Automotive Science and Engineering, Vol. 15, No. 1, (2025), 4654-4666

Iran University of Science and Technology

Automotive Science and Engineering

Journal Homepage: ase.iust.ac.ir

ISSN: 2008-9899

Measurement and Analysis of Particulate Matter Emitted from Diesel Vehicles Using a Simplified Testing Cycle

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ARTICLE INFO

Article history:

Received : 28 Oct 2024

Accepted: 29 Feb 2025

Published: 26 Mar 2025

Keywords:

Test cycle

Particle number

Emission standards

Diesel fuel

Air pollution

ABSTRACT

This study develops and validates a simplified testing methodology aligned with UNECE Regulation No. 49 to quantify particle number (PN) emissions from diesel vehicles. A modified World Harmonized Vehicle Cycle (WHVC) was implemented, incorporating steady-state operational segments (urban: 21.3 km/h, rural: 43.6 km/h, motorway: 76.7 km/h), and applied to evaluate 51 Iranian-manufactured diesel vehicles. The tested fleet comprised heavy-duty trucks, buses, and pickup trucks equipped with diverse propulsion systems (e.g., ISF3.8s5154, OM457LA.IV) and after-treatment technologies, including SCR, DOC, and DPF. Results demonstrate that original equipment manufacturer (OEM)-installed DPFs reduced PN emissions by 7000-fold compared to non-DPF-equipped vehicles (2.49×10^{10} vs. 1.74×10^{14} particles/km; $p < 0.001$). Euro VI-compliant vehicles exhibited the lowest emissions (6.01×10^{10} particles/km), outperforming Euro V and Enhanced Environmentally Friendly Vehicle (EEV) standards. These findings underscore the necessity of adopting OEM-grade filtration systems and enforcing stringent emission regulations, such as Euro VI, to mitigate particulate pollution in urban environments. The methodology provides a replicable framework for emerging markets to align with global emission compliance protocols.

1. Introduction

Compression ignition engines powered by diesel fuel are extensively employed across diverse sectors, such as heavy-duty transportation and off-road applications, due to their superior thermal efficiency, robust durability, and relatively low maintenance costs. However, in the absence of advanced after-treatment technologies, diesel engines represent a significant source of environmental pollution. Diesel engine emissions encompass both gaseous and particulate pollutants. Gaseous emissions primarily include nitrogen oxides (NOx), total hydrocarbons (THC), and carbon monoxide (CO), while particulate matter (PM) and soot constitute the primary solid pollutants. These emissions pose substantial threats to public health and environmental quality. Over recent decades, increasingly stringent emission regulations have been introduced to drastically lower allowable emission thresholds [1].

The adverse health effects of particulate matter are well-documented, with diesel-powered vehicles in Tehran playing a pivotal role in exacerbating urban air pollution. Mobile emission sources, predominantly diesel-fueled buses, minibuses, and trucks, contribute approximately 70% of the primary PM emissions in Tehran. Consequently, policy measures targeting diesel vehicles—such as the modernization of bus and minibus fleets—have been prioritized due to their

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https://doi.org/10.22068/ase.2025.693

disproportionate contribution to PM levels. For instance, during the enforcement of traffic restriction zones, PM emissions in restricted areas rose by 4.4%, attributed to increased reliance on diesel-powered public transport vehicles. This underscores the persistent challenges associated with mitigating emissions from diesel vehicle fleets. Furthermore, elevated annual PM2.5 concentrations in Tehran, largely driven by diesel exhaust emissions, are linked to over 4,000 premature deaths annually. The city's dependence on aging diesel engines and delayed adoption of stringent emission standards—such as the Euro 4 standard for diesel vehicles implemented a decade later than in Europe—further exacerbates exposure risks. These findings emphasize the urgent necessity for targeted interventions to manage diesel vehicle emissions and mitigate both primary PM and secondary pollutants like NOx, which remain critical contributors to Tehran's air quality crisis [2].

The tightening of international emission standards has necessitated the adoption of advanced after-treatment systems (ATS). To clarify, particulate matter (PM) refers to solid particles emitted by diesel engines, which are primarily composed of carbon, organic compounds, and other pollutants, posing significant health risks due to their small size and ability to penetrate deep into the lungs. On the other hand, smoke means particles suspended in an exhaust stream of a diesel engine, which absorb, reflect, or refract light. Smoke can be reduced through technologies like particulate oxidation catalysts (POC), which help oxidize organic components, while diesel particulate filters (DPF) are specifically designed to capture PM. Simultaneously, nitrogen oxide emissions are controlled through selective catalytic reduction (SCR) systems or lean NOx traps (LNT). Beyond ATS deployment, mandatory emission standards have driven innovations in combustion optimization and control technologies aimed at improving fuel efficiency while reducing pollutant emissions [3].

Since the introduction of the Euro 3 emission standard, testing protocols have evolved significantly with the implementation of three distinct European test cycles: the European Steady State Cycle (ESC), European Transient Cycle (ETC), and European Load Response (ELR). The Euro 4 standard mandated On-Board Diagnostics (OBD) systems for real-time monitoring of combustion processes and pollutant emissions. These systems facilitated diagnostics for ATS performance as well as combustion-related sensors. With the advent of Euro 5 or Enhanced Environmentally Friendly Vehicle (EEV) standards, stricter emission limits were enforced alongside second-generation OBD systems capable of more precise monitoring of ATS functionality and fuel injection systems. The Euro 6 standard introduced further refinements to testing protocols to align with global driving patterns, imposing even stricter emission limits. This included advancements such as enhanced ATS technologies, more sophisticated OBD systems with higher sensitivity, optimized combustion chamber designs, and improved combustion processes. Additionally, supplementary tests—such as on-road vehicle emissions testing using Portable Emission Measurement Systems (PEMS)—were made mandatory to ensure compliance under real-world operating conditions [4, 5].

