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SYSTEMATIC LITERATURE REVIEW: TRAFFIC PERFORMANCE ANALYSIS OF U-TURN FACILITIES

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ABSTRACT

U-turn facilities near fuel stations generate compounded traffic conflict conditions that substantially degrade road performance. This study conducts a Systematic Literature Review guided by the PRISMA 2021 protocol to synthesize research on traffic performance at U-turn facilities, with specific focus on fuel station proximity. A total of 675 records were retrieved from Google Scholar, ScienceDirect, Scopus, and GARUDA, of which 30 peer-reviewed studies published between 2016 and 2025 were selected through structured screening and five-criterion quality assessment. Findings indicate that opposing traffic volume and geometric configuration are the dominant determinants of delay and level-of-service degradation. Fuel station proximity compounds these effects beyond levels observed at general median openings. Comparative analysis reveals a consistent performance hierarchy: Signalized MUT ≈ RCUT > P-MUT > CMU, with RCUT reducing crash frequency by up to 70.63%. This review represents the first systematic synthesis specifically addressing U-turn facilities at fuel station locations as an integrated traffic conflict zone.

Keywords: traffic flow, U-turn facilities, fuel station, gas station, traffic performance

ABSTRAK

Fasilitas putar balik arah (U-turn) yang berada di dekat stasiun pengisian bahan bakar menimbulkan kondisi konflik lalu lintas yang lebih kompleks dan secara signifikan menurunkan kinerja jalan. Studi ini melakukan Systematic Literature Review dengan mengacu pada protokol PRISMA 2021 untuk menyintesis berbagai penelitian mengenai kinerja lalu lintas pada fasilitas U-turn, dengan fokus khusus pada kedekatannya dengan stasiun pengisian bahan bakar. Sebanyak 675 artikel diperoleh dari Google Scholar, ScienceDirect, Scopus, dan GARUDA. Dari jumlah tersebut, 30 artikel ilmiah yang telah melalui proses telaah sejawat dan diterbitkan pada periode 2016–2025 dipilih melalui proses penyaringan terstruktur dan penilaian kualitas berdasarkan lima kriteria. Hasil kajian menunjukkan bahwa volume lalu lintas berlawanan arah dan konfigurasi geometrik merupakan faktor dominan yang memengaruhi peningkatan tundaan dan penurunan tingkat pelayanan jalan. Kedekatan fasilitas U-turn dengan stasiun pengisian bahan bakar memperparah dampak tersebut melebihi kondisi yang umumnya terjadi pada bukaan median biasa. Analisis komparatif menunjukkan adanya hierarki kinerja yang konsisten, yaitu Signalized MUT ≈ RCUT > P-MUT > CMU, dengan RCUT mampu menurunkan frekuensi kecelakaan hingga 70,63%. Kajian ini merupakan sintesis sistematis pertama yang secara khusus membahas fasilitas U-turn pada lokasi stasiun pengisian bahan bakar sebagai zona konflik lalu lintas yang terintegrasi.

Kata kunci: *arus lalu lintas, fasilitas U-turn, stasiun pengisian bahan bakar, SPBU, kinerja lalu lintas*

1. Introduction

The number of vehicles in major cities continues to increase every year. This condition causes many roads to become congested and leads to traffic jams in various major cities [1]. This leads to a decline in road traffic performance, especially at conflict points such as turnaround points for turning vehicles. One study shows that the Median U-Turn design is increasingly being implemented in countries with heavy traffic, such as Egypt [2], where it demonstrated a 57% improvement in throughput at single-lane intersections compared to conventional intersections. Another study conducted in Egypt also proposed a method to improve U-turn capacity at median openings based on a traffic gap acceptance model. A study in China found that implementing the Parallel U-Turn (P-MUT) design can reduce queue lengths and increase operational efficiency at busy intersections [3]. Meanwhile, in Cambodia, vehicles performing U-turns must wait for an acceptable gap in opposing

traffic flow, which frequently causes congestion and increases the risk of collisions [4]. These findings collectively suggest that while U-turns are intended to facilitate directional changes, their non-strategic placement and improper geometric design can significantly disrupt the main traffic flow, exacerbate traffic conflicts, increase delays, and reduce road capacity.

The same phenomenon is observed in Indonesia. In Tasikmalaya, an increase in U-turning vehicles was found to negatively impact road capacity and level of service, resulting in unstable traffic flow [5]. Studies in Sidoarjo and East Jakarta further confirmed that insufficient spacing between U-turn openings leads to increased vehicle delays and reduced travel speeds [6]. Research in Makassar additionally highlighted that U-turn facilities contribute to elevated traffic noise levels by intensifying vehicle conflicts during turning maneuvers [7]. On Jalan Raja H. Fisabilillah in Batam, U-turn maneuvers at median openings were found to reduce average vehicle speed, increase delay times, and disrupt main traffic flow due to conflicts between turning and through vehicles. Similarly, on Gajahmada Street, Batam, the closure of a U-turn facility increased average vehicle speed and reduced the degree of saturation (DS) from 0.47 to 0.40, while improving the level of service (LOS) from C to B [8]. These findings reinforce the conclusion that geometric planning and regulatory management of U-turn maneuvers significantly influence urban traffic efficiency and safety.

Of particular concern are U-turn facilities located in proximity to commercial areas, especially fuel stations (gas stations/SPBU). In such locations, traffic conflicts are compounded by the simultaneous movement of vehicles performing U-turns and vehicles entering or exiting the station premises. Studies indicate that this interaction can lead to substantial reductions in road performance, including decreased vehicle speed, increased queue length, and deteriorated level of service [9]. Despite their practical significance, U-turn facilities near fuel stations remain critically understudied compared to U-turns at general median openings or signalized intersections.

Although numerous studies have examined U-turn facilities across various countries, most existing research focuses on U-turns at general median openings, signalized intersections, or highway segments, without specifically addressing the compounding effect of adjacent fuel station access on traffic performance. Furthermore, no comprehensive Systematic Literature Review (SLR) has been conducted that specifically synthesizes findings on U-turn facilities near fuel stations (SPBU) as an integrated traffic conflict zone. The variation in geometric conditions, traffic volumes, analytical methods, and driver behavior across different study contexts further limits the comparability and generalizability of existing findings. This gap in the literature represents a significant obstacle to the development of evidence-based design guidelines for U-turn facilities in commercial areas, particularly in developing countries such as Indonesia.

