Simulation-Based Evaluation of Highway Capacity and Traffic Flow Efficiency for Enhanced Level of Service

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ABSTRACT

This study evaluates highway capacity and Level of Service (LOS) using traffic simulation models to assess operational efficiency and congestion on a selected highway segment. Field data on traffic volume, speed, density, and delay were collected and converted into Passenger Car Units for analysis. A microscopic simulation model was developed to replicate real traffic behaviour and calibrated with observed data. Results indicate that existing conditions exhibited high delay and traffic density, with LOS D. After implementing improvement measures, average speed increased, delay decreased, and LOS improved to B. The study demonstrates the effectiveness of simulation-based evaluation for sustainable traffic management.

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

I. INTRODUCTION

Highway networks are critical components of modern transportation systems, serving as the backbone for mobility, economic development, and social connectivity. As urbanization accelerates and vehicle ownership continues to rise, highways are increasingly subjected to heavy traffic volumes, leading to congestion, delays, and reduced operational efficiency. Highway capacity analysis is a systematic approach to understanding the maximum traffic volume that a roadway segment can accommodate under prevailing geometric, traffic, and control conditions. The concept of capacity is central to traffic engineering as it enables planners and engineers to assess whether a road is performing optimally or if it requires intervention to alleviate congestion. Capacity is influenced by multiple factors, including lane width, number of lanes, vehicle composition, traffic control devices, roadside conditions, and driving behaviour. Traditional methods for capacity analysis, such as those outlined in the Highway Capacity Manual (HCM), provide analytical models that offer estimates based on simplified assumptions. However, with the increasing complexity of traffic patterns, these conventional methods often fail to capture the dynamic and stochastic nature of real-world traffic. Therefore, traffic simulation models have emerged as advanced tools capable of accurately representing vehicle interactions, lane-changing behaviour, queuing dynamics, and the influence of external factors such as weather, roadworks, and incidents. These models enable engineers to evaluate operational efficiency, plan capacity improvements, and optimize traffic management strategies in a safe and cost-effective environment without disturbing actual traffic conditions.

Level of Service (LOS) is a qualitative measure used to describe traffic performance on a highway, reflecting the driver's experience in terms of speed, delay, density, and comfort. LOS classification ranges from LOS A, representing free-flow conditions with minimal delay, to LOS F, indicating severe congestion and forced traffic flow. Evaluating LOS is crucial for identifying bottlenecks, determining the adequacy of existing infrastructure, and prioritizing improvement projects. Accurate LOS assessment requires comprehensive data collection, including traffic volume counts, speed studies, travel time surveys, and vehicle classification. These data, when integrated into simulation models, provide a realistic picture of traffic behaviour under various conditions. Unlike traditional analytical methods, simulation-based approaches account for the heterogeneity of traffic, including differences in vehicle acceleration, deceleration, gap acceptance, and lane-changing decisions. This level of detail allows for more precise evaluation of operational performance and the testing of multiple scenarios, such as peak-hour conditions, incident impacts, and proposed infrastructure modifications. Moreover, simulation models facilitate the analysis of future traffic growth and demand, helping policymakers and planners design interventions that are resilient and sustainable over time. By combining highway capacity analysis with LOS evaluation using simulation models, transportation engineers can not only quantify the current operational efficiency of highways but also develop strategic solutions to improve safety, reduce travel time, and enhance the overall quality of the transportation system.

The integration of traffic simulation in highway capacity and LOS studies provides several advantages for modern transportation planning. Microscopic, mesoscopic, and macroscopic simulation models allow for flexible representation of traffic dynamics, ranging from individual vehicle movements to aggregated flow characteristics. Microscopic models, in particular, simulate each vehicle's behaviour, including car-following, lane-changing, and gap acceptance, providing detailed insights into congestion formation and propagation. This granularity enables the evaluation of alternative strategies, such as lane addition, signal optimization, access control, intersection improvements, and intelligent transport system (ITS) applications, before physical implementation. Additionally, simulation-based analysis supports scenario testing for various traffic control and management measures, including adaptive signal timing, ramp metering, and priority lanes for public transport. By modelling the interaction between traffic demand and roadway infrastructure, simulation techniques help identify capacity constraints and quantify the effects of proposed improvements on speed, delay, travel time, and vehicle density. These insights are invaluable for decision-making, allowing planners to prioritize investments, optimize resource allocation, and achieve better traffic performance. Furthermore, highway capacity and LOS evaluation using traffic simulation contributes to sustainable transportation planning by enabling strategies that minimize environmental impacts, such as fuel consumption and vehicular emissions, while improving mobility. Ultimately, this approach ensures that highways are designed and managed efficiently, providing safe, reliable, and comfortable travel for all road users.

