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Assessment of Vehicular Emission Concentration during Queue Dissipation at Urban Signalized Intersections: A Case Study from Warangal, India

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Abstract:
Urban signalized intersections are key contributors to localized air pollution due to vehicle idling, acceleration, and deceleration during stop-and-go traffic conditions. This study investigates the behavior of major pollutant concentrations—specifically $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2—during the queue dissipation phase at four critical urban intersections in Warangal, India. The objective is to assess how emissions surge when vehicles accelerate after signal changes, providing insight into pollution peaks during short but frequent intervals. The study focuses on four signalized intersections: Adalat Circle, Kazipet Junction Viewpoint, Kakatiya University Road Intersection, and P. Marg. The sites named above were selected keeping in mind the objectives of research as the differ in traffic volumes, land-use characteristics, and environmental settings-ranging from dense urban cores to semi-urban academic zones. Real-time air quality monitoring and video-based traffic flow observations were conducted simultaneously to link queue lengths, vehicle compositions, and dissipation durations with emission levels. Study findings indicates that pollutant concentrations increase sharply during queue dissipation, with the most severe spikes at Adalat Circle and P. Marg, which experience heavy traffic and limited natural ventilation due to dense surrounding structures. In contrast, Kakatiya University and Kazipet Junction exhibited relatively lower concentrations due to moderate traffic and more open surroundings. This study underscores intersection-specific emission analysis and provides actionable insights for traffic-signal timing, proper planning of urban area and pollution mitigation in emerging urban areas. The findings have implications for policymakers and traffic engineers aiming to reduce pollution exposure in high-risk zones.

Key Words: Vehicular Emission, Queue Dissipation, Transport management, Pollution

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- **Introduction:**

India, as a rapidly developing nation, is undergoing an accelerated phase of urbanization and motorization. This recent development also has led to a substantial rise in vehicle ownership and use, both private and public, across metropolitan and Tier-II cities. This surge has brought with it numerous challenges—chief among them being urban air pollution and traffic congestion, particularly concentrated around signalized intersections. Over the past few decades, the urban road transportation sector has become a major contributor to ambient air pollution, with vehicular emissions accounting for a significant portion of particulate and gaseous pollutants in city environments (Singarapu et al., 2024). As traffic volumes increase, intersections and junctions—especially those along arterial roads—experience frequent vehicle queuing, idling, acceleration, and deceleration, all of which contribute to disproportionate increases in pollutant emissions. The environmental impact is exacerbated at signalized intersections, where vehicle queue dissipation—the process of vehicles starting to move after a red signal—triggers emission spikes due to sudden acceleration, particularly from heavy vehicles and aging engines. During these dissipation phases, emissions of key pollutants such as $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2 can increase several-fold compared to cruising traffic conditions. These localized emission surges play a critical role in degrading air quality near intersections and pose direct health risks to road users, pedestrians, and nearby residents (Pandian et al., 2009). The traffic flow dynamics during queue dissipation are influenced by driver reaction time and vehicle headways. The lead vehicle in a queue typically takes longer to react to signal changes, and each successive vehicle tends to move with reduced headway. This behavior results in a wave-like dissipation pattern, which prolongs the emission event and contributes to pollutant buildup at the micro-environmental scale (Mondal & Gupta, 2019). Such variations in traffic-induced emission have become more and more essential in the context of urban transport and environmental planning. Managing and mitigating emissions from traffic queues has emerged as a critical research challenge, especially in densely populated Indian cities where real-time air quality monitoring and traffic optimization are still developing. A detailed assessment of emission concentrations during queue dissipation presents valuable insights for urban traffic engineering, signal design, and policy formulation aimed at minimizing air pollution at the most critical urban traffic nodes (Shepelev et al., 2022). In light of these challenges, the present study focuses on the assessment of vehicular emission concentrations during queue dissipation at four key signalized intersections in Warangal, India. The spots were selected based on their varied traffic characteristics and environmental contexts, enabling a comprehensive understanding of emission dynamics in different urban microenvironments.

- **Objectives and Methodology**

The primary purpose of this study is to evaluate real-time pollutant emissions during the queue dissipation phase at signalized intersections with varied traffic and environmental conditions. The study aims to analyze the relationship between traffic behavior—particularly vehicle idling, acceleration, and queue length—and the concentration of pollutants such as CO, NO_2, $PM_{2.5}$, and PM_{10}. Four intersections—Adalat Circle, Kazipet Junction, P. Marg, and Kakatiya University Road—were selected based on traffic volume, environmental influence, and roadside activity. Data collection included video-based traffic observation, signal timing, classified vehicle counts, and real-time pollutant monitoring using Aeroqual Series 500. Additional data such as vehicle specifications were extracted using vehicle number plate recognition and RTO applications, while emission data was sampled from PUC centers. VISSIM for traffic micro-simulation and ENVIVER for emission estimation has been used for simulation and modeling. Field emissions were validated through a multiple linear regression model, and to evaluate accuracy RMSE and R^2 values were used. The methodology enables a comprehensive understanding of how traffic dynamics during queue dissipation influence localized vehicular emissions under real urban conditions.