Therefore, this study conducts a Systematic Literature Review (SLR) guided by the PRISMA 2021 protocol to address this gap. This study aims to synthesize previous research findings on the impact of U-turn facilities near fuel stations on traffic performance, identify the dominant factors affecting delay, capacity, and level of service, and compare the effectiveness of various U-turn geometric designs. The novelty of this study lies in its focused synthesis of literature at the intersection of two underexplored dimensions: U-turn facility design and fuel station access management, offering a structured analytical framework that has not previously been established in the existing body of knowledge.

To achieve this objective, this study addresses three research questions:

1. What is the effect of U-turn facilities in commercial areas, particularly near fuel stations, on traffic performance as documented in previous research?
2. What factors most significantly influence capacity and level of service at U-turn facilities, based on the available literature?
3. What analytical methods dominate studies on this topic, and what are the emerging research trends over the past decade?

The findings of this SLR are intended to provide evidence-based recommendations for planners, traffic engineers, and policymakers in designing safer and more efficient U-turn facilities, particularly in high-access commercial zones in developing urban contexts.

2. Literatur Review

This section presents the theoretical and conceptual foundations underpinning the study of U-turn facilities and their relationship to traffic performance. It covers the fundamental concepts of

U-turn facility design, the theoretical basis of traffic performance measurement, and the classification of U-turn facility types as established in the existing literature.

2.1 Concept and Definition of U-Turn Facilities

U-turn facilities are critical elements of urban road networks, designed to enable vehicles to reverse their direction of travel through openings in the road median. According to [10] median openings for U-turn maneuvers can significantly affect travel speed on multilane roads, particularly when traffic volumes are high. In dense urban environments, these facilities serve an important function in improving accessibility and reducing travel distance for drivers who need to change direction without accessing an intersection. However, the presence of U-turn activity introduces a point of conflict between turning vehicles and through-moving traffic, which can reduce operational speed, increase the probability of collisions, and degrade the overall performance of the road segment.

The geometric characteristics of U-turn facilities including median width, turn radius, number of lanes, and distance from adjacent intersections are primary determinants of how efficiently and safely a U-turn maneuver can be executed. Inadequate geometry forces vehicles, particularly large ones such as buses and trucks, to occupy opposing lanes during the maneuver, thereby creating extended periods of traffic disruption [11].

2.2 Traffic Performance Theory

Traffic performance at a road segment or facility is typically evaluated through a set of measurable indicators. According to the Indonesian Road Capacity Manual (MKJI 1997) [12] and the Indonesian Road Capacity Guidelines (PKJI 2014)[13], the primary performance indicators include: vehicle speed (km/h), traffic flow or volume (vehicles/hour), degree of saturation (DS = volume / capacity ratio), delay (seconds/vehicle), queue length (meters or vehicles), and Level of Service (LOS), classified from A (free flow) to F (forced/breakdown flow).

These indicators are used across studies to quantify the extent to which a U-turn facility degrades or improves traffic conditions on the affected road segment. A degree of saturation above 0.85 generally indicates that a road is approaching its capacity limit, and a LOS of D or below signals operationally unacceptable conditions (MKJI, 1997). Understanding these metrics is essential for interpreting the comparative findings of studies reviewed in this paper.

2.3 Classification of U-Turn Facility Types

Based on geometric design and operational characteristics, U-turn facilities can be classified into three main types:

a. **Conventional Median U-Turn (CMU)** The CMU is the most commonly found U-turn design in Indonesia and many developing countries. It consists of a direct opening in the road median that allows vehicles to cross opposing lanes and reverse direction. While simple in construction, the CMU is associated with higher conflict rates due to the direct interaction between U-turning vehicles and opposing through traffic, especially at locations near high-activity access points such as fuel stations.

b. **Restricted Crossing U-Turn (RCUT)** The RCUT design restricts direct crossing movements across the median and instead redirects traffic to a designated U-turn lane located at a safer distance from the main intersection. This design reduces direct conflict points between turning and through vehicles, resulting in improved traffic flow and reduced delays compared to the CMU.

c. **Parallel Median U-Turn (P-MUT)** The P-MUT design directs vehicles into a parallel auxiliary lane before executing the U-turn maneuver. This separation of the turning movement from the main traffic stream minimizes disruption to through traffic and has been shown to significantly reduce queue lengths at high-volume locations [3].

A comparative summary of these three design types is presented in Table 1 below.

2.4 U-Turn Facilities in Commercial Areas: The Case of Fuel Stations

The proximity of U-turn facilities to commercial access points, particularly fuel stations (SPBU), introduces an additional layer of traffic complexity. Vehicles entering and exiting fuel stations generate access conflict that overlaps spatially and temporally with U-turning vehicles, creating compound disruption to main-road traffic flow. This phenomenon is

theoretically grounded in Road Access Management theory, which holds that the location, spacing, and design of access points relative to turning facilities are critical determinants of road segment performance [14].

Table 1. Theoretical Comparison of U-Turn Facility Design Types

Design Type	Conflict Level	Delay Potential	Suitable Condition	Key Reference
CMU	High	High	Low-volume roads	Hu et al. (2022)
RCUT	Medium	Medium	Medium–high volume, near intersections	Muharam et al. (2025)
P-MUT	Low	Low	High-volume urban corridors	[3]

Driver Behavior Theory further explains this dynamic: drivers approaching a fuel station often execute U-turns opportunistically, accepting smaller traffic gaps than would be considered safe under standard gap acceptance models, in order to minimize travel time [15]. This behavioral tendency amplifies the conflict risk at U-turn points near fuel stations compared to those at general median openings.

These theoretical foundations establish that U-turn facilities near fuel stations constitute a distinct and more complex traffic environment than general median openings, and therefore warrant dedicated analytical attention a gap that motivates the systematic review conducted in this study.

3. Research Methodology

3.1 Research Design and Literature Search Strategy

This study employed a Systematic Literature Review (SLR) approach guided by the PRISMA 2021 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as established by Page et al. (2021). The SLR methodology was selected because it provides a transparent, reproducible, and structured process for identifying, evaluating, and synthesizing evidence from multiple independent studies. This approach is particularly appropriate for mapping the current state of knowledge on U-turn facility performance near fuel stations, where findings are dispersed across heterogeneous study contexts.

