4.3.2. O-MIT-02 – Model-based development and optimisation of retrofit solutions for exhaust emissions control

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Abstract

Urban air quality remains a critical challenge in modern societies with the urban vehicle fleets being the primary sources of pollution. Retrofitting these fleets could significantly contribute to air quality improvement. This study presents a systematic methodology for developing retrofit solutions, aiming to reduce solid particle number (SPN) emissions from urban fleet vehicles not already equipped with a particulate filter. The approach integrates extensive experimental testing to support model development for various candidate particulate filter technologies and coatings. The developed models are utilized for model-assisted design and optimisation of retrofit solutions through parametric analysis tailored to different vehicle types.

A detailed case study on a Euro 6d Skoda Octavia CNG presents the application of the methodology aiming to develop optimized coated GPF (cGPF) configurations that achieve at least 90% filtration efficiency with acceptable engine backpressure. Additionally, experimental results confirmed that engine backpressure is not increased significantly, ensuring a stable operation of the exhaust aftertreatment system. Overall, the proposed methodology is time- and resource- efficient requiring minimal testing and it can be applicable to fleet level.

Introduction

Air pollution and climate change constitute a critical challenge for modern societies, posing critical risks to public health. Despite recent advancements in vehicle electrification, a significant proportion of the global vehicle fleet is expected to remain dependent on internal combustion engines for the foreseeable future (Möring-Martínez et al., 2025). The emissions released from the vehicles continue to be a major contributor to air quality degradation, especially in urban areas. In this context, the deployment of retrofit technologies that can effectively reduce the pollutant emissions from in-use vehicles can significantly support the transition toward cleaner transportation. Considering particulate matter, a significant portion of ultrafine particles derive from on-road vehicles (Ricarte et al., 2025). Although diesel engines are the main emitters, CNG and gasoline engines are also emitting considerable portions of particulate matter, that needs to be mitigated. Additionally, NO_x emissions are posing significant risks for public health as they are related to respiratory inflammation and cardiovascular issues. (Taha, 2025; Zhang, 2018).

The aim of this study is to develop a systematic model-based methodology for developing and optimizing tailpipe retrofit solutions for vehicles that are operating in urban areas and are not equipped with particulate filter, aiming for at least 90% reduction of the regulated SPN10 parameter, eliminating the need for extended testing. A GPF technology was chosen as the most appropriate solution to control particulate emissions. In this respect, an extended testing campaign was performed to assess the filtration efficiency and the pressure drop of different GPF technologies with different coatings, under various operating conditions, both on engine test bench and on the vehicle. Based on the acquired experimental data, precise models predicting the filtration efficiency and the pressure drop of the cGPFs were developed. By testing a wide range of filters with different coatings, a comprehensive library of models for various technologies was created. The target vehicles were tested to determine their raw emissions and utilizing the developed models, the most appropriate retrofit solution was model-based designed and optimized based on the restrictions of every application. This study is mainly focused on the SPN10 reduction of passenger cars.

Methodology

The aim of this study is to develop retrofit solution for urban fleet vehicles not equipped with a particulate filter, running high mileage in city environments. The retrofit development methodology integrates both experimental and model-based methods aiming to control SPN10. Initially, the vehicles are tested to establish their baseline tailpipe emissions and to identify potential existing constraints that may affect retrofit implementation. Subsequently, potential retrofit devices are considered, and their experimental testing is performed. The experimental procedures are primarily focused on characterising the filters and their coatings, in terms of filtration efficiency, pressure drop and catalytic activity. The acquired data are utilized to support the model development of the different components.

The development and the optimization of the retrofit solution rely on an iterative model-assisted approach. More specifically, retrofit concepts are formulated by selecting one or more of the tested and modelled components. Their performance is evaluated, with the vehicle's baseline tailpipe emissions serving as input data. Following the initial assessment of each concept, further model-based optimisation of the system is carried out. In this way, a complete retrofit system is designed without the need for time- and resource-consuming experimental testing. Once the final configuration of the system is determined, it is developed and installed on the vehicle to validate the model-based predictions.

