Traffic Congestion Analysis and Carbon Footprint Assessment using IRC and Indo-HCM Methods

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ABSTRACT- Rapid urbanization and the growing vehicular population in Indian cities have intensified traffic congestion, leading to operational inefficiencies, prolonged delays, fuel wastage, and elevated CO_2 emissions. This study presents an integrated congestion-emission assessment framework combining traffic performance metrics such as volume-to-capacity (v/c) ratio, saturation flow, delay, and Level of Service (LOS) with carbon emission estimation using Indian Roads Congress (IRC) and Indo-HCM standards. Field data were collected from high-traffic intersections at Bhumkar Bridge in Pune, capturing vehicle volume, composition, speed, queue length, idling duration, and fuel-type distribution. Traffic classification was converted to Passenger Car Units (PCUs) to standardize heterogeneous traffic, while Artificial Neural Network (ANN) modeling predicted congestion indices and CO_2 emissions under varying traffic and geometric conditions. Saturation flow, capacity, and LOS analyses revealed that sub-arterial and 4-lane roads operate well beyond design capacity during peak hours, causing LOS F conditions and substantial emissions. Heavy vehicles, including buses and HCVs, contribute disproportionately to the carbon footprint despite their lower numbers. ANN optimization demonstrated high predictive accuracy ($R^2 = 0.9928$) and enabled scenario-based evaluation of traffic management strategies. The framework supports sustainable urban traffic planning, enabling targeted interventions such as signal optimization, lane management, and low-emission strategies. The findings highlight the critical interplay between congestion and environmental impact, offering practical insights for improving mobility, reducing emissions, and promoting low-carbon urban transport in rapidly growing Indian cities.

Keywords: Traffic congestion, Carbon emissions, Level of Service, Passenger Car Units, Saturation flow, ANN modeling, Urban intersections, Pune

I. INTRODUCTION

Rapid urbanization and the escalating vehicular population in Indian metropolitan regions have created a pressing challenge for urban mobility: severe traffic congestion. Cities like Pune, among Maharashtra's fastest-growing urban centers, exemplify this phenomenon, particularly at high-traffic hotspots such as Bhumkar Bridge[1]. These intersections, located along the heavily used Mumbai–Bengaluru Highway (NH-48), experience intense traffic pressure from a combination of local commuters, intercity vehicles, commercial freight, and through highway traffic. The complexity of traffic at these locations is compounded by heterogeneous vehicle types, inconsistent lane discipline, roadside encroachments, high turning volumes, and inadequate pedestrian infrastructure[2]. Consequently, the operational efficiency of these corridors is significantly reduced, and delays during peak hours are both frequent and prolonged[3]. Beyond the inconvenience to road users, such congestion imposes substantial economic costs due to wasted time, reduced productivity, and increased fuel consumption[4]. Traffic congestion extends its impacts beyond mobility, creating substantial environmental and energy-related consequences. Idling vehicles and stop-and-go traffic patterns result in significant fuel wastage and contribute to elevated CO_2 emissions, which accelerate environmental degradation[5]. Despite this, conventional traffic assessment methods, as outlined by the Indian Roads Congress (IRC) and the Indian Highway Capacity Manual (Indo-HCM), have largely focused on flow characteristics, roadway capacity, vehicular delay, and Level of Service (LOS)[6].

While these metrics are essential for understanding traffic performance, they often fail to account for the environmental implications of congestion, such as increased fuel consumption and greenhouse gas emissions. In cities like Pune, where rapid urban expansion is accompanied by a surge in vehicular demand, this omission underscores a critical gap in the evaluation of urban transportation systems[7]. The inability to link traffic efficiency with environmental outcomes limits the development of holistic strategies for sustainable urban mobility[8]. Addressing this gap, the present study proposes an integrated congestion-emission assessment framework tailored for mixed-traffic conditions in Indian cities[9]. By combining traffic performance indicators such as volume-to-capacity (v/c) ratio, saturation flow, vehicular delay, and LOS with corresponding carbon emission metrics, this approach allows for a comprehensive understanding of the interplay between congestion and environmental pollution. Field data from Bhumkar Bridge serve as the basis for this analysis, enabling the quantification of the relationship between urban traffic delays and associated emissions[10]. The framework integrates outputs from Indo-HCM with emission factors recommended by the Central Pollution Control Board (CPCB) and Intergovernmental Panel on Climate Change (IPCC), thereby providing a robust mechanism to evaluate the environmental footprint of traffic congestion[11]. Insights derived from this study are expected to inform sustainable traffic management strategies, support urban planning interventions, and facilitate the development of low-carbon mobility solutions, not only for Pune but also for other rapidly urbanizing cities across India[12]. By linking traffic performance with environmental outcomes, the research advances a pathway toward improved mobility, reduced emissions, and enhanced urban livability in growing metropolitan regions.

II. RELATED WORK

Urban traffic congestion and its environmental implications have been widely studied across various metropolitan contexts. Xiaomei Li et al. (2025) examined the intertwined challenges of traffic congestion and carbon emissions in Shanghai using a system dynamics approach, integrating a TOPSIS-based multi-criteria evaluation to assess policy effectiveness[13]. Their study demonstrated that congestion, emissions, and pollution are tightly coupled in non-coordinated feedback loops, highlighting that single-policy interventions are insufficient for sustainable urban mobility. Similarly, Huihui Wang et al. (2023) developed a complex modeling framework combining multi-agent simulation with system dynamics to reduce transportation-related CO_2 emissions in Beijing[14]. Their analysis emphasized the significance of integrated policies, including congestion pricing, parking fees, and transit fare adjustments, demonstrating that a comprehensive approach can reduce emissions by over 50% relative to a business-as-usual scenario. In the Indian context, Subodh Kinjawadekar et al. (2024) analyzed traffic congestion in Pune, focusing on critical intersections like Wageshwar Temple and Kesnand Phata[15]. They highlighted the compounded effects of rapid urbanization, vehicle growth, and inadequate infrastructure, revealing that poor traffic management and insufficient signaling exacerbate congestion, increase fuel consumption, and elevate accident risks. Malaya Mohanty et al. (2024) further explored the influence of three-wheelers on urban traffic dynamics, establishing that their presence significantly reduces vehicular speed (by 4–35%) and degrades Level of Service (LOS), often converging towards LOS C[16]. These studies collectively indicate that traffic congestion in Indian cities is driven by a combination of heterogeneous vehicle types, inadequate infrastructure, and insufficient policy integration, resulting in both operational inefficiencies and environmental consequences.

Pedestrian dynamics and intersection design also play a critical role in urban traffic performance and sustainability. Rakesh Khatri and Udit Jain (2025) evaluated Pedestrian Level of Service (PLOS) using the US Highway Capacity Manual 2016 and assessed its applicability to Indian conditions, revealing limitations in existing Indian frameworks like IRC 103 and Indo-HCM when applied to mixed-traffic environments[17]. K. Sangeeth and Uttam Kumar Roy (2025) emphasized that pedestrian mobility is foundational to urban livability and proposed a Continuous Pedestrian Movement (CpM) methodology to better capture sidewalk performance, delays, and conflicts in diverse urban contexts. On intersection capacity, Arathi A.R. et al. (2023) examined the effect of skew angles on uncontrolled intersection capacity, showing that existing Indo-HCM models overestimate capacity for angles beyond 100°, and introduced adjustment factors to improve accuracy[18]. Jeevan Paudel et al. (2024) conducted a traffic capacity and LOS assessment at the New Baneshwor intersection in Kathmandu, demonstrating severe congestion (LOS F) during peak hours and highlighting variations between Indo-HCM and Nepal Road Standards in estimating vehicular saturation flow and control delays[19]. At a methodological level, Bharti Naheliya et al. (2023) improved short-term traffic flow prediction using a hybrid GSA-LSTM model, achieving higher accuracy than conventional ARIMA and ANN models, which is particularly relevant for dynamic traffic management in congested urban nodes[20]. Collectively, these studies underscore the necessity of integrating traffic performance metrics, pedestrian considerations, and emission analysis to design sustainable, low-carbon urban transport strategies, aligning closely with the present study's focus on congestion-emission assessment in Pune's mixed-traffic conditions.

III. RESEARCH METHOD

The research methodology for this study, titled "Integrated Framework for Traffic Congestion Assessment and Carbon Emission Reduction Using Indian IRC and Indo-HCM Methods with ANN Modeling in Pune", adopts a quantitative, data-driven, and simulation-supported approach. The methodology integrates traditional traffic engineering standards with modern computational modeling to assess traffic performance, congestion patterns, and environmental impacts in mixed-traffic urban corridors.

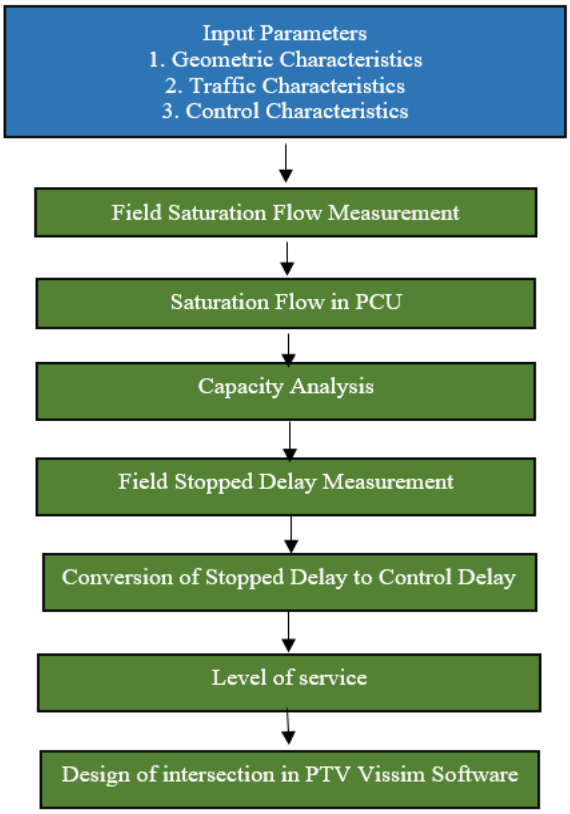

Fig 1. Research Method

The study focuses on two high-priority intersections in Pune: Bhumkar Bridge, located along the Mumbai–Bengaluru Highway (NH-48), which experience severe traffic congestion due to a combination of local, intercity, and commercial traffic flows.

