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Real-World Emission Assessment of Diesel Passenger Cars in Urban Traffic: A Comparative Analysis of Compliance with Bharat Stage VI Standards

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Abstract. Urban air pollution, significantly influenced by vehicle emissions, poses severe health risks, particularly in rapidly urbanizing cities. This study investigates real-world emissions from diesel-powered passenger cars under mixed traffic conditions, focusing on compliance with Bharat Stage VI (BS VI) standards. Using Portable Emission Measurement Systems (PEMS), emission factors for Carbon Monoxide (CO), Oxides of Nitrogen (NOx), and the combined mass of Hydrocarbons and Oxides of Nitrogen (THC + NOx) were measured. Results revealed exceedances of 75%, 103.75%, and 40.59% for CO, NOx, and THC + NOx, respectively, underscoring inefficiencies in emission control technologies. Variability in emissions was linked to vehicle age, maintenance, driving behaviors, and challenging road conditions. These findings highlight the critical gap between laboratory-tested and real-world emissions, emphasizing the need for stricter regulations, advanced emission technologies, and public awareness campaigns. The study offers actionable insights for urban air quality improvement and policy development to reduce vehicular pollution.

Keywords: Real-World Emission Testing; Diesel Vehicle Emissions; Bharat Stage VI Compliance; Emission Control Systems; Diesel-Powered Passenger Cars; Real-World Driving Conditions; Portable Emission Measurement Systems (PEMS).

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1. Introduction

Urban air pollution is significantly influenced by vehicle emissions, posing severe health and environmental challenges globally. Studies have consistently shown a strong correlation between vehicle emissions and adverse health effects, particularly cardiovascular and respiratory diseases [1, 2]. Pollutants such as Carbon Monoxide (CO), Oxides of Nitrogen (NOx), and particulate matter are recognized as major contributors to these health risks, with implications for conditions like heart and lung diseases [2, 3, 4, 5, 6]. Vulnerable groups, such as children and the elderly, are disproportionately affected, with urban air pollution contributing to an alarming rise in mortality rates worldwide [7].

The problem is particularly acute in rapidly urbanizing regions of developing countries, where mixed traffic conditions and inadequate public transportation systems exacerbate the issue. Increased reliance on personal vehicles, including diesel-powered cars, has further compounded the problem. Diesel vehicles, while economically favorable due to lower fuel costs and higher mileage, emit significant quantities of NOx and black carbon, both of which have severe environmental and health impacts. Countries like India and China have seen a sharp increase in car ownership, leading to longer commutes, frequent congestion, and elevated emission levels [8, 9, 10].

Emission regulations, such as the stringent Bharat Stage VI (BS VI) standards in India, aim to mitigate these effects by enforcing stricter limits on vehicular emissions. However, these standards are typically based on laboratory tests that do not adequately reflect the complexities of real-world driving conditions. Laboratory tests often fail to capture the impact of variables such as stop-and-go traffic, unpredictable driving patterns, and diverse road gradients, which are characteristic of urban arterial roads in developing nations [11, 12, 13].

Real-world emission testing is thus critical for bridging the gap between regulatory standards and actual vehicular performance. It provides a more accurate representation of emissions under everyday conditions, helping policymakers and manufacturers to design more effective mitigation strategies. This study focuses on diesel-powered passenger cars, which constitute a significant share of urban vehicle fleets and are known for their higher emissions compared to gasoline-powered vehicles. By investigating real-world emissions in Jodhpur, a rapidly growing urban center in India, the study offers insights that are relevant to similar cities globally.

This paper addresses key gaps in existing research by emphasizing real-world emission testing over laboratory-based assessments. It examines the compliance of diesel passenger cars with Bharat Stage VI standards under mixed traffic conditions, offering a more comprehensive understanding of the challenges in meeting these regulations. The research aims to:

1. Establish real-world emission factors for pollutants such as CO, NOx, and THC + NOx from diesel passenger cars under diverse urban traffic conditions.
2. Compare these real-world emission factors with Bharat Stage VI standards to evaluate compliance.