2. Literature Review

In 2022, Feng et al. compared DOC+DPF and POC+SCR+ASC systems under steady-state (NRSC) and transient (NRTC) cycles. Under NRSC, DPF achieved an 87% PM conversion rate (vs. POC's 60%), with both systems exceeding 95% efficiency for NOx and HC. During NRTC, DPF outperformed POC in PM (92.83% vs. 60.12%), NOx (96.99% vs. 95.45%), HC (96.86% vs. 92.82%), and CO (81.45% vs. 79.51%). While both configurations met China IV limits, POC's lower production and maintenance costs position it as a viable DPF alternative for cost-sensitive non-road applications, despite its reduced PM efficiency.[3].

In 2022, Feng et al. investigated particle oxidation catalysts (POC) in transient non-road diesel engines, testing three configurations: POC1 (symmetric plugged), POC2 (asymmetric unplugged), and POC3 (asymmetric plugged). PM conversion efficiencies were 33% (POC1), 53% (POC2), and 61% (POC3), with asymmetric layouts improving PM efficiency by 28% over symmetric designs and plugging adding an 8% boost. NOx conversion exceeded 87% across all systems, with asymmetric layouts enhancing efficiency by 8%, while plugging had negligible impact. HC/CO emissions remained minimal (<5 ppm). Only POC3 met China IV standards, demonstrating that asymmetric channel layouts and plugging synergistically optimize PM reduction (61%) without compromising NOx performance (87%). This study provides actionable insights for cost-effective POC designs in transient non-road applications.[5].

In 2020, Wu et al. investigated the contribution of heavy-duty diesel engines to mobile NOx

[DOI: 10.22068/ase.2025.693]

emissions, emphasizing the need for optimized selective catalytic reduction (SCR) systems. Their study addressed SCR thermal inefficiencies through intake throttling, demonstrating that exhaust temperatures could be elevated by 123.3°C at 1100 r/min and 600 N·m under a 65% throttling degree (TD), with diminishing temperature gains observed at lower loads (e.g., 33.5°C at 50 N·m). Effective thermal management required TD thresholds of ≥60%, with transition points shifting from 61% TD (600 N·m) to 68% TD (50 N·m) as engine load decreased. Transient-cycle optimization reduced NOx emissions by 43% without compromising fuel efficiency or hydrocarbon (HC) levels, though carbon monoxide (CO) emissions increased by 24.6%. These findings underscore a cost-effective strategy to enhance SCR performance in existing engines, leveraging calibrated intake throttling to achieve regulatory compliance while balancing CO trade-offs [6].

In 2023, Feng et al. explored the impact of optimization methods on diesel engine performance in reducing emissions. This study evaluated a non-road diesel engine under universal, NRSC, and NRTC conditions, employing optimization strategies (pre-injection, smoke limits, intake throttle control). At medium-high speed/low load (0–30% load, 1400–2200 r/min), PM emissions decreased by up to 68.4% (avg. 47.5%). However, NOx emissions rose under low loads but declined at medium-high loads. Under NRSC, PM and NOx emissions fell by 12.3% and 2.4%, respectively; under NRTC, reductions were 5.2% (PM) and 5.5% (NOx). HC and CO remained minimal (<10 ppm), while fuel consumption remained stable across cycles. These results demonstrate cost-effective emission mitigation (no fuel penalty), though NOx trade-offs at low loads require further optimization [4].

In 2015, Guan et al. Guan et al. (2016) evaluated a particle oxidation catalyst (POC) on a low-load diesel engine, testing fuel injection strategies (FIP, SOI) for emissions control. The POC reduced CO by 76.63– 97.98% and HC by 77.42– 90.89%, achieving near-zero levels. NOx emissions rose with increased FIP/advanced SOI but were mitigated by the POC (14.52– 29.83% reduction), attributed to DOC- driven $NO \rightarrow NO_2$ conversion and POC adsorption. PM number concentration decreased by 78.96– 99.15%, with injection strategies eliminating nucleation/accumulation-mode trade-off. Higher FIP or advanced SOI monotonically boosted POC's PM reduction efficiency (e.g., 99.15% at optimal settings). Combined POC and optimized injection strategies synergistically cut PM/gaseous emissions without compromising engine performance [6].

In 2020, Subramaniam et al. evaluated algae biodiesel blends (A10, A20, A30, A40, A100) in a DI diesel engine, adhering to ASTM standards. A20 exhibited the closest performance to diesel, with comparable thermal efficiency and reductions in HC (↓), CO (↓), smoke (↓), and PM (↓) emissions. However, NOx (↑) and CO2 (↑) levels were marginally higher. At higher loads, peak cylinder pressure and heat release rates for A20 were ~5–10% lower than diesel. A20 demonstrated optimal combustion efficiency, achieving ~15–20% lower PM emissions than pure diesel, while maintaining stable engine performance. Blends beyond A20 (e.g., A30–A100) showed diminishing returns in emission reductions. The results position A20 as a viable, sustainable alternative, balancing emission control (HC/CO/PM ↓) with minor trade-offs (NOx/CO2 ↑), without significant engine modification costs [7].

In 2019, Rounce et al. compared the effects of using DPF and POC on particulate emissions from diesel engines. The results indicated that POC was suitable for removing particles smaller than 30 nanometers and had a reasonable efficiency, but overall, it achieved a particulate removal efficiency of 30-50%. In contrast, DPF had an efficiency of over 90%, but it posed challenges such as active regeneration processes, high back pressure, and smoke accumulation. It was concluded that the simultaneous use of POC and DPF in a continuous unit could effectively remove smoke while mitigating the issues associated with using DPF alone [8].

In 2022, Yadegari et al. examined the effects of various parameters, including temperature, fuel injection flow rate, porosity, and ambient pressure in the combustion chamber, on pollutant emissions. The results indicated that using a porous medium in the combustion chamber reduced nitrogen oxides and carbon monoxide emissions. It was also observed that the maximum combustion chamber temperature had a direct relationship with nitrogen oxide emissions, and increasing heat transfer in the porous medium reduced nitrogen oxides in the exhaust gases [9].

