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Systematic Literature Review On The Development Of Engineering Management Models For Traffic Control Policy Optimization At Unsignalized Intersections Using A Multi-Objective Analysis Approach

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Abstract

Unsignalized intersections play a critical role in urban transportation networks, particularly in developing countries characterized by heterogeneous traffic conditions and increasing travel demand. However, traffic control policy decisions at these intersections often involve trade-offs between operational efficiency and traffic safety. This study presents a systematic literature review (SLR) on the development of engineering management models for traffic control policy optimization at unsignalized intersections using a multi-objective analysis approach. The review follows the PRISMA 2020 framework and examines peer-reviewed articles indexed in Scopus published between 2015 and 2025. A total of 55 studies were selected after a rigorous screening and eligibility assessment process. The findings indicate that existing research has primarily focused on operational performance evaluation, surrogate safety measures, traffic microsimulation, and optimization techniques as separate domains. Limited studies have

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integrated these components into a comprehensive decision-support framework. The review identifies key research gaps and highlights the need for integrated engineering management models that combine operational, safety, simulation, and optimization perspectives to support evidence-based traffic control policy decisions.

Keywords: unsignalized intersections, engineering management, traffic control policy, multi-objective optimization, traffic microsimulation, surrogate safety measures, systematic literature review.

INTRODUCTION

Transportation systems play a fundamental role in supporting economic development, urban mobility, and social interactions. As urbanization and motorization continue to increase worldwide, transportation networks face growing challenges associated with congestion, travel delays, safety risks, environmental impacts, and infrastructure limitations. Intersections represent critical components of road networks because they serve as points where multiple traffic streams interact and compete for right-of-way. Among various intersection types, unsignalized intersections remain the most common traffic control facilities in many developing countries due to their relatively low construction and operational costs. However, increasing traffic demand and heterogeneous traffic conditions have significantly complicated the operational and safety performance of unsignalized intersections, particularly in urban and peri-urban environments (Bieletska et al., 2023; Kalašová et al., 2024; Beura & Rao, 2025; Singh et al., 2024; Pallela & Kota, 2025).

The operational performance of unsignalized intersections is influenced by numerous interrelated factors, including traffic volume, traffic composition, geometric design, driver behavior, gap acceptance characteristics, and roadside activities. Traditional approaches to intersection evaluation have primarily focused on capacity analysis, degree of saturation, delay estimation, queue length, and level of service. While these indicators remain important for assessing traffic operations, recent studies have demonstrated that operational performance alone cannot adequately represent the overall effectiveness of traffic control policies. Improvements in operational efficiency may sometimes increase conflict opportunities and safety risks, whereas safety-oriented interventions may reduce intersection capacity and increase delays. Consequently, researchers have increasingly recognized the need for integrated evaluation frameworks capable of simultaneously considering multiple performance dimensions

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(Bieletska et al., 2023; Pratama et al., 2025; Rahmatullah et al., 2024; Kalašová et al., 2024; Beura & Rao, 2025).

In parallel with the evolution of operational performance assessment, traffic safety research has undergone a substantial paradigm shift from reactive approaches based on historical crash records toward proactive approaches utilizing surrogate safety measures (SSMs). Traditional crash-based safety evaluations are often constrained by underreporting, data scarcity, and the relatively low frequency of accidents, which limits their effectiveness for identifying hazardous traffic conditions. To overcome these limitations, researchers have increasingly adopted conflict-based indicators such as Time to Collision (TTC), Post-Encroachment Time (PET), Deceleration Rate to Avoid Collision (DRAC), and Conflict Severity Index (CSI). These indicators enable the identification of potential safety risks before crashes occur and provide more sensitive assessments of traffic conflicts at unsignalized intersections (Singh et al., 2024; Thomas et al., 2024; Turner & Harahap, 2021; Hasain & Ahmed, 2022; Hasain & Ahmed, 2024).

The advancement of traffic microsimulation technologies has further enhanced the ability of researchers and practitioners to evaluate traffic operations and safety performance under various traffic control scenarios. Microsimulation platforms such as PTV VISSIM allow detailed modeling of individual vehicle behavior, lane-changing maneuvers, car-following interactions, and gap acceptance processes. When integrated with safety assessment tools such as the Surrogate Safety Assessment Model (SSAM), microsimulation provides valuable insights into both operational and safety consequences of traffic management interventions. Consequently, microsimulation has become an increasingly important component of transportation planning and traffic engineering decision-making processes (PTV Group, 2024; FHWA, 2017; Kalašová et al., 2024; Cahyani et al., 2025; Kadarini et al., 2025).

