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After treatment systems catalyst zone coating

Technical and economical analysis of a cost cutting innovative solution for industrial internal combustion engines

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Abstract

Development of after-treatment systems for Industrial application has been critical in last decades, whereas worldwide regulations have been tightened. In this study a technical and economical analysis of the zone coating technology for the three-way catalyst has been conducted in Iveco group FPT Industrial ATS Purchasing team, in order to develop after-treatment solutions for CNG heavy-duty engines. The need to be compliant with more stringent environmental regulations must be matched with cost reduction activities pursuing due to recent years increase of catalyst PGM market prices. FPT Industrial position and its ATS Platform workflow strategy is crucial, in a scenario of new technologies phase-in (Battery Electric vehicles and Fuel-Cell Electric Vehicles) and emissions regulations improvement. Effects of three-way catalyst axial coat zoning, coating formulation implementation, washcoat composition and Platinum Group Metals loading are considered. Technical and economical evaluation within FPT Industrial ATS Purchasing team are showed, by relating to a CNG heavy-duty Euro VI step E2 application.

Contents

Introduction

The work reported in this thesis is the result of months of activities in Advance Purchasing team of FPT Industrial After-treatment systems (ATS) Platform. The technology analysed in both technical and economic aspects is the axial zone coating of catalysts for industrial heavy-duty application. The project was born within the ATS Platform in an optic of cost reduction activity for the up-coming Euro VI step E2 regulations tightening for CNG engines. I did look for and appreciate the possibility to work for a multinational designer and manufacturer of transmissions, e-transmissions, axles, diesel and CNG engines within the on-road and off-road vehicles sectors. Moreover, the practical application on on-road heavy-duty vehicles manufacturing emphasizes the importance of this study and the technology in object (whose particularity is to be unique in the world in its implementation for industrial CNG engines) in a scenario of climate crisis and new alternative technologies where still it is important to develop internal combustion engine pollutant reduction capabilities. To complete the picture, the shocking increasing trend of raw materials precious metals prices makes the feature in study crucial for the manufacturing and industrial economic standpoint. Original Equipment Manufacturers will over and over increase their effort to develop enabling solution to being environmental and legislation compliant and economically efficient as much as possible. All of that was guideline to the author while developing the study. To summarize, the content of this work paper will range between the panoramic of Iveco Group and FPT Industrial brands, a literature and internal company analysis of the future share of internal combustion engines vehicles within industrial sector, followed by an overview of all after-treatment systems solutions and architectures in automotive and industrial field under a technical viewpoint. The technical analysis is completed by explaining how these features are implemented and worked out in the ATS Platform in FPT Industrial and what the zone coating really is in both technical literature view and practical application for FPT Industrial on-road CNG engines dedicate to Euro VI E2 heavy-duty vehicles. Finally, since the project represents a cost reduction activity, an economical analysis is made starting from the Platinum Group Metal market behaviour deep view and by implementing all concept learned within the ATS Platform into an economic indication of zone coating impact for a manufacturer application like this.

Chapter 1 - FPT Industrial

1.1 Brand overview

FPT Industrial is a brand of Iveco group, dedicated to design, production, sales and after-sales of powertrains and transmissions/axles for industrial on-road, off-road, marine and power generator applications. The Brand was born in 2011, by former Fiat Group split with Fiat Industrial, that collected all industrial and marine sector applications. Later in 2013 Fiat Industrial merged with CNH Global to form CNH Industrial. From 1st January 2022, with the split from CNH Industrial of all activities related to bus and industrial vehicles, newform Iveco group holds FPT Industrial alongside other Iveco group brands:

- Iveco
- Iveco bus
- Iveco Capital
- Iveco Defence Vehicles
- Heuliez Bus
- Astra
- Magirus

Figure 1 – Iveco group brand panoramic

With overall 8 Brands, 28 plants, 29 R&D centers, and 34.000 employees, Iveco group is a multinational across the full range of commercial and specialty vehicles, complete powertrain offering, a global leader in the transport and commercial vehicle industries, serving different customers around the world. Product range includes Light, Medium and Heavy Commercial Vehicles, Powertrains, Buses, Financial Services, Specialty Vehicles.

Figure 2 - IVECO Group logo – 2019 [*ivecogroup.com]*

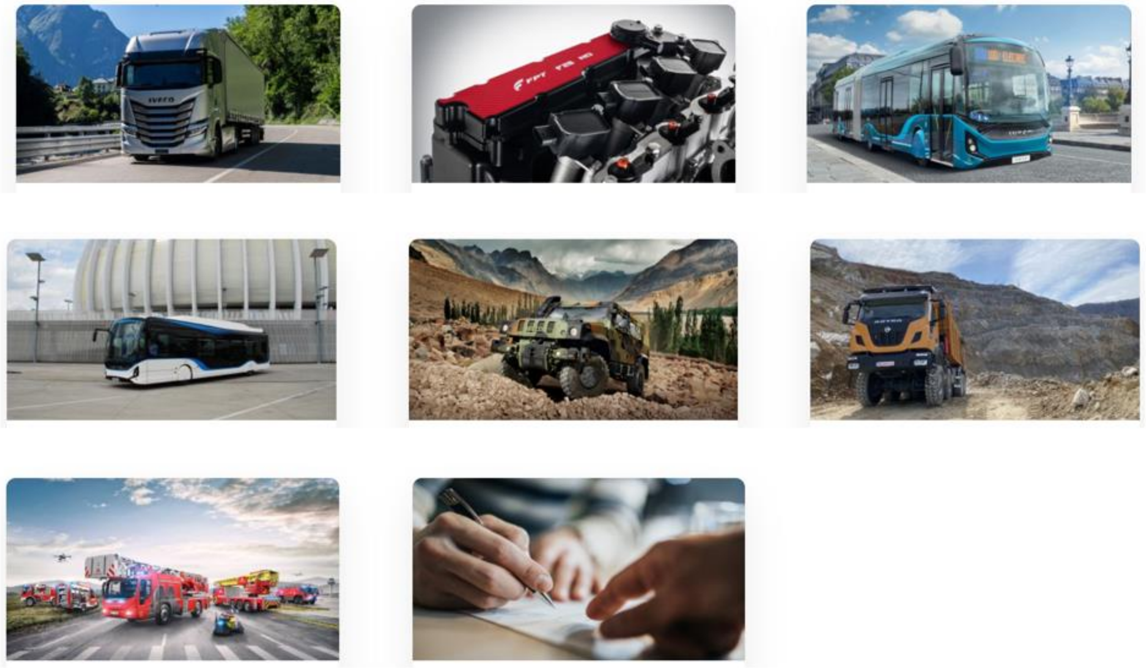


Figure 3 - From top-left products of: Iveco – FPT Industrial - Iveco Bus – Heuliez – IDV – Astra – Magirus – Iveco Capital [courtesy of *ivecogroup.com*]

IVECO designs, manufactures, and commercialises heavy, medium and light duty commercial vehicles. IVECO BUS is one of the major players in the European passenger transport sector, and it includes a complete range of urban and intercity buses, tourism coaches, and minibuses. HEULIEZ is the market leader in electric city buses in France. IDV is a highly specialised defence and civil protection equipment brand. ASTRA is a global expert in large-scale, heavy-duty quarry and construction vehicles. Magirus is the highly reputed firefighting vehicle and equipment manufacture. Iveco Capital is the financing arm which supports them all, serving as the cornerstone of Iveco Group's new business models.

FPT Industrial is a world leader in industrial powertrains and alternative propulsions for on- and off- road vehicles, as well as marine and power generation applications. The extensive product offering includes six engine families, transmissions, front and rear axles, and a complete natural gas engine range on the market for industrial applications. The six engine families range from 42 hp up to 1.006 hp, transmissions with maximum torque of 200 Nm up to 500 Nm, front and rear axles from 2 to 32 ton GAW (Gross Axle Weight). A dedicated ePowertrain team is accelerating the transition to sustainable mobility with electric propulsions, energy storage solutions and battery management systems, that shows potentials for the applications within US Brand Nikola joint-venture of Iveco group.

Figure 4 - FPT Industrial logo

FPT has a yearly production of about 600.000 engines and 250.000 transmissions, with a customer basis represented by a 51% of Captive companies (so within Iveco group) and 49% no-Captive. It has 10 plants, 7 R&D centres, 73 dealers and 800 service points around the globe with a man-power of 8.000 employees.

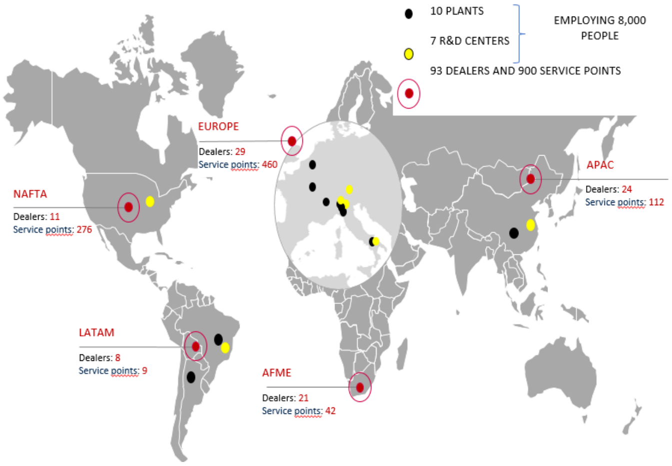


Figure 5 - Panoramic of FPT plants, centres and dealers in main economic market activity

Engines could be catalogued in four mains applications typology: on-road, off-road, power generation (PG) and marine. Engine families are those of F1, F5, NEF, Cursor and Vector

The range of engines for on-road applications is based on three advanced engineering powertrain families (F1, NEF and CURSOR) and it spans between displacements from 2.3 to 12.9 litres, power ratings from 97 to 570 hp and maximum torque levels from 240 to 2,500 Nm. Each of them include natural gas units. They are mainly dedicated to light commercial vehicles, trucks and buses. Off-road engines applications are dedicated mainly to agricultural and constructions vehicles plus power units. Agricultural sector adopts F-series, NEF, Cursor and Vector engine families. Depending on the mission, they could adopt variable-geometry and two-stage turbochargers as well as high-pressure Common Rail injection and patented after-treatment systems. Other non-road machineries applications are equipped with power ranges from 40 to 670 kW and displacements from 2.8 to 20 litres. This large power range generates a large number of applications: they can be embedded on excavators, wheel loaders, skid steer loaders, graders, dozers, forklifts, snowploughs and cranes. FPT Industrial offers a complete range (NEF, Cursor, F1) of engines for marine applications. Moreover, FPT Industrial has a series of solutions that ensure power when needed through power generators. Series used for this purpose are among Serie8000 engine family, NEF, Cursor and F5.

1.2 Values and Mission

The mission FPT Industrial is to

- Achieve and maintain technological leadership in all industrial powertrain fields, pursuing innovation, product excellence and continuous improvement.
- Achieve Customer satisfaction. Guided by the needs of both direct and final Customers.
- To promote a growth that can be sustainable, based on respect for the environment

FPT is driven by values of Innovation, Quality, Sustainability and Trustworthiness.

Chapter 2 - Future scenario for industrial internal combustion engines

2.1 The CO_2 emission reduction ambitions on complying with the Paris agreement

One of the most important European Union goals is the reaching for climate carbon neutrality by 2050. In June 2021 both the European Parliament and the European Council signed the European Climate Law. This level of ambition is aligned with the Paris Agreement to limit the global temperature increase limiting it to 1.5° with respect actual level. Today transport sector is responsible for about one quarter (around 23%) of energy-related greenhouse gas (GHG) emissions and the heavy-duty vehicles one is accounting for 25% of these emissions across the 27 member States of the European Union [1]. The EU regulation 2019/1242 marks the goal percentage GHG emissions reduction for Heavy-duty vehicles (HDVs) of 15% and 30% for the years 2025 and 2030 respectively, compared to a 2019 basis [2]. However, it is almost sure that while this work under development (2022) the European commission will revise the currently adopted CO_2 standards for Heavy Duty Vehicles HDVs. Meanwhile, in parallel to these regulations for HDVs, the commission proposed that all new LDVs fleets must be zero-emission vehicles (ZEVs) by 2035. Moreover, according to the International Council on Clean Transportation (ICCT) the target reduction should be increased toward 60% in 2030 and 100% in 2040, pushing a full ICE phase-out by 2038 to be compliant with European Climate Law [3].

The introductive part of this paperwork will shortly describe and show internal combustion engines future market share forecasts according to different scenarios. There is still limited number of studies on future ZEVs market penetration, they will be briefly summed up and compared, considering their difference in boundary conditions and considerations, as well as their effects on GHG (Green House Gases) emissions. The analysis will be divided in medium-short future time field (up to next decade) and far field (up 2050). Among these scenarios, it is important to underline OEM manufacturers approach and future strategies, as well as their announcements.

Heavy-duty vehicles are trucks and buses with gross vehicle weights (GVW) above 3.5 tonnes. They are classified in VECTO 18 category groups according to the EU CO_2 certification regulation

2017/2400 [3]. It is based on chassis configuration, axle configuration and permissible laden weight. VECTO tool is a simulation model developed to be implemented in certification legislation under EU type approval. Zero-emission HDVs actual market share is still limited in low volumes percentages (between 0.66% and 1% in 2019) [3]. Behalf this current scenario the past decade has been driven by Emission Legislation: -80% NOx emissions -50% of Particular Matter emissions (from Eu5/V to E6d final/EVI step E, from Tier3 to Stage V) were achieved. Meanwhile CO_2 reduction by 10% was driven by customer, not legislation [FPT Industrial]. Electrification started in passenger cars (now double digit in EU), while in Industrial application was only an R&D limited business (Bus sector is the only exception). Hydrogen wave started in the last 2 years as option for Zero emission Trucks. The CO_2 incoming legislations is completed at worldwide level in the below figure for what On-road vehicles legislations regard:

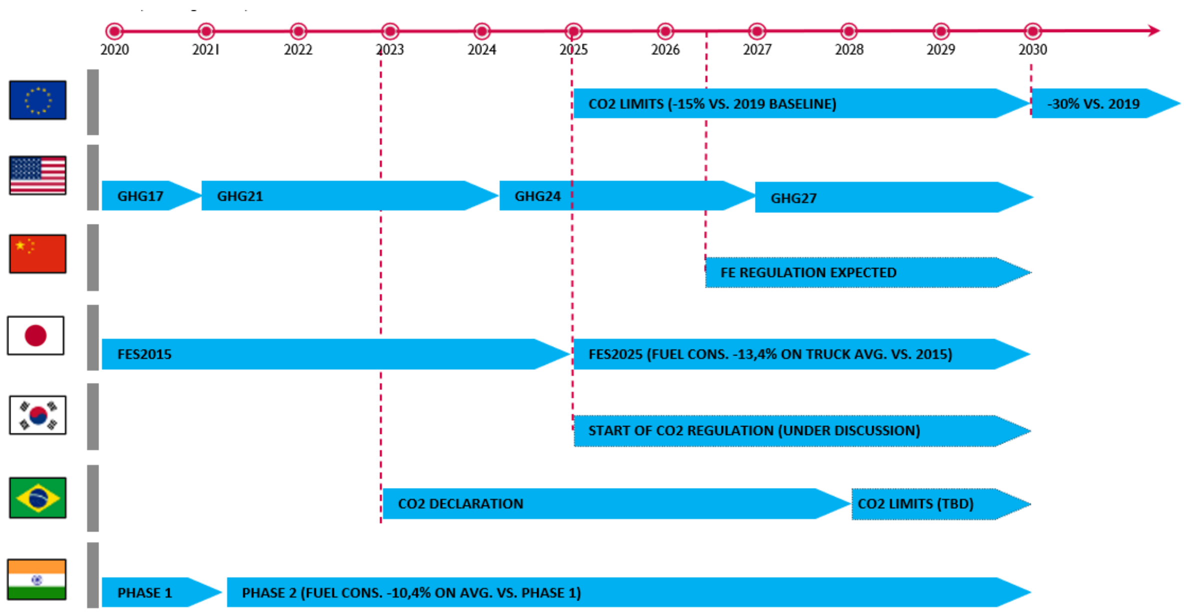


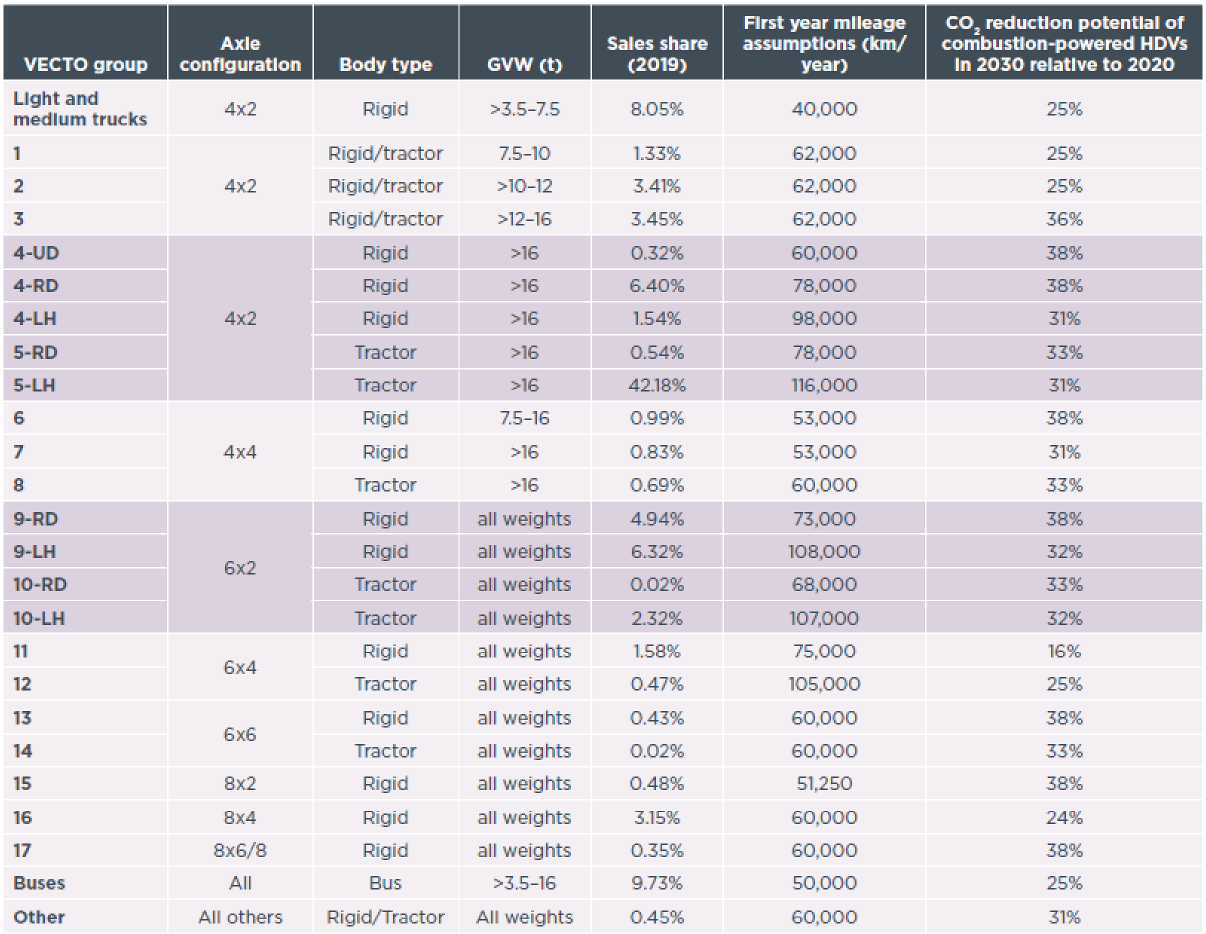
Figure 6 - Global On-road emissions scenario for CO_2 regulation [FPT Industrial]

Generally speaking the Off-road legislations are still in definition for what regard CO2 emissions. First discussion are on going in United States and potentially China V at least. In chapter 4 worldwide pollutant emissions regulations are explained for both on-road and off-road vehicles.

2.2 Actual and next decade scenario overview

European commission did not yet set HDVs emission target for a period afterward 2030 [3]. At end of 2022 actual legislation could be revise, and maybe it could be considered also to extend and to set new targets for 2035 and 2040 [3]. Thanks to these considerations, it is safe to affirm that the next decade scenario degree of uncertainty is much lower with respect post 2030.

As introduced before, 2019/1242 sets CO_2 limit for new sold vehicles. The regulation affects HDVs classes in just four categories over the 25 VECTO group, as explained in table 1. These four are groups 4,5,9 and 10 and account for approximatively two third of all HDV CO_2 emissions [2 and 3].



VECTO group	Axle configuration	Body type	GVW (t)	Sales share (2019)	First year mileage assumptions (km/year)	CO_2 reduction potential of combustion-powered HDVs in 2030 relative to 2020
Light and medium trucks	4x2	Rigid	>3.5–7.5	8.05%	40,000	25%
1	4x2	Rigid/tractor	7.5–10	1.33%	62,000	25%
2		Rigid/tractor	>10–12	3.41%	62,000	25%
3		Rigid/tractor	>12–16	3.45%	62,000	36%
4-UD	4x2	Rigid	>16	0.32%	60,000	38%
4-RD		Rigid	>16	6.40%	78,000	38%
4-LH		Rigid	>16	1.54%	98,000	31%
5-RD		Tractor	>16	0.54%	78,000	33%
5-LH		Tractor	>16	42.18%	116,000	31%
6	4x4	Rigid	7.5–16	0.99%	53,000	38%
7		Rigid	>16	0.83%	53,000	31%
8		Tractor	>16	0.69%	60,000	33%
9-RD	6x2	Rigid	all weights	4.94%	73,000	38%
9-LH		Rigid	all weights	6.32%	108,000	32%
10-RD		Tractor	all weights	0.02%	68,000	33%
10-LH		Tractor	all weights	2.32%	107,000	32%
11	6x4	Rigid	all weights	1.58%	75,000	16%
12		Tractor	all weights	0.47%	105,000	25%
13	6x6	Rigid	all weights	0.43%	60,000	38%
14		Tractor	all weights	0.02%	60,000	33%
15	8x2	Rigid	all weights	0.48%	51,250	38%
16	8x4	Rigid	all weights	3.15%	60,000	24%
17	8x6/8	Rigid	all weights	0.35%	60,000	38%
Buses	All	Bus	>3.5–16	9.73%	50,000	25%
Other	All others	Rigid/Tractor	All weights	0.45%	60,000	31%

Table 1 – HDV VECTO group categories [3]

Regulation affected categories are rigid lorries and tractors with 4x2 axle configuration and GVW over 16 tons and all rigid lorries and tractors with 6x2 axle configuration. The ICCT also modeled all categories, adding for each information on country-level market sales in 2005-2020 period. Onto this data, survival curve and mileage data were later added and finally mileage degradation profile was then considered. All of this will be useful to compute eventual tailpipe CO2 emissions by year in Mt considering different scenario and comparing them not only by regulation but also by effectiveness. Average specific manufacturer CO_2 will be then computed over vehicle being sold, and manufacturers who would not respect 15% and 30% emission reduction target by 2025 and 2030 will face specific fines. Fines are up to 4,250€ for each gram of CO2 per each tkm in 2025-2030 period and will be then rise to 6,800€ for every gCO2/tkm from 2030 on [2].

A zero or low-emission vehicle (ZLEV) is defined by tank-to-wheel (TTW) approach on emissions. ZLEVs vehicles are basically all those vehicles that emit less than half of reference CO_2 emission level [2]. A ZLEV credit system is actual present in legislation. Thanks to it, for each ZEV being sold it is counted as two on the weighted average. In 2025 the credit system will be substituted by a benchmark-based crediting system with 2% market share sales of ZLEVs from 2025 on. If an OEM ZEV fleet share is higher, the manufacturer will be 'awarded' with 1% discount from its average specific CO_2 yearly emission for every percentage point over the benchmark one up to a 3% maximum discount. Plus, the manufacturers could collect credit points between 2025 and 2029 [2]. It is trivial to understand that to be compliant with new future standards manufacturers so can use basically two methods: improving fuel efficiency of combustion-engine trucks or to increase sales of ZLEVs. Under the current scenario ZEVs vehicle adoption is low, so it has small impact on the reduction of the target amount that will be sustained from ICE powered HDVs through efficiency improvement. ICCT data shows a target reduction from 15% to 14.76% in 2025 and from 30% to 29.79% in 2030 [3]. The efficiency improvement can be modeled from different sources and not only by improvement in engines: some examples are those related to truck load technologies, aerodynamics, rolling resistance, light-weighting and so on. Imposing an overall 3% efficiency improvement per year it could be demonstrated that actual 2030 CO_2 standards can be achieved through this intensive internal combustion engines presence scenario. This concept could be confirmed in Column 3 of Table 1, it shows efficiency limits achievable for each category, computed by early described vehicle simulation model. The existing literature does not choice one best solution [2]. Matheu et al. forecasted an expected ZEV share between 1.3% and 10% in 2025 and from 15% to 30% in 2030 [4]. Existing literature still seems to be not so uniform in a dominating alternative fuel technology. Impact of policies also need some additional studies. Breed et al. obtained market uptake curves of ZEV HDVs based on gap between required total CO_2 reduction and one achieved by diesel HDVs improvement, according to different possible manufacturers strategy choice. Ranges of ZEV uptake goes from 0 to 7% in 2025 and from 4% to 22% in 2030 [4]. It is worth to notice that it is unlikely that in this phase manufacturers will choice all the same strategy. The study assumes a mixture of ZEV penetration between 10% and 15% in 2030.

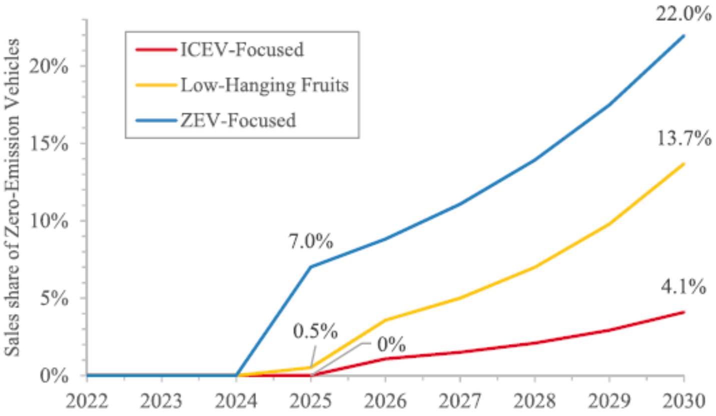


Figure 7 - Percentage of ZEV sales required to meet the emission regulation in the technology strategy scenarios [2]

2.2.1 FPT Industrial scenario

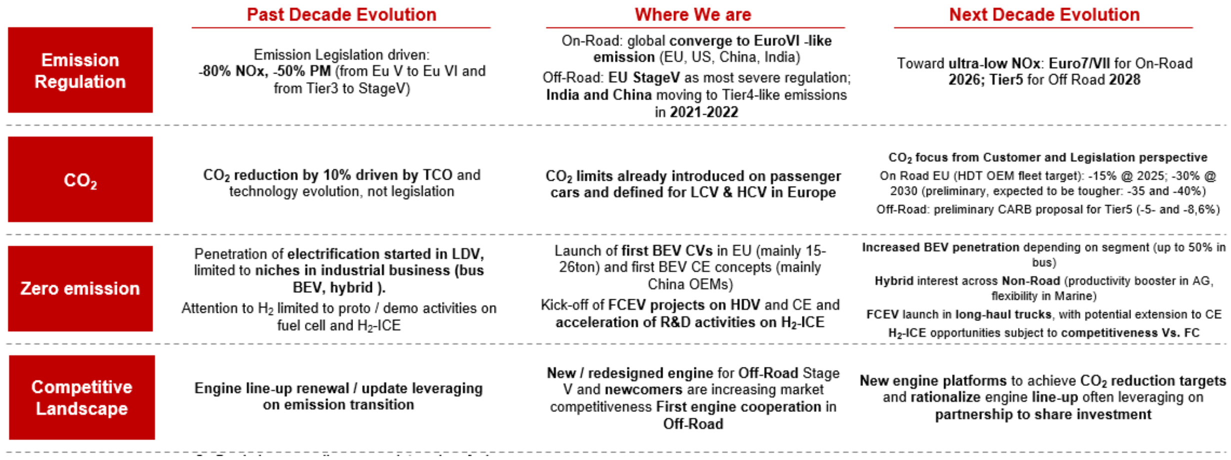
According to FPT Industrial we are now in an industry turning point, where more than 99% of revenues (and profit) are still generated by ICE powertrains, but where an increasing percentage of R&D/Capex have to be dedicated to Zero Emission product, while keeping investment in traditional technologies. The On-road sector, emission regulations are global converging to Euro VI-like emission (EU, US, China, India). Off-road industry sees EU Stage V as most severe regulation, with India and China moving to Tier4-like emissions in biennium 2021-2022. For what regards CO_2 emissions, if in past decade CO_2 reduction was driven by TCO (Total Cost of

Ownership) and technology evolution, today we have CO_2 limits already introduced on passenger cars and defined for LCV & HCV in Europe and more likely to be defined for other markets/segments (exploratory discussion started at OEMs / institution level for Off-Road). All of this must be seen in a competitive landscape~~.~~ Newcomers are increasing market competitiveness. The scenario will lead also to build new or redesign engines following continuous improvement, remaining in off-road field actual trend is to go toward EGR-free strategy.

ZLEV is explored with launch of first BEV CVs in EU and first BEV Construction Equipment CE concepts (mainly China OEMs). On parallel side there is the kick-off of FCEV projects on HDT and CE and acceleration of R&D activities on H_2-ICE from key players and often with **engineering consultant** (FEV, AVL).

In next decade there will be a continuous focus on challenging emission reduction (both in on-road and off-Road fields) with expected waves in 2026 (On Road) and 2028 (Off Road) timeframe. Legislation will also undergo towards ultra-low NOx in wide operating conditions: Euro7/VII for On-Road is expected in 2026 and US Tier 5 for Off Road in 2028. Meanwhile, CO_2 emission reduction will focus for both customer and legislation perspective (at fleet or at vehicle level according to geography) **not only in On Road field.** Near the On Road EU HDVs target so far described there will be in fact also a preliminary Californian CARB proposal for Tier5.