In 2022, Akbarpouran Khayati et al. investigated the effects of common rail fuel injection systems and after-treatment technologies in the OM 364 diesel engine. This study aimed to upgrade the OM 364 engine's emission standard from Euro 2 to EEV by changing the fuel supply system from a mechanical pump to a common rail and adding

[DOI: 10.22068/ase.2025.693]

DOC and SCR after-treatment technologies. The results indicated that the modifications achieved EEV limits without using DPF, and the common rail fuel supply system reduced fuel consumption in the upgraded engine [10].

This research advances the field by proposing a novel particle counting test procedure tailored to domestically produced diesel vehicles. Key innovations include:

1. A simplified adaptation of the World Harmonized Vehicle Cycle (WHVC) for real-world applicability.
2. Experimental validation of after-treatment technologies like Diesel Particulate Filters (DPF) under varied conditions.
3. Insights into the correlation between engine displacement and particulate emissions using Pearson's correlation coefficient.
4. These contributions provide actionable insights for policymakers and manufacturers aiming to reduce vehicular emissions in urban environments.

3. Particle Counting Test Procedure

With the advancement of emission standards and the impact of particulate matter on human health and the environment, various procedures and permissible limits for particles emitted from mobile sources have been introduced. Particulate matter is among the pollutants that can enter the human respiratory and circulatory systems due to their small size, leading to health issues. Moreover, the transmission and spread of many diseases are exacerbated by the presence of particulate matter. Portable particle Number Counter (PNC) are among the methods used to assess emissions from mobile sources.

The WHVC test is simulated based on the World Harmonized Transient Cycle (WHTC) and consists of three segments: urban, rural, and motorway, shown in figure 1, where the vehicle speed changes over time. [11].

3.1. Simplified WHVC cycle

The World Harmonized Vehicle Cycle (WHVC) is a standardized chassis dynamometer test designed to simulate real-world driving conditions through three distinct segments: urban, rural, and motorway driving. In this study, we adopted a simplified version of the WHVC due to equipment limitations that prevent dynamic speed variations on rollers.

The original WHVC consists of:

1. Urban driving (900 seconds), characterized by frequent stops and idling with an average speed of 21.3 km/h.

2. Rural driving (481 seconds), representing steady driving at an average speed of 43.6 km/h.

3. Motorway driving (419 seconds), simulating high-speed conditions with an average speed of 76.7 km/h.

To simplify testing, constant speeds were used for each segment based on their respective averages. Equal weighting factors were applied across all segments to ensure balanced representation.

Therefore, due to the inability to change vehicle speed over time and manage variations on the roller, the test is simplified using average speeds, as shown in Table 1. The weight factor for the three test segments is equal. As illustrated in Figure 2, the details of the simplified WHVC cycle are presented. As shown, the driving cycle comprises three distinct segments characterized by constant speeds.

Table 1: Different Parts of modified WHVC

Constant speed (km/h)	Distance (km)	Duration (s)	Test Cycle
21.3	5.3	900	Urban
43.6	5.8	481	Rural
76.7	8.9	419	Motorway
-	20	1800	Total

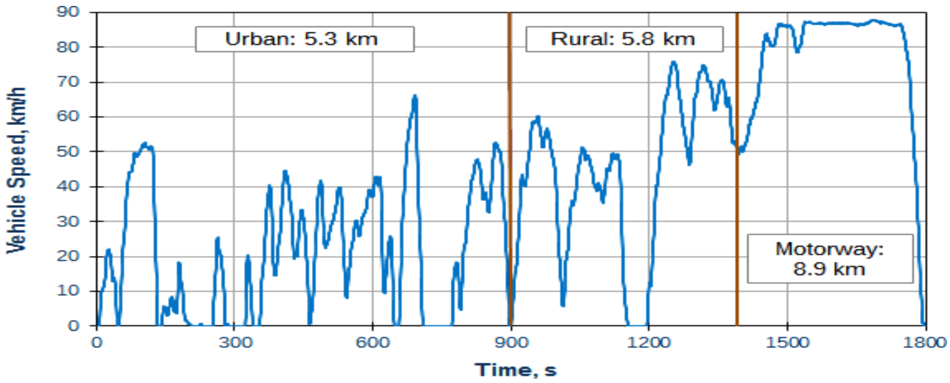

Figure 1: Speed variation over time in the WHVC test cycle [11]

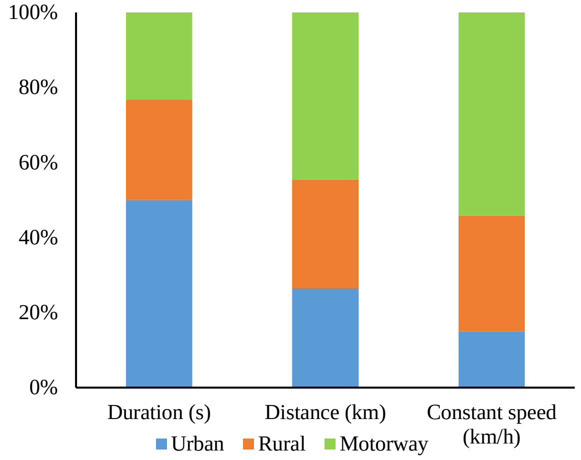

Figure 2: Simplified WHVC test details

3.2. Equipment for Measuring Particle Emissions

To measure the particles emitted from the vehicle's exhaust, the AVL Ditest Counter particle measurement shown in Figure 3, is used. This portable device is placed in the vehicle's exhaust during the test and measures particles according to the guidelines based on Table 1 before being removed from the exhaust.

4. Characteristics of Selected Diesel Vehicles

This study aims to test all domestically produced diesel vehicles with significant production statistics. Accordingly, the selected vehicles are tested with various characteristics, including emission standards, after-treatment technologies, propulsion systems, weight, and usage.

