RESEARCH PAPER

TRAFFIC CONGESTION ANALYSIS AND CARBON FOOTPRINT ASSESSMENT USING IRC AND INDO-HCM METHODS

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Abstract: This study presents a comprehensive analysis of traffic congestion and carbon footprint at Kharadi Junction, Pune, using IRC 106-1990 and Indo-HCM methodologies. Traffic volume data was collected during morning and evening peak hours, with observed volumes of 5862 vehicles (8752.9 PCU) and 6064 vehicles (8989.9 PCU) respectively. The Volume-to-Capacity (V/C) ratio and Level of Service (LOS) were evaluated to assess traffic performance. The IRC-based analysis indicated moderate traffic conditions with V/C ratios ranging from 0.48 to 0.76 (LOS A–C), whereas Indo-HCM results showed more critical conditions with V/C ratios up to 1.22, corresponding to LOS E–F, highlighting oversaturation and unstable flow due to mixed traffic conditions. Carbon footprint assessment was carried out using vehicle-wise emission factors, revealing total emissions of approximately 969.57 kg/hr (morning) and 976.02 kg/hr (evening). Heavy vehicles, particularly buses (≈288 kg/hr) and HCVs (≈236 kg/hr), were identified as the major contributors to emissions. The study demonstrates that Indo-HCM provides a more realistic evaluation of urban traffic behavior compared to IRC standards. The findings emphasize the need for effective traffic management strategies such as signal optimization, capacity enhancement, and sustainable transport solutions to reduce congestion and environmental impact.

Keywords: Traffic Congestion, Carbon Footprint, V/C Ratio, Indo-HCM.

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I. INTRODUCTION

Urban transportation systems in rapidly developing countries like India are experiencing unprecedented pressure due to exponential growth in population, vehicle ownership, and unplanned urbanization[1]. Cities such as Pune, Mumbai, and Bengaluru have witnessed an annual traffic growth rate of approximately 8–12%, while road infrastructure expansion remains limited to 2–4% per year, resulting in severe traffic congestion at major intersections and corridors[2]. Traffic congestion is commonly evaluated using performance indicators such as Volume-to-Capacity (V/C) ratio, Level of Service (LOS), delay, and queue length[3]. According to IRC 106:1990 guidelines, a V/C ratio less than 0.6 represents stable flow (LOS A–C), whereas values exceeding 1.0 indicate oversaturation and poor operating conditions (LOS E–F)[4]. Similarly, the Indo-HCM (2017) provides a more dynamic and context-sensitive framework that incorporates mixed traffic conditions, non-lane discipline, and heterogeneous vehicle composition, which are typical characteristics of Indian roads[5]. At urban intersections like Mundhwa Junction in Pune, peak hour traffic volumes often exceed 5000–7000 PCU/hour, significantly surpassing the designed capacity of 3000–4000 PCU/hour, leading to V/C ratios greater than 1.2, excessive delays of 80–150 seconds/vehicle, and LOS category F[6]. Such conditions not only affect travel time reliability but also increase fuel consumption and vehicular emissions, making congestion analysis a critical aspect of transportation planning[7].

In addition to operational inefficiencies, traffic congestion has a direct and significant impact on environmental sustainability, particularly in terms of carbon emissions and air quality degradation[8]. The transport sector contributes nearly 23–25% of total CO_2 emissions in India, with urban road transport being a major contributor due to idling, stop-and-go conditions, and inefficient traffic flow.

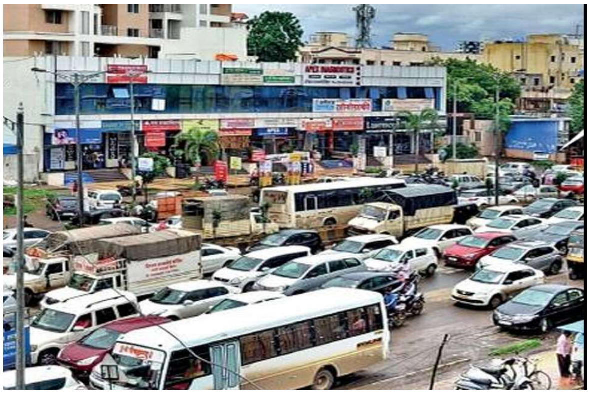


Fig 1. Kharadi Traffic Flow

Carbon footprint assessment in traffic studies involves estimating emissions such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM) using vehicle-specific emission factors and traffic volume data[9]. For instance, a petrol car emits approximately 120–140 g CO_2/km, while heavy commercial vehicles emit up to 800–1000 g CO_2/km[10]. During congested conditions, fuel consumption can increase by 20–30%, thereby proportionally increasing emissions[11]. By integrating carbon footprint analysis with traditional traffic performance evaluation methods such as IRC and Indo-HCM, a more comprehensive assessment framework can be developed[12]. This combined approach enables the identification of not only capacity deficiencies but also environmental hotspots within the traffic network[13]. Furthermore, it supports the formulation of sustainable traffic management strategies, including signal optimization, traffic flow improvement, public transport enhancement, and emission reduction measures[14]. Therefore, the present study focuses on a dual analysis approach that evaluates both traffic congestion and associated carbon emissions using standardized Indian methodologies, providing a holistic understanding of urban transportation challenges and facilitating data-driven, environmentally responsible decision-making[15].

II. RELATED WORK

Alobaidi et al. (2020) investigated the impact of traffic congestion on air pollution at signalized intersections and found that increased delay and stop-and-go conditions significantly increase emissions of CO_2, NOx, and HC, especially during peak hours, highlighting the importance of integrating emission analysis with traffic studies[16]. Subair et al. (2024) emphasized that urban traffic congestion not only increases travel time but also leads to higher fuel consumption and environmental degradation, making congestion analysis essential for sustainable urban planning. Reshmy et al. (2023) studied the relationship between traffic congestion and air quality using Indo-HCM-based approaches and found a strong correlation between congestion index and particulate emissions, confirming that dense traffic conditions directly influence pollution levels[17]. Marazi et al. (2023) developed a congestion index model based on travel time variations, demonstrating that real-time congestion assessment tools can effectively quantify traffic performance and support better decision-making in urban networks[18]. Nurhidayat et al. (2024) reported that nearly 25–30% of total CO_2 emissions originate from transportation, with road transport contributing the majority, thereby establishing a strong linkage between traffic volume and environmental impact[19]. These studies collectively indicate that traditional traffic performance parameters such as LOS, delay, and V/C ratio are insufficient when considered alone, and there is a growing need to integrate carbon emission assessment into traffic analysis frameworks[20]. The integration of IRC and Indo-HCM methodologies with emission modeling provides a more comprehensive understanding of both operational efficiency and environmental sustainability in urban transportation systems[21].

