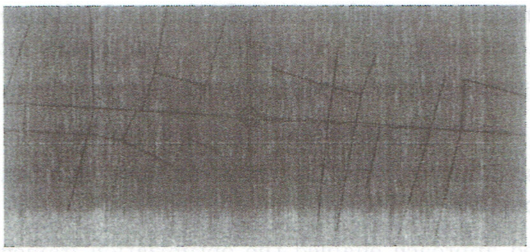

Figure 1: Road network model used for the preliminary experiment (schematic placeholder).

Table 1: Comparison of traffic performance metrics before and after ATT optimization

Metric	Baseline	Optimized Result
Average travel time (s)	334.57	191.84
Average speed (m/s)	1.18	1.75
Average waiting time (s)	186.48	210.40
Number of completed trips	262	246
Maximum queue length	213	245

We believe the reason for this phenomenon is as follows: ATT is a network-level average metric that reflects overall performance but fails to capture localized congestion [4]. As a result, the optimization algorithm is unable to specifically target heavily congested intersections. Consequently, segments that are already uncongested may become even smoother, while intersections that are truly congested continue to experience significant delays.

4 Objective of the Study

In response to the limitations of single-objective optimization, the purpose of this study is to develop a traffic signal optimization system capable of:

1. Enhancing overall traffic performance.
2. Mitigating congestion at critical intersections.
3. Handling multiple performance metrics simultaneously.
4. Ensuring balanced evaluation across heterogeneous intersections.

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) was selected for this study because of the suitability for multi-objective optimization and it have ability to generate a diverse set of Pareto-optimal solutions.

5 Application of NSGA-II to Signal Control

NSGA-II [5] evaluates candidate solutions across multiple objectives and identifies non-dominated solutions representing different performance trade-offs. Instead of producing a single "best" configuration, the algorithm yields a set of solutions balancing competing objectives. In this study, different control strategies were applied depending on the congestion level of each intersection:

- Congested intersections: optimization focused on split to reallocate green time.
- Non-congested intersections: optimization targeted offset to enhance progression along the corridor.

This differentiated approach enabled the optimization framework to adapt to the distinct needs of each intersection.

6 Overall Framework of the Proposed Optimization System

Figure 2 presents the workflow of the proposed NSGA-II and SUMO [6] integrated optimization framework. The process begins with importing the road network and vehicle demand data. An initial population of signal control parameters is generated, and each candidate is evaluated through TraCI-based [7] interaction with SUMO. SUMO runs the traffic simulation and returns key performance indicators such as delay, speed, and queue length.

Based on these outputs, congestion levels at each intersection are identified. Split optimization is applied to congested intersections, while offset optimization is used for uncongested ones. The intersection-level metrics are then aggregated into a unified objective function for fair evaluation across the entire corridor.

NSGA-II performs non-dominated sorting, updates the Pareto front, and generates new individuals through elitism and reproduction. This iterative cycle continues until convergence, producing a set of balanced, Pareto-optimal signal control solutions.

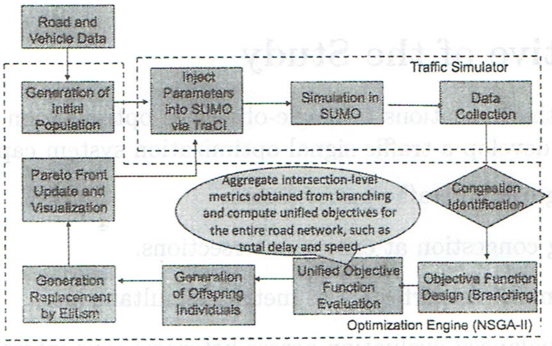

Figure 2: Workflow of the proposed NSGA-II–SUMO integrated traffic signal optimization framework (schematic placeholder).

7 Evaluation of Candidate Objective Metrics

The road network used in this experiment is shown in Figure 3. It consists of a single four-leg intersection. At this intersection, only the green-time split was optimized, and the results are summarized in Table 2.

The findings indicate the following:

- Average speed and average waiting time both exhibited stable and consistent optimization outcomes, with no significant random fluctuations.
- Maximum queue length varied considerably and was highly sensitive to small changes in traffic demand, making it unreliable as an optimization objective.Throughput (the number of vehicles completing their trips) showed only a weak relationship with signal timing adjustments and was therefore unsuitable as an objective [8].

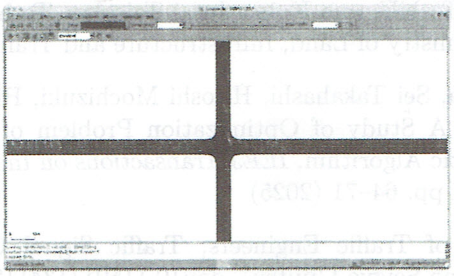

Figure 3: Single-intersection SUMO simulation model used for objective evaluation (schematic placeholder).

Table 2: Experimental results of split optimization at a single four-leg intersection

	Trial 1			Trial 2		
Metric	Baseline	Optimized	Improvement	Baseline	Optimized	Improvement
Average speed (m/s)	6.931	7.298	5.30%	6.724	7.041	4.72%
Average waiting time (s)	98.095	86.690	11.53%	99.732	81.846	17.93%
Maximum queue length	26	24	7.69%	24	25	−4.17%
Throughput	0.9237	0.9275	0.41%	0.9163	0.9363	2.18%

Between average speed and average waiting time, the optimization effect was more substantial for average waiting time, indicating that it is more responsive to changes in signal timing and more accurately reflects congestion reduction. Consequently, average waiting time was selected as the primary objective for evaluating congestion [9].

8 Future Work

Future research will focus on developing a unified objective function capable of evaluating all candidate solutions fairly, regardless of where congestion occurs or how severely each intersection is affected. Because different individuals generate congestion at different locations with varying intensities, NSGA-II requires a consistent evaluation standard to enable meaningful comparison during non-dominated sorting[10].

To achieve this, future work will construct an objective formulation that integrates both the location and the severity of congestion across the entire corridor. Each intersection will be assigned an appropriate weight that reflects its typical congestion impact, and the weighted sum of congestion metrics will be used to produce a unified performance measure for each individual[11].

This unified objective design will allow the optimization framework to assess heterogeneous intersections in a consistent manner, improving the robustness and fairness of multi-objective optimization results.

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