- ***Literature related to Effect of Vehicular Delay on Emission***

It has been observed that in situations where intersection spacing and capacity are fixed, the occurrence of oversaturation leads to the growth of traffic flow queues. Consequently, increased delays and frequent stops experienced by vehicles result in higher fuel consumption. To address this issue, Signalized Synchronization System (SSS) proves to be highly advantageous in lowering fuel consumption for automobiles in oversaturated states. The accomplishment of SSS helps optimize signal timings and coordination, leading to smoother traffic flow and reduced fuel usage. On the other hand, it is vital to address that junction spacing also take part in a considerable role in determining the amount of fuel consumed by vehicles. In oversaturated conditions, where higher acceleration and deceleration maneuvers are prevalent, shorter junction spacing is projected. This suggests that the spacing between intersections has a notable impact on fuel consumption, and reducing the spacing can result in increased fuel usage due to the higher demand for frequent speed changes. Overall, the studies emphasize the importance of considering both oversaturation and junction spacing in fuel consumption analysis, with SSS proving to be an effective solution to mitigate fuel consumption in oversaturated traffic conditions.

- **Pandian et al.(2009)** investigated the impact of traffic, vehicle, and road features like gradient on vehicular emissions. Different types of intersections and roadways often experience low ambient air quality due to the various operating modes that vehicles undergo while approaching these intersections. In order to estimate fuel consumption under different states of saturation and oversaturation, a theoretical model was developed. The study clearly viewed that operating modes during vehicle operation have the most significant influence on the rate of fuel consumption. Furthermore, the study identified the mainly dominant parameter for estimating vehicular emissions, which is highly relevant and measurable. Factors such as fleet speed, idle condition during red signals, speed during acceleration and deceleration, queue formation rate, traffic flow rate, and environmental conditions all have a considerable impact on the estimation of vehicular exhaust emissions. These findings emphasize the importance of considering the various operating modes and factors affecting fuel consumption and vehicular emissions. By understanding and quantifying these parameters, more accurate estimations can be made, leading to improved strategies for managing and reducing environmental impacts associated with vehicular exhaust emissions.

- **Feng Zhu et al.(2013)** predicted delays and emissions for signalized junctions. Unlike the static models or those relying on time-invariant average speeds, this study focused on dynamic traffic models that could accurately replicate the speed profile of traffic. By considering the characteristics of vehicles' arrival and departure, as well as the parameters of signal timing, such as the total number of stops influenced by signal control and the average idle time of queuing vehicles, a more practical and realistic approach to calculating vehicle emissions was developed. The utilization of dynamic traffic models allowed for a more accurate representation of real-world traffic conditions, capturing the variability in vehicle speeds and the impact of signal timing on traffic flow. By incorporating these factors into the emission calculation process, the provided technique offers a practical and effective method for estimating car emissions. This approach takes into account the specific behaviors and conditions of vehicles within the traffic flow, providing a more comprehensive understanding of emissions at the network level. By considering the dynamic nature of traffic and the parameters related to signal timing and queuing vehicles, the technique presented in this study contributes to more accurate and practical calculations of vehicle emissions.
- **Wu et al.(2020)** proposed a method for establishing criteria to categorize intersections as saturated or oversaturated based on parameters such as intersection capacity, traffic demand, and the capacity of the specific intersection under investigation regarding emissions during queue formation. However, the duration of vehicle operations during idling, acceleration, and deceleration is influenced by the signal control technique implemented at the intersection, the traffic flow conditions at that specific intersection, and the geometry of the intersection route. The study considered

various variables and developed an emission model that establishes the relationship between traffic parameters, vehicle characteristics, and intersection variables with vehicular emissions. To develop these models, vehicle characteristics can be obtained through experimental data collection. By incorporating these factors and relationships, the study aims to provide a comprehensive understanding of the emission levels associated with different traffic scenarios at intersections. This approach allows for the development of effective strategies and models for managing and mitigating vehicular emissions based on specific traffic and intersection characteristics.