FPT Industrial forecasts that global Industry will be largely dominated by ICE products (>85%), but in specific markets and segments (like buses one) we will assist to impressive acceleration on electrified solution (up to 50%). This prevision is absolutely aligned with actual studies. Increased BEV penetration depending on segment will drive higher electricity demand. Hybrid interest is across non-road sector (it is a productivity booster in agricultural sector, an enabler of flexibility in marine, a peak shaving and lowering load in power generators). Fuel-Cell electric vehicles (FCEVs) launch is limited in long-haul trucks, with potential extension to construction equipment. Hydrogen internal combustion engine powertrains opportunities are subject to competitiveness versus FCEVs. In ICE field a company like FPT will be interested in new engine platforms to achieve CO_2 reduction targets and rationalize engine line-up, again leveraging on partnerships to share investments. According to FPT Industrial, all of that will require a consolidation phase among players, both on traditional and new technologies. OEMs need to invest into multiple technologies to secure long term multipower lineup, rising the overall effort for each player. Signs of disinvestment on conventional technologies can be an opportunity for FPT Industrial, capturing mid- and long-term businesses driven by make-buy revised strategy. Figure 8 recap all these concepts on company forecast scenario.



	Past Decade Evolution	Where We are	Next Decade Evolution
Emission Regulation	Emission Legislation driven: **-80% NOx, -50% PM** (from Eu V to Eu VI and from Tier3 to StageV)	On-Road: global **converge to EuroVI -like emission** (EU, US, China, India) Off-Road: **EU StageV** as most severe regulation; **India and China** moving to Tier4-like emissions in **2021-2022**	Toward **ultra-low NOx**: **Euro7/VII** for On-Road **2026; Tier5** for Off Road **2028**
CO_2	**CO_2 reduction by 10% driven by** TCO and technology evolution, not legislation	**CO_2 limits already introduced on passenger cars and defined for LCV & HCV in Europe**	**CO_2 focus from Customer and Legislation perspective** On Road EU (HDT OEM fleet target): -15% @ 2025; -30% @ 2030 (preliminary, expected to be tougher: -35 and -40%) Off-Road: preliminary CARB proposal for Tier5 (-5- and -8,6%)
Zero emission	Penetration of **electrification started in LDV,** limited to **niches in industrial business (bus BEV, hybrid).** Attention to H_2 limited to proto / demo activities on fuel cell and H_2-ICE	Launch of **first BEV CVs** in EU (mainly 15-26ton) and first BEV CE concepts (mainly China OEMs) Kick-off of **FCEV projects on HDV** and CE and **acceleration of R&D activities on H_2-ICE**	**Increased BEV penetration** depending on segment (up to 50% in bus) **Hybrid** interest across **Non-Road** (productivity booster in AG, flexibility in Marine) **FCEV** launch in **long-haul trucks**, with potential extension to CE H_2-ICE opportunities subject to **competitiveness Vs. FC**
Competitive Landscape	**Engine line-up renewal / update leveraging on emission transition**	**New / redesigned engine** for **Off-Road** Stage V and **newcomers** are increasing market competitiveness **First engine cooperation** in **Off-Road**	**New engine platforms** to achieve CO_2 **reduction targets** and **rationalize** engine **line-up** often leveraging on **partnership to share investment**

Figure 8 – FPT Industrial key trends in industrial changing environment [FPT Industrial]

In terms of market share, figure 9 gives indications on share of sales in next decade according to described scenario.

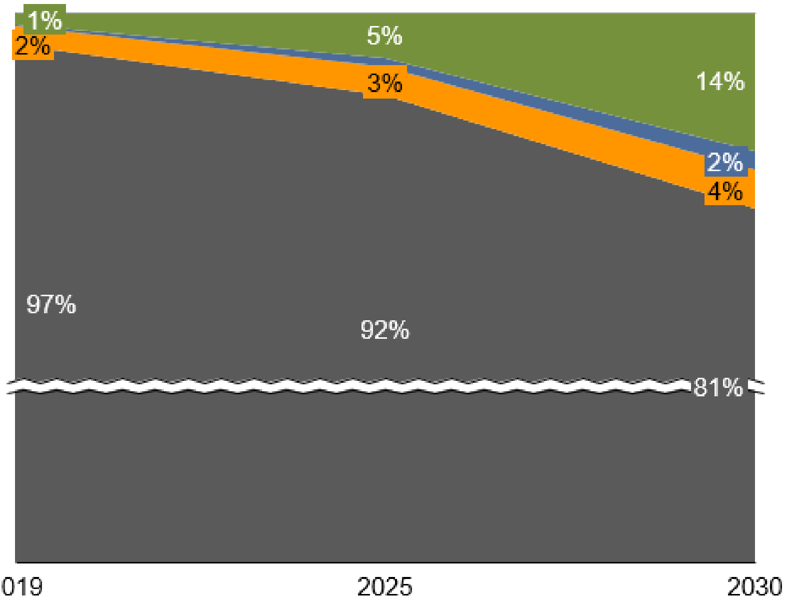


Figure 9 - Powertrain forecast in next decade [FPT Industrial]

Worldwide total industry volume in 2021 was about 11 million unit big. We can see that in 2030 ICEs vehicles will represent more than 85% of total industry volume. However, we can see a rapid increase of alternative solutions, leaded by ZLEVs (mostly FCEVs and battery electric vehicles). The increase rate is quite gentle before 2025, then strongly augmenting by the end of the decade thanks to better battery technologies, infrastructures and lower TCO. Total industry is driven by On-road vehicles (63%), followed by Off-road (33%) with few percentages left to Power Generators and Marine sectors (figure 10).

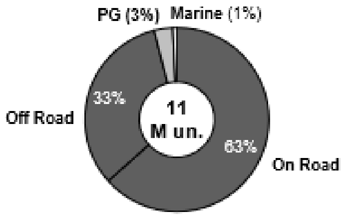


Figure 10 – Global Powertrain Mix [FPT Industrial]

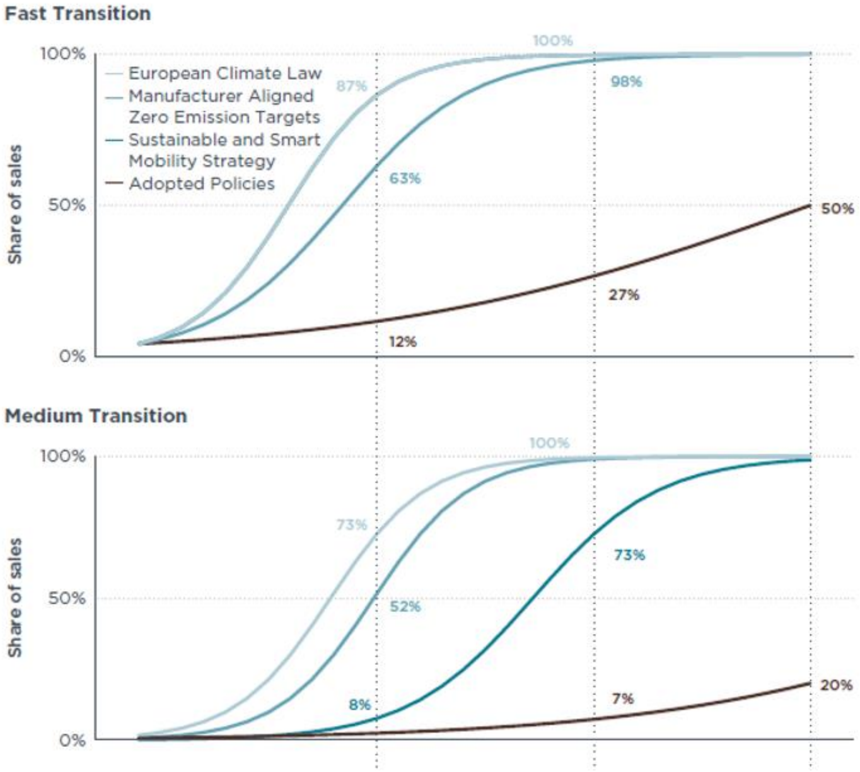
In next decade we will see that, in on-road field, light and heavy markets will drive electrification, followed by medium engines. Main energy drivers will be the upcoming CO_2 regulations and the TCO parity achievement. The push on electrification will be visible from 2025 on. In Heavy market both BEVs and FCEVs can play an important role.

In off-road applications BEV penetration is higher in compact machines for urban operation, however minor share growth is expected also in midrange CE construction equipment. Hybrids, currently a niche on CE (Excavators etc) will slightly grow in both construction equipment and agricultural sector. Hydrogen fuel cell will have limited uptake, with H_2 ICE as alternative zero emission in Off Road.

The slightly little 1% portion of Power Generators and Marine sectors is going to see just a rising interest on biomethane solution, with marine hybrid and/or full electric just in specific niche application, both for Pleasure and Commercial vehicles.

2.3 Reaching carbon neutrality: 2050 different scenarios overview

The 2022 ICCT paper on HDVs CO_2 standards needed for Europe to meet its annual target models four different scenarios with different level of stringency from 2030 to 2040. The first one is based on current implementing standards trend, the second one adopts sustainable and smart mobility strategies according to EU commission. Then also the announced sales target of HDVs OEM manufacturers are analysed. Finally, the last scenario is dedicated on decision-level required to achieve a 90% of emissions reduction by 2050 on 1990 basis, according to ICCT [3]. The study so will consider not only possible legislation paths but try to model CO_2 emission reductions results for each of these paths, and then onto this basis it tries to suggest possible likely scenario adoption. The computations are made on a **Tank-to-wheel** approach, based on a fleet modelling that also considers stock ageing curve and different usage profiles, as well as freight activity (that will increase on 1990 and 2019 basis) and with assumption of 3% increase of efficiency of new combustion-engine powered vehicles. Improvements in freight logistics activities were not considered. So, the pace of ZEVs is the main driver for the distinction between different paths overviews. For simplicity ICCT applied an S-curve adoption distribution, typical of new technologies implementations. For ZEVs it will depend obviously by infrastructural level, TCO, models availability in market and customers habits. ZEV adoption trend undergoes different slopes and magnitude paths varying by different vehicles categories, as stated also within FPT for next decade summary. ICCT [3] divided three different vehicle groups starting from VECTO classification through their ZEV adoption rate. Buses and medium and light vans/trucks are defined as fast transition vehicles (mainly in VECTO group 0). Urban and regional drive cycle vehicles are object of a medium transition (groups 1,2,3,6 and RD of 4,5,9,10). Long-haul duty cycle and heavy trucks are classified as slow transition vehicles (groups 7,8, from 11 to 17 and LH of 4,5,9,10). Figure 11 summarizes the ZEV market share sales scenario results.



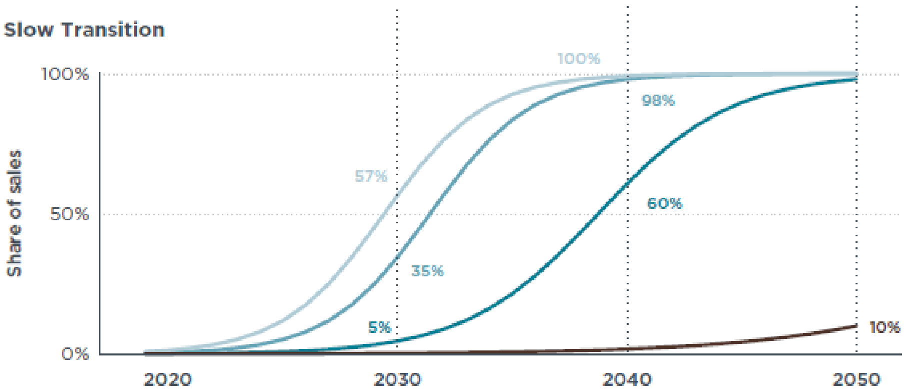
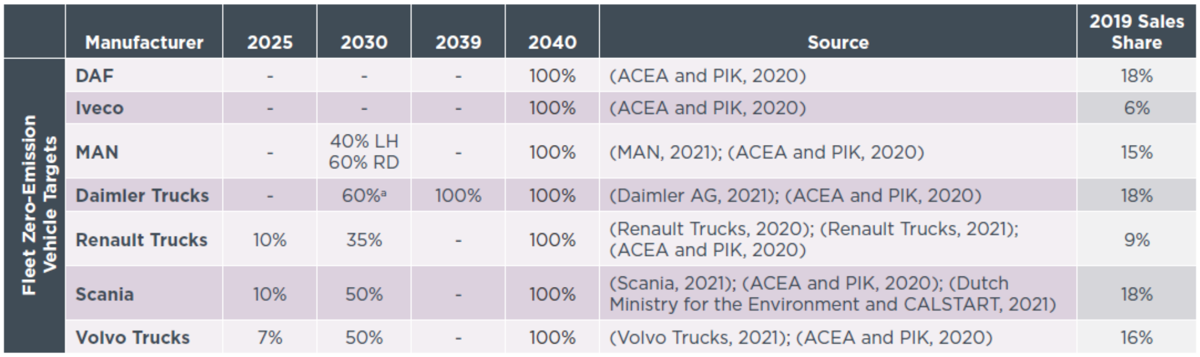


Figure 11 - ZEV sales share depending on speed of transition and scenario typology [3]

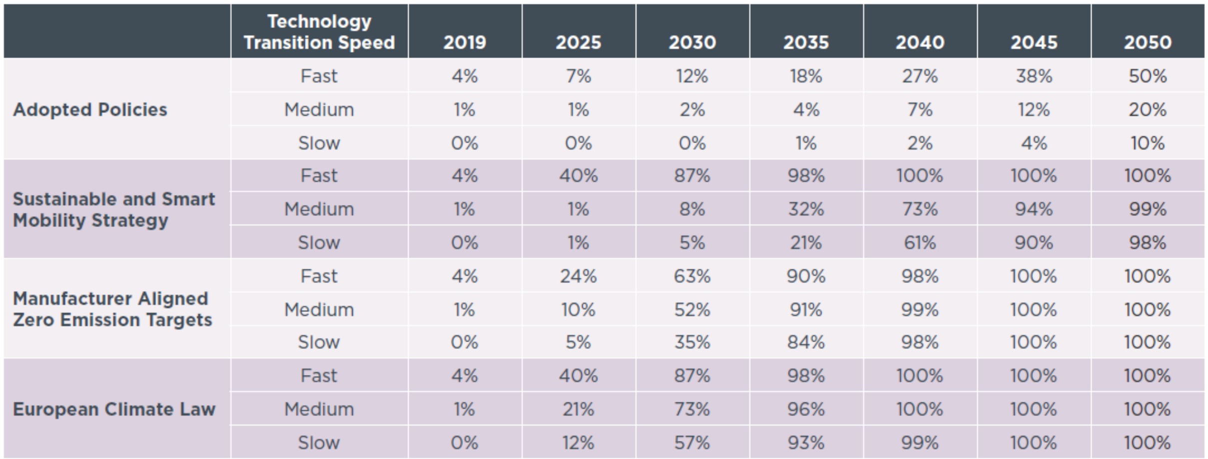
In current adopted scenario, assuming absence of a strong regulation, lack of infrastructure and cost narrowing, there will be not a strong increase of ZEV sales shares. In 2050 just fast transitioning categories would reach 50% ZEV market share sales. According to Sustainable and Smart Mobility Strategy document of EU commission in 2030 80,000 ZEVs will be in circulation and by 2050 all buses and lorries will be zero-tailpipe-emission ones [3]. Next to this picture, there is also commitment of manufacturers through ACEA and PIK 2020 document that defines the efforts to sell only fossil-free commercial vehicles by 2040. It's important to underline that fossil-free vehicles could include also combustion powered engines through biofuels and synthetic fuels. ICCT for coherence in studying scenarios effects considered them all as zero-tailpipe-emission vehicles. The commitment then varies across the years before 2040. A short description is given in table 2.



	Manufacturer	2025	2030	2039	2040	Source	2019 Sales Share
Fleet Zero-Emission Vehicle Targets	DAF	-	-	-	100%	(ACEA and PIK, 2020)	18%
	Iveco	-	-	-	100%	(ACEA and PIK, 2020)	6%
	MAN	-	40% LH 60% RD	-	100%	(MAN, 2021); (ACEA and PIK, 2020)	15%
	Daimler Trucks	-	60%ᵃ	100%	100%	(Daimler AG, 2021); (ACEA and PIK, 2020)	18%
	Renault Trucks	10%	35%	-	100%	(Renault Trucks, 2020); (Renault Trucks, 2021); (ACEA and PIK, 2020)	9%
	Scania	10%	50%	-	100%	(Scania, 2021); (ACEA and PIK, 2020); (Dutch Ministry for the Environment and CALSTART, 2021)	18%
	Volvo Trucks	7%	50%	-	100%	(Volvo Trucks, 2021); (ACEA and PIK, 2020)	16%

Table 2- OEMs announcement plans for phase-in of zero-emission or fossil-free HDVs [3]

The final scenario, according to ICCT, is the one needed to get in 2050 90% transport sector CO2 emissions reduction on 1990 baseline [3]. In table 3 the scenarios trend for every category, updated on five years basis.



	Technology Transition Speed	2019	2025	2030	2035	2040	2045	2050
Adopted Policies	Fast	4%	7%	12%	18%	27%	38%	50%
	Medium	1%	1%	2%	4%	7%	12%	20%
	Slow	0%	0%	0%	1%	2%	4%	10%
Sustainable and Smart Mobility Strategy	Fast	4%	40%	87%	98%	100%	100%	100%
	Medium	1%	1%	8%	32%	73%	94%	99%
	Slow	0%	1%	5%	21%	61%	90%	98%
Manufacturer Aligned Zero Emission Targets	Fast	4%	24%	63%	90%	98%	100%	100%
	Medium	1%	10%	52%	91%	99%	100%	100%
	Slow	0%	5%	35%	84%	98%	100%	100%
European Climate Law	Fast	4%	40%	87%	98%	100%	100%	100%
	Medium	1%	21%	73%	96%	100%	100%	100%
	Slow	0%	12%	57%	93%	99%	100%	100%

Table 3 - Share of ZE-HDV sales in 5-year for each scenario [3]

Reading the data, we can see a sort of alignment to FPT predictions, lying between adopted policies and manufacturer aligned target scenarios. Obviously, data are difficult to compare, as FPT 2030 forecast is on **total worldwide** mix (and so with different boundary conditions), while here we got a scenario based on different transition level in European soil for trucks and buses. By limiting on trucks and buses only, in fact, the market share of ZLEVs shift to higher percentages. However, is good to conceive a ZEV market share uptake around 50% in 2030 for HDV fast transitioning categories with a total average of 15% of ZEV shares in 2030 (curiously similar to fast transition case in adopted policies). The data are also coherent to Breek et al. and Maurice et al. studies, grouping existing literature. The ICCT table data are a very good estimator, but they are affected by different model considerations influence. Moreover, the assumption made on manufacturer commitments (not considering ICE fossil-free possibility) can change a little bit the data reading. It can be however considered to have diversification over energy mix and technology investments as the correct strategy. The post 2030 scenario seems to be more uncertain. Poorness of studies available in literature and quantity of discussion related to different technologies, energy mixes, infrastructure and decision may confirm that uncertainty.

ICCT paper tries to work out a solution feasible to achieve stringent European climate targets. By doing that the CO_2 reduction amount will be the main driver on technological mix choice. The figure 12 will show subsequent total HDV emission ($MtCO_2$) trajectories curve in EU-27 modelled in these four scenarios, with 5 years data repeated in table 4. Comparison with new fleet average gCO_2/tkm reduction is available in figure 13

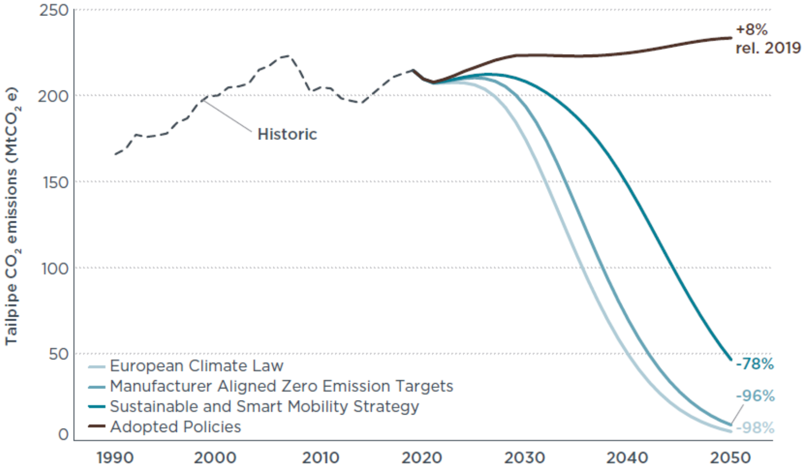
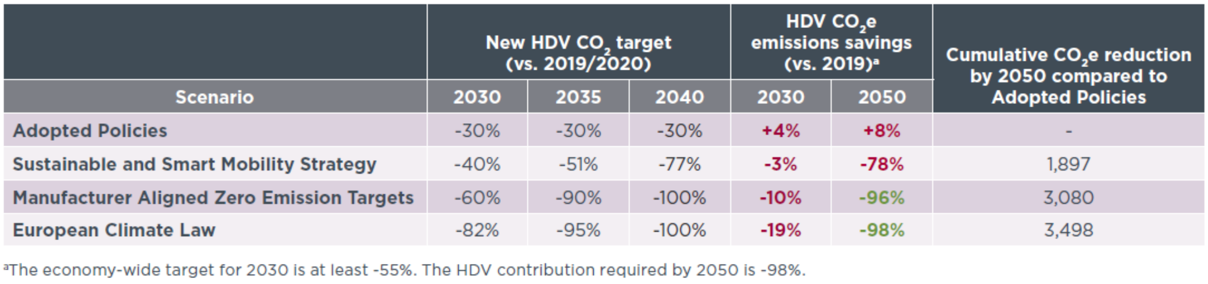


Figure 12 – 2020-2050 HDV emission trends for different scenarios [3]



	New HDV CO_2 target (vs. 2019/2020)			HDV CO_2e emissions savings (vs. 2019)[a]		Cumulative CO_2e reduction by 2050 compared to Adopted Policies
Scenario	**2030**	**2035**	**2040**	**2030**	**2050**	
Adopted Policies	-30%	-30%	-30%	**+4%**	**+8%**	-
Sustainable and Smart Mobility Strategy	-40%	-51%	-77%	**-3%**	**-78%**	1,897
Manufacturer Aligned Zero Emission Targets	-60%	-90%	-100%	**-10%**	**-96%**	3,080
European Climate Law	-82%	-95%	-100%	**-19%**	**-98%**	3,498

[a] The economy-wide target for 2030 is at least -55%. The HDV contribution required by 2050 is -98%.

Table 4 – Cumulative heavy-duty emissions reductions with respect 2019 [3]

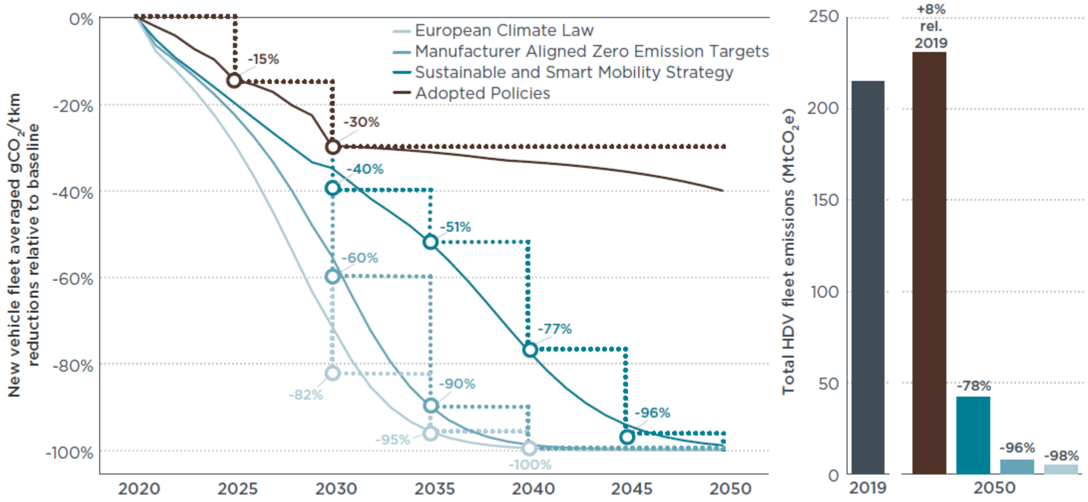


Figure 13 – New vehicles fleet average yearly emissions reduction relative to 2020 and relative 5 years target (right) – Total HDV fleet emissions in $MtCO_{2eq}$ in 2019 and 2050 (right) [3]

As we have seen, adopted policies scenario leads to achievement of 2025 and 2030 scenario on new fleet CO_2 average). However, studies [2] also affirm that while a 15% and 30% CO_2 emissions reduction should be feasible by diesel improvement, the second largest target should add many additional costs and are more difficult to achieve, although they could be still cheaper or aligned to additional costs of ZEVs within that temporal limit. According to ICCT, increasing trend of freight activities need different actions uptake as it will lead of an overall increase of CO_2 emissions on 2019 basis. ICCT suggests a full ICE phase-out by 2038 for full regulations compliance (98% reduction) [3]. Curiously fast transition ZEV market share adoption is equal for the sustainable strategy and the last scenario suggested by ICCT, that's because increasing ZEV shares on buses may relax effort of shift on trucks. It is worth to notice that manufacturers' announcements shortly fall in reduction necessary to be compliant with 2050 targets, still the difference could be critical in global worming potential scenario.

2.3.1 Boundary conditions brief overview

The discussion held so far is somewhat limited to some considerations. A deep study leading towards a life cycle assessment (LCA) is not purpose of the present work, but it could be vital to remember some conditions to understand future penetration of internal combustion engine in HDV market.

FEV consulting group identified four measures to achieve low carbon pathways:

- Optimisation of usage
- Electrification of powertrains *{of our interest in order to understand ICE penetration}*
- Efficiency increase of vehicles
- Adaptation of energy carriers

Three balances could be used, leading to different scenario results:

- Tank-to-wheel
- Well-to-wheel
- Life-cycle analysis

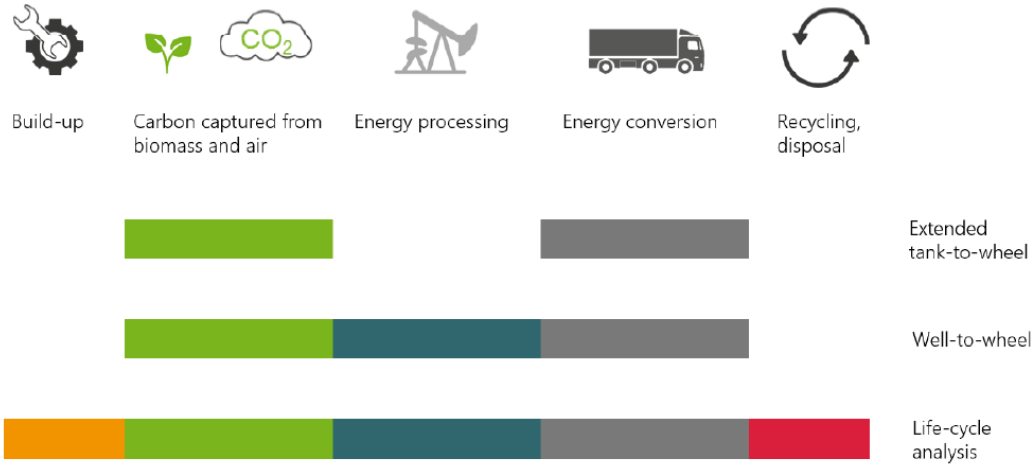


Figure 14 – Overview of GHGs emission by considered life portion cycle [1]

Again, different policies could be present to reach the same result: from 80% to 95% of CO_2 emission reduction. The four measures are added and computed sequentially, from the optimisation of usage to the adaptation of energy carriers through blend shares of renewable energy for each year [1]. Then two balances could be considered (tank-to-wheel and well-to-wheel) for each scenario, leading to a certain CO_2 reduction according to market share scenario.

In the TTW case study the electrification of powertrains is the most important measure along with adaptation of energy, while in WTW balance the adaptation of energy has to be the main driver.

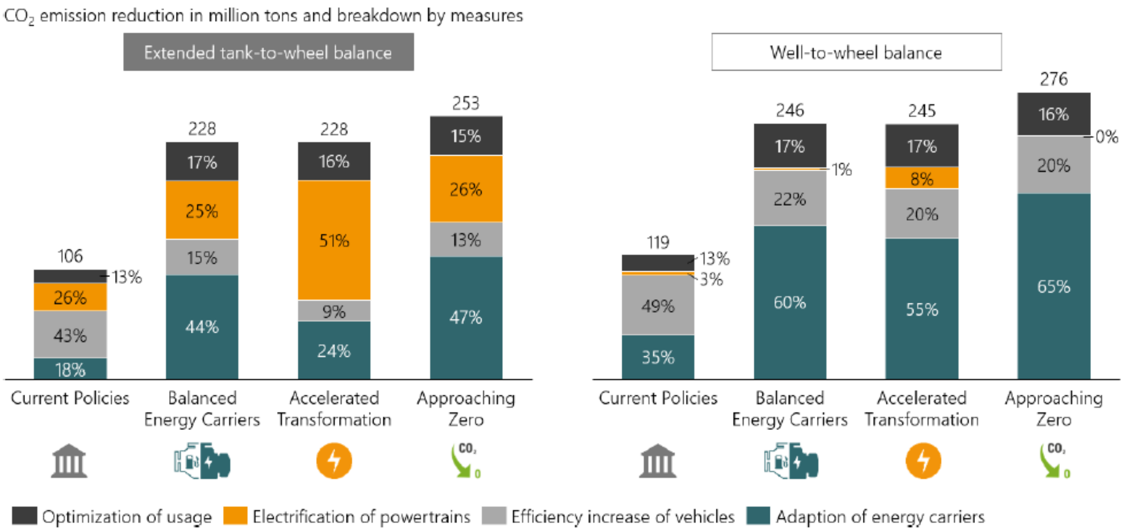


Figure 15 – CO2 emission reduction comparison in four different scenarios [1]

In approaching zero scenario the protagonist is the energy provision. FEV asks for high investments in electricity and generation from renewable source. In this path 27% of 2050 energetic demand is covered by gaseous fuel from renewable sources. In this way the penetration of ICE seems that might be much higher.