The literature search was conducted across four academic databases selected based on their relevance to civil engineering and transportation research: **(**1) Google Scholar, selected for its broad coverage of both international and Indonesian-language publications; (2) ScienceDirect, selected for its high concentration of peer-reviewed engineering and transportation journals; (3) Scopus, selected for its rigorous indexing standards and citation tracking capability; and (4) GARUDA (Garba Rujukan Digital), selected specifically to capture Indonesian-language studies published in nationally accredited journals. These four databases were consistently applied throughout all stages of the search process.

The search was conducted between January and March 2025, covering publications from 2016 to 2025. To ensure systematic and reproducible retrieval, Boolean search strings were constructed using combinations of primary and secondary keywords, as presented in Table 2.

Table 2. Boolean Search Strings Used in Literature Retrieval

Database	Search String
Google Scholar	("U-turn" OR "median opening") AND ("traffic performance" OR "level of service" OR "delay") AND ("fuel station" OR "gas station" OR "SPBU")
Science Direct	("U-turn facility" OR "median U-turn") AND ("traffic flow" OR "road capacity") AND ("petrol station" OR "fuel station")
Scopus	("U-turn" OR "turnaround") AND ("traffic delay" OR "traffic conflict" OR "LOS") AND ("commercial area" OR "gas station")
GARUDA	("putaran balik" OR "bukaan median") AND ("kinerja lalu lintas" OR "tingkat pelayanan") AND ("SPBU" OR "stasiun pengisian bahan bakar")

3.2 Inclusion and Exclusion Criteria

Articles retrieved from the database search were evaluated against a set of pre-defined inclusion and exclusion criteria to ensure the relevance,

quality, and temporal currency of the selected studies. These criteria are presented in Table 3.

Table 3. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles	Conference abstracts, theses, patents, non-peer-reviewed reports
Publication year	2016–2025	Published before 2016
Language	English or Indonesian	Any language other than English or Indonesian
Topic focus	U-turn facilities, median openings, traffic performance, or fuel station access in urban areas	Topics unrelated to U-turn facilities or traffic engineering
Geographic scope	Any country, with emphasis on urban road contexts	Rural or highway contexts with no urban traffic characteristics
Full-text availability	Full text accessible in PDF format	Abstract-only or paywalled without institutional access

3.3 Quality Assessment of Selected Studies

To ensure methodological rigor, all articles that passed the inclusion/exclusion screening were subjected to a quality assessment process prior to final inclusion. Quality was evaluated based on the following criteria, each scored on a binary scale (1 = met, 0 = not met):

- Q1: Is the research objective clearly stated?
- Q2: Is the study methodology explicitly described and replicable?
- Q3: Are traffic performance indicators (speed, delay, LOS, capacity) quantitatively measured?
- Q4: Are the results presented with sufficient data to support the conclusions?
- Q5: Is the study published in a journal indexed by Scopus, SINTA, or an equivalent recognized indexing body?

Articles were required to achieve a minimum quality score of 3 out of 5 to be included in the final synthesis. This threshold ensured that only studies with adequate methodological transparency and data quality were incorporated. All 30 articles included in the final synthesis met this minimum threshold.

3.4 Article Selection Process (PRISMA Flow)

The article selection process followed the four-stage PRISMA 2021 protocol: Identification, Screening, Eligibility, and Inclusion, as illustrated in Figure 1.

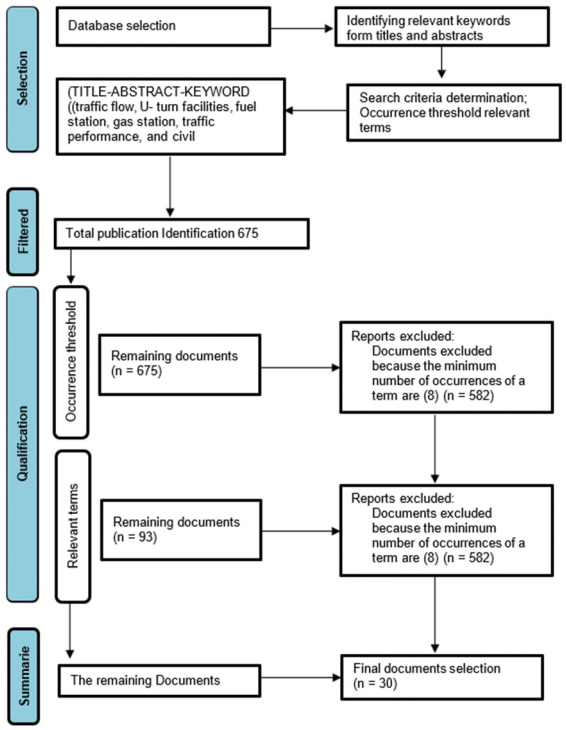

Figure 1. PRISMA 2021 Flow Diagram

Stage 1 Identification: An initial keyword-based search across the four selected databases yielded a total of 675 records. These records were retrieved based on the Boolean search strings presented in Table 2 and represented a broad range of studies related to U-turn facilities, traffic flow, and road performance.

Stage 2 Screening: All 675 records were screened based on their titles and abstracts. During this stage, 582 records were excluded for the following reasons: duplication across databases (n = 124), topics unrelated to U-turn facilities or traffic performance (n = 298), publication year outside the 2016–2025 range (n = 87), and language other than English or Indonesian (n = 73). Following this screening, 93 records were retained for full-text evaluation.

Stage 3 Eligibility: Full texts of the 93 remaining records were retrieved and assessed against the inclusion/exclusion criteria and the quality assessment rubric described in Section 3.3. Articles that did not specifically address traffic performance at U-turn facilities, lacked quantitative

performance data, or failed to meet the minimum quality score were excluded. This stage resulted in 63 records being excluded, leaving 30 articles eligible for final inclusion.

Stage 4 Final Inclusion: A total of 30 articles were included in the final synthesis. These articles comprise both national studies (conducted in Indonesia) and international studies from countries including Egypt, China, Cambodia, and Malaysia, covering a range of analytical methods and geographic contexts relevant to the research objectives.