- ***Analysis of major pollutant concentration with queue dissipation:***

At the selected intersection, the analysis of pollutant concentration during traffic congestion revealed that PM_{10} levels were consistently higher than $PM_{2.5}$, likely due to coarse particulate matter generated from road dust resuspension and vehicle movement. The formation and dissipation of vehicle queues significantly influenced the concentration of gaseous pollutants. During idle conditions, when vehicles are stationary at red signals, CO_2 and NO_2 concentrations showed a noticeable increase, attributed to continued engine operation and exhaust accumulation in a confined microenvironment. However, as the signal turned green and the queue began to dissipate, a rapid decline in the levels of these pollutants was observed. This is primarily due to the dilution effect caused by the movement of vehicles and increased airflow, which disperses the pollutants more effectively. The findings underscore the dynamic nature of emissions at intersections and highlight queue dissipation as a critical phase influencing local air quality patterns.

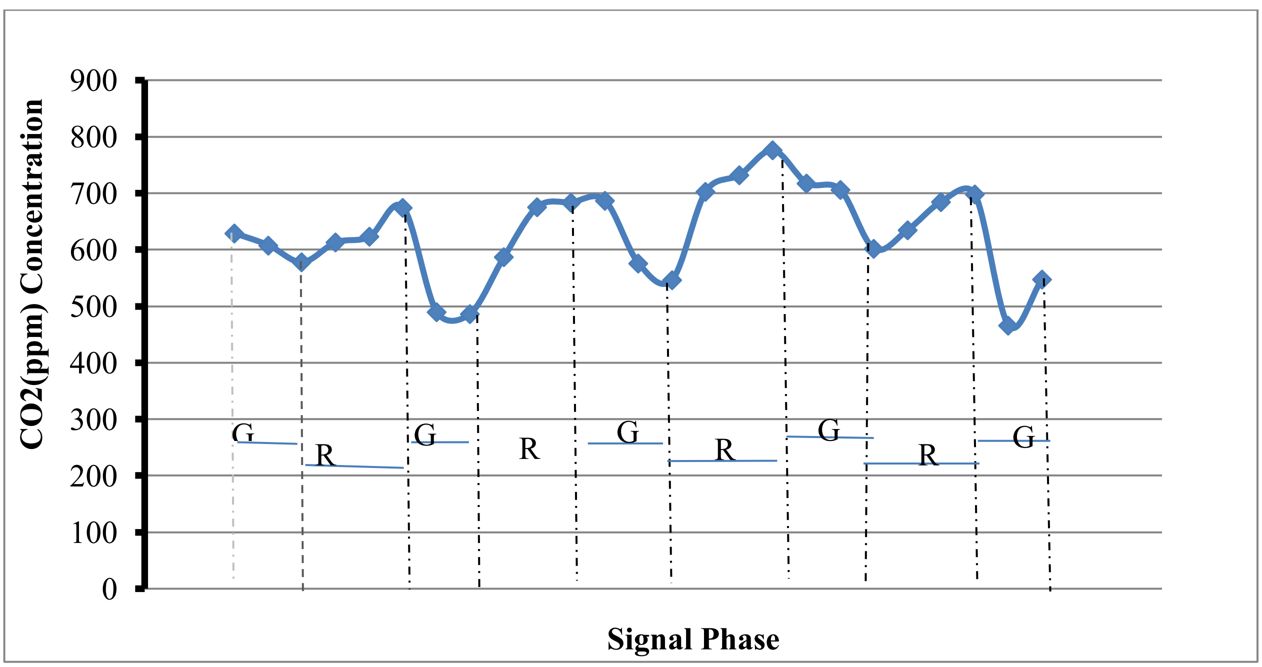


