

A Quantitative Approach for Mapping and Assessing Diesel Particulate Filter Regeneration Events in Diesel Engines

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Abstract—Regeneration of diesel particulate filters (DPFs) is crucial for maintaining the performance of diesel engines and minimizing harmful particulate matter (PM) emissions from exhaust. However, conventional regeneration strategies often suffer from incomplete soot removal and inefficient monitoring. These issues efficiency and approach is proposed for mapping and quantifying the real-world DPF regeneration process for diesel engines complying with the stringent emission standards. We introduce a novel metric, the differential pressure drop percentage (DPDP), to detect regeneration events and quantify soot burn quality. The proposed method utilizes real-time sensor data obtained through the vehicle's On-Board Diagnostics (OBD) system. The algorithm processes sensor data and robustly maps the regeneration quality. The performance of regeneration event detection and soot burn quality has been validated based on diagnostic trouble codes (DTCs) raised by the engine control unit (ECU). Our proposed method demonstrates that predictive maintenance can be used to manage strategies for diesel exhaust after-treatment systems, which can effectively reduce increased maintenance costs and operational downtime.

Index Terms—Diesel particulate filter, Engine control unit (ECU), DPF regeneration, Diagnostic Trouble Code (DTC)

I. INTRODUCTION

Diesel engines are extensively employed in commercial vehicles and heavy-duty machinery due to their robustness and fuel efficiency. However, their exhaust emissions contain a complex mixture of hazardous pollutants, including ultrafine carbon particles—commonly referred to as diesel particulate matter (PM)—which are typically coated with various organic compounds [1]. These particles pose significant risks to both environmental and human health. Most diesel PM particles are smaller than 2.5 microns in diameter ($PM_{2.5}$), enabling them to penetrate deep into the respiratory system and even enter the bloodstream, thereby contributing to respiratory and cardiovascular diseases. Regulatory bodies such as the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) have classified diesel PM as a toxic air contaminant with carcinogenic potential [3], [8].

In response to these health and environmental concerns, many nations have implemented stringent emission regulations aimed at reducing particulate emissions from internal combustion engines. To meet these evolving standards,

researchers have focused on various mitigation strategies, including improvements in fuel composition, in-cylinder emission reduction technologies, and advanced exhaust aftertreatment systems. Among these, diesel particulate filters (DPFs) have emerged as one of the most effective aftertreatment solutions, capable of capturing and storing over 90% of particulate emissions from diesel exhaust streams [1].

Over prolonged operation, diesel particulate filters (DPFs) accumulate soot and ash within their porous structure, progressively reducing filtration efficiency. This accumulation leads to increased exhaust backpressure, which adversely affects engine performance by elevating fuel consumption and reducing power output [6]. Consequently, monitoring and managing the DPF's condition is essential for maintaining engine efficiency and ensuring continued compliance with emission standards.

To sustain optimal engine operation and meet regulatory requirements, the trapped particulate matter in the DPF must be periodically removed through a process known as regeneration. This process oxidizes and eliminates accumulated soot, either passively—when favorable exhaust temperatures are naturally reached—or actively, via engine control unit (ECU) interventions that elevate exhaust temperatures. In active regeneration, additional fuel is typically injected either during the exhaust stroke through post-injection or directly into the exhaust stream via a hydrocarbon injection system. This fuel does not contribute to engine propulsion but instead raises the temperature of the aftertreatment system, facilitating soot oxidation within the DPF and converting it to ash that is expelled with the exhaust.

However, ineffective or incomplete regeneration can lead to persistent filter clogging, higher fuel consumption, and eventual damage to the DPF or engine components. To address this, various approaches have been proposed to estimate soot load, including indirect techniques based on sensor measurements and mathematical modeling [2], [7], [5]. Nevertheless, current systems often lack robust mechanisms for quantifying the effectiveness of individual regeneration events and for assessing DPF health over extended operation [5]. Therefore, there is a clear need for practical and reliable methods to monitor DPF condition

and optimize regeneration strategies, thereby safeguarding engine performance and ensuring long-term compliance with stringent emission regulations.