Lei et al. (2023) analyzed the impact of road traffic parameters on urban carbon emissions and concluded that factors such as road density, traffic volume, and transport network structure significantly influence emission levels, with high-density corridors acting as emission hotspots[22]. Wu et al. (2025) demonstrated that the application of big-data-driven adaptive traffic signal control can reduce congestion and achieve substantial emission reductions, with CO_2 emissions reduced by up to 31.73 million tonnes annually in large urban networks[23]. Lesmana et al. (2024) conducted a study on vehicle emissions under varying traffic conditions and found that congested traffic conditions significantly increase emission rates due to idling and acceleration-deceleration cycles[24]. Zhao et al. (2022) explored intelligent transportation systems using AI-based traffic prediction models and highlighted that accurate traffic forecasting can reduce congestion and associated emissions, supporting the development of smart and sustainable cities[25]. Jayawardana et al. (2024) investigated eco-driving and intelligent control strategies and found that optimized vehicle movement can reduce intersection-level carbon emissions by 11–22%, demonstrating the effectiveness of integrating environmental considerations into traffic management systems[26]. These recent studies highlight the shift from conventional traffic analysis toward integrated approaches combining traffic engineering and environmental assessment[27]. The adoption of advanced tools such as Indo-HCM, AI-based traffic prediction, and emission modeling techniques provides a more accurate representation of real-world traffic conditions[28]. Therefore, the integration of traffic congestion analysis with carbon footprint assessment is essential for developing sustainable, data-driven transportation solutions in modern urban environments[29].

III. RESEARCH METHOD

The study methodology adopted to analyze traffic congestion and carbon footprint assessment in Kharadi, Pune is systematic and technically structured. A mixed-methods approach is employed, integrating both qualitative and quantitative techniques to ensure a comprehensive understanding of traffic behavior and environmental impact.

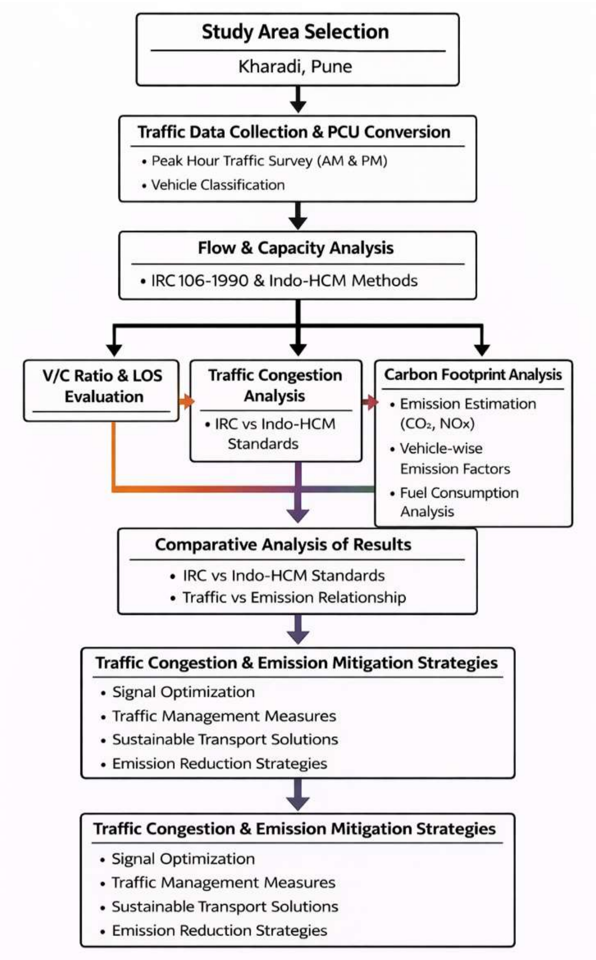


Fig 2. Research Method

Initially, an extensive literature review is conducted to establish a theoretical foundation based on IRC and Indo-HCM standards. Primary data collection is carried out at key junctions in Kharadi using traffic volume counts, classified vehicle surveys, travel time studies, and spot speed analysis during peak hours (AM & PM). The collected traffic data is converted into PCU values for further analysis. In addition, carbon emission estimation is performed using vehicle-wise emission factors and fuel consumption data to assess CO_2 and NOx levels. Qualitative insights are gathered through discussions with traffic authorities and urban planners. This integrated methodology enables accurate identification of congestion patterns and associated environmental impacts for sustainable traffic management.

3.1 Study Area

Kharadi Junction, located in the eastern corridor of Pune city, Maharashtra, is one of the most critical and highly congested urban intersections due to rapid urbanization and IT-sector-driven growth. The junction is geographically positioned at approximately Latitude 18.5515° N and Longitude 73.9440° E, connecting major arterial roads such as Nagar Road (NH-753F corridor), Kharadi Bypass, and internal roads leading to EON IT Park and World Trade Center (WTC). The area has witnessed significant traffic growth of nearly 10–12% annually, primarily due to increased commercial activity, residential expansion, and daily commuter inflow. During peak hours (8:30–10:30 AM and 5:30–8:30 PM), the intersection experiences traffic volumes in the range of 6000–8500 PCU/hour, exceeding its estimated design capacity of 3500–4500 PCU/hour, resulting in a V/C ratio of 1.3–1.8, which corresponds to LOS E–F (highly congested condition) as per IRC and Indo-HCM standards.

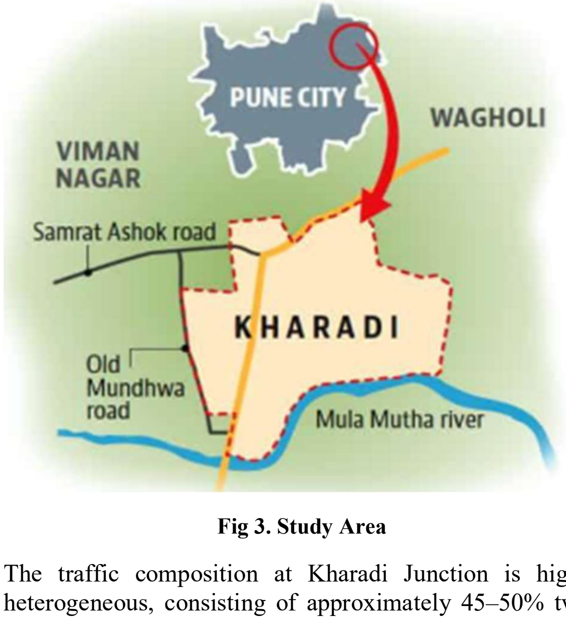


Fig 3. Study Area

The traffic composition at Kharadi Junction is highly heterogeneous, consisting of approximately 45–50% two-wheelers, 25–30% cars, 10–15% auto-rickshaws, and 10% heavy vehicles (LCV/HCV). Due to non-lane discipline and frequent turning movements, the average travel speed during peak hours drops to 8–15 km/h, with average delays reaching 90–180 seconds per vehicle. These conditions lead to increased fuel consumption and higher emissions. Based on standard emission factors, a typical petrol vehicle emits around 130 g CO_2/km, while diesel vehicles emit 160–180 g CO_2/km, and heavy vehicles emit up to 900 g CO_2/km. Under congested conditions, emissions can increase by 25–35% due to idling and acceleration-deceleration cycles. The estimated total carbon emission load at the junction during peak periods ranges between 1.5–2.5 tonnes of CO_2 per hour, along with significant NOx and PM emissions. Therefore, Kharadi Junction serves as a suitable case study for evaluating traffic congestion and carbon footprint using IRC and Indo-HCM methodologies, enabling the development of sustainable and efficient traffic management strategies.