By using the same driver for all tests, this study controls for driver variability, allowing for more accurate comparisons between vehicle types and road conditions, as driving style greatly influences emissions.

The findings contribute to the global discourse on emission reduction strategies and underscore the importance of localized studies in shaping effective regulatory policies also highlight the limitations of current emission control technologies and the impact of real-world driving conditions on vehicular emissions. This paper is structured as follows: Section 2 reviews relevant literature, Section 3 outlines the study area and methodology, Section 4 presents the results and their implications, and Section 5 concludes with key findings and policy recommendations.

2. Literature Review

Measuring vehicle emissions during real-world driving presents significant challenges due to the complexity of accurately capturing emissions in diverse conditions. Various methods have been developed for this purpose, with Portable Emission Measurement Systems (PEMS) gaining particular popularity for their reliability and precision in recording emissions under a wide range of driving and environmental conditions. Real Driving Emissions (RDE) testing, adopted by many developed countries, assesses vehicle emissions during actual driving using tools like PEMS, remote sensing devices, on-board diagnostics (OBD), chassis dynamometers, and field studies. These approaches collect real-world emissions data, offering valuable insights to shape effective regulations aimed at reducing vehicular pollution and enhancing air quality. Numerous studies have specifically used PEMS to analyze exhaust emissions from diesel-powered vehicles, highlighting its effectiveness in evaluating real-world emissions [16].

R. O'Driscoll et al. [17] studied NOx emissions from Euro 6 diesel cars with different emission control systems and found that on-road emissions often exceeded lab limits. Using PEMS data from 39 vehicles, they observed NOx emissions up to 22 times the limit, averaging 0.36 g/km—4.5 times above the Euro 6 standard—with 44% as primary NO_2. Urban NOx levels rose with frequent acceleration, with

PEMS readings showing NOx emissions 1.6 times and NO_2 emissions 2.5 times higher than COPERT estimates, emphasizing the need for emission reduction strategies in cities.

H. C. Frey, H.-W. Choi, and K. Kim [18] measured emissions from passenger railroad locomotives in rail yard load tests using PEMS. Testing three locomotives with diesel engines (3,000 hp) and HEP engines (600 hp), they recorded emissions using ultra-low-sulfur diesel under various throttle levels and electrical loads. Over 97% of the data met quality standards, and results for the main engines were consistent with other studies, particularly for NOx and CO. This study provides a foundation for future locomotive emissions testing and offers baseline data for regulatory assessments.

J. Gallus, U. Kirchner, R. Vogt, and T. Benter [19] studied the impact of driving styles and routes on emissions under Euro-6c RDE standards. Using PEMS, they monitored Euro-5 and Euro-6 diesel vehicles, finding that aggressive driving increased CO_2 and NOx emissions, while CO and HC emissions remained stable. Route features, such as altitude gain and road grade, also raised CO_2 and NOx emissions due to high engine loads, highlighting the importance of factoring in real driving conditions.

H. S. Chong, Y. Park, S. Kwon, and Y. Hong [20] analyzed emissions from Euro 6 diesel engines in real-world driving using PEMS with GPS tracking. The study focused on NOx, CO, unburned hydrocarbons, and CO_2 emissions under various conditions, linking emissions to fuel consumption rates, which aids in accurate real-time emissions predictions.

M. Kousoulidou et al. [21] developed emission factors for different car technologies in Italy, finding that while gasoline cars generally met standards, diesel vehicles—especially Euro 5 models—often exceeded NOx limits in real driving. The results suggest a need for more real-world data, particularly for Euro 4 and newer diesel models, to address urban air quality concerns.

T. Lee et al. [22] assessed NOx emissions from Euro 3-5 diesel cars in Korea, comparing the New European Driving Cycle (NEDC) with the Korean Driving Cycle (KDC). NOx control was weaker in the KDC, with emissions exceeding Euro 5 limits by up to eight times. This study emphasizes the need for additional real-world testing and certification standards to address these differences.