3.5 Data Extraction and Analysis

Data extraction was systematically performed on all 30 included articles using a standardized extraction template. For each article, the following information was recorded:

1. Research identity: author(s), year of publication, country/city of study location
2. Analytical method employed: field observation, MKJI/PKJI calculation, microsimulation, gap acceptance model, or a combination thereof
3. Traffic performance parameters measured: vehicle speed (km/h), degree of saturation (DS), traffic delay (seconds/vehicle), queue length (m), and Level of Service (LOS)
4. Key findings and design recommendations related to U-turn geometry or access management

The extracted data were subsequently analyzed using a thematic narrative synthesis approach. Findings were grouped into four thematic categories: (1) geometric factors influencing U-turn performance (median width, turn radius, distance from intersection); (2) traffic volume and flow characteristics; (3) access management issues at fuel station locations; and (4) comparative performance of alternative U-turn design types (CMU, RCUT, and P-MUT).

3.6 Risk of Bias Assessment

The risk of bias in the included studies was evaluated at the study level across three dimensions. First, location bias is present in most studies, as findings are derived from single road segments or specific intersections, limiting spatial generalizability to broader road networks [14]. Second, temporal bias is a concern because the majority of field data were collected during peak hours only, which may not fully represent off-peak or seasonal traffic conditions [16]. Third, methodological bias is relatively low for Indonesian studies, as most applied standardized analytical frameworks, which promote consistency in measurement procedures. However, international studies employed a wider range of methods (microsimulation, gap acceptance models, field surveys), which introduces variability in how performance metrics are defined and measured across studies.

Additionally, reporting bias may exist in this review, as studies on U-turn facilities near fuel stations remain limited in number. The relative scarcity of such studies means that the findings of this review may disproportionately reflect conditions from locations where research has been conducted, rather than the full spectrum of real-world contexts. Despite these limitations, the included studies collectively provide a sufficient evidence base for identifying dominant performance factors and informing design recommendations, which are the primary objectives of this review.

4. Result

This study is based on literature from publications from 2016 to 2025, covering various geographical regions and publishers with 93 studies. The research was conducted in various locations and highlights the diversity in scientific research. This diversity draws on research from various global regions and describes the current situation in Southeast Asian countries, such as China, Cambodia, and Indonesia, as well as in Middle Eastern countries, such as Egypt, which have contributed significantly to this paper. Using the publish-or-perish (PoP) framework, this article integrates contributions from various sources and examines global publication trends and their impact on civil engineering and transportation research. The global gap in this paper is the examination of U-turns at gas stations, where vehicle entry and exit activities, combined with U-turn maneuvers, disrupt traffic flow.

4.1 Risk of Bias in Studies

This section presents the synthesized findings from 30 peer-reviewed studies identified through the systematic literature search and selection process described in Section 3. The results are organized into four thematic categories: (1) bibliometric analysis and publication trends; (2) geometric factors affecting U-turn performance; (3) traffic volume, access management, and level of service; and (4)

comparative performance of alternative U-turn design types. A comprehensive synthesis table of all 30 included studies is presented in Table 4.

4.1 Bibliometric Analysis and VOSviewer Keyword Mapping

A total of 675 publications were initially retrieved from the four selected databases. Following the PRISMA screening process, 30 articles published between 2016 and 2025 were retained for final synthesis. These studies originate from diverse geographic regions, including Indonesia, China, Egypt, Cambodia, Iraq, Jordan, Malaysia, and the United States, reflecting a broad international body of knowledge on U-turn facility performance.

Bibliometric mapping was conducted using VOSviewer software to visualize keyword co-occurrence patterns across the 675 retrieved documents. The resulting network map is presented in Figure 2.

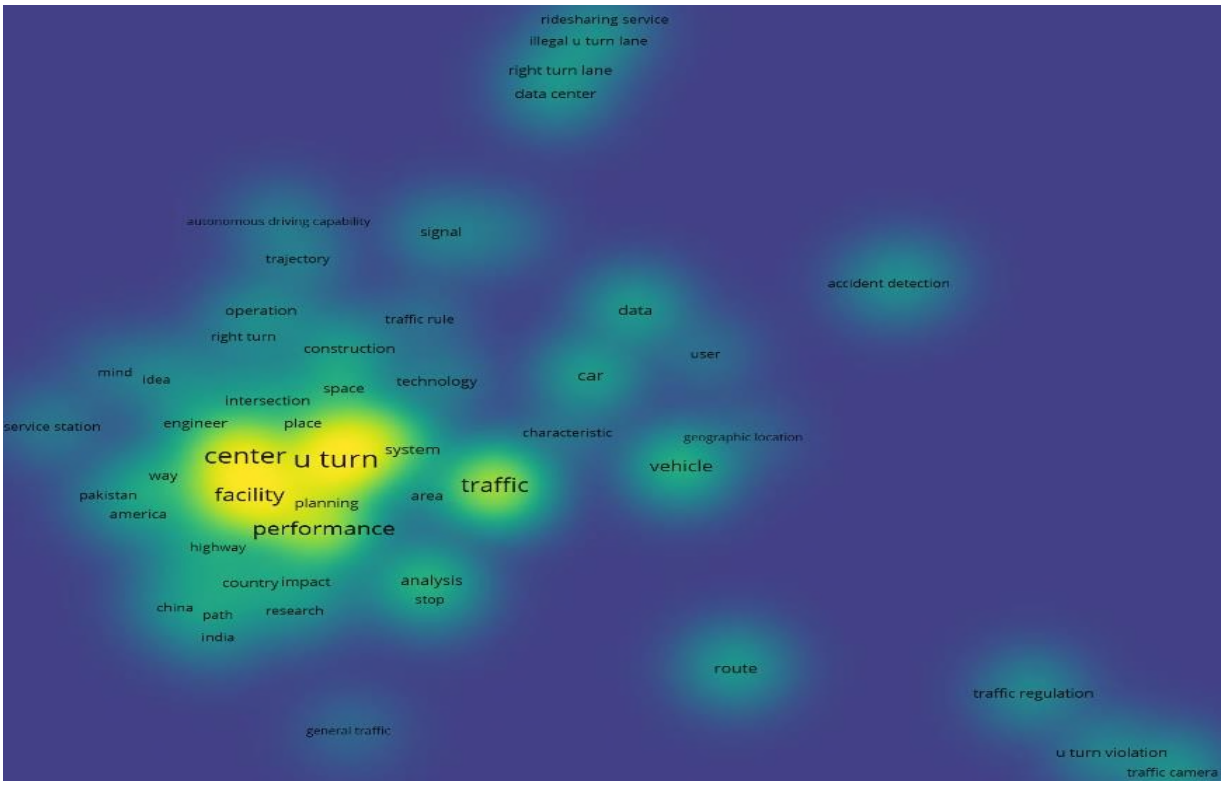

Figure 2. VOSviewer Keyword Co-occurrence Network Map

Figure 3 illustrates the keyword co-occurrence network generated from the 675 retrieved publications, where node size reflects keyword frequency and cluster color indicates thematic groupings identified by VOSviewer's algorithmic clustering.