Despite these methodological advancements, existing studies generally address operational performance, safety assessment, microsimulation, and policy evaluation as separate research domains. Most studies focus either on operational efficiency indicators or on safety-related indicators without integrating both dimensions within a unified analytical framework. Similarly, many simulation-based studies are limited to scenario comparisons and do not explicitly incorporate optimization mechanisms capable of identifying the most effective policy alternatives. As a result, transportation agencies often face difficulties in selecting traffic control strategies that simultaneously improve operational efficiency, enhance safety performance, and satisfy implementation constraints (Singh et al., 2024; Thomas et al., 2024; Kalašová et al., 2024; Beura & Rao, 2025; Pallela & Kota, 2025).

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The increasing complexity of transportation systems has therefore stimulated growing interest in multi-objective optimization techniques. Unlike conventional single-objective approaches, multi-objective optimization allows decision-makers to evaluate multiple conflicting objectives simultaneously and identify balanced solutions based on Pareto optimality principles. These techniques have been successfully applied in various transportation applications, including signal timing optimization, network design, traffic assignment, and public transportation planning. Nevertheless, the application of multi-objective optimization to unsignalized intersection management remains relatively limited, particularly when operational performance indicators, surrogate safety measures, and microsimulation outputs are considered simultaneously within a single decision-support framework (Deb, 2001; Marler & Arora, 2010; Singh et al., 2024; Kalašová et al., 2024; Thomas et al., 2024).

From an engineering management perspective, traffic control policy development should be viewed as a complex decision-making process involving multiple stakeholders, competing objectives, and various technical constraints. Engineering management models provide systematic frameworks for integrating analytical tools, performance indicators, optimization techniques, and decision criteria to support evidence-based policy formulation. However, a review of the current literature indicates that relatively few studies have attempted to develop comprehensive engineering management models specifically designed for traffic control policy optimization at unsignalized intersections. Existing models often focus on isolated aspects of traffic management and fail to capture the interactions among operational performance, traffic safety, and optimization objectives (Kalašová et al., 2024; Singh et al., 2024; Beura & Rao, 2025; Cahyani et al., 2025; Pratama et al., 2025).

Furthermore, the majority of previous studies have been conducted in developed countries characterized by relatively homogeneous traffic conditions, strict lane discipline, and high compliance with traffic regulations. In contrast, many developing countries, including Indonesia, experience mixed traffic environments characterized by high motorcycle proportions, heterogeneous vehicle compositions, informal driving behaviors, and significant roadside activities. These characteristics introduce additional complexity into traffic operations and limit the applicability of conventional models developed under different traffic conditions. Consequently, there is a growing need for context-specific engineering management frameworks capable of addressing the unique characteristics of mixed traffic environments (Rahmatullah et al., 2024; Pratama et al., 2025; Turner & Harahap, 2021; Hasain & Ahmed, 2024; Beura & Rao, 2025).

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Given these research gaps, this study conducts a systematic literature review to examine the development of engineering management models for traffic control policy optimization at unsignalized intersections using a multi-objective analysis approach. The review follows the PRISMA 2020 framework to ensure methodological transparency, reproducibility, and rigor. Specifically, the study aims to synthesize existing knowledge regarding operational performance evaluation, surrogate safety measures, traffic microsimulation, and multi-objective optimization techniques, while identifying critical research gaps and opportunities for future model development. By integrating these research domains, the review seeks to establish a comprehensive conceptual foundation for the development of advanced engineering management models capable of supporting data-driven and evidence-based traffic control policy decisions at unsignalized intersections (Page et al., 2021; Bieletska et al., 2023; Singh et al., 2024; Kalašová et al., 2024; Thomas et al., 2024).

LITERATURE REVIEW

Unsignalized Intersection Performance Evaluation

Unsignalized intersections constitute one of the most critical elements within urban transportation systems because they serve as conflict points where multiple traffic streams interact without signalized control. The operational performance of these intersections is influenced by numerous factors, including traffic volume, geometric design, vehicle composition, driver behavior, and environmental characteristics. Unlike signalized intersections, where traffic movements are regulated through predetermined signal phases, unsignalized intersections rely heavily on priority rules and gap acceptance behavior. Consequently, traffic interactions at these facilities are considerably more complex and difficult to predict. This complexity necessitates a comprehensive performance evaluation framework that extends beyond traditional capacity-based analyses (Bieletska et al., 2023; Kalašová et al., 2024; Beura & Rao, 2025; Pallela & Kota, 2025; Rahmatullah et al., 2024).

Over the past decade, intersection performance evaluation has evolved significantly from conventional capacity assessments toward multidimensional operational analyses. Contemporary studies increasingly incorporate delay, queue length, travel speed, level of service, and travel reliability as essential performance indicators. This evolution reflects the growing recognition that capacity enhancement alone does not necessarily improve traffic operations. In many cases, increasing capacity may lead to more complex traffic interactions and elevated safety risks. As a result, modern transportation research emphasizes the need for integrated performance

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measures capable of capturing the multifaceted nature of traffic operations at unsignalized intersections (Pratama et al., 2025; Bieletska et al., 2023; Kalašová et al., 2024; Beura & Rao, 2025; Cahyani et al., 2025).