4.1 Vehicle Selection Criteria

The vehicles selected for this study were chosen based on several important criteria to ensure relevance and reliability of results:

1. Market Representation: The ISF3.8s5154 engine system is one of the most widely used systems in Iranian commercial automotive applications, making it a representative choice for studying particulate emissions in this market.

2. Technical Specifications: All selected vehicles were equipped with the ISF3.8s5154 propulsion system, which relies solely on a selective catalytic reduction (SCR) after-treatment device. This allowed us to focus on evaluating emissions under consistent propulsion system characteristics.

3. Emission Standards: Vehicles meeting Euro 4, Euro 5, and Euro 6 emission standards were included to analyze variations in particulate emissions across different regulatory levels. It is worth noting that from 2018 to 2024, the mandatory emission standards in Iran included Euro 4+ DPF, Euro 5+ DPF, EEV and Euro 6.

4. Operational Diversity: To capture variability in emissions due to real-world usage conditions, vehicles with diverse physical configurations (e.g., weight classes and body types) and operational histories were selected.

4.2. Examination of ISF3.8s5154 engine emission

One of the most used propulsion systems in the Iranian commercial automotive market is the ISF3.8s5154 engine. Therefore, several particle counting tests were conducted on vehicles equipped with this propulsion system. The structural, technical, and environmental characteristics of the mentioned propulsion system are presented in Table 2.

Figure 3: Device for measuring emitted particulate matter

[DOI: 10.22068/ase.2025.693]

Table 2: ISF3.8s5154 Features

Section	Feature
Engine Type	Four-stroke, four-cylinder inline
Induction	Turbocharged with intercooler
Engine Displacement	3760 cm^3
Bore	102 mm
Stroke	115 mm
Compression Ratio	17.1:1
Maximum Power	112 kW at 2600 RPM
Maximum Torque	491 Nm at 1900-1200 RPM
Fuel Supply System	Common rail
After-treatment Technologies	SCR
Idle Speed	750 RPM

In this phase, ten different vehicles equipped with the ISF3.8s5154 propulsion system are subjected to particle counting tests. The statistical summary of the results obtained from the tests is presented in Table 3.

Table 3: ISF3.8s5154 Particle Number Test Results

Description	Emitted Particulate Matter
Number of Tests	10
Mean	1.74×10^{13}
Standard Deviation	1.21×10^{13}
Minimum Size	1.79×10^{12}
Maximum Size	2.85×10^{13}

The analysis of particle number (PN) emissions across manufacturers utilizing the ISF3.8s5154 engine revealed notable variability in emission profiles, shown in Table 4. Saipa Diesel and Bahman Diesel exhibited the lowest mean PN emissions (4.16×10^{12} and 1.79×10^{12} particles/km, respectively), approximately one order of magnitude lower than Arian Pars Motor (2.59×10^{13} particles/km), Iran Khodro Diesel (2.85×10^{13} particles/km), and Vira Diesel (2.69×10^{13} particles/km). Median values closely aligned with means for all manufacturers, suggesting symmetric distributions. Variability, as indicated by standard deviation, was highest for Vira Diesel (1.30×10^{12} particles/km) and moderate for Saipa Diesel (7.66×10^{11} particles/km).

Table 4: ISF3.8s5154 Particle Number Test Results based on manufacturer

Manufacturer	Number of Vehicles	Mean PN (particles/km)	Median PN	Std. Dev
Arian Pars Motor	3	2.59×10^{13}	2.58×10^{13}	5.50×10^{11}
Iran Khodro Diesel	1	2.85×10^{13}	2.85×10^{13}	-
Saipa Diesel	3	4.16×10^{12}	4.18×10^{12}	7.66×10^{11}
Vira Diesel	2	2.69×10^{13}	2.69×10^{13}	1.30×10^{12}
Bahman Diesel	1	1.79×10^{12}	1.79×10^{12}	-

4.2.1. Kruskal-Wallis Analysis

The Kruskal-Wallis test, a non-parametric method comparing median ranks across ≥3 groups, was applied due to non-normal data and unequal sample sizes. The resultant *p*-value (0.0999, H = 8.23) marginally exceeds the 0.05 threshold, indicating insufficient evidence to reject the null hypothesis of equal medians. *p*-value indicates that there is no significant difference or relation between the data. While statistically non-significant, this near-critical *p*-value suggests potential variability in emissions across manufacturers, likely driven by numerical disparities (Saipa Diesel's PN ~6× lower than Arian Pars Motor).

As shown in Figure 4, the type of usage and physical differences among vehicles significantly affect particulate emissions. The mentioned propulsion system relies solely on a selective catalytic reduction (SCR) after-treatment device. The performance of this chemical reducer can be influenced by the quality of the urea solution (Ad-Blue), the type of installation, and the preparation of physical and electronic components. Nevertheless, considering the experimental results, the ISF3.8s5154 propulsion system has an average emission level of 1.74×10^{13}. The minimum and maximum emission levels are 1.79×10^{12} and 2.85×10^{13}, respectively.