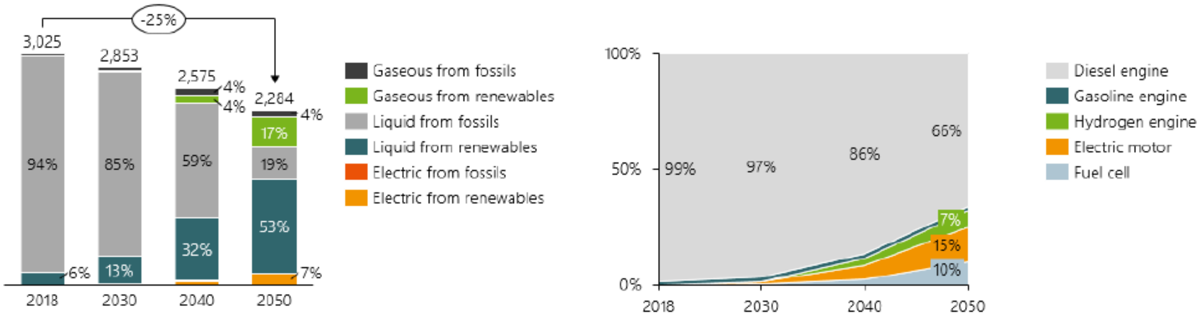


Figure 16 – Approaching zero scenario results [1]

The result from this path seems to be far for what manufacturers are committed to, and even far from legislation. It is quite interesting as it shows that 'optimistic' percentage of share from ICE comes from different boundaries considerations. It can show that ICE can even still play a role in a future of diversification scenario, that still try to go toward sustainability. The combustion of methane CNG is still valid to reduce CO_2 emissions. Iveco and Volvo offer HDV with CNG engines. It will be the heart of our paper for the specific technology application under study and in consideration. However, it is at same time always correct to predict and push a rapid increase of electric and FCEV solution from 2030 on, for both legislation and various improvement reasons. Yet in fact, it hasn't been discussed the TCO level and infrastructural level. Studies agree that from 2030 on, ZEV could be economically attractive, thanks to cost reductions of development and infrastructural development. As well as LCA studies, that also for passenger cars are differentiate by different fuel and/or electricity blends, leading in different results (especially on amount of km necessary to get advantage of electric vehicles over ICE ones).

2.4 Conclusions

The study of different scenario is important to set the first milestone: ICE efficiency improvement is still a key factor concerning GHG emission reduction. Although we are in an industry turning point and a consolidation phase is required, efforts on internal combustion engines are yet important. Moreover, the legislation is increasing level of pollutant emission reductions toward Euro VII-like levels, pushing on NOx and PM reduction level and implementation of RDE regulation with PEMs. The competitive landscape will complete the picture, with a background made of increase in raw material costs and shortages. It is needed to reach high level of pollutant emission reduction capability again with low-cost industrial solution, keeping high level of product competitiveness and decreasing industrial and ownership costs. From this, solutions like after treatment systems zone coating could be beneficial. Regarding CO_2 emission reduction and internal combustion engine market share penetration, choice on different path scenario need to have industry stakeholder aligned and prepared, as well as authorities. They should create a framework capable of trace and follow a unique strategy in next decades.

Chapter 3 - Pollutant emissions in internal combustion engines

3.1 Primary pollutant emissions from internal combustion engines

3.1.1 Primary pollutant emissions for SI engines

Primary pollutants are those pollutants compounds directly related to human activity. Even if the combustion process could be ideally chemically defined [5], real combustion in ICEs leads to pollutant emissions formation. Ideal reaction of a hydrocarbon fuel C_xH_y would lead to non-harmful products (CO_2, H_2O, N_2 and O_2). Meanwhile, real reaction of hydrocarbons with oxygen from atmosphere gives an amount of H_2O and CO_2 with trace of numerous other compounds including hydrocarbons (CH_4, C_2H_2, C_2H_6, C_2H_8, CHO, etc.), carbon monoxide (CO), nitrogen oxides (NO, N_2O) and reduced nitrogen (NH_3 and HCN), sulfur gases (SO_2 etc.), halocarbons (CH_3Br etc.) and particles [5]. They are about 1% of all products, mainly represented by compounds like CO, HC, NOx and Particular Matter PM. The ideal combustion reaction [5]:

$$C_aH_b + \left(a + \frac{b}{4}\right)(O_2 + 3.773\ N_2) \rightarrow aCO_2 + \frac{b}{2}H_2O + 3.773\ \left(a + \frac{b}{4}\right)N_2$$

Where:

$$b/_{a} \cong 1.85$$

It is worth to notice that CO_2 is classified like non-harmful because of its non-toxicity, but its GHG effects are well known. However, being result of ideal combustion process (at about 14% of exhaust gases) the only way to reduce carbon dioxide is by reducing fuel consumption or by using a combustible fuels of less carbon atoms (like methane). Thus, a higher engine efficiency is needed. After-treatment systems so will be focused mainly on primary pollutants like CO, HC, all NOx and PMs etc. with CO_2 out of ATS perimetry.

In spark ignition engines it is common to have [5]

- Carbon monoxide CO (1-2% in volume or 100 g/kg of fuel)
- Unburned hydrocarbons HC (10^3 ppm by volume or 10 g/kg of fuel)
- Nitrogen oxides NOx (10^3 ppm by volume or 10g/kg of fuel)

Instead, PM and sulphur oxides SO_x are negligible, mainly due to the typical flame front burning of a stoichiometric mixture and low sulphur fuel content. For pollutants like CO, HC and PM, the formation mechanisms are coupled with the combustion process, so the understanding of formation mechanisms requires the comprehension of the combustion chemistry [5]. Most important NOx formation process is not part of fuel combustion mechanism. But the reactions producing those compounds are within an environment which is consequence of the combustion itself, so the comprehension of combustion features is important. Kinetics of chemical reactions also plays a fundamental role, with concentration of species in exhaust system quite different from what we can see in cylinder.

The thermal formation of NOx is caused by oxidation of N_2 in an environment at temperatures exceeding a certain threshold. The threshold is identified around 1850 K [5]. High-temperatures and peak pressures conditions favours NOx pollutant formation. In combustion chamber we shall consider two different zones: the burned gas zone of combustion and the unburned gas region. They are separated by the flame front. Although the zones are uniform in pressure, they may present huge differences in temperature. First particles that starts burning increase more their temperature with respect last particle. If we plot different temperatures against crank angle, the temperature of the burned gases exceeds 1000 K and it is very different from the unburned gases ones (<1000 K). The temperature in the burned gas zone, in fact, could reach about 2500 K at the spark, and then it will continue to increase since the (exothermal) combustion process release energy, heating up the cylinder. Moreover, the piston compresses the mixture while reaching top dead centre, contributing to the temperature increase. The first part of mixture involved in combustion reaches higher temperatures, while the latter burns at the end when the piston is in expansion phase, and temperature starts to decrease [5]. So being the NOx formation driven by temperature of burned gas, the higher they are and the higher will be the NOx formation rate. Then, during expansion stroke, the cooling down of the charge will freeze chemical reactions, leaving NO concentrations well above values we would expect from chemical equilibrium at exhaust. Main reactions responsible of this oxidation mechanism are Zeldovich ones [5 and 6]:

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

In reaction #1, leading to NO formation, high activation energy is needed, so high temperatures are required. The reaction generates an unstable free nitrogen atom, that in reaction #2 reacts with oxygen and forms NO and a free oxygen atom, which, in turns, combines to another nitrogen atom and so on. Finally, in reaction#3, OH radicals can also react with nitrogen, to form NO and hydrogen. All the Zeldovich reactions mechanism could be explained knowing that a simple chemical reaction is the result from simultaneous combination of number 'a' molecules of compound A, 'b' molecules of compound B and 'c' molecules of C. The reaction can be written as the following:

$$aA + bB + cC + \cdots \leftrightarrow rR + sS + \cdots$$

It is also important to consider that there are two kinds of reactions are present: a forward and a backward one. For each, the rate of the reaction can be expressed as a product of the concentrations of the single reactants, elevated to its stoichiometric coefficient [6].

$$r = k\, C_A^a C_B^b C_C^c$$

The coefficient 'k' is a reaction rate constant that indicates a strong dependence on temperature. The relationship between k and T is given by the Arrhenius equation.

$$k = k_0\, e^{-\frac{Ea}{RT}}$$

- R = universal gas constant (R=8.314 [kJ/kmol K]);
- T = absolute temperature [K];
- Ea = activation energy of the reaction
- k_0 = Boltzmann factor, which defines the fraction of all the collisions that have a sufficient energy to make the reaction happen.

Condition of thermodynamics equilibrium may be established when concentrations of reactants A, B, C, ... will co-exist in the system with certain concentrations of products. From the kinetics point of view, this situation stands for a dynamic balance. Meanwhile, before it is reached, the net rate of the reaction is then equal to the difference between the forward and reverse reaction rates. Generally speaking, in ICE reactions case, temperature is changing too fast to let the equilibrium be reached. We know how the first portion of mixture burning is the one that reaches the highest temperatures, and it is also the one where the highest NO concentration production is expected (due also to longer available time to cumulate production of NO). The opposite held for the last portion of mixture involved in the combustion process: it has the lowest temperatures and has the lowest NO concentration. Finally, at the expansion stroke, the reactions freeze, leaving NO concentrations well above kinetic equilibrium level. In SI engines most of nitrogen oxides are mainly constituted by NO (about 98-99%), while NO_2 percentage is small (about 1-2%) [5]. The composition-mix between the two is important to be known in the choice of the aftertreatment system typology due to different components enhancing characteristics. Moreover, even if the most important NOx formation mechanism is the described thermal one, there are other mechanisms, such as the so-called **Prompt formation mechanism**, related to the reaction taking place between nitrogen and hydrocarbon intermediate radicals [5 and 6].

$$CH + N_2 \rightarrow HCN + N$$

The product is a ternary compound that has the ability of react with oxygen to form NO. This last mechanism usually gives a negligible contribution of NO formation, and it is located inside the flame front, where hydrocarbons concentrations are high. Moreover, it is an extremely fast process with temperature sensitivity.

NOx formation mechanism is not the only pollutant production mechanism, the CO formation occurs during the oxidation process of fuel hydrocarbons through different steps. Ideally hydrocarbon molecular structure is modified until CO_2 and water vapour are obtained.

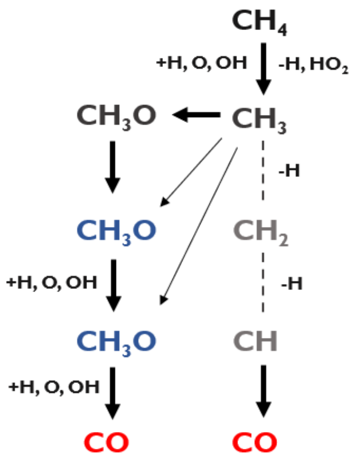


Figure 17 – CO formation mechanism scheme in SI engines

$$CH_4 \rightarrow CH_3 \rightarrow CH_2 \rightarrow CH \rightarrow CO$$

From first CH_3 molecule

$$CH_3 \rightarrow CH_3O \rightarrow CH_2O \rightarrow CHO \rightarrow CO$$

It is visible that different possible paths are present: here for example the starting methane molecule is first losing the hydrogen atoms, with then formation of peroxides, aldehydes, chitons and CO finally, then oxidized in CO_2. However, the oxidation reaction of CO to CO_2 is slower in comparison with the previous steps that led to CO formation. Because of this reaction rate difference, all the fuel may start the oxidation process and reach the intermediate oxidation level of CO, but only part of the CO formed will be able to reach the complete oxidation level corresponding to CO2 (about 3% vol. should be expected at $\lambda = 0.9$). The phenomena is much higher for rich mixtures. The processes that govern CO exhaust levels are so kinetically controlled [5]. Nevertheless, if a sufficient amount of oxygen is available, CO oxidation to CO_2 happens via OH radicals reaction, forming CO_2 and a free hydrogen atom [5]

$$CO + OH \rightarrow CO_2 + H$$

At the temperatures proper of SI engines combustion (over 2800 K) reaction rates are sufficient to get a chemical equilibrium. So even if level of oxygen is enough to fully oxidise CO in CO_2, reverse reactions present in equilibrium will lead to **dissociation** of CO_2 into CO and OH. Again, successive expansion phase with its decreasing temperatures will freeze the reactions, preventing further CO oxidation. As consequence, exhaust CO concentration will be higher than those predict by chemical equilibrium at related temperatures. If we represent CO emissions by air/fuel ratio, we clearly see dependence on mixture typology. The trend shows a linear decrease in lean side, with a sudden slope change in slight lean area and rapid increasing CO concentrations in rich regions [5].

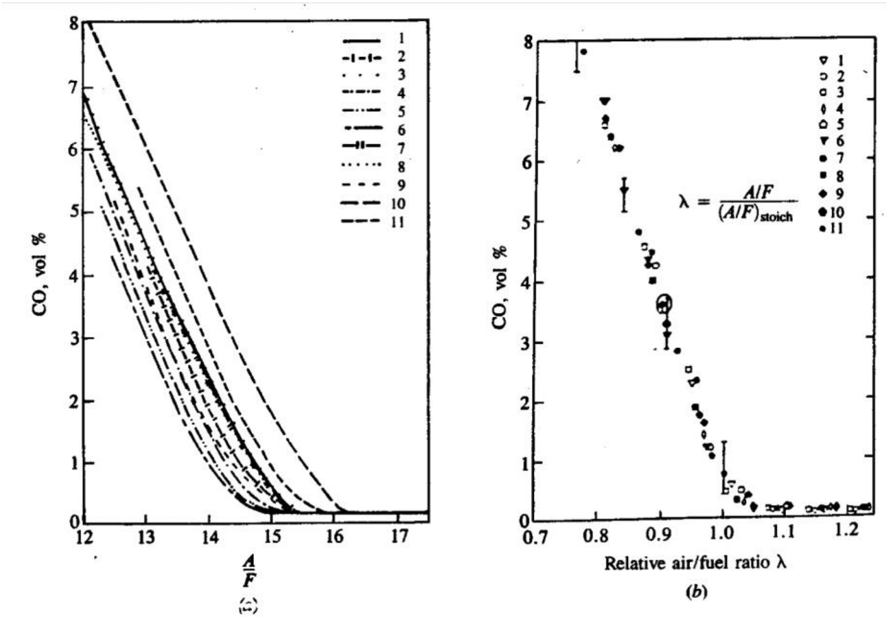


Figure 18 – CO emission level trend in vol % versus air/fuel ratio [5]

So, all the fuel rich operating conditions (like cold starts, transients and so on) may cause an increase in CO emissions, as well as air/fuel ratio imbalance between cylinders. As practical evidence shows [5] exhaust CO production are due to relative air/fuel ratio. It is though important to add that at low temperatures the inverse CO_2 dissociation into CO takes place with a negligible reaction rate (very slow), while at high temperatures it is obviously significative. Therefore, it is true that CO is formed as a consequence of rich air/fuel ratio, nevertheless even if the engine is fueled with stoichiometric, or lean, mixture CO is still formed because of dissociation, still present as phenomena. For fuel-lean mixtures, CO emissions measured at tailpipes are higher than predictions from kinetical-controlled analysis of bulk gas [5].

If CO and NOx emissions are mainly due to mixture composition, temperature and pressure conditions, the same cannot be said for unburned hydrocarbons HC, whose formation mechanism is much more complicated. Even if they are called ‘unburned hydrocarbons’, they are not constituted by fuel escaped from combustion process without being chemically processed. The chemical composition of those molecules is different from exhaust and intake. It is almost unlikely that fuel remains unchanged at chemical level. Less than 50% of HC are made of unburned fuel: partial oxidation products and pyrolysis products are the major contributors to HC. It is in fact possible that a significant portion (about 10%) of fuel does not burn as expected. The phenomena is main due to fuel trapped into combustion chamber crevice, wall thermal boundary layers and the bulk quenching due to residuals slowing down combustion reaction processes. Still, luckily at tailpipe just 1% of the total amount of fuel injected is emitted as unburned hydrocarbons. Up to 80% of fuel trapped into crevices and thermal boundary layer is going to burn within cylinder during expansion stroke and in first part of exhaust system just downstream of exhaust valve. This is the so-called ‘postflame oxidation’. Postflame oxidation accounts so for HC reduction, but also to engine efficiency loss. The main formation mechanisms of unburned hydrocarbons in SI engines are [5]:

- Mixture trapped into crevice volumes (30-60% of the total HC for a warmed-up engine)
- Fuel trapped into the oil layer (5-30% of total HC for a warmed-up engine)
- Flame quenching at the combustion chamber walls (wall quenching - 5-20% of total HC)
- Bulk quenching or incomplete combustion (usually significant for $\lambda >> 1$ only, or high EGR)
- Fuel trapped by deposits (0-25% of total HC).

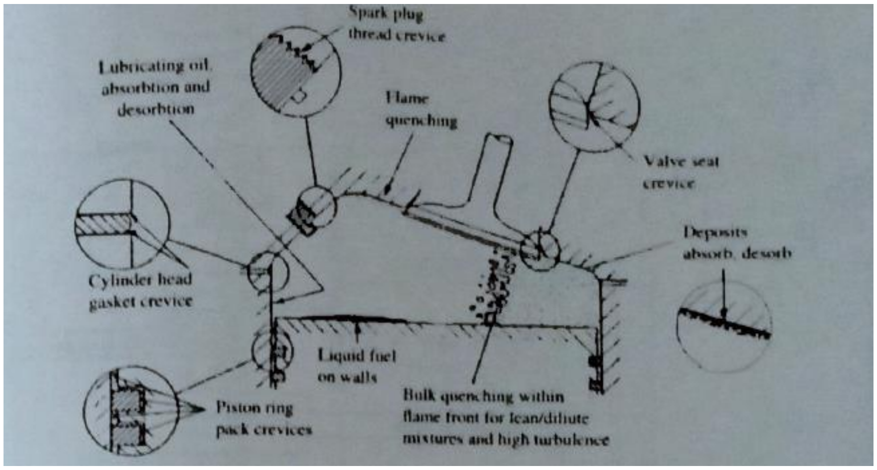


Fig 19 – Hydrocabon formation mechanisms in SI engines [5]

In compression stroke the pressure rises, portion of the mixture is forced to enter into the crevices of the combustion chamber. Later, during the expansion, when the pressure of the combustion chamber drops below the pressure level into the crevices, the trapped mass will consequently flow back into the chamber, but it is not able complete its oxidation process [5]. It is in fact too late to complete the combustion event. The major responsible in this mechanism feature is the ring pack volume, that can trap up to 10% of in-cylinder mass [5]. For what regard the fuel trapped in oil layer, some excess oil usually remains onto the liner and this oil can behave as a sponge, absorbing fuel. It usually happens during the compression stroke, when the fuel partial pressure is high [5]. Afterwards, during the expansion stroke, at low partial pressure of the fuel mixture, the oil layer desorbs the hydrocarbon molecules previously trapped, but at that time they are also in this case unable to complete their combustion process. From 5 to 20% of HC emissions are due to flame quenching at combustion chamber walls, due to thermal boundary layer in which mixture temperature is close to liner temperature, too low for hydrocarbons oxidation reactions [5]. Moreover, bulk quenching of the burned gas happens when the flame front slows down its travelling speed across the chamber in expansion phase, where temperatures and pressure of the mixture drop down. If temperature is dropping down too fast, the flame front can come to a stop, leaving part of the mixture unburned. This phenomenon is more likely to happen for slow combustion processes, such as those characterized by lean mixtures or high residuals, leading also to misfire phenomena. As a result, a high EGR rate will risk to increase HC emissions. Fuel trapped by deposits will lead to HC formation too, deposits that are present for example on intake valve and on combustion chamber walls. The former absorb fuel during the acceleration transients, and they then release fuel during deceleration phases, causing mixture enleanment during tip-in and enrichment during tip-out, and thus increasing HC emissions during transients. The latter can trap and release fuel with a mechanism similar to that of the oil layer, thus leading to an increase of HC emissions with engine age. Also, during cold engine condition and cold starts, HC emissions are significantly higher due to incomplete fuel evaporation and the relative mixture enrichment needed [5].

3.1.2 Primary pollutant emissions for CI engines

Diesel fuel is a mix of hydrocarbons that can be represented by the cetane, $C_{16}H_{34}$, with a long straight chain molecule with high reactivity [5]. Diesel fuel is capable of undergo oxidation reactions without any need of external trigger, so no spark is needed. Fuel jet atomize and vaporize, being surrounded by hot compressed air. Once fuel vapors are mixed with air, combustion may start without the need of an external trigger. The process is not capable of adapting to different speeds, however no throttle is needed at part load, the control of mixture is given just by injecting less fuel. Diesel engines usually operate lean, needing so specific after-treatment systems with respect spark ignition engines. In SI engines we have a clear separation of mixture preparation and combustion, with an interface between burned and unburned gas represented by flame front surface. In CI engines preparing and combustioning phases are almost mixed together (slightly separated just during the phase of ignition delay). So said, referring to average A/F ratio and average temperature of the mixture is not so meaningful as it is for SI engines. Actual CI engines combustion modeling is spatially and temporally defined by a first premixed combustion phase and then a diffusive one. The premixed phase is usually rich, and it is important for the definition of PMs in case in which local air/fuel ratios are equal to 0.5 (and/or equivalence ratio equal to 2). First PAHs compounds, which are soot precursors, will born around 5.0° ASI (after start of injection). Diffusive burning is important for the NOx rate control and it spatially surrounds the entire jet up to the liquid fuel penetration area.

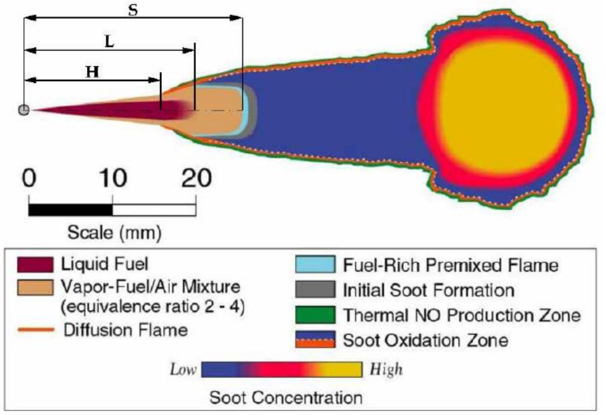


Figure 20 – Compression Ignition engines combustion model structure [7]

While CO and HC formations could be assumed almost similar to SI engines for our after-treatment systems analysis, the same could not be affirmed for NOx formations and PMs and soot emissions. According to J.B. Heywood, the fact that diesels operate at lean side makes CO diesel emissions low enough to be unimportant [5]. The HC mechanism formation is slightly altered by the fact that diesel fuel contains hydrocarbons compounds with higher molecular weights and boiling point with respect gasoline. The complex and heterogeneous nature of diesel combustion cause complexity, that leads to several process contribution to diesel engines hydrocarbon emissions. There are two main paths by which HC can be produced within diesel combustion escape. It can happen if the mixture become too lean to autoignite or too rich in some local areas. The lower combustion temperatures make possible for the postflame oxidations to happen only later in expansion process. However, main HC mechanisms are due to so called 'overleaning', 'undermixing' (related so also to injection pressure) and quenching and misfiring (related to coolant temperatures, cycle-by-cycle variability and engine operating load (higher at engine load). Multiple injections, today lot used, can also worsen the situation. Engine-out HC for diesel engines are low (order of 0.1% of fuel) over almost all engine operating conditions. Strategies for advanced combustion for anticipate a sort of 'premixing' of fuel and air before the normal combustion occurs (HCCI and PCCI) improve soot and NOx emissions but worsen HC. But it is important to add that HC can also play a role in operation of after-treatment devices like NOx traps and DOCs. Although also for the mechanism of NOx formation we can claim it is the same already described and discussed in SI engines, the cumulated NOx found inside the combustion chamber does not start to accumulate during the combustion process, since the first amount of fuel is burning under too rich conditions to form nitrogen oxides, that as known need lean environments. Once combustion process ends, NOx formation, of about 1/3 of the total, is present since hot enough burned gases, surrounded by air with fresh oxygen, are still available (ideal condition for NOx formation, until temperatures slow down). There is no significative NO formation from the premixed burn, with a combustion that is too fuel-rich to produce significant oxides. The first NO appears in a thin layer around the jet periphery just after the establishment of the diffusion flame. Then, NO formation continues in the post-combustion hot gases. NO formation investigations show that the NO forms on the lean side of the diffusion flame and in the hot post-combustion gases, indicating that the temperatures in these regions are critical for controlling NOx emissions from DI diesel engines [5 and 7]. Another main difference with respect to SI engines, is the ratio between NO_2 and NO. In SI engines, as already said, almost 100% of nitrogen oxides is constituted by NO. In diesel engines, on the opposite, higher emissions of NO_2 are present, especially at lower engine speeds (more time to achieve further NO_2 oxidation) and lower loads (that means higher oxygen availability). It is important to underline this difference, as we will see that some after-treatment systems are enhanced with NO_2 presence and are performing better if feed with NO_2 instead of NO. For what soot concerns, as previously stated, diesel combustion requires, for soot formation, very rich mixture (equivalence ratio from 2 and 4), and high temperature (above 1300 K). If temperature is too low enough, soot formation is limited. Initial soot formation is fast with very rich ($\varphi > 4$) local mixtures at relatively low temperatures (1600 K) [7]. Rapid soot formation happens in aromatics condensation reactions after premixed rich side, and lead to the formation of soot precursors identified in polycyclic aromatics hydrocarbons. After losing hydrogen atoms, the rings are going to cluster together in a kind of agglomerate (from Platelet to Particles – in the order of magnitude of nanometers) [5]. Indirect (slow) formation is also present: once the products of the rich premixed combustion burn out as a near stoichiometric diffusion flame at the jet periphery, a postflame oxidations is present, with a big percentage of soot (but not the whole of it) burning out thanks to oxygen availability. Unlike the other gaseous exhaust emissions, PM is not made of well-defined chemical species [5].

The definition of particulate matter types is determined, in fact, by its sampling method. The definition of PM leads to "any matter" either solid or liquid material (condensated) present in the diluted and cooled diesel exhaust. Particulates are formed by carbon particles in agglomerate, they adsorb other compounds creating structures of complex physical and chemical properties. Particulates have a dual or bimodal size distribution: they are a composed by nuclei mode and accumulation mode particles [5]. Nuclei mode particles are very small, known as 'nanoparticles'. They are volatile and mainly consist of hydrocarbon and condensates hydrated sulfuric acid, formed from gaseous precursors as temperature is decreasing in the exhaust system after mixing with cold air. A small percentage of nuclei particles consist of solid material, such as carbon or metallic ash from lube oil additives. Nuclei mode particles constitute the majority of particle number – on the order of 90%, but only a small percentage of the PM mass. Accumulation mode particles are formed by agglomeration of primary carbon particles and other solid materials, with presence also of adsorption of gases and condensation of vapors. They are composed of carbons mixed with condensed heavy hydrocarbons, but there also can be sulfur compounds, metallic ash, cylinder wear metals, etc. Diameters of the accumulation mode particles are between 0.04 and 1 μm with a maximum concentration between 0.1 and 0.2 μm. Most PM mass emission (but only a small proportion of the total particle number) is composed of agglomerated particles [5]. Moreover, to better understand PM size distribution, it is needed to introduce the definition of "Aerodynamic diameter". Particulate Matter classification on the basis of this definition [8]:

- PM_{10}: particulates having aerodynamic diameter lower than 10 μm;
- Fine particles: particulates of aerodynamic diameter lower than 2.5 μm;
- Ultrafine particles: particulates of aerodynamic diameter lower than 0.1 μm (100 nm);
- Nanoparticles: particulates having aerodynamic diameter lower than 50 nm.

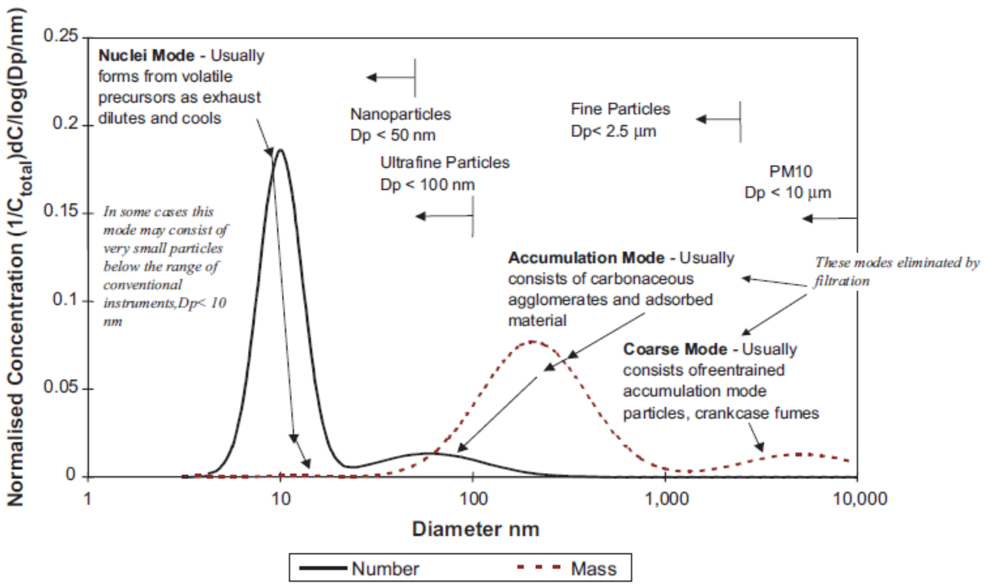


Figure 21 Classification of diesel engine PM according to size [8]

Most of the PM mass is due to accumulation mode (around 100 nm) and the bigger coarse mode from crankcase fumes, but there are much more nanoparticles, especially nuclei mode around 10 nm, so small that they can penetrate bronchial system of human health. Recent legislations pay attention on size distribution and number, tightening sampling of particulate at lower and lower aerodynamic diameter. Particulate Matter (PM) can be also traditionally divided into three main fractions, which can be further sub-categorized, as follows [5]:

- Solid fraction (**or carbon soot**)
    - elemental carbon
    - ash
- Soluble organic fraction (**SOF**)
    - organic material from engine oil
    - organic material from fuel
- Sulfate particulates (SO_4)

- sulfuric acid
- water

Particulate Matter (PM) composition can vary significantly as a function of the engine operating point, with high SOF content at low load and low speed and low temperatures. Solids and SO_4 are present at higher temperatures, load and engine speeds [FPT Industrial].