In this paper, we propose a novel approach for mapping and quantifying the diesel particulate filter (DPF) regeneration process in diesel engines. A new diagnostic metric, the Differential Pressure Drop Percentage (DPDP), is introduced to accurately detect regeneration events and evaluate the quality of soot oxidation. The proposed method leverages real-time sensor data—such as exhaust temperature, pressure drop across the DPF, and soot loading—acquired through the vehicle’s On-Board Diagnostics (OBD) system. This data is processed in the cloud using a dedicated algorithm to assess regeneration effectiveness and DPF condition in a robust manner. The processing can also be done over the edge on the installed OBD device itself if computational resources are available. Due to the nature of the algorithm, it can be run on the bare minimum of computational resources.

Our approach combines regeneration quantification with clogging level tracking to provide early warnings regarding overall DPF health [9]. The method is validated against diagnostic trouble codes (DTCs) generated by the engine control unit (ECU), demonstrating its potential for predictive maintenance and enhanced control strategies in diesel exhaust aftertreatment systems.

The remainder of this paper is structured as follows. Section II provides a brief overview of the DPF regeneration process. Section III details the OBD data acquisition methodology and the algorithm used for DPF monitoring. Section IV describes the alert generation framework. Finally, Section V presents conclusions and outlines directions for future work.

II. BACKGROUND AND MOTIVATION

A. DPF Regeneration

Diesel Particulate Filters (DPFs) operate by trapping soot from engine exhaust gases; however, due to their finite capacity, periodic regeneration is essential. The Engine Control Unit (ECU) periodically initiates regeneration events to oxidize the accumulated particulate matter (PM) and restore DPF functionality.

The rate of regeneration is primarily governed by the kinetics of soot oxidation, which strongly depends on exhaust temperature [10]. This relationship is illustrated in Fig. 1.

As shown, at lower temperature ranges (360°C to 400°C), the soot oxidation rate is relatively slow, resulting in incomplete removal of accumulated soot. In contrast, when the exhaust temperature exceeds 500°C, oxidation occurs rapidly and more completely. For commercial diesel engines, active regeneration typically raises the exhaust temperature to approximately 550°C to 600°C and sustains it for around 45 minutes to ensure effective soot removal.

B. Types of Regeneration

There are three main types of DPF regeneration: *Passive*, *Active*, and *Parked* regeneration. Each operates under different driving and engine conditions.

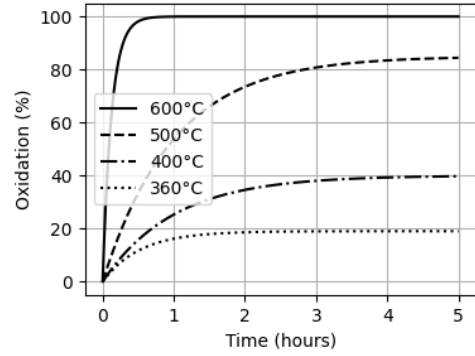


Fig. 1. Soot oxidation rate as a function of temperature [10].

- **Passive Regeneration:** This occurs automatically during normal driving when exhaust temperatures exceed 350°C, such as during steady highway operation. No additional fuel injection or ECU intervention is required. However, during frequent short trips or urban driving conditions, exhaust temperatures may not reach the required threshold, making passive regeneration insufficient.
- **Active Regeneration:** When soot accumulation exceeds a predefined threshold, the ECU triggers active regeneration by increasing exhaust temperature to between 500°C and 650°C. This is achieved by injecting additional fuel—either via post-injection during the exhaust stroke or directly into the DPF through a hydrocarbon dosing system. The combusted fuel generates the heat required to oxidize the trapped soot into ash, which is then expelled through the exhaust. The ECU monitors vehicle speed to ensure safe conditions for regeneration (e.g., above 40 km/h); interruptions such as frequent stops in city traffic can lead to incomplete regeneration cycles.
- **Parked (or Forced) Regeneration:** When passive and active regeneration are inadequate, a parked regeneration is performed—typically at a service center—using diagnostic tools to manually initiate the process while the vehicle remains stationary. This procedure requires careful monitoring to prevent thermal damage to the DPF.

III. SYSTEM OVERVIEW AND METHODOLOGY

This section describes the overall architecture and step-by-step methodology used to detect and quantify DPF regeneration events in diesel engines.

