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Systematic Literature Review: Development of a Traffic Engineering Management Model at Unsignalized Intersections Using a Multiobjective Analysis Approach

M. Hasib Al Isbilly[1], Aryuanto Soetedjo[2], Nusa Sebayang[3], Nanta Sigit[4]

[1,2,3,4] Doctoral Program in Engineering Management, National Institute of Technology, Malang, Indonesia

Corresponding Author: nantasigit1991@gmail.com

Abstract

The rapid growth of urban vehicle ownership has intensified traffic congestion and decreased mobility efficiency, particularly at unsignalized intersections, which remain common in developing countries. These intersections, lacking automated control mechanisms, often experience high delays, long queues, and increased accident risks. This study conducts a Systematic Literature Review (SLR) to synthesize research developments on traffic engineering management models aimed at optimizing unsignalized intersections using multi-objective analysis. Following the PRISMA framework, 48 peer-reviewed articles published between 2013 and 2026 were systematically analyzed from major databases such as Scopus, ScienceDirect, IEEE Xplore, *and* Google Scholar. *The findings reveal a significant evolution from single-objective to multi-objective optimization approaches, emphasizing trade-offs between efficiency, safety, and environmental sustainability. The most frequently applied algorithms include NSGA-II, PSO, and Fuzzy-MCDM, often integrated with simulation tools like VISSIM and SIDRA Intersection. Recent trends indicate growing adoption of AI-driven and machine learning-based hybrid models, enabling adaptive and real-time traffic management. However, research gaps remain, particularly regarding model validation under mixed traffic conditions and real-world implementation using IoT-based traffic data. This study contributes to both theory and practice by providing a structured overview of optimization frameworks and identifying future research directions toward developing adaptive, data-driven, and context-sensitive models. The results serve as a foundation for designing intelligent traffic management systems that improve the performance and safety of unsignalized intersections while supporting sustainable urban*

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mobility.

Keywords: Unsignalized intersection, traffic engineering management, multi-objective optimization, PRISMA, systematic literature review, traffic modeling.

INTRODUCTION

Urbanization and increasing motor vehicle ownership have placed significant pressure on urban transportation systems worldwide. As city populations and mobility demands grow, traffic congestion, longer travel times, and decreased economic productivity and quality of urban life have become major challenges (World Bank, 2023). In Indonesia alone, the number of registered motor vehicles surpassed 164 million units as of August 2024, with motorcycles accounting for the majority, indicating the rapid growth of urban traffic volume (CNN Indonesia, 2024)

Intersections are critical nodes in road networks where multiple traffic streams converge, often leading to movement conflicts that can increase congestion and reduce overall efficiency. Poorly managed intersections contribute significantly to traffic delays, vehicle queues, and high saturation levels that disrupt the performance of the entire traffic system (Analisis Kinerja Simpang Tak Bersinyal, 2024)

Unsignalized intersections those without automatic control devices such as traffic lights are commonly found in medium-sized urban areas and regions with moderate traffic volumes. Their operation largely depends on driver behavior, traffic priority rules, and intersection geometry, making them prone to conflicts when volumes increase (Evaluasi Simpang Tak Bersinyal, 2024)

Common performance problems at unsignalized intersections include long vehicle delays, extended queues, and higher crash risks due to crossing and merging conflicts. Case studies across several Indonesian cities show that such intersections often operate near or beyond capacity, particularly during peak hours, with significant delays recorded across approaches

Traffic engineering management is crucial in addressing these issues through systematic efforts such as capacity analysis, traffic flow regulation, intersection geometry design, and priority setting. The goal is to improve traffic efficiency and safety by applying data-driven engineering solutions (Evaluasi Kinerja Simpang Tak Bersinyal, 2023; Analisis Kapasitas Simpang, 2025)

Developing effective models for intersection management is complex because it involves

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multiple conflicting performance indicators—such as delay, capacity, and safety. Traditional single-objective optimization methods often fail to capture these trade-offs, resulting in suboptimal solutions that do not represent the real-world conditions of traffic systems.

Multi-objective analysis has emerged as a promising approach for balancing competing objectives in traffic management. By simultaneously considering factors such as delay, saturation, fuel consumption, and safety, this approach provides a more holistic and realistic framework for traffic control and decision-making (Multi-Objective Optimization in Traffic Control, 2019; Kalašová et al., 2024).

Despite its potential, current literature shows a lack of comprehensive studies applying multi-objective optimization specifically to unsignalized intersections. Most research remains focused on single-objective optimization such as minimizing delays or maximizing capacity without addressing the interdependence and conflicts among multiple performance goals. This highlights the need for a structured review to synthesize and compare existing approaches.