3.2 Reactions in After-Treatment-Systems

3.2.1 Three-way catalyst TWC

A catalyst is defined as a substance influencing the rate of a chemical reaction but is not part of the original reactants or final products, being in this way not consumed or altered in the reaction [5]. In transforming reactants to products, a catalyst is able to provide a path with lower activation energy. Catalyst is provided with two fundamentals properties: activity and selectivity. Activity is related to ability of enhance reaction rate, meanwhile selectivity refers to the ability of enhance and speed up certain reaction rather than others. The higher the activity of the catalyst, the higher the reaction rate of the reaction. [5]

Catalyst systems can be classified as:

- Homogeneous catalysts
- Heterogeneous catalysts

In a heterogeneous catalyst systems the catalyst is in different phase than the reactants, for example a solid catalyst acting on a gas phase reactions, meanwhile an homogeneous catalyst is one that is soluble in the reaction medium. Moreover, the heterogeneous catalysts can be also divided into supported and unsupported catalysts. A supported catalyst is a made with a carrier substance, with the proper form and a large surface on which the catalyst is layered. In unsupported catalyst, overall catalyst structure (like the substrate) consists of the catalytic medium. In aftertreatment case, the gaseous exhaust reactants flow through solid (substrate) heterogeneous (precious metals) supported (carrier) catalysts. In most systems, metallic or ceramic monolithic support structures are coated with a refractory oxide carrier (alumina), on which a noble metal catalyst is impregnated. The layer which is bonded to a monolithic honeycomb support is called washcoat. Through the washcoat, a loading of noble metals (PGM) is homogeneously dispersed.

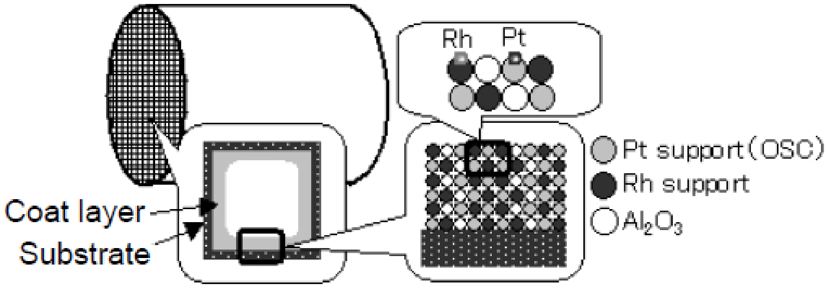


Figure 22 – Image structure of a conventional three-way [9]

Common formulations derive from Gasoline applications [5]:

- Ceramic or metallic substrate
- Support material (usually gamma Al_2O_3)
- PGM based washcoat.
    - **Platinum (Pt)**
    - **Palladium (Pd)**
    - **Rhodium (Rh)**

Pt and Pd are both effective to oxidise carbon monoxide (CO) and hydrocarbons, Rh is added to reduce NOx to Nitrogen. As we will see in deeper details, a zone coating with separate Rh layer promotes the interaction of NOx with the reductants on catalytic sites. In automotive engineering, the term “catalyst” does not indicate the material promoting the pollutant oxidation activity, but instead the entire device made up of [5]:

- An external shell (canister or canning)

- A substrate (honeycomb ceramic or metallic monolith): the typical measurement of the channel density is given by cells per square inch (cpsi),
- Washcoat or carrier (the most used is “gamma-alumina Al_2O_3);
- Catalyst (usually a precious metal as Pt, Pd, Rh).

As rule of thumb, a catalyst volume comparable with the engine displacement is needed

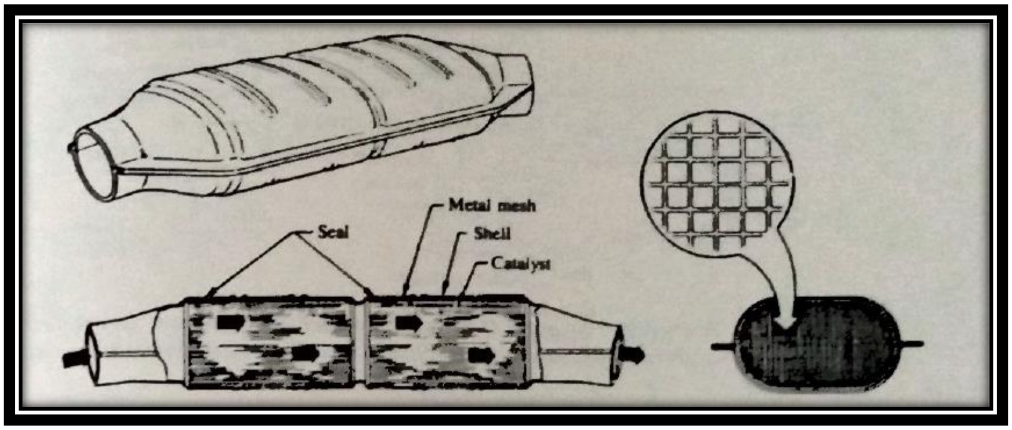
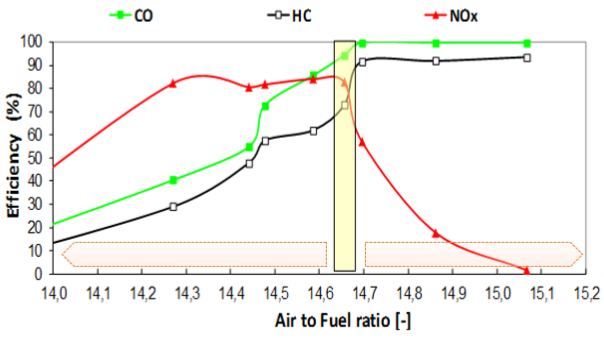


Figure 23 - Monolith design of catalytic converter for SI engines emissions control. Seal and metal mesh highlighted [5]

Three-way catalysts (TWC) are designed to simultaneously convert **CO**, **HC** and **NO_x** according shown oxidation/reduction reactions. TWC effect strongly depends on accurate control of air to fuel ratio. In order to achieve high simultaneous conversions of HC/CO and NO_x, their concentrations in the exhaust must be in stoichiometric proportion (in stoichiometric reaction window)



Oxidations	$CO+1/2\ O_2$	→	CO_2
	$HC+O_2$	→	H_2O+CO_2
Reductions	$NO+CO$	→	$1/2N_2+CO_2$
	$NO+H_2$	→	$1/2N_2+H_2O$
	$HC+NO$	→	$N_2+H_2O+CO_2$

Fig 24 – Three-way catalyst efficiency versus air/fuel ratio and main reactions [FPT Industrial]

High conversion efficiencies (80-90%) are possible to be achieved only if the engine is fueled with quasi-stoichiometric mixture (less than 1% deviation window from stoichimetric value). This is due also to pollutant chemical kinetics in relation with relative air/fuel ratio presence.

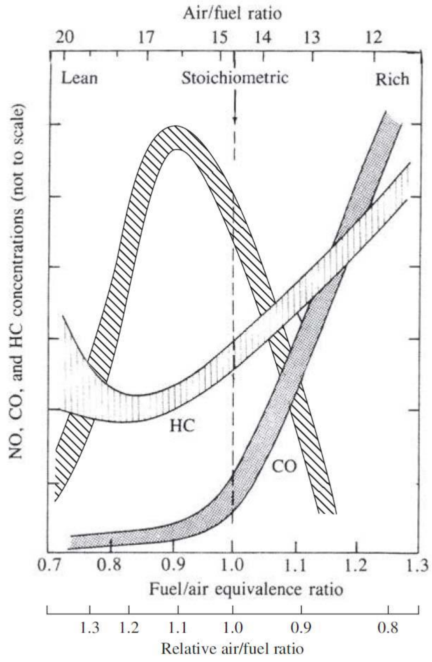


Figure 25 – NO, CO and HC concentration vs fuel/air equivalence ratio [5]

When the first automotive regulations were introduced, an oxidation catalyst only was implemented. It was able to oxidize unburned hydrocarbons and CO [8]. Then, the following type was the so-called Dual bed catalyst. The engine ran rich to enable NOx reduction over Pt/Rh catalyst with a second bed catalyst to oxidise excess of CO and HC, with introduction of air in between [8]. While the actual catalyst is the so-called three-way catalyst TWC, which groups the functions of the previous two. When engine is operated stoichiometric, both NO reduction and HC and CO oxidation can be achieved [5]. Enough level of reducing gases will be present to reduce NO, and enough O_2 to oxidise carbon monoxides and hydrocarbons. By the early 1980s Pt/Rh three-ways were used with electronic fuel injection, lambda sensors (oxygen sensors) and a microprocessor to give engine closed loop control around stoichiometric point [8]

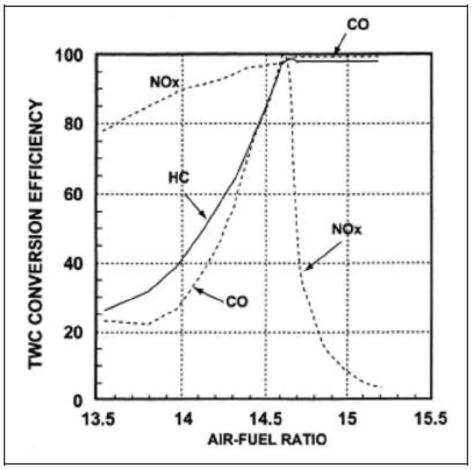


Figure 26 - Three-way catalyst performances in function of air-fuel ratio for CO/HC/NOx [10]

The catalytic reactions inside the catalysts can be summed up in 7 steps. The complete conversion process happens through the following physical and chemical steps [5]:

- Bulk diffusion of reactants. Reactant from the exhaust will contact the catalytic sites in the carrier outer surface. It then diffuses through the gas boundary layer in the proximity of the carrier.
- Pore diffusion of reactants. Most of reactant molecules must diffuse through the porous carrier toward the deepest internal dispersed active sites.
- Adsorption of reactants. After the molecule of reactant arrives then at the catalytic surface, it must chemisorb onto a catalytic site.
- Catalytic reaction. Catalytic reactions, which occur in the active sites, which then converts reactants to product B.
- Desorption of products. After the reaction, products desorb from the catalytic sites
- Pore diffusion of products. Product will diffuse through the pore carrier network to the outside surface.
- Bulk diffusion of products. Once arrived at the outside surface, products must diffuse into the bulk gas flow.

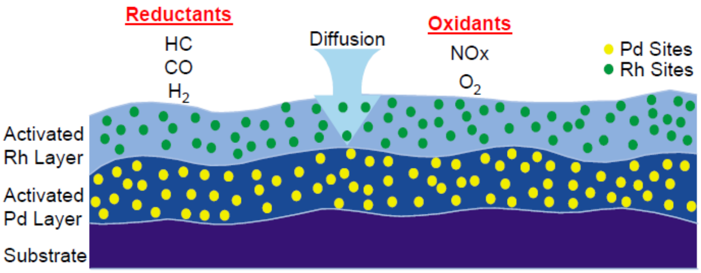


Fig 27 – Structure of TWC active reducing and oxidant layers [FPT Industrial]

At low temperatures, chemical reaction speed rate is slow at diffusional level. The phenomena is a regime that is reaction kinetics-controlled. As the temperature exceed a certain threshold, the reaction can proceed with high activation energies and control of the overall rate is then on pore diffusion rather than chemical. Finally, at highest temperatures, both the chemical and pore diffusion rates become sufficiently fast. In this manner bulk mass transfer, that has a small dependence on temperature level, becomes rate limiting. This last concept is somehow traduced in temperature dependence of the catalyst efficiency, that brings to the concept of light-off temperature (LOT). Initially it was defined as 'the minimum temperature necessary to initiate the catalytic reaction', then a more precise definition linked the LOT to the temperature at which conversion efficiency reaches 50% (in fact it is also referred as T50). Obviously the most active the catalyst is, the lowest will be its LOT.

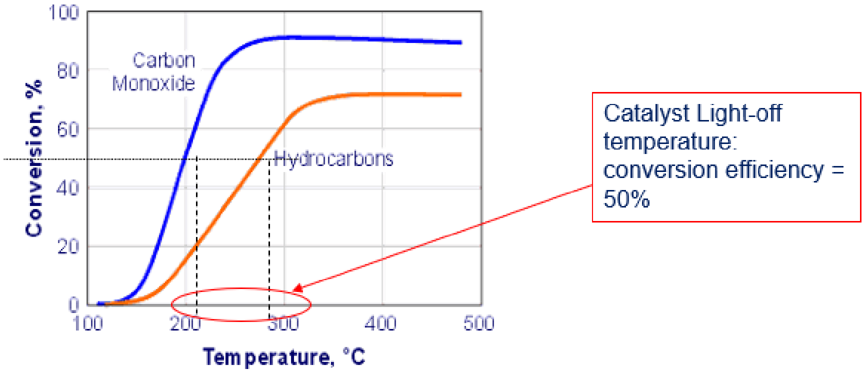


Figure 28 - Conversion of HC and CO over diesel oxidation catalyst [from *dieselnet.com*]

At very beginning two catalysts substrates were investigated: pellets and monoliths [8]. The latter have open parallel channels across which gases flow. Pellet substrates were made of spherical particles, mostly in gamma alumina, placed in canning. Their disadvantages were higher pressure drops and attrition causing catalyst loss. At same time, monolith guarantees no catalytic activity, and just deposit PGMs into substrate walls is not means of catalytic performances and durability. Therefore by treating monoliths with high surface area γ-alumina and coating the monoliths with both this high surface area carrier and PGMs the problem was solved [8]. Their advantages include compactness, larger frontal area and low backpressure and attrition resistance that bring to reduced catalyst loss. Monolith honeycombs became standard in today's automotive catalyst production. They have lot of small parallel channels (flow-through typology) with supporting material that can be either metallic or ceramic. The cross-sectional view almost always embedded is the circular one. In late 1970s the usage of metal foil as monolithic substrates substituted the pellets material [8]. Advantages with their metallic thin foils are that they are ready to be welded on exhaust line, their higher geometrical surface area, lower backpressure and absence of thermal cracking but instead good mechanical strength [8]. First applications however had some durability problem of the iron-based alloy in the extreme exhaust corrosive environment that is proper of the exhaust gas streams. Iron-Chromium-Aluminium ferritic steels gave already the right resistances, but the most successful substrate materials are based on extruded and high temperatures fired composition of **cordierite $2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$**, which represent most of automotive substrate typology in production [8]. Examples of metal foils characterising substrates are showed in the below picture at left, while extruded cordierite substrate is at right.

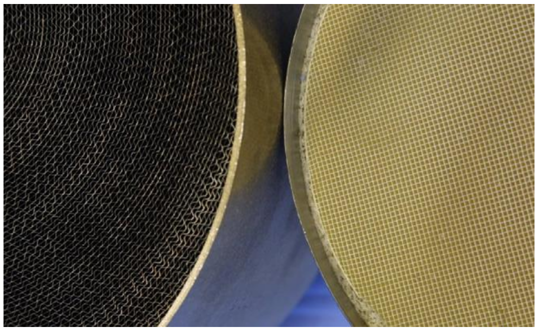
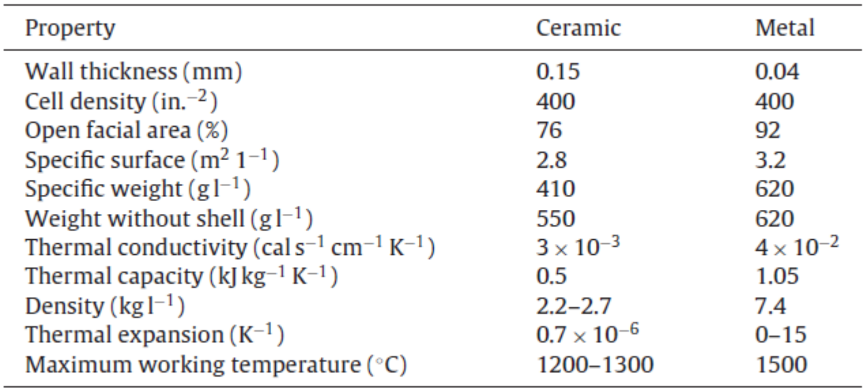


Figure 29 - Examples of a metal foil catalyst substrateand an extruded cordierite substrate [8]

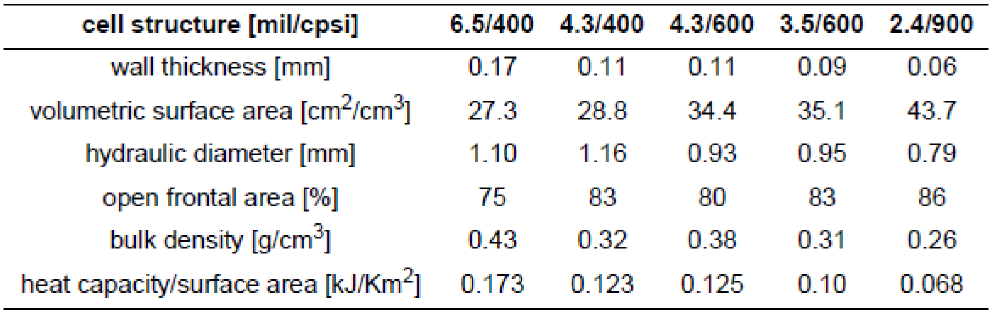
Ceramic substrates have usually squared honeycomb cells, while most metallic have sinusoidal channels. As we will investigate in following chapters, the ceramic monolith is usually hold in a steel canning mantle by a so-called ‘intumescent mat’ that expands in heating and ensures that monolith is retained. Usually, an important parameter to evaluate monolith characteristics is the cell density, which measured in cells (or channels) per squared inch (cpsi). Usually, the order of magnitude is of hundreds of cells per square inch of cross section.



Property	Ceramic	Metal
Wall thickness (mm)	0.15	0.04
Cell density (in.$^{-2}$)	400	400
Open facial area (%)	76	92
Specific surface ($m^2\ 1^{-1}$)	2.8	3.2
Specific weight ($g\ l^{-1}$)	410	620
Weight without shell ($g\ l^{-1}$)	550	620
Thermal conductivity ($cal\ s^{-1}\ cm^{-1}\ K^{-1}$)	3×10^{-3}	4×10^{-2}
Thermal capacity ($kJ\ kg^{-1}\ K^{-1}$)	0.5	1.05
Density ($kg\ l^{-1}$)	2.2–2.7	7.4
Thermal expansion (K^{-1})	0.7×10^{-6}	0–15
Maximum working temperature (°C)	1200–1300	1500

Table 5 - Physical properties of ceramic and metallic substrates [8]

Target properties are high operating temperatures, high mechanical strength, low density and thermal capacity to have a faster warm-up, low coefficient of thermal expansion and last but not least a good compatibility with washcoat and exhaust environments. Costs are also considered. Thermal shock resistance is good for both cordierite ceramic and metallic, but for thermal expansion coefficient and thermal conductivity respectively. Cordierite weights less but thin foils construction of metallic substrates can achieve low apparent densities. Both have good target reaching, cordierite is preferred over last year implementation thanks to lower costs, thin walls lower backpressure. Higher maximum working temperatures achievable with metallic substrates make them preferrable in case of closed-couple and high temperatures applications instead. Scmidt et al. classified some characteristics of cordierite substrates, here below reported.



cell structure [mil/cpsi]	6.5/400	4.3/400	4.3/600	3.5/600	2.4/900
wall thickness [mm]	0.17	0.11	0.11	0.09	0.06
volumetric surface area [cm^2/cm^3]	27.3	28.8	34.4	35.1	43.7
hydraulic diameter [mm]	1.10	1.16	0.93	0.95	0.79
open frontal area [%]	75	83	80	83	86
bulk density [g/cm^3]	0.43	0.32	0.38	0.31	0.26
heat capacity/surface area [kJ/Km^2]	0.173	0.123	0.125	0.10	0.068

Table 6 - Characteristics of some cordierite substrates [11]

The thickness of each substrate wall/channel is expressed in mil (1/1000 inch), close to 120 μm. Increasing the number of cell densities (cpsi) it is needed to decrease the channel thickness to get almost the same open frontal area and backpressure properties and/or heat capacity on surface area. If we see pressure drop against substrate geometry and structure, we can figure out and confirm that increasing number of channels the pressure drop increases, phenomena to mitigate by thinning walls [11]. The volumetric surface area is an important parameter to consider too, the higher it is and the higher there is surface onto which catalyst conversion can be achieved for the same volumetric dataset, improving in particular catalyst conversion efficiency at high temperatures. It can be increased by increasing number of cells per square inch. Extruded cordierite monoliths are the most implemented thanks to good thermal shock resistance and low coefficient of thermal expansion [10]. Metallic ones can have a bigger open frontal area and so high geometrical area per volume and lower backpressure. With higher thermal conductivity they guarantee higher light-off performances, but also more thermal expansions and less mechanical strength [10]. Reducing the mass of substrates can improve also performances, for example by increasing porosity level the same backpressure and thermal stability could be achieved but with more surface area at disposal for catalytic reactions [10]. Ceramic substrates have lower specific surface area and higher porosity with respect metallics. Anyway, both have low specific surface, while larger values are required to deposit catalyst. As we know the solution found is to get high surface area material coating into channel walls, found as an additional layer of metal oxides coated on walls of metallic or ceramic structure. It is the 'washcoat', porous high-surface area inorganic oxides, mainly represented by γ-Al_2O_3.

Comparison of some design parameters for some substrates, taken as examples, are showed in following figure

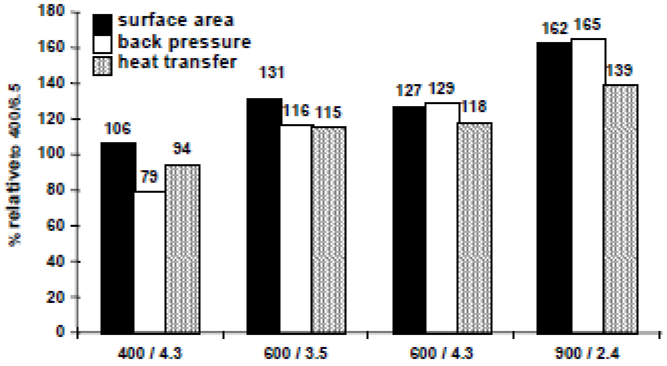


Fig 30 Substrate design parameters for different architectures [11]

Also the thickness and distribution of washcoat must be monitored for pressure drop control. The thicker is the carrier layer, and obviously the higher is the pressure drop. On the other side, a good carrier deposition is needed to tolerate aging and degradation phenomena, that we will later see.

Washcoat loading	none	high	medium	low
pressure drop	100 %	139 %	124 %	119 %

Table 7 - pressure drop for a substrate with different washcoat loading levels [11]

According to Schmidt et al, a medium coating load is the favourable to avoid too much CO/NOx conversion efficiency degradation due to aging but also to not increase too much pressure losses. So we experienced how coating of the support could interact with pressure drops and characteristics performances proper of the substrates. More in detail, the monolithic substrates are supports coated with these high-surface area oxides of inorganic types [*dieselnet.com*]. They have the name washcoat after the name of application. So washcoat stands for the refractory oxides coated in monolith. Its main function is to assure the right area needed for dispersion of catalytic metals. Moreover, the washcoat may additionally prevent undesired reactions between catalytic components. Washcoat materials are mainly Al_2O_3, SiO_2, TiO_2, CeO_2, ZrO_2, V_2O_5, La_2O_3 and zeolites [10 and 12]. For them, their main usage could be as described carrier (γ-alumina) or stabilizers (SiO2, ZrO2), or enhancing a catalyst characteristic called Oxygen Storage Capacity (OSC) like the Cerium oxides, or even have catalytic activity on their own. Target specifications required are those of high specific surface area and thermal stability for a washcoat. The application methodology involves a water based slurry (from which the name). Once the substrate is wet with the slurry, it is then dried and calcinated at high temperatures in oven. It is important to underline that precious metals for the catalyst (of the PGM group) can be present or not in the washcoat slurry [12]. If not, they are usually applied in a following step, often called impregnation. In impregnation, once the substrate has been already washcoated, it is passed in a water-based solution with precious metals catalytic precursors [12]. Once it dries and calcinates, the precursors will then decompose in final form. As reported in almost all base literature, most common catalyst are from platinum group metals (PGM) [5-8-10-12]: Pt, Pd, Rh. Even if the details of washcoating process are carefully traded by chemical catalyst coating makers (often in collaboration as suppliers with FPT Industrial), overview on manufacturing process of catalyst coating could be traced. First of all a water-based slurry is prepared from the γ-alumina powder and/or other oxides. After proper mixing, the alumina powder in water becomes a colloidal system [12]. It is important to set the milling of alumina powder to get the required particle size, since it can interact with mechanical strength and adhesion of the washcoat in the substrate. Powder milling can be done before (with air jet or hard materials) or during slurry preparation in wet milling solution [12]. There are lot of methods to apply slurry to monolith, from manual substrate dipping to robotized versions [12]. The main differences between methods is whether the slurry is recycled to coat a numbers of substrates or if it is metered in amount for each single substrate. It works either for single coating case or if coating and catalyst impregnation is done in a single slurry passage. In first recycling cases, the monoliths could be either immersed in the coating liquid or alternatively the latter may be poured over. The slurry recycling present disadvantages because slurry components could deposit preferentially on coated parts, leaving the rest of the slurry with composition changed, the process should be carefully controlled. With introduction of high cell density substrates almost all process passed to metered typology. An example of metered one is shown in following figure:

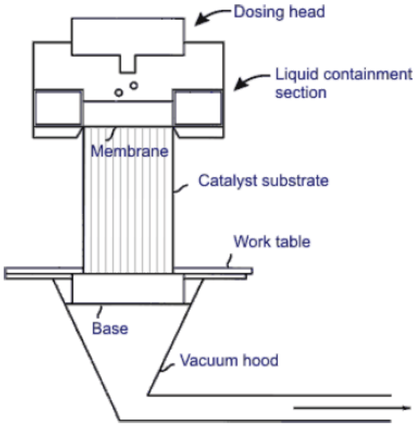


Figure 31 – Catalyst substrate metered manufacturing coating process [12]

The water-based slurry is poured from the top, where the dosing head feature is present, capable of metering the right amount of coating media, either if it is just washcoat slurry or impregnation solution also. Once this water-based solution is poured on top face of monolith (at the centre of the figure), it is forced into substrates channels by using vacuum [12] (from the bottom part of the catalyst substrate and the machinery). The slurry volume is selected enough to guarantee full retainment within substrate channels and no liquid is poured in the bottom downstream face. According to dieselnet.com, in other solutions the slurry is at first metered, and then with the help of a container pan, once the substrate had been positioned in this pan, the slurry is drawn in channels using vacuum from the top. In case of multi-layer coating (for catalyst design or coating process constraints reasons), each of the layer is dried and therefore calcinated, doubling coating passages in process. Aluminium oxide or alumina is the carrier material for catalyst deposition in automotive catalyst washcoat. The application is in high surface area gamma structure (γ-Al_2O_3) that has a crystalline structure and characterised by high purity, even if it easily reacts with sulphur compounds, that can be a problem in diesel catalysts. The starting preparation is from the monohydrate ($Al_2O_3 \cdot H_2O$) also known as boehmite, whose precursors receive a calcination phase transition at temperatures from 500°C to 850°C [12]. Once gamma-alumina is formed, a surface area between 100 m^2/g and 200 m^2/g is obtained [12]. Main issue related to gamma alumina, is its stability at high temperatures [12]. At temperatures higher than 1150°C-1200°C, the transition from gamma-alumina to alpha-alumina takes place and it is not reversible. About two orders of magnitude of surface area could be lost, being α-Al_2O_3 of about 1-1,5 m^2/g [12]. Some stabilizers could be added in washcoat formulation to help thermal stability and hinder temperature problems. Surface stabilizers are lanthaniu, barium and cerium oxides, while Na_2O can enhance alumina sintering [12].

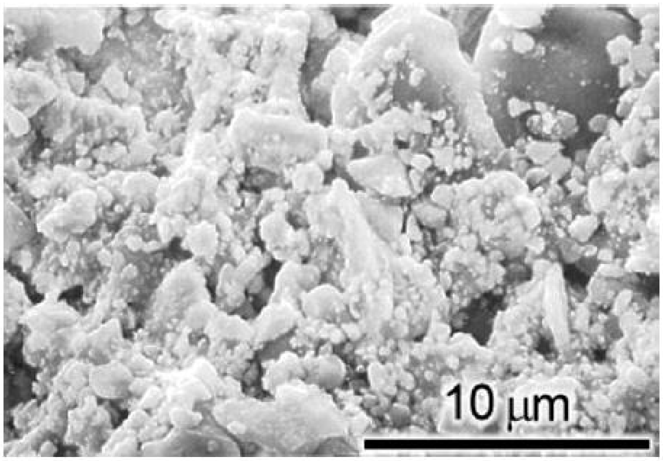


Figure 32 - SEM photography of a diesel oxidation catalyst washcoat [12]

Ceria (CeO_2) or ceria-based materials are utilised as promoters for Oxygen Storage Capacity of the three-way [12]. Oxygen Storage Capacity is a key feature in catalyst operations. Recalling the stoichiometric windows, we know that conversion efficiencies for NOx/HC/CO are not immediately dropping down as the stoichiometric value is passed (either toward lean or rich side), closed-loop control endowed with lambda-oxygen sensors allow the engine air/fuel ratio 'swing' around stoichiometric value. Since this 'swinging' environment of engine control nature, it is essential for the catalyst to store oxygen during lean operation (for oxidation purposes) to then release during rich ones. The catalyst characteristic is called Oxygen Storage Capacity, referred as OSC. According to J.B. Heywood, by adding cerium oxide up to 20-25% of alumina washcoat material, can help to release oxygen forming Ce_2O_3 when the exhaust is in rich window that then can absorb and make oxygen be stored in catalyst surface when exhaust gases are lean, with the transition [5]

$$2\ CeO_2 \leftrightarrow Ce_2O_3 + O$$

Ceria is the most important promoter in automotive three-ways. Ceria-based materials are added in alumina later in TWC to provide OSC. The oxygen storage function of the catalyst is possible through the described cycling between Ce^{4+} and Ce^{3+}. Other effects are alumina stabilization, noble metal dispersion and sintering avoidance, stream reforming reaction promotion. In diesel catalysts it can oxidate/cracking organic fraction of diesel particulates [12]. Cerium oxide by former calcination of cerium compounds has surface area about 150 m^2/g and can withstand about 1000°C. Zirconia is added to increase thermal stability [12]. According to Rood et al.[10] Ceria-Zirconia (CeO_2-ZrO_2) is used instead of pure ceria in order to avoid thermal stability issues of ceria above 800-1000°C (reached by exhaust gases) of sintering typology. Thermal stability could be improved also adding other stabilizer elements like Rare Earth oxides/metals (ReO) or alkaline earth metals. Ce-Zr has been studied in different ratios. Even the best OSC Ce-Zr ratios however show ageing problems in long-term, in particular for phase-separation. Introduction of rare earth metals (Y, La, Pr, Nd) can stabilize the material [10]. Moreover, the type of carrier support may influence dispersion of Pt, Pd and Rh. Ceria and Titania supports can be effective in hindering Pd metallic formation, while zirconia is beneficial in preserving Rh in aging. Manufacturers and literature were and are currently active in founding best formulations among catalyst carriers and precious metals presence to be effective in aging, against deactivation and sintering phenomena, thermal stable and good in performances (monitored as light-off temperatures for each pollutants). The choice of where to deposit precious metals is important too, leading to enhancing of catalyst performance and avoiding bad carrier/catalyst interactions. According to Rood et al. Pd/Al_2O_3 only catalyst performs better than a carrier of both alumina and ceria-zirconia. Incorporation of ceria and zirconia was found helpful in LOT performances for HC and NO, inhibiting sintering of Pt and providing OSC [10]. If possible, mixed oxides could be also coprecipitated in a single material. In addition, different % mol or % in weigh inclusions of ReO and alkaline earth materials have been studied with different catalyst formulations. In Pt-Rh inclusion of Nd improve both OSC and catalytic activity. Addition of La and Pr improve situation too. Rood et al. groups different literature studies, either for ReO added without alumina in carrier or in presence of alumina. One of the studies showed how the effects of ReO dopants could be beneficial even with alumina in the washcoat composition.