Z. Liu et al. [23] measured emissions from diesel buses in Beijing using PEMS and an ELPI, comparing real-world data with lab certification results. CO and HC emissions met standards, but brake-specific NOx (bsNOx) levels were much higher—up to 120% over limits for Euro III buses and nearly double for Euro IV, due to inactive SCR systems at low temperatures. This highlights the need for real-world testing.

L. Lv et al. [24] examined emissions from LNG and diesel semi-trailers in northern China under real driving conditions. Emission rates, particularly for NOx, were much higher than previous lab results due to frequent stops and starts. The study suggests additional on-road testing and use of Diesel Particulate Filters (DPF) to reduce particulate emissions, noting that LNG vehicles showed high unburned methane emissions.

S. Mahesh, G. Ramadurai, and S. M. S. Nagendra [25] studied emissions from BS IV diesel cars in Chennai using PEMS. Emission factors varied with road conditions, averaging 1.28 g/km for CO, 0.13 g/km for HC, and 0.59 g/km for NOx. Annual emissions for Chennai were estimated at 7,000 tonnes of CO, 750 tonnes of HC, and 2,400 tonnes of NOx, providing insight into urban emissions amid moves toward electric vehicles and improved public transport.

K. Pang, K. Zhang, and S. Ma [26] highlighted the need for accurate emission inventories for non-road diesel equipment, like forklifts, which contribute significantly to air pollution. Using a Portable Emission Measurement System (PEMS), they analyzed emissions across three duty cycles: idling, moving, and working, on twelve forklifts. Fuel-based emission factors showed more consistency than time-based factors, with NO emissions posing a primary challenge for emissions control. The study's findings differed from existing models, underscoring the need for locally relevant, fuel-based emission factors derived from real-world data to better inform non-road equipment emission inventories.

G. Wang et al. [27] tested emissions from 15 light-duty diesel vehicles, focusing on hydrocarbons (HC), nitrogen oxides (NOx), and ozone-forming VOCs. Stricter emission standards reduced HC and NOx, with emissions of these pollutants decreasing at higher speeds, while CO_2 emissions increased. The dominant emissions were alkanes, with aromatics and alkenes contributing significantly to ozone formation. Key VOCs with high ozone potential included propene and ethene. In 2018, H. Wang et al. [28] studied emissions at high altitudes on a China IV diesel vehicle, finding CO emissions rose by 209% at 2990 meters compared to sea level, with the highest emissions in urban areas. Both particle numbers (PN) and NOx increased with altitude, though NOx slightly decreased at the highest altitude. This study highlighted altitude's impact on emissions, crucial for effective regulation.

S. K. Kuppili et al. [29] studied emissions from 58 passenger cars in Delhi under real driving conditions across five routes. Diesel cars emitted, on average, 3.99 g/km CO, 0.34 g/km HC, and 0.54 g/km NO, while petrol cars emitted 7.26 g/km CO, 0.17 g/km HC, and 0.62 g/km NO. Emissions varied based on road, traffic, vehicle type, and driving style, with higher speeds and acceleration causing increases. Optimal emissions were observed at speeds of 40–60 km/h and accelerations between −0.5 and 0.5 m/s^2. The study estimated city-wide daily emissions at 60.8 tonnes of CO, 4.8 tonnes of HC, and 9.72 tonnes of NO, underscoring the need for real-world monitoring beyond standard compliance tests. R. Suarez-Bertoa et al. [30] examined emissions (NOx, NO_2, CO, PN, CO_2) from 19 Euro 6 vehicles (diesel, gasoline, CNG) on the road, both within and outside RDE conditions. Diesel vehicles generally met NOx limits and had low PN and CO emissions. A Euro 6b gasoline direct injection vehicle with a particulate filter showed low PN emissions, indicating improved controls. However, dynamic driving increased CO emissions up to 7.5 times, and certain gasoline vehicles showed peak PN emissions, emphasizing the need for consistent standards across pollutants and fuel types.

