Vol 6, Issue 3, March 2026 www.ijesti.com E-ISSN: 2582-9734
International Journal of Engineering, Science, Technology and Innovation (IJESTI)

Highway Capacity Analysis and Level of Service Evaluation Using Advanced Traffic Simulation Models for Urban Roads: A Review

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ABSTRACT

Highway capacity analysis and Level of Service (LOS) evaluation are essential for understanding roadway performance under increasing traffic demand. Rapid urbanization, vehicle growth, and mixed traffic conditions have created congestion, delay, and safety issues on highways and urban corridors. This study focuses on the use of traffic simulation models for evaluating highway capacity and LOS more realistically than conventional analytical methods. Simulation tools help analyse vehicle movement, delay, density, speed, and queue formation under different traffic scenarios. The study highlights the importance of simulation-based approaches for improving traffic management, reducing congestion, and supporting sustainable transportation planning.

Keywords: *Highway Capacity, Level of Service, Traffic Simulation, Congestion Management.*

I. INTRODUCTION

Highway transportation systems have been recognized as the backbone of economic growth and regional connectivity in both developed and developing countries. Rapid urbanization, population growth, industrial expansion, and increasing vehicle ownership have significantly intensified traffic demand on existing roadway infrastructure. As a result, many highways and urban road corridors have experienced severe congestion, delays, safety concerns, and operational inefficiencies. Highway capacity analysis and Level of Service (LOS) evaluation have therefore become essential components in transportation engineering for assessing roadway performance and identifying suitable traffic management strategies. Capacity analysis refers to the determination of the maximum number of vehicles that can reasonably pass through a roadway segment or intersection under prevailing roadway, traffic, and environmental conditions, while LOS represents the qualitative assessment of traffic operations based on parameters such as speed, travel time, density, delay, and driver comfort. Traditionally, the Highway Capacity Manual (HCM) has been widely adopted as the standard methodology for evaluating roadway performance and assigning LOS categories ranging from A to F. However, with the increasing complexity of heterogeneous traffic conditions, mixed vehicle compositions, and dynamic travel behaviors, conventional analytical methods have often been found insufficient for accurately representing real-world traffic operations. Consequently, advanced traffic simulation models such as PTV VISSIM, AIMSUN, and microscopic simulation tools have increasingly been utilized for detailed highway capacity evaluation and operational analysis. Ahmed et al. (2026) reported that multilane roundabouts in Islamabad experienced severe congestion due to rising traffic demand exceeding roadway capacity, and simulation using PTV VISSIM successfully improved LOS from F to D by reducing delays and queue lengths. Similarly, Salam (2022) emphasized that capacity and LOS evaluation using HCM 2016 methods on urban multilane highways revealed operational conditions varying between LOS C and D under heterogeneous traffic conditions. These studies demonstrated that simulation-based approaches provided more realistic and reliable assessments compared with traditional analytical techniques.

In recent years, traffic simulation models have emerged as highly effective tools for analyzing complex transportation systems because they enable researchers and planners to replicate real-world driving behavior, evaluate operational scenarios, and test alternative infrastructure strategies without disturbing actual traffic conditions. Microscopic traffic simulation models, in particular, have gained widespread acceptance due to their ability to simulate individual vehicle interactions, lane-changing behavior, car-following characteristics, and intersection dynamics. Such models have been extensively used for evaluating intersections, weaving sections, bicycle infrastructure, autonomous vehicle operations, freeway segments, and urban traffic networks. Navandar (2025) reviewed uncontrolled intersections under mixed traffic conditions and highlighted that aggressive driver behavior, violations of traffic priority rules, and heterogeneous traffic composition made traffic operations highly unpredictable, thereby requiring advanced simulation approaches for accurate capacity and LOS evaluation. Likewise, Roy et al. (2024) investigated the influence of autonomous shuttle services on urban road capacity using microscopic traffic simulation and observed that increasing shuttle frequency caused higher delays and reduced travel speeds, although optimized shuttle speeds improved overall traffic performance. Furthermore, Avelar Brêtas et al. (2024) proposed a simulation-based method for evaluating LOS at elongated roundabouts on rural highways and found that simulation outputs closely matched field observations. Traffic simulation has also proven valuable in evaluating non-conventional transportation infrastructure. Grigoropoulos et al. (2021) assessed bicycle highway infrastructure through simulation modeling and concluded that optimized bicycle signal timings significantly enhanced overall traffic performance. Similarly, Azadpeyma and Kashi (2019) applied VISSIM simulation for metro station capacity evaluation and observed substantial performance improvements through operational modifications such as reduced train headways and automated ticketing systems. These investigations collectively demonstrated that traffic simulation models provided flexibility, precision, and adaptability in analyzing modern transportation systems under varying traffic conditions.