Titanium Dioxide (TiO_2) is used in some diesel catalysts as non-sulphating agent, while Zirconium dioxide (ZrO_2) is a ceria thermal stabilizer and a non-sulphating component, with a surface area between 100 and 150 m^2/g. It can lose some surface area once 700°C are reached, so usage of dopants like La, Si and Y is effective. Finally, zeolites presence is through these alumina-silicate compounds of synthetic or natural origin [12]. They have a well-defined crystalline structure and pore size. Dimension of the pores falls between 3 and 8 Å [12]. Thereby, any exhaust compound molecule that is larger will be blocked in the zeolite cage. It is a sort of molecular sieve and they act like sieves. Commercial zeolites embedded in catalysts include mordenite, Y, ZSM-5 [12]. The carrier selection is strictly related to the PGM mix choice. The choice is related to performances in catalytic activity, over engine air/fuel window, engine typology and engine out emissions. The choices are related to economical aspect too, as we will further see in following chapters. Economical aspects are often related to PGM market trends, in terms of demands, offers, reserves of PGMs and recycling paths, mining companies and labour situation etc. Generally [5]:

- Pt and Pd are better for oxidation reactions of CO and HC.
- Rh is preferrable for NO reduction.

For NOx reduction the ranking is Rh > Pd > Pt [5]. For low molecular weights hydrocarbons, Pd is more active than Pt, the opposite happens for long chains high molecular weights hydrocarbons (more related to diesel combustion) [5]. Platinum has highest catalytically activity for Diesel oxidation reactions while Palladium ensures durability by Pt-Pd alloy formation, preventing Pt sintering at high temperatures. Early oxidation catalyst used Pt with additional small amounts of Pd or Rh to provide this durability [8]. With incoming of legislations for NOx reduction, the synergetic between Pt and Rh was often chosen to have contemporary conversion of the three pollutants thanks to Pt and Rh NOx reduction good performances and the Pt overall oxidation capability over HC and CO [8]. Improving of catalyst performances made possible to switch at first to Pd/Rh catalyst and then to Pd only three-ways, where good HC performances were achieved, even if there are lower NOx and CO performances. It is worth to notice that this strategy was a lot perceived in the past also because the Pd was at that time less costly than Pt. At the moment there is an inversion of tendency, as the Pd price had overthrown Pt one since some years. The choice could be made for single engine/engine family and/or application, also taking care of several poisonings effects and interactions with washcoat. Pd, for example, is sensitive to poisoning by sulphur and lead [8]. This is reason why leaded gasolines and sulphur-content fuels were banned in almost all countries with the 1990s massive introduction of engine injectors feeding (instead of carburettors) closed loop control three-way endowed light-duty, medium and heavy-duty vehicles. Further descriptions of poisoning effects accounting three way catalysts will follow. It is good to account however that Pd and Pt are not interchangeable [10] without design considerations, and also Rood et al. confirms that Pd is less stable than Pt. In below figures main oxidation and reduction reactions are reported for a CNG engine:

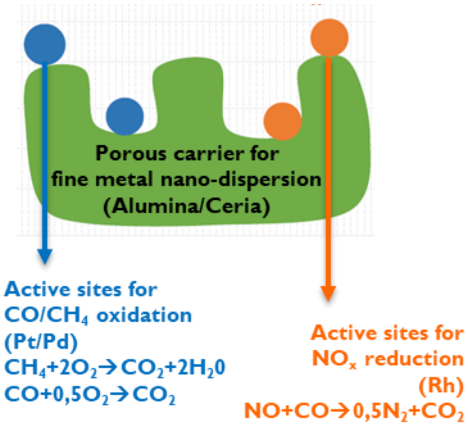
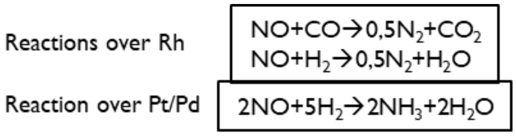


Figure 33 – Oxidation and reduction reaction in substrate for CNG engines TWC [FPT]

CO and HC have to be oxidized to carbon dioxide and water. NO can be instead reduced by using CO as reducing agent. It is worth to notice that NOx reduction over Rh is resulting in nitrogen, while over Pt and Pd is resulting for ammonia production.



Reactions over Rh $NO+CO \rightarrow 0{,}5N_2+CO_2$ $NO+H_2 \rightarrow 0{,}5N_2+H_2O$

Reaction over Pt/Pd $2NO+5H_2 \rightarrow 2NH_3+2H_2O$

$$NO + CO \rightarrow \frac{1}{2} N_2 + CO_2$$

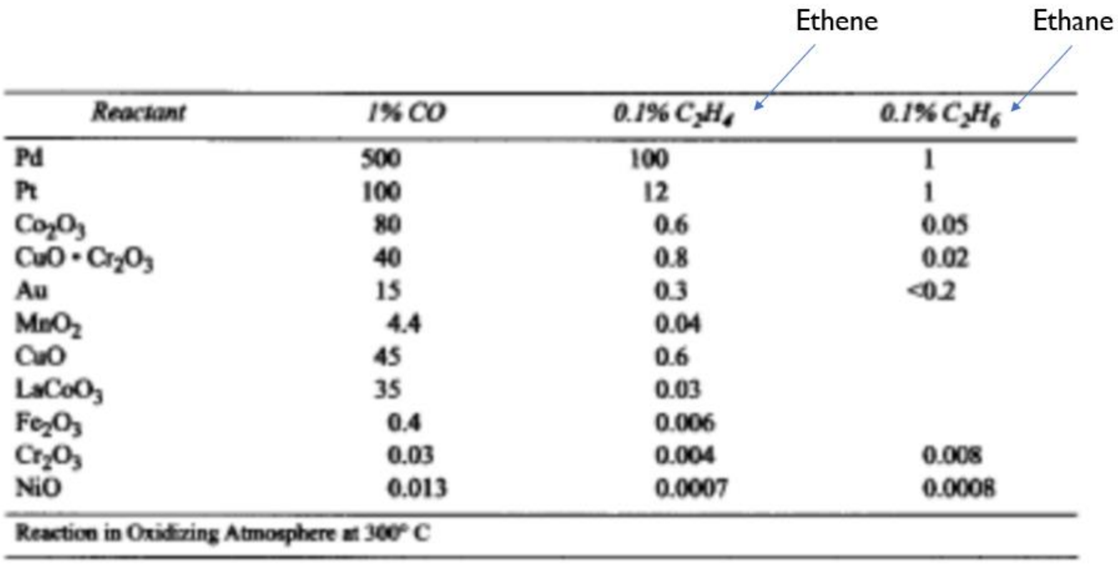
$$2NO + 5CO + 3H_2O \rightarrow 2NH_3 + 5CO_2$$

$$NO + H_2 \rightarrow \frac{1}{2} N_2 + H_2O$$

$$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O$$

[5]

Some examples of catalytic reactions activity rating for some precious metals or metals oxides are below reported in J.B Heywood book, reporting pollutant concentration cases in exhaust gases and relative catalytic reactions:



Reactant	*1% CO*	*0.1% C_2H_4*	*0.1% C_2H_6*
Pd	500	100	1
Pt	100	12	1
Co_2O_3	80	0.6	0.05
$CuO \cdot Cr_2O_3$	40	0.8	0.02
Au	15	0.3	<0.2
MnO_2	4.4	0.04	
CuO	45	0.6	
$LaCoO_3$	35	0.03	
Fe_2O_3	0.4	0.006	
Cr_2O_3	0.03	0.004	0.008
NiO	0.013	0.0007	0.0008

Reaction in Oxidizing Atmosphere at 300° C

Table 8 – Catalytic reactants reaction activity rating [5]

Rood et al. reported studies conducted from one of the biggest substrates coaters companies, related to the search of the right PGM synergy and loading quantities and their ratios. Pd/Rh and

Pt/Rh catalysts were tested over aged 950°C 80h condition (a lot used across manufacturers as they represent 160,000 km of usage, a road usage present in legislations limits). Evidence showed that increasing Pt and Pd loading is not related to big improvements in terms of HC or NOx reduction performances. Meanwhile, even if OEMs are seeking for low-Rh formulations, because of Rh is the most expensive of the three metals and most of its demand is automotive driven, this study reported showed that high Rh presence boost performances. Moreover, low Rh makes its Ceria interaction strong at higher temperatures [10] leading to loss of activity. However, if it can be valid in an homogeneous coating formulation, we will see that exploiting the thermodynamics and fluids-dynamics characteristics from different catalyst axial zone coatings formulation, makes possible to reduce Rh loading while also keeping good performances.

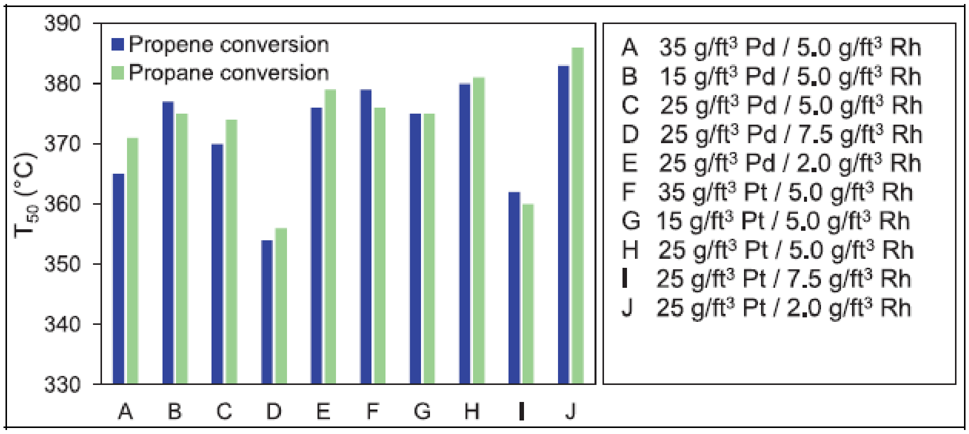


Figure 34 - T50 conversion of HC for different Pt/Rh and Pd/Rh loadings [10]

It is important to underline that washcoat formulation, in various stabilizers presence, could improve activity in relation of PGM ratios and prevent sintering and deactivation phenomena. Catalyst deactivation is mainly related to Pd/Pt and Rh alloys formation at high temperatures proper of ageing conditions [5 10]. Further explanations on segregated washcoat, involving separated PGM deposition on different carrier supports, and double washcoat layering will follow and can be considered in PGM choice, as well obviously for different zones formulations of the coating, that define the zone coating concept. Another important concept parameter to stress out and to consider in catalyst study is the Space velocity one. It is the ratio between the volumetric exhaust gas flow rate at given condition (mostly the STP standard ones) measured in m^3/h over the reaction volume, which in turn is the catalyst one (measured in m^3).

$$SV = {}^{volume\ flow\ rate\ of\ exhaust}/_{catalyst\ volume}$$

[5]

The space velocity represents how many times per unit of time the volume of the catalyst is substituted by new reactants. It is measured in [$time^{-1}$] (most in h^{-1}) and it is nothing different from a residence time measurement of the exhaust gas (reactants) into the catalyst site in the monolith. Too much higher space velocities (with a too small catalyst volume) means that the residence time of the exhaust gas reactants are too low, and therefore catalytic activity is mass-transfer limited. At low space velocities (less than 50.000 or 70.000 h^{-1}) ceramic monoliths provide better CO and HC conversions, while at higher ones metallic substrates are better due to large surface area and mass-transfer properties [10]. Moreover, another parameter to take into account is the catalyst ageing or deactivation phenomena. During real life catalyst are exposed to different organic and inorganic species originating from various sources (fuels, fluids), as well as various and often extreme temperature conditions. Catalyst durability investigations involve testing of a fresh catalyst, followed by the test of a catalyst aged in controlled conditions (oven ageing or engine ageing). Superposition of ageing and poisoning processes during real life of the catalyst makes it very difficult to represent properly the ageing in laboratory. Catalyst deactivation could be divided in thermal degradation and poisoning. Thermal degradation involves [FPT Industrial]:

- Cracks and ring-off
- Washcoat damages
- Precious metal migration
- Active component clustering and oxidation
- Collapsing of zeolite framework

Poisoning is instead due to different mechanisms. Overall, they can be divided in reversible phenomena and irreversible ones. In reversible, it is possible to restore the initial efficiency, usually at high temperatures. In irreversible ones, there is a not recovered loss of efficiency. Along with the thermal and poisoning effects, there is also the field ageing due to real mission of the catalyst, in terms of idling, low temperature and possible condensations. The three clusters are resumed in below picture [FPT Industrial].

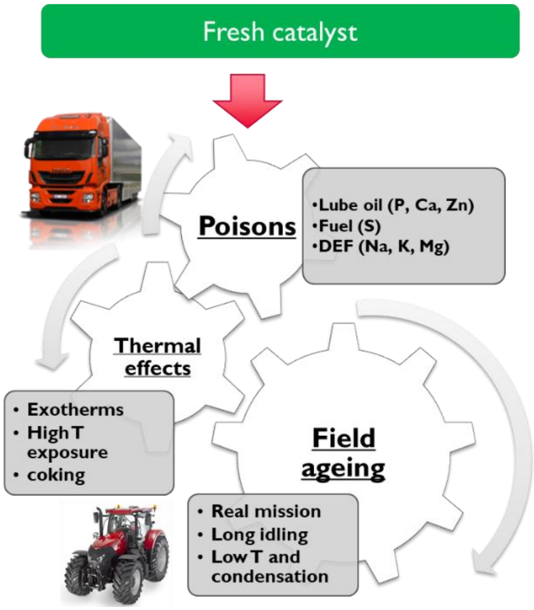


Figure 35 – Catalyst deactivation mechanisms [FPT Industrial]

Among the most important irreversible catalyst deactivation phenomena [5 – FPT Industrial]:

- Fuel poison adsorption
- Fouling
- Coking
- Precious metals sintering
- Active components migration
- Washcoat phase change
- Substrate disintegration

One of the most important deactivation phenomena to monitor in catalyst chemical definition and design is the sintering. Once the catalytic component had been dispersed on the carrier, it can be common that their crystals become unstable and grow or alloy. If crystals grow too much, available catalytic spots and catalytic surface area will decline. Exhaust gases will have less catalytic spots where react. The mechanism is known as catalyst sintering. As we have seen, composition of washcoat and ReO stabilizers adding could be important to avoid that. Sintering is not reversible.

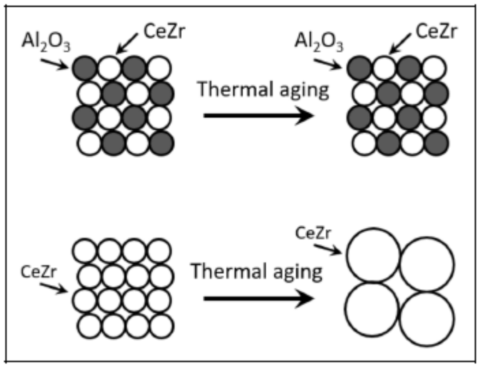


Fig 36 - Sintering behaviour of CeZr and CeZr/Al_2O_3 in aging [10]

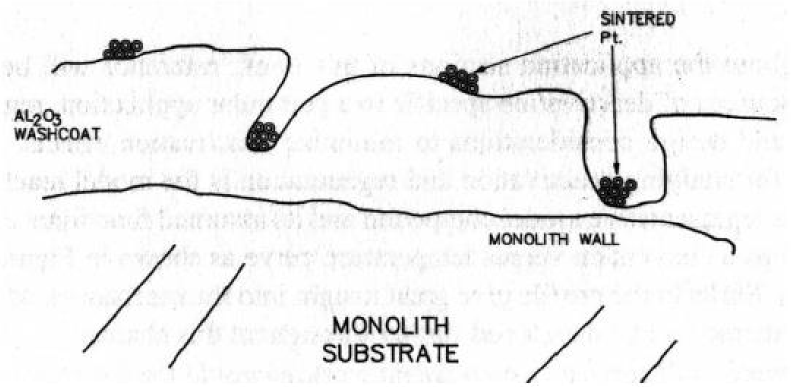


Figure 37 - Pore sintering due to higher temperatures reducing washcoat porosity [5]

Moreover, also poisoning effects could damage catalysts: we had overview on reason why leaded gasolines were banned. In past lead oxides were present in gasolines as knock suppressor. They can lead to permanent catalyst deactivation phenomena. In selective poisoning the poison compound directly react with the precious metal active crystal site or with the substrate and make them non-active. In non-selective poisoning there is hindering of catalyst active crystal sites due to phenomena like masking or fouling, that makes the catalyst non accessible. The poisoning can be either temporary or permanent [5]. Permanent ones are such of Pb, Hf and Cd, some other (SO_2 on Pt) chemisorb on catalyst site and block reactions, but it is reversible by desorbing the poison via heat treatment, washing or mechanical removal.

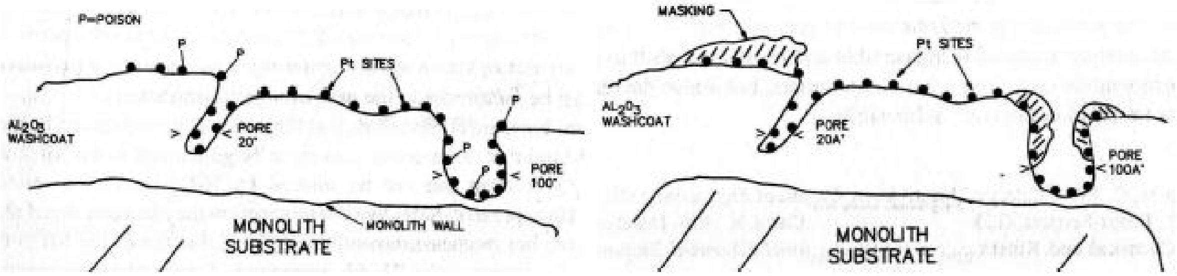


Figure 38 - Poisoning (left) and masking and/or fouling (right) [5]

In table 9 different deactivation phenomema due to chemical compounds present in fuel/exhaust gases and catalyst composition are resumed. It gives an overview on deactivation mechanisms and root causes:

Item	Deactivation mechanism	Recovery
S	▪ Masking of active sites; ▪ Pore blocking (SO2 and SO3 adsorption);	Reversible deactivation (Thermal treatment @ 450°C)
Soot and HC	▪ masking of its active sites; ▪ Adsorption of un-oxidized hydrocarbons, with potential additional transformation to more high deposits ("coke").	Reversible deactivation (Thermal treatment @ 600°C)
Ca, Na, K	▪ Degradation of key functions of the DOC, including the CO, HC and NO oxidation. ▪ The deterioration effect increased with the weight of Na and K.	Irreversible poisoning
Fe, Cu, Zn, Pb, Ni , Cr	▪ Chemical poisoning	Irreversible poisoning
P	▪ Physical masking ▪ Chemical poisoning ▪ Higher @ catalyst front zone	Irreversible deactivation: Could not be removed in-situ (thermal treatment) even under reducing atmosphere
Thermal Ageing	▪ Sintering of precious Metals ▪ Higher @catalyst rear zone	Irreversible deactivation

Table 9 – Deactivation mechanism overview

For Sulphur poison, there is ubiquitous among inorganic contaminants, even with ULS (Ultra low Sulphur) fuels. Cumulative exposure of a catalyst over a lifetime could reach kilograms of sulphur. The result is masking and pore blocking of active sites, but reversible at high temperatures. Soot and unburned hydrocarbons reversible poisoning is similar too, with additional possible adsorption on HC and cocking phenomena (the evaporation of light HC fractions and cracking of high boiling fractions that cohere and adsorb each other at high temperatures). The deactivation mechanism can be reversed by oxidizing soot and coke, via NO_2 or by O_2 oxidation (at high temperatures). Irreversible poisonings are from Ca, Na, K, Fe, Cu, Zn, Pb, Ni, Cr and P [FPT Industrial]. Ca, Na, K can originates for example from biodiesel and deteriorate DOC mainly, while chemical poisoning affects three-way that meet Fe, Cu, Zn, Pb, Ni, Cr where metal contaminants are mainly originated from engine and exhaust system construction materials. For P, masking and chemical poisoning effects co-exist in irreversible way, and the contamination appears in the form of a P containing overlayer on the washcoat surface (Zn, Ca and Mg phosphates) or phosphate compounds formed directly from washcoat components. For what regards the zeolites, their structure is mostly stable up to 800° C treatments. Increasing the collapsing temperature at which zeolite structure still maintains during thermal aging is a key for zeolite endowed after-treatments.

3.2.2 Diesel Oxidation Catalyst DOC

The DOC (nominally Diesel Oxidation Catalyst) is a component thought to enhance a series of oxidation reactions exploiting the excess of oxygen, in operating conditions of the compression ignition engine. At high exhaust temperature DOC is able to achieve up to 90% conversion efficiency on HC and CO. DOC catalytic activity could be extended to polycyclic aromatics hydrocarbons (PAHs) and to Soluble Organic Fraction (SOF) of Particulate Matter. In fact, since a fraction of the measured PM is composed by HC, if it is possible by means of the catalyst to oxidize the unburned hydrocarbons when they are still in the gaseous phase in the exhaust, not only a reduction of unburned hydrocarbon emissions is obtained, but even a reduction in the measured PM emission. Effects relevance are related on amount of SOF portion in PM: in a low-load operating point of the engine, where there is creation of a lot of SOFs for low relative amount of soot, the catalyst is capable of being effective reducing PM. Otherwise for operating points in which PM is almost made of soot it would be not possible to have good PM reduction results from DOC. The flow through monolith with catalytic coating involves:

$$CO + \frac{1}{2}O_2 \ \rightarrow CO_2$$

$$HC + O_2 \ \ \rightarrow CO_2 + H_2O$$

$$PAH + O_2 \ \ \rightarrow CO_2 + H_2O$$

$$Aldheydes + O_2 \ \ \rightarrow CO_2 + H_2O$$

[FPT Industrial]

At inlet we have CO, Aldehydes, HC, PAHs, being then oxidized in CO_2, H_2O, with poor effectiveness on SO_2 and NO.

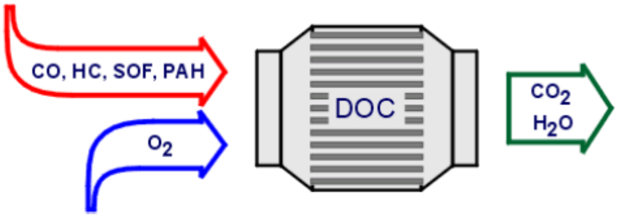


Figure 39 – Diesel Oxidation Catalysts chemical processing [FPT Industrial]

The DOC is nothing different from a three-way catalyst in terms of structure, substrate (cordierite), washcoat (gamma-alumina and stabilizers) and precious metals. The only difference is the **absence of Rhodium**, not needed to reduce NOx (especially if engine management strategies are actuated or EGR level is endowed). High level of CO and HC conversion efficiency are obtained through noble metal use like Platinum and Palladium that shows a very high catalytic activity. In applications that need high CO conversions at temperatures, high Pt loadings are used, up to 150 g/ft^3. [FPT Industrial]. Pt is the precious metal that is most active for long chains hydrocarbons typical of diesel combustion. The Pd activity is lower, on opposite trend of what happens for gasoline [5]. But on heavy duty vehicles side, too much Pt could be detrimental, boosting sulfur dioxide oxidation and producing more particulate. In passenger cars the usage of oxidation inhibitor (like V_2O_5) is fundamental, even if it could reduce catalytic activity. The monolith is usually a ceramic one, in past applications large cells were used, with cells density about 200 cpsi, in order to prevent clogging due to particulate. Nowadays higher cell densities are common. Number of channels (and volume of the catalyst) affects the conversion efficiency, increasing as these characteristics increase. On the contrary, the LOT mainly depends on precious metals selection. As anticipated, DOC brings poor effectiveness on compounds different from CO and HC. Apart from PM discussion, presence of sulfur dioxide SO_2 and NO must be careful treated. Oxidation of sulfur dioxide SO_2 to SO_3 (sulfur trioxide), leading to subsequent formation of sulfuric acid (H_2SO_4) in exhaust environment, which can then combine with water molecules, nucleate and so forming liquid particles composed of hydrated sulfuric acid, called sulfate particulates, may affects the total particulate matter emissions from the engine. Sulfates production bring significant increases of the total PM emissions, especially when high sulfur fuels are used. Oxidation of NO to NO_2 is also to be monitored, being the latter more toxic. However, on the contrary. it can be helpful to enhance the NO to NO_2 conversion to increase the regeneration of diesel particulate filters by the so-called CRT® effect (that is soot oxidation by NO_2) or to increase the performances of SCR and NOx catalysts, in particular at low temperatures range [FPT Industrial]. In fact, increasing NO_2 fraction in exhaust gases improves low temperature activity of any SCR catalyst, with faster reaction: optimum NO_2/NO content percentage ratio is 50/50, being the normal situation for a diesel engine (with no EGR content) on 95% NO and 5% NO_2 (and 99/1 for gasolines). In SCRT Systems, DOC upstream of the SCR catalyst is used to improve the SCR performance by oxidizing NO to NO_2. In figure we can see the enhancing of NOx conversion efficiency of this coupling solution, with presence of the optimized upstream DOC supposed to enhance optimum NO_2 presence [FPT Industrial]. The efficiency is monitored as function of temperature and the highlighted operating temperature window of the catalyst. The optimum NO_2/NOx content was reported at about 50% (vol.) which agrees with the NO_2/NO ratio of around 1 for the optimized catalyst reaction reported below [FPT Industrial]

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

Moreover, in a diesel engine CO and HC concentrations are an order of magnitude lower with respect to SI engines. This will lead to a lower increase of temperature during oxidation activity: it is problematic so to heat up the DOC. To resolve this issue, usage of zeolites in washcoat to trap HC is quite common. Incorporate zeolites improve performances in cold-start conditions, especially to oxidise HCs [8]. Zeolites are acting like molecular sieves and adsorbs HC preventing inhibition of active Pt sites. It will so also positively affect CO apparent oxidation performance. At higher temperatures HC and CO are then desorbed and normally oxidised on catalytic sites.

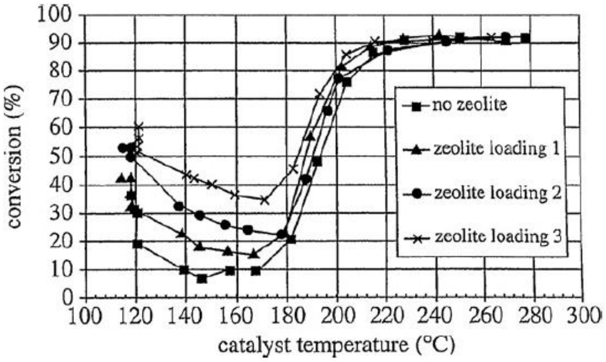


Figure 40 - Effect of thermally stable zeolites in DOC. Apparent oxidation of HC increases at lower temperatures by molecules adsorption in zeolites cages. [8]

Stabilisation of the PGM could be done via segregated washcoats [12] and via accurate selection of Pt/Pd in order to enhance alloy and avoid their sintering effects [8] achieving higher activity even after ageing conditions.

3.2.3 NOx reduction catalysts

NOx reduction catalysts may be necessary not only for diesel engines but also for gasoline engines operating lean (ex. GDI engines). Different approaches had been studied during last years for NOx control in CI engines, summarising in [5 – FPT Industrial]:

- Selective catalytic reduction with hydrocarbons (deNOx or lean NOx catalyst)
- Lean NOx traps (LNT)
- Selective catalytic reduction with ammonia SCR

The first two technologies are from passenger cars sector, while the SCR approach has been first developed mainly for heavy-duty transport sectors and then transferred also to passenger cars. The former deNOx is thought to use hydrocarbons as the reducing agent (instead the more used ammonia). For example by picking propane as a reducing agent, the follow reaction holds:

$$10NO + C_3H_8 \rightarrow 5N_2 + 4H_2O + 4H_2O$$

[FPT Industrial]

This deNOx chemistry can be realised ideally in two ways: the passive deNOx configuration is made by using the hydrocarbons emitted from engine itself, while the active one uses additional hydrocarbons through injection of fuel upstream the catalyst. Active systems, although have a better efficiency, present higher system overall complexity and fuel economy penalties. Most promising formulations are Copper exchanged zeolite (Cu/ZSM_5) or Platinum on alumina (Pt/Al_2O_3) [FPT Industrial]. Main drawbacks of these catalysts category are their narrow temperature windows, insufficient thermal durability and sulphur tolerance. Also, conversion efficiency is quite low, with a peak between 40-60%. The overall effects, combined, provide an efficiency of conversion of just 10-2% in a homologation cycle like the ECE/EUDC. Therefore, their application had been abandoned.