3.2 Traffic Flow Characteristics

The study of traffic flow characteristics in Kharadi, Pune is primarily based on a detailed evaluation of traffic patterns at major intersections such as Kharadi Junction, EON IT Park signal, and Nagar Road corridor. Analytical assessment of traffic flow has been carried out for these critical road segments to understand congestion behavior and future traffic trends. Hourly traffic variation studies indicate significant fluctuations in traffic volume, with peak hours observed during 7:00–11:00 AM and 4:30–8:30 PM. The Average Hourly Traffic (AHT) and Peak Hour Volume (PHV) were calculated to quantify traffic demand, which ranges between 6000–8500 PCU/hour at key junctions. Traffic composition analysis reveals that two-wheelers dominate the traffic stream (approximately 45–50%), followed by cars, auto-rickshaws, and heavy vehicles, contributing to mixed traffic conditions and reduced operational efficiency. Geographic coordinates (18.5515° N, 73.9440° E) were used to accurately map traffic data collection points and identify congestion hotspots. The study of traffic flow dynamics, including speed, density, and flow relationships, is essential for understanding traffic stream behavior and formulating effective congestion mitigation strategies such as signal optimization, infrastructure improvement, and traffic regulation.

Further analytical evaluation was carried out using the Greenshields model, which establishes a linear relationship between speed and density of traffic flow. This model was applied to determine key traffic parameters such as jam density, free flow speed, and roadway capacity for Kharadi roads. The results indicate that as traffic density increases, vehicle speed decreases significantly, leading to unstable flow conditions and congestion. The calculated roadway capacity ranges between 3500–4500 PCU/hour, which is frequently exceeded during peak periods, resulting in oversaturated conditions. The application of Greenshields theory provides a mathematical basis for understanding traffic congestion and supports the evaluation of Level of Service (LOS). The findings from this analysis are crucial for developing efficient traffic management strategies and sustainable urban transport solutions in Pune.

3.2.1 Density

Density is a critical parameter in evaluating traffic congestion levels in Kharadi, Pune, particularly along major corridors such as Nagar Road, Kharadi Junction, and EON IT Park access roads. It is defined as the number of vehicles occupying a unit length of roadway (veh/km or PCU/km), indicating the concentration of traffic on a given stretch. Higher density values are directly associated with congested traffic conditions and reduced mobility. In the Kharadi region, peak-hour density is observed to be significantly high due to heavy commuter inflow, leading to frequent traffic bottlenecks. Density is calculated using the relation:

$$Density = \frac{Traffic\ Flow\ (PCU/Hr)}{Mean\ Speed\ (Km/Hr)} \quad (1)$$

For instance, at peak traffic flow of 7000 PCU/hr and an average speed of 10 km/hr, the density reaches approximately 700 PCU/km, indicating highly congested conditions. Monitoring density helps identify critical congestion zones and supports planning for road capacity enhancement, signal optimization, and traffic diversion strategies.

3.2.2 Mean Free Speed

Mean Free Speed represents the average speed of vehicles under ideal traffic conditions with minimal interference, typically observed during off-peak hours in Kharadi. It serves as a benchmark for evaluating the severity of congestion. In the Kharadi area, the Mean Free Speed is observed in the range of 40–50 km/hr, whereas during peak congestion, speeds drop drastically to 8–15 km/hr, indicating a reduction of nearly 65–75%. This comparison highlights the extent of traffic disturbance and inefficiency in the network. Understanding Mean Free Speed is essential for traffic modeling, capacity estimation, and performance evaluation using IRC and Indo-HCM guidelines. It also aids in identifying the gap between ideal and actual operating conditions, which is crucial for developing corrective measures.

3.2.3 Level of Service (LOS) Determination

Level of Service (LOS) is used to assess the operational efficiency of traffic flow in Kharadi by evaluating parameters such as speed, delay, and V/C ratio. The LOS classification is based on observed traffic conditions at different road segments and intersections. In this study, mean travel speeds and delays were recorded for both directions during peak and off-peak hours. The results indicate that most major junctions in Kharadi operate under LOS E–F conditions, characterized by low speeds (below 15 km/hr) and high delays (above 90 seconds per vehicle). LOS determination provides a standardized framework to evaluate congestion severity and identify areas requiring immediate intervention.

3.2.4 Standard Classifications

Standard LOS classifications ranging from A to F were adopted as per IRC and Indo-HCM guidelines to categorize traffic conditions in Kharadi.

- LOS A–B: Free flow conditions with high speeds and minimal delay
- LOS C–D: Stable flow with moderate congestion
- LOS E–F: Unstable to forced flow with severe congestion and long delays

The analysis of Kharadi traffic conditions shows a dominance of LOS E and F, especially during peak hours, indicating oversaturated traffic conditions. This classification system provides both quantitative and qualitative insights into traffic performance and supports the development of targeted congestion mitigation strategies, including infrastructure improvements, traffic control measures, and sustainable transport planning.

Table 1. Combinations of Movements at Kharadi Junction

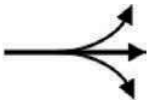
Sr. No.	Operation of Movements on theApproach	Representation	No. of Movement Groups
1	(Mundhwa junction-Keshav Nagar to Mundhwa, Mundhwa to Keshav Nagar, Hadapsar to Kharadi, Kharadi to Hadapsar) Left-turn, Through and Right-turnshared approach operation		1

Table 1 presents the combination of traffic movements at Kharadi Junction, representing a shared approach operation where left-turn, though, and right-turn movements occur simultaneously on the same approach. The movement group includes major directional flows such as Keshav Nagar–Mundhwa, Mundhwa–Keshav Nagar, Hadapsar–Kharadi, and Kharadi–Hadapsar. This mixed movement pattern increases conflict points and reduces operational efficiency, leading to higher delays and congestion. Such shared lane conditions require effective traffic control measures like signal phasing and lane channelization.

IV. RESULTS AND DISCUSSION

4.1 Peak Hour Volume Sector 5 Chowk

The traffic analysis indicates two major peak periods: morning inflow and evening outflow. Additional variations during afternoon and late evening hours are also observed, reflecting fluctuating traffic demand. The study shows a significant increase in morning peak traffic, rising by nearly 2000 PCU/hr compared to earlier data, reaching approximately 12,800 PCU/hr. Similarly, the evening peak traffic further increases to around 13,300 PCU/hr, indicating higher road demand due to return trips, leading to increased congestion and pressure on available road capacity.