G. Triantafyllopoulos et al. [31] studied CO_2 and NOx emissions in diesel vehicles, particularly the effects of EU-mandated Real Driving Emissions (RDE) tests. Lab and on-road tests with three Euro 6 diesel cars revealed significant differences between standard tests (WLTP, NEDC) and real-world emissions, with real driving tests showing more accurate levels. Emissions varied widely, especially in hilly or complex urban areas, highlighting the limitations of pre-RDE NOx controls that don’t fully reflect real-world conditions.

M. André and M. Rapone [32], in the ARTEMIS project, analyzed passenger car emissions across various driving cycles to create emission models suited to European conditions. They tested emissions from nine cars on specific cycles and 30 on adapted versions, focusing on the effects of urban, rural, and motorway driving, as well as vehicle types and standards, on pollutants like CO, HC, NOx, CO_2, and PM. Urban driving led to higher diesel and CO_2 emissions, while congested and high-speed motorway conditions increased CO_2 and NOx emissions. Using partial least squares regression, the study highlighted speed and acceleration as primary emission drivers, and grouped cycles into reference patterns to enhance emissions estimates in the ARTEMIS model.

The literature highlights the complexity and variability of vehicle emissions under real-world conditions, underscoring the limitations of laboratory testing in accurately representing on-road scenarios. Overall, the findings suggest that real-world emission monitoring is critical to developing effective regulatory measures, as laboratory tests alone cannot fully capture the diverse and dynamic factors affecting vehicular emissions. The insights from these studies emphasize the need for data-driven approaches to develop more robust emission standards, ultimately aiming to improve urban air quality and reduce the environmental impact of road transportation.

3. Study Area and Methodology

3.1. Study Area

The study was conducted in Jodhpur, the second-largest city in Rajasthan, India, characterized by its rapid urbanization and growing vehicular population. Known as "Sun City" for its predominantly sunny weather, Jodhpur has a population of 1.138 million and faces infrastructure challenges due to its rapid growth. Public transport systems in the city are inadequate, leading to increased reliance on private vehicles and frequent traffic congestion.

To capture a representative sample of urban traffic conditions, the study area encompassed three main arterial roads with diverse geometric features, traffic conditions, and surrounding land uses, as shown in Fig. 1. The selected route spanned approximately 12.9 km, featuring twelve traffic signals and a mostly flat profile. The roads included both divided and undivided segments with varying lane configurations. This diversity ensured that the selected routes reflected typical urban traffic conditions found in other rapidly urbanizing cities.

Table 1 presents the vehicle composition and volumes observed during the study period. Passenger cars and two-wheelers accounted for 87.24% of all vehicles, with two-wheelers contributing 51.40%. The heterogeneous traffic flow included auto-rickshaws (6.29%), light commercial vehicles, and heavy motor vehicles, highlighting the mixed nature of urban traffic in developing cities.