As visualized in the network map above, the clustering of keywords reveals both the dominant research streams and the relatively underexplored intersection between U-turn facility design and fuel station access management, which forms the central analytical focus of this review.

Analysis of the VOSviewer map reveals three primary keyword clusters. The first and most dominant cluster centers on the keywords "U-turn," "traffic flow," "delay," and "level of service," indicating that operational performance measurement remains the central concern of this research field. The high co-occurrence frequency of these terms confirms that delay and LOS are the most consistently used performance metrics across studies globally. The second cluster groups keywords including "median opening," "capacity," "gap acceptance," and "geometric design," reflecting a strong research interest in the physical and behavioral determinants of U-turn maneuver efficiency.

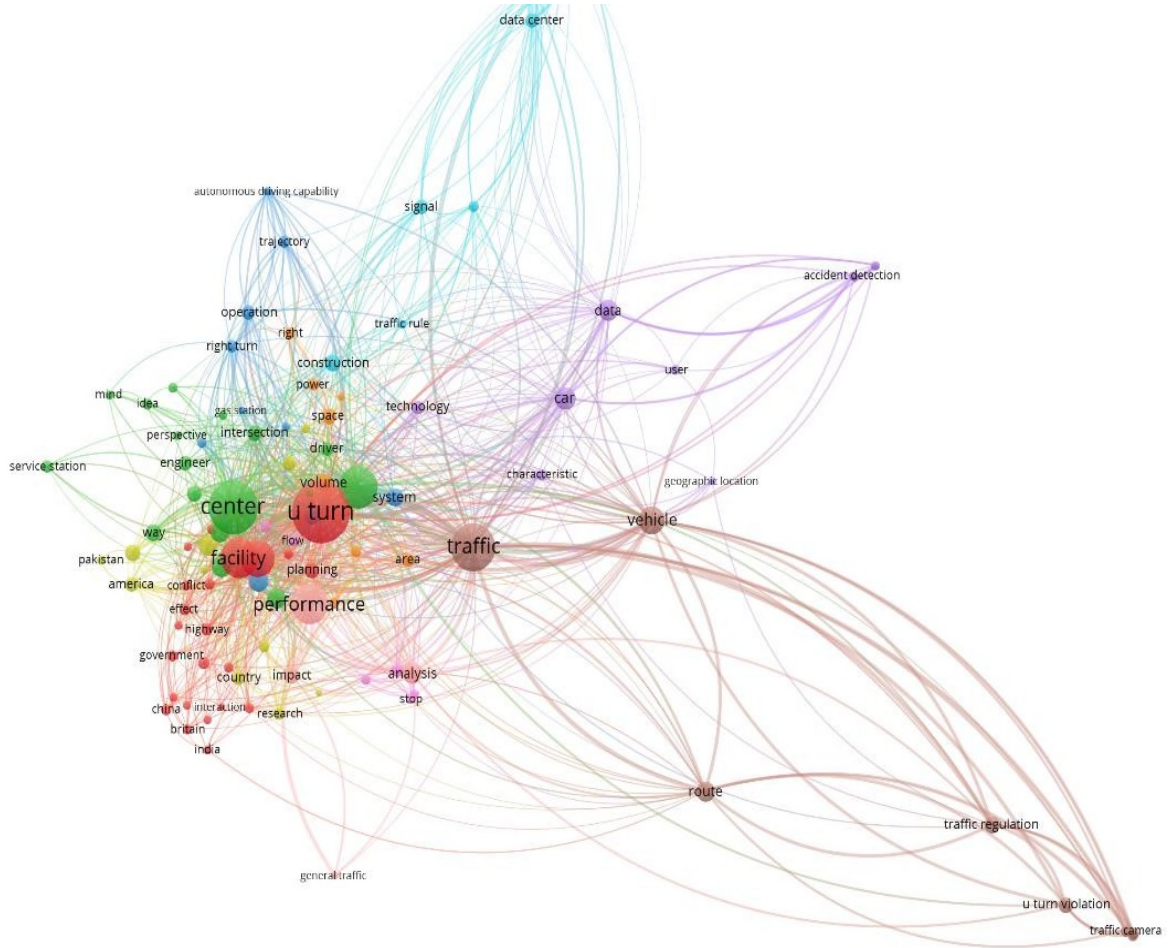

Figure 3. Visualization of the Relationship Between Research Keywords

The third, smaller cluster links "fuel station," "gas station," "SPBU," and "access management," which represents an emerging but still underrepresented research direction. The relatively small size of this cluster visually confirms the research gap identified in this study: the intersection of U-turn facilities and fuel station access management has received significantly less scholarly attention compared to general U-turn performance studies. In terms of temporal trends, keyword frequency analysis shows a marked increase in publications using microsimulation tools (VISSIM, PTV) after 2020, alongside growing use of alternative intersection design terminology (RCUT, MUT, P-MUT), suggesting a global shift toward simulation-based evaluation of innovative U-turn geometries.

4.2 Risk of Bias Across Studies

Articles on U-turn facilities near fuel station areas remain limited in the existing literature. Most prior studies examined U-turns on general public roads without specifically analyzing the compounding effect of high-frequency vehicle entry and exit at adjacent fuel stations. Additionally, some studies present methodological limitations such as single-location data collection, peak-hour-only observation periods, and reliance on nationally specific standards (e.g., MKJI 1997, PKJI 2014) that may not generalize across different traffic environments. These factors constitute a moderate risk of contextual and temporal bias in the included literature.

4.3 Synthesis Table of 30 Included Studies

The following table presents a structured comparison of all 30 studies included in this systematic review, organized by author, study location, analytical method, performance variables measured, and key findings.

4.4 Thematic Synthesis of Findings

Geometric Factors Geometric characteristics consistently emerge as primary determinants of U-turn performance across the reviewed studies. Median width, turning radius, distance between U-

turn openings, and proximity to intersections collectively determine maneuver smoothness and conflict probability. [17] demonstrated through microsimulation that modifying median geometry specifically widening the median and adjusting the turning radius substantially improves U-turn capacity and reduces conflict frequency. [3] identified that the distance between the median opening and the nearest intersection is a critical parameter, with shorter distances producing exponentially higher conflict rates. [18] further established that average critical gap at mid-block U-turn facilities is approximately 3.8 seconds, and that geometric constraints forcing vehicles to accept smaller gaps than desired are directly associated with higher delay and lower capacity.