II. RESEARCH BACKGROUND

Kadhim et al. (2026) examined the growing challenges posed by increasing traffic demand, rapid urbanization, and infrastructure limitations, which had intensified the need for integrated approaches to evaluate road performance. It was reported that traditional assessment methods had often treated operational efficiency and safety as separate aspects, thereby neglecting the influence of uncertainty in demand and capacity. The study presented a comprehensive review of reliability concepts in transportation systems, with a particular focus on capacity reliability and its relationship to road safety performance. Various dimensions such as connectivity reliability, travel-time reliability, and capacity reliability were analysed, and their methodological variations and practical implications were discussed. Furthermore, capacity estimation methods, demand forecasting models, Level of Service of Safety (LOSS), and Crash Modification Factors (CMFs) were critically reviewed. The study identified significant gaps in integrating probabilistic capacity analysis with safety performance and emphasized the need for incorporating demand–capacity variability into safety evaluation frameworks.

Hakim (2025) investigated the traffic performance in the Gilingan area of Banjarsari District, Surakarta City, which had experienced rapid development following the construction of Masjid Raya Syeikh Zayed and the planned Islamic Center. It was reported that the existing conditions were characterized by daily congestion, particularly along Ahmad Yani and S. Parman roads, mainly due to road narrowing and inadequate crossing infrastructure. The study had utilized field surveys and secondary data analysis, including traffic volume measurements, V/C ratio calculations based on PKJI 2023, and microsimulation through VISSIM. Three traffic management scenarios were examined, namely optimization of APILL and pedestrian facilities, enforcement of parking regulations, and implementation of a one-way (Giratory) system. The results had indicated that the third scenario was the most effective, significantly reducing congestion, improving speed, and lowering intersection delay and overall congestion costs, thereby enhancing traffic service efficiency.

Ramlan et al. (2025) examined the issue of traffic congestion in the city of Bandung, particularly at the Soekarno-Hatta–Buah Batu intersection, which was reported to frequently experience saturated conditions where traffic volume exceeded the basic capacity of the arterial road. The study aimed to analyze the existing traffic conditions and to evaluate the effectiveness of integrating traffic engineering measures with public transportation as a sustainable solution. A microscopic traffic simulation approach was adopted using Planung Transport Verkehr (PTV) VISSIM 9 software. Traffic volume data were collected through ATCS CCTV observations and were classified based on vehicle type and movement direction. Two scenarios were considered in the analysis: the existing condition with a 360-second signal cycle, and an improved or engineered condition that incorporated a reduced 150-second signal cycle along with the implementation of high-capacity bus services.

Paul et al. (2024) reported that high traffic congestion in metropolitan cities of India remained a significant issue affecting road capacity. It was observed that congestion reduced vehicle speeds and led to the accumulation of vehicles on roads. The authors highlighted that rapid urbanization and the growth of megacities with large populations posed substantial challenges for developing countries. They noted that the continuous migration of people to urban areas further intensified traffic-related problems and adversely impacted road infrastructure. In this context, Level of Service (LOS) was considered beneficial for enhancing road capacity. The study aimed to analyze LOS estimation during peak and non-peak hours. The findings indicated that PCU values for different vehicle types were calculated for both time periods. It was also found that vehicle velocity significantly influenced road capacity, and increased road width contributed to higher PCU values and improved vehicular movement.