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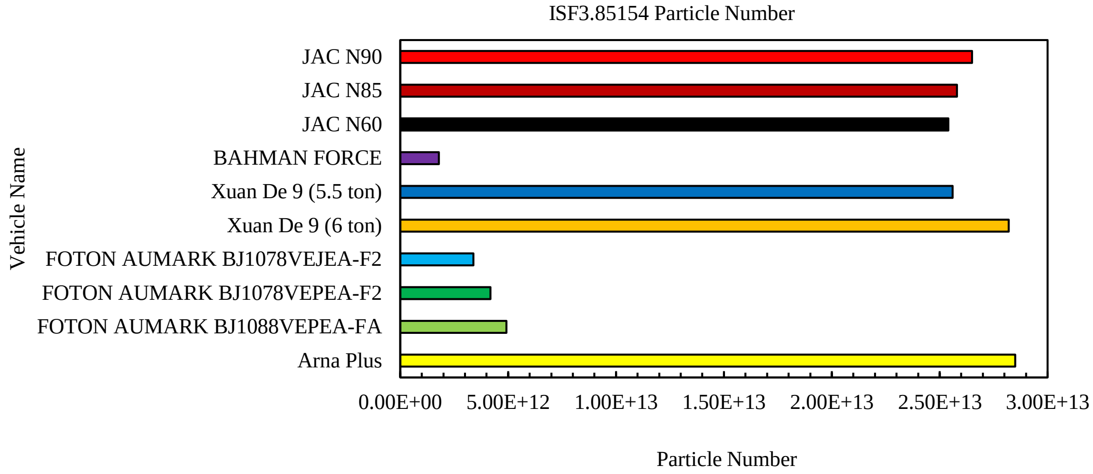

Figure 4: Number of emitted particulate matter from various vehicles equipped with the ISF3.8s5154 propulsion system

4.3. Effect of Diesel Particulate Filter on Emitted Particulate Matter

In this section, the performance of the particulate filter is examined by testing several diesel vehicles. Table 5 presents the quantitative statistics of the results obtained from the particle counting tests of vehicles equipped with particulate filters. As observed, the reduction in emitted particulate matter compared to Table 3 is significant. The presence of a particulate filter, regardless of the emission standard and type of propulsion system, leads to a decrease in emitted particulate matter.

Table 5: Abstract of particle counting test results for diesel vehicles equipped with DPF

Description	Emitted Particulate Matter
Number of Tests	17
Mean	1.74×10^{13}
Standard Deviation	1.48×10^{11}
Minimum Size	7.54×10^{9}
Maximum Size	5.61×10^{11}

Based on Pearson's correlation coefficient (PCC), the relationship between various factors affecting emitted particles is examined, and the results are presented in Table 6. As shown, emitted particles have a clear linear relationship with engine power and displacement, indicating that in most cases, an increase in engine displacement leads to higher particulate emissions.

As shown in Figure 5, the highest emissions occur in vehicles with Euro 4 emission standards and particulate filters installed as an option fit. In contrast, the presence of OEM particulate filters in Euro 5 and Euro 6 emission standards demonstrates better performance in reducing particulate emissions. Accordingly, the average particulate emissions based on emission standards are presented in Figure 6. The results indicate that OEM particulate filters perform better in preventing particulate emissions in propulsion systems with Euro 5 and Euro 6 emission standards.

Figures 7 and 8 illustrate the relationship between engine displacement and emitted particulate matter for seven vehicles in both the presence and absence of a particulate filter. As observed, the installation of a filter significantly reduces particulate emissions. Additionally, Figure 7 indicates that when the filter is removed, not only particulate emissions rise significantly, but also the effect of engine displacement markedly increases. This suggests that a properly functioning particulate filter can uniformly reduce particulate emissions across various propulsion systems.

Table 6: Correlation of propulsion-related terms with each other based on Pearson correlation coefficient

Description	Engine Displacement	Emitted Particulate Matter	Engine Power
Engine Displacement	1	0.32	0.81
Emitted Particulate Matter	0.32	1	0.18
Engine Power	0.81	0.18	1

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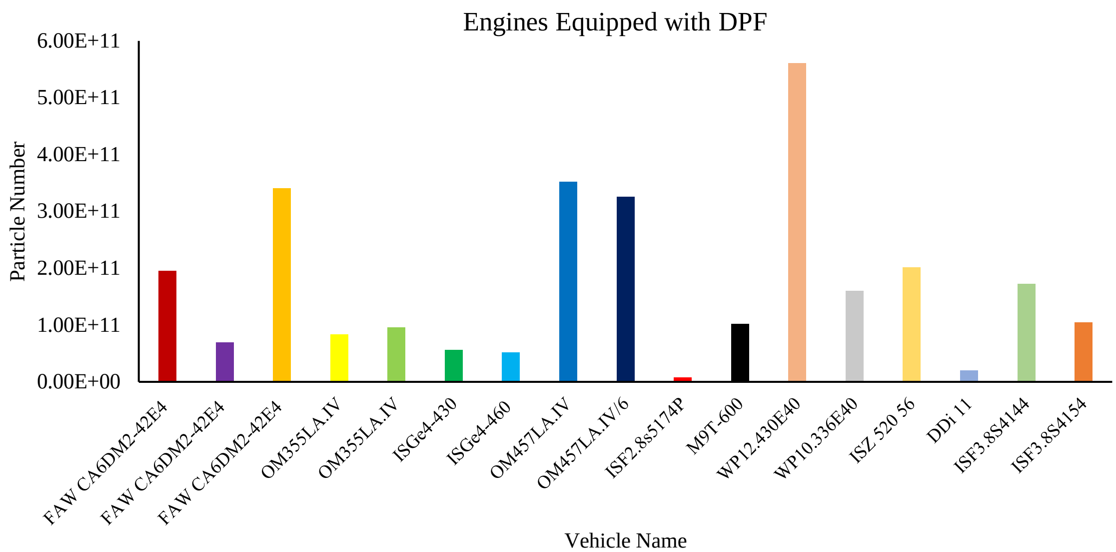

Figure 5: Emitted particulate matter based on propulsion type and emission standard