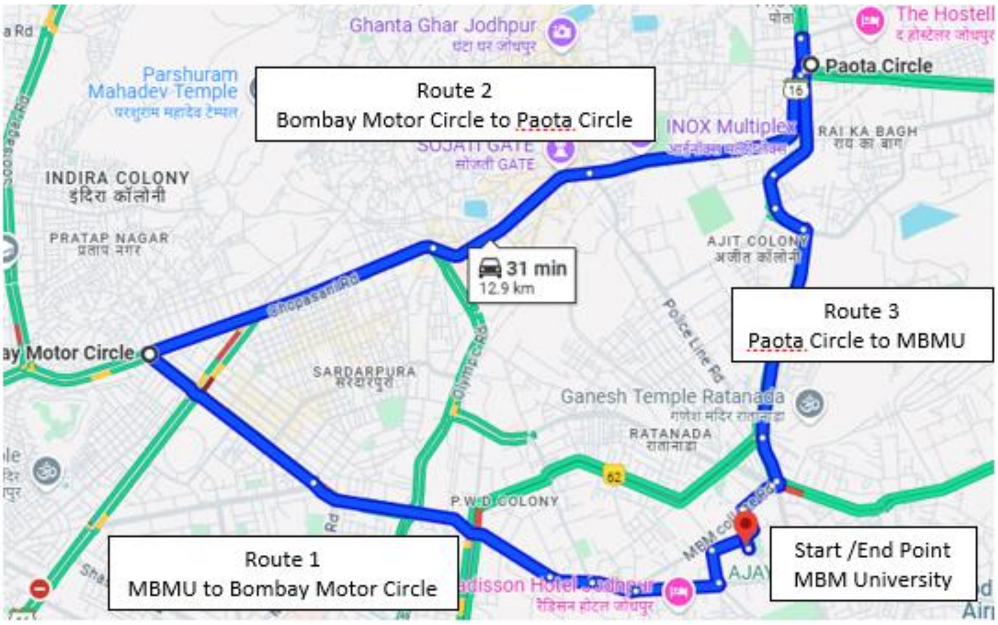

Figure 1. Study Routes (Source: Google Map)

Table 1. Description of Test routes and Vehicle volumes across various study periods

Route Name	Study Periods	Volume (No.)					
		TW	AR	Car	LCV	HMV	Total
Route 1: MBMU to Bombay Motor Circle ***(Length: 4.2 km)*** ***(Land Use: I and C)*** **Two & Four-lane divided road with signalized intersections**	09:00-10:00	1,200	150	800	60	100	2,310
	13:00-14:00	1,400	170	950	70	110	2,700
	18:00-19:00	1,500	180	1,000	80	120	2,880
Route 2: Bombay Motor Circle to Paota Circle ***(Length: 5.1 km)*** ***(Land Use: C and Rec.)*** **Four-lane divided road with Rotary**	09:00-10:00	2,000	250	1,500	100	150	4,000
	13:00-14:00	2,300	280	1,700	110	170	4,560
	18:00-19:00	2,500	300	1,800	120	180	4,900
Route 3: Paota Circle to MBMU ***(Length: 3.6 km)*** ***(Land Use: I and R)*** **Four-lane divided road with Rotary**	09:00-10:00	1,100	140	750	50	90	2,130
	13:00-14:00	1,300	160	850	60	100	2,470
	18:00-19:00	1,400	170	900	70	110	2,650

Note: TW: Two-wheeler, AR: Auto-rickshaw, LCV: Light commercial vehicle, HMV: Heavy motor vehicle. Land use: Institutional (I), Residential (R), Recreational (Rec), Commercial (C).

3.2. *Study Methodology*

Passenger cars are a significant part of Jodhpur personal vehicle fleet, and their numbers are expected to increase as incomes rise. Currently, over 124,000 registered passenger cars operate in the city, with around 30% running on diesel (MoRTH, 2020). The study focused on 10 diesel-powered passenger cars sourced from different manufacturers. These vehicles were selected to represent a range of models complying with Bharat Stage VI (BS VI) emission standards. The vehicle specifications are detailed in Table 2. All vehicles were tested under identical conditions to ensure consistency in the results.

Table 2. Specifications of Test Vehicles used in study

Specification	**Car 1**	**Car 2**	**Car 3**	**Car 4**	**Car 5**	**Car 6**	**Car 7**	**Car 8**	**Car 9**	**Car 10**
Displacement (cm^3)	1,498	1,461	1,247	1,598	1,498	1,368	1,496	1,500	1,598	1,395
Curb Weight (kg)	1,150	1,120	1,080	1,200	1,170	1,130	1,160	1,140	1,210	1,090
No. of Cylinders	4	4	4	4	4	4	4	4	4	4
Emission Standard	BS VI	BS VI	BS VI	BS VI	BS VI	BS VI	BS VI	BS VI	BS VI	BS VI
Transmission	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Odometer Reading (km)	30,421	45,678	25,432	67,890	33,210	54,123	29,784	48,567	60,250	40,312