Figure: 1, CO_2 Concentration Variation with Signal phase

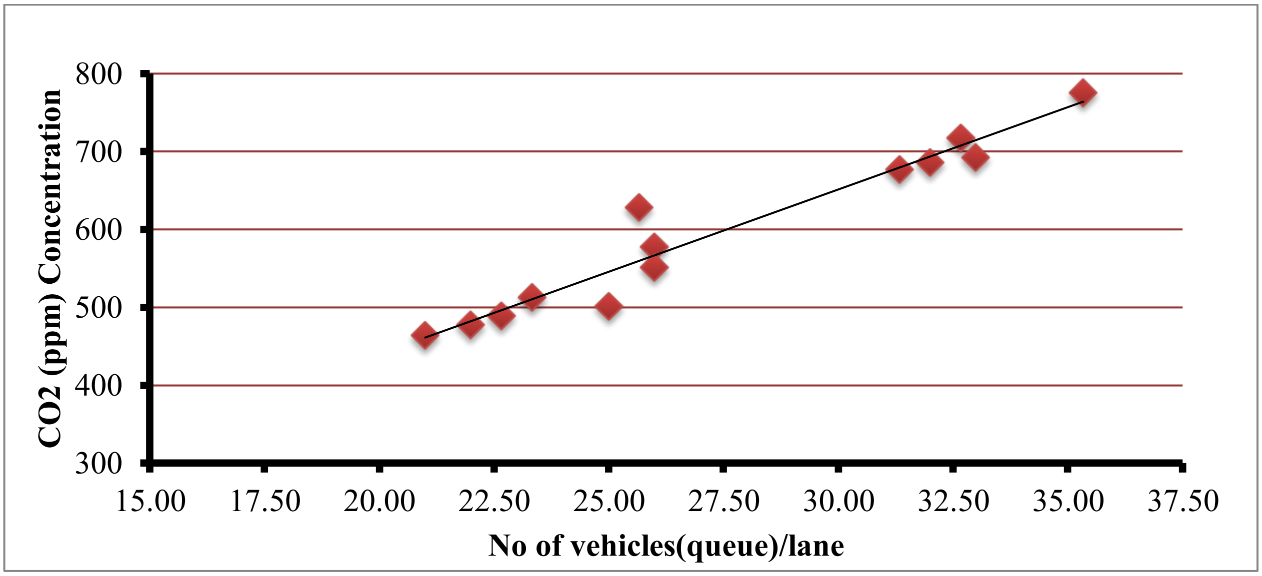


Figure: 2, CO2 Concentration variation with queue dissipation

The temporal variation of CO_2 concentration (in ppm) is illustrated in Figure 1, while Figure 2 demonstrates the impact of queue discharge on CO_2 levels. Similarly, Figures 3 and 4 represent the variation and queue dissipation effect on NO_2 concentration. The graphical data clearly show that CO_2 concentration is significantly higher than NO_2 at all observed intervals, which is expected due to CO_2 being the primary byproduct of fuel combustion across all vehicle types. However, both pollutants exhibit a similar trend during the queue dissipation phase—as vehicles begin to accelerate and move forward, the concentration levels of both CO_2 and NO_2 drop significantly. This reduction can be attributed to improved air circulation and reduced exhaust accumulation as idling vehicles disperse. The observations support the conclusion that vehicle queue formation increases local pollutant concentration, whereas queue discharge helps reduce immediate pollutant build-up, thereby influencing short-term air quality dynamics at signalized intersections.