3.1 Data Collection

The first phase involves comprehensive field data collection at the selected intersections and arterial roads. Observational techniques, including video-based traffic surveys, are employed to capture traffic parameters such as vehicle volume, composition, speed, delay, and queue length. Additional environmental inputs, including idling duration, fuel type distribution, and emission-related variables, are also recorded to support carbon footprint estimation. Vehicle classification is conducted according to the Indo-HCM 2017 and IRC standards (IRC:106-1990; IRC:SP:41-1994), ensuring that both motorized and non-motorized traffic types are accounted for. The collected data forms the basis for estimating saturation flow, capacity, Level of Service (LOS), and volume-to-capacity ratios (v/c) for the studied intersections.

3.2 Input Parameters

Traffic analysis relies on several input parameters categorized into geometric, traffic, and control characteristics:

3.2.1 Geometric Characteristics

Key geometric features include approach width, lane configuration, presence of exclusive turn lanes, and bus bays. These factors influence the unit base saturation flow (USF0) and the effective capacity of intersection approaches. Adjustments for flare effects and anticipated early movement (anticipation effect) are applied to capture real-world discharge patterns of highly maneuverable vehicles, such as two-wheelers and auto-rickshaws.

3.2.2 Traffic Characteristics

Traffic characteristics are captured through classified peak-hour turning movement counts, which are converted into Passenger Car Units (PCUs) to standardize heterogeneous vehicle types. Vehicle categories include two-wheelers, auto rickshaws, cars, light commercial vehicles, heavy commercial vehicles, buses, cycles, cycle rickshaws, and hand/animal-drawn vehicles. The peak rate of flows (v) is calculated using the peak hour factor (PHF), ensuring consistency with Indo-HCM 2017 recommendations.

3.2.3 Control Characteristics

Control parameters include cycle time, green time, amber (change) interval, all-red (clearance) interval, and phase plan. Shared or exclusive operation of vehicle movements is considered depending on traffic composition, volume-to-capacity ratios, and pedestrian activity. Analysis periods of 15 minutes (T = 0.25 h) are employed to capture peak congestion, and the critical volume-to-capacity ratio (v/c) is computed for each movement group.

3.3 Saturation Flow and Capacity Estimation

The prevailing saturation flow (SF) for each approach is calculated using:

$$\mathrm{USF_0} = \begin{cases} 630; for\ w < 7.0\ m \\ 1140 - 60w; for 7.0 \le w \le 10.5m \\ 500;\ for\ w > 10.5m \end{cases} \longrightarrow \qquad \textbf{(2)}$$

Where,

$\mathrm{USF_O}$ = Unit base saturation flow rate (in PCU / hour / m)

w = effective width of approach in meters (m).

The prevailing saturation flow of the intersection approach for the movement group under consideration is then obtained as presented in Equation 3.3.

$$\mathbf{SF = w \times USF_0 \times f_{bb} \times f_{br} \times fis} \longrightarrow \textbf{(3)}$$

Where,

- SF = Prevailing saturation flow rate in PCU/hour
- w = effective width of the approach in ‘m’ used by the movement group
- $\mathrm{USF_0}$ = Unit base saturation flow rate
- f_{bb} = Adjustment factor for bus blockage due to curbside bus stop
- f_{br} = Adjustment factor for blockage of through vehicles by standing right turning vehicleswaiting for their turn.
- f_{is} = Adjustment factor for the initial surge of vehicles due to approach flare and anticipation effect.

where gi is the effective green time, and C is the total cycle length. The volume-to-capacity ratio (v/c) is calculated to determine the degree of saturation and assess the LOS for each intersection. LOS ranges from A (free flow) to F (forced flow with long queues and unstable conditions) as per Indo-HCM 2017 standards.

3.4 ANN-Based Congestion Modeling

To enhance predictive capabilities, an Artificial Neural Network (ANN) model is developed using MATLAB or Python. The ANN, typically a feedforward backpropagation network, predicts congestion indices and delays under varying roadway and traffic conditions. Inputs include traffic volume, lane width, turning ratios, signal timing, and geometric parameters, while outputs are congestion index and average delay. The model undergoes supervised learning with a 70:30 training-testing split and is validated using Mean Squared Error (MSE) and R^2 metrics. Sensitivity analysis identifies the most influential variables, enabling targeted congestion mitigation strategies. Additionally, emission-related parameters are integrated into the ANN to predict CO_2 emissions and identify high-pollution segments.

3.5 Carbon Footprint Assessment

The study quantifies CO_2 emissions associated with traffic congestion at Bhumkar Bridge. Vehicle flow is converted from PCU to vehicle counts for each category:

For each vehicle category *j* (TW, Auto, Car, LCV, Bus, HCV), the hourly vehicle flow is obtained from PCU volume using:

$$N_j = \frac{V_j^{PCU}}{PCU_j}$$

Where:

- N_j= number of vehicles of type *j* (veh/h)
- V_j^{PCU}= volume in PCU/h for vehicle type *j*
- PCU_j = PCU value for vehicle type *j* (from Indo-HCM)

3.6 Case Study: Bhumkar Bridge

The case study focuses on two critical intersections with high congestion, heterogeneous traffic, and frequent oversaturation. Field data on traffic volume, speed, queue length, and geometric characteristics are collected and analyzed using IRC and Indo-HCM standards, while the ANN model predicts congestion and CO_2 emissions. The results guide mitigation strategies, including signal optimization, adaptive lane management, dynamic rerouting, and emission-reduction interventions, aimed at improving mobility and minimizing environmental impact.

3.7 Integration and Decision Support

The combination of field-based traffic assessment, saturation flow calculations, ANN modeling, and carbon emission estimation provides a robust framework for urban traffic planning and sustainable mobility solutions. By correlating LOS, v/c ratios, and emission metrics, this methodology allows for data-driven interventions tailored to Pune's mixed-traffic conditions, offering insights for broader application in other rapidly urbanizing Indian cities

IV. RESULTS AND DISCUSSION

The Results and Discussion chapter presents a comprehensive evaluation of traffic flow characteristics, roadway capacity, and congestion levels at Bhumkar Bridge based on detailed field data collected during morning and evening peak periods. The analysis has been carried out using both IRC (Indian Roads Congress) guidelines and Indo-HCM (Indian Highway Capacity Manual) methodology, enabling a comparative understanding of traffic performance under conventional and advanced analytical frameworks. The structured Excel-based calculations developed in this study integrate traffic volume data, Passenger Car Unit (PCU) conversion, saturation flow estimation, capacity determination, Volume-to-Capacity (V/C) ratio analysis, and Level of Service (LOS) classification. The results are systematically organized into multiple tables, beginning with traffic volume distribution for morning and evening periods, followed by saturation flow calculations as per IRC and Indo-HCM, capacity estimation, and finally V/C ratio and LOS evaluation. The morning traffic analysis indicates that the junction experiences extremely high vehicular load, with a total of 50,423.1 PCU, while the evening period records 48,941.5 PCU, confirming that Bhumkar Bridge operates under heavy traffic demand throughout the day. The arm-wise distribution further highlights that all four approaches contribute significantly to total congestion, with certain arms such as Dhayari and Katraj exhibiting relatively higher traffic intensities. This balanced yet high demand across all directions indicates a complex traffic interaction scenario with multiple conflict points, making the junction highly susceptible to congestion and delays.

5.1 Peak Hour Volume Bhumkar Bridge

The morning peak hour traffic count at Bhumkar Bridge reveals significant vehicular movement across multiple directions, with a total of 34,711 vehicles and 50,423.10 PCUs recorded. Breaking down the data, light vehicles (2W, 3W, 4W) dominate the flow, with 10,006 two-wheelers, 1,996 three-wheelers, and 7,811 four-wheelers contributing heavily to traffic.

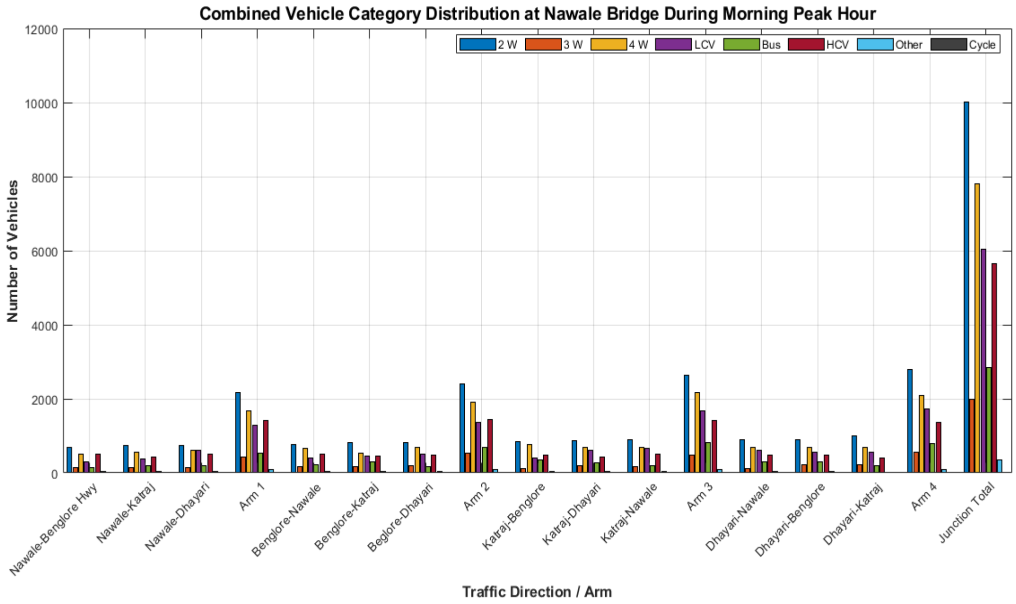

Fig 2. Bhumkar Bridge Morning Peak Hour Traffic Count

Light commercial vehicles (LCVs) totaled 6,036, while buses and heavy commercial vehicles (HCVs) accounted for 2,840 and 5,648, respectively. Cycles were minimal at 357, and other categories contributed 17 vehicles. Among arms, Arm 3 (Katraj–Nawale/Dhayari/Benglore segments) recorded the highest traffic of 9,276 vehicles (13,405.65 PCUs), followed closely by Arm 4 with 9,384 vehicles (13,512 PCUs), indicating major flows toward Dhayari and Nawale. The distribution highlights that two-wheelers and LCVs form the backbone of peak-hour traffic, while buses and HCVs, though fewer, significantly elevate PCU totals due to their higher equivalence factors, demonstrating the bridge's critical role in regional connectivity.