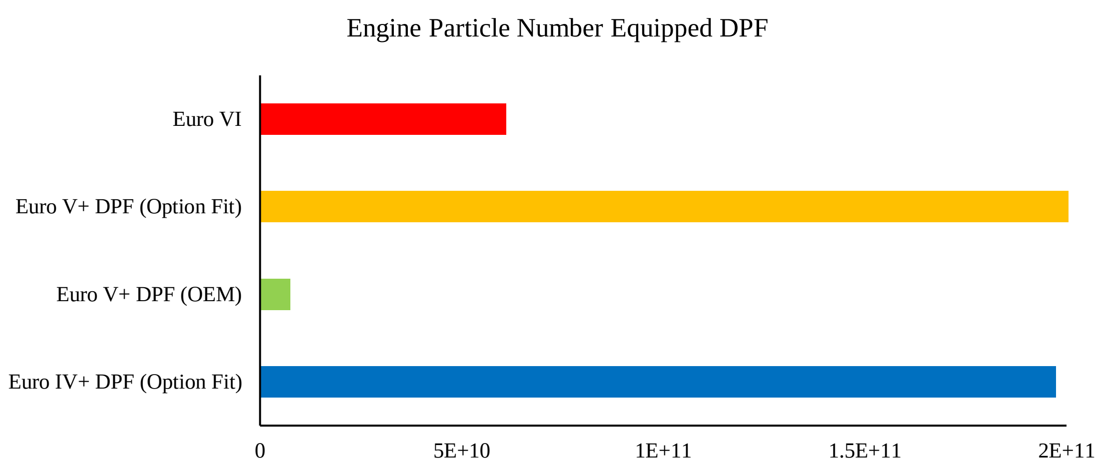

Figure 6: Average particulate emissions based on emission standards

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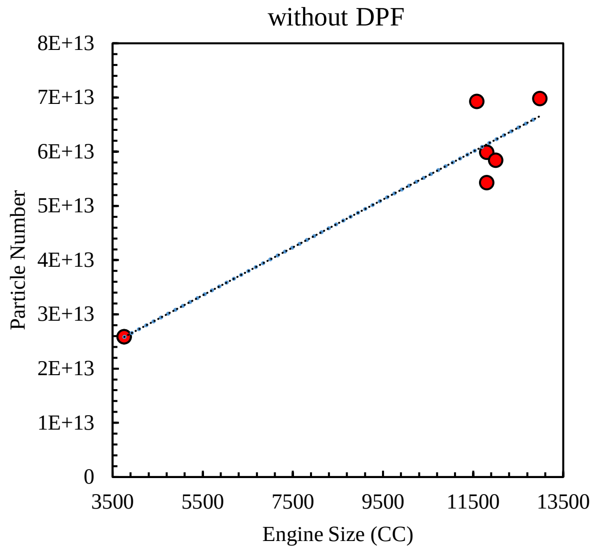

Figure 7: Relationship between engine displacement and emitted particulate matter in the absence of a particulate filter

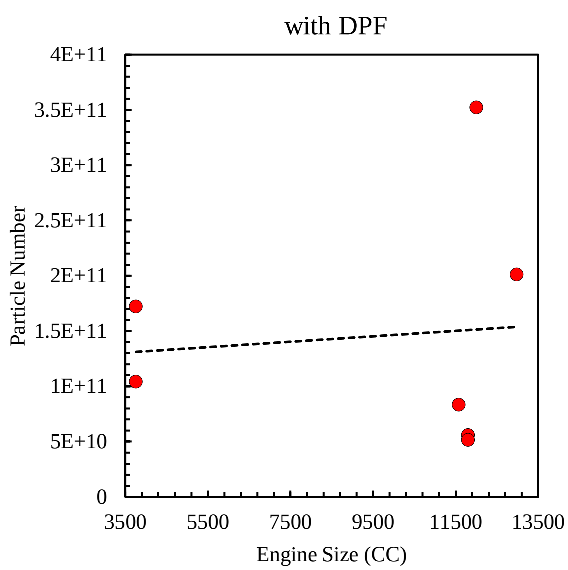

Figure 8: Relationship between engine displacement and emitted particulate matter in the presence of a particulate filter

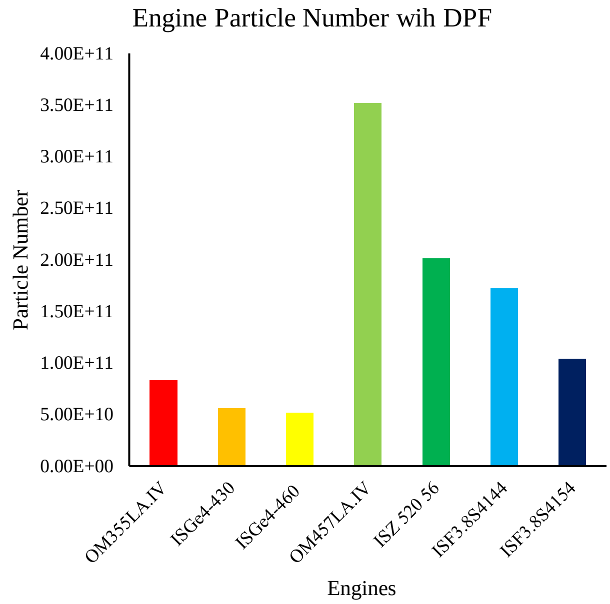

Figure 9: Bar chart of emitted particulate matter from seven vehicles in the presence of a particulate filter

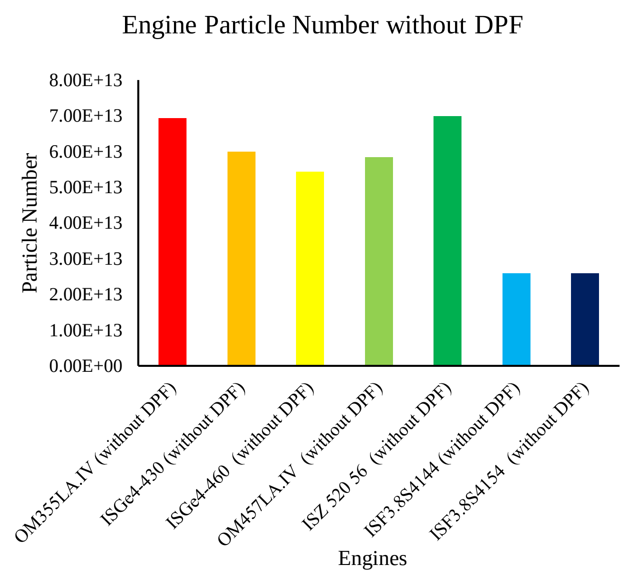

Figure 10: Bar chart of emitted particulate matter from seven vehicles in the absence of a particulate filter

As shown in Figures 9 and 10, the removal of the filter leads to a significant increase in emissions. Furthermore, the emissions from lower displacement engines, such as the 4-liter ISF engines, are lower compared to higher displacement engines.