On-road speed data were collected using a Garmin eTrex 10 GPS device, which recorded second-by-second vehicle speed for each test run. Emission data were captured using an AVL Ditest 1000 gas analyzer. This analyzer measured CO, CO_2, and HC using Non-Dispersive Infrared (NDIR) technology and NOx and O_2 with an electrochemical cell. Both devices were calibrated before the study and validated for accuracy before each test session. To simulate real-world driving conditions, the study focused on urban arterial roads characterized by mixed traffic flows, varying road types (divided and undivided), frequent stop-and-go conditions, and significant lane changes due to the presence of two-wheelers and auto-rickshaws. Seven round trips were conducted during August and September 2024, covering both peak and off-peak traffic periods. Peak hours were identified through traffic volume surveys and occurred from 9:00 a.m. to 10:00 a.m. and 6:00 p.m. to 7:00 p.m., with other times designated as off-peak. All tests were conducted on urban roads under ambient temperatures ranging from 25°C to 30°C. The road surfaces were mostly flat, with minor undulations. Traffic signals, roadside parking, and mixed land use created realistic urban driving scenarios. Each test run began and ended at the main gate of MBM University, Jodhpur (Figure 1), and ensuring consistency across runs. To maintain consistency and minimize driver-related variability, the same experienced driver operated all test vehicles throughout the study. The driver adhered to normal urban driving behaviors, including acceleration, deceleration, idling, and cruising, ensuring representative emission measurements. Outliers or extreme emission events were identified using statistical thresholds based on the dataset's standard deviation. These values were excluded from the analysis to prevent skewed results while maintaining the integrity of the data.

4. Results and Discussion

The measured emission concentrations (expressed in % volume or ppm) were converted to emission factors (g/km) by assuming a steady exhaust flow rate for each vehicle operating mode—idling, acceleration, deceleration, and cruising. To calculate the instantaneous emission rate (ER) for each pollutant, exhaust concentration, vehicle speed, and exhaust flow were used as follows [25]:

$$ER_{[P]} = [P] * FR * \rho_P \tag{1}$$

In this formula, [P] is the pollutant concentration at that moment (expressed in % volume or ppm), FR is the exhaust flow rate in liters per second (L/s), and ρ_P represents the density of the pollutant in grams per liter (g/L). The emission factor was calculated by dividing the total emissions by the distance covered.

4.1. *Emission Factors of Diesel-Powered Passenger Cars*

The emission factors for Carbon Monoxide (CO), Nitrogen Oxides (NOx), and the combined mass of Hydrocarbons and Oxides of Nitrogen (THC + NOx) were calculated for 10 diesel-powered passenger cars tested along the designated routes. The results, shown in Table 3, highlight variations across vehicles, with all tested cars exceeding at least one of the Bharat Stage VI (BS VI) emission standards.

For Carbon Monoxide (CO), the average CO emission factor across vehicles was 0.875 g/km, exceeding the BS VI standard of 0.50 g/km by 75%. Vehicles such as Cars 2, 3, 5, and 10 recorded the highest CO emissions (ranging from 0.90 to 1.00 g/km), indicating inefficiencies in combustion processes and emission control systems. High CO emissions suggest poor air-fuel mixture ratios or malfunctioning catalytic converters.

Table 3. Emission factors of Test Diesel-Powered Passenger Cars

Test Vehicle No.	Mass of Carbon Monoxide (CO)	Mass of Oxides of Nitrogen (NOx)	Combined Mass of Hydrocarbons and Oxides of Nitrogen (THC + NOx)
Car 1	0.85	0.14	0.25
Car 2	1.0	0.12	0.2
Car 3	0.95	0.2	0.22
Car 4	0.87	0.13	0.26
Car 5	0.9	0.18	0.24
Car 6	0.86	0.15	0.21
Car 7	0.8	0.19	0.27
Car 8	0.72	0.17	0.26
Car 9	0.75	0.15	0.23
Car 10	0.95	0.2	0.25
Average Emission factor (g/km)	**0.875**	**0.163**	**0.239**
BS VI Emission Standard (g/km)	**0.50**	**0.08**	**0.17**

For Oxides of Nitrogen (NOx), none of the vehicles met the stringent BS VI standard of 0.08 g/km for NOx. The average NOx emission factor was 0.163 g/km, 103.75% above the regulatory limit. Cars 3 and 10, with NOx emissions of 0.20 g/km, were the highest emitters. These results highlight the challenges of controlling NOx emissions, often linked to high-temperature combustion and suboptimal functioning of Selective Catalytic Reduction (SCR) systems. The combined emission factor for THC + NOx averaged 0.239 g/km, exceeding the BS VI standard of 0.17 g/km by 40.59%. Vehicles like Cars 4, 7, 8, and 10 surpassed this limit, with Car 7 emitting the highest value (0.27 g/km). This indicates gaps in the efficiency of Diesel Particulate Filters (DPFs) and other control technologies under real-world conditions.