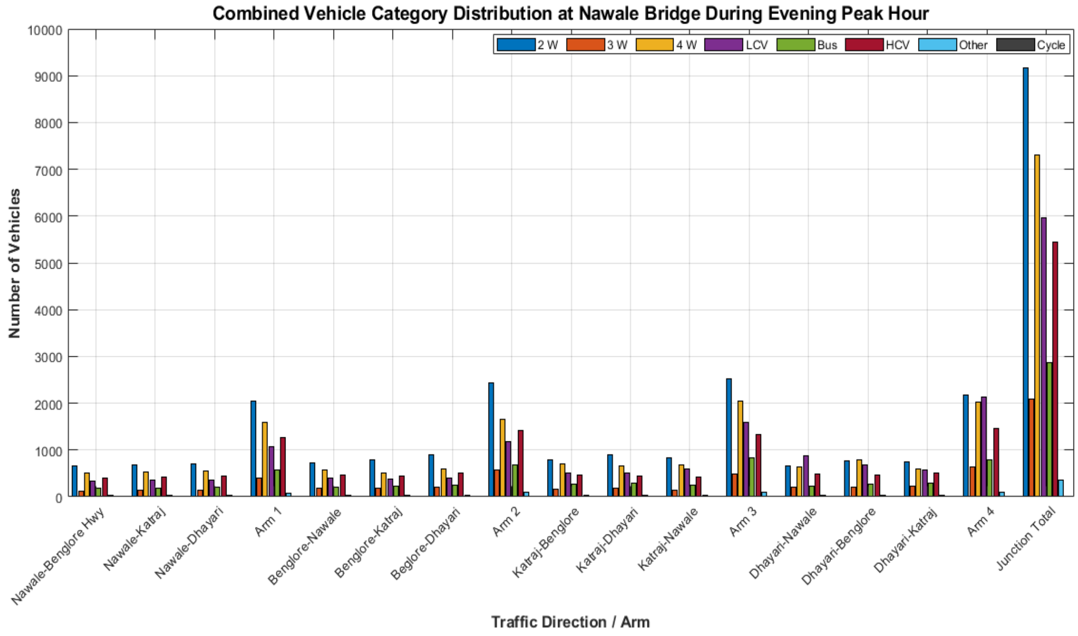

Fig 3. Bhumkar Bridge Evening Peak Hour Traffic Count

The evening peak hour traffic at Bhumkar Bridge shows a total of 33,225 vehicles and 48,941.50 PCUs, slightly lower in vehicle count than the morning peak but maintaining comparable PCU levels, indicating heavier vehicle composition.

Two-wheelers remain dominant with 9,158 units, followed by four-wheelers (7,311) and three-wheelers (2,087). Light commercial vehicles (LCVs) totaled 5,965, while buses and heavy commercial vehicles (HCVs) contributed 2,872 and 5,453, respectively. Cycles and other vehicles remained minimal at 360 and 19. Arm-wise distribution shows Arm 4 (Dhayari outbound segments) carrying the heaviest traffic at 9,292 vehicles (14,255.50 PCUs), reflecting strong commuter flows toward Dhayari in the evening. Arm 3 follows closely with 8,903 vehicles (12,882.10 PCUs). Compared to the morning, evening traffic sees increased LCVs and bus volumes, suggesting return journeys of commercial and public transport vehicles. Overall, peak-hour traffic patterns highlight two-wheelers and LCVs as predominant, while HCVs and buses significantly elevate PCU counts, emphasizing the bridge's strategic importance in regional traffic movement.

5.2 Saturation Flow Calculation as Per IRC Recommendations for Flow

The saturation flow analysis for Bhumkar Bridge approaches, following IRC guidelines, shows clear variation based on road type, carriageway, and effective width. The arterial sections with wide 6-lane divided two-way carriageways—specifically Nawale–Benglore Highway and Benglore–Nawale, each with 10.50 m effective width—have the highest saturation flow at 5,512.50 PCU/hr, indicating their ability to handle substantial peak-hour traffic efficiently.

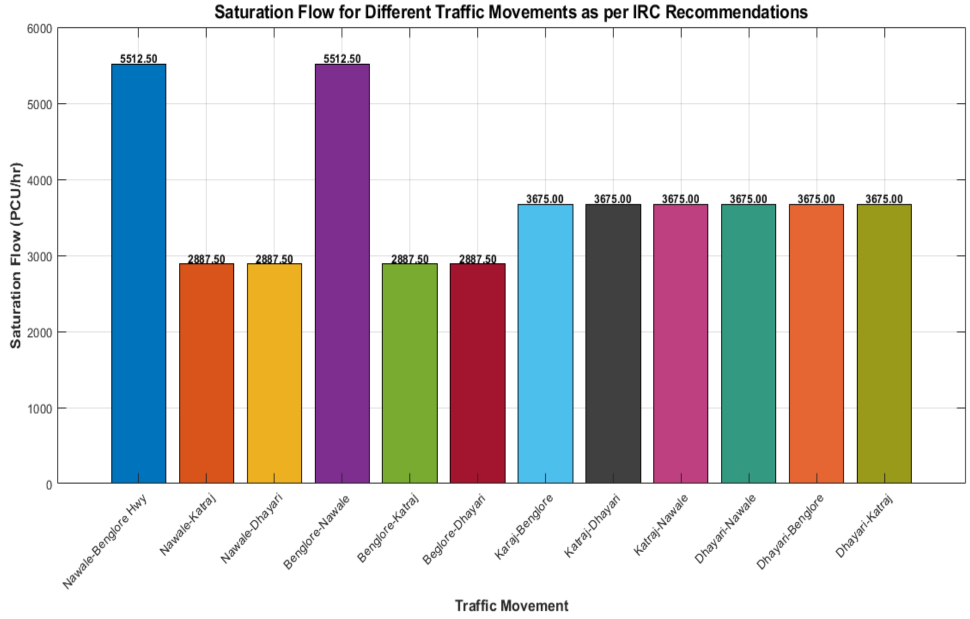

Fig 4. Saturation Flow Calculation as per IRC Recommendations

Sub-arterial bypass roads, such as Nawale Katraj, Nawale–Dhayari, Benglore Katraj, and Benglore–Dhayari, are narrower 2-lane two-way roads with 5.50 m width, and their saturation flow drops to 2,887.50 PCU/hr, reflecting limited capacity for heavy vehicles and congestion-prone conditions. The remaining arterial 4-lane divided two-way roads including Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, and Dhayari outbound links with 7 m effective width show moderate saturation flow of 3,675 PCU/hr, balancing vehicular capacity and road geometry. These IRC-based flows serve as a benchmark for evaluating actual peak traffic volumes and assessing congestion management strategies.

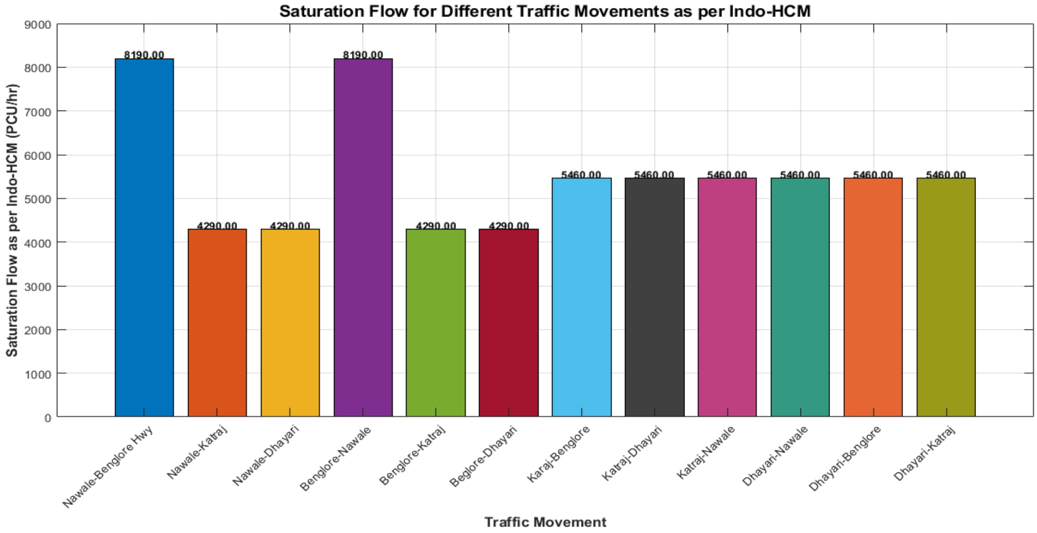

Fig 5. Saturation Flow Calculation as per Indo-HCM

The saturation flow analysis based on Indo-HCM methodology demonstrates a higher flow capacity compared to IRC estimates, reflecting the use of a unit base saturation flow rate of 780 PCU/hr/m. For arterial 6-lane divided two-way roads such as Nawale–Benglore Highway and Benglore–Nawale with 10.50 m effective width, the saturation flow reaches 8,190 PCU/hr, indicating substantial ability to accommodate peak-hour traffic. Sub-arterial 2-lane bypass roads, including Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari, with 5.50 m width, have a lower flow of 4,290 PCU/hr, showing capacity constraints for narrower roads. Arterial 4-lane divided two-way roads such as Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, and Dhayari outbound links, with 7 m effective width, achieve intermediate saturation flows of 5,460 PCU/hr. Compared to IRC values, Indo-HCM flows are consistently higher, providing a more optimistic estimate of capacity, useful for traffic signal design, intersection evaluation, and peak-hour congestion management across Bhumkar Bridge approaches.