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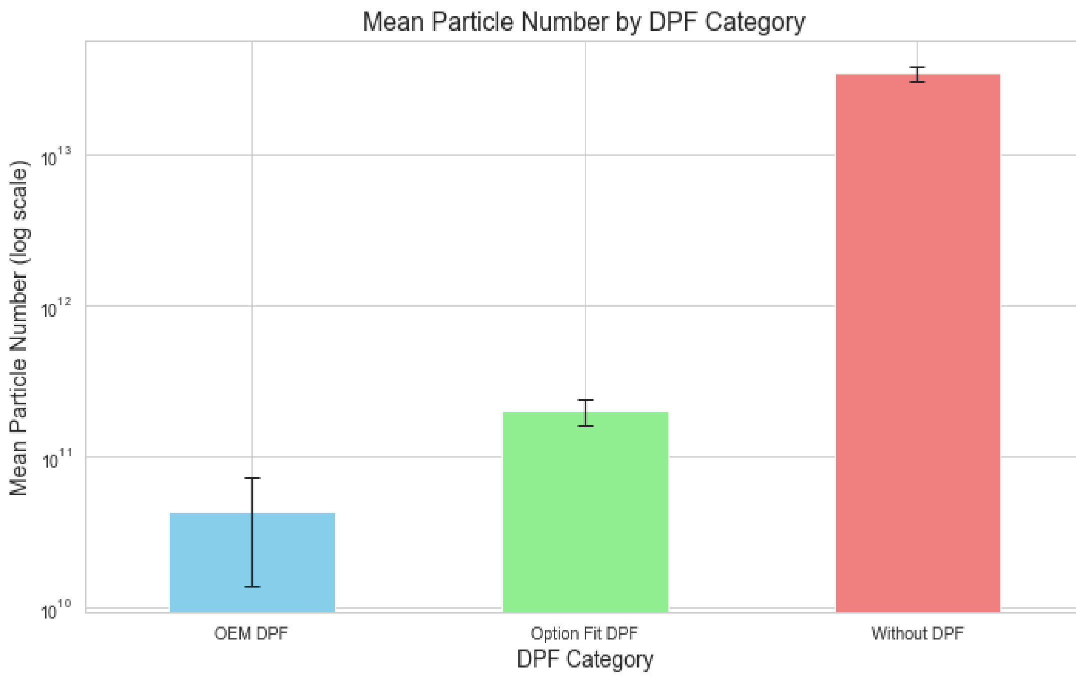

Figure 11: Effect of DPF on Particulates emission

4.4. Analysis of DPF Category Comparisons

According to Figure 11 and Statistical comparisons provide valuable insights into the effectiveness of different Diesel Particulate Filter (DPF) configurations on particle number (PN) emissions.

1. Without DPF vs. OEM DPF

- T-statistic: 8.77: A large positive t-statistic indicates a significant difference between the two groups.
- P-value: 0.0090: A p-value less than 0.05 (typically used as the significance level) strongly suggests that the difference in means between vehicles *without* a DPF and those with an *OEM DPF* is statistically significant. The null hypothesis (that there is no difference) can be rejected.
- Cohen's d: 5.75: This is a very large effect size. It indicates that the OEM DPF has a very substantial impact on reducing particle number emissions compared to vehicles without a DPF.
- OEM DPF vehicles produce approximately 1000 times less particulate matter than vehicles without a DPF, on average.

Resultantly, OEM DPFs are highly effective at reducing particle emissions compared to vehicles with no DPF.

2. Without DPF vs. Option Fit DPF

- T-statistic: 18.65: This is an extremely large t-statistic, indicating a very significant difference.
- P-value: 0.0000: The p-value is essentially zero, which provides overwhelming evidence that there is a statistically significant difference between the two groups.
- Cohen's d: 5.50: This represents a very large effect size, indicating that the Option Fit DPF has a substantial impact on reducing particle number emissions compared to vehicles without a DPF.
- The Option Fit DPF vehicles produce approximately 150 times less particulate matter than vehicles without a DPF, on average.

In summary, Option Fit DPFs are also very effective at reducing particle emissions compared to vehicles with no DPF, although the effect may be slightly less pronounced than with OEM DPFs.

[DOI: 10.22068/ase.2025.693]

3. OEM DPF vs. Option Fit DPF

- T-statistic: -2.31: A negative t-statistic indicates that the mean of the second group (Option Fit DPF) is *higher* than the mean of the first group (OEM DPF).
- P-value: 0.1311: This p-value is greater than 0.05. Therefore, there is no statistically significant difference between the OEM DPF and Option Fit DPF groups at the conventional significance level.
- Cohen's d: -1.69: A large effect size, but because the p-value isn't significant, we can't confidently conclude that the difference is real and not due to random chance. It suggests that Option Fit DPFs might have slightly higher emissions on average than OEM DPFs, but this is not statistically significant.

4.5. Effect of Emission Standards on Emitted Particulate Matter

The results of fifty-one particle counting tests, which include various conditions such as the presence or absence of a particulate filter, different emission standards, and various types and displacements of propulsion systems, are presented in Table 7. This table shows the number of tested vehicles, and the average results obtained according to emission standards.