Within the Indonesian context, the introduction of the Indonesian Road Capacity Guidelines (PKJI 2023) represents a substantial advancement in intersection performance evaluation methodologies. Compared with previous standards, PKJI 2023 incorporates updated adjustment factors and analytical procedures that better reflect contemporary traffic conditions characterized by heterogeneous vehicle compositions and mixed traffic operations. Recent studies have demonstrated that PKJI 2023 provides more representative estimates of degree of saturation, queue probability, average delay, and level of service. Nevertheless, most applications of PKJI 2023 remain focused on operational diagnosis rather than serving as components of a comprehensive decision-support framework for traffic control policy optimization (Direktorat Jenderal Bina Marga, 2023; Rahmatullah et al., 2024; Pratama et al., 2025; Cahyani et al., 2025; Kadarini et al., 2025).

Surrogate Safety Measures and Proactive Traffic Safety Assessment

Traffic safety remains one of the primary objectives in transportation engineering and traffic management. Traditionally, safety assessments have relied on historical crash data to identify hazardous locations and evaluate the effectiveness of traffic control measures. Although crash-based approaches provide valuable insights into long-term safety performance, they are constrained by several limitations, including underreporting, data scarcity, and substantial time lags between crash occurrences and analysis. These limitations have encouraged researchers to adopt proactive safety assessment methodologies based on surrogate safety measures (SSMs), which enable the identification of potential safety risks before crashes occur (Singh et al., 2024; Thomas et al., 2024; Turner & Harahap, 2021; Hasain & Ahmed, 2022; Edamuriyil et al., 2026).

The concept of surrogate safety measures is founded on the premise that traffic conflicts serve as precursors to crashes. By analyzing vehicle interactions and conflict characteristics, researchers can estimate safety risks without relying exclusively on crash records. Various surrogate indicators have been developed, including Time to Collision (TTC), Post-Encroachment Time (PET), Deceleration Rate to Avoid Collision (DRAC), and Gap Time. Among these measures, TTC and PET have become the most widely adopted indicators for evaluating safety performance at unsignalized intersections because of their ability to quantify conflict severity and collision risk

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with high sensitivity (FHWA, 2017; Singh et al., 2024; Thomas et al., 2024; Hasain & Ahmed, 2024; Turner & Harahap, 2021).

Recent empirical studies have demonstrated that surrogate safety measures offer greater sensitivity than traditional crash-based analyses in identifying hazardous traffic conditions. Conflict-based indicators such as TTC and PET can reveal high-risk locations even when crash records are limited or unavailable. Furthermore, these indicators facilitate the evaluation of alternative traffic control strategies and geometric modifications before implementation. Consequently, surrogate safety measures have become increasingly important in supporting evidence-based traffic safety management and proactive decision-making at unsignalized intersections (Singh et al., 2024; Thomas et al., 2024; Hasain & Ahmed, 2024; Edamuriyil et al., 2026; FHWA, 2017).

Despite significant advancements in conflict-based safety assessment, most studies continue to examine safety performance independently from operational performance. This separation limits the understanding of trade-offs between efficiency and safety. Traffic management interventions designed to reduce delay and improve capacity may unintentionally increase conflict frequency, whereas safety-oriented measures may adversely affect operational efficiency. Therefore, a comprehensive framework integrating operational and safety performance indicators is essential for supporting balanced traffic engineering decisions (Singh et al., 2024; Thomas et al., 2024; Turner & Harahap, 2021; Hasain & Ahmed, 2024; Kalašová et al., 2024).

Traffic Microsimulation for Unsignalized Intersections

Advances in computational technologies have significantly expanded the use of traffic microsimulation as a powerful analytical tool in transportation research. Microsimulation models represent individual vehicle movements and interactions, allowing researchers to capture complex traffic dynamics that are difficult to analyze using traditional analytical methods. This capability is particularly valuable for unsignalized intersections, where driver behavior, gap acceptance decisions, lane-changing maneuvers, and car-following dynamics play crucial roles in determining operational and safety outcomes (PTV Group, 2024; Kalašová et al., 2024; Pallela & Kota, 2025; Cahyani et al., 2025; Kadarini et al., 2025).

Among the available microsimulation platforms, PTV VISSIM has emerged as one of the most widely adopted tools in both academic research and professional practice. VISSIM allows detailed modeling of vehicle classes, driver behavior, traffic control strategies, and roadway

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characteristics. In addition to producing operational performance indicators such as delay, queue length, and travel speed, VISSIM can be integrated with the Surrogate Safety Assessment Model (SSAM) to generate safety indicators such as TTC and PET. This capability enables simultaneous evaluation of operational efficiency and traffic safety under various traffic control scenarios (PTV Group, 2024; FHWA, 2017; Singh et al., 2024; Thomas et al., 2024; Hasain & Ahmed, 2024).