The integration of traffic simulation models with highway capacity analysis has also facilitated the development of efficient traffic management strategies, intelligent transportation systems, and sustainable roadway planning approaches. Traditional LOS evaluation techniques mainly focused on traffic density and speed; however, modern transportation studies increasingly consider travel time reliability, network topology, environmental impacts, multimodal integration, and safety performance. Pulugurtha and Imran (2020) stated that travel time reliability had become a critical parameter in evaluating freeway operational performance, with LOS thresholds varying according to roadway speed conditions. Ahmed et al. (2023) further emphasized that roadway links should be analyzed not only based on traffic flow characteristics but also considering their topological importance within the road network. Their study revealed that targeted interventions on critical roadway links improved LOS and significantly reduced travel delays in downtown Boise, Idaho. In addition, Ramadan et al. (2021) examined weaving sections on urban roads using PTV VISSIM and reported substantial differences between simulation-based LOS estimation and conventional HCM approaches under high volume-to-capacity ratios. These findings highlighted the necessity of simulation-based methods for accurately capturing traffic dynamics in congested urban environments. With the rapid advancement of intelligent transportation systems, connected vehicles, autonomous mobility, and smart city infrastructure, highway capacity analysis using traffic simulation models has become increasingly important for designing efficient, safe, and sustainable transportation networks. Therefore, this study focuses on highway capacity analysis and Level of Service evaluation using traffic simulation models to understand traffic behavior, assess roadway performance, and identify suitable strategies for improving operational efficiency and reducing congestion in modern transportation systems.

II. RESEARCH BACKGROUND

Ahmed (2026) reported that most junctions, particularly multilane roundabouts in Islamabad, Pakistan, were experiencing severe traffic congestion due to the rapid increase in vehicular volume, where traffic demand exceeded available road space. It was indicated that, given Pakistan's diverse driving conditions, effective vehicular traffic modelling remained a debated issue. The study emphasized that enhancing the traffic capacity of multilane roundabouts was crucial for addressing urban traffic challenges. Focusing on the DHA Phase 1 roundabout at GT Road, a detailed analysis of traffic delay was conducted using the Highway Capacity Manual (HCM) and PTV Vissim simulation software. The analysis revealed that the Level of Service (LOS) improved from F to D. Significant reductions in delay and queue length were observed across all approaches. Furthermore, a solution was proposed, which substantially minimized congestion and improved overall traffic performance.

Navandar (2025) examined uncontrolled intersections, describing them as at-grade intersections without explicit traffic control measures. It was observed that traffic behavior at such intersections became highly complex due to the absence of proper regulation, particularly under mixed traffic conditions. The study highlighted that variations in driver characteristics, aggressive driving tendencies, and frequent violations of priority rules further aggravated operational challenges. As a result, traffic flow at uncontrolled intersections was found to be highly unpredictable. Considering that a significant proportion of intersections in developing countries like India were uncontrolled, the study emphasized the need to evaluate their performance from both capacity and safety perspectives. The article presented a comprehensive review of research conducted over the previous three decades, covering aspects such as critical gap and lag, passenger car equivalents, conflicting flows, capacity, level of service, and simulation approaches. It was also suggested that the findings could guide future research directions.

Roy et al. (2024) examined the transformative potential of autonomous vehicles in modern transportation systems and suggested that rapid technological advancements were expected to enhance accessibility and safety in human mobility. It was reported that autonomous shuttle services had been introduced across various urban environments worldwide, necessitating detailed assessment of their safety and mobility performance. The study aimed to calibrate the movement of autonomous shuttles within a microscopic traffic simulation model due to the limited availability of real-world data. A prototype shuttle system operating in Lake Nona, Orlando, Florida, was emulated under different time conditions. Real-world trajectory data were utilized to replicate shuttle behavior accurately. The findings indicated that increased shuttle frequency led to higher delay percentages and reduced travel speeds. However, optimizing shuttle speeds during peak and off-peak hours was found to improve overall traffic conditions, thereby supporting better policy formulation and infrastructure planning.

Avelar Brêtas et al. (2024) examined the design of roadway intersections in Brazil, noting that such designs were generally based on guidelines provided in official manuals and documents like the Highway Capacity Manual (HCM). However, it was observed that certain alternative intersection types, including elongated roundabouts (ERs), were not addressed in these standards. The study proposed a method to estimate the level of service for ERs located on two-lane rural highways. Traffic data were collected from field observations to capture varying traffic patterns and to determine desired speeds at ER sites. The Aimsun Next traffic simulator was utilized to generate multiple hypothetical scenarios, facilitating the development of models for evaluating performance measures such as average delay (di) and extra distance travel time (EDTT). The proposed method was validated, and the results indicated that the estimated values closely matched field observations.