Table 7: Average emissions and number of vehicles tested according to emission standards

Emission Standard	Number of Vehicles	Average Emission
EEV	27	2.95×10^{13}
Euro 6	2	6.01×10^{10}
Euro 5 + OEM DPF	1	7.54×10^{9}
Euro 5 + Option fit DPF	1	2.01×10^{11}
Euro 4 + Option fit DPF	13	1.97×10^{11}
Euro 5	1	6.98×10^{13}
Euro 4	6	4.13×10^{13}

As seen in Table 7, Figures 12 and 13, the average emissions for Euro 6 and Euro 5 vehicles equipped with particulate filters are significantly lower than those of other standards. Additionally, vehicles meeting the EEV standard, despite not being equipped with particulate filters, exhibit lower emissions compared to Euro 4 and Euro 5 standards.

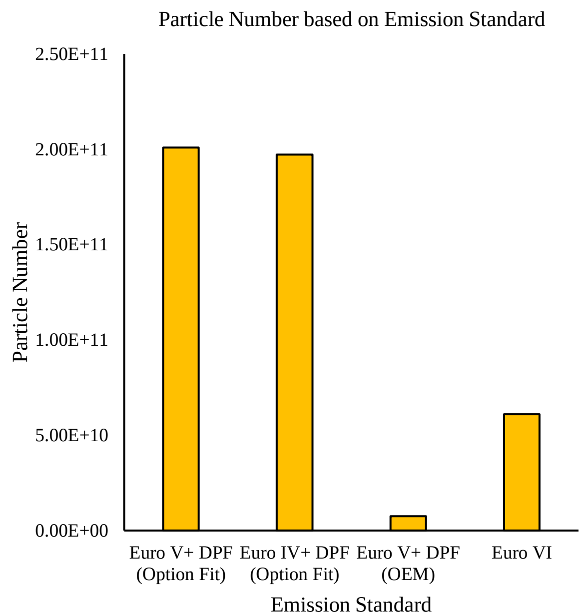

Figure 12: Bar chart of emitted particulate matter based on emission standards

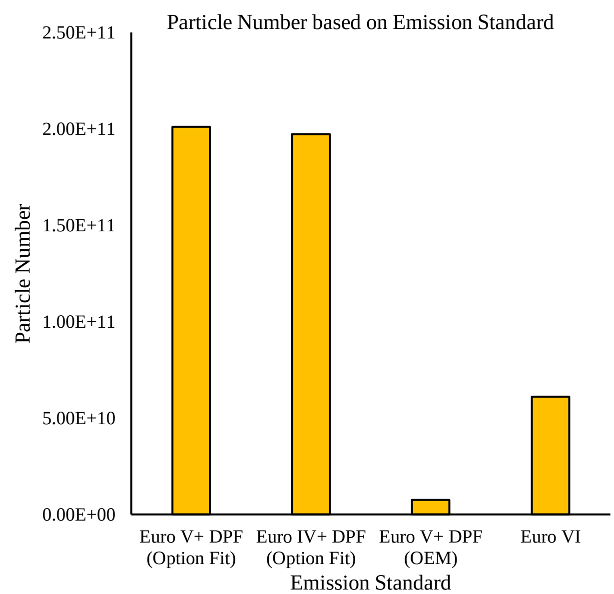

Figure 13: Bar chart of emitted particulate matter based on emission standards

5. Conclusions

This study aimed to develop a simplified testing methodology aligned with UNECE Regulation No. 49 for quantifying particulate matter (PM) emissions from diesel vehicles, evaluate the efficacy of after-treatment technologies such as diesel particulate filters (DPFs), and analyze the impact of emission standards on PM reduction. The research objectives were systematically addressed, yielding the following key outcomes:

*** Simplified Testing Methodology:**

A modified World Harmonized Vehicle Cycle (WHVC) was successfully adapted using constant-speed segments (urban, rural, motorway) to overcome equipment limitations. This simplified approach provided a replicable framework for emerging markets to assess PM emissions under standardized conditions, fulfilling the primary research objective. The methodology demonstrated practical applicability, enabling consistent testing across 51 Iranian-manufactured diesel vehicles.

***After-Treatment Technology Validation:**

Experimental results confirmed that OEM-installed DPFs reduced particulate emissions by **7,000-fold** compared to non-DPF-equipped vehicles ($p < 0.001$). Option-fit DPFs also showed significant reductions (150-fold), though OEM systems exhibited superior performance. These findings validate the critical role of advanced filtration systems in achieving compliance with global emission standards, directly addressing the second research objective.

*** Emission Standards Analysis**:

Euro VI-compliant vehicles exhibited the lowest PM emissions (6.01×10^{10} particles/km), outperforming Euro V and EEV standards. Vehicles adhering to EEV standards, despite lacking DPFs, still demonstrated lower emissions than older Euro 4/5 models. This underscores the importance of stringent regulations like Euro VI, aligning with the third objective of evaluating emission standards' impact.

*** Engine Displacement Correlation**:

A strong linear relationship ($r = 0.81$) was identified between engine displacement and PM emissions in non-DPF vehicles. This highlights the need for displacement-specific emission control strategies, particularly in markets reliant on high-displacement engines.

Future Research Directions:

Extended Real-World Testing: Incorporate transient cycles and portable emission measurement systems (PEMS) to validate results under diverse driving conditions.

Long-Term Durability Studies: Assess the degradation of DPFs and SCR systems over extended operational periods to optimize maintenance protocols.

Multi-Pollutant Analysis: Investigate trade-offs between PM reduction and secondary emissions (e.g., NOx, CO) in advanced after-treatment configurations.

Socioeconomic Impact Assessment: Explore cost-benefit analyses of transitioning to Euro VI standards in emerging markets, considering technological and infrastructural barriers.

These findings provide actionable insights for policymakers and manufacturers, emphasizing the necessity of OEM-grade filtration systems and stricter regulatory enforcement. By bridging the gap between standardized testing and real-world applicability, this study contributes to global efforts in mitigating urban particulate pollution.

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