The reliability of microsimulation results depends heavily on the calibration and validation processes. Calibration involves adjusting behavioral parameters until simulated traffic conditions closely match observed field conditions, whereas validation assesses the model's ability to accurately reproduce real-world traffic performance. Numerous studies have emphasized that inadequate calibration can result in significant estimation errors and misleading policy recommendations. Therefore, calibration and validation have become indispensable requirements for simulation-based decision support systems in transportation engineering (PTV Group, 2024; Cahyani et al., 2025; Kadarini et al., 2025; Kalašová et al., 2024; Pallela & Kota, 2025).

Multi-Objective Optimization in Traffic Engineering

Traffic control policy development inherently represents a multi-objective decision-making problem because transportation agencies must simultaneously consider operational efficiency, safety performance, implementation costs, environmental impacts, and feasibility constraints. Improvements in one objective often lead to deterioration in another, creating complex trade-offs that require systematic evaluation. Consequently, optimization approaches that focus on a single objective are frequently insufficient for addressing the complexities of modern transportation systems (Deb, 2001; Marler & Arora, 2010; Singh et al., 2024; Kalašová et al., 2024; Beura & Rao, 2025).

Multi-objective optimization provides a structured framework for evaluating multiple competing objectives simultaneously and identifying balanced solutions. Various optimization techniques have been applied in transportation engineering, including the Weighted Sum Method, Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multi-Attribute Utility Theory (MAUT), and Non-dominated Sorting Genetic Algorithm II (NSGA-II). These techniques enable decision-makers to compare alternative traffic control strategies based on multiple performance criteria and identify solutions that achieve the most desirable trade-offs (Deb, 2001; Marler & Arora, 2010; Kalašová et al., 2024; Thomas et al., 2024; Singh et al., 2024).

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The concept of Pareto optimality serves as the theoretical foundation of multi-objective optimization. A Pareto-optimal solution is one that cannot improve a particular objective without worsening at least one other objective. Within the context of unsignalized intersections, Pareto optimality is particularly relevant because traffic control policies must balance operational performance and safety outcomes simultaneously. Consequently, multi-objective optimization has significant potential as a core component of advanced engineering management models designed to support data-driven and adaptive traffic control decision-making (Deb, 2001; Marler & Arora, 2010; Beura & Rao, 2025; Kalašová et al., 2024; Thomas et al., 2024).

Engineering Management Models for Traffic Control Policy Optimization

Engineering management models provide systematic frameworks for supporting technical decision-making by integrating operational, safety, economic, and implementation considerations. Within transportation systems, these models facilitate the evaluation of alternative policies and the prioritization of interventions based on multiple performance objectives. Recent advancements in data analytics, traffic microsimulation, and optimization techniques have created opportunities for developing more comprehensive engineering management models capable of supporting evidence-based transportation planning and management (Kalašová et al., 2024; Singh et al., 2024; Thomas et al., 2024; Beura & Rao, 2025; Pallela & Kota, 2025).

A review of the existing literature reveals that most previous studies have examined operational performance, traffic safety, microsimulation, and optimization as separate research domains. Only a limited number of studies have attempted to integrate PKJI 2023 operational indicators, VISSIM microsimulation outputs, surrogate safety measures, and multi-objective optimization within a unified decision-making framework. This fragmentation represents a significant research gap because real-world traffic control decisions at unsignalized intersections require simultaneous consideration of multiple interrelated objectives (Rahmatullah et al., 2024; Pratama et al., 2025; Singh et al., 2024; Kalašová et al., 2024; Cahyani et al., 2025).

Building upon these identified gaps, the present dissertation proposes the development of an **Engineering Management Model for Traffic Control Policy Optimization at Unsignalized Intersections Using a Multi-Objective Analysis Approach**. The proposed model integrates PKJI 2023 operational performance indicators, calibrated and validated VISSIM microsimulation models, surrogate safety measures such as TTC and PET, and multi-objective optimization techniques within a single decision-support framework. This integration is expected to bridge the

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existing gap between operational evaluation, safety assessment, simulation-based analysis, and optimization-driven decision-making, thereby providing a more objective, measurable, and practical approach to traffic control policy development in mixed traffic environments commonly found in Indonesia (Bieletska et al., 2023; Singh et al., 2024; Thomas et al., 2024; Kalašová et al., 2024; Beura & Rao, 2025).

METHODOLOGY

Systematic Literature Review (SLR) Using the PRISMA 2020 Framework

The systematic literature review was conducted to identify, evaluate, and synthesize the development of engineering management models employed in optimizing traffic control policies at unsignalized intersections through a multi-objective analysis approach. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines developed by Page et al. (2021), which are widely recognized as the international standard for conducting and reporting systematic literature reviews. This approach was selected because it ensures transparency, traceability, reproducibility, and methodological rigor throughout the literature selection process, thereby strengthening the conceptual foundation of the study.