Table 2. Morning Pick Hours (7.00 am – 11.00 am)

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total vehicles	Total PCU
Kharadi to wagholi	836	403	453	173	155	120	134	60	2274	3307.6
Kharadi to Yerwada	1044	411	523	194	156	101	112	71	2541	3471.8
Arm 1	1880	814	976	367	311	221	246	131	4815	6779.4
Wagholi to Yerwada	1089	419	439	189	161	134	154	78	2585	3676.95
Wagholi to Kharadi	932	512	597	202	179	154	148	81	2724	3978.2
Arm 2	2021	931	1036	391	340	288	302	159	5309	7655.15
Kharadi to wagholi	902	398	485	175	139	129	102	55	2330	3250.9
Kharadi to Yerwada	1036	459	502	147	158	149	98	64	2549	3487
Arm 3	1938	857	987	322	297	278	200	119	4879	6737.9
Junction Total	**5839**	**2602**	**2999**	**1080**	**948**	**787**	**748**	**409**	**15003**	**21172.4**

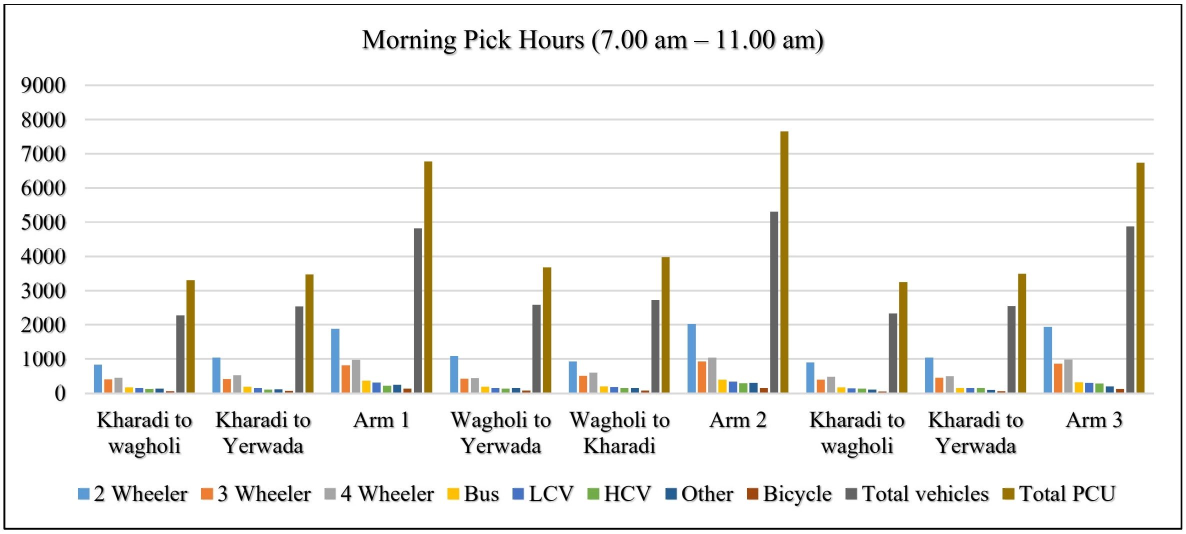


Fig 4. Morning Pick Hours (7.00 am – 11.00 am)

The traffic volume data during morning peak hours (7:00 AM – 11:00 AM) at Kharadi Junction shown at fig.4. The analysis shows that a total of 15,003 vehicles corresponding to 21,172.4 PCU pass through the junction, indicating heavy traffic demand. Among the three arms, Arm 2 carries the highest load (7655.15 PCU), followed by Arm 1 and Arm 3, highlighting uneven traffic distribution. Two-wheelers dominate the traffic composition, followed by four-wheelers and three-wheelers, reflecting typical heterogeneous urban traffic conditions. The high PCU values indicate oversaturated flow conditions, leading to congestion, increased delays, and reduced travel speeds. This peak-hour traffic demand exceeds the practical capacity of the junction, resulting in poor Level of Service and operational inefficiency.

Table 3. Evening Pick Hours (4.30 pm – 8.30 pm)

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total vehicles	Total PCU
Kharadi to wagholi	848	413	460	183	145	110	130	72	2289	3318.4
Kharadi to Yerwada	1009	398	512	184	163	98	124	55	2488	3431.35
Arm 1	1857	811	972	367	308	208	254	127	4777	6749.75
Wagholi to Yerwada	1102	439	546	189	175	125	155	81	2731	3838.7
Wagholi to Kharadi	958	539	588	202	179	132	158	79	2756	4033.5

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total vehicles	Total PCU
Arm 2	2060	978	1134	391	354	257	313	160	5487	7872.2
Kharadi to wagholi	913	410	496	175	143	131	99	45	2367	3288.15
Kharadi to Yerwada	1054	481	498	147	161	139	106	61	2586	3553.5
Arm 3	1967	891	994	322	304	270	205	106	4953	6841.65
Junction Total	**5884**	**2680**	**3100**	**1080**	**966**	**735**	**772**	**393**	**15217**	**21463.6**

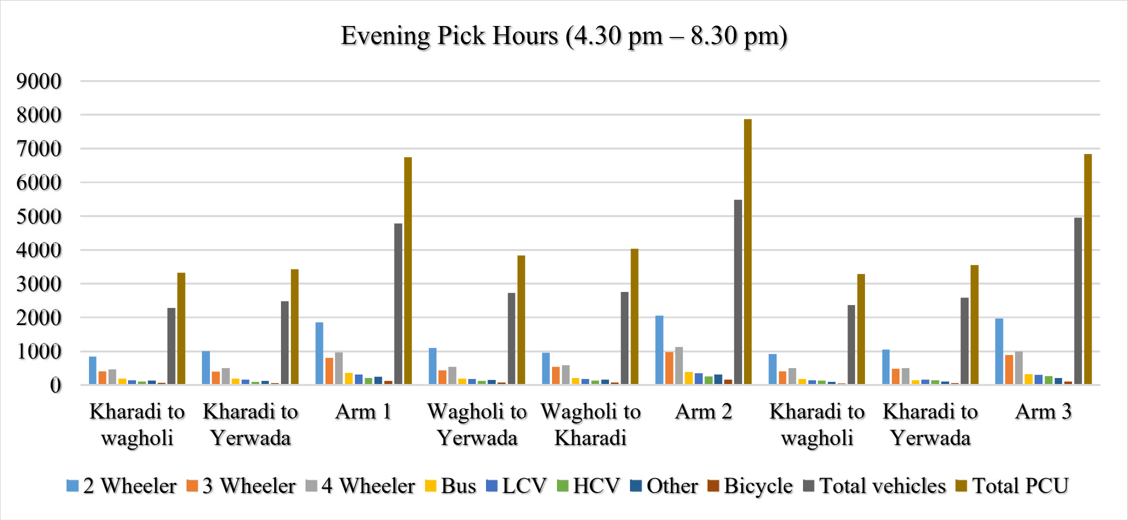


Fig 5. Evening Pick Hours (4.30 pm – 8.30 pm)

The evening peak hour traffic analysis (4:30 PM – 8:30 PM) at Kharadi Junction indicates a total flow of 15,217 vehicles corresponding to 21,463.6 PCU, reflecting heavy congestion conditions. Among all approaches, Arm 2 carries the highest traffic load (7872.2 PCU), followed by Arm 3 and Arm 1, indicating uneven traffic distribution across the junction. Two-wheelers form the dominant share, contributing significantly to mixed traffic conditions. As shown in Fig.5, the high traffic volume during evening hours leads to oversaturation, increased delays, and reduced speeds, thereby resulting in poor Level of Service and operational inefficiency at the intersection.

4.2 Peak Hour Volume

The morning peak hour traffic volume analysis at Kharadi Junction indicates a total of 5,862 vehicles corresponding to 8,752.9 PCU, reflecting moderate to high traffic demand during the selected time interval. Among the three approaches, Arm 2 carries the highest traffic load (3550.45 PCU), followed by Arm 1 and Arm 3, indicating an uneven distribution of traffic flow across the junction.