5.3 Capacity Using Design Service Volume as Per IRC for Morning and Evening Peak Counts

The capacity assessment using Design Service Volume (DSV) as per IRC provides insight into the ability of Bhumkar Bridge approaches to handle peak-hour traffic. For arterial 6-lane divided two-way roads like Nawale Benglore Highway and Benglore–Nawale, with 3 lanes per direction and an effective width of 10.50 m, the design service volume per lane is 1,800 PCU/hr, giving a total capacity of 5,400 PCU/hr, suitable for heavy peak flows.

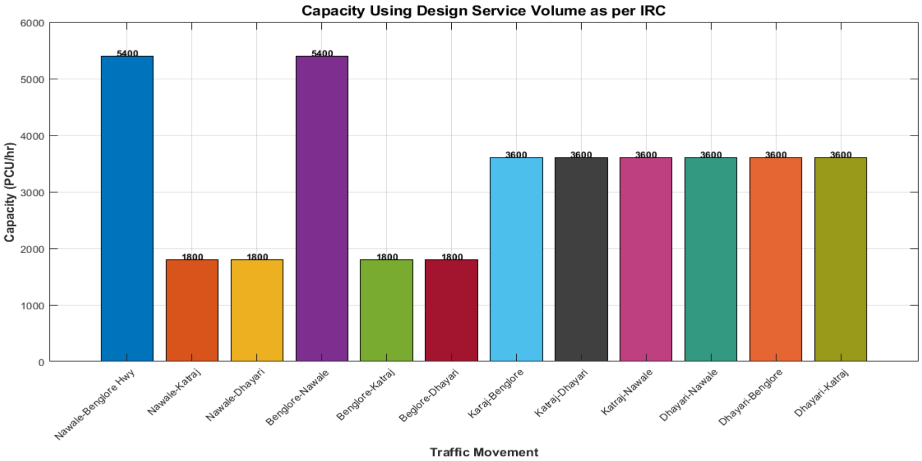

Fig 6. Capacity Using Design Service Volume as per IRC for Morning and Evening Peak Counts

Sub-arterial 2-lane bypass roads, such as Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore Dhayari, with 1 lane per direction and 5.50 m width, have a capacity of 1,800 PCU/hr, reflecting the limited throughput of narrower roads. Arterial 4-lane divided two-way roads Karaj Benglore, Katraj Dhayari, Katraj Nawale, and Dhayari outbound links with 2 lanes per direction and 7 m width, have intermediate capacity of 3,600 PCU/hr. These capacities serve as benchmarks to compare with morning and evening peak-hour counts, helping identify sections operating near or beyond design capacity, highlighting potential congestion points and guiding traffic management interventions.

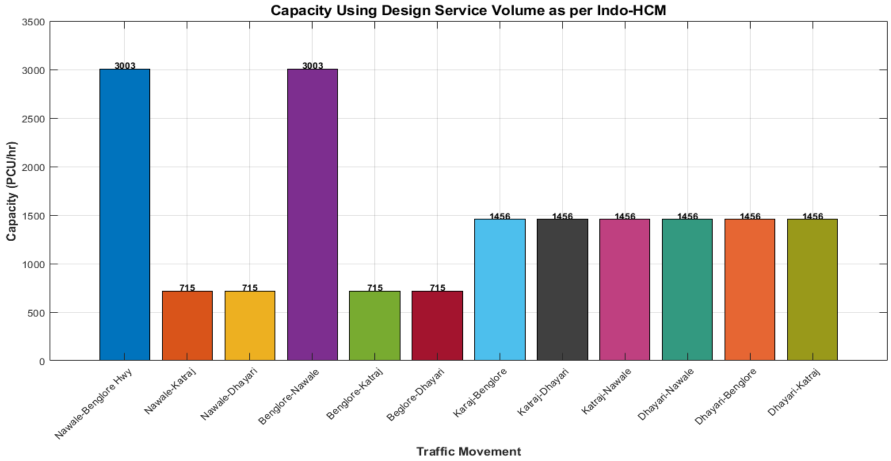

Fig 7. Capacity Using Design Service Volume as per Indo-HCM for Morning and Evening Peak Counts

The capacity evaluation using Design Service Volume (DSV) per Indo-HCM integrates both saturation flow and signal timing to determine the effective capacity of Bhumkar Bridge approaches during peak hours. For arterial 6-lane divided two-way roads like Nawale–Benglore Highway and Benglore–Nawale, with a saturation flow of 8,190 PCU/hr, effective green time of 55 seconds, and cycle time of 150 seconds, the calculated capacity is 3,003 PCU/hr, indicating the peak throughput under signalized conditions. Sub-arterial 2-lane bypass roads—Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari—with saturation flow of 4,290 PCU/hr and 25-second effective green, have a lower capacity of 715 PCU/hr, reflecting limited flow during signal phases. The arterial 4-lane divided two-way roads (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, and Dhayari outbound links), with 5,460 PCU/hr saturation flow and 40-second green, achieve 1,456 PCU/hr. These capacities highlight how signal timing, lane width, and saturation flow together constrain peak-hour traffic, providing a more realistic measure for intersection and corridor performance planning.

5.4 Volume-Capacity Ratio as per IRC (Morning Peak and Evening Peak)

The Volume-Capacity (V/C) ratio analysis based on IRC capacities for Bhumkar Bridge approaches highlights critical congestion levels during morning and evening peak hours. For arterial 6-lane roads like Nawale–Benglore Highway and Benglore–Nawale, V/C ratios remain below 1 in both peaks (0.627–0.741 in morning; 0.607–0.698 in evening), indicating these links operate well within capacity.

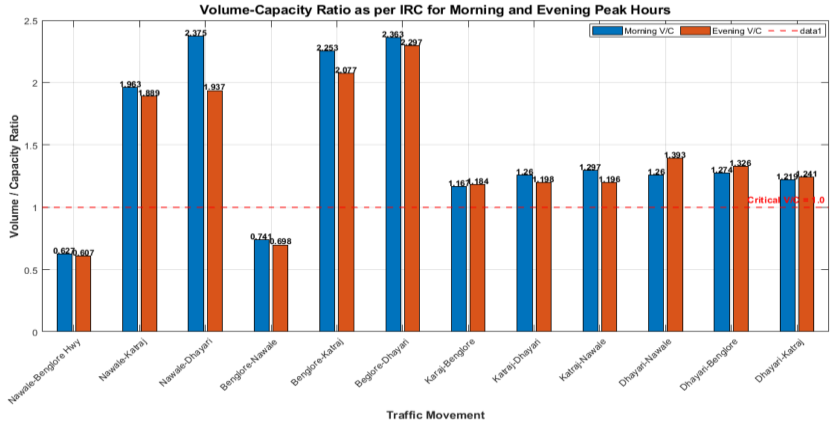

Fig 8. Volume-Capacity Ratio as per IRC (Morning Peak and Evening Peak)

Conversely, sub-arterial 2-lane bypass links—Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari—experience severe congestion, with morning V/C ratios ranging 2.253–2.375 and evening 1.889–2.297, reflecting traffic volumes more than double their design capacity, leading to extreme saturation. Arterial 4-lane divided two-way roads (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, Dhayari outbound) show moderate overcapacity, with morning V/C ratios of 1.167–1.297 and evening 1.196–1.393, indicating frequent peak-hour congestion. Overall, the analysis suggests that while major 6-lane arterials maintain smooth flow, sub-arterial and 4-lane segments are significantly over capacity, necessitating traffic management, lane optimization, or signal timing improvements to reduce peak congestion and delays.

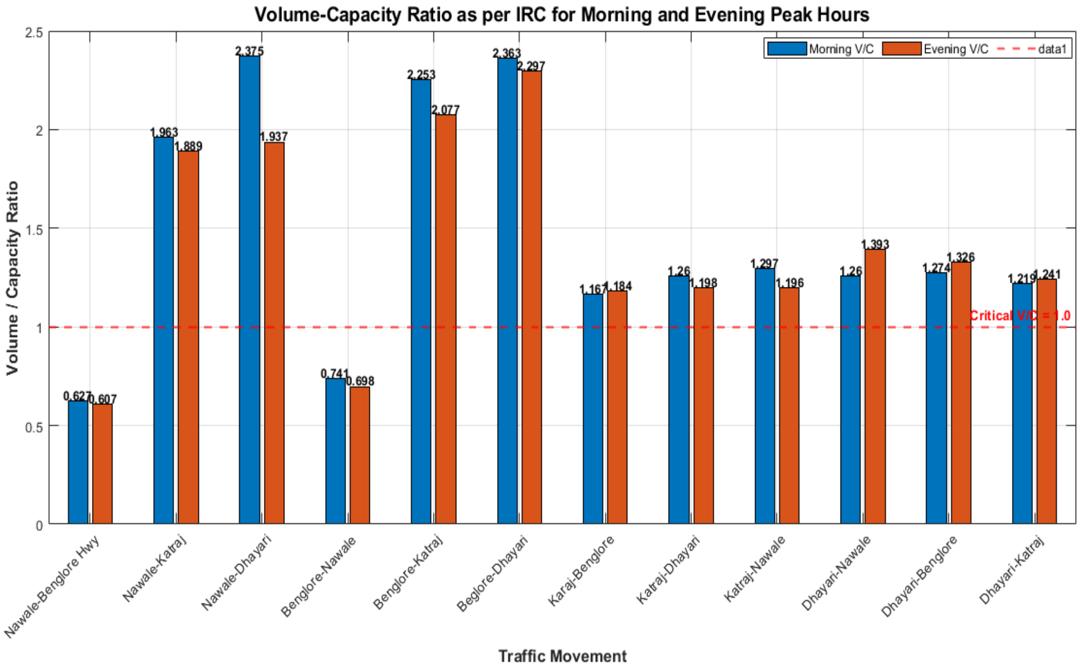

Fig 9. Volume-Capacity Ratio as per Indo-HCM (Morning Peak and Evening Peak)

The Volume-Capacity (V/C) ratio analysis using Indo-HCM capacities for Bhumkar Bridge approaches indicates that most links operate well beyond their signalized peak capacity, highlighting severe congestion. For arterial 6-lane divided roads such as Nawale–Benglore Highway and Benglore–Nawale, morning V/C ratios are 1.128–1.332 and evening 1.091–1.254, showing these links are slightly over capacity but still manageable compared to smaller roads. In contrast, sub-arterial 2-lane bypass roads—Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari—exhibit extreme overloading, with morning V/C ratios 4.943–5.979 and evening 4.755–5.782, indicating traffic volumes exceed capacity by nearly 5–6 times, leading to severe delays and saturation. Similarly, arterial 4-lane divided two-way links (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, Dhayari outbound) show morning V/C ratios of 2.886–3.207 and evening 2.928–3.443, reflecting high over-saturation during both peaks. Overall, the Indo-HCM analysis emphasizes that sub-arterial and 4-lane segments are critically over capacity, requiring urgent interventions such as signal optimization, lane expansion, or traffic diversion to relieve congestion.