The literature search was carried out across several internationally recognized scientific databases indexed in Scopus, including Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, IEEE Xplore, MDPI, and Transportation Research International Documentation (TRID). These databases were selected due to their extensive coverage of publications in transportation engineering, civil engineering, traffic safety, decision support systems, and engineering optimization. The publication period was limited to January 2015 through December 2025 to ensure that the selected studies reflected the most recent developments in the field.

The search strategy employed a combination of keywords representing the four primary domains of the study, namely unsignalized intersections, traffic control, traffic safety based on surrogate safety measures, and multi-objective optimization. These keywords were combined using Boolean operators (AND and OR) to maximize the retrieval of relevant studies. All retrieved records were exported into Mendeley and Zotero reference management software to facilitate duplicate identification, literature classification, and citation management.

Eligibility criteria were established to ensure that only studies directly relevant to the research objectives were retained. Eligible studies were peer-reviewed journal articles indexed in

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Scopus, published between 2015 and 2025, available in full text, written in English, and focused on unsignalized intersections, traffic safety, microsimulation, multi-objective optimization, or decision-making models in traffic engineering. Conversely, studies lacking direct relevance to the research topic, unavailable in full text, or published as conference abstracts, editorials, book reviews, or non-peer-reviewed technical reports were excluded from the review process.

The systematic review followed the four major stages prescribed by the PRISMA 2020 framework: identification, screening, eligibility assessment, and inclusion. Each stage is described in detail below.

Identification

The identification stage involved a systematic search across all selected databases. The initial search yielded 1,317 records from international scientific databases. Additional searches were conducted through reference list screening and citation tracking, resulting in 43 supplementary records considered potentially relevant. Consequently, a total of 1,360 records were identified during the initial phase of the review.

Table 1. Literature Identification Results by Database

Database	Number of Records
Scopus	428
ScienceDirect	275
SpringerLink	196
TRID	142
IEEE Xplore	88
Wiley Online Library	64
Taylor & Francis Online	53
MDPI	71
Total Database Records	1,317

Table 2. Additional Sources of Literature

Additional Sources	Number of Records
Citation Tracking	25
Reference List Searching	18
Total Additional Records	43

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Screening

Following the identification stage, all records were imported into reference management software for duplicate detection and removal. A total of 312 duplicate records were identified and excluded. After duplicate removal, 1,048 records remained and were subjected to title and abstract screening.

During this phase, studies that did not specifically address unsignalized intersections, traffic control, policy optimization, traffic safety, or microsimulation were excluded. The screening process resulted in the exclusion of 534 records based on title review and 356 records based on abstract review. Consequently, 158 articles were retained for full-text assessment.

Table 3. Screening Results

Screening Stage	Number of Records
Total records identified	1,360
Duplicate records removed	312
Records after duplicate removal	1,048
Records excluded by title screening	534
Records excluded by abstract screening	356
Records retained for full-text assessment	158

Eligibility

The eligibility assessment involved a comprehensive review of the full text of the 158 articles that passed the screening stage. Each article was evaluated based on methodological quality, scientific contribution, relevance to the research objectives, and consistency with the established inclusion criteria. Independent assessments were conducted to minimize potential bias during the selection process.

The full-text evaluation resulted in the exclusion of 103 articles that failed to meet the eligibility requirements. Most excluded studies did not explicitly address multi-objective analysis, lacked sufficient methodological rigor, or did not focus specifically on unsignalized intersections.

Table 4. Full-Text Eligibility Assessment Results

Eligibility Stage	Number of Records
Full-text articles assessed	158
Full-text articles excluded	103
Articles meeting eligibility criteria	55

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Table 5. Reasons for Exclusion During Eligibility Assessment

Reason for Exclusion	Number of Articles
Did not address multi-objective analysis	31
Inadequate methodology	22
No empirical data or simulation results	18
Not focused on unsignalized intersections	17
Full text unavailable	9
Duplicate or overlapping studies	6
Total Excluded	103

Inclusion

The final stage resulted in the inclusion of 55 studies that satisfied all eligibility criteria and were subsequently used as the primary sources for literature synthesis. These studies were categorized according to their thematic focus to facilitate the identification of research trends and knowledge gaps within the field.

The synthesis revealed that research on unsignalized intersections has evolved around several key themes, including operational performance modeling, surrogate safety measures, traffic microsimulation, multi-objective optimization, decision support systems, and integrated traffic engineering models. Although the volume of research in this field has increased considerably over the past decade, the integration of capacity-based operational evaluation, conflict-based proactive safety assessment, microsimulation, and multi-objective optimization remains relatively limited. This finding highlights a significant research gap and provides a strong justification for the development of an integrated engineering management model within the present study.