Ahmed et al. (2023) examined recent advancements in network science and reported that the topological characteristics of network elements, particularly links, carried significant implications for system performance. The study emphasized that roadway segments should be evaluated not only based on traffic conditions but also considering their position within the network. The authors aimed to develop a framework for identifying critical road links using topological measures such as centrality and assessing the impact of systematic interventions. A real-world road network in downtown Boise was analyzed through microscopic traffic simulation. The findings indicated that targeted interventions on congested and critical links improved the level of service from LOS F to LOS E and from LOS D to LOS C. Additionally, reductions in travel time and vehicular delay were observed for high-demand origin-destination pairs. The study concluded that integrating topological attributes with traffic flow parameters enhanced overall road network performance and supported effective traffic management strategies.

Salam (2022) conducted a study to evaluate the capacity and level of service of an urban multi-lane highway characterized by heterogeneous traffic composition. It was reported that capacity represented the maximum sustainable hourly flow rate, while level of service served as an indicator of roadway performance and quality. The study adopted the methodology outlined in HCM 2016. Data were collected from four selected highway segments that satisfied the specified manual conditions. Traffic volume data were obtained using both the moving car method and the stationary method. Additionally, relevant geometric parameters were measured. The peak hour factor was determined for each segment. Spot speed analysis was carried out to verify posted speed limits and estimate free flow speed. The findings indicated that most segments operated between level of service C and D, with base capacity ranging from 1850 to 1900 pc/h/ln.

Grigoropoulos et al. (2021) examined the increasing trend of bicycle traffic in urban areas and noted that it had compelled transport authorities to reconsider spatial allocation among different transport modes. It was observed that transport policies had favored the development of high-quality bicycle infrastructure to enhance safety, improve traffic conditions, and promote bicycling over vehicular transport. The study highlighted that in cities with a growing share of cyclists, bicycle highways had been proposed to reduce pressure on public transport and road networks. However, due to high costs and spatial constraints, extensive planning had been deemed necessary. The authors indicated that the impacts of such infrastructure on overall traffic performance had not been sufficiently explored. Using a simulation model based on Munich's pilot route, the study assessed traffic impacts and found that optimal performance was achieved through unidirectional bicycle highways combined with extended bicycle signal timings.

Ramadan et al. (2021) investigated that traffic movement in weaving sections was not limited to highways but also significantly influenced urban roads. The study aimed to examine two-sided weaving sections on urban roads, noting that the Highway Capacity Manual Sixth Edition had primarily focused on freeway weaving sections. It was reported that three different two-sided weaving sites were selected to represent varying traffic conditions, and simulations were conducted using PTV Vissim to estimate the level of service (LOS). The results obtained from calibrated and validated models were compared with those derived from the HCM equations. The findings indicated that HCM produced similar LOS and density values at a V/C ratio of 0.44. However, at higher V/C ratios of 0.63 and 0.93, significant discrepancies were observed, with simulation results showing considerable variation from the HCM method.

Pulugurtha and Imran (2020) examined the challenges associated with assessing operational performance for transportation agencies, emphasizing the complex and dynamic characteristics of traffic movement. It was reported that operational performance had traditionally been classified qualitatively

using a six-level letter-grade Level of Service (LOS) scale, ranging from A to F, as defined in the Highway Capacity Manual. The study indicated that density had been used as a primary parameter for freeway segments, while speed and travel time had been widely adopted by practitioners for decision-making. Furthermore, it was highlighted that travel time reliability had emerged as a critical performance indicator in modern transportation systems. The authors stated that initiatives under the Strategic Highway Research Program had aimed to quantify LOS using reliability measures. Their findings suggested that travel time thresholds varied with speed limits, while reliability thresholds decreased as speed limits declined, indicating nuanced relationships between operational performance and speed conditions.

Azadpeyma and Kashi (2019) examined metro stations as a critical component of rail transportation infrastructure, emphasizing that improvements in station capacity could enhance overall network performance. They defined station capacity as the ability to ensure safety and comfort for the expected passenger volume. In their study, passenger flow at Shohada Square metro station was analyzed and simulated using VISSIM software. Based on simulation outcomes and guidelines from the TCRP manual, six different scenarios were evaluated under varying conditions. The study identified two key strategies for improving station performance. It was found that removing manual ticket purchase facilities led to a 43% improvement in the performance of the control space area. Additionally, reducing train headway from 240 seconds to 180 seconds increased available platform space per pedestrian by 35%. The authors concluded that the proposed simulation-based approach could be applied to assess and optimize other metro and transportation stations.