5.5 LOS As Per Design Service Volume (Morning Peak)

The Level of Service (LOS) analysis for Bhumkar Bridge approaches during the morning peak, based on IRC 106-1990 Design Service Volume, reveals a mixed operational performance. Arterial 6-lane links such as Nawale Benglore Highway and Benglore–Nawale, with V/C ratios of 0.627 and 0.741, operate at LOS B, indicating stable flow with minor delays and generally smooth traffic conditions.

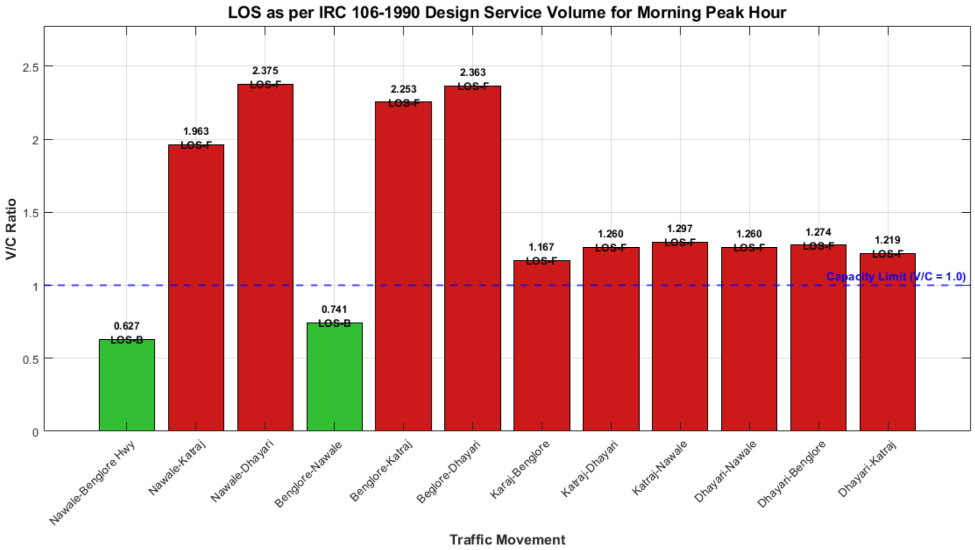

Fig 10. LOS as per IRC 106-1990 Design Service Volume (Morning Peak)

In contrast, sub-arterial 2-lane bypass links Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari exhibit very high V/C ratios ranging 1.963–2.375, resulting in LOS F, which denotes highly congested conditions with stop-and-go movement and severe delays. Similarly, arterial 4-lane divided two-way links (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, Dhayari outbound links), with V/C ratios of 1.167–1.297, also operate at LOS F, reflecting frequent congestion during peak hours. Overall, the morning peak LOS highlights that while major 6-lane arterials function efficiently, most 2-lane and 4-lane approaches are operating beyond capacity, emphasizing the need for capacity enhancement or traffic management interventions.

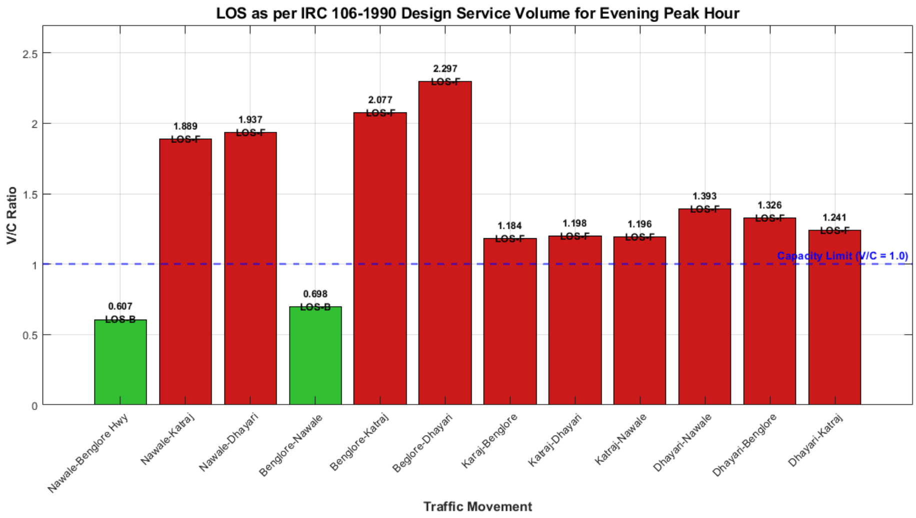

Fig 11. LOS as per IRC 106-1990 Design Service Volume (Evening Peak)

The Level of Service (LOS) assessment for Bhumkar Bridge approaches during the evening peak, based on IRC 106-1990 Design Service Volume, shows a continuation of morning trends with slight variations. The arterial 6-lane divided roads—Nawale–Benglore Highway and Benglore–Nawale—have V/C ratios of 0.607 and 0.698, maintaining LOS B, which indicates stable flow with minor delays and comfortable operating conditions. In contrast, sub-arterial 2-lane bypass links—Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari—record high V/C ratios between 1.889 and 2.297, corresponding to LOS F, reflecting severe congestion with frequent stop-and-go conditions. Similarly, arterial 4-lane divided two-way links (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, and Dhayari outbound segments) have V/C ratios of 1.184–1.393, also at LOS F, showing significant peak-hour delays. Overall, the evening peak LOS indicates that while major arterials continue to operate efficiently, most sub-arterial and 4-lane approaches are heavily congested, underscoring the need for capacity improvements or traffic management measures.

5.6 LOS as Per Design Service Volume (Evening Peak)

The Level of Service (LOS) evaluation for Bhumkar Bridge approaches during the morning peak, using Indo-HCM standards, indicates that all approaches are operating at LOS F, reflecting extreme congestion and oversaturated conditions.

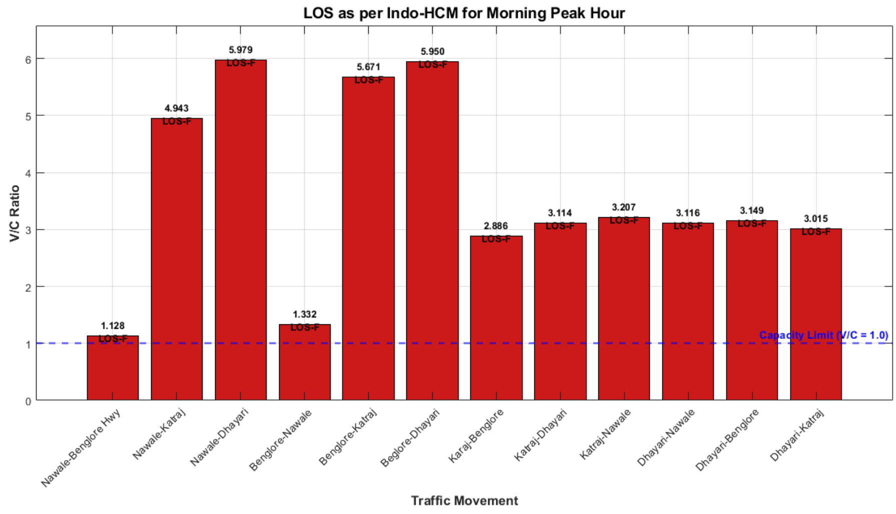

Fig 12. LOS as per Indo-HCM (Morning Peak)

Even the major 6-lane arterials Nawale–Benglore Highway and Benglore–Nawale with V/C ratios of 1.128 and 1.332, are beyond capacity, resulting in stop-and-go traffic and significant delays. The sub-arterial 2-lane bypass roads— Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, and Benglore–Dhayari experience severe overloading, with V/C ratios from 4.943 to 5.979, meaning traffic volumes exceed 4–6 times the available capacity, causing persistent queues and operational instability. Likewise, the arterial 4-lane divided links (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, and Dhayari outbound links) record V/C ratios 2.886–3.207, showing serious congestion and frequent stoppages. Overall, the morning peak Indo-HCM analysis highlights a critical need for capacity enhancement, traffic management, or signal optimization across all Bhumkar Bridge approaches to alleviate extreme congestion.

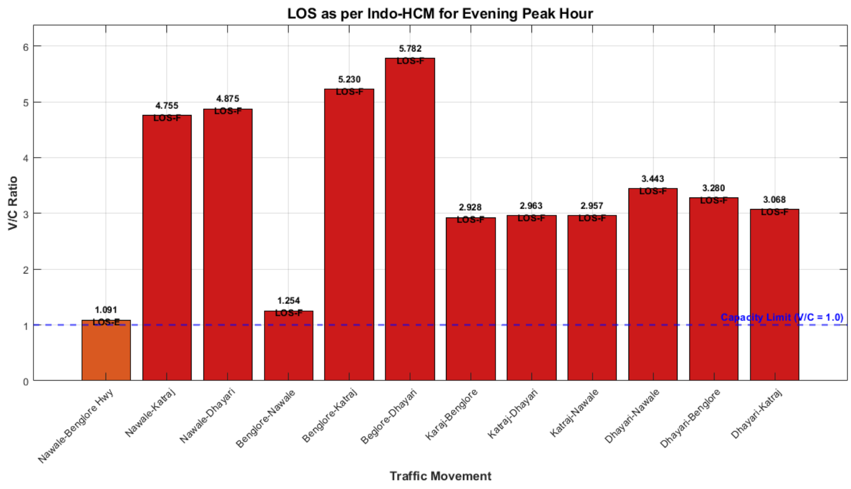

Fig 13. LOS as per Indo-HCM (Evening Peak)

The Level of Service (LOS) analysis for Bhumkar Bridge approaches during the evening peak, based on Indo-HCM standards, indicates that most links are severely over capacity. The Nawale–Benglore Highway, with a V/C ratio of 1.091, operates at LOS E, indicating very unstable flow with frequent delays. All other approaches, including sub-arterial 2-lane bypass roads (Nawale–Katraj, Nawale–Dhayari, Benglore–Katraj, Benglore–Dhayari) and arterial 4-lane links (Karaj–Benglore, Katraj–Dhayari, Katraj–Nawale, Dhayari outbound links), exhibit V/C ratios ranging from 2.928 to 5.782, resulting in LOS F, reflecting extreme congestion, persistent queues, and stop-and-go conditions. Notably, sub-arterial links experience volumes exceeding 4–5 times their capacity, highlighting critical bottlenecks. Overall, the evening peak Indo-HCM LOS assessment emphasizes that while the major 6-lane arterial functions slightly better than smaller roads, all other approaches are heavily oversaturated, underscoring the urgent need for capacity expansion, signal optimization, or traffic management interventions to reduce congestion and improve operational efficiency.