Traffic Volume and Flow Characteristics Traffic volume on both the U-turning approach and the opposing through-traffic stream is consistently identified as the most influential operational variable. Multiple studies confirm that as opposing volume increases, the available gap frequency decreases, resulting in longer waiting times, extended queue formation, and progressive LOS degradation [4]. In Indonesian contexts, studies applying PKJI 2023 confirm that DS values above 0.75 consistently correspond to LOS D or lower during peak hours at U-turn locations.

Access Management at Fuel Station Locations U-turn facilities located adjacent to fuel station access points present a compounded traffic conflict environment. Studies at Sultan Alauddin fuel station in Makassar [9] consistently demonstrate that the simultaneous occurrence of U-turning vehicles and fuel station entry/exit movements produces conflict intensities and delay magnitudes that exceed those observed at general median openings under equivalent traffic volumes. [8] further demonstrated that closing a U-turn adjacent to a commercial area in Batam improved DS from 0.47 to 0.40 and upgraded LOS from C to B, directly quantifying the performance benefit of access management intervention.

Comparative Performance of Alternative U-Turn Designs Evidence from simulation-based studies consistently indicates that alternative U-turn designs outperform the Conventional Median U-Turn (CMU) in high-volume conditions. [11] demonstrated that the Advance Left Turn (UALT) design reduces delay by 73.48% and queue length by 84.85% compared to conventional designs. [19] confirmed that RCUT designs reduce conflict points and crash risk substantially compared to CMU. Alhadidi et al. (2024) found that signalized MUT outperforms five alternative configurations in delay, stops, speed, and emissions in a dense urban arterial context. Reported that the R/MUT combination design reduces travel time by up to 40% at near-capacity volumes. These findings collectively establish a performance hierarchy: UALT ≈ Signalized MUT > RCUT > P-MUT > CMU, with the performance advantage of alternative designs increasing proportionally with traffic volume.

5. Discussion

5.1 Interpretation of Results

The findings synthesized in this review reveal a consistent and multidimensional pattern: U-turn facilities near fuel stations constitute a substantially more complex traffic conflict environment than general median openings under equivalent traffic volume conditions. This section provides a critical analytical interpretation of the synthesized results, organized around three dimensions: the dominant factors driving delay, a comparative assessment of U-turn design performance, and the implications for road design in developing country contexts.

5.1.1 Dominant Factors Contributing to Delay at Fuel Station U-Turn Locations

Across the 30 studies reviewed, traffic volume on the opposing through-traffic stream emerges as the single most influential determinant of delay at U-turn facilities. As opposing volume increases, the frequency of acceptable gap occurrences decreases, resulting in prolonged waiting times and progressive queue formation. This relationship is not linear; studies by [4], collectively demonstrate that delay escalates disproportionately once opposing volume exceeds a critical threshold typically when the degree of saturation (DS) surpasses 0.75.

At locations adjacent to fuel stations, this volume-delay dynamic is further compounded by access conflict generated by vehicles entering and exiting the fuel station premises. Studies conducted at SPBU locations in Makassar [9] and on Jalan Raja H. Fisabilillah in Batam demonstrate that the simultaneous occurrence of U-turning vehicles and fuel station entry/exit movements produces conflict intensities and delay magnitudes that exceed those recorded at general median openings under equivalent traffic volumes. This compounding effect represents a structurally distinct operational

condition, not merely a higher-volume variant of general U-turn performance a distinction that has significant implications for design and regulatory frameworks.

Table 4. Thematic Synthesis of Selected Studies on U-Turn Traffic Performance

Theme	Representative Studies	Methods Used	Main Variables	Synthesized Finding
U-turn and road performance	Al Hanif & Darsono (2022); Sari (2022); Fahmi (2025); Febriyani et al. (2025); Saputra et al. (2023)	Field observation; MKJI/PKJI	Speed, delay, DS, LOS, queue	U-turn movements generally reduce speed, increase delay and queue length, and degrade LOS during peak hours.
Fuel station proximity	Kunna (2025); related studies in commercial road corridors	Field observation; access conflict analysis	Speed, delay, LOS, access conflict	Fuel station access compounds U-turn conflicts because entering and exiting vehicles interact with turning and through traffic.
Geometric and traffic-volume factors	Hu et al. (2022); Zhao et al. (2024); Muharam (2025); Omarov et al. (2022); Khan et al. (2024)	VISSIM; analytical model; gap acceptance; field survey	Median spacing, turn radius, opposing volume, critical gap, capacity	Geometry and opposing traffic volume are the dominant determinants of U-turn delay and operational capacity.
Alternative U-turn design performance	Abdel-wahed (2024); Alhadidi et al. (2024); Molan & Howard (2022); Howard et al. (2023); Luo et al. (2025)	Simulation; field survey; SSAM; CRITIC method	Delay, stops, travel time, conflicts, LOS	Signalized MUT, RCUT, P-MUT, and R/MUT generally outperform conventional median U-turns by separating conflict movements.
Safety and environmental effects	Mishra & Pulugurtha (2022); Javed (2024); Guin & Robinson (2021); Hossein et al. (2026); Hustim (2025)	Empirical Bayes; SLR; VISSIM; MOVES; noise measurement	Crash frequency, conflicts, emissions, noise	RCUT and MUT treatments tend to reduce conflicts and crash risk, although effects on travel distance and emissions depend on traffic composition.
Overall research trend and gap	Synthesis of the 30 selected studies reviewed in the SLR	PRISMA screening; thematic synthesis; bibliometric mapping	Traffic performance, geometry, access management, safety	Most studies address general U-turns, while U-turn facilities near fuel stations remain underexplored as integrated traffic conflict zones.

Note: The complete article-by-article extraction table may be placed in an appendix or supplementary material if required by the journal.

Geometric characteristics constitute the second dominant factor category. Median width, turning radius, distance from adjacent access points, and the number of available turning lanes collectively determine how efficiently and safely a U-turn maneuver can be completed. [17] demonstrated through microsimulation that geometric modifications particularly median widening and turning radius adjustment substantially improve U-turn capacity and reduce conflict frequency. Critically, at fuel station locations, the spatial proximity between the U-turn opening and the fuel station driveway effectively reduces the functional turning radius available to vehicles, exacerbating geometric constraints beyond what formal road design parameters would suggest.