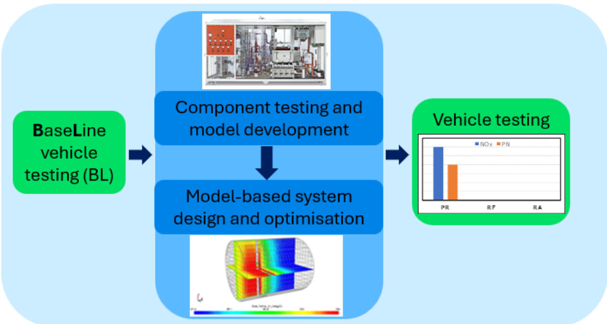


Figure1: Methodology of retrofit design and optimisation for a specific application

Experimental Specifications

A passenger car (PC), a light commercial vehicle (LCV) and a heavy-duty vehicle (HDV) are selected, corresponding to taxi, delivery van and urban bus applications, respectively. The vehicle specifications are summarized in Table and the PC and the LCV are depicted in figure 2.

Table 1: Specifications of vehicle applications

	HDV	LCV	PC
Application	Urban bus	Citroen Berlingo	Skoda Octavia
Engine Displacement (L)	7.7	1.6	1.5
Euro Emissions Standard	Euro 6b	Euro 6b	Euro 6d
Original Exhaust Aftertreatment System	ccTWC+uTWC	ccTWC	ccTWC+uTWC
Fuel	CNG	Gasoline	CNG & Gasoline

Figure 2: Vehicle Applications, the Citroen Berlingo (left side) and the Skoda Octavia (right side)

Experimental measurements at the chassis-dynamometer were performed for each vehicle application. Specifically, parameters such as mass flow rate, temperatures, gaseous emissions, particle emissions and other relevant data were recorded at engine out, downstream of the close-coupled three-way catalyst (ccTWC) and downstream of the underfloor TWC (uTWC) position. Thus, every vehicle was comprehensively characterised in terms of emission targets, while all necessary data for model-based retrofit development were recorded. At the same time, important constraints including spatial limitations, operating temperature range, and allowable pressure drop were also defined.

Aiming to achieve the SPN10 emissions reduction target, a particulate filter is utilized to control particle emissions for all applications. To additionally control NO_x emissions, GPFs with catalytic coatings were preferred over bare samples. The samples are presented in Table 2.

- ✓ HDV application: different TWC coating, composed of platinum (Pt), rhodium (Rh) and palladium (Pd) were selected. 5 different coatings with varying Pd/Pt/Rh ratio and different washcoat loadings were examined, aiming to achieve high filtration efficiency and promote NOx control.
- ✓ PC and LCV application: the coating is mainly composed of copper (Cu) and additionally contains Pd and Rh. Cu was used to control the cost of the retrofit system. The coating type applied was in-wall or in- and on-wall aiming to maximize filtration efficiency.

Table 2: Retrofit technologies examined specifications

Application	Retrofit technologies	Coating Type	Dimensions
HDV	cGPF	In-wall Pt/Pd/Rh TWC	DxL=241.3x127mm, 300cpsi/9mils
LCV	cGPF	In- and on-wall Cu/Pt/Pd TWC	DxL=118.7x127.3mm, 300cpsi/9mils

PC	cGPF	In-wall Pt/Pd TWC	DxL= 143.8x152.4mm, 300cpsi/9mils
		In- and on-wall Cu/Pt/Pd TWC	DxL= 118.1x127.8mm, 300cpsi/9mils

The cGPFs were evaluated at the Synthetic Gas Bench (SGB) and the Engine Test Bench (ETB), to assess their performance regarding filtration efficiency, pressure drop and catalytic activity. The applied testing protocols aim to filtration efficiency, pressure drop and catalytic activity characterisation and support of the modelling procedures (Bollerhoff et al., 2012; Koltsakis et al., 1997).

Experimental Facilities

- ✓ Engine Test Bench

The ETB experiments were conducted at a 2l gasoline engine equipped with a TWC, placed upstream of the tested samples. The main species CO, CO_2, H_2O, CH_4, C_3H_6, THC, NO, NH_3, N_2O, NO, O_2 were measured with an AVL Sesam i60 FT gas analyser (AVL, 2017). The SPN10 concentration, the pressure drop, the mass flow rate and temperatures were recorded upstream and downstream of the sample.