The data highlights substantial deviations from BS VI standards, particularly for NOx and combined THC + NOx emissions, with Cars 3 and 10 being the most frequent offenders. This variability underscores the importance of real-world emission testing to identify high-emitting vehicles and ensure compliance with emission regulations. Stricter monitoring and regulatory measures are necessary to mitigate emissions and address inefficiencies in emission control systems effectively.

The average emission factor for CO is 0.875 g/km, which is 75% higher than the BS VI standard of 0.50 g/km. This substantial increase indicates inefficient combustion processes or suboptimal emission control technologies in the tested vehicles. The average NOx emission factor is 0.163 g/km, which is a staggering 103.75% higher than the BS VI standard of 0.08 g/km. This highlights a critical challenge in controlling NOx emissions, often associated with high-temperature combustion in diesel engines. The average combined emission factor is 0.239 g/km, which is 40.59% higher than the BS VI limit of 0.17 g/km. This excess underscores the need for better emission control technologies to manage both hydrocarbons and NOx effectively. The significant percentage increases across all pollutants emphasize the gap between real-world emissions and regulatory standards, underscoring the importance of robust compliance monitoring and advancements in emission control systems.

The variation in emission factors among diesel-powered passenger cars arises from several factors. Vehicle age and maintenance significantly impact emissions, older vehicles or poorly maintained vehicles with higher odometer readings generally showed higher emissions due to wear and tear on engine components and exhaust systems. For instance, Cars 3 and 10, with higher mileage, exhibited consistently elevated emission levels. Poor maintenance practices, such as delayed oil changes or clogged DPFs, further exacerbate emissions [34]. Variability in emission factors across vehicles underscores differences in engine technologies and control systems. Advanced systems like SCR and DPF performed better but still failed to meet BS VI limits under real-world driving conditions. This suggests the need for more robust designs capable of handling transient operating conditions [35, 39]. Driving behavior, such as frequent acceleration, deceleration, and idling in mixed traffic significantly impact emissions. Aggressive driving increases CO and NOx emissions, as seen in Cars 2 and 10. Similarly, prolonged idling contributes to higher CO concentrations due to incomplete combustion [36]. Real-world factors such as road gradients, traffic density, and ambient temperature also influenced emission variability. Higher emissions were observed during peak traffic hours due to frequent stops and starts [37].

These factors highlight the need for regular maintenance and stricter emission testing. The substantial exceedances of BS VI standards, particularly for CO and NOx, have critical implications for urban air quality and public health. High NOx levels contribute to the formation of ground-level ozone and fine particulate matter, exacerbating respiratory and cardiovascular diseases. Elevated CO emissions can impair oxygen delivery in the body, posing risks to vulnerable populations, including children and the elderly.

4.2. Estimation of Emissions from Diesel-powered vehicles

The number of diesel powered cars in Indian cities has seen a significant rise in recent years due to better mileage (km/L) with respect to Petrol powered cars [38]. Estimating the total emissions from diesel cars operating within Jodhpur City provides valuable insights into their environmental impact. Total emissions are calculated using the measured emission factors from this study and vehicle kilometers traveled, using the equation (2):

$$Total\ Emission = \sum(Emission\ factor\ \times Vehicle\ Kilometers\ Travelled) \tag{2}$$

The average emission factors of CO, NOx, and THC + NOx are 0.875, 0.163, and 0.239 g/km, respectively. Currently, over 0.124 million passenger cars operate in Jodhpur City, with approximately 30% running on diesel. Using this data, the estimated daily emissions are 1.302 tonnes/day for CO, 0.243 tonnes/day for NOx, and 0.356 tonnes/day for THC + NOx respectively by considering the VKT of diesel passenger cars per day in Jodhpur City. These estimates highlight the urgent need for effective mitigation strategies to address vehicular emissions in rapidly urbanizing cities.