A. Data Acquisition

To detect and monitor the DPF events effectively, we collect multiple vehicle parameters in real-time through the On-Board Diagnostics (OBD) port. These mainly include differential pressure across the DPF, exhaust temperature, vehicle speed, engine Revolution Per Minute (RPM), and engine load etc. Data is collected and sampled at 8-second intervals using a proprietary hardware device (Intangles

Lab's product) and transmitted to the cloud for further processing. Differential pressure measured across the DPF gets affected by many other parameters other than soot clogging alone. Differential pressure measured across a fully clogged DPF will show less value if the engine is running at low speed and low load and vice versa. To handle this variations, we consider the differential pressure values only when the engine is running at the peak-torque rated RPM (specification given by manufacturers) and at sufficient engine load (above 30%).

B. Differential Pressure as a measure for particulate matter emission/Soot Load

Differential pressure can be used as a measure of the particulate matter trapped in the DPF [6]. The technique involves measuring the differential pressure across a DPF element that traps diesel particulate matter directly from the engine exhaust. As soot accumulates, it creates an obstruction in the exhaust flow, which results in an increase in differential pressure across the filter. There is a strong correlation between the DPF pressure drop and the levels of soot loading in DPF systems. Monitoring this pressure drop is crucial for maintaining engine efficiency, reducing fuel consumption, and preventing engine damage. When the ECU detects high differential pressure, it initiates a regeneration cycle. A successful regeneration process burns off soot and converts it to ash. This causes a noticeable drop in differential pressure. Figure 2 illustrates a typical example of a high differential pressure drop following effective regeneration.

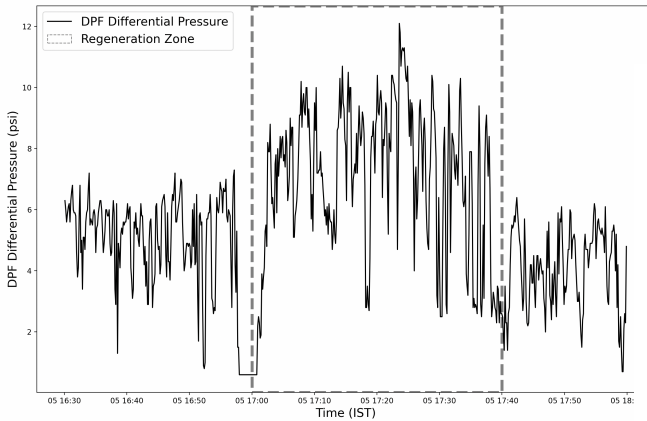


Fig. 2. High differential pressure drop due to good quality DPF regeneration

Various soot load estimation methods for DPFs have been reviewed in [2], [7], [5]. In particular, these methods emphasize the relationship between the pressure drop and the soot load. For regular cleaning of the DPF, the ECU keeps track of the differential pressure and initiates regeneration when a higher differential pressure is detected. If the regeneration process succeeds, the accumulated soot is burnt and converted to ash, causing a gradual drop in differential pressure. Similarly, if the regeneration process fails to burn

the accumulated soot, then the filtration efficiency of the DPF goes down. Figure 3 shows an example of insufficient differential pressure drop due to low-quality regeneration.

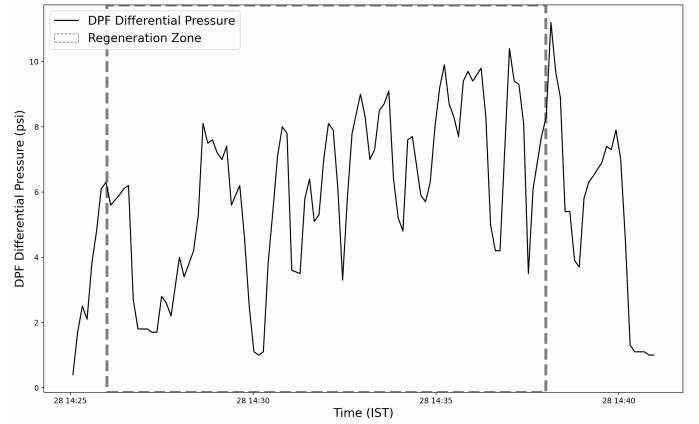


Fig. 3. Insufficient differential pressure drop due to low-quality DPF regeneration