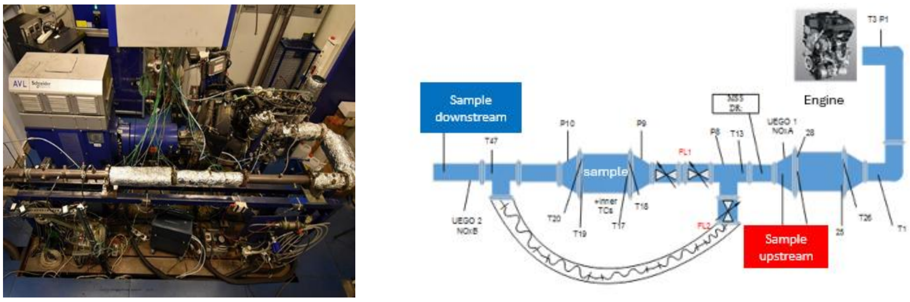


Figure 3: Engine test bench layout

- ✓ Vehicle Testing

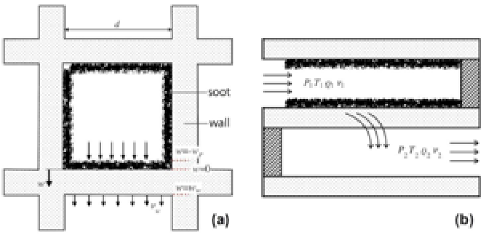
The vehicle testing was performed on a chassis dynamometer, under controlled laboratory conditions to define the pre- and post- retrofit emissions of the vehicle, as shown at Figure 4. The main gaseous and particle emissions were measured at engine out, between the existing TWCs and tailpipe position in both baseline and post-retrofit configurations. The processing of the measurements was conducted using the Concerto 5 with AVL Data Toolbox 2 (AVL, 2016)

Figure 4: Chassis dynamometer facilities at Laboratory of Applied Thermodynamics

Model Development

The modelling procedures were conducted in the environment of the commercial software Exothermia Suite. More specifically, physico-chemical models capable of predicting emissions conversion efficiency, soot filtration efficiency, pressure drop and thermal behaviour within an exhaust aftertreatment system were developed. The models incorporate tunable parameters, which are determined based on experimental data. The data originate from experimental campaigns including various protocols designed to decouple the complex phenomena that occur inside the aftertreatment devices, thereby facilitating the calibration process. The validation of the model is based on ETB transient cycles.

The main wall-through equations for mass, momentum, energy and species balance are presented in Figure , while further details can be found at Exothermia Suite user guide (Exothermia Suite, 2025; Karamitros et al., 2014).



Energy Balance

Gas phase (inlet channel): $C_{p,g}\rho_1 v_1\big|_z \frac{\partial T_1}{\partial z} = h_1 \frac{4}{d_1}(T_s - T_1)$

Gas phase (outlet channel): $C_{p,g}\rho_2 v_2\big|_z \frac{\partial T_2}{\partial z} = \left(h_2 + C_{p,g}\rho_w v_w\right)\frac{4}{d}(T_s - T_2)$

Solid phase: $\rho_s \cdot C_{p,s}\frac{\partial T_s}{\partial t} = \lambda_{s,z}\frac{\partial^2 T_s}{\partial z^2} + H_{conv} + H_{wall} + H_{react}$

Species Balance

$$v_w \frac{\partial y_j}{\partial w} - D_{w,j}\frac{\partial}{\partial w}\left(f_w \frac{\partial y_j}{\partial w}\right) = \frac{f_w}{c_m}\sum_k n_{j,k} R_k$$

Mass Balance

$$\frac{\partial}{\partial z}\left(d_i^2 \rho_i v_i\right) = (-1)^i \cdot 4 d \rho_w v_w$$

Axial Momentum Balance

$$\frac{\partial p_i}{\partial z} + \frac{\partial}{\partial z}\left(\rho_i v_i^2\right) = -\alpha_1 \mu v_i / d_i^2$$