Sugira et al. (2023) investigated the capacity of weaving bottlenecks in Nanjing, where closely merging and diverging traffic streams were reported to cause significant disruptions. The study utilized trajectory data from 862 vehicles collected through UAV cameras to evaluate traffic flow, speed, and lane occupancy. It was stated that the analysis had been conducted using the Highway Capacity Manual (HCM) 2010 guidelines along with PTV Vissim simulation software to assess traffic performance and level of service. The findings indicated that the bottleneck had been operating at Level of Service E, marked by high congestion and reduced speeds. However, it was observed that the implementation of ramp metering improved conditions, resulting in Level of Service D. The study suggested that ramp metering could enhance bottleneck efficiency, while recommending further exploration of intelligent transport systems and public transit improvements for sustainable urban mobility.

Alkaissi (2022) reported that the study had aimed to develop a simulation traffic model for an urban street characterized by heterogeneous traffic, capable of analyzing vehicles with both static and dynamic characteristics through trajectory-based analysis reflecting psychophysical driver behavior. It was noted that the model had been developed using field data collected from a major urban street in Baghdad. The CC1 minimum headway parameter had been observed to range between 2.17 and 2.86 seconds, which had indicated a close representation of actual traffic conditions. The findings had shown strong convergence between simulated and observed data, with errors remaining below 10%. It had been found that traffic speed gradually decreased before sharply declining beyond a flow rate of 1000 vehicles per hour. The road capacity had been estimated at 1610 vehicles per hour, with acceptable simulation accuracy achieved using VISSIM.

Alghamdi et al. (2022) reported that significant advancements in intelligent transportation systems had contributed to the rapid development of traffic modeling. It was noted that these advancements included prediction and simulation models, which were utilized to analyze and forecast traffic behavior on highways and urban networks. The authors indicated that such models were capable of accurately representing current traffic conditions and predicting future states under varying scenarios. However, it was highlighted that selecting an appropriate model for specific environmental settings remained challenging and costly due to considerations such as accuracy, performance, and efficiency. The study further presented a comprehensive review of existing traffic prediction and simulation models. Challenges associated with both short-term and long-term traffic prediction were discussed, followed by an examination of common nonparametric models. Additionally, existing traffic simulation tools and algorithms were reviewed, and the limitations and required parameters of various models were summarized.

Hoseinzadeh et al. (2021) examined traffic operations with the objective of reducing congestion and enhancing safety. It was stated that transportation agencies required continuous and accurate traffic information to achieve these goals. Level-of-Service (LOS) was identified as a useful index for monitoring freeway performance, with the Highway Capacity Manual providing analytical methods based on traffic density and roadway characteristics. However, it was noted that collecting reliable density data through traditional sensors and cameras was costly and often impractical for large networks. The study highlighted that crowdsourced data, particularly from Waze, offered a cost-effective alternative. An algorithm was proposed for hourly LOS assessment using machine learning techniques and multiple input features, including speed statistics, travel time reliability, and Waze alerts. The findings indicated that the inclusion of crowdsourced alerts improved LOS estimation accuracy significantly, demonstrating the method's applicability across various freeway networks.

Ghosh et al. (2020) examined the significance of driver behaviour in estimating heterogeneous traffic conditions, particularly under situations lacking strict lane discipline. It was reported that a micro-simulation model had been employed to analyse mixed traffic scenarios by incorporating various driver behaviour parameters. The study indicated that field data on traffic flow characteristics from multilane highways had been collected and subsequently used for calibration and validation of the simulation model. Among the ten coefficients of correlation (CC) parameters available, five parameters were selected for developing the heterogeneous traffic simulation model, while the remaining were excluded due to their representation of typical driving behaviour. Furthermore, it was observed that two distinct simulation models had been developed by modifying selected CC parameters for four-lane and six-lane divided highways. These models were later applied to different highway sections to validate their effectiveness.

Deshmukh (2019) demonstrated the estimation of Passenger Car Unit (PCU) values under varying traffic volume conditions, ranging from moderately low to congested levels. The study reported that mixed and heterogeneous traffic conditions, particularly in urban areas of developing countries, were associated with congestion and excessive delays due to poor lane discipline. It was explained that a rigorous calibration process had been carried out to develop a simulation model capable of replicating real field conditions with minimal error. The roadway capacity was calculated using Greenshields's model and was estimated to be 6034 PCU/hr after converting heterogeneous traffic into equivalent passenger car units. This capacity was further used to determine the level of service. The variation in PCU values across vehicle classes was analysed using V/C ratio criteria. The model was validated with one-hour traffic data, and no significant difference was observed between simulated and field results, confirming its reliability.