5.7 Carbon Footprint Calculation and Congestion–Emission at Bhumkar Bridge

The relationship between congestion levels and carbon footprint across different vehicle categories at Bhumkar Bridge under observed peak traffic conditions. The analysis is based on the classified directional traffic counts collected during the morning and evening peak periods. Since Bhumkar Bridge carries highly heterogeneous traffic composed of two-wheelers, three-wheelers, four-wheelers, light commercial vehicles (LCV), buses, heavy commercial vehicles (HCV), other vehicles, and cycles, a category-wise carbon footprint approach has been adopted. This approach provides a more realistic environmental assessment than a single average emission factor because each vehicle category differs significantly in fuel consumption, operating characteristics, and carbon dioxide emission intensity.

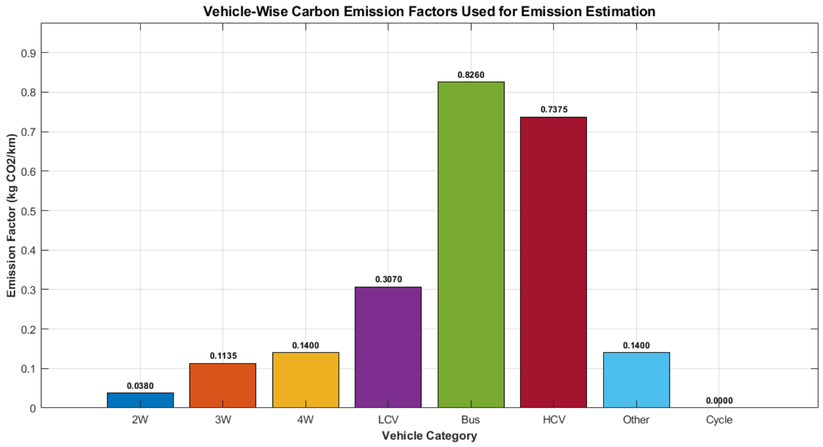

Fig 14. Vehicle-Wise Carbon Emission Factors Used

The vehicle-wise carbon emission factors used for the Bhumkar Bridge traffic analysis quantify the CO_2 emissions per kilometer traveled for different vehicle types. Two-wheelers (2W) are the least emitting motorized vehicles, producing 0.038 kg CO_2/km, while three-wheelers (3W) and four-wheelers (4W) generate 0.1135 kg CO_2/km and 0.140 kg CO_2/km, respectively. Light commercial vehicles (LCVs) emit significantly higher at 0.307 kg CO_2/km, reflecting their larger engines and loads. Public transport buses (Bus) contribute the most among common road vehicles at 0.826 kg CO_2/km, while heavy commercial vehicles (HCVs) produce 0.7375 kg CO_2/km, indicating their substantial environmental impact despite fewer numbers. "Other" vehicles are assigned 0.140 kg CO_2/km, similar to standard four-wheelers, while cycles produce 0 kg CO_2/km, representing zero emissions. These factors allow accurate estimation of total vehicular carbon emissions for morning and evening peak-hour traffic, supporting environmental impact assessment and sustainable traffic planning strategies.

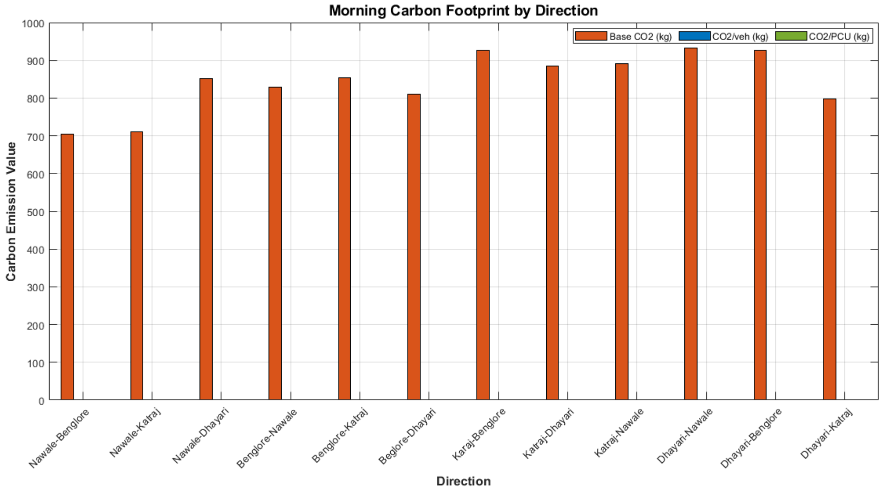

Fig 15. Morning Carbon Footprint by Direction

In contrast, the lowest CO₂ emission is recorded in Nawale to Benglore Highway (703.4395 kg) despite 2325 vehicles, suggesting relatively lower emission intensity. The highest CO₂ per vehicle is found in Benglore to Katraj (0.3086 kg/veh) and Katraj to Benglore (0.3082 kg/veh), reflecting the impact of heavier or less efficient vehicles. Similarly, CO₂ per PCU is maximum in Katraj to Benglore (0.2202 kg/PCU), indicating higher emission load per unit traffic. Conversely, Dhayari to Katraj shows the lowest emission intensity (0.2569 kg/veh and 0.1817 kg/PCU). Overall, both traffic volume and vehicle composition significantly influence directional carbon emissions.

5.7.1 Evening Direction-Wise Carbon Footprint Calculation Results

The evening carbon footprint analysis across different directions reveals clear variations driven by traffic intensity and vehicle composition. The highest CO₂ emission is recorded in the Dhayari to Nawale direction (965.6655 kg) with 3137 vehicles and 5013.10 PCU, making it the most critical emission corridor during the evening peak

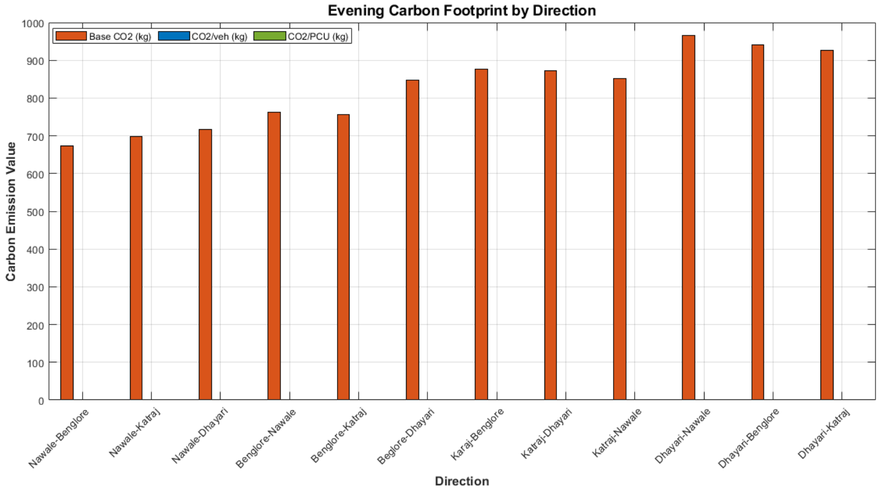

Fig 16. Evening Carbon Footprint by Direction

This is followed by Dhayari to Benglore (939.8635 kg) and Dhayari to Katraj (925.7020 kg), indicating strong outbound movement from Dhayari. In contrast, the lowest emission is observed in Nawale to Benglore Highway (672.2415 kg) with 2261 vehicles and 3277.40 PCU. The highest CO₂ per vehicle is seen in Dhayari to Katraj (0.3134 kg/veh) and Dhayari to Nawale (0.3078 kg/veh), suggesting higher emission intensity possibly due to congestion or heavy vehicles. Similarly, CO₂ per PCU is highest in Nawale to Dhayari and Karaj to Benglore (0.2057 kg/PCU), while the lowest is in Dhayari to Nawale (0.1926 kg/PCU). Overall, the results indicate that both traffic volume and vehicle mix significantly influence evening carbon emissions.

5.8 Category-Wise Carbon Footprint Comparison

The category-wise carbon footprint analysis for morning and evening periods clearly highlights the dominant contributors to overall emissions. The total number of vehicles decreases from 34,711 in the morning to 33,225 in the evening, resulting in a slight reduction in total CO₂ emissions from 10,114.586 kg to 9,883.933 kg.