Figure 5: Main wall-through model equations for mass, momentum, energy and species balance. (Karamitros et al, 2014)

<u>Passenger Car Application – cGPF model accuracy</u>

The accuracy of the cGPF model was evaluated based on a cold-start worldwide harmonized light-duty test cycle (WLTC). Figure 6Figure presents both the experimental and simulated SPN10 emissions upstream and downstream of the cGPF, at vehicle's tailpipe position. The top graph depicts the overall comparison, while the bottom graph provides a zoomed-in view of the outlet emissions, demonstrating that the model prediction remains within a 15% deviation from the experimental data. As expected, a significant amount of SPN10 emissions were emitted during the initial phase of the cycle (cold start), however the filter can efficiently capture these emissions, achieving approximately 93% filtration efficiency. The model can accurately replicate the experimental trends, providing accurate prediction and supporting the model-assisted design of the retrofit system.

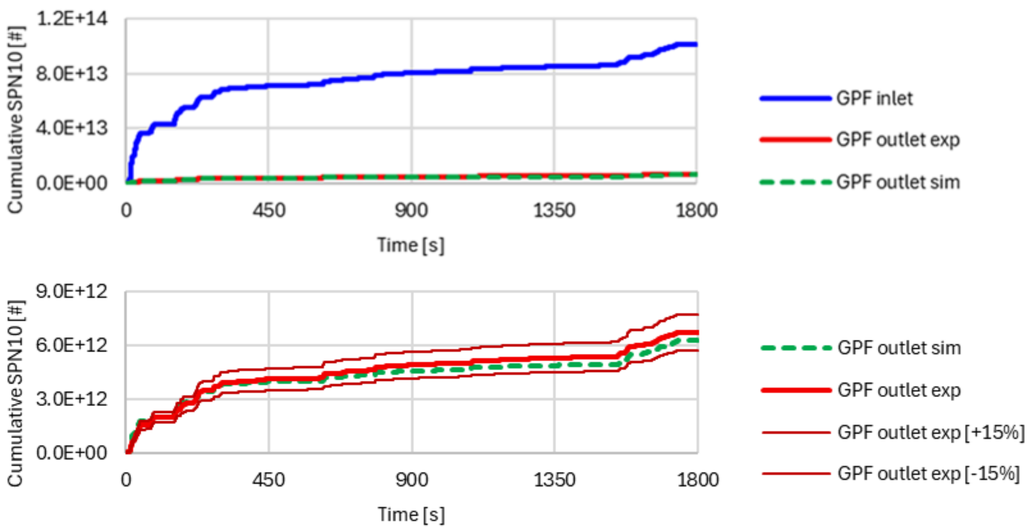


Figure 6: Accuracy of cumulative SPN10 emissions prediction for the reference cGPF at cold WLTC performed at ETB.

Figure 7 illustrates the experimental results and the model predictions for the pressure drop across the cGPF during a cold WLTC cycle. The model can effectively capture the experimental trends of the dynamic pressure drop variation throughout the cycle, providing a strong validation of its accuracy.

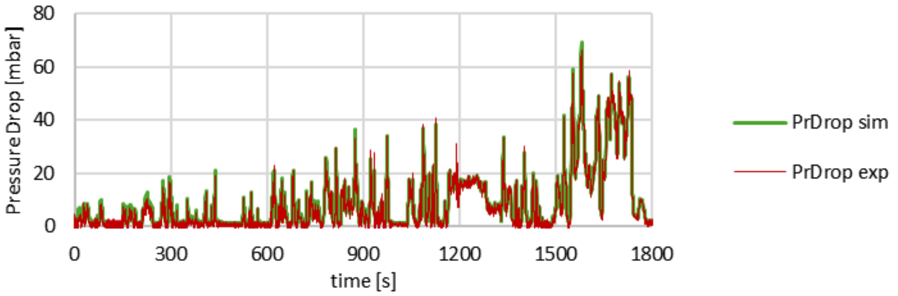


Figure 7: Model accuracy of pressure drop prediction at a cold WLTC performed at ETB

Results and Discussion

Vehicle baseline measurement

The proposed methodology was utilised to develop a retrofit system for controlling SPN10 emissions in a passenger car (Skoda Octavia). The vehicle was tested at the chassis-dyno to define its target emissions. Figure 8 illustrates the tailpipe SPN10 emissions from a cold-start WLTC cycle, using CNG as a fuel on Skoda Octavia application.