Driver behavior, particularly gap acceptance decisions, constitutes a third contributing factor. Evidence from [20] confirms that drivers approaching fuel stations tend to accept smaller traffic gaps than standard gap acceptance models predict, motivated by the desire to minimize detour distance. This behavioral deviation increases conflict probability and contributes to the elevated delay and crash risk observed at these locations, independent of volume and geometric conditions.

5.1.2 Comparative Performance of U-Turn Design Types

The evidence synthesized in this review establishes a clear performance hierarchy among the three principal U-turn design types evaluated: the Conventional Median U-Turn (CMU), the Restricted Crossing U-Turn (RCUT), and the Parallel Median U-Turn (P-MUT). The CMU, which remains the dominant design in Indonesia and most developing countries, consistently records the highest delay, highest conflict frequency, and most severe LOS degradation under high-volume conditions. Its direct-crossing configuration creates maximum overlap between U-turning vehicles and opposing through traffic, resulting in extended gap-waiting periods and progressive queue formation. At fuel station locations, CMU performance deteriorates more rapidly than at general median openings, as the access conflict from the adjacent station compounds the inherent conflict structure of the design.

The RCUT design substantially reduces direct conflict by redirecting minor-street movements to designated U-turn crossovers located downstream of the main conflict point. Evidence from [21] indicates that unsignalized RCUT conversions reduce total crash frequency by 70.63% and fatal-and-injury crashes by 76.10% compared to conventional stop-controlled intersections in rural areas. In operational terms, RCUT designs reduce the number of simultaneous conflict points at the primary intersection, thereby improving through-traffic flow and reducing average delays. Guin et al. (2023) further demonstrated that the mainline emission benefits of RCUT are particularly pronounced when mainline volume substantially exceeds side-street volume a condition commonly observed at high-frequency fuel station locations on arterial roads.

The P-MUT design, which channels turning vehicles into a parallel auxiliary lane prior to executing the U-turn, offers the lowest conflict intensity among the three designs. [3] demonstrated that P-MUT implementation significantly reduces queue lengths at high-volume urban corridors. However, the P-MUT design requires substantially greater right-of-way width than either the CMU or RCUT, rendering it less applicable in the constrained road cross-sections characteristic of Indonesian urban arterials and commercial corridors. [19] further noted that the operational benefits of alternative U-turn designs including both RCUT and P-MUT configurations are maintained and potentially enhanced under higher connected and autonomous vehicle (CAV) penetration rates, suggesting long-term compatibility with emerging transportation technologies.

In summation, the comparative evidence supports the following performance hierarchy: Signalized MUT ≈ RCUT > P-MUT > CMU, with the performance differential widening as traffic volume and access conflict intensity increase. The selection of design type should therefore be calibrated not only to current traffic volume but also to the proximity and activity level of adjacent commercial access points.

The keyword co-occurrence network presented above reflects the global distribution of research attention within this domain. The relatively small cluster size associated with fuel station-specific U-turn research visually confirms that the intersection of access management and U-turn design remains an underexplored research frontier, providing justification for the analytical focus adopted in this review.

5.1.3 Implications for Road Design in Developing Country Contexts

The findings of this review carry specific and actionable implications for road design practice in Indonesia and comparable developing countries. First, the continued predominance of the CMU design in Indonesian urban roads as reflected in the national standards of both MKJI 1997 and PKJI 2014/2023 may be contributing systematically to suboptimal traffic performance at high-access commercial corridors. The evidence presented in this review suggests that Indonesian road planning authorities should consider incorporating RCUT design guidelines specifically for U-turn facilities located within a defined proximity threshold of fuel stations or similar high-frequency commercial access points.

Second, access management regulations governing the spacing between U-turn openings and commercial driveways require strengthening. The current Indonesian regulatory framework does not specify a minimum separation distance between U-turn openings and adjacent fuel station access points. Establishing such a standard grounded in the gap acceptance and conflict analysis evidence reviewed in this paper would provide planners and local governments with an evidence-based tool for mitigating compound access conflict.

Third, the methodological dominance of PKJI-based analytical approaches in Indonesian studies, while ensuring consistency, limits the comparative generalizability of findings. The adoption of microsimulation tools (PTV VISSIM, PKJI 2023) alongside field-based measurement, as demonstrated by [17] and Pradana et al. (2025), represents a methodgological advancement that should be more broadly adopted in Indonesian transportation research to enable scenario-based evaluation of design alternatives prior to implementation.

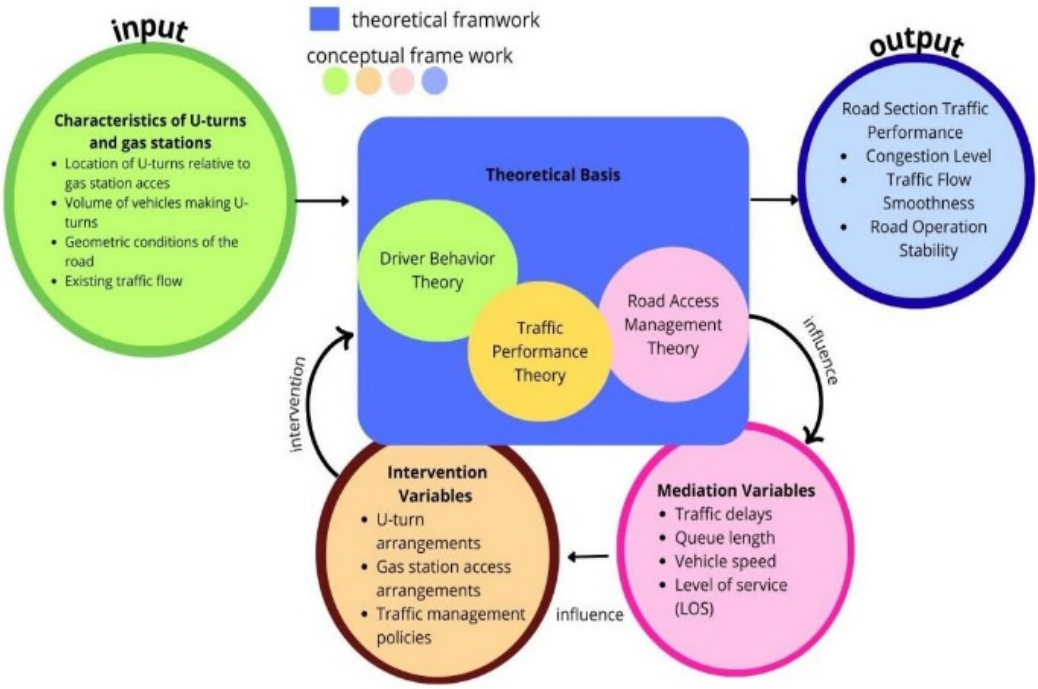

Figure 4. Visualization of the Relationship Between Research Keywords

5.2 Limitations

Several methodological and contextual limitations should be acknowledged in interpreting the findings of this review.