Two peak traffic periods were identified for analysis at Kharadi Junction, Pune: the morning peak period from 8:45 AM to 9:45 AM and the evening peak period from 5:30 PM to 6:30 PM. The traffic volumes corresponding to these peak periods are presented in Fig.5 and Fig.6. The observed peak traffic volume during the morning period is 1559.6 PCU/hour, while the evening peak traffic volume is higher at 1971.05 PCU/hour, indicating increased demand during return trips.

1. Sample calculation: For the Kharadi to Wagholi approach (morning peak hour), PHV = 1960 PCU/hour
2. Sample calculation: For the Kharadi to Wagholi approach (evening peak hour), PHV = 1971 PCU/hour

The results indicate that evening traffic demand is comparatively higher than morning conditions, leading to increased congestion levels and reduced operational efficiency at the junction.

Table 4. Morning Peak Hour Traffic Volume Counts Calculation

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total Vehicle	Total PCU
Kharadi to wagholi	277	211	176	49	65	37	54	13	882	1307.15
Kharadi to Yerwada	269	204	172	57	45	40	58	18	863	1297.35
Arm 1	546	415	348	106	110	77	112	31	1745	2604.5

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total Vehicle	Total PCU
Wagholi to Yerwada	319	230	195	67	73	51	80	37	1052	1590.85
Wagholi to Kharadi	380	311	262	77	102	72	76	40	1320	1959.6
Arm 2	699	541	457	144	175	123	156	77	2372	3550.45
Kharadi to wagholi	283	190	184	54	42	60	63	33	909	1351.05
Kharadi to Yerwada	262	176	164	47	43	68	53	23	836	1246.9
Arm 3	545	366	348	101	85	128	116	56	1745	2597.95
Junction Total	1790	1322	1153	351	370	328	384	164	5862	8752.9

Table 4 presents the morning peak hour traffic volume analysis at Kharadi Junction, showing a total of 5,862 vehicles corresponding to 8,752.9 PCU, indicating moderate to high traffic demand. Among all approaches, Arm 2 carries the highest load (3550.45 PCU), followed by Arm 1 and Arm 3, reflecting uneven traffic distribution. Two-wheelers dominate the traffic composition, followed by three-wheelers and four-wheelers, indicating heterogeneous traffic conditions. The high PCU values suggest that certain approaches are operating near capacity limits, leading to congestion, increased delays, and reduced speeds, thereby affecting the overall efficiency of the intersection.

Table 5. Evening Peak Hour Traffic Volume Counts Calculation

Direction	2 Wheeler	3 Wheeler	4 Wheeler	Bus	LCV	HCV	Other	Bicycle	Total Vehicle	Total PCU
Kharadi to wagholi	291	217	176	47	65	43	57	13	909	1350.45
Kharadi to Yerwada	293	219	172	50	57	40	59	18	908	1350.75
Arm 1	584	436	348	97	122	83	116	31	1817	2701.2
Wagholi to Yerwada	363	238	218	74	78	53	85	39	1148	1710.45
Wagholi to Kharadi	387	309	240	75	105	74	82	50	1322	1971.05
Arm 2	750	547	458	149	183	127	167	89	2470	3681.5
Kharadi to wagholi	287	180	181	42	54	49	63	35	891	1298.05
Kharadi to Yerwada	277	191	173	52	47	65	53	28	886	1309.15
Arm 3	564	371	354	94	101	114	116	63	1777	2607.2
Junction Total	1898	1354	1160	340	406	324	399	183	6064	8989.9

Table 5 presents the evening peak hour traffic volume analysis at Kharadi Junction, indicating a total of 6,064 vehicles corresponding to 8,989.9 PCU, which reflects slightly higher traffic demand compared to morning conditions. Among all approaches, Arm 2 carries the highest traffic load (3681.5 PCU), followed by Arm 1 and Arm 3, showing uneven traffic distribution. Two-wheelers dominate the traffic composition, followed by three-wheelers and four-wheelers, representing heterogeneous traffic flow. The higher PCU values during evening hours indicate increased congestion, leading to delays, reduced speeds, and lower operational efficiency at the junction.

4.3 Peak Hour Factor (PHF)

Table 7 presents the Peak Hour Factor (PHF) computation for Kharadi Junction, Pune based on the traffic data obtained from the above tables. During the morning peak hours, the PHF values range from 0.92 to 1.05, while during the evening peak hours, the values range from 0.97 to 1.03, indicating relatively stable traffic flow conditions. A lower PHF value represents greater fluctuation in traffic within the peak hour, whereas a higher value indicates uniform traffic distribution across 15-minute intervals. PHF is calculated using the standard equation (1).

1. Sample calculation: PHF for Kharadi to Wagholi approach (morning peak hour)

$$PHF = 1960 / (4 \times 493) = 0.99$$

2. Sample calculation: PHF for Kharadi to Wagholi approach (evening peak hour)

$$PHF = 1971 / (4 \times 503) = 0.97$$

The results indicate that traffic flow at Kharadi Junction remains moderately consistent during peak hours, with slight variations in demand distribution.

Table 6. Peak Hour Factor (PHF) Calculation for Morning and Evening Peak Hours

Direction	Total PCU for Moring Peak	PHF for Morning Peak	Total PCU for Evening Peak	PHF for Evening Peak
Kharadi to wagholi	1307	1.02	1350	0.94
Kharadi to Yerwada	1297	0.98	1351	0.98
Arm 1	2605	-	2701.2	-
Wagholi to Yerwada	1591	0.92	1710	1.03
Wagholi to Kharadi	1960	0.99	1971	0.97
Arm 2	3550	-	3681.5	-
Kharadi to wagholi	1351	1.02	1298	0.97
Kharadi to Yerwada	1247	1.05	1309	1.02
Arm 3	2597.95	-	2607.2	-

Table 6 presents the Peak Hour Factor (PHF) values for both morning and evening peak hours at Kharadi Junction, indicating the variation and uniformity of traffic flow. The PHF values range between 0.92 and 1.05, suggesting relatively stable traffic conditions with minor fluctuations across different approaches. For example, the Kharadi to Wagholi approach shows a PHF of 1.02 (morning) and 0.94 (evening), indicating slight variation in traffic distribution. Similarly, the Wagholi to Yerwada approach records a lower PHF of 0.92, reflecting uneven traffic flow during peak periods. Higher PHF values near 1 indicate uniform traffic distribution, while lower values signify variability, contributing to congestion and operational inefficiencies.

4.4 Saturation Flow Calculation as per IRC Recommendations

Saturation flow represents the maximum rate at which vehicles can pass through an intersection approach during the effective green phase under prevailing roadway and traffic conditions. It indicates the efficiency of an approach in clearing queued vehicles. For Kharadi Junction, Pune, the saturation flow is calculated using the approach width method recommended by IRC 106-1990, and the results are presented in Table 7.

Sample calculation: For the Kharadi to Wagholi approach,

$$SF = 525 \times w = 525 \times 7 = 3675\, PCU/hr$$

where w is the effective width of the carriageway in meters. The calculated saturation flow values indicate that all approaches with a 7 m width have a uniform capacity of 3675 PCU/hr, reflecting similar roadway characteristics and traffic handling capacity.