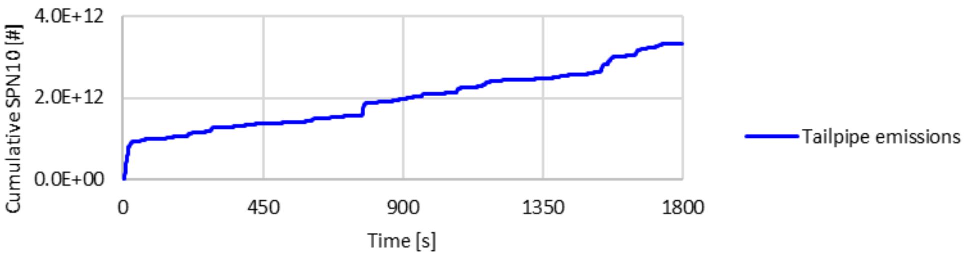


Figure 8: PC (Skoda Octavia) tailpipe SPN10 cumulative emissions for a cold-start WLTC cycle, using CNG as fuel

Retrofit system development

A coated GPF was selected as the most appropriate retrofit solution, with a Cu-based TWC coating, applied both in- and on-wall of the filter. Although the coating is added for catalytic activity purposes, it significantly influences filtration efficiency and pressure drop performance (Belot et al., 2020).

Taking into consideration the vehicle spatial constraints and preferring not to influence the already existing TWCs, the cGPF is positioned downstream of the underfloor TWC, as shown in Figure 9.

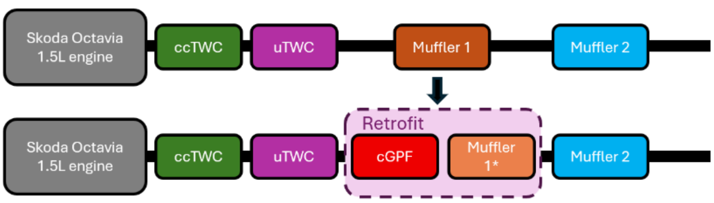


Figure 9: Retrofit system position on Skoda Octavia exhaust line

An initial reference sample of the cGPF was designed and its properties are summarised in Table 3.

Table 3: Properties of the reference cGPF for the Skoda Octavia application

Properties	cGPF	Properties	cGPF
Cell Density [cpsi]	300	Diameter [mm/in]	118 / 4.66
Wall Thickness [mils]	9	Length [mm/in]	175 / 5.00
Washcoat type	Cu-based TWC		

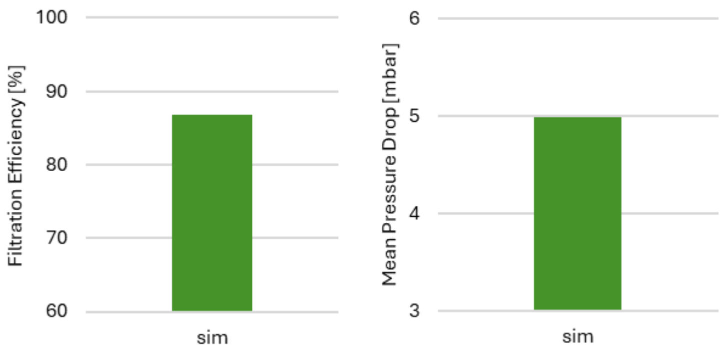


Figure 10: Model prediction of filtration efficiency and pressure drop at a cold CNG WLTC on Skoda Octavia

The configuration of the reference sample is included in the model-based approach and, by utilizing the developed model of the cGPF, its performance was predicted for the Skoda Octavia and specifically for a cold-start WLTC cycle, using CNG as a fuel. As presented in Figure 10, the reference sample is expected to achieve 87% filtration efficiency and reach mean pressure drop of 5 mbar, values close to the desired targets.