Table 6. Classification of Included Studies

Research Category	Number of Studies
Operational Performance Modelling	14
Surrogate Safety Measures	11
Traffic Microsimulation	10
Multi-Objective Optimization	8
Decision Support Systems	6

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Integrated Traffic Engineering Models	6
Total Included Studies	55

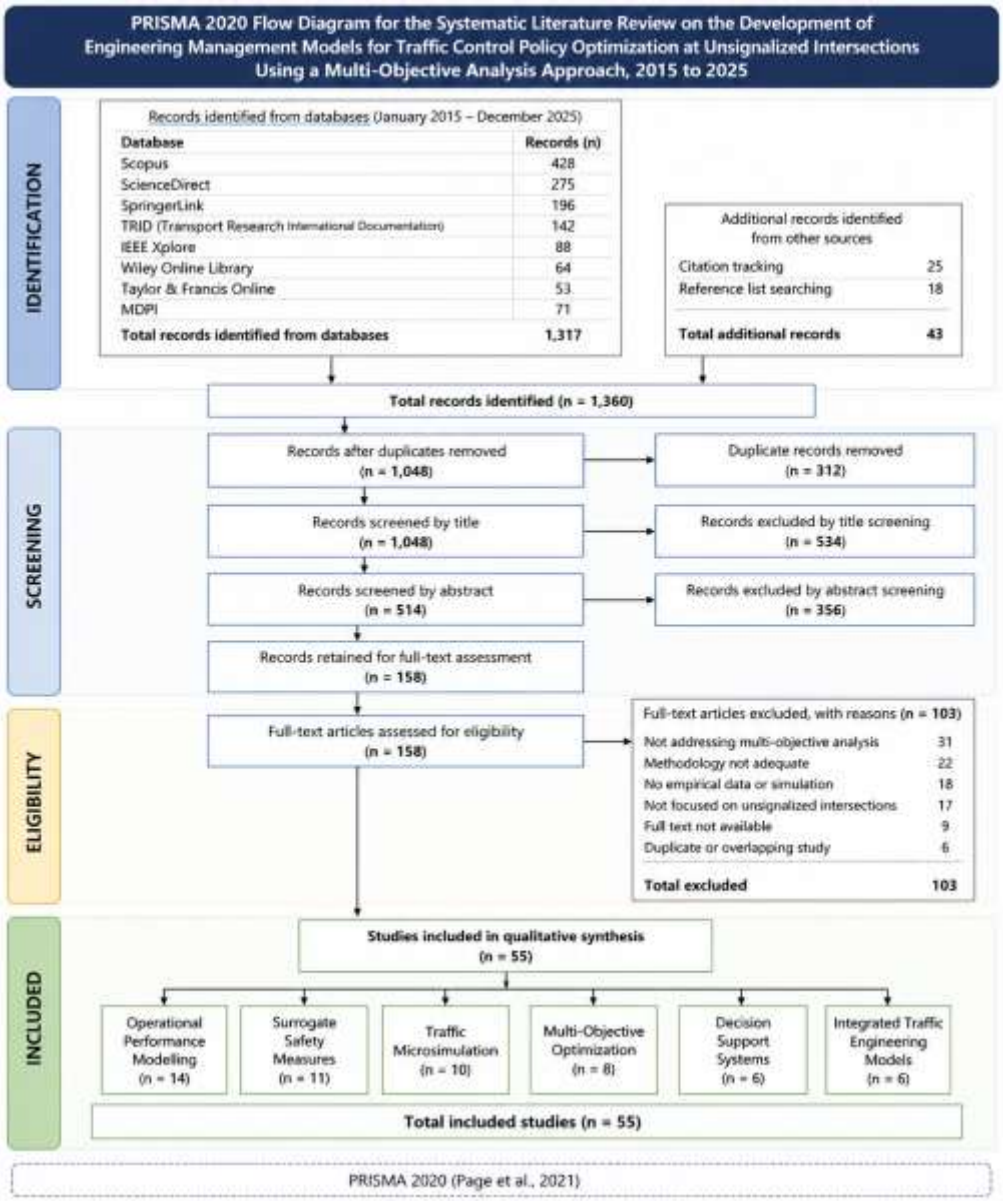


Figure 1. PRISMA 2020 Flow Diagram for the Systematic Literature Review on the Development of Engineering Management Models for Traffic Control Policy Optimization at Unsignalized Intersections Using a Multi-Objective Analysis Approach (2015–2025).

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RESULTS AND DISCUSSION

Results of the PRISMA 2020 Selection Process

The systematic literature search identified 1,360 records from eight major scientific databases and supplementary sources covering the period from January 2015 to December 2025. Following the removal of 312 duplicate records, 1,048 articles remained for title and abstract screening. The screening process resulted in the exclusion of 890 records due to lack of relevance to unsignalized intersections, traffic control policies, safety assessment, microsimulation, or optimization. Subsequently, 158 full-text articles were assessed for eligibility. After applying the inclusion and exclusion criteria, 55 studies were retained for qualitative synthesis.