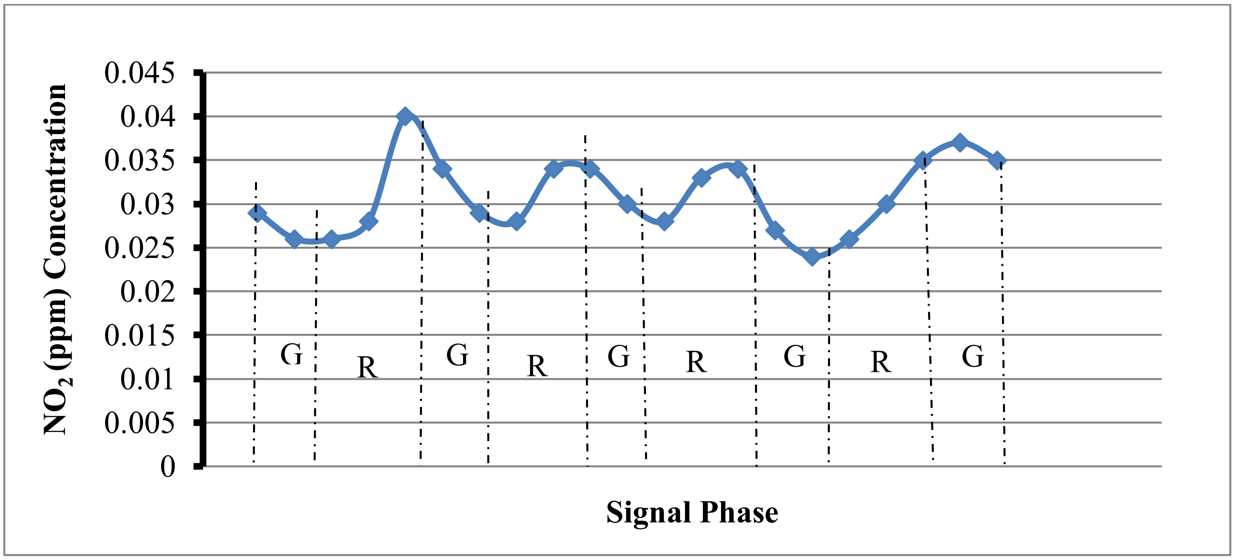


Figure: 3, NO_2 Concentration variation with time

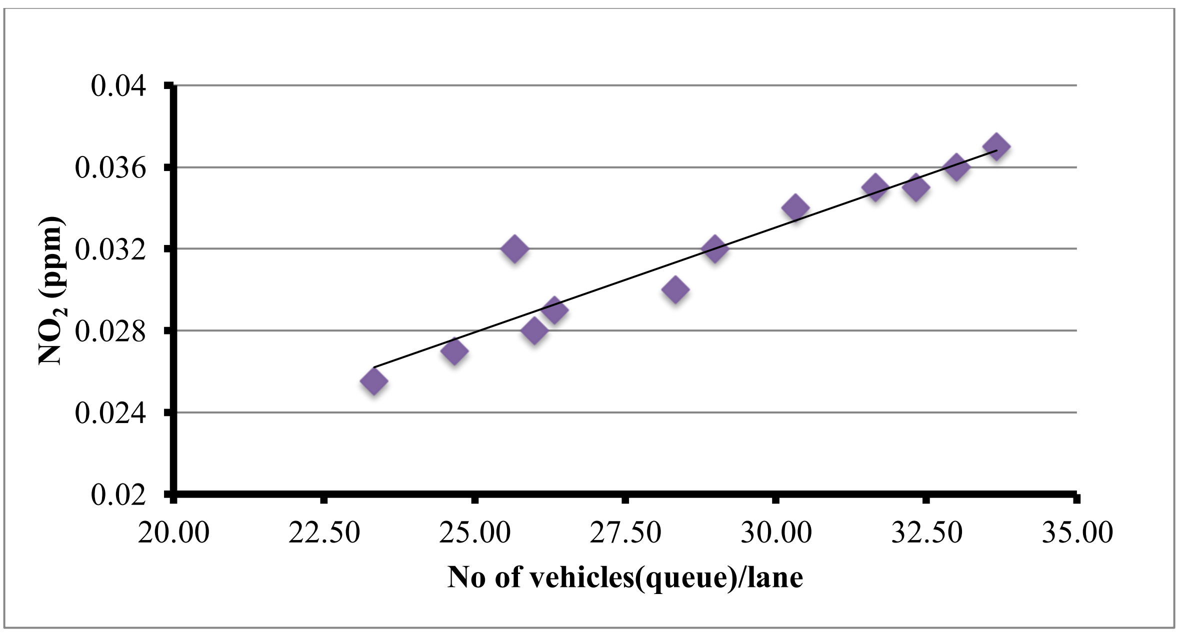


Figure: 4, NO2 Concentration Variation with Queue dissipation

- ***Evaluating Field Emission and Modeling***

To estimate real-world vehicle emissions at signalized intersections, a comprehensive analysis was conducted using data obtained from Pollution Under Control (PUC) certificates. These certificates provided detailed information on various vehicle characteristics, including vehicle number, registration date, vehicle age, fuel type, body type, cylinder capacity, model name, manufacturer, emission norms, and vehicle class.

Most importantly, emissions data for CO_2, CO, and O_2 were available, serving as the dependent variables in the modeling effort. Using this dataset, multiple linear regression (MLR) models were developed to estimate field emissions. The independent variables chosen for the model included the age of the vehicle (Ag), vehicle type (Vt), and emission norms (En). These variables were selected due to their significant influence on emission performance, where older vehicles and less stringent emission norms are generally associated with higher emissions. As shown in Table 01, the regression analysis yielded strong results. The CO_2 model achieved an R^2 of 0.837, indicating a strong correlation between the predictors and the actual emissions. The model equation was: CO_2 = 18.52 + (0.086 × Ag) + (1.549 × Vt) − (0.263 × En) Similarly, the O_2 model demonstrated an R^2 of 0.878, showing excellent explanatory power, with the equation: O_2 = 1.559 + (0.012 × Ag) + (0.0251 × Vt) − (3.009 × En). The CO model, while slightly less accurate with an R^2 of 0.732, still provided valuable insights. Its model form was: CO = 2.677 + (0.00087 × Ag) − (3.2188 × Vt) + (0.00036 × En).These models collectively illustrate the importance of incorporating vehicle type, age, and emission norms when estimating field emissions, especially in urban intersections where varied vehicle mixes and conditions.