The reference sample was developed, installed and tested on the vehicle under various transient cycles to evaluate its on-vehicle performance and validate the accuracy of the developed model. Figure 11 depicts both experimental results and model predictions for filtration efficiency (left) and pressure drop (right) during a cold WLTC, using CNG as a fuel. As shown, the experimentally observed filtration efficiency was approximately 85%. The model can effectively predict experimental behaviour. Minor deviations between experimental data and simulation are in an acceptable range and may be caused by assumptions such as uniform washcoat distribution. Regarding pressure drop, the model can accurately predict the mean pressure drop of the WLTC, supporting a confident prediction of the pressure, a critical factor that can influence the overall system performance.

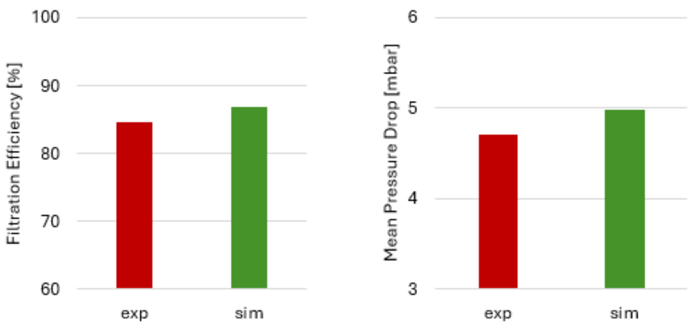


Figure 11: Experimental results and model prediction of filtration efficiency and pressure drop at a cold CNG WLTC on Skoda Octavia

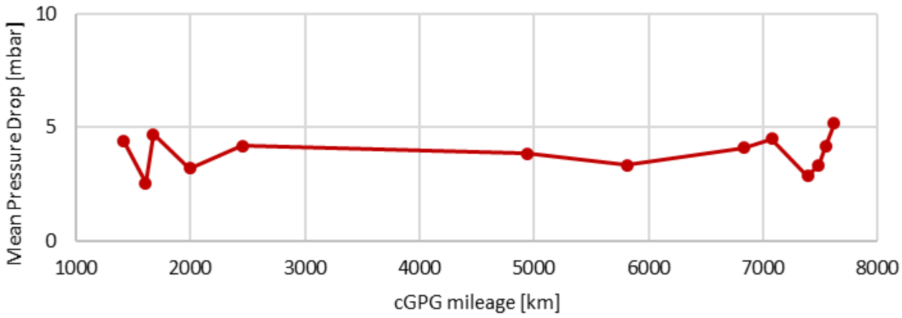


Figure 12: Mean pressure drop evolution at a cold WLTC CNG cycle on Skoda Octavia

During the testing campaign, the vehicle operated with the retrofit system for around 7500km. The cGPF pressure drop was recorded throughout the testing, thus the evolution of mean pressure drop per cycle was recorded as a function of the accumulated mileage. In Figure 12, the mean pressure drop that was recorded at various cold WLTCs is reported as a function of driven distance. As shown, no noticeable increase in pressure drop was observed, indicating that there is no soot or ash accumulation that could possibly impact the performance of the cGPF (Tan et al., 2023).

Optimisation of the retrofit system

As presented at Figure 11, the configuration of the reference sample is not able to reach the 90% target for the SPN10 filtration efficiency, because of the particle distribution and the low SPN10 emissions, thus a parametric analysis is conducted, to discover different cGPF configurations that can reach the desired target. The baseline measurements from cold CNG WLTC of the vehicle were utilised as inputs for the modelling process. The filtration efficiency and mean pressure drop of the cGPF were assessed as function of the volume and the wall thickness. The effect of the length was investigated while maintaining the diameter constant at the maximum allowable value (4.66 inches), based on the available packaging space on the vehicle.

Figure 13 depicts filtration efficiency and pressure drop for different cGPF configurations that vary in length and wall thickness. Increase of the filter length leads to higher filtration efficiency, while it causes a slight increase in pressure drop. Similarly, increasing the wall thickness is increasing the filtration efficiency, however it is significantly contributing to pressure drop rise. Notably, as wall thickness increases, the necessary length for achieving the target 90% is reduced.