Therefore, another application typology has been developed: the Lean NOx trap. Despite its name, it is not a physical trap (like a DPF could be) but a chemical one. In order to increase the using temperature range of catalyst, materials for NOx storage have been integrated inside the deNOx catalysts. The adsorbers, which are incorporated into the catalyst washcoat, chemically bind nitrogen oxides during lean engine operation systems work through a two stages cycle [5]:

1. NOx storage inside the catalytic coating, during the lean operating conditions
2. Trap regeneration due to desorption and NO selective reduction of NOx, during the rich operating conditions

Barium or lanthanum oxides can chemisorb NO_2 formed by former catalytic oxidation (as the DOC one, the so-called CRT effect). When closed-to-rich operation condition are achieved, nitrates reduction to N_2 is achieved and regeneration of pre-existent oxides will occur. Usually, capacity of LNT in the fresh state is about 2g of NOx per each catalyst volume litre. Depending upon on emissions, catalyst size and conditions, and the desired NOx reduction, it is better to perform regeneration every 30-120 seconds [FPT Industrial]. Duration of NOx adsorber regeneration is short, between one and a- few seconds. Figure 41 well explains both the stages

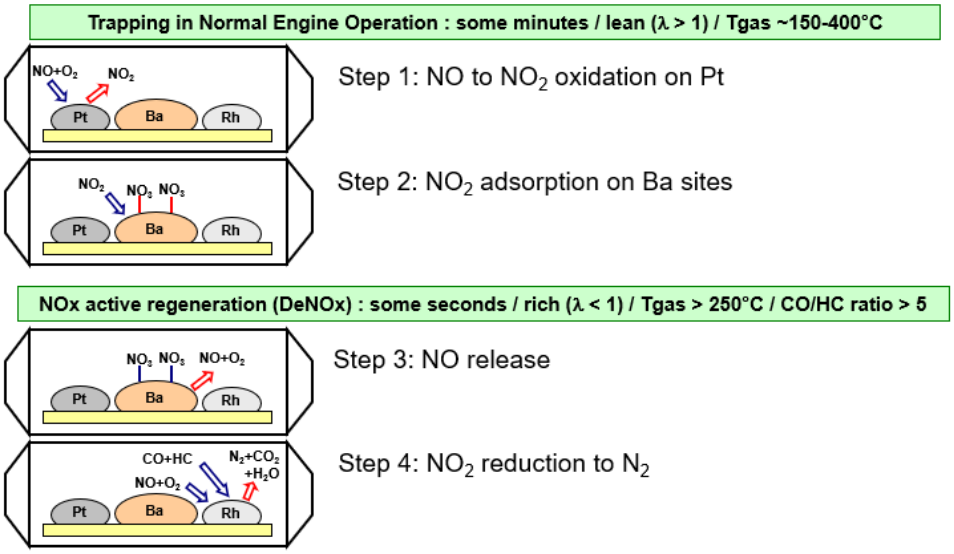


Fig 41 – Lean NOx traps working phases [FPT Industrial]

LNT NOx adsorbers are used in some diesel engines, mostly in light-duty applications. It is not highly recommended for those engines producing a lot of NOx. It is an alternative low-cost solution to SCR but with limited conversion efficiency. It has the same structure of the diesel oxidation catalyst (DOC), often replacing it, taking care of NOx reduction and HC&CO oxidations. During deNOx phase, unwanted N_2O and NH_3 can be produced. NH_3 production can be maximized and then exploited putting an SCR catalyst after LNT. The biggest drawback of this kind of ‘trap’ is its susceptibility to sulphur poisoning. Chemical reaction of sulphur are equivalent to NOx ones, but the link between Ba and SO_3 is stronger in respect to NO_2:

- SO_3 cannot be released during DeNOx phase
- trapping efficiency will fast decrease due to S poisoning.

Even the usage of ultra-low sulphur fuel would not be sufficient, and de-sulfation strategies must so be included in the catalyst management. The de-sulfation regeneration phase involves a dedicated combustion mode, with a rich mixture and high temperature level of exhaust gases (from 500° to 700°) for some minutes (from 10 to 15) [5]. It is performed with lower frequency event with respect deNOx phase (about one over 1000km), however it will produce a fuel consumption penalty, NVH problems, catalyst thermal ageing, control strategy complexity etc. [FPT Industrial]. All of that would lead to a decrease also of NOx conversion efficiency.

Urea SCR technology has been implemented as main NOx reduction strategy for HD diesel engines: it proceeds through the injection of the reducing agent inside exhaust flow before the catalyst. Urea SCR systems include an SCR catalyst, auxiliary downstream oxidation catalysts and upstream urea injection system which supplies urea solution upstream of the SCR catalyst.

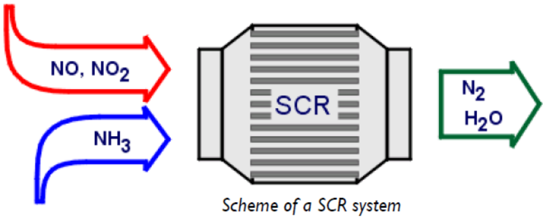


Fig 42 – SCR chemical processing [FPT Industrial]

SCR processes utilizing nitrogen containing reductants such as ammonia or urea are available for stationary diesel engines and for industrial ones. The specific urea/ammonia reducing agent has generally different commercial forms. AdBlue for instance is the commercial name for a 32,5% urea solution in water [FPT Industrial]. Fluid is stored in a specific tank and injected through a dosing valve on exhaust. At high temperatures (higher than 180°) it decomposes in NH_3 through hydrolysis reaction. NH_3 deposits on the substrate of the catalyst, where NOx flow. Catalytic oxidation-reduction reactions of nitrogen oxides will then take place inside the catalyst bed.

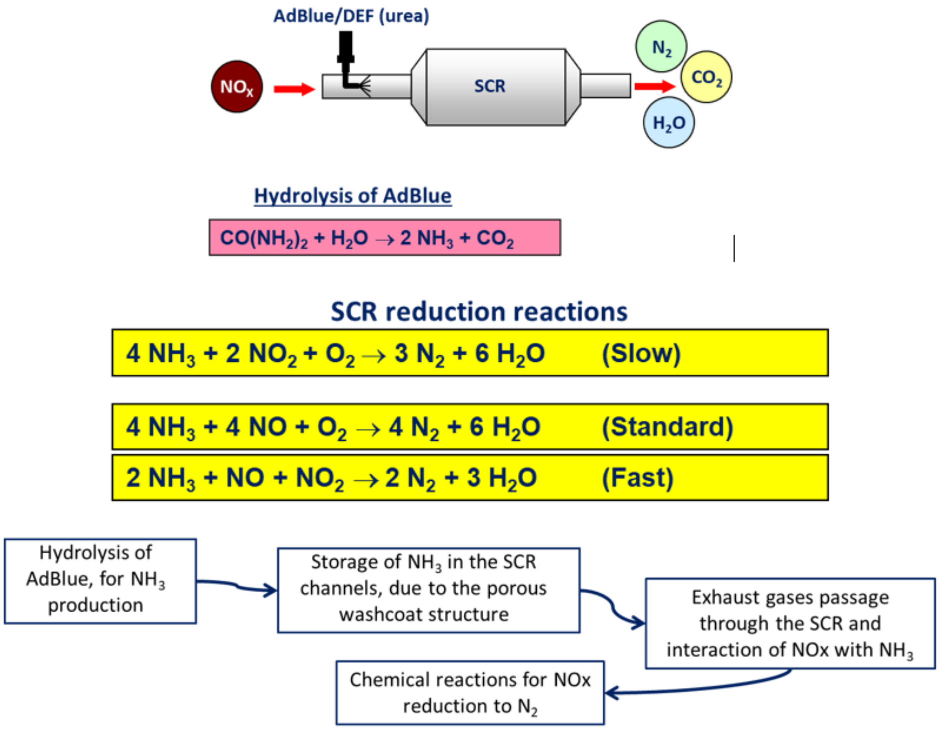
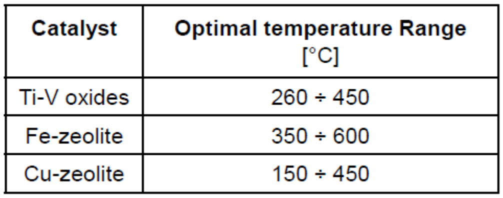


Fig 43 - SCR reduction reaction and scheme [FPT Industrial]

High NOx reductions could be achieved, depending on the catalyst temperature window and on the urea injection control strategy, which remains a challenge under transient operating conditions. Most common technologies (Vanadium and Cu/Fe Zeolite) have wide and different activity temperature windows [FPT Industrial]. Different solutions are available (fully extruded, coated on standard or high porous substrates) in order to improve specific features. Extruded ones have increased lower temperatures activity and are more stable in aged conditions. While for coated one, even if they show decreased level of lower temperatures activity, they allow possibility of zoning and layering of the coating. The coating on high porous substrates allows for a trade-off between the functionality of the extruded and the flexibility of the standard coated. Selective catalytic reduction of NOx with ammonia was first discovered over a platinum catalyst. The Pt technology can be used only at low temperatures (<250°C), due to its poor selectivity for NOx- reduction at higher temperatures [5]. The two groups of base metal SCR catalysts - vanadium and zeolite based - were later developed and can operate at higher temperatures. A V_2O_5/Al_2O_3 catalyst was used for first for high temperature application. Ti-V oxides are mainly active starting from 260° up to about 450° (exhaust gas temperature), with high temperature activity and stability improved in new formulation changing V_2O_5 content. However, this upper temperature limit is still not sufficient for certain hot gas applications. So metal exchange zeolites application were developed. For what regards metal exchange zeolites we can have mainly solutions with Fe Zeolites and Cu-Zeolites. Fe zeolites can operate at temperatures higher than 600° without thermal degradation. It has low selectivity to ammonia oxidation, leading to full NOx reduction efficiency even at high temperatures. the upper temperature limit is determined by catalyst durability (collapsing of zeolite framework). Cu-zeolites based catalysts have high efficiency at low temperatures but are affected by S poisoning and its efficiency at high T is lower than Fe-zeolites. Resuming, typical operating temperature windows of SCR (V_2O_5/TiO_2) catalysts are about 250-450°. The low temperature activity is insufficient for low load diesel engines operations. One method to increase low temperature performance of the catalyst is to increase NO_2 content in exhaust gases, thanks to already seen DOC promotion of NO oxidation into NO_2. The LOT can decrease down to 150°. Different catalysts temperature window could be found in below table



Catalyst	**Optimal temperature Range [°C]**
Ti-V oxides	260 ÷ 450
Fe-zeolite	350 ÷ 600
Cu-zeolite	150 ÷ 450

Table 10 – Optimum Temperature ranges for each catalyst typology [FPT Industrial]

Ti-V oxides catalyst performances are stable up to 50 hours ageing at 600°C. FPT engines adopt a thermal protection threshold to prevent the SCR catalyst from exposure to high temperatures. Stability can be improved in new formulation changing V_2O_5 content, with a trade-off between activity and ageing resistance to be found (low temperature performance is enhanced with low V_2O_5 content while at the contrary thermal ageing resistance need high V_2O_5 content).

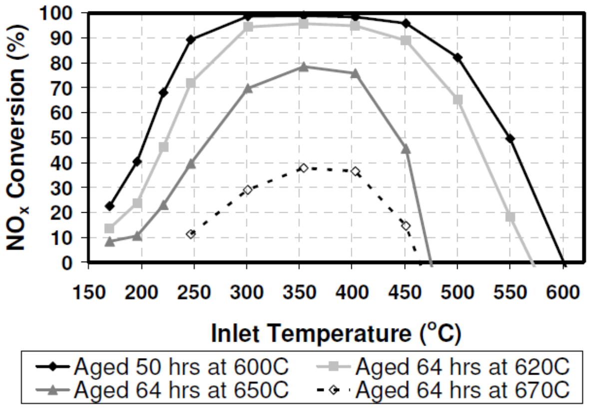


Figure 44 – Nox conversion % versus temperature for different aged SCR profiles [13]

Other requirements for SCR system optimisation could arise from the optimised exhaust system layout for maximum NOx conversion, that brings to the adoption of a mixer for gas and NH_3 distribution, till the optimisation of the exhaust gas temperature level by good positioning in vehicle and enhancing DOC LOT and DPF heating. A good NO_2/NO ratio upstream the catalyst is important too, as we already have seen [5]. The main advantage of SCR, which contributed to the widespread use of SCR in industrial applications, is its high NOx conversion efficiency, reaching a 90% peak [5]. SCR has successfully been adopted, from large stationary diesel engines till mobile ones, including marine, trucks and diesel passenger cars. Main drawbacks are costs, space requirements, urea solution consumption and control needed, as the vehicle could theoretically run once the solution is finished, but the legislation regulations obviously forbid that. But the main drawback is the possible generation of ammonia emissions (the so-called ammonia slip). Some legislations regulate that emissions typology too (ex. Tier 4 and/or Euro VI legislations limiting NH_3 content in exhaust at 10 ppm). The possible unreacted ammonia must be so removed. The CUC (Clean Up Catalyst) is a sort of strip of oxidation catalyst, integrated in the outlet of SCR, provided to control ammonia slip and neutralize any excess of NH_3 [FPT Industrial]

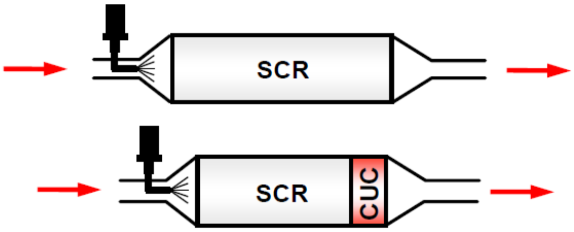


Figure 45 – CUC additional catalyst downstream SCR [FPT Industrial]

The main oxidation reactions are:

$$2NH_3 + \frac{3}{2}O_2 \rightarrow N_2 + 3H_2O$$

$$2NH_3 + 2O_2 \rightarrow N_2O + 3H_2O$$

$$2NH_3 + \frac{5}{2}O_2 \rightarrow 2NO + 3H_2O$$

[FPT Industrial]

3.2.4 Diesel Particulate Filter DPF & Catalyzed Particulate Filter CPF

The Diesel Particulate Filters are systems that physically trap the particulate, avoiding losing it in atmosphere. The filters represent the most efficient technology for the reduction of particulate emissions, due to the deposition mechanism on the surface of the solid particulate part. DPF for LD and HDV applications are usually of the wall through type, and they operate like a mechanical filter, blocking solid particles in the gas stream. Gases can pass only through sectors of monolith wall that allow passage of gas, stopping particulate particles and solids in exhaust. It is a sort of chessboard structure.

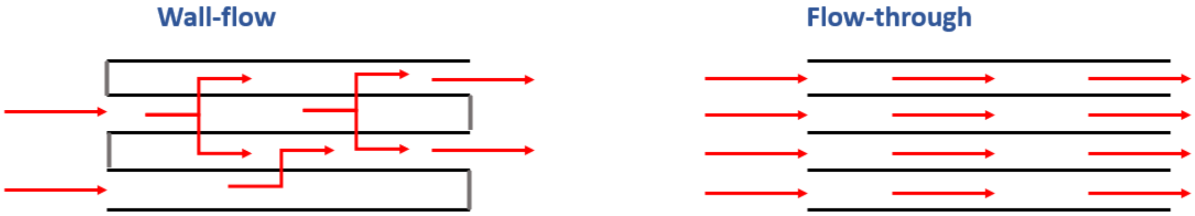


Figure 46 – Wall-flow vs Flow-through Diesel Particulate Filter [FPT Industrial]

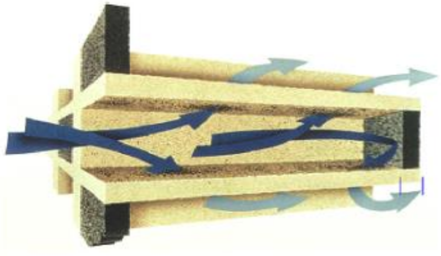


Figure 47 - Schematic of a ceramic wall-flow filter [8]

DPF usually adopts a cordierite or SiC (Silicon Carbide) or AT (Aluminum Titanate) substate, with channels that are plugged in alternate way to force the gas flowing through the porous walls. By doing that, particulates are mechanically trapped. Filtration occurs in two stages: at first through the porous wall by means of the so-called deep bed or depth filtration. Afterwards, once the first layer has been deposited, soot starts accumulating. Grow up of soot contribute to the so-called cake filtration mechanism [FPT Industrial]. The soot layer starts to become thicker and thicker as particle accumulates, as well as the pressure drop that increases, more rapid at the beginning and then almost linear with time. Initial DPF depth (deep bed) filtration relies on three main mechanisms of aerosol particles deposition: diffusion, interception and impaction.

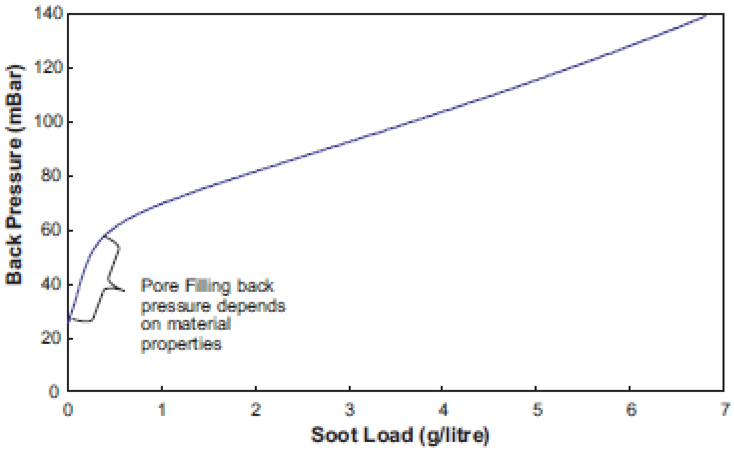
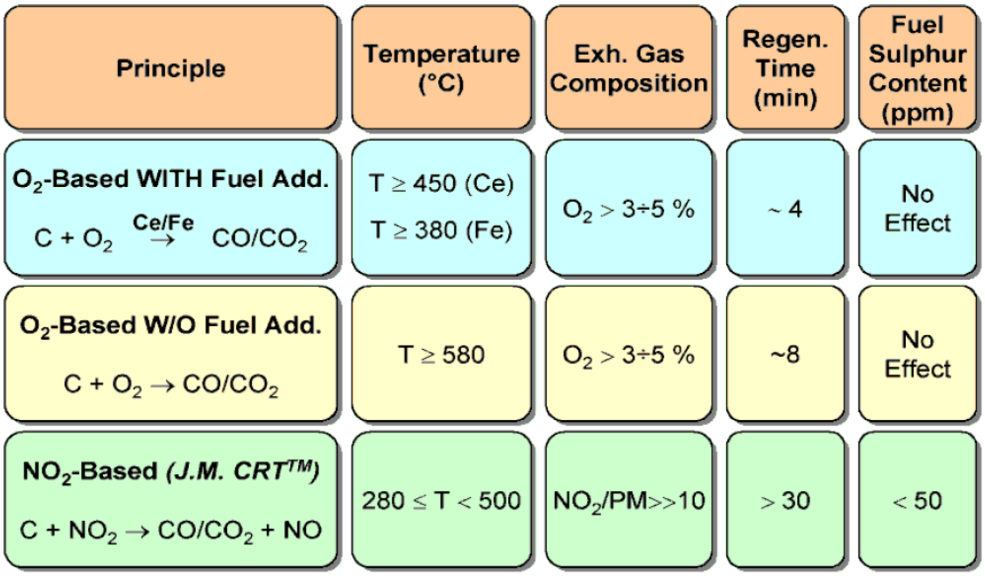


Figure 48 - Typical backpressure across a diesel filter as function of PM trapped [8]

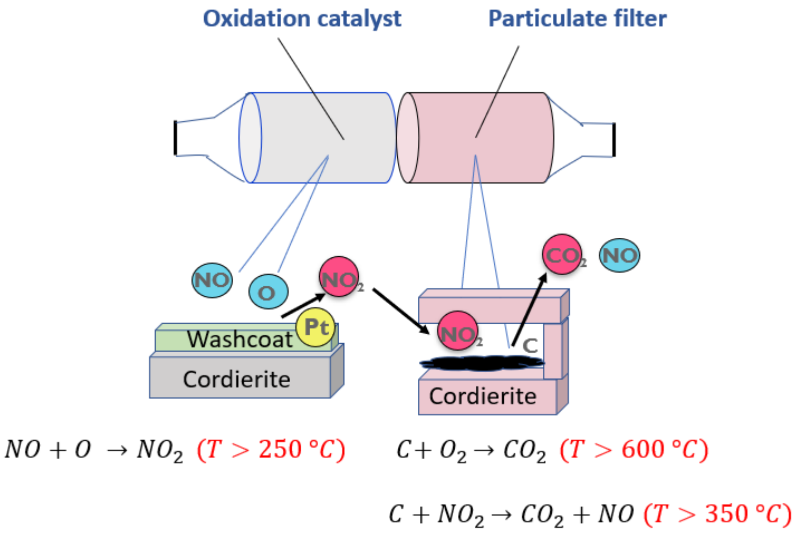
Meanwhile mass of trapped soot linearly increases over time. At end of linear delta pressure increase, the pressure drop will start to increase rapidly. Soot and ash accumulate within the walls and inside the inlet channels. While soot is removed during filter regeneration the ash remains in the filter causing a gradual irreversible increase in the filter pressure drop. The ash storage capacity can be increased by designing the substrate to provide more volume on the upstream (inlet) side of the monolith. The asymmetric design would provide a greater surface area for storing the ash leaving the ash filled inlet channels more open in comparison to the conventional design. Obviously, it is better to limit operation of DPF to B region of previous graph. To do that, regeneration is settled by oxygen soot burning. But to do that, temperatures higher than 600-650°C are needed. These temperatures are difficultly reached. NO_2 presence is although capable of burning soot at much lower temperature (around 250-350°C). It is the only chance to have spontaneous regeneration, thanks to the so-called CRT® (continuous regenerating technology) effect. However, the phenomena could be not enough. What it is needed is an increase in exhaust temperature. The possibilities of achieving that are related to mission profile of the vehicle (more difficult for light duty ECE and EUDC cycles) and control strategies [FPT Industrial].



Principle	**Temperature (°C)**	**Exh. Gas Composition**	**Regen. Time (min)**	**Fuel Sulphur Content (ppm)**
O_2-Based WITH Fuel Add. $C + O_2 \xrightarrow{Ce/Fe} CO/CO_2$	$T \geq 450$ (Ce) $T \geq 380$ (Fe)	$O_2 > 3 \div 5$ %	~ 4	No Effect
O_2-Based W/O Fuel Add. $C + O_2 \rightarrow CO/CO_2$	$T \geq 580$	$O_2 > 3 \div 5$ %	~8	No Effect
NO_2-Based *(J.M. CRT™)* $C + NO_2 \rightarrow CO/CO_2 + NO$	$280 \leq T < 500$	$NO_2/PM >> 10$	> 30	< 50

Table 11 – Different DPF regeneration method comparison

Another possibility is to enhance NO_2 for filter regeneration, produced by DOC from NO in the exhaust gas [5]. NO_2 has high capability to oxidize C to CO_2 at low T (350° C). Sulphur in the fuel strongly inhibits the formation of NO_2 in the oxidation catalyst. Ultra-high low S level fuels are needed.



$$NO + O \rightarrow NO_2 \ (T > 250\ °C) \qquad C + O_2 \rightarrow CO_2 \ (T > 600\ °C)$$

$$C + NO_2 \rightarrow CO_2 + NO \ (T > 350\ °C)$$

Figure 49 - CRT® scheme

The regeneration must be invisible to the drivers (no changes in the vehicle conditions) and have to occur without their help. In order to make the filter regenerate, the following mechanisms are used:

- Increase of exhaust temperature
- Decrease of ignition particulate temperature with the use of catalysts
- Decrease of ignition particulate temperature with the use of catalysts through the use of oxidant reagents

Regeneration via oxygen could occur thanks to

1- Turbocharger management
2- Multiple injections activations, by retarding injection
3- Post-injecting fuel

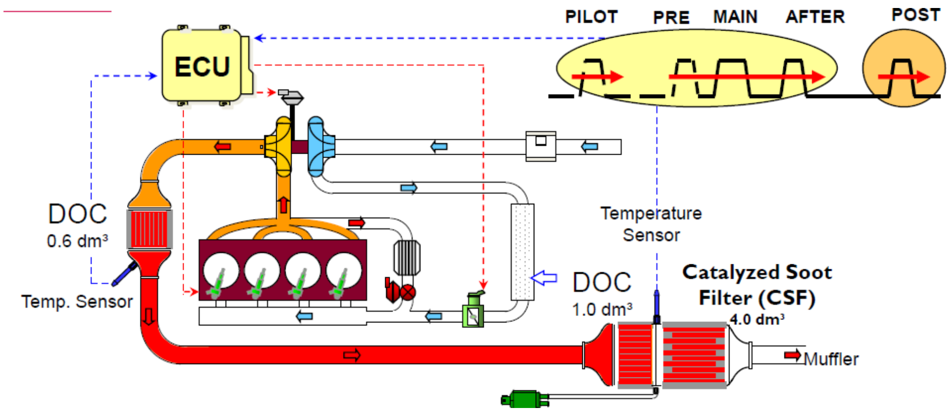


Figure 50 – Multiple injections regeneration method scheme [14]

Fuel which is not able to burn will increase HC emissions, HC can be burned by DOC upstream DPF. The temperature is so increased in almost all engine map. DPF cycles continuously between an accumulation and regeneration phase, with ECU waiting for a good window opportunity to get the regeneration event when engine is used at high load, being sure that LOT had been reached for all after-treatment systems components. Problematic occurrences related to the regeneration events are the followings:

- Fuel consumption increase
- Increase of lubricant oil dilution in regeneration by in-cylinder post injections
- Possible DPF damages in case of uncontrolled regeneration events (ex. drop to idle) and/or if the soot deposited over the filter exceeds a safety threshold (soot limit)
- Risk of accelerated aging or thermal damages to other aftertreatment components placed downstream of the DPF
- Risk of engine malfunctioning due to DPF clogging, if regeneration event fails

For what the pressure drop regards, it is a complex concept, depending on several parameters. It is quite difficult to correlate it to accumulated soot mass, so a mathematical statistical approach is preferred [5 - FPT Industrial].

$$\Delta P_{trap} = \Delta P_{in} + \Delta P_{soot} + \Delta P_{wall} + \Delta P_{out}$$

The parameters considered arise from the delta pressure of inlet and outlet cross section of the wall-through monolith, the soot-related delta-p and the wall one. Soot may accumulate in different way, depending from exhaust flow conditions through the mechanical porous trap. It depends from the velocity with which the particles are depositing. If velocity of particles is low, particles will have more time to deposit and will form a thicker cake soot layer, more porous and so producing less delta pressure. It would affect control strategy and regeneration window selection, so ECU should be aware of that selecting a statistical approach, over the estimated accumulated soot mass. Main DPF requirements are of high filtration efficiency (> 90%), high thermal resistance (up and over 1200 °C), high mechanical resistance and low pressure drop. SiC (Silicon Carbide) offers the best compromise across these requirements, but at higher costs [FPT Industrial]. The canning process and main components are similar to three-way one, with the intumescent mat used to hold the substrate monolith in the external shell. Parameters of the monolith are again the Open Frontal Area, the substrate cells density, the specific and total filtration area (SFA and TFA) that define respectively the total channel surface area per unit of substrate volume and the product of SFA and filter volume. Different DPF monolithic cell designs are possible: from conventional squared, to hexagon/triangle, to octagon/square, to asymmetrical squares and finally wavy cells [FPT Industrial]. Since Heavy duty vehicles are often equipped with CNG engines, in this case a CPF technology has also been developed. Dedicated CNG only technologies are to date not available, but standard passenger car formulation and expertise can be used. In passenger cars, from Euro 6 regulations, limitations to both SI and CI PM emissions have been introduced (may require the adoption of some particular after-treatment system – Gasoline Particulate Filter GPF). It is in particular effective on Gasoline Direct Injection engines too, with the local fuel rich combustion event (at the spark) that bring lot of particulates, similar to diesel combustion. It can be stated that the device is the same-one implemented in Diesel engines: it is a mechanical filter of wall-through type (and not flow-through monolith), composed by a sort of chess-board structure. GPF are systems that physically trap the particulate through the deposition mechanism on the surface of the solid particulate part. It is a cylindrical extruded ceramic monolith with high and controlled porosity, in this way the walls work as a sieve for particles [FPT Industrial].The gases so are forced to exit through the porous walls, made in ceramic materials (e.g. Cordierite or Silicon Carbide). The monolith is capable to support extremely high temperatures, up to 2000°C since SI engines undergo higher temperatures with respect to compression ignition ones. Filtration efficiency depends on cells parameters (cell density, wall thickness) and material properties (porosity, mean pore size). Smaller the pore diameter is, and thicker the wall is, the better the filtration efficiency [FPT Industrial]. Again, at the beginning there is the deep bed filtration mechanism, followed by the cake layering. Also in this case, filter efficiency increases with time, up to a point of limit maximum backpressure. It is trivial that the filter so must be regenerated by burning the soot accumulated. This time the temperature is not a big issue since the exhaust temperature is in SI engines case is high enough.