Table: 01

Regression Analysis Results for pollutants

Pollutant type	R-square	Adj. R-square	Model form
CO_2	0.837	0.8377	$CO_2 = 18.52 + \left(0.086 * A_g\right) + (1.549 * V_t) - (0.263 * E_n)$
O_2	0.878	0.8784	$O_2 = 1.559 + \left(0.012 * A_g\right) + (0.0251 * V_t) - (3.009 * E_n)$
CO	0.732	0.7231	$CO = 2.677 + \left(0.00087 * A_g\right) - (3.2188 * V_t) + (0.00036 * E_n)$

To assess the validity and reliability of the developed regression models, an Analysis of Variance (ANOVA) was performed, and the regression statistics are presented in Table 02. For all three pollutant models, the p-values for most predictors were below 0.05, indicating that the relationships identified were statistically significant. In the case of the CO_2 model, all coefficients, including age (Ag), vehicle type (Vt), and emission norms (En), showed strong t-stat values and low p-values, reinforcing the robustness of the model. The standard errors were also very small, suggesting high precision in coefficient estimates. Notably, the age of the vehicle showed a significant positive correlation with CO_2 and CO emissions, confirming that older vehicles contribute more to emissions under real-world traffic conditions. The O_2 model also demonstrated statistical strength, with low p-values and high t-statistics for most predictors. Although the t-stat for vehicle type in the O_2 model was comparatively lower, its influence remained statistically significant. In the CO model, the influence of vehicle type was negative, suggesting that certain vehicle types (likely diesel or heavy vehicles) emit lower levels of CO, possibly due to combustion characteristics. The model's intercepts and coefficients aligned with practical emission behavior observed in urban traffic. Overall, the ANOVA results validated the accuracy of the regression models, and these models were then applied to estimate emissions for selected field vehicles. This approach provided a reliable method to simulate real-time emissions based on easily retrievable vehicle information, enhancing the understanding of emission behavior during queue dissipation at urban intersections.

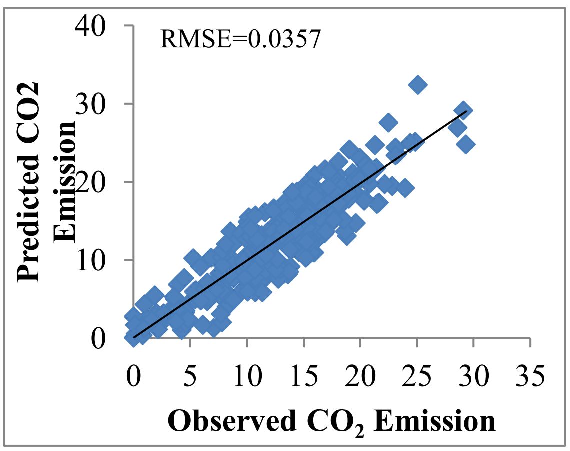
Table: 02

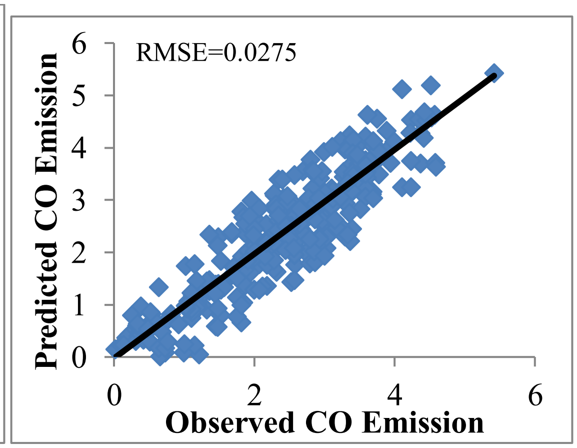
Regression Statistic for Developed Model

		Coefficients	***Standard Error***	***t Stat***	***P-value***
CO_2	Intercept	18.52	0.009	21.450	0.001
	A_g	0.086	0.000	-6.335	0.001
	V_t	1.549	0.033	1.673	0.005
	E_n	-0.263	0.166	-1.587	0.011
O_2	Intercept	1.559	0.080	19.574	0.001
	A_g	0.012	0.000	-9.545	0.001
	V_t	0.025	0.030	-0.831	0.041
	E_n	-3.009	0.015	0.645	0.051
CO	Intercept	2.677	0.146	18.293	0.001
	A_g	0.001	0.000	3.780	0.002
	V_t	3.218	0.056	-3.929	0.001
	E_n	-1.016	0.028	-0.595	0.003

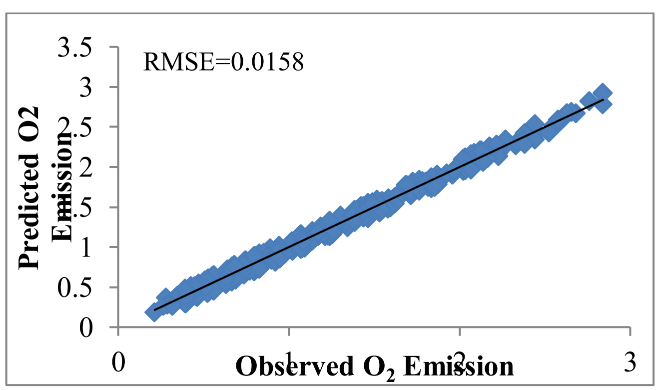
- ***Validation of the Field emission:***