III. KEY FINDINGS FROM STUDY

Author & Year	Objective	Methodology/Tools Used	Major Findings
Ahmed et al. (2026)	To evaluate congestion and LOS at multilane roundabouts	HCM analysis and PTV VISSIM simulation	LOS improved from F to D with reduced delays and queue lengths
Navandar (2025)	To review capacity and LOS of uncontrolled intersections	Literature review of mixed traffic studies	Mixed traffic and driver behavior caused unpredictable operations
Roy et al. (2024)	To analyze autonomous shuttle impact on urban roads	Microscopic traffic simulation using trajectory data	Higher shuttle frequency increased delays; optimized speed improved traffic
Avelar Brêtas et al. (2024)	To estimate LOS for elongated roundabouts	AIMSUN Next simulation and field validation	Simulation results closely matched observed field conditions
Ahmed et al. (2023)	To identify critical road links and improve LOS	Microscopic traffic simulation with network centrality analysis	Interventions improved LOS and reduced travel time
Salam (2022)	To evaluate capacity and LOS of urban multilane highways	HCM 2016 methodology with field surveys	Highways operated mostly between LOS C and D
Grigoropoulos et al. (2021)	To analyze traffic effects of bicycle highways	Urban traffic simulation model	Unidirectional bicycle highways improved operational efficiency

Ramadan et al. (2021)	To assess LOS of urban weaving sections	PTV VISSIM simulation and HCM comparison	Significant variation observed between simulation and HCM results
Pulugurtha & Imran (2020)	To model freeway LOS based on travel time reliability	Reliability-based LOS modeling	Reliability thresholds decreased with lower speed limits
Azadpeyma & Kashi (2019)	To analyze metro station LOS and capacity	VISSIM simulation and TCRP guidelines	Reduced headways improved pedestrian platform performance

IV. CONCLUSION

Highway capacity analysis and Level of Service evaluation have become increasingly important in transportation engineering due to rapid urbanization, rising traffic demand, and growing roadway congestion. Traditional analytical methods such as those recommended in the Highway Capacity Manual have provided valuable frameworks for assessing roadway performance; however, the increasing complexity of heterogeneous traffic conditions, mixed vehicle composition, and dynamic driver behavior has highlighted the limitations of purely theoretical approaches. The reviewed studies demonstrated that traffic simulation models such as PTV VISSIM, AIMSUN, and other microscopic simulation tools offered more accurate and realistic representations of traffic operations under varying roadway and environmental conditions. Simulation-based analyses enabled detailed evaluation of intersections, weaving sections, bicycle highways, freeway corridors, metro stations, and autonomous vehicle systems by replicating individual vehicle interactions and operational behaviors. The literature also indicated that simulation tools effectively supported the identification of congestion points, optimization of traffic flow, reduction of delays, and improvement of roadway LOS. Several studies reported significant operational improvements after implementing simulation-based traffic management strategies, including reduced queue lengths, enhanced travel speeds, and improved network reliability. Furthermore, modern traffic performance evaluation has evolved beyond conventional speed and density measures to include travel time reliability, network topology, multimodal transportation impacts, and intelligent transportation systems. The integration of advanced traffic simulation with highway capacity analysis therefore provides transportation planners and engineers with a powerful decision-support framework for sustainable roadway planning and efficient traffic management. Overall, the reviewed literature confirmed that traffic simulation models are essential tools for evaluating and improving highway operational performance, particularly under complex and heterogeneous traffic conditions encountered in modern urban transportation systems.

V. FUTURE SCOPE

- Future studies may focus on integrating artificial intelligence and machine learning algorithms with traffic simulation models for real-time highway capacity prediction and adaptive traffic management.
- Research can be extended toward the evaluation of connected and autonomous vehicle impacts on roadway capacity, safety, and Level of Service under mixed traffic environments.
- Advanced simulation frameworks may be developed to incorporate environmental parameters such as fuel consumption, emissions, and energy efficiency into LOS assessment models.

- Future investigations may emphasize multimodal transportation systems by integrating pedestrian, bicycle, public transit, and freight movement analysis within highway simulation environments.
- There is significant scope for developing region-specific LOS and capacity models for developing countries where heterogeneous traffic conditions differ substantially from HCM assumptions.
- Integration of Geographic Information Systems (GIS), Internet of Things (IoT), and big data analytics with traffic simulation can improve traffic monitoring and infrastructure planning accuracy.
- Further research may examine the effects of smart traffic control systems, adaptive signal coordination, and intelligent corridor management strategies on highway operational performance.
- Simulation-based evaluation of emergency evacuation traffic, disaster management scenarios, and resilient transportation systems can be explored in future transportation planning studies.
- Future work may also focus on cloud-based and digital twin traffic simulation systems for real-time monitoring and dynamic roadway performance optimization.
- Additional research is required to improve calibration and validation techniques for microscopic simulation models to ensure better representation of real-world driver behavior and traffic dynamics.

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