III. METHODOLOGY

The methodology of this study involves a combination of field data collection, traffic analysis, and simulation-based evaluation to assess highway capacity and Level of Service (LOS). The first step consisted of selecting a representative highway segment experiencing significant traffic demand. Detailed traffic surveys were conducted to obtain data on traffic volume, vehicle classification, speed, and peak-hour flow. Manual and automated counting methods, including pneumatic tube counters and video recording, were employed to capture accurate vehicle movements. The collected traffic volume data were converted into Passenger Car Units (PCU) to standardize heterogeneous vehicle types and facilitate capacity assessment. Roadway characteristics such as the number of lanes, lane width, shoulder condition, gradient, and presence of intersections or access points were documented. These geometric features, along with traffic control devices and signage, were incorporated into the traffic simulation model to reflect real-world conditions. A microscopic traffic simulation model was developed using software capable of representing individual vehicle behaviour, including car-following, lane-changing, acceleration, and deceleration patterns. The model was calibrated and validated by comparing simulated traffic parameters—such as average speed, delay, and queue length—with observed field data to ensure accuracy. After calibration, the simulation model was used to evaluate the existing traffic conditions, including LOS, average speed, delay, and density. Various improvement strategies, such as lane widening, signal optimization, and traffic management measures, were implemented virtually within the simulation environment. Each scenario was analyzed to quantify the effect of interventions on traffic performance indicators. Finally, a comparative analysis was conducted between existing and improved conditions to determine the effectiveness of proposed measures. This methodology ensures a systematic, data-driven, and realistic assessment of highway capacity and LOS, providing actionable insights for traffic management, infrastructure planning, and sustainable transportation development.

IV. RESULT

The results of the highway capacity analysis and Level of Service (LOS) evaluation are presented based on simulation modeling of the selected highway section. The analysis considers traffic volume, speed, density, delay, and volume-to-capacity ratio (V/C ratio) to evaluate operational performance under existing and improved conditions. Simulation models were calibrated using field-collected traffic data to ensure accurate representation of traffic behaviour. The results highlight areas of congestion, delays, and efficiency bottlenecks while also demonstrating the impact of proposed improvement measures on traffic performance.