A Multiple Regression Model was formed in order to get the emission of the real field running vehicles and 30% data was used to validate the model formed, validation parameters such as RMSE and R-square value was determined. After developing the models, it is necessary to validate them using the data sample. Validation is the process of using the developed models to estimate the values of the dependent variable at known conditions and then comparing the observed and predicted values. In this study, 70% of the data is used to develop the models, and 30% is used to validate the developed models. The sample data used for the validation is selected randomly using the RAND() function available in Microsoft excel. After choosing the sample, the validation is done using statistical software. The results obtained from the validation are shown in Figure 5.5.After validation of results these Multi Linear Regression equations has been used to get the emission of actual running vehicle in the field whose specification has been found by using RTO application as shown in Table 5.3.





(a) (b)



(c)

Figure: 5, Validation diagrams for the developed Field Emission from PUC samples (a) for CO_2, (b) for CO, (c) for O_2

During the analysis, a sample of five vehicles was selected to estimate real-world emissions using a multiple linear regression model developed from field data. The emission outputs for these sample vehicles were calculated and presented in Table 04, while the traffic flow data corresponding to their operational conditions is shown in Table 03. Traffic volume was recorded for a one-hour period (2:00 PM to 3:00 PM) at Adalat Circle, a key signalized intersection in Warangal with four major approaches. The Kazipet approach showed the highest vehicular load at 2848 PCU/hr, indicating a heavily congested corridor with significant stop-and-go movement during signal phases. The Hanamkonda PS and Bhadrakali approaches followed with 1717.5 PCU/hr and 1306.5 PCU/hr, respectively, while Hunter Road had the lowest flow at 691.5 PCU/hr. These variations in Passenger Car Units (PCU/hr) reflect different levels of vehicular density and queuing, which directly influence pollutant emission behavior during queue dissipation. By linking the traffic data with emission estimates from the selected vehicle sample, the study establishes a reliable connection between real-time intersection traffic characteristics and vehicular pollutant output, thereby supporting the development of targeted emission control strategies and better intersection management.

Table: 03

Total PCU data for the intersection

Time	Leg	Total PCU (PCU/hr)
2:00 to 3:00 pm	Approach from Kazipet	2848
2:00 to 3:00 pm	Approach from Bhadrakali	1306.5
2:00 to 3:00 pm	Approach from Hanamkonda PS	1717.5
2:00 to 3:00 pm	Approach from Hunter Road	691.5

To validate the multiple linear regression emission model, a sample of five vehicles operating at the intersection was selected, and their emissions were estimated using the regression equations developed in the study. Table 04 presents the emission data for these vehicles, showing a wide range in CO, O_2, and CO_2 emissions depending on vehicle class, fuel type, age, and emission norms. For instance, the motor scooter (AP29BN8431), an older two-wheeler with BS-III emission standards, recorded the highest CO_2 emission at 31.53 g/m, indicating a strong correlation between vehicle age and pollutant output. Similarly, the goods carrier (TS03RL9282) emitted the highest CO concentration (0.192% v), likely due to its petrol engine and commercial usage pattern. On the other hand, a newer motor cab (TS27T6937) using PETROL/CNG fuel type and under BS-I norms, showed relatively lower emissions across all pollutants, confirming that fuel type and emission standards significantly influence field-level emissions. The variation in pollutant levels across these samples reinforces the need to consider vehicle-specific attributes in emission modeling. These values also demonstrate the practical applicability of the developed model in estimating realistic emissions during vehicle queue dissipation phases at signalized intersections.

Table: 04

Estimated Emission data for the running vehicle on the field

Registration No	Maker	Fuel type	Age	Emission norms	Vehicle class	CO(% v)	O_2 (gm)	CO_2 (gm)
TS03UC6836	VK1611.0D 4R	DIESEL	04-03-20	BS-I	Bus	0.020	0.6100	3.543
TS10EM4074	CITY 1.5	PETROL	09-08-17	BS-IV	Motor Car	0.023	0.0112	24.26
TS27T6937	MARUTI	PETROL/CNG	27-10-22	BS-I	Motor Cab	0.011	0.0446	7.42
AP29BN8431	DISCOVER	PETROL	02-12-11	BS-III	M-Scooter	0.0772	0.0355	31.53

TS03RL92 82	Super Carry	PETRO L	18-11-21	BS-IV	Goods Carrier	0.192	0.01 59	29.8 4