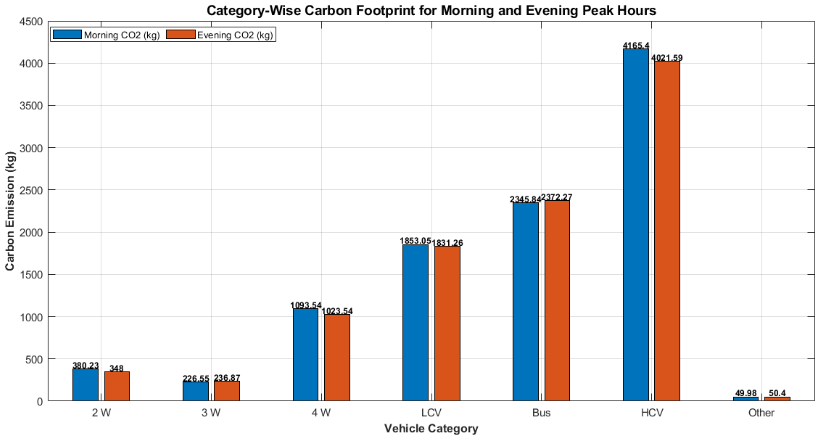

Fig 17. Category-Wise Carbon Footprint for Morning and Evening

Heavy Commercial Vehicles (HCV) contribute the highest emissions in both periods, with 4165.400 kg in the morning and 4021.5875 kg in the evening, despite a reduction in vehicle count from 5648 to 5453, indicating their high emission factor (0.7375 kg/km). Buses are the second-largest contributors, with emissions increasing from 2345.8400 kg to 2372.2720 kg due to a slight rise in vehicles. Light Commercial Vehicles (LCV) also show significant emissions (1853.0520 kg morning; 1831.2550 kg evening). In contrast, 2-wheelers and 3-wheelers contribute relatively lower emissions despite higher counts. Cycles produce zero emissions. Overall, emission contribution is highly dependent on vehicle type rather than just vehicle volume.

5.8.1 Category Share in Morning

The category-wise share of carbon emissions in the morning period clearly indicates that Heavy Commercial Vehicles (HCV) are the dominant contributors, accounting for the highest share of 41.18%, reflecting their high emission factor and significant presence in traffic flow. This is followed by buses, contributing 23.19%, which also have a high emission factor due to fuel consumption and passenger capacity.

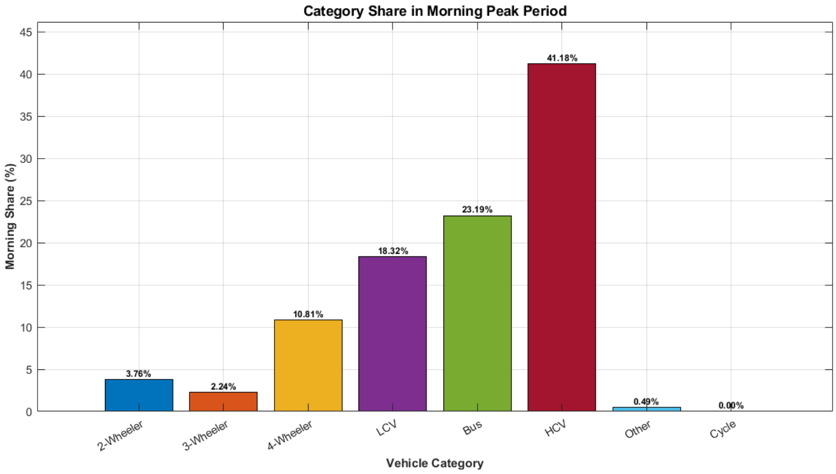

Fig 18. Category Share in Morning

Light Commercial Vehicles (LCV) contribute 18.32%, highlighting their substantial role in freight movement and urban logistics. In comparison, 4-wheelers account for 10.81% of total emissions, indicating moderate impact despite their relatively high numbers. Two-wheelers contribute only 3.76%, while 3-wheelers account for 2.24%, showing that smaller vehicles have a limited contribution to overall emissions. The “Other” category contributes a minimal 0.49%, and cycles contribute 0.00%, as they produce no emissions. Overall, the data demonstrates that emission share is heavily skewed toward heavy vehicle categories rather than total vehicle count.

5.8.2 Category Share in Evening

The category-wise share of carbon emissions in the evening period shows a similar pattern to the morning, with Heavy Commercial Vehicles (HCV) contributing the highest share at 40.69%, indicating their dominant impact on overall emissions due to high emission factors. Buses are the second-largest contributors with 24.00%, showing a slight increase compared to the morning, likely due to increased passenger movement during peak hours.

Light Commercial Vehicles (LCV) contribute 18.53%, reflecting their consistent role in goods transportation. Four-wheelers account for 10.36% of emissions, showing a marginal decrease from the morning period. Two-wheelers and three-wheelers contribute relatively lower shares of 3.52% and 2.40%, respectively, despite their higher numbers, due to lower emission factors.

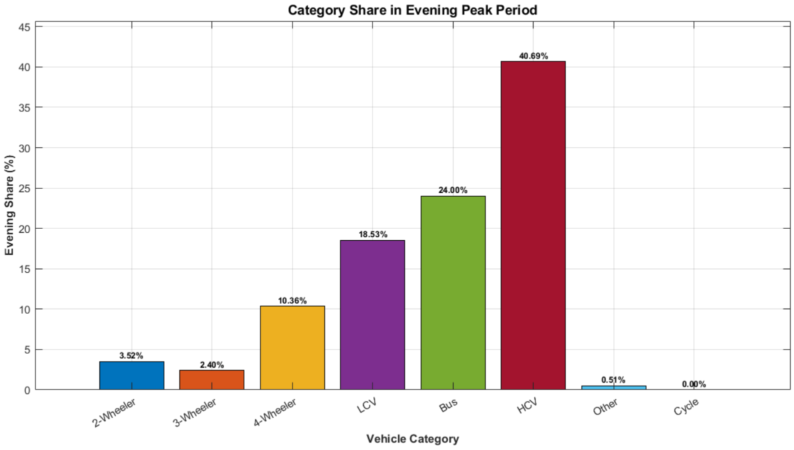

Fig 19. Category Share in Evening

The “Other” category contributes only 0.51%, while cycles contribute 0.00% as they produce no emissions. Overall, the results confirm that heavy vehicles dominate emission contribution regardless of time period.

5.9 Congestion–Carbon Relationship Data

The relationship between congestion and carbon footprint has been examined using Indo-HCM-based V/C ratios already derived from the traffic analysis and the calculated movement-wise CO2 values.

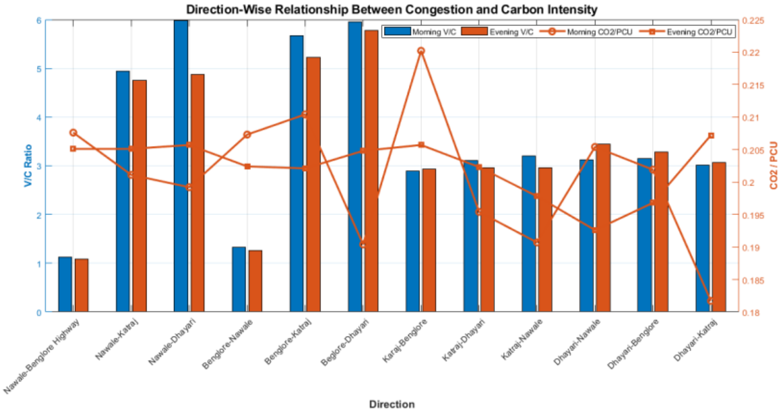

Fig 20. Direction-Wise Congestion and Carbon Footprint Relationship

The direction-wise relationship between congestion (V/C ratio) and carbon footprint reveals a strong but composition-dependent pattern across both morning and evening periods. Highly congested routes such as Nawale to Dhayari (V/C 5.9787 morning; 4.8753 evening) and Benglore to Katraj (5.6712 morning; 5.2300 evening) show elevated CO_2 emissions of 851.5450 kg and 853.0805 kg respectively, indicating that higher congestion generally leads to increased emissions. However, the relationship is not strictly linear, as seen in Karaj to Benglore, where moderate congestion (2.8862 morning) produces a high CO_2/PCU of 0.2202, the highest among all directions, due to heavier vehicle composition. Similarly, Dhayari to Nawale records the highest total CO_2 emissions (932.1725 kg morning; 965.6655 kg evening) despite moderate congestion levels (3.1164 and 3.4431). Lower congestion routes like Nawale to Benglore Highway (1.1284 morning; 1.0914 evening) show comparatively lower emissions. Overall, the findings confirm that carbon emissions are influenced not only by congestion levels but also significantly by vehicle mix and traffic composition.

5.10 ANN Optimization Results

5.10.1 Model Performance

The optimized ANN used hidden layers (64, 32, 16), alpha 0.001, and learning rate 0.005. On holdout evaluation, the model achieved MAE 2.095, RMSE 2.486, R2 0.9928, congestion-level accuracy 0.9388, and LOS accuracy 0.9388. These values indicate strong internal consistency for the operational congestion index derived from the observed demand profile.

5.10.2 2025 Baseline Condition

The baseline operational condition estimated from the observed 2025 data is shown below.

The baseline condition for 2025 indicates moderate congestion levels during both morning and evening periods, with noticeable variation in traffic intensity and service quality. The evening period records a slightly higher average 4-hour traffic count of 767.361 vehicles compared to 760.418 in the morning, resulting in a higher congestion index of 41.295, which corresponds to Level of Service (LOS) C, indicating stable but constrained traffic flow with reduced speeds. In contrast, the morning period shows a lower congestion index of 30.385 with LOS B, reflecting relatively smoother traffic conditions and better operational efficiency. Although both periods fall under moderate congestion, the evening peak demonstrates comparatively higher traffic pressure and reduced service quality than the morning period.

5.10.3 Recommended Central Forecast for Practice Use

For a non-flat and technically defensible practice forecast, the +3% compound annual growth rate (CAGR) case is recommended as the central planning scenario. This does not alter the original dataset. Instead, it applies a transparent growth assumption to the observed 2025 traffic base and then uses the optimized ANN to evaluate future congestion and LOS.

The recommended central forecast indicates a rapid deterioration in traffic conditions from 2026 to 2030, driven by a steady increase in traffic volume. In 2026, the evening period shows a forecast average 4-hour count of 790.381 with a congestion index of 76.144 (Severe, LOS E), while the morning reaches 783.231 with 72.836 (High, LOS E). By 2027, both periods hit the maximum congestion index of 100.000, indicating severe congestion with LOS F, and this critical condition persists through 2028, 2029, and 2030. Traffic volume continues to rise, reaching 889.581 (evening) and 881.533 (morning) by 2030. The results clearly show that without intervention, the system will experience extreme congestion, with continuous LOS F conditions, indicating breakdown flow, long delays, and highly unstable traffic operations in both peak periods.