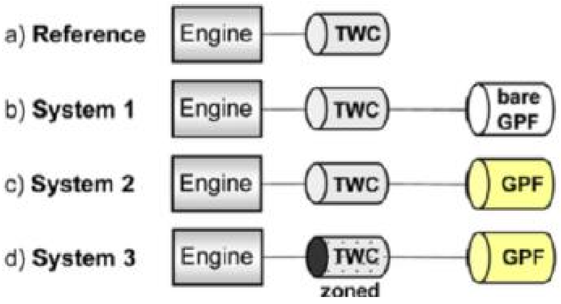


Figure 51 - Passenger cars possible GPF implementation [15]

In figure three different architecture possibilities for passenger cars applications. Next to the reference system, there is the possibility to couple the TWC with an uncoated CPF in underbody, or a coated one as well, here is reported only solution of coated GPF married to a zone coated TWC. As we will see the innovation in study will admit a bare GPF too downstream a zone coated catalyst, leading to precious metals loading costs decrease. Spontaneous CPF regeneration leads to eliminate all those drawbacks typical of DPF regeneration case. Moreover, by comparing the fuel consumption and CO_2 emissions over automotive engine cycles it has been highlighted an almost nihil impact due to the architecture configuration

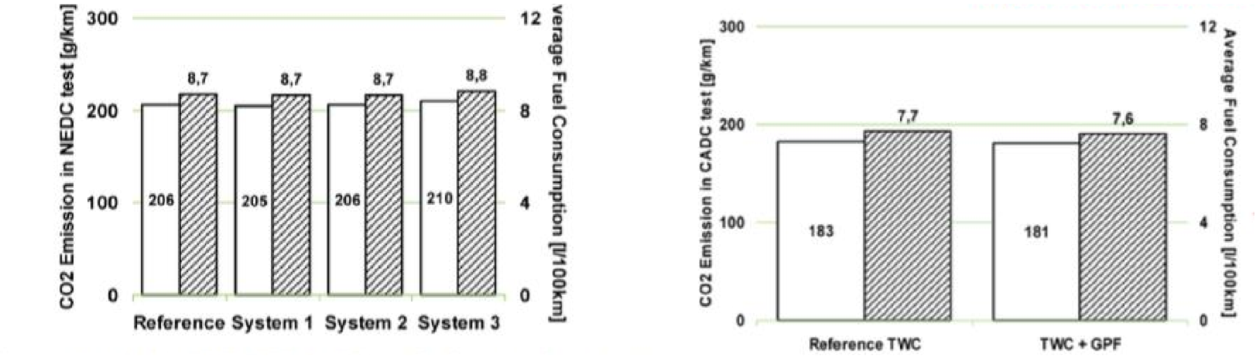


Figure 52 – Measured CO_2 emissions over reference architectures for different cycles [15]

For what regards pressure drop, filters with porosity around 50% can be used as uncatalyzed CPF, higher porosity (~65%) are intended for catalysed filters. A higher porosity leads to a lower delta pressure. A risk related to passive continuous regeneration is the ash accumulation onto CPF wall: ash is collected at the channel ends in actively regenerated filters. Particle numbers were well reduced by GPF over whole range of particle size, in particular around nano-meters dimensions [FPT Industrial].

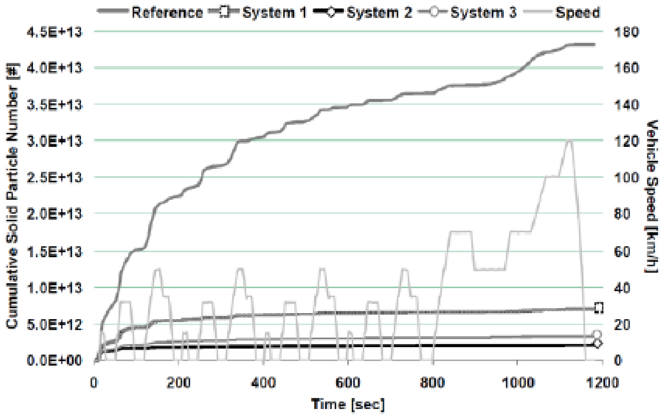


Figure 53 - Passenger car 2.0L – solid particle number emission profile in NEDC cycle [15]

In figure 54 we can find architecture adoption trend of different OEMs, in LD and HD segments

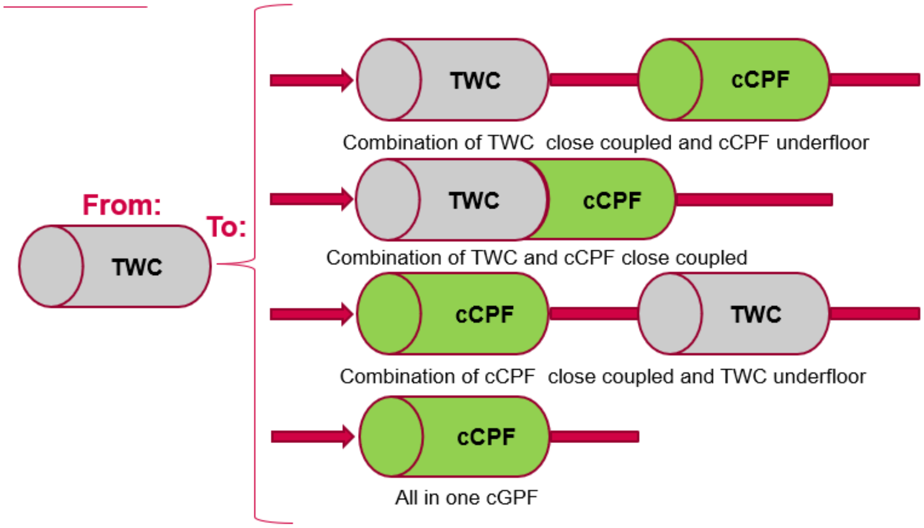


Figure 54 – Different architecture implementation of GPFs

Underfloor CPFs is an adding on solution for already existing systems. They have low packaging limitations: relatively large CPF volumes for potentially high ash accumulation. The overall backpressure is low, but passive regeneration may be not sufficient. On the other hand, close coupled solution can exploit a passive regeneration under most operating conditions, thanks to an higher thermal energy at disposal at exhaust. Drawbacks of this solution are the packaging limitation and possible delay in catalyst light-off due to thermal mass presence of CPF. The last single brick solution is made by a catalyzed CPF that replaces the TWC. The soot regeneration is good, although there is again an increase of thermal mass (compared to the TWC equivalent volume) that brings to a minor conversion efficiency of the gaseous emissions, in particular at cold start conditions. Moreover, a higher washcoat amount is needed, that brings to higher backpressure. According to literature reference, CPF in underfloor position has 15% higher filtration efficiency with respect to closed couple, and larger CPF volumes improve filtration efficiency. The reason is due to lower wall gas flow velocity and volumetric gas flow rate. CPF endowed vehicles show potentials for acoustic improvement and subsequent possibility for reducing muffler overall volume. Bare CPF performances are influenced by soot layer formation, so they are linked to operating point history and test-procedure type.

3.2.5 SCR on filter (SCRof)

Another option at disposal is a sort of combination of DPF and SCR for the control of PM and NOx emissions [16]. Anticipating the architecture layouts discussion, in a standard system for compression ignition engine usually a DOC is followed by a catalysed DPF followed then by a SCR. With the SCRof a zeolite washcoat is placed on DPF substrate, with injection of urea DEF solution upstream of it (like it happens in a SCR case). We got a single component behaving simultaneously like a DPF for PM control and SCR for NOx emissions control. In a conventional SCRT systems [16 – FPT Industrial]:

1. 1 DOC converts HC and CO
2. 2 DPF traps and passively regenerates soot
3. 3.SCR catalyst removes NOx
4. 4.CUC (ammonia oxidation catalyst) converts NH_3 slip to avoid secondary emissions

Combining the soot filtration function and the SCR NOx reduction function into one single flow through unit named SCRof, SCR substrate(s) can be eliminated.

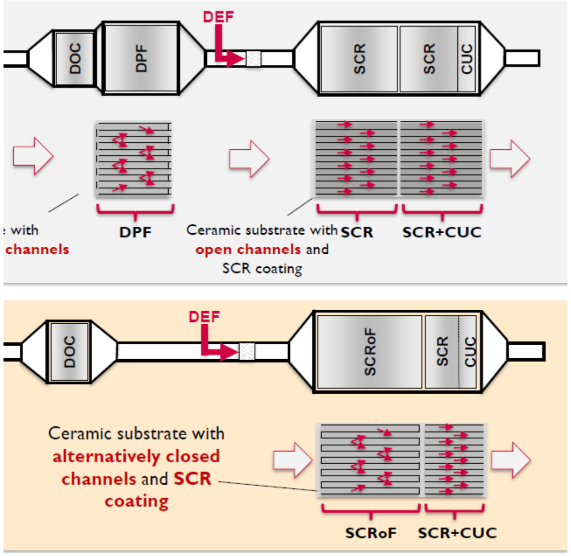


Figure 55 – SCRof implementation trend [FPT Industrial]

In a DPF+ SCR solution, exhaust gases enter porous wall of DPF and exit with less PM content but still NOx presence. A unique SCR system with porous wall will treat both the pollutants.

Total system cost is therefore reduced, as is the package volume and weight. It has a fast warm-up and good benefits in NOx emissions reduction. The system has less total thermal mass and can be heated up much faster than the conventional system [FPT Industrial]. Development of an SCR on Filter requires simultaneous optimization of multiple parameters: SCR Activity, Filtration Efficiency and Backpressure. High deNOx activity must be ensured via appropriate washcoat loading in the wall. Meanwhile, soot filtration must meet particulate emissions targets, requiring low porosity for filtration [FPT Industrial]. Moreover, coated parts must guarantee appropriate mechanical strength requirements. These requirements are usually met with a filter substrate porosity not lower than 50 ÷ 55% [FPT Industrial]. One drawback of the system is that On-Road exhaust temperature does not allow to use SCRof in “passive” regeneration mode, it must be so enhanced via the already seen active strategies.

Chapter 4 - Legislation framework for industrial vehicles

4.1 Passenger cars legislation brief overview

European Union emission regulations for new light duty vehicles have been implemented through various regulatory steps [17]:

- Euro 1 standards (from 07-1992)
- Euro 2 standards (from 01-1996)
- Euro 3/4 standards with directive 98/69/EC, respectively from 01.2000 and 01.2005
- Euro 5/6 with regulation 715/2007 respectively from 09.2009 and 09.2014 and further implementations of:
    - Regulation 459/2012—PN limits for gasoline vehicles and final Euro 6 OBD
    - Regulation 630/2012—provisions for hydrogen, hydrogen/natural gas and hybrid and electric vehicles
    - Real Driving Emissions (RDE) regulations
    - WLPT/WLTC testing

Emissions are nowadays tested over Worldwide harmonized Light vehicles Test Cycle (WLTC), which replaced previous NEDC (New European Driving Cycle) [17]. In Euro 1 and Euro 2 legislations the applied cycle was composed by a Urban cycle followed by an Extra-urban driving cycle (EUDC) with the peculiarity that during at cold start conditions (first 40 seconds) no emission control was applied [17]. With the aim of fill the gap between the real and the measured emissions, the European Commission introduced in 2017 the so-called WLTC, which should be more representative of the real driving conditions [17].

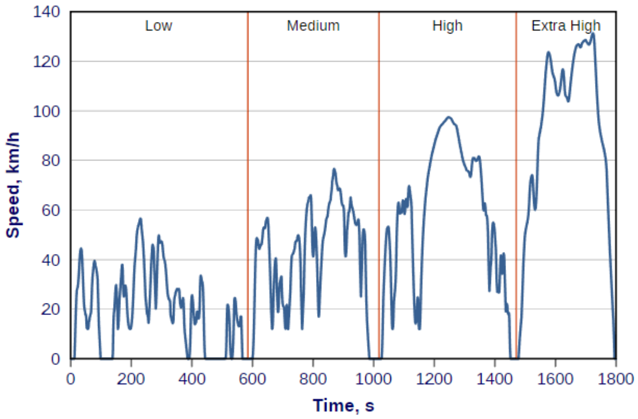


Figure 56 - WLTC cycle [*dieselnet.com*]

In United States EPA Tier 3 emission were proposed in March 2013. They are aligned with CARB Californian LEV III standards and are phased-in over period range 2017-2025. OEMs must certify vehicles over seven certification bins and must meet a fleet-average emission standards for their vehicle fleet in a given model year. Unlikely European emissions standard, they are fuel neutral. It is a difference we will find sometimes also for industrial vehicles. According to dieselnet.com:

- Both bins and fleet average standards are expressed using the sum of NMOG+NOx emissions.
- The bins are named using their corresponding NMOG+NOx limit in mg/miles.
- The fleet average NMOG+NOx emissions must reach 30 mg/mi (Bin 30 = Tier 2 Bin 2) by 2025
- The required emission durability has been increased to 150,000 miles up from 120,000 miles

Notice that Tier 3 regulates also heavy-duty vehicles (HDV) such as heavy-duty pick-ups and vans that are certified in chassis as complete vehicles. Vehicles are tested over the FTP-75 test procedure. According to dieselnet.com the entire FTP-75 cycle consists of the following segments:

1. Cold start transient phase (ambient temperature 20-30°C)
2. Stabilized phase
3. Hot soak

4. Hot start transient phase

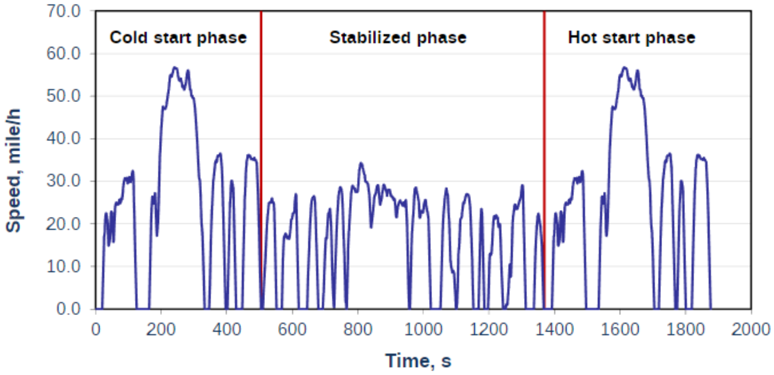


Figure 57 - USA EPA Urban Dynamometer Driving Schedule (FTP-75) [*dieselnet.com*]

Following European and US legislations, different type approval procedure had been formulated. According to *delphi technologies* the legislation framework timeline from 1985 to 2025 in a worldwide scenario is:

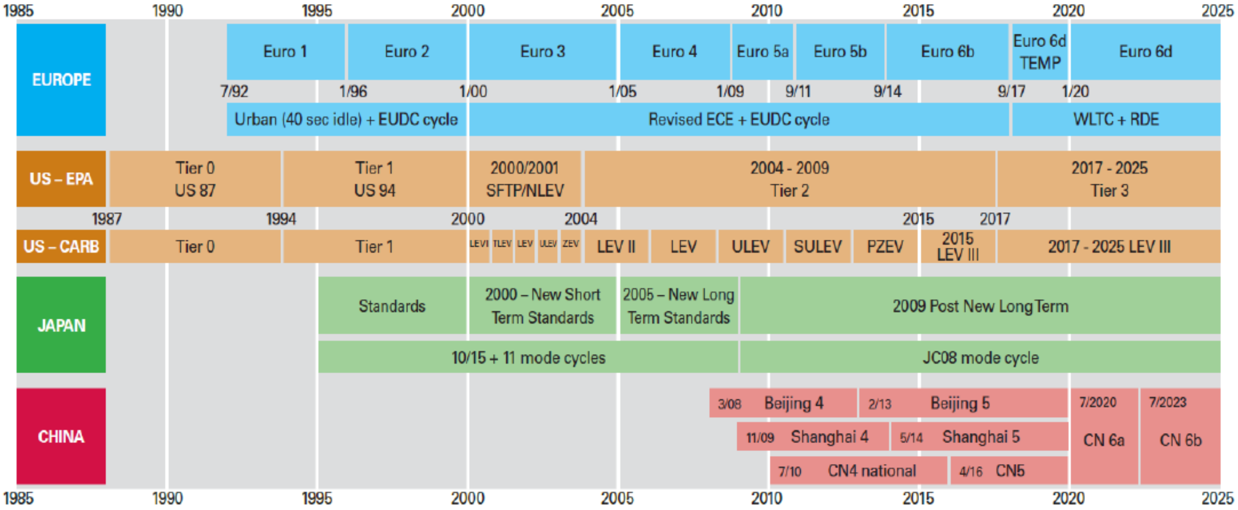


Figure 58 –Passenger cars legislation framework timeline (1985 – 2025) [*Delphi.com*]

4.2 Europe legislations

4.2.1 EU On-road vehicles

European emissions standards for HDV are worldwide known as Euro I, II, …VI. The nomenclature highlights difference with legislation for LDV, for which Arabic numerals are instead used. Sometimes HDV legislation could be found written as 'EURO' in capital letter to further distinguish with respect passenger cars regulations. Euro V and earlier emission standards are valid to vehicles with a *"technically permissible maximum laden mass" over 3,500 kg* [18] fitted with both CI and *positive ignition engines* (NG or LPG engines). Later, with Euro VI standards fuel neutrality was introduced. Euro VI standards apply to categories of vehicles M1, M2, N1 and N2 for which mass exceeds 2,610 kg and to all M3 and N3 motor vehicle [18]. Originally, HDV standards in Europe were introduced by 'directives', then translated into national legislations. With Euro VI directives were transposed to directly applicable regulations. Here it is a little historical time chronological step list [18]:

- Euro I was introduced in 1992, followed by Euro II in 1996. At these times, even if standards applied to both trucks and urban buses, the latter were still just on voluntary form.
- In 1999 Euro III was introduced by directive, valid from 2000 on. The same happened in 2005 and 2008 for Euro IV and V standards
- In 2001 prohibition of defeat device was ruled
- Directive 2005/55/EC introduced OBD requirements in 2005
- Euro VI standards were introduced by regulation in 2009, became effective in 2013/2014. Big difference is the introduction of PN limits, off-cycle and PEMS testing and harsher OBD requirements

Two different kind of testing requirements and cycles generate two sets of emission standards.

- Steady-state Testing: applicable to diesel (CI) engines only
- Transient testing: applicable to both diesel and gas (positive ignition, PI) engines.

EU emission standards for heavy-duty CI (diesel) engines: Steady-state testing

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				1/kWh	1/m
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0	0.612		
	1992, > 85 kW		4.5	1.1	8.0	0.36		
Euro II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
Euro III	*1999.10 EEV only*	ESC & ELR	*1.5*	*0.25*	*2.0*	*0.02*		*0.15*
	2000.10		2.1	0.66	5.0	0.10^a		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	

[a] PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}

EU emission standards for heavy-duty CI (diesel) and PI engines: Transient testing

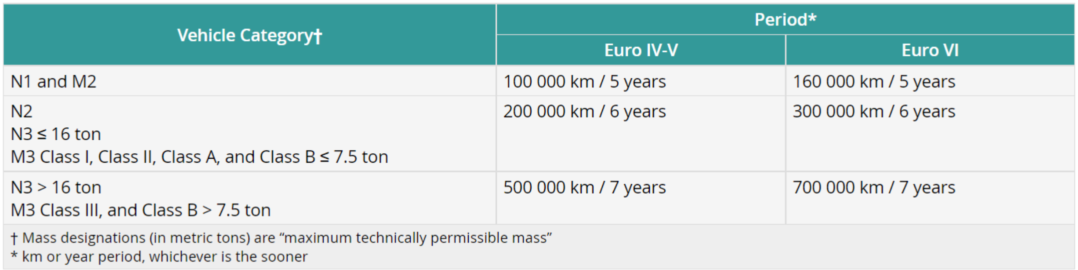
Stage	Date	Test	CO	NMHC	CH_4^{a}	NOx	PM^b	PN
			g/kWh					1/kWh
Euro III	*1999.10 EEV only*	ETC	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*	
	2000.10		5.45	0.78	1.6	5.0	0.16^c	
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03	
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03	
Euro VI	2013.01	WHTC	4.0	0.16^d	0.5	0.46	0.01	6.0×10^{11e}

[a] for gas engines only (Euro III-V: NG only; Euro VI: NG + LPG)
[b] not applicable for gas fueled engines at the Euro III-IV stages
[c] PM = 0.21 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}
[d] THC for diesel (CI) engines
[e] PN limit for PI engines applies for Euro VI-B and later [4374]

Figure 59 – EU emission standards timeline for HDV [18]

Additionally, for Euro VI it holds

- An ammonia (NH_3) concentration limit of 10 ppm to CI (WHSC + WHTC) and positive ignition (WHTC) engines [18]
- Emission Durability (2005.10/2006.10) for which manufacturers must demonstrate engines compliance with the emission limit values for the whole useful life periods depending on the vehicle category



Vehicle Category†	Period*	
	Euro IV-V	Euro VI
N1 and M2	100 000 km / 5 years	160 000 km / 5 years
N2 N3 ≤ 16 ton M3 Class I, Class II, Class A, and Class B ≤ 7.5 ton	200 000 km / 6 years	300 000 km / 6 years
N3 > 16 ton M3 Class III, and Class B > 7.5 ton	500 000 km / 7 years	700 000 km / 7 years

† Mass designations (in metric tons) are "maximum technically permissible mass"
* km or year period, whichever is the sooner

Figure 60 – EU vehicle categories from Euro IV [18]

Earlier regulatory emissions test cycles were performed through ECE-R-49 and then ESC and ETC cycles (European Stationary and Transient Cycles). These cycles were characterised by different steady-state mode and prescriptions, as well as different transient driving cycles. Since the Euro VI stage, engines are tested over the WHSC and WHTC tests. In addition, the latest Euro VI regulation adds off-cycle and in-service conformity testing []. Tests are carried out on the engine, which is tested on an engine dyno (not chassis dyno), and not on the vehicle, as for LD applications. The final emission results are now expressed in g/kWh. The global technical regulation (GTR) developed by the UN ECE GRPE group created a worldwide harmonized heavy duty certification (WHDC) procedures for engine exhaust emissions. The proposed regulation is based on the worldwide pattern of real heavy commercial vehicle use. Two representative test cycles have been created covering typical driving conditions in the EU, USA, Japan and Australia.

- World harmonized transient cycle (WHTC), with both cold and hot start requirements
- World harmonized steady state cycle (WHSC), which is hot start steady state procedure

The WHTC is a transient engine dynamometer schedule of 1800s duration. Normalized engine speed and torque values over the WHTC cycle are schematically shown below.

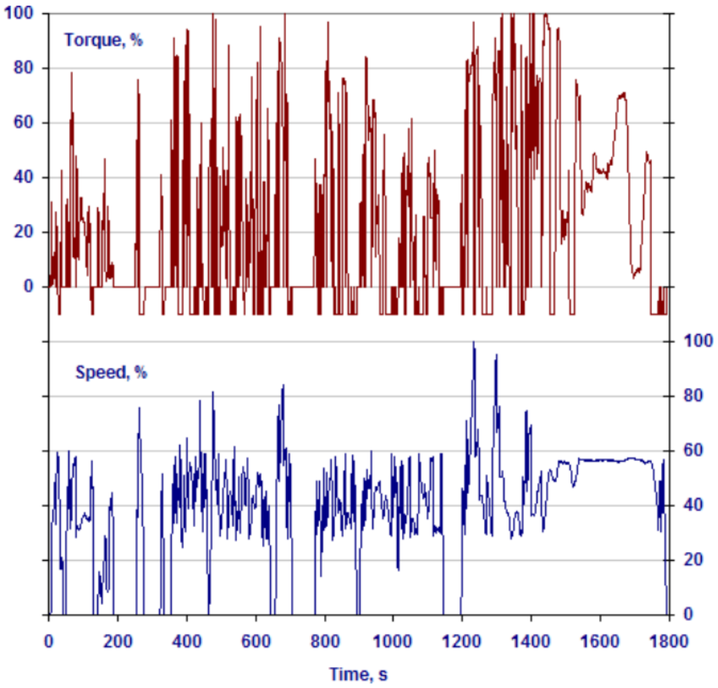
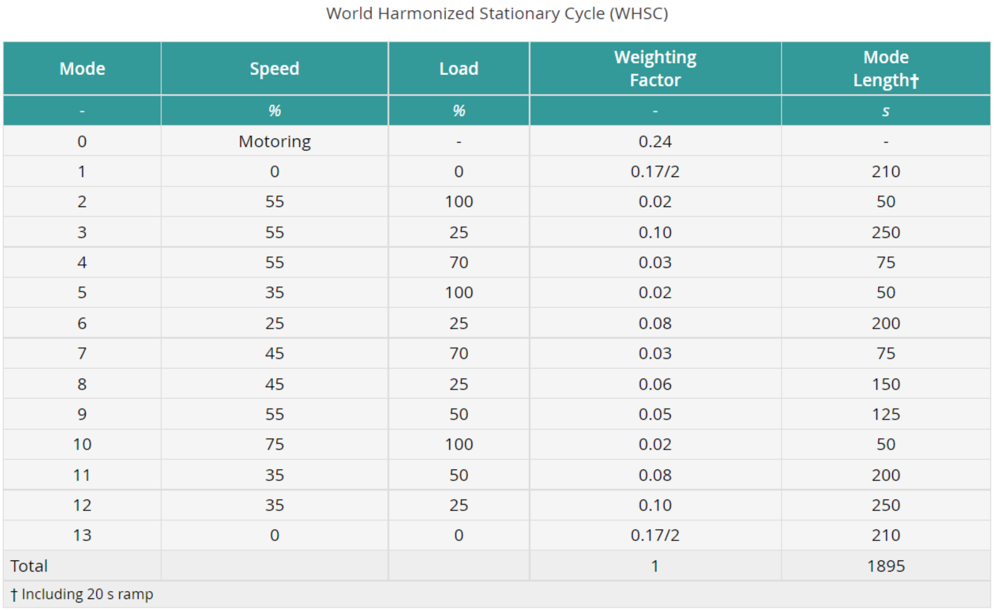


Figure 61 - World harmonized transient cycle (WHTC) [*dieselnet.com*]

The WHSC is a ramped steady state test cycle, with a sequence of 13 engine test modes with defined speed and torque criteria at each mode and defined ramps between these modes.

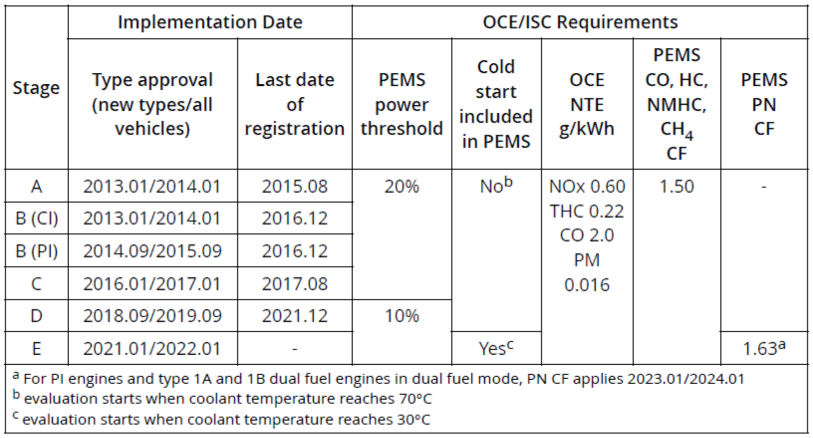

World Harmonized Stationary Cycle (WHSC)

Mode	Speed	Load	Weighting Factor	Mode Length†
-	%	%	-	s
0	Motoring	-	0.24	-
1	0	0	0.17/2	210
2	55	100	0.02	50
3	55	25	0.10	250
4	55	70	0.03	75
5	35	100	0.02	50
6	25	25	0.08	200
7	45	70	0.03	75
8	45	25	0.06	150
9	55	50	0.05	125
10	75	100	0.02	50
11	35	50	0.08	200
12	35	25	0.10	250
13	0	0	0.17/2	210
Total			1	1895

† Including 20 s ramp

Figure 62 - World harmonized steady state cycle (WHSC) [*dieselnet.com*]

The WHSC is run with hot start, with engine preconditioning at mode 9. The idle mode is splitted in two modes, mode 1 at the beginning and mode 13 at the end of the test cycle. For calculation of the brake specific emissions, the actual cycle work is calculated by integrating actual engine power over the cycle. The weighting factors (WF) are given for reference only. Some Euro VI provisions, including OCE/ISC testing and OBD requirements, are phased-in over several years. The corresponding stages of the emission standards are referred to as Euro VI-A through Euro VI-E [18]. Euro VI regulation introduced off-cycle emissions (OCE) testing requirements. OCE measurements, performed during the type-approval testing, have two elements: laboratory testing following the NTE (not-to-exceed) limit approach and in-use PEMS testing. In the NTE limit approach, engine map is divided in a grid to get a control area [18]. The testing involves the random selection of three grid cells and emission measurement at 5 points per cell. The PEMS procedure at type approval is similar to PEMS testing for In-Service Conformity (ISC) [18]. Testing requirements involve field measurements on vehicles that have accumulated a minimum of 25,000 km using PEMS. A conformity factor (CF) of 1.5 applies to gaseous emissions over WHTC emissions standard. Since Euro VI step E ISC there is also inclusion of a CF equal to 1,63 for PN emissions and partial cold start measurements, that will be important in the definition of the zone coated technology implementation within FPT Industrial. The legislation, in fact, has a two-years implementation due-date difference between CI engines (from 01.2022) and CNG ones (from 01.2024) [18].