The regeneration event is identified based on the input temperature conditions being met ($DPF\ InletTemperature > 500^{\circ}C$). Before the regeneration instance begins, the system records and stores 25 pressure measurements as the "pre-event pressure" by averaging 25 pressure samples collected. After the regeneration instance concludes, the system stores one or more pressure measurements as the "post-event pressure." Further processing is done based on the mean values of the pre and post pressure sample to avoid the noise in the data. The typical data acquired through the vehicle's OBD port is shown in Figure 4,

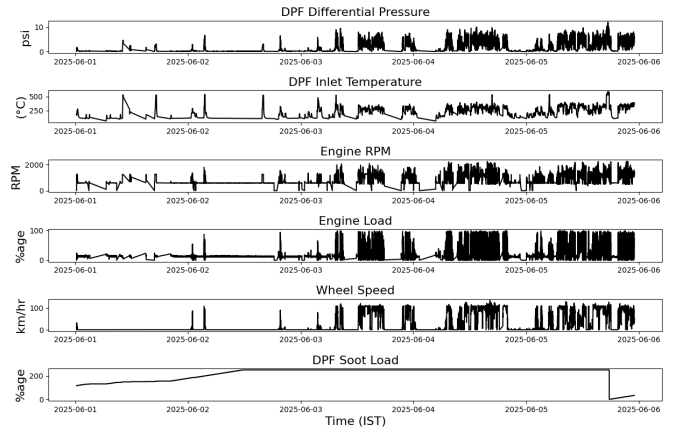


Fig. 4. On-Board Diagnostic Data

C. Proposed Algorithm

The proposed algorithm is designed to continuously monitor the differential pressure (ΔP) across the DPF and track the clogging and quantify each regeneration event using the novel Differential Pressure Drop Percentage ($DPDP$)

metric. This metric is calculated based on the drop in post-event pressure compared to the pre-event pressure. The algorithm details and use of the metric are as mentioned below.

- **Outlier Removal:** Remove differential pressure values above the 95th percentile and below the 5th percentile from both pre- and post-event buffers to eliminate outliers and noisy/saturated data.
- **Mean Calculation:** Compute the mean differential pressure from the buffer before regeneration, \bar{P}_{pre} , using N_{pre} samples, as

$$\bar{P}_{pre} = \frac{1}{N_{pre}} \sum_{i=1}^{N_{pre}} P_{pre,i}$$

and similarly, compute the mean differential pressure from the buffer after regeneration, \bar{P}_{post} , using N_{post} samples:

$$\bar{P}_{post} = \frac{1}{N_{post}} \sum_{i=1}^{N_{post}} P_{post,i}$$

- **Corner Case Handling:** Address mathematical corner cases (e.g., division by zero- In the case of a newly installed DPF or when a sensor issue occurs, we might encounter the \bar{P}_{pre} buffer having a value of zero.)
- **DPDP Calculation:** Calculate the Differential Pressure Drop Percentage (DPDP) as:

$$DPDP = \frac{\bar{P}_{pre} - \bar{P}_{post}}{\bar{P}_{pre}} \times 100$$

where \bar{P}_{pre} and \bar{P}_{post} are the mean differential pressures before and after regeneration, respectively.

- **Soot Burn Quality Assessment:** Soot burn quality is assessed using the below-mentioned criteria.
 - If $DPDP < -50$ (which means the post-regeneration pressure is double that of pre-regeneration pressure, i.e. $\bar{P}_{post} > 2\bar{P}_{pre}$), irrespective of the pre-regeneration pressure, assign soot burn as *Fail*.
 - If $\bar{P}_{pre} > DP_Level_1$ (where DP_Level_1 is the lower pressure threshold) and $DPDP < 0$, assign the soot burn as *Fail*.
 - Otherwise, compute the soot burn quality, Q_{burn} , as:

$$Q_{burn} = 1 - e^{-k \times DPDP/100}$$

Q_{burn} is designed to have values between 0 and 1; the value of k is to be chosen accordingly.