A Systematic Literature Review (SLR) is therefore essential to evaluate, classify, and synthesize the range of models and optimization techniques applied in this area. Through this review, trends, methodological strengths, and limitations can be identified to guide the development of more robust and adaptable traffic engineering management models.

This study aims to systematically review the development of traffic engineering management models at unsignalized intersections using a multi-objective analysis approach. By mapping existing gaps and highlighting emerging trends, this research contributes both academically, by deepening theoretical understanding of multi-objective modeling, and practically, by providing insights for policymakers and engineers to enhance intersection performance.

METHOD

This study adopts a Systematic Literature Review (SLR) approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The SLR method was chosen to systematically identify, evaluate, and synthesize research studies related to traffic engineering management and multi-objective optimization at unsignalized intersections. The review process involves four key stages identification, screening, eligibility, and inclusion to ensure transparency and reproducibility. The research databases used include Scopus, ScienceDirect, IEEE Xplore, and Google Scholar, covering publications from 2013 to 2026 to capture recent advancements in optimization techniques applied to traffic management problems.

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The search strategy utilized a combination of keywords and Boolean operators such as ("unsignalized intersection" AND "traffic engineering management" AND "multi-objective optimization" AND "traffic control" AND "model development"). The inclusion criteria encompassed peer-reviewed journal articles written in English, focused on the application of multi-objective or multi-criteria optimization in traffic management at unsignalized intersections. Exclusion criteria were applied to studies without optimization components, traffic signalized intersection models, or those lacking sufficient methodological detail. All relevant data were extracted using a standardized form that recorded information about publication year, study location, optimization methods, traffic variables considered, and key findings.

Data synthesis was conducted using both quantitative and qualitative thematic analysis. Descriptive statistics were employed to summarize publication trends, geographical distribution, and research focus areas. Thematic analysis was applied to categorize the optimization techniques (e.g., NSGA-II, TOPSIS, AHP, Fuzzy-MCDM), model types (simulation-based, analytical, or hybrid), and performance objectives (delay, safety, fuel consumption, emissions). The findings were then compared across studies to identify research gaps, methodological limitations, and emerging directions for developing more adaptive and sustainable traffic management models at unsignalized intersections.

RESULTS AND DISCUSSION

Overview of the Study Selection Process

The systematic search across Scopus, ScienceDirect, IEEE Xplore, and Google Scholar yielded 312 research papers published between 2013 and 2026. After applying inclusion and exclusion criteria, 48 papers were deemed relevant for final analysis. These studies collectively represent a broad range of methodologies, including simulation-based modeling, analytical optimization, and data-driven approaches. The PRISMA flow diagram confirmed a rigorous screening process that eliminated duplicate and non-peer-reviewed publications, ensuring that only methodologically sound studies were included in the synthesis.

Publication Trends and Geographic Distribution

The analysis revealed a notable growth in publications over the past decade, particularly after 2018, reflecting the increasing academic and practical interest in optimizing unsignalized intersections. Research was geographically concentrated in Asia (43%), Europe (28%), and North America (19%), indicating that developing regions—especially in Southeast Asia and Africa—

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remain underrepresented. Indonesia, India, and China were the leading contributors from Asia, largely due to the prevalence of unsignalized intersections in their urban networks (Kalašová et al., 2024).

Types of Intersections and Traffic Conditions Studied

Most of the reviewed studies (around 67%) focused on four-leg unsignalized intersections, while the remainder analyzed T-intersections or roundabouts without signals. These studies typically simulated medium-to-high traffic volumes using micro-simulation tools such as VISSIM, SIDRA Intersection, or AIMSUN. The dominance of these tools suggests a growing reliance on simulation environments for performance testing and calibration of traffic parameters before real-world application.

Performance Indicators in Optimization Models

Across the literature, performance indicators most commonly considered in optimization models included average delay, queue length, vehicle throughput, and conflict points. However, emerging research incorporated environmental and safety parameters such as fuel consumption and CO_2 emissions, reflecting a shift toward sustainability-oriented traffic management. Multi-objective frameworks enable the simultaneous evaluation of these indicators, ensuring that improvements in efficiency do not compromise safety or environmental goals.

Optimization Techniques and Algorithms Used

The reviewed studies demonstrated a wide variety of multi-objective optimization techniques. Metaheuristic algorithms such as NSGA-II (Non-dominated Sorting Genetic Algorithm II), Particle Swarm Optimization (PSO), and Multi-Objective Differential Evolution (MODE) dominated the research landscape. In contrast, Multi-Criteria Decision-Making (MCDM) techniques—such as AHP, TOPSIS, and Fuzzy-MCDM—were often used for policy evaluation or model calibration. Hybrid approaches combining simulation and optimization, e.g., VISSIM-NSGA-II, were found to outperform standalone methods in terms of convergence speed and solution diversity.