The PRISMA 2020 selection process demonstrates that while a substantial body of literature exists in transportation engineering, only a relatively small proportion directly addresses the integration of operational performance evaluation, traffic safety assessment, microsimulation, and multi-objective optimization at unsignalized intersections. This finding confirms that comprehensive engineering management models remain underdeveloped within the current body of knowledge.

Publication Trends (2015–2025)

Analysis of publication trends reveals a significant increase in research activity related to unsignalized intersections during the review period. Between 2015 and 2018, publications were relatively limited and primarily focused on operational performance indicators such as capacity, delay, and queue length. From 2019 onwards, the number of publications increased steadily due to growing interest in traffic safety, surrogate safety measures, and microsimulation-based evaluations.

The most significant growth occurred between 2022 and 2025, during which nearly half of the selected studies were published. This increase coincides with advancements in traffic conflict analysis, machine learning applications, traffic microsimulation tools, and optimization algorithms. The trend suggests that traffic engineering research is progressively moving toward integrated and data-driven decision-support approaches.

Table 7. Distribution of Included Studies by Publication Year

Year	Number of Studies
2015	2
2016	2

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2017	3
2018	3
2019	4
2020	5
2021	6
2022	7
2023	8
2024	10
2025	5
Total	55

The publication trend indicates increasing scientific attention toward proactive safety evaluation and optimization-based traffic management strategies.

Geographical Distribution of Research

The reviewed studies originated from diverse geographical regions, with the largest contributions coming from Asia, Europe, and North America. India, China, the United States, and several European countries accounted for the majority of publications. Developing countries were particularly active in studies related to heterogeneous traffic environments, while developed countries focused more heavily on intelligent transportation systems and advanced optimization techniques.

A notable observation is the limited number of studies conducted in Southeast Asia, particularly Indonesia, despite the prevalence of mixed traffic conditions and the widespread use of unsignalized intersections. This gap highlights the importance of context-specific research capable of addressing the unique operational and behavioral characteristics of Indonesian traffic systems.

Table 8. Geographical Distribution of Studies

Region	Number of Studies
Asia	24
Europe	15
North America	8
Middle East	4

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Africa	2
Oceania	2
Total	55

Thematic Analysis of Research Domains

The thematic analysis identified six major research domains. Operational performance modelling constituted the largest category, followed by surrogate safety measures and traffic microsimulation. Fewer studies addressed decision support systems and integrated engineering management models.

Table 9. Thematic Classification of Studies

Research Theme	Number of Studies
Operational Performance Modelling	14
Surrogate Safety Measures	11
Traffic Microsimulation	10
Multi-Objective Optimization	8
Decision Support Systems	6
Integrated Engineering Management Models	6
Total	55

The dominance of operational and safety-focused studies suggests that the literature remains fragmented. Although substantial progress has been made within individual research domains, integration across domains remains limited.

Evolution of Operational Performance Assessment

The reviewed literature indicates a transition from traditional capacity-based evaluation toward multidimensional performance assessment. Earlier studies primarily relied on analytical methods derived from gap acceptance theory and capacity estimation procedures. Recent research increasingly incorporates travel reliability, queue dynamics, and traffic interactions into performance evaluation frameworks.

The introduction of PKJI 2023 further supports this transition by providing updated methodologies that better reflect heterogeneous traffic conditions. However, most PKJI-based

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studies remain diagnostic rather than prescriptive, focusing on identifying operational deficiencies rather than optimizing traffic control policies.

This finding suggests that operational performance assessment alone is insufficient for supporting strategic traffic management decisions. Future frameworks should integrate operational indicators with safety and optimization measures to provide a more comprehensive basis for policy development.

Evolution of Traffic Safety Assessment

Traffic safety research has experienced a significant methodological shift from crash-based analyses toward surrogate safety measures. TTC and PET emerged as the most frequently used indicators due to their ability to quantify conflict severity and collision risk.

Several studies demonstrated strong relationships between surrogate safety indicators and future crash occurrences. Conflict-based approaches were found to be particularly useful in environments where crash data are incomplete or unreliable. Moreover, safety indicators can be extracted directly from microsimulation outputs, enabling safety evaluation before policy implementation.

Despite these advantages, safety assessment remains largely disconnected from operational performance evaluation. This separation limits the ability of decision-makers to evaluate trade-offs between efficiency and safety.

Integration of Microsimulation and Safety Assessment

Microsimulation has become a central analytical tool for evaluating traffic management strategies. VISSIM was the most frequently used software among the reviewed studies because of its flexibility in modelling heterogeneous traffic conditions and driver behaviors.

The integration of VISSIM with SSAM represents one of the most important methodological developments identified in the review. This integration enables simultaneous estimation of operational indicators such as delay and queue length and safety indicators such as TTC and PET.

Nevertheless, many studies continue to use microsimulation solely for scenario comparison rather than incorporating optimization techniques. As a result, microsimulation outputs are often underutilized in decision-making processes.