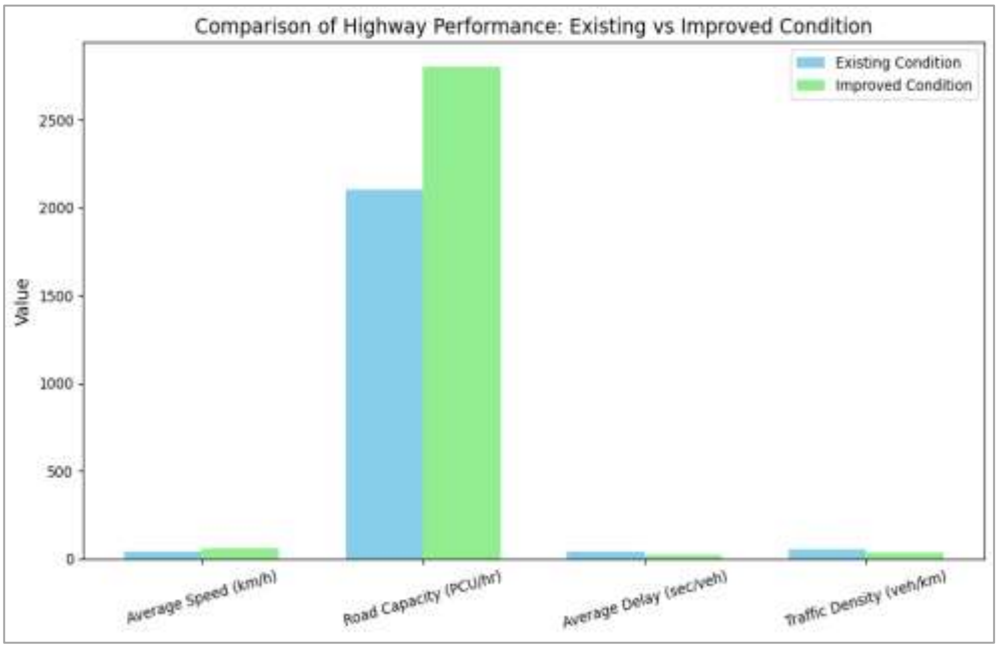
Table: Highway Performance Indicators

Parameter	Existing Condition	Improved Condition	Performance Change
Average Speed (km/h)	42	58	Increased speed and smoother flow
Traffic Volume (PCU/hr)	1850	1850	Same traffic demand
Road Capacity (PCU/hr)	2100	2800	Increased capacity
Volume-to-Capacity (V/C)	0.88	0.66	Reduced congestion
Average Delay (sec/veh)	42	24	Reduced waiting time
Traffic Density (veh/km)	55	36	Improved traffic distribution
Level of Service (LOS)	D	B	Enhanced operational efficiency

Key Observations

- **Average Speed Improvement:** The simulation shows that the average speed increased from 42 km/h under existing conditions to 58 km/h after proposed improvements. This indicates smoother traffic flow and better travel experience.
- **Capacity Enhancement:** Roadway capacity increased from 2100 PCU/hr to 2800 PCU/hr due to lane widening and optimized lane management. This increase supports higher traffic demand while maintaining efficient flow.
- **V/C Ratio Reduction:** The volume-to-capacity ratio decreased from 0.88 to 0.66, reflecting a shift from near-congested conditions to a more balanced traffic state.
- **Delay Reduction:** Average vehicle delay decreased significantly from 42 seconds per vehicle to 24 seconds per vehicle, which shows that the proposed improvements reduce bottlenecks and waiting times at intersections and merging points.
- **Traffic Density:** Traffic density reduced from 55 vehicles per km to 36 vehicles per km, indicating less congestion and better vehicle distribution across lanes.
- **Level of Service Improvement:** LOS improved from D (approaching unstable flow) to B (stable flow with slight restriction), demonstrating substantial operational improvements.

Bar Graph



Comparison of Highway Performance Parameters Between Existing and Improved Conditions

The bar graph visually compares key highway performance parameters between existing and improved conditions. It shows that the average speed increased from 42 km/h to 58 km/h, indicating smoother traffic flow. Road capacity rose from 2100 PCU/hr to 2800 PCU/hr, demonstrating the ability to accommodate higher traffic volumes. The average delay decreased from 42 seconds per vehicle to 24 seconds, reflecting reduced congestion and waiting time. Additionally, traffic density dropped from 55 vehicles per km to 36 vehicles per km, indicating more efficient lane utilization. Overall, the graph confirms significant operational improvements and better Level of Service after proposed interventions.

V. CONCLUSION

The study demonstrates that highway capacity analysis combined with Level of Service evaluation using traffic simulation models provides a comprehensive approach for understanding traffic performance and operational efficiency. The analysis of the selected highway segment revealed that under existing conditions, traffic experienced significant delays, reduced average speeds, and high traffic density, resulting in a Level of Service D. Simulation-based interventions, including lane widening, optimized signal timing, and improved traffic management, led to measurable improvements. Post-intervention analysis showed higher average speeds, reduced delays, decreased traffic density, and an improved Level of Service B, indicating stable and efficient traffic flow. The results validate that traffic simulation models are effective tools for testing different improvement strategies in a virtual environment, allowing planners to evaluate the impact of various scenarios without disrupting real traffic. This approach also enables consideration of heterogeneous vehicle behaviour, intersection control, and future traffic growth, ensuring that proposed measures are realistic and sustainable. Overall, the study highlights that integrating simulation-based evaluation into highway planning supports evidence-based decision-making, enhances mobility, reduces congestion, improves safety, and promotes the efficient use of road infrastructure. The methodology and findings can serve as a guide for policymakers and traffic engineers in designing and implementing operational improvements for urban and intercity highways.

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