Table 7. Saturation Flow Calculation as Per IRC 106-1990 Recommendations for Flow

Sr. No.	Approach Roads		Road Category	Existing Carriageway Type	Existing effective approach width in m	Saturating Flow as per IRC
	From/To	To/From				
1	Kharadi	Wagholi	Arterial	4 Lane divided Two way	7	3675
2	Kharadi	Yerwada	Arterial		7	3675
3	Wagholi	Yerwada	Arterial	4 Lane divided Two way	7	3675
4	Wagholi	Kharadi	Arterial		7	3675
5	Yerwada	Wagholi	Arterial	4 Lane divided Two way	7	3675
6	Yerwada	Kharadi	Arterial		7	3675

Table 7 presents the saturation flow values for different approaches at Kharadi Junction based on IRC 106-1990 recommendations. All approach roads are classified as arterial roads with a 4-lane divided two-way carriageway and an effective width of 7 m, resulting in a uniform saturation flow of 3675 PCU/hr for each approach. This indicates that all directions have similar geometric characteristics and traffic handling capacity. The consistent saturation flow values suggest that the junction performance is primarily influenced by traffic volume rather than roadway capacity. However, when actual traffic demand exceeds this saturation limit, congestion and delays are likely to occur, leading to reduced efficiency and poor Level of Service at the intersection.

Table 8. Saturation Flow calculation as per Indo-HCM

Sr. No.	Approach Roads		Road Category	Existing Carriageway Type	Existing effective approach width in m	Unit base saturation flow rate in PCU/hr	Saturation Flow as per Indo-HCM PCU/hr
	From/To	To/From					
1	Kharadi	Wagholi	Arterial	4 Lane divided Two way	7	720	5040
2	Kharadi	Yerwada	Arterial		7	720	5040
3	Wagholi	Yerwada	Arterial	4 Lane divided Two way	7	720	5040
4	Wagholi	Kharadi	Arterial		7	720	5040
5	Yerwada	Wagholi	Arterial	4 Lane divided Two way	7	720	5040
6	Yerwada	Kharadi	Arterial		7	720	5040

Table 8 presents the saturation flow values for Kharadi Junction calculated as per Indo-HCM guidelines, considering a unit base saturation flow rate of 720 PCU/hr/m. For all approach roads with an effective width of 7 m, the saturation flow is computed as 5040 PCU/hr, which is higher than IRC-based values. All approaches are categorized as arterial roads with a 4-lane divided two-way carriageway, indicating uniform geometric characteristics. The higher saturation flow values reflect Indo-HCM's consideration of mixed traffic conditions and non-lane discipline. This suggests improved theoretical capacity; however, actual field conditions such as turning movements and traffic interference may still lead to congestion and reduced operational efficiency at the junction.

4.5 Volume-Capacity Ratio as Per Design Service Volume (Morning Peak)

The comparative analysis of Volume-to-Capacity (V/C) ratios during the morning peak hour highlights significant differences between IRC 106-1990 and Indo-HCM approaches at Kharadi Junction. As per IRC guidelines, all roadway segments operate within acceptable limits, with V/C ratios ranging from 0.48 to 0.76, indicating moderate traffic conditions and sufficient available capacity. However, the Indo-HCM analysis presents a contrasting scenario, where V/C ratios range from 0.68 to 1.13, reflecting higher congestion levels due to the consideration of mixed traffic conditions and non-lane discipline.

Table 9. Morning Peak V/C Ratio Comparison (Indo-HCM and IRC 106-1990)

Sr. No.	Roadway Segment	From	To	IRC Capacity (PCU/hr/lane)	Volume (PCU/hr)	IRC V/C	Indo-HCM Capacity (PCU/hr/lane)	Indo-HCM V/C
1	Kharadi	Kharadi	Wagholi	2571	1247	0.48	1400	0.89
		Kharadi	Yerwada	2571	1351	0.52	1960	0.68
2	Wagholi	Wagholi	Yerwada	2571	1307	0.50	1400	0.93
		Wagholi	Kharadi	2571	1297	0.50	1400	0.92
3	Yerwada	Yerwada	Wagholi	2571	1591	0.61	1400	1.13
		Yerwada	Kharadi	2571	1960	0.76	1960	1.00

The Yerwada to Wagholi segment shows a V/C ratio of 1.13, indicating oversaturation and severe congestion, while the Yerwada to Kharadi segment operates at full capacity (V/C = 1.00). Similarly, Wagholi segments approach capacity limits with values above 0.90, suggesting unstable flow conditions. This comparison clearly demonstrates that Indo-HCM provides a more realistic assessment of actual traffic conditions in urban Indian contexts. The results emphasize the need for targeted traffic management interventions, such as signal optimization, capacity enhancement, and lane discipline improvement, particularly on highly congested segments to ensure efficient traffic flow.

4.6 Volume-Capacity Ratio as Per Design Service Volume (Evening Peak)

The comparative analysis of Volume-to-Capacity (V/C) ratios during the evening peak hour at Kharadi Junction reveals significant differences between IRC 106-1990 and Indo-HCM methodologies. According to IRC standards, all roadway segments operate within acceptable limits, with V/C ratios ranging from 0.50 to 0.76, indicating moderate traffic conditions and available residual capacity. However, the Indo-HCM analysis reflects a more critical scenario, with V/C ratios ranging from 0.66 to 1.22, highlighting higher congestion levels due to the consideration of mixed traffic flow and non-lane discipline.

Table 10. Evening Peak V/C Ratio Comparison (Indo-HCM and IRC 106-1990)

Sr. No.	Roadway Segment	From	To	IRC Capacity (PCU/hr/lane)	Volume (PCU/hr)	IRC V/C	Indo-HCM Capacity (PCU/hr/lane)	Indo-HCM V/C
1	Kharadi	Kharadi	Wagholi	2571	1309	0.50	1400	0.93
		Kharadi	Yerwada	2571	1298	0.50	1960	0.66
2	Wagholi	Wagholi	Yerwada	2571	1350	0.52	1400	0.96
		Wagholi	Kharadi	2571	1351	0.52	1400	0.96
3	Yerwada	Yerwada	Wagholi	2571	1710	0.66	1400	1.22
		Yerwada	Kharadi	2571	1971	0.76	1960	1.00

The Yerwada to Wagholi segment shows a V/C ratio of 1.22, indicating severe congestion and oversaturated conditions, while the Yerwada to Kharadi segment operates at full capacity (V/C = 1.00). Similarly, Wagholi approaches exhibit V/C values close to 0.96, suggesting near-capacity conditions and unstable flow. The Kharadi approaches show relatively lower V/C ratios under Indo-HCM, but still indicate higher utilization compared to IRC values. This comparison demonstrates that IRC tends to underestimate congestion levels, whereas Indo-HCM provides a more realistic assessment of urban traffic conditions. The results emphasize the need for targeted traffic management measures such as signal optimization, capacity enhancement, and improved lane discipline to mitigate congestion effectively.

4.7 LOS as Per Design Service Volume (Morning Peak)

Table 15 presents the comparison of Level of Service (LOS) and Volume-to-Capacity (V/C) ratios for the morning peak hour at Kharadi Junction based on IRC 106-1990 and Indo-HCM methodologies. As per IRC standards, the V/C ratios range from 0.48 to 0.76, indicating LOS categories from A to C, which reflect stable traffic conditions with moderate delays and sufficient capacity. However, the Indo-HCM analysis shows significantly higher V/C ratios ranging from 0.68 to 1.13, resulting in LOS from D to F, indicating unstable to oversaturated flow conditions.