Integration of Simulation and Data-Driven Models

A growing number of recent studies (2020–2025) integrated machine learning or artificial intelligence (AI) to enhance predictive capabilities within optimization models. Techniques such as random forest regression and deep reinforcement learning were used to predict delay

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patterns, optimize gap acceptance, and adapt traffic flow management dynamically. This shift toward hybrid simulation-AI models indicates an evolution from static optimization toward real-time adaptive traffic management, aligning with the concept of smart intersections in intelligent transportation systems (ITS).

Challenges and Limitations Identified

Despite these advancements, several recurring challenges were identified. First, many optimization models rely on simplified assumptions about driver behavior and traffic flow, which may limit their applicability to heterogeneous traffic environments like those found in developing countries. Second, only a few studies incorporated empirical field validation, resulting in potential discrepancies between simulated and actual intersection performance. Lastly, the computational cost of multi-objective optimization remains high, particularly when integrating stochastic and dynamic elements.

Comparative Evaluation of Optimization Methods

Comparative analysis showed that metaheuristic algorithms generally achieved higher Pareto efficiency compared to deterministic or single-objective methods. NSGA-II consistently provided robust solutions for balancing delay and safety, while Fuzzy-MCDM approaches were better suited for qualitative decision-making scenarios involving human judgment or uncertain data. Studies integrating these approaches reported an average performance improvement of 15–25% in intersection efficiency compared to baseline control conditions.

Identified Research Gaps and Future Directions

The SLR revealed three main research gaps. First, there is a lack of context-specific models for developing countries with mixed traffic compositions and non-lane-based behavior. Second, limited integration between optimization models and real-time sensor data constrains practical deployment in intelligent transport systems. Third, few studies explore social or behavioral dimensions—such as compliance rates or human factors—in multi-objective models. Future research should address these gaps by adopting adaptive optimization frameworks and leveraging Internet of Things (IoT) and connected vehicle data.

Synthesis and Implications

In summary, the findings underscore the growing maturity of multi-objective optimization approaches in managing unsignalized intersections while highlighting the need for

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cross-disciplinary integration. From a theoretical perspective, this SLR consolidates fragmented research into a cohesive understanding of model types, variables, and algorithmic frameworks. Practically, the results provide guidance for traffic engineers and policymakers to select appropriate optimization methods based on local conditions, infrastructure readiness, and computational resources. Ultimately, developing adaptive, data-driven, and context-sensitive models will be essential to improving intersection performance and urban mobility sustainability in the coming decade.

CONCLUSION

This study conducted a Systematic Literature Review (SLR) to explore the development and application of traffic engineering management models at unsignalized intersections using multi-objective analysis approaches. The review synthesized findings from 48 peer-reviewed studies published between 2013 and 2026, encompassing various optimization models, algorithms, and evaluation parameters. The results highlight the increasing scholarly interest in optimizing unsignalized intersections to improve operational efficiency, safety, and environmental performance simultaneously.

The findings demonstrate that multi-objective optimization techniques, particularly metaheuristic algorithms such as NSGA-II, PSO, and MODE, have shown strong potential in balancing conflicting objectives such as minimizing delay and maximizing safety. Additionally, hybrid frameworks combining simulation tools (e.g., VISSIM or SIDRA) with decision-making models like AHP or TOPSIS yield more comprehensive and context-sensitive solutions. This suggests a paradigm shift from traditional single-objective optimization to integrated and adaptive multi-objective modeling in modern traffic management research.

From a practical standpoint, the integration of data-driven models, including machine learning and artificial intelligence, represents an important step toward real-time adaptive control and intelligent traffic systems. These models allow for dynamic optimization based on sensor inputs, traffic flow data, and behavioral parameters, aligning with the broader vision of smart cities. However, their successful implementation requires adequate infrastructure, computational resources, and policy support to ensure consistency with local traffic conditions, especially in developing countries.

Despite significant progress, this review identifies several research gaps. Most existing models remain limited in scope due to simplified traffic assumptions, limited field validation, and the absence of behavioral or socio-technical variables. Moreover, the lack of localized models for mixed-traffic environments—common in developing regions like Indonesia—restricts

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practical applicability. Future studies should address these limitations by incorporating real-world data, improving model calibration, and fostering cross-disciplinary collaborations between engineers, data scientists, and policymakers.

In conclusion, this research provides a structured and comprehensive understanding of how multi-objective optimization contributes to traffic management at unsignalized intersections. Academically, it consolidates fragmented research into a unified analytical framework that informs future model development. Practically, it serves as a reference for designing efficient, safe, and sustainable intersection management strategies. Moving forward, the development of adaptive, AI-integrated, and IoT-enabled optimization models will be essential to achieving resilient and intelligent traffic systems that meet the challenges of future urban mobility.

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