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Multi-Objective Optimization for Traffic Control Policies

The review identified increasing use of multi-objective optimization techniques within transportation engineering. Methods such as NSGA-II, Pareto optimization, weighted sum approaches, AHP, and TOPSIS were commonly employed to address competing objectives.

Most optimization studies focused on minimizing delay, reducing queue lengths, and improving capacity utilization. However, relatively few studies incorporated safety indicators as explicit optimization objectives. Consequently, many optimization frameworks remain biased toward operational efficiency.

The literature suggests that future optimization models should simultaneously minimize delay, queue length, and traffic conflicts while considering implementation feasibility and resource constraints.

Research Gap Matrix

Table 10. Research Gap Matrix

Research Domain	Existing Findings	Research Limitations	Identified Gap
Operational Performance	Strong focus on capacity and delay	Limited safety integration	Need for operational-safety integration
Surrogate Safety Measures	Effective conflict assessment	Limited operational linkage	Need for integrated evaluation
Traffic Microsimulation	Accurate scenario evaluation	Mostly descriptive analysis	Need for optimization integration
Multi-Objective Optimization	Effective decision support	Rarely includes safety indicators	Need for safety-oriented optimization
Decision Support Systems	Useful for policy evaluation	Limited traffic engineering application	Need for engineering management framework
Engineering Management Models	Emerging research area	Fragmented methodologies	Need for comprehensive integrated model

The matrix clearly demonstrates that no existing framework fully integrates all four dimensions simultaneously.

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Proposed Engineering Management Model

Based on the literature synthesis, a conceptual Engineering Management Model is proposed. The model consists of four interconnected components:

The first component is operational performance evaluation based on PKJI 2023 indicators, including capacity, degree of saturation, delay, queue probability, and level of service.

The second component is proactive traffic safety assessment using surrogate safety measures such as TTC, PET, and conflict frequency.

The third component is calibrated and validated traffic microsimulation using PTV VISSIM and SSAM to evaluate alternative traffic control scenarios.

The fourth component is multi-objective optimization that identifies optimal policy alternatives by minimizing delay, queue length, and traffic conflicts simultaneously.

The interaction among these components forms an integrated decision-support framework capable of supporting evidence-based traffic control policy development at unsignalized intersections.

Theoretical and Practical Implications

Theoretically, the findings contribute to the advancement of engineering management theory by demonstrating the importance of integrating operational, safety, simulation, and optimization perspectives within a unified framework. The study extends existing traffic engineering literature beyond traditional operational evaluations and introduces a holistic decision-making perspective.

Practically, the proposed framework provides transportation agencies with a structured methodology for evaluating traffic control policies at unsignalized intersections. The framework enables decision-makers to balance operational efficiency and traffic safety while considering local traffic conditions and implementation constraints. Such an approach is particularly relevant for developing countries characterized by heterogeneous traffic environments and limited infrastructure resources.

Novelty of the Study

The primary novelty identified through this systematic literature review lies in the integration of PKJI 2023 operational indicators, surrogate safety measures, traffic microsimulation, and multi-objective optimization into a single Engineering Management Model for Traffic Control Policy Optimization at Unsignalized Intersections. Unlike previous studies that

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examine these components separately, the proposed framework establishes a comprehensive decision-support mechanism capable of evaluating operational performance, safety outcomes, and policy effectiveness simultaneously. This integration represents a significant contribution to both transportation engineering research and engineering management practice.

CONCLUSION

This systematic literature review examined the development of engineering management models for traffic control policy optimization at unsignalized intersections using a multi-objective analysis approach. Following the PRISMA 2020 framework, 55 eligible studies published between 2015 and 2025 were systematically analyzed. The findings indicate that research in this field has primarily evolved around four major domains: operational performance evaluation, surrogate safety measures, traffic microsimulation, and multi-objective optimization. Operational studies predominantly focus on capacity, delay, queue length, and level of service, while safety studies emphasize conflict-based indicators such as Time to Collision (TTC) and Post-Encroachment Time (PET). In addition, traffic microsimulation has become a widely adopted tool for evaluating alternative traffic control scenarios, whereas multi-objective optimization has increasingly been employed to address competing traffic management objectives. Despite these advancements, the existing literature remains fragmented, with most studies examining these domains independently rather than within an integrated decision-support framework.

The review further reveals a significant research gap in the development of comprehensive engineering management models capable of simultaneously integrating operational performance indicators, proactive safety measures, traffic microsimulation outputs, and multi-objective optimization techniques. Existing approaches generally lack the ability to balance efficiency and safety objectives within a unified policy evaluation framework, particularly under heterogeneous traffic conditions commonly observed in developing countries. Therefore, future research should focus on developing integrated engineering management models that combine PKJI 2023 operational indicators, surrogate safety measures, calibrated microsimulation models, and multi-objective optimization methods. Such integration has the potential to provide more objective, transparent, and evidence-based support for traffic control policy decision-making at unsignalized intersections while contributing to safer, more efficient, and sustainable transportation systems.

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