5. Conclusion and Policy Recommendation

This study analyzed real-world emissions from diesel-powered passenger cars in Jodhpur, highlighting significant exceedances of Bharat Stage VI (BS VI) emission standards. Emission factors for CO, NOx, and THC + NOx surpassed regulatory limits by 75%, 103.75%, and 40.59%, respectively. These findings underline inefficiencies in emission control systems and the impact of real-world driving conditions, such as mixed traffic, frequent stops, and lack of lane discipline.

The study also highlighted significant variability among vehicles, with older and poorly maintained models showing higher emissions. None of the tested cars met the BS VI limit for NOx (0.08 g/km), with Cars 3 and 10 recording the highest NOx emissions at 0.20 g/km—more than double the permissible level. For THC + NOx, Cars 4, 7, 8, and 10 exceeded the standard of 0.17 g/km, with Car 7 emitting the highest value of 0.27 g/km. CO emissions were also substantially higher, averaging 0.875 g/km compared to the standard of 0.50 g/km. These results highlight the inefficiencies in emission control technologies, particularly in vehicles with outdated or poorly maintained systems. The variation in emission factors is influenced by vehicle-specific factors, including age, maintenance, and emission technologies. Poorly maintained vehicles with outdated or inefficient control systems contributed to higher emissions. Additionally, aggressive driving behaviors, fuel quality, and varying road and weather conditions further exacerbated emissions. These results emphasize the need for localized emission studies to develop tailored solutions. The study assumes a steady exhaust flow rate during different vehicle operating modes. While this simplification facilitates analysis, it may not capture transient emission events. Future studies could incorporate dynamic exhaust flow modeling for improved accuracy.

The findings from this study underscore the critical gap between laboratory-tested and real-world emissions, highlighting the inefficiencies of current emission control technologies under dynamic urban traffic conditions. The elevated emission levels observed in diesel-powered passenger cars not only breach Bharat Stage VI (BS VI) standards but also pose significant challenges to urban air quality management and public health. The variability in emissions across vehicles, influenced by factors such as engine technology, vehicle maintenance, and driving behaviors, emphasizes the need for targeted interventions.

To effectively bridge this gap and achieve substantial emission reductions, it is essential to address both technological and behavioral aspects of vehicular pollution. Strengthened regulations, enhanced technological innovation, and increased public awareness are key pillars for mitigating the environmental and health impacts of diesel vehicle emissions. The following recommendations aim to guide policymakers and stakeholders in implementing comprehensive strategies for emission reduction.

1. Enhanced Monitoring and Regulations: Real-world emission testing should be integrated into regulatory frameworks to ensure compliance beyond laboratory conditions. Policies mandating stricter maintenance schedules and periodic checks for high-emitting vehicles could reduce overall emissions.
2. Advancements in Emission Control Technologies: Manufacturers should prioritize the development of more efficient SCR and DPF systems to meet emission standards under diverse conditions. Research into alternative fuels and hybrid technologies could also mitigate the environmental impact of diesel vehicles.
3. Public Awareness Campaigns: Educating vehicle owners on the importance of regular maintenance and eco-friendly driving practices could significantly reduce emissions. Incentives for adopting cleaner vehicles and transitioning to electric or hybrid models would further support emission reduction goals.

Finally, future research should focus on expanding real-world emission studies to include rural and high-altitude regions, where driving conditions and vehicle performance may vary significantly. Investigating the impact of fuel quality, including adulterated diesel or low-grade fuels, on emissions is critical for developing more robust regulations. Additionally, exploring emerging technologies, such as IoT-enabled Portable Emission Measurement Systems (PEMS), could enhance the accuracy and scope of emission monitoring, providing data-driven insights for policymakers and stakeholders. These steps are critical for reducing emissions and improving air quality in rapidly urbanizing cities.

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