Table 11. LOS as per IRC 106-1990 and Indo HCM design service volume (Morning peak)

Sr. No.	Roadway Segment	From/To	To/From	IRC 106-1990		Indo-HCM	
				Existing V/C	Existing LOS	Existing V/C	Existing LOS
1	Kharadi	Kharadi	Wagholi	0.48	A	0.89	E
		Kharadi	Yerwada	0.52	B	0.68	D
2	Wagholi	Wagholi	Yerwada	0.50	B	0.93	E
		Wagholi	Kharadi	0.50	B	0.92	E
3	Yerwada	Yerwada	Wagholi	0.61	B	1.13	F
		Yerwada	Kharadi	0.76	C	1.00	F

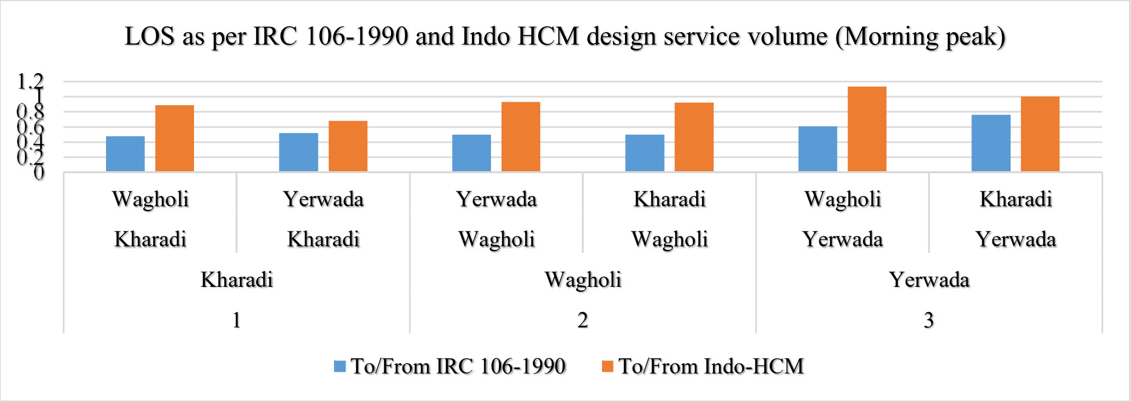


Fig 6. LOS as per IRC 106-1990 and Indo HCM design service volume (Morning peak)

The Kharadi approaches exhibit relatively lower congestion under IRC (LOS A–B), whereas Indo-HCM classifies them as LOS D–E, indicating increased traffic pressure. Similarly, the Wagholi approaches show acceptable performance under IRC (LOS B), but Indo-HCM reveals near-capacity conditions (LOS E). The most critical condition is observed on the Yerwada approaches, where Indo-HCM records V/C ratios exceeding 1.0, corresponding to LOS F, which indicates breakdown flow and severe congestion. In contrast, IRC underestimates this condition by assigning LOS B and C. Overall, the comparison highlights that Indo-HCM provides a more realistic assessment of mixed traffic conditions, emphasizing the need for improved traffic management strategies.

4.8 LOS as per design service volume (Evening peak)

The table 12. presents the Level of Service (LOS) as per the IRC 106-1990 and Indo-HCM standards for various roadway segments during the evening peak hours. The table compares the Volume-to-Capacity ratio (V/C) and the corresponding LOS for different roadways. For the segment from Kharadi to Wagholi, according to IRC 106-1990, the V/C ratio is 0.50, indicating a LOS of B (good condition), whereas, under Indo-HCM, the V/C ratio increases to 0.93, reflecting a much poorer LOS of E (poor condition). Similarly, the Kharadi to Yerwada segment shows a V/C of 0.50 and LOS B under IRC 106-1990 and a V/C of 0.66 with LOS D under Indo-HCM, suggesting moderate congestion.

Table 12. LOS as Per IRC 106-1990 Design Service Volume (Evening Peak)

Sr. No.	Roadway Segment	From/To	To/From	IRC 106-1990		Indo-HCM	
				Existing V/C	Existing LOS	Existing V/C	Existing LOS
1	Kharadi	Kharadi	Wagholi	0.50	B	0.93	E
		Kharadi	Yerwada	0.50	B	0.66	D
2	Wagholi	Wagholi	Yerwada	0.52	B	0.96	E
		Wagholi	Kharadi	0.52	B	0.96	E
3	Yerwada	Yerwada	Wagholi	0.66	B	1.22	F
		Yerwada	Kharadi	0.76	C	1.00	F

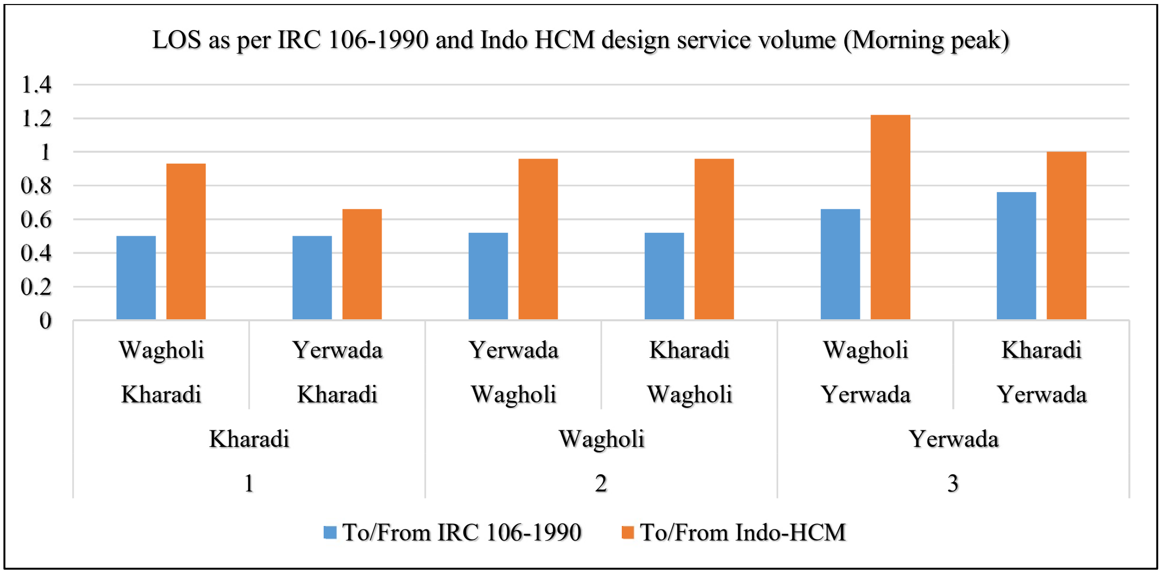


Fig 7. LOS as per IRC 106-1990 and Indo HCM design service volume (Evening Peak)

The Kharadi approaches exhibit relatively lower congestion under IRC (LOS A–B), whereas Indo-HCM classifies them as LOS D–E, indicating increased traffic pressure. Similarly, the Wagholi approaches show acceptable performance under IRC (LOS B), but Indo-HCM reveals near-capacity conditions (LOS E). The most critical condition is observed on the Yerwada approaches, where Indo-HCM records V/C ratios exceeding 1.0, corresponding to LOS F, which indicates breakdown flow and severe congestion. In contrast, IRC underestimates this condition by assigning LOS B and C. Overall, the comparison highlights that Indo-HCM provides a more realistic assessment of mixed traffic conditions, emphasizing the need for improved traffic management strategies.