ANN holdout actual versus predicted congestion index

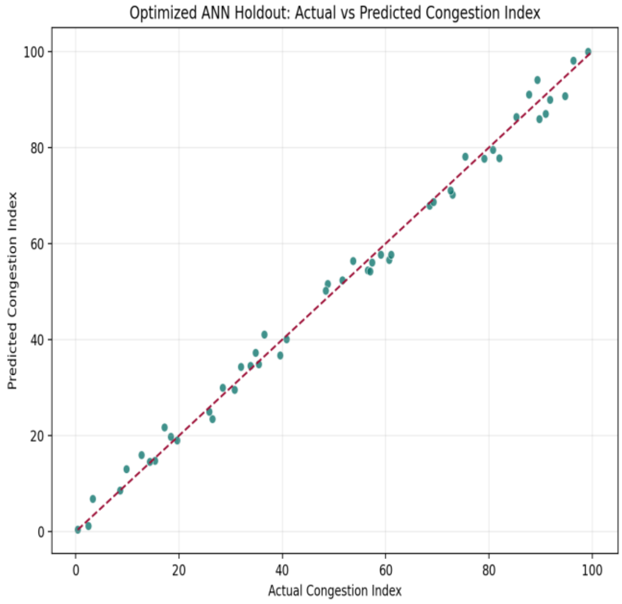

Fig 21. Optimization ANN- Actual Vs Predicted

The scatter plot of Actual vs Predicted Congestion Index demonstrates a strong positive linear relationship, indicating high prediction accuracy of the optimized ANN model. Most data points closely align with the 45-degree reference line (y = x), showing minimal deviation between actual and predicted values across the full range (0 to 100). For lower values (0–20), predictions are nearly exact, while in the mid-range (40–70), slight variations of ±2–5 units are observed. At higher congestion levels (80–100), predictions remain consistent with minor dispersion. Overall, the model effectively captures congestion patterns with high precision and reliability across all value ranges.

Congestion-level confusion matrix

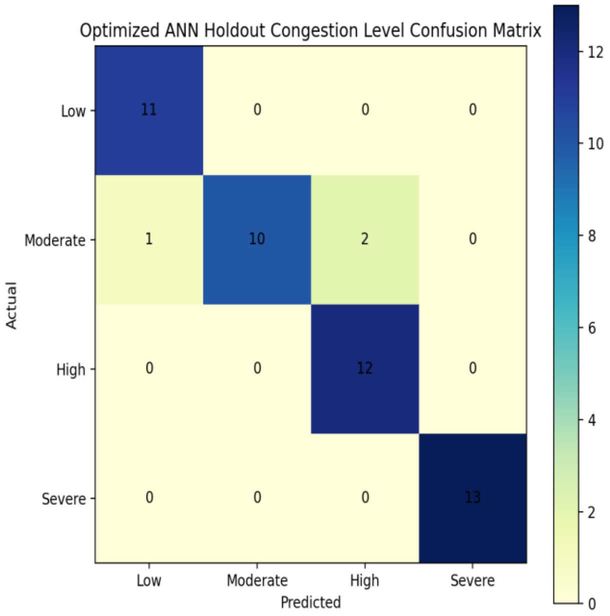

Fig 22. Optimized ANN Results Confusion Matrix

The confusion matrix of the optimized ANN model shows excellent classification performance across all congestion levels. For the “Low” category, all 11 instances are correctly classified (11 correct, 0 misclassified), indicating 100% accuracy. In the “Moderate” category, 10 instances are correctly predicted, with minor misclassifications of 1 as “Low” and 2 as “High,” showing slight overlap in boundary conditions. The “High” category achieves perfect classification with all 12 instances correctly predicted (12 correct, 0 errors). Similarly, the “Severe” category shows the highest accuracy with all 13 instances correctly classified. Overall, out of 49 total observations, only 3 misclassifications occur, demonstrating very high model accuracy and strong reliability in congestion level prediction.

LOS confusion matrix

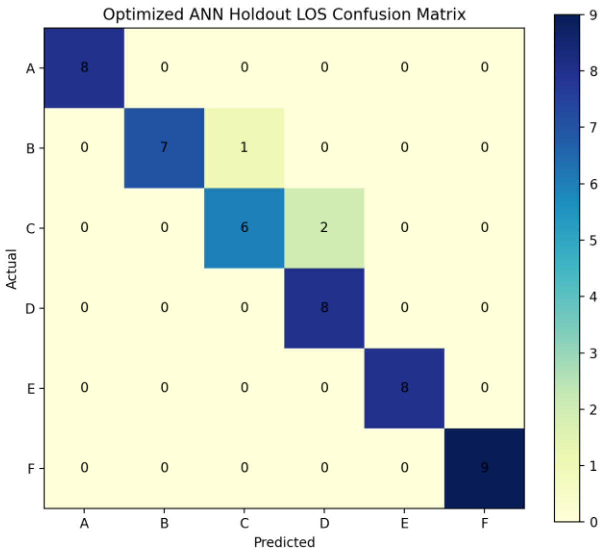

Fig 23. Optimized ANN LOS Confusion Matrix

The confusion matrix for the optimized ANN LOS classification demonstrates very high accuracy across all service levels from A to F. For LOS A, all 8 instances are correctly classified (8 correct, 0 errors), indicating perfect prediction. In LOS B, 7 instances are correctly predicted, with only 1 misclassified as LOS C. For LOS C, 6 instances are correctly classified, while 2 are slightly overestimated as LOS D, showing minor boundary overlap. LOS D, E, and F categories achieve perfect classification, with 8, 8, and 9 correct predictions respectively and no misclassifications. Overall, out of 48 total observations, only 3 misclassifications occur, reflecting excellent model performance and strong reliability in accurately predicting traffic Level of Service categories across varying congestion conditions.

Five-Year Scenario Growth Trend

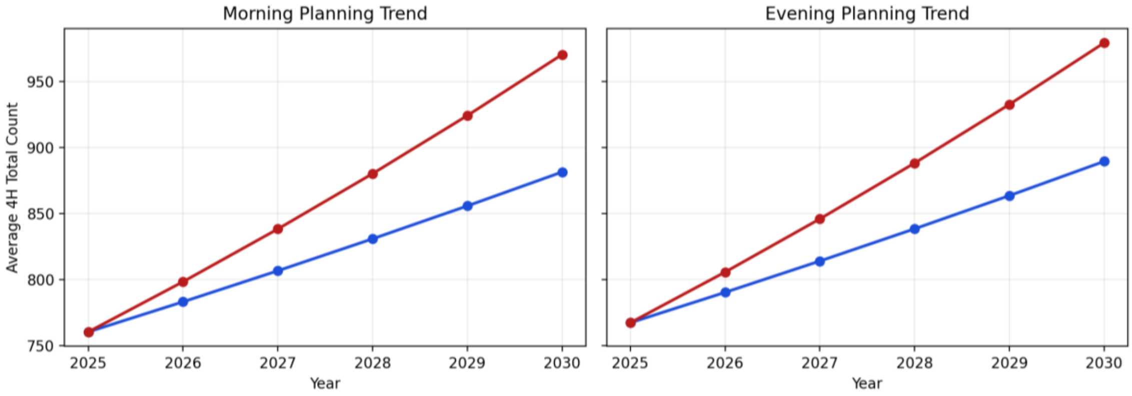

Fig 24. Morning and Evening Planning Trend

The planning trend graphs for both morning and evening periods show a consistent and significant increase in traffic volume from 2025 to 2030. In the morning period, the average 4-hour total count rises steadily from around 760 in 2025 to approximately 970 by 2030 for the upper trend, while the lower trend increases from about 760 to 880, indicating gradual growth under both scenarios. Similarly, in the evening period, traffic increases from nearly 765 in 2025 to about 980 in 2030 (upper trend), and from 765 to around 890 (lower trend). The gap between upper and lower trends widens over time, highlighting increasing uncertainty and demand pressure. Overall, both periods exhibit a strong upward trajectory, suggesting future congestion challenges.

V. CONCLUSION

The overall analysis of Bhumkar Bridge confirms that the corridor operates under severe traffic stress during both morning and evening peak periods, with major implications for congestion and environmental sustainability. The total morning traffic reached 34,711 vehicles with 50,423.10 PCU, while the evening traffic recorded 33,225 vehicles with 48,941.50 PCU, indicating persistent peak-period pressure in both directions. Carbon footprint estimation further shows that the intersection generates a very high environmental load, with 10,114.586 kg CO_2 during the morning peak and 9,883.933 kg CO_2 during the evening peak. Although the morning period has slightly higher total emissions, the evening period shows a marginally higher emission intensity per vehicle and per PCU, reflecting the effect of traffic composition. The movement-wise analysis identifies Dhayari to Nawale as the most environmentally critical direction, producing 932.1725 kg CO_2 in the morning and 965.6655 kg CO_2 in the evening. Similarly, Dhayari to Benglore and Karaj to Benglore also emerge as high-impact movements, indicating that the Dhayari and Katraj approaches are the major contributors to both traffic pressure and carbon emissions. This establishes that Bhumkar Bridge is not only a congestion hotspot but also a significant source of transport-related carbon burden. The category-wise carbon analysis reveals that the environmental load is dominated by heavy vehicle classes rather than by the numerically largest traffic class. Even though 2-wheelers account for 10,006 vehicles in the morning and 9,158 in the evening, they contribute only 380.228 kg CO_2 and 348.004 kg CO_2, respectively, due to their low emission factor. In contrast, HCVs generate 4,165.400 kg CO_2 in the morning and 4,021.5875 kg CO_2 in the evening, making them the largest contributors to total carbon emissions. Buses and LCVs also contribute substantially, with buses producing 2,345.840 kg CO_2 in the morning and 2,372.272 kg CO_2 in the evening, while LCVs contribute 1,853.052 kg CO_2 and 1,831.255 kg CO_2, respectively. These findings prove that the relationship between congestion and carbon footprint is not determined only by traffic volume or PCU, but strongly by vehicle composition. Therefore, congestion mitigation at Bhumkar Bridge must go beyond geometric or signal-based solutions and include targeted control of freight-intensive and heavy-emission traffic streams.

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