- **Why exponential scaling?**
 - The post regeneration mean pressure, \bar{P}_{post} , can never be practically zero, as a newly installed DPF has non zero pressure drop for optimal filtering.
 - There is an upper limit for pre-regeneration mean pressure, \bar{P}_{pre} . It is bounded by the threshold for active regeneration (e.g., 4 psi for engines of 2000–8000 cc engine). Active regeneration starts beyond this threshold.

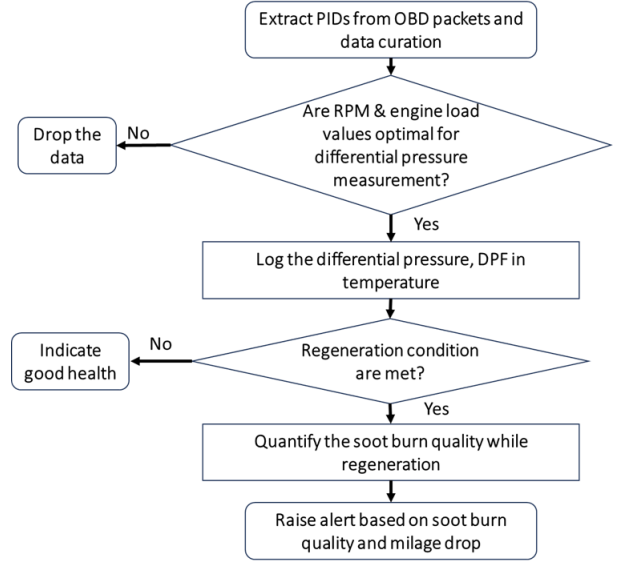


Fig. 5. Flow Chart of the Proposed Algorithm

TABLE I
SOOT BURN QUALITY MAPPING BASED ON DPDP VALUE

Sr No.	DPDP Value	Burn Quality (%)	Label
1	0 – 33	0 – 33	Low
2	33 – 66	33 – 66	Medium
3	66 – 100	66 – 100	High
4	< 0	NA	Failed

- Above two condition limits the Relative fall in differential pressure range.
- To compensate for this, exponential scaling is used to map the relative fall in differential pressure to a [0, 1] range for consistency assessment.

The overall flow of the proposed algorithm is illustrated in Figure 5. The quantification of the soot burn quality assessed by the proposed algorithm is tabulated in Table I.

D. Alert Logic

The alert logic utilizes both the current mean post-regeneration differential pressure (\bar{P}_{post}) and the calculated soot burn quality (Q_{burn}) to determine maintenance alerts. The thresholds DP_Level_1 , DP_Level_2 , DP_Level_3 , and DP_Level_4 correspond to increasing levels of differential pressure that trigger alert escalation.

As an illustrative example, for engines in the 12000–15000 CC(Cubic Centimeter) displacement range operating between 1000–2200 rpm, four differential pressure levels were defined to categorize soot accumulation severity. The thresholds were set at $DP_Level_1 = 5$, $DP_Level_2 = 6$, $DP_Level_3 = 7$, and $DP_Level_4 = 8$ psi. Higher DP levels correspond to increased exhaust backpressure and a greater likelihood of DPF regeneration failure or clogging.

The alert-generation logic proceeds as follows

- Initialize the alert value to -1 by default. Which means hold on to the previous state unless the below logic changes any state (no alert).
- At the the algorithm entry level, if $\bar{P}_{\text{post}} > DP_Level_4$ (high threshold), raise a **Major alert**.
- If $DP_Level_3 < \bar{P}_{\text{post}} \leq DP_Level_4$, (medium to high threshold), a **Minor alert** is raised.
- If it Q_{burn} is classified as *Fail* and $DP_Level_2 < \bar{P}_{\text{post}} \leq DP_Level_3$, raise a **Minor alert**.
- If Q_{burn} is classified as *Fail* and $\bar{P}_{\text{post}} > DP_Level_3$, raise a **Major alert**.
- If $\bar{P}_{\text{post}} < DP_Level_1$, (low threshold), any existing alert is cleared.

The validation of the alerts generated by the proposed algorithm has been matched by comparing respective events of Diagnostic Trouble Codes (DTCs) raised by the ECU.