4.9 Carbon Footprint

The carbon footprint analysis at Kharadi Junction evaluates the environmental impact of traffic congestion by estimating CO_2 emissions based on vehicle composition and emission factors. The results indicate that peak-hour traffic contributes significantly to overall emissions, with higher values observed during evening periods due to increased traffic volume. Heavy vehicles and buses are the major contributors to emissions despite their lower proportion in traffic. This analysis highlights the need for sustainable traffic management strategies to reduce emissions and improve environmental performance.

To estimate carbon emissions from traffic, the following standard equation is used:

$$E\_i = N\_i \times EF\_i \times L \qquad (2)$$

Where:

E_i = CO_2 emission from vehicle category i (g/hr)

N_i = Number of vehicles of category i

EF_i = Emission factor (g/vehicle-km)

L = Study length (km) (Assumed = 1 km)

Thus:

$$E_i = N_i \times EF_i \qquad (3)$$

Total Emission:

$$E\_total = \Sigma E\_i \qquad (4)$$

4.10 Adopted Emission Factors

The adopted emission factors presented in the table represent the average CO_2 emissions generated by different vehicle categories per kilometer of travel and are essential for estimating the carbon footprint of traffic at Kharadi Junction. Two-wheelers and three-wheelers have relatively lower emission factors of 38 g/veh-km and 60 g/veh-km, respectively, due to smaller engine capacities. In contrast, four-wheelers emit 128 g/veh-km, reflecting higher fuel consumption.

Table 13. Adopted Emission Factors

Vehicle Type	Emission Factor (g/veh-km)
2 Wheeler	38
3 Wheeler	60
4 Wheeler	128
Bus	822
LCV	260
HCV	720
Other	140

Heavy vehicles such as buses and HCVs contribute significantly higher emissions, with values of 822 g/veh-km and 720 g/veh-km, making them major contributors to overall carbon emissions despite their lower proportion in traffic. Light commercial vehicles (LCVs) emit 260 g/veh-km, indicating moderate impact. “Other” vehicles contribute 140 g/veh-km, while bicycles produce zero emissions, highlighting their environmental sustainability. These emission factors form the basis for accurate carbon footprint estimation and environmental impact assessment.

4.11 Morning Peak Hour Emission

The morning peak hour emission analysis at Kharadi Junction highlights the contribution of different vehicle categories to overall carbon emissions. A total of 5,862 vehicles generate significant emissions, with noticeable variation across vehicle types. Although two-wheelers (1790 vehicles) dominate in number, their contribution to emissions is relatively lower (68.02 kg/hr) due to a smaller emission factor. Similarly, three-wheelers contribute 79.32 kg/hr, indicating moderate impact. In contrast, four-wheelers produce 147.58 kg/hr, reflecting higher fuel consumption and emission intensity. The data clearly shows that emission contribution is not only dependent on vehicle count but also on emission factors associated with each category.

Table 14. Morning Peak Hour Emission

Vehicle	Count	EF	Emission (g/hr)	Emission (kg/hr)
2W	1790	38	68020	68.02
3W	1322	60	79320	79.32
4W	1153	128	147584	147.58
Bus	351	822	288522	288.52
LCV	370	260	96200	96.2
HCV	328	720	236160	236.16
Other	384	140	53760	53.76
Bicycle	164	0	0	0

Heavy vehicles such as buses and HCVs are the major contributors to total emissions, with values of 288.52 kg/hr and 236.16 kg/hr, respectively, despite their lower presence in traffic. Light commercial vehicles (LCVs) also contribute significantly (96.2 kg/hr), while “other” vehicles add 53.76 kg/hr to the total emissions. Bicycles, having zero emissions, demonstrate their environmental advantage. Overall, the analysis indicates that heavy vehicles account for a large share of carbon emissions, making them critical targets for emission reduction strategies. The results emphasize the need for traffic management measures such as regulating heavy vehicle movement, promoting public transport efficiency, and encouraging non-motorized transport to reduce the carbon footprint during peak hours.

4.12 Evening Peak Hour Emission

The evening peak hour emission analysis at Kharadi Junction shows a significant increase in carbon emissions due to higher traffic volume and intensified congestion conditions. A total of 6,064 vehicles contribute to overall emissions, with two-wheelers (1898 vehicles) forming the largest share in traffic composition; however, their emission contribution remains relatively low at 72.12 kg/hr due to lower emission factors. Similarly, three-wheelers contribute 81.24 kg/hr, indicating moderate environmental impact. Four-wheelers generate 148.48 kg/hr, reflecting higher fuel consumption and emission levels compared to smaller vehicles. The analysis clearly indicates that emission contribution is influenced by both vehicles count and emission intensity.

Table 15. Evening Peak Hour Emission

Vehicle	Count	EF	Emission (g/hr)	Emission (kg/hr)
2W	1898	38	72124	72.12
3W	1354	60	81240	81.24
4W	1160	128	148480	148.48
Bus	340	822	279480	279.48
LCV	406	260	105560	105.56
HCV	324	720	233280	233.28
Other	399	140	55860	55.86

Heavy vehicles continue to be the dominant contributors to total carbon emissions during the evening peak. Buses contribute 279.48 kg/hr, while heavy commercial vehicles (HCVs) contribute 233.28 kg/hr, despite their relatively lower numbers. Light commercial vehicles (LCVs) also show a notable contribution of 105.56 kg/hr, indicating their impact on urban emissions. The “other” category contributes 55.86 kg/hr, adding to the cumulative emission load. Compared to the morning peak, the evening period shows slightly higher total emissions, indicating increased congestion and prolonged vehicle idling. These findings highlight the need for effective traffic management strategies such as restricting heavy vehicle entry during peak hours, improving signal coordination, and promoting cleaner and sustainable transport options to reduce overall carbon emissions.

5. Conclusion

The overall analysis of traffic congestion and carbon footprint at Kharadi Junction highlights significant operational and environmental challenges under both IRC and Indo-HCM methodologies. The traffic volume during peak hours reaches 5862 vehicles (8752.9 PCU) in the morning and 6064 vehicles (8989.9 PCU) in the evening, indicating high demand exceeding optimal capacity levels. The V/C ratio analysis shows that while IRC values remain within acceptable limits (0.48–0.76), Indo-HCM reflects realistic congestion with values reaching 1.13 (morning) and 1.22 (evening), corresponding to LOS E–F, indicating oversaturated and unstable flow conditions. Carbon footprint assessment reveals that total emissions are approximately 969.57 kg/hr (morning) and 976.02 kg/hr (evening), with buses (≈288 kg/hr) and HCVs (≈236 kg/hr) being the major contributors despite lower traffic share. The outcomes clearly indicate that Indo-HCM provides a more accurate representation of mixed traffic conditions, and congestion is significantly higher than estimated by IRC standards. The study emphasizes the need for targeted interventions such as signal optimization, heavy vehicle regulation, and promotion of non-motorized transport. Implementing these measures can improve traffic efficiency, reduce delays, and significantly lower carbon emissions at Kharadi Junction.

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