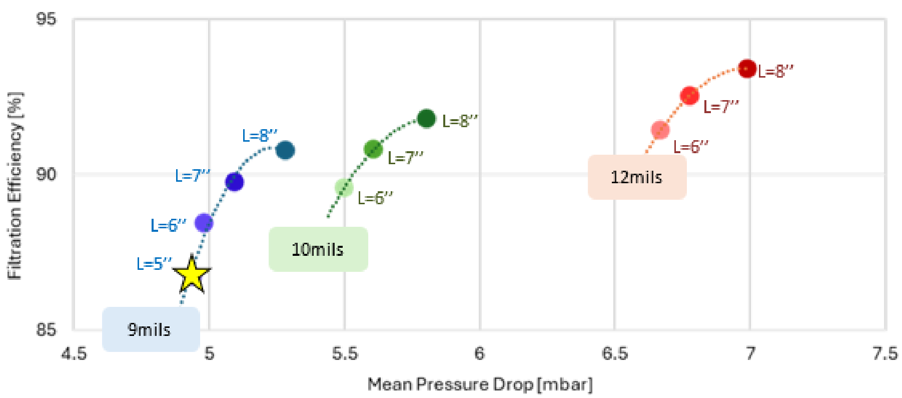


Figure 13: Wall thickness and length impact on pressure drop and filtration efficiency at Skoda Octavia cold WLTC CNG (D=118mm, cell density=300cpsi). The star refers to the reference sample.

The results indicate that the target filtration efficiency can be reached through different GPF configurations. The final determination of the cGPF must also consider the catalytic coating and the gaseous emissions reduction target. Variation in the cell density and the wall thickness affect the amount of the coating that can be impregnated or positioned on the wall, thus it will affect the reduction of the NOx, as NOx reduction is directly related to the washcoat loading (Tan, 2023).

Conclusion and Future Work

This study proposes a systematic, model-assisted methodology for the development and optimization of retrofit solutions aiming at significant reduction of emissions from urban vehicle fleet, such as PCs, LCVs and HDVs. More specifically, the approach targets at least 90% reduction of SPN10 and simultaneously at least 50% reduction of NOx emissions. The methodology presented relies on a library of models for different technologies of filters and coatings, which was developed through extensive experimental testing. The library is the key tool for the model-assisted design of the retrofit solutions for various vehicles, considering all the constraints of the vehicle.

The developed methodology was successfully applied to a passenger car case study, resulting in the design of different cGPF configurations, able to achieve the desired SPN10 reduction. Additionally, the evolution of the pressure drop of the cGPF was recorded experimentally, with results indicating no increase due to soot or ash accumulation. The study additionally focuses on keeping the pressure drop at considerable levels to avoid adverse effects on engine operation and fuel consumption. By combining the experimental testing for the model development and the model-assisted design and optimization of the retrofit system, the presented methodology is substantially time- and cost-efficient and, additionally, it can be smoothly applied to fleet-level applications.

Future work will incorporate simultaneous SPN10 and NOx emissions control. Additionally, the impact of soot and ash accumulation will be assessed by applying a model-based approach across high range of vehicle mileage with the retrofit.

Acknowledgements

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Abbreviations

Abbreviation	Full Term
ASC	Ammonia Slip Catalyst
ccTWC	Close coupled Three Way Catalyst
cGPF	Coated Gasoline Particulate Filter
CNG	Compressed Natural Gas
ETB	Engine Test Bench
GPF	Gasoline Particulate Filter
HDV	Heavy Duty Vehicle
LCV	Light Commercial Vehicle
LNT	Lean NOx Trap
PC	Passenger Car
Pd	Palladium
Pt	Platinum
Rh	Rhodium
SCR	Selective Catalytic Reduction
SGB	Synthetic Gas Bench
SPN	Solid Particle Number
TWC	Three Way Catalyst
uTWC	Underfloor Three Way Catalyst
WLTC	Worldwide Harmonized light-duty Test Cycle