First, the scarcity of studies specifically examining U-turn facilities adjacent to fuel stations constitutes a fundamental evidence constraint. The majority of reviewed studies addressed U-turn performance at general median openings or signalized intersections, with only a limited subset notably [9], specifically investigating fuel station proximity effects. This scarcity limits the strength of conclusions that can be drawn regarding the magnitude of access conflict effects and constrains the generalizability of synthesized findings to SPBU-specific contexts.

Second, the Boolean search strings employed in this review, while systematically constructed across four databases, may not have captured all relevant studies using alternative terminology for U-turn facilities (e.g., "median opening," "J-turn," "directional crossover") or fuel stations (e.g., "petrol station," "filling station," "SPBU equivalent"). The possibility of retrieval bias, in which terminology-dependent searches systematically exclude relevant studies, cannot be entirely eliminated.

Third, a substantial proportion of the reviewed studies collected field data exclusively during peak-hour traffic periods, which may not fully represent the operational conditions of U-turn facilities during off-peak hours, weekends, or seasonal demand variations. This temporal sampling limitation introduces potential bias in estimated delay and LOS values, which may overstate average performance degradation relative to full-day operational conditions.

Fourth, methodological heterogeneity across the reviewed studies particularly between Indonesian studies employing MKJI/PKJI-based analytical frameworks and international studies utilizing microsimulation, gap acceptance models, or empirical Bayes safety evaluation methods limits the direct quantitative comparability of

findings. Performance metrics defined and measured under different analytical frameworks cannot be meaningfully aggregated without appropriate standardization, which was not feasible within the scope of this thematic narrative synthesis.

Fifth, this review is restricted to peer-reviewed journal articles published between 2016 and 2025 in English or Indonesian. Studies published in other languages, grey literature reports, and government technical documents which may contain relevant operational data from traffic engineering practice were excluded. This restriction may underrepresent practical implementation experience, particularly from countries with limited English-language publication outputs.

5.3 Implications for Practice, Policy, and Future Research

5.3.1 Implications for Engineering Practice

The findings of this review have direct implications for road geometric design practice. Traffic engineers designing or evaluating U-turn facilities in proximity to commercial access points particularly fuel stations should apply a heightened conflict risk assessment that accounts for the compounding effect of concurrent U-turn and access movements. The evidence supports the prioritization of geometric interventions that increase physical separation between the U-turn opening and the adjacent driveway, including channelization, auxiliary deceleration lanes for fuel station access, and mandatory turning lanes that redirect U-turning vehicles away from the primary access conflict zone. Where right-of-way constraints preclude geometric solutions, operational interventions such as restricted operating hours for U-turn facilities, access management signage, and enforced minimum gap requirements should be considered.

5.3.2 Implications for Policy and Regulation

At the policy level, the findings of this review support the development of national-level access management standards specifically addressing U-turn facilities near commercial zones. Indonesian road planning regulations should incorporate a minimum required separation distance between U-turn median openings and adjacent fuel station driveways, informed by gap acceptance analysis and conflict probability thresholds derived from the reviewed evidence. Furthermore, local government spatial planning instruments should require traffic impact assessments (TIAs) for new fuel station developments proposed within a defined influence radius of existing U-turn facilities on arterial roads. The findings also support the inclusion of RCUT and P-MUT design alternatives within updated Indonesian road geometric design manuals, providing planners with evidence-based alternatives to the conventional CMU design in high-volume commercial contexts.

5.3.3 Directions for Future Research

The evidence gaps identified in this review define several high-priority directions for future investigation. Primary among these is the need for dedicated empirical studies collecting field data specifically at U-turn facilities adjacent to fuel stations across multiple Indonesian cities, using standardized data collection protocols that capture full-day traffic patterns rather than peak-hour observations alone. Such studies would enable the development of location-specific delay and capacity models that account for the compounding access conflict dynamics documented in this review.

Second, comparative simulation studies evaluating the relative performance of CMU, RCUT, and P-MUT designs in the specific geometric and traffic volume conditions of Indonesian fuel station corridors would provide planners with evidence-based design selection criteria tailored to local conditions. [20] demonstrated that capacity estimation models developed under homogeneous traffic assumptions require substantial adaptation for mixed-traffic environments; equivalent adaptation is needed for the Indonesian heterogeneous traffic context.

Third, the integration of emerging analytical approaches including connected vehicle trajectory data analysis, machine learning-based conflict prediction, and environmental performance assessment would enhance the methodological rigor of future U-turn performance studies and align Indonesian transportation research with international practice, as demonstrated by [19] in the context of CAV-integrated RCUT evaluation.

6. Conclusion

This systematic literature review synthesized findings from 30 peer-reviewed studies published between 2016 and 2025, examining traffic performance at U-turn facilities with particular

focus on locations adjacent to fuel stations (SPBU). Three principal conclusions emerge from the evidence. First, U-turn facilities near fuel stations generate compounded traffic conflict conditions combining U-turning vehicle movements with fuel station entry/exit activities that produce greater delay, longer queues, and more rapid level-of-service degradation than general median openings under equivalent traffic volumes. Second, opposing traffic volume and geometric configuration are the dominant performance determinants, with degree of saturation exceeding 0.75 consistently corresponding to LOS D or below at peak hours. Third, alternative designs outperform the Conventional Median U-Turn, with the RCUT reducing crash frequency by up to 70.63% and demonstrating superior operational efficiency. No prior systematic review has specifically addressed U-turn facilities at fuel station locations as an integrated conflict zone, confirming the novelty of this study. Future research should prioritize field-based empirical studies at SPBU-adjacent U-turn locations across multiple Indonesian cities using standardized full-day data collection protocols.

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