- **Findings of the Study:**

  - **Queue Dissipation Significantly Affects Pollutant Concentration**- The study found that pollutant levels—especially CO_2 and NO_2—are elevated during vehicle idling at red signals. As vehicles begin to dissipate the queue at green signals, a noticeable drop in these concentrations occurs. This trend indicates that vehicle acceleration and dispersion improve air circulation, reducing pollutant buildup. However, the initial moments of queue dissipation still release concentrated exhaust due to sudden acceleration.
  - **CO_2 Levels Dominated the Pollutant Profile**- Among the monitored pollutants (CO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, O_2), CO_2 was the most dominant, both in quantity and response to traffic conditions. Even during short observation periods, CO_2 concentrations showed a strong correlation with traffic volume, queue length, and vehicle type, making it a critical indicator of vehicular pollution at signalized intersections.
  - **Vehicle Characteristics Strongly Influence Emission Output**- Emissions were modeled using vehicle attributes such as age, emission norms, and fuel type. The multiple linear regression models developed for CO_2, NO_2, and CO showed strong predictive accuracy ($R^2 > 0.73$). Older vehicles and those with outdated emission norms (e.g., BS-I, BS-III) emitted significantly more pollutants, validating the model's application for field-level emission estimation.
  - **Traffic Volume Impacts Local Air Quality**- Intersections with higher PCU/hr values, such as the Kazipet approach (2848 PCU/hr), exhibited greater pollutant concentration, confirming that traffic density directly influences emission levels, especially during signal phases involving stop-and-go behavior.
  - **Simulation and Validation Tools Proved Effective**- The use of VISSIM for traffic simulation and ENVIVER for emission modeling allowed for accurate recreation of field conditions. Model outputs were successfully validated using real-world data, indicating that such integrated tools are effective for predictive emission analysis at complex urban intersections.

- **Suggestions**

To address the growing concern of vehicular emissions at urban signalized intersections, several strategic interventions can be recommended based on the study findings. Firstly, optimizing traffic signal timings to reduce vehicle idling time can significantly decrease the concentration of pollutants such as CO_2 and NO_2 during queue formation. Adaptive signal control systems that respond in real time to traffic volumes and queue lengths could enhance traffic flow efficiency and reduce emission peaks. Secondly, promoting the use of cleaner fuel technologies and accelerating the phase-out of older vehicles with outdated emission norms (such as BS-I and BS-II) can directly impact the overall emission load at intersections. Regular monitoring and strict enforcement of vehicle emission standards through digital PUC tracking would ensure compliance and data accuracy. Thirdly, dedicated infrastructure for non-motorized transport, such as cycle lanes and pedestrian crossings, could reduce the dependency on private vehicles, thereby lowering traffic density and associated emissions. Additionally, installing green buffers such as roadside vegetation near intersections may help in capturing particulate matter and improving micro-level air quality. From a planning perspective, integrating emission data into urban mobility models can aid in prioritizing intersection redesign and traffic management measures in high-emission zones. The adoption of simulation and emission modeling tools like VISSIM and ENVIVER, as demonstrated in this study, should be expanded to other urban locations to enable proactive emission assessment and scenario testing. Finally, raising public awareness about the impact of idling and encouraging eco-driving practices can support bottom-up behavioral change, contributing to emission reduction in the long term. Together, these strategies offer a multi-dimensional approach that combines policy, infrastructure, technology, and public participation to mitigate the impact of vehicular emissions during queue dissipation phases at urban signalized intersections. Such efforts are essential for ensuring sustainable urban mobility and protecting environmental and public health in rapidly growing Indian cities.

- **Conclusion**

This study presents a comprehensive assessment of vehicular emission concentration during queue dissipation at urban signalized intersections, with a focused case study from Warangal, India. By analyzing real-time traffic data, pollutant measurements, and vehicle specifications, it was observed that emissions—particularly CO_2 and NO_2—rise significantly during vehicle idling and begin to decrease as the queue dissipates. The study highlights the dynamic nature of emissions, influenced not only by traffic flow but also by vehicle type, age, fuel used, and emission norms. Through the application of multiple linear regression models, emissions for selected vehicles were accurately estimated, and the use of traffic simulation (VISSIM) combined with emission modeling (ENVIVER) allowed effective validation of field conditions. The findings emphasize the critical impact of intersection-level traffic behavior on local air quality, especially in high-density urban corridors. Overall, the study reinforces the need for targeted interventions such as adaptive signal control, fleet modernization, and emission-based traffic planning. The methodology and results serve as a valuable framework for traffic engineers and urban planners seeking to integrate emissions assessment into intersection design and traffic management strategies. By addressing emissions during queue dissipation, cities can move toward more sustainable and health-conscious transportation systems.

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