IV. RESULTS AND DISCUSSION

This work presents a novel algorithm for quantification and prediction of DPF regeneration and clogging using differential pressure data. To the best of our knowledge, no comparable methods have been found in literature for benchmarking. Therefore, the results and predictions of the proposed algorithm are validated using Diagnostic Trouble Codes (DTCs) provided by the ECU, which demonstrates its effectiveness in real-world applications. Figures 6a, 6b, 6c illustrates representative examples of DPF regeneration events characterized by high, low, and medium burn quality, respectively, occurring at different time intervals.

- Fig. 6b depicts a regeneration event with low burn quality, lasting 26 minutes and exhibiting a burn quality of 10%.
- Fig. 6c shows a medium-quality regeneration lasting 50 minutes with a burn quality of 47%.
- Fig. 6a presents a high-quality regeneration event, lasting 38 minutes, with a burn quality of 84%.

It has been observed that low and medium burn-quality regenerations typically occur when the vehicle operates at insufficient speeds, generally below approximately 40 Km/h, and when the regeneration duration is shorter than 15 minutes. These conditions are inadequate for achieving optimal burn quality during DPF regeneration.

It has also been observed that multiple failed quantified regeneration events are often followed by DPF clogging-related DTCs. These DTCs typically follow up approximately 10 to 15 hours after the failed regeneration events, thereby demonstrating the predictive capability of the proposed soot load quantification algorithm in anticipating potential DPF clogging issues. As illustrated in Fig. 7, two consecutive failed regeneration events are followed by two high soot load-associated DTCs with a lead time of approximately 10 hours.

Table 2 summarizes all Diagnostic Trouble Codes (DTCs) recorded between April and June 2025 from six vehicles. Most of the observed fault codes were associated with Diesel Particulate Filter (DPF) malfunctions, including repeated

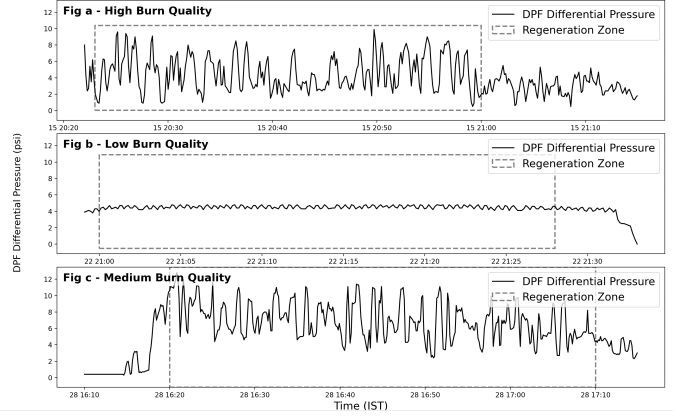


Fig. 6. Burn quality captured as (a) High, (b) Low, and (c) Medium.

instances of soot accumulation (P24A4), efficiency reduction (P2002), and sensor circuit faults (P2452, P24B0). Notably, these DTCs were consistently preceded by predictive alerts labeled “DPF High Differential Pressure”, which occurred after several failed or low-quality soot burn attempts as measured by the DPDP metric. This correlation shows that DPDP can effectively predicts soot load accumulation and potential DPF clogging issues in advance.

Apart from the suggested DPDP metric, the other metric utilized is the OEM-specific 3719 soot load signal. The signal 3719 is a derived quantity and is a function of multiple parameters such as engine RPM, engine load, differential pressure, and other physical parameters; meaning the drop or rise depicted in the signal may not be completely due to soot formation but might be due to rise and fall in other parameters. Therefore, the actual clogging might be higher and lower than that indicated by the 3719 signal. In these cases, DPDP provides more reliable quantifier for soot load. Additionally, 3719 is a proprietary signal that could or may not be readily available from all OEMs. The Sootload 3719 signal has a dynamic range from 0 to 250%, with 100% being the threshold at which regeneration ideally initiates. As shown in Fig. 8, the first regeneration shows a drop from 231% soot-load to nearly 0%, while the second shows a drop from 32% to 0%. The corresponding burn quality percentages are quantified as 90% and 48%, respectively. Overall, the DPDP metric offers a more direct and consistent assessment of soot accumulation, making it a valuable tool for real-time DPF health monitoring and early fault detection.

V. CONCLUSION

In this paper, a method is proposed to quantify the DPF regeneration using the differential pressure drop across the DPF caused by soot burn along with a way to monitor the DPF health in real time.

Conclusions can be drawn: (1) Differential pressure across DPF can be used to monitor the health of DPF. (2) Quantification of the regeneration event along with continuous differential pressure tracking helps in predicting the DTCs.

TABLE II
PREDICTED ALERTS VALIDATION WITH DIAGNOSTIC TROUBLE CODES (DTCs)

Predicted DPF Alert Time	DTC Code + Description	DTC Time
Apr 18th 2025 11:52 am	P24A4 - Diesel Particulate Filter Restriction – Soot Accumulation Too High	Apr 19th 2025, 6:09:29 am
	P2452 - Diesel Particulate Filter Pressure Sensor A Circuit	May 6th 2025, 7:12:49 am
Apr 29th 2025 9:54:52 am	P2002 - Diesel Particulate Filter Efficiency Below Threshold Bank 1	May 1st 2025, 5:51:51 pm
	P2452 - Diesel Particulate Filter Pressure Sensor A Circuit	May 13th 2025, 2:56:02 pm
	P244B - Diesel Particulate Filter (Dpf) Differential Pressure Too High	May 13th 2025, 3:50:48 pm
Apr 18th 2025 09:46:38 am	P24B0 - Particulate Matter Sensor Circuit Low	Apr 26th 2025, 4:23:26 am
	P2452 - Diesel Particulate Filter Pressure Sensor A Circuit	Apr 28th 2025, 3:58:00 pm
	P244B - Diesel Particulate Filter (Dpf) Differential Pressure Too High	May 29th 2025, 7:56:12 am
Apr 28th 2025 4:22:35 pm	P2458 - Diesel Particulate Filter Regeneration Duration	May 30th 2025, 10:38:28 am
Apr 29th 2025 12:05:36 am	P24B0 - Particulate Matter Sensor Circuit Low	Apr 29th 2025, 12:19:38 pm
	P2002 - Diesel Particulate Filter Efficiency Below Threshold Bank 1	May 3rd 2025, 9:58:54 am
	P2458 - Diesel Particulate Filter Regeneration Duration	May 7th 2025, 8:09:13 am
Jun 18th 2025 3:48:16 pm	P2458 - Diesel Particulate Filter Regeneration Duration	Jun 21st 2025, 6:01:45 am
	P2452 - Diesel Particulate Filter Pressure Sensor A Circuit	Jun 21st 2025, 7:33:46 am
	P2002 - Diesel Particulate Filter Efficiency Below Threshold Bank 1	Jun 21st 2025, 11:14:10 am
	P24A4 - Diesel Particulate Filter Restriction – Soot Accumulation Too High	Jun 27th 2025, 3:21:23 pm
	P2459 - Diesel Particulate Filter Regeneration Frequency Bank 1	Jun 29th 2025, 5:59:02 pm

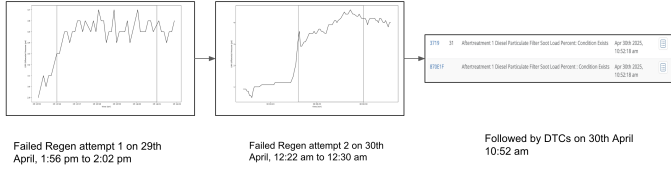


Fig. 7. Multiple Failed Regeneration Events followed by DPF Soot Load associated DTCs

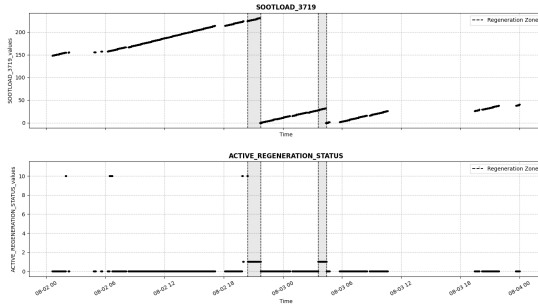


Fig. 8. Drop depicted by Sootload 3719 signal- the first regeneration shows a drop from 231% soot-load to almost 0% soot load, similarly the second regeneration event shows a drop from 32% to 0%. The burn quality percentage quantified by the methodology suggested is 90% and 48% respectively

(3) The proposed algorithm works in a streaming manner and hence monitors DPF health in real time.

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