Stage	Implementation Date		OCE/ISC Requirements				
	Type approval (new types/all vehicles)	Last date of registration	PEMS power threshold	Cold start included in PEMS	OCE NTE g/kWh	PEMS CO, HC, NMHC, CH_4 CF	PEMS PN CF
A	2013.01/2014.01	2015.08	20%	No[b]	NOx 0.60 THC 0.22 CO 2.0 PM 0.016	1.50	-
B (CI)	2013.01/2014.01	2016.12					
B (PI)	2014.09/2015.09	2016.12					
C	2016.01/2017.01	2017.08					
D	2018.09/2019.09	2021.12	10%				
E	2021.01/2022.01	-		Yes[c]			1.63[a]

[a] For PI engines and type 1A and 1B dual fuel engines in dual fuel mode, PN CF applies 2023.01/2024.01
[b] evaluation starts when coolant temperature reaches 70°C
[c] evaluation starts when coolant temperature reaches 30°C

Figure 63 - Euro VI OCE/ISC requirements [18]

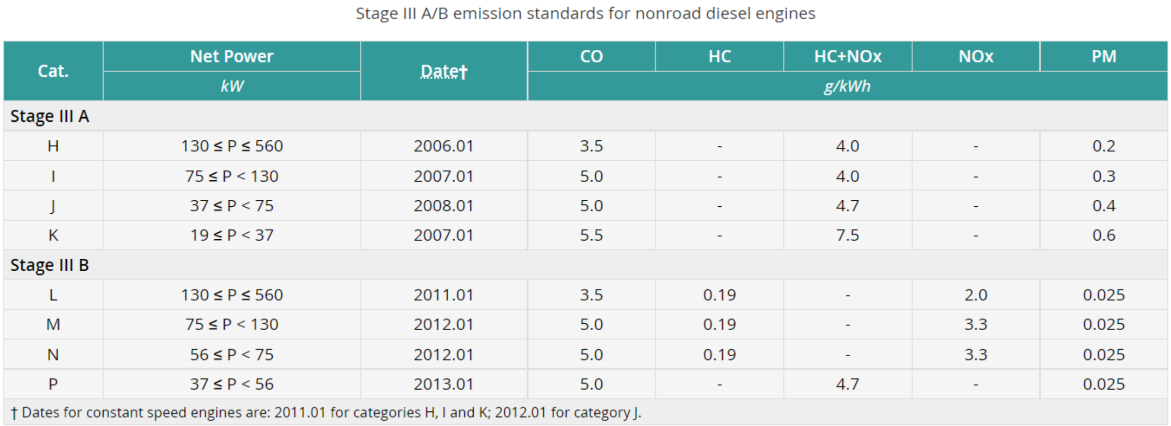
Step E 1 (from January ’22) main characteristic is the Conformity Factor (CF) of 1.5 on NOx in Cold Start (CS) condition during PEMS, while Step E 2 Legislation (January 2024) add on top of Step E1 a Conformity Factor (CF) of 1.63 on Particulate Number (PN) during PEMS [18]. A Gasoline Particulate Filter adoption became mandatory.

4.2.2 EU Off-road vehicles

European emissions legislations for so-called non-road mobile machinery (NRMM) are present in Europe through tier bins that are gradually more stringent, called Stage I, II…V standards. Before 2016/1628 regulation that introduced ultimate Stage V standards, emissions for small spark-ignition non-road engine were regulated through a directive. However, from that moment emission requirements were reunited for all categories of both compression ignition and positive ignition mobile non-road engines [19]. In a chronological-time step list:

- In 1999 Stage I was implemented, after being promulgated in December 1997. Stage II was updated from 2001 to 2004.
- In 2002 small SI engines below 19 kW standards were added. Directive 2002/88/EC gave possibility to extend Stage II to constant speed engines.
- Stage III/IV standards were adopted from 2004 to 2014. Stage III standards—which are further divided into Stages IIIA and IIIB—are phased-in from 2006 to 2013. Stage IV enter into force in 2014 [].
- Stage V standards were ultimate in 2016 and became effective in 2019. Division is from engine below 56 kW and above 130 kW. A further implementation arrived in 2020 for engine between 56 and 130 kW.

In Stage I/II standards machineries included are industrial drilling rigs, compressors, construction wheel loaders, bulldozers, nonroad trucks, highway excavators, forklift trucks, road maintenance equipment, snow plows, ground support equipment in airports, aerial lifts and mobile cranes [19]. For what regards agricultural and forestry tractors, they had same standard but different chronological implementation. In 2002 Directive 2002/88/EC gave possibility to extend Stage II to constant speed engines. From Stage III also railroad locomotive engines and marine engines used for inland waterway vessels are covered. Stage III/IV standards also include a limit for ammonia emissions, which must not exceed a mean of 25 ppm over the test cycle. Stage III B standards introduced a PM limit of 0.025 g/kWh, designed to force the use of diesel particulate filters [19]. In reality, a significant amount of engines were able to meet the PM limit through in-cylinder technologies, without filters.



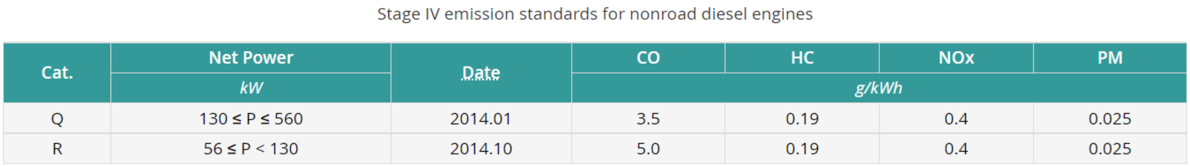
Stage III A/B emission standards for nonroad diesel engines

Cat.	Net Power	Date†	CO	HC	HC+NOx	NOx	PM
	kW		g/kWh				
Stage III A							
H	130 ≤ P ≤ 560	2006.01	3.5	-	4.0	-	0.2
I	75 ≤ P < 130	2007.01	5.0	-	4.0	-	0.3
J	37 ≤ P < 75	2008.01	5.0	-	4.7	-	0.4
K	19 ≤ P < 37	2007.01	5.5	-	7.5	-	0.6
Stage III B							
L	130 ≤ P ≤ 560	2011.01	3.5	0.19	-	2.0	0.025
M	75 ≤ P < 130	2012.01	5.0	0.19	-	3.3	0.025
N	56 ≤ P < 75	2012.01	5.0	0.19	-	3.3	0.025
P	37 ≤ P < 56	2013.01	5.0	-	4.7	-	0.025

† Dates for constant speed engines are: 2011.01 for categories H, I and K; 2012.01 for category J.

Figure 64 – EU Stage III A/B emission standards for off-road diesel engines [19]

Stage IV standards introduced a very stringent NOx limit of 0.4 g/kWh, which has triggered a widespread use of NOx aftertreatment (typically urea-SCR) on affected categories of engines.

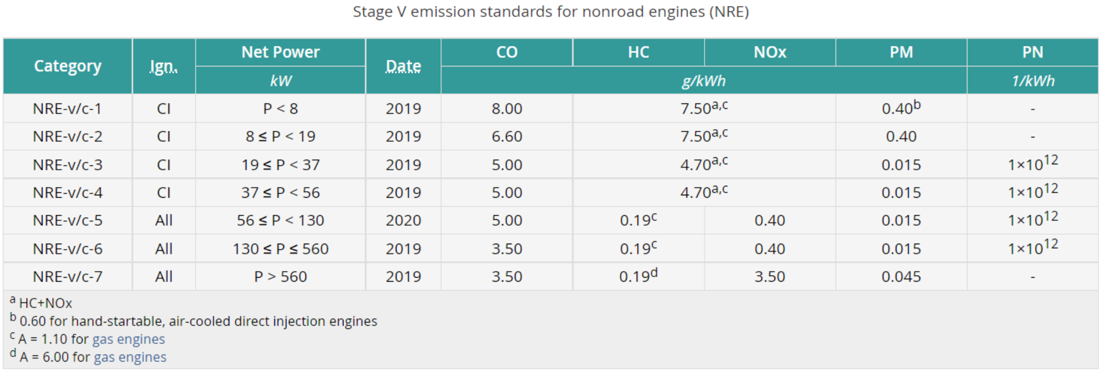


Stage IV emission standards for nonroad diesel engines

Cat.	Net Power	Date	CO	HC	NOx	PM
	kW		g/kWh			
Q	130 ≤ P ≤ 560	2014.01	3.5	0.19	0.4	0.025
R	56 ≤ P < 130	2014.10	5.0	0.19	0.4	0.025

Figure 65 - EU Stage IV emission standards for off-road diesel engines [19]

Stage V standards adopted PN emission limits for several CI engines. The PN limit is designed to ensure that a highly efficient particle control technology—such as wall-flow particulate filters—be used on all affected engine categories. The Stage V regulation also tightened the mass-based PM limit for several engine categories, from 0.025 g/kWh to 0.015 g/kWh.



Stage V emission standards for nonroad engines (NRE)

Category	Ign.	Net Power	Date	CO	HC	NOx	PM	PN
		kW		g/kWh				1/kWh
NRE-v/c-1	CI	P < 8	2019	8.00	7.50[a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50[a,c]		0.40	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	2019	3.50	0.19[d]	3.50	0.045	-

[a] HC+NOx
[b] 0.60 for hand-startable, air-cooled direct injection engines
[c] A = 1.10 for gas engines
[d] A = 6.00 for gas engines

Figure 66 - EU Stage V emission standards for off-road diesel engines [19]

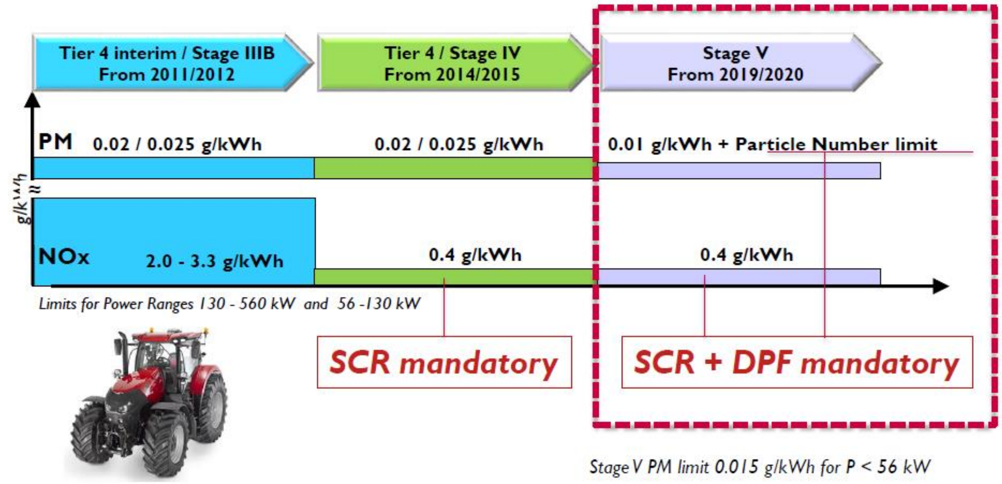


Figure 67 – EU off-road legislation limits and technical need evolution [FPT Industrial]

Stage V Particle Number limit mae the adoption of Particulate Filter mandatory. As we can see it is much later with respect LD and HDV applications regulations. In the former table, for engine categories where an A factor is defined, the HC limit for fully and partially **gaseous fueled engines** indicated in the table is replaced by the one calculated from the formula [19]:

$$HC = 0.19 + (1.5 \times A \times GER)$$

where GER is the average gas energy ratio over the appropriate cycle. Current Stage V is regulating different engines categories: from in hand-held machinery, passing to snowmobile and all SI engines used in all terrain and side-by-side vehicles. More tables and limits are published by authorities and reported in the portal *dieselnet.com*. Next to these emission legislations features, Stage III A/B and V regulated inland waterway vessels and rail traction engines respectively. Stage V also prohibits defeat devices. To represent emissions during real conditions, a new transient test procedure—the Non-Road Transient Cycle (NRTC)—was developed in cooperation with the US EPA [19]. The new test will be used in parallel with Non-Road Steady Cycle (NRSC). The picture is completed by NTE (Not to exceed) testing.

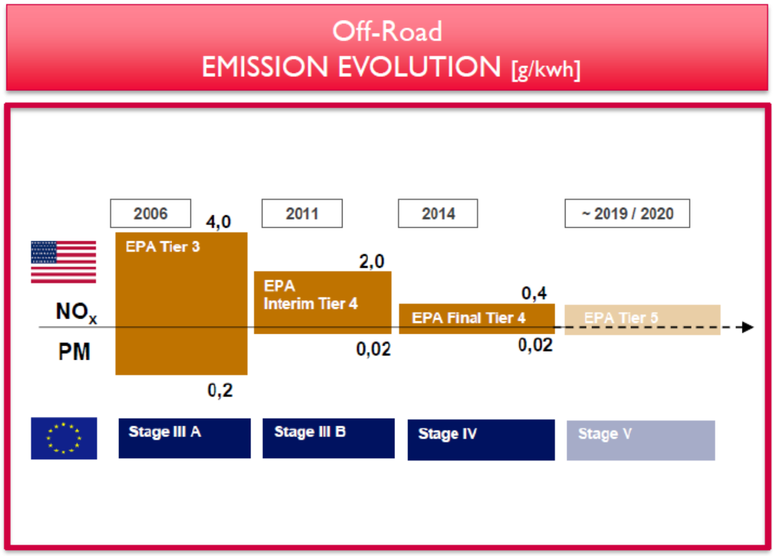


Figure 68 – EU off-road emission evolution [g/kWh] in comparison to EPA US Tier limits [FPT Industrial]

NRTC (Non-Road Transient Cycle) is an engine dynamometer transient test with a well -defined schedule. There is a time sequence of engine speed and torque, the test sequence of speed and torque is defined internationally, including contribution of **USA, European Union and Japan**. The cycle is run twice:

1. Cold start
2. Hot start

The weighted emissions are:

1. 1.An average of the hot (90%) and cold (10%) cycle for ECE
2. 2.An average of the hot (95%) and cold (5%) cycle for EPA

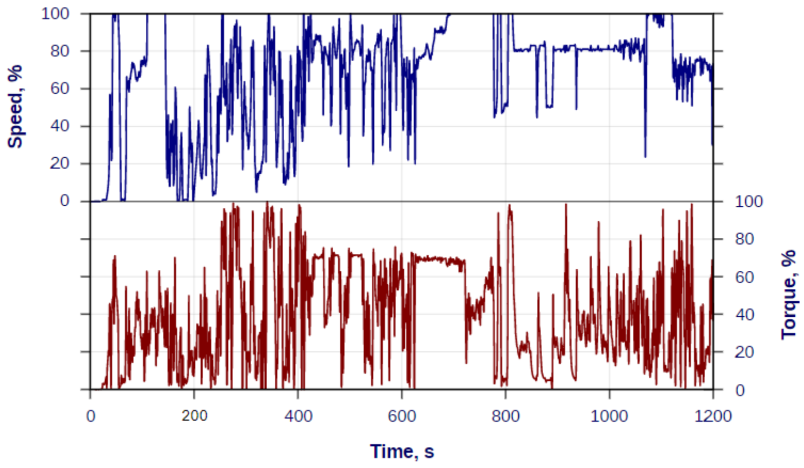


Figure 69 - NRTC (Non-Road Transient Cycle) [*dieselnet.com*]

Again, NRSC (Non-Road Steady State Cycle) is the international standard used for engines emission certification and/or type approval in many worldwide diffused countries, including USA, European Union and Japan. NSRC is a sort of collection of all applicable test cycles designed for different engine applications. Each of these cycles represent a sequence of several steady state modes with different weighting factors. The 8 Mode cycle can be run in two different ways [*dieselnet.com*]:

- Standard (8 Mode Cycle)
- RMC (Ramped Modal Cycle)

NTE testing establishes again a control area, the "NTE Area", which represents engine speeds and loads easy to be matched in normal vehicle operation, where not to exceed limits are set. It is an additional set of requirements introduced to control engine emissions outside the test cycles modes, over a range of speed and load combinations.

4.3 USA legislations

4.3.1 USA On-road vehicles

US EPA and California CARB set US federal emission standards for HDVs engines. Emissions are usually measured in g/bhp hr being over an engine dyno, and not a chassis one. Also in this case, like it happens for LD applications, the US legislation sets fuel neutral emission standards. The time step over US HDVs engines regulation is the following one [20]:

- First standard set was regulated in 1974. Tightening of the standards occurred several times in the next two decades. Most important ones were the tightening of PM emissions in 1991 (0.25 g/bhp hr) and 1994 (0.10 g/bhp hr) [] as well as NOx limits (1998, 4g/bhp hr)
- In 1997 new model year 2004 standards were adopted
- In 2000 MY 2007 and later HDV standards were signed, with a phase-in during 2007-2010 period [].
- California low NOx standards became optional from 2015 and is going to be mandatory between 2024 and 2027
- From MY 2017 OEMs must meet GHG emissions standards
- In 2020 CARB brought a new California low NOx regulation for HDV. FTP cycle emission regulations will become more tight in NOx limit of 0.050g/bhp hr from 2024 and of 0.02 g/bhp hr from 2027. Moreover, a new cycle certification is going to be introduced with its own NOx limits, plus durability requirements. In 2022 EPA re-opened its aligned set of standards with this new CARB low NOx level, at first it was proposed in 2020 too, then abandoned for a while in 2021.

The FTP (Federal Test Procedure) heavy-duty transient cycle is currently used for emission testing of heavy-duty on-road engines in the USA. The cycle includes "motoring" segments and, therefore, requires an electric dynamometer capable of both absorbing and supplying power. The transient test was developed to take into account a variety of heavy-duty truck and bus driving patterns in American cities, including traffic in and around the cities on roads and expressways. The FTP cycle consists of four phases [*dieselnet.com*]:

- New York Non-Freeway (NYNF) phase typical of light urban traffic with frequent stops and starts
- Los Angeles Non-Freeway (LANF) phase typical of crowded urban traffic with few stops

- Los Angeles Freeway (LAFY) phase simulating crowded expressway traffic in Los Angeles
- A repetition of the first NYNF phase.

The variation of normalized speed and torque with time is shown in Figure 70.

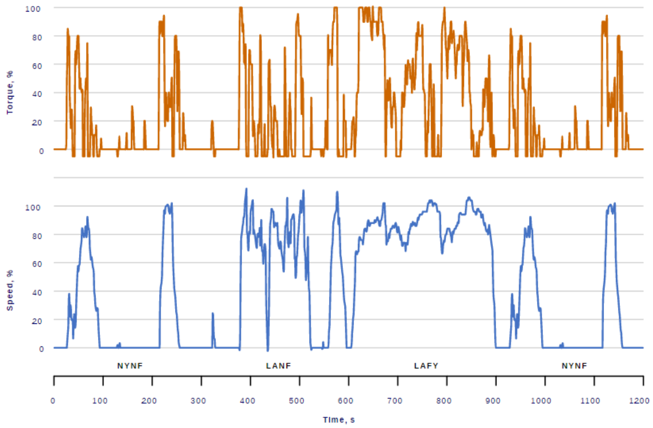
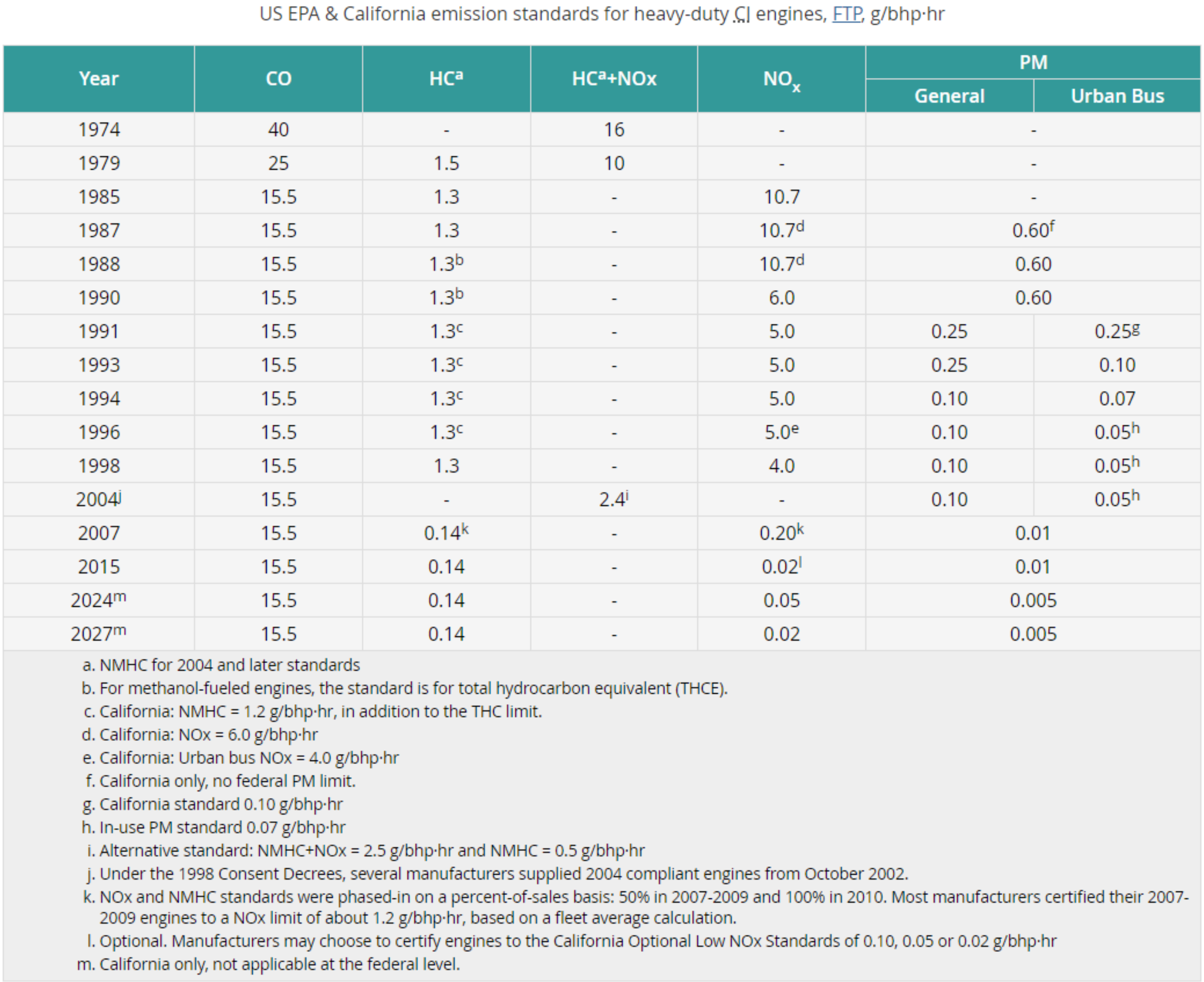


Figure 70 – FTP cycle variation of normalized speed and torque versus time [*dieselnet.com*]

A summary is given in the below table, including California low NOx standards.



US EPA & California emission standards for heavy-duty CI engines, FTP, g/bhp·hr

Year	CO	HC[a]	HC[a]+NOx	NO_x	PM	
					General	Urban Bus
1974	40	-	16	-	-	
1979	25	1.5	10	-	-	
1985	15.5	1.3	-	10.7	-	
1987	15.5	1.3	-	10.7[d]	0.60[f]	
1988	15.5	1.3[b]	-	10.7[d]	0.60	
1990	15.5	1.3[b]	-	6.0	0.60	
1991	15.5	1.3[c]	-	5.0	0.25	0.25[g]
1993	15.5	1.3[c]	-	5.0	0.25	0.10
1994	15.5	1.3[c]	-	5.0	0.10	0.07
1996	15.5	1.3[c]	-	5.0[e]	0.10	0.05[h]
1998	15.5	1.3	-	4.0	0.10	0.05[h]
2004[j]	15.5	-	2.4[i]	-	0.10	0.05[h]
2007	15.5	0.14[k]	-	0.20[k]	0.01	
2015	15.5	0.14	-	0.02[l]	0.01	
2024[m]	15.5	0.14	-	0.05	0.005	
2027[m]	15.5	0.14	-	0.02	0.005	

a. NMHC for 2004 and later standards
b. For methanol-fueled engines, the standard is for total hydrocarbon equivalent (THCE).
c. California: NMHC = 1.2 g/bhp·hr, in addition to the THC limit.
d. California: NOx = 6.0 g/bhp·hr
e. California: Urban bus NOx = 4.0 g/bhp·hr
f. California only, no federal PM limit.
g. California standard 0.10 g/bhp·hr
h. In-use PM standard 0.07 g/bhp·hr
i. Alternative standard: NMHC+NOx = 2.5 g/bhp·hr and NMHC = 0.5 g/bhp·hr
j. Under the 1998 Consent Decrees, several manufacturers supplied 2004 compliant engines from October 2002.
k. NOx and NMHC standards were phased-in on a percent-of-sales basis: 50% in 2007-2009 and 100% in 2010. Most manufacturers certified their 2007-2009 engines to a NOx limit of about 1.2 g/bhp·hr, based on a fleet average calculation.
l. Optional. Manufacturers may choose to certify engines to the California Optional Low NOx Standards of 0.10, 0.05 or 0.02 g/bhp·hr
m. California only, not applicable at the federal level.

Figure 71 – US EPA & Californian emission standards for HDV [20]

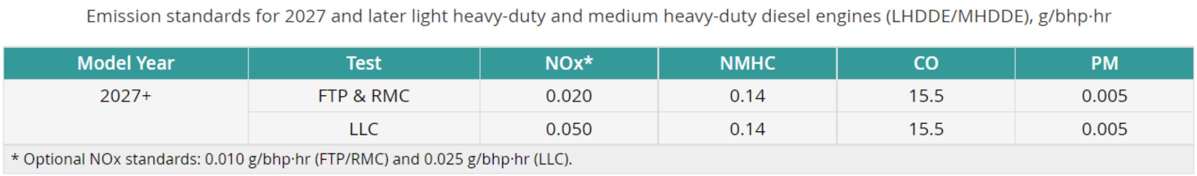
In addition, it holds:

- Smoke opacity limit, since 1974
- Idle CO Standard, since 1988 for CI engines, from 1990 by methanol and from 1994 for CNG and LPG engines
- Idle NOx standard – for California only since 2007

OBD diagnostic is valid from 2005-2007 model years [20]. In 1998 a series of settlements between EPA, CARB and OEMs brought to be illegal any engine control strategy that imply a switch to a more fuel-efficient highway cruising engine map, that however might bring to higher level of NOx emissions. Settlements involve fines and a new steady-state SET test cycle with limit equal to FTP by a 1.25 multiplying coefficient factor [20]. MY 2007 and later HDV emission standards were signed in 2000 with very tight limits for PM (0.001 g/bhp hr) and NOx (0.20 g/bhp hr). While the PM standard was effective instantaneously, NOx limits were phased-in between 2007 and 2010 on a share percentage basis. It is so common to refer to 2010 standards, as they were somehow different from 2007 ones, but there is no difference instead apart from phase-in adoption. From this last MY, as anticipated, next to FTP testing also SET test and NTE test conformities is asked. For the latter, limit values are of FTP standards multiplied by 1.5. Moreover, additional provisions for 2007 emissions are [20]:

- Crankcase ventilation
- DEF refill interval for SCR installed vehicles. A minimum interval is defined according at least to vehicle fuel capacity.
- Ammonia emissions slip up to 10 ppm over test cycles

For what regards the CARB HDV low NOx new program, in 2020 a 90% NOx emission reduction over the 2024-2031 period has been approved. It is going to apply to all compression ignition and Otto cycle engines in medium duty vehicles and HDV category for US (from more than 10,000 lbs weight). In addition to the already cited lower NOx and PM standards, a new load cycle of certification, called LLC, is going to be ruled as new provision, setting corresponding NOx limits (from 0.20 g/bhp hr of 2024 period to 0.05 g/bhp hr of 2027). Moreover, a durability useful life sets of limits is enhanced for the two different cycles and vehicle/engine categories, resumed in tables below. Last but not least, a new more stringent idle NOx level has been indicated.

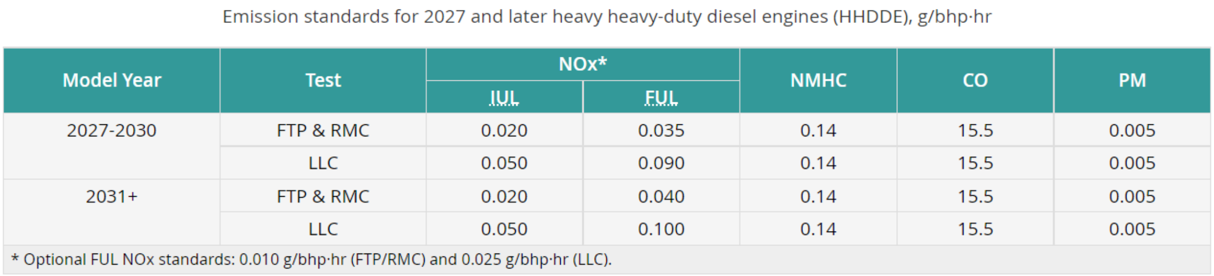


Emission standards for 2027 and later light heavy-duty and medium heavy-duty diesel engines (LHDDE/MHDDE), g/bhp·hr

Model Year	Test	NOx*	NMHC	CO	PM
2027+	FTP & RMC	0.020	0.14	15.5	0.005
	LLC	0.050	0.14	15.5	0.005

* Optional NOx standards: 0.010 g/bhp·hr (FTP/RMC) and 0.025 g/bhp·hr (LLC).

Figure 72 – MY 2027+ US EPA HDV emission standards [20]

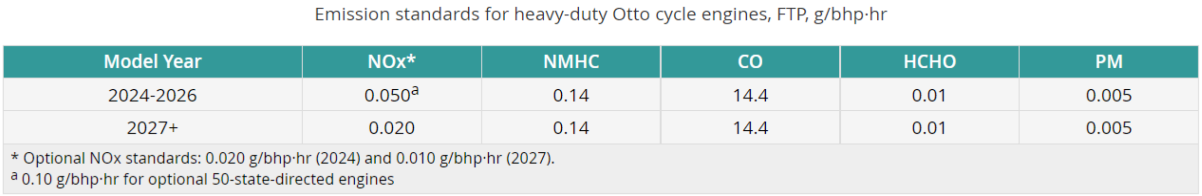


Emission standards for 2027 and later heavy heavy-duty diesel engines (HHDDE), g/bhp·hr

Model Year	Test	NOx*		NMHC	CO	PM
		IUL	FUL			
2027-2030	FTP & RMC	0.020	0.035	0.14	15.5	0.005
	LLC	0.050	0.090	0.14	15.5	0.005
2031+	FTP & RMC	0.020	0.040	0.14	15.5	0.005
	LLC	0.050	0.100	0.14	15.5	0.005

* Optional FUL NOx standards: 0.010 g/bhp·hr (FTP/RMC) and 0.025 g/bhp·hr (LLC).

Figure 73 - MY 2027+ and 2031+ US EPA HDV emission standards [20]



Emission standards for heavy-duty Otto cycle engines, FTP, g/bhp·hr

Model Year	NOx*	NMHC	CO	HCHO	PM
2024-2026	0.050[a]	0.14	14.4	0.01	0.005
2027+	0.020	0.14	14.4	0.01	0.005

* Optional NOx standards: 0.020 g/bhp·hr (2024) and 0.010 g/bhp·hr (2027).
[a] 0.10 g/bhp·hr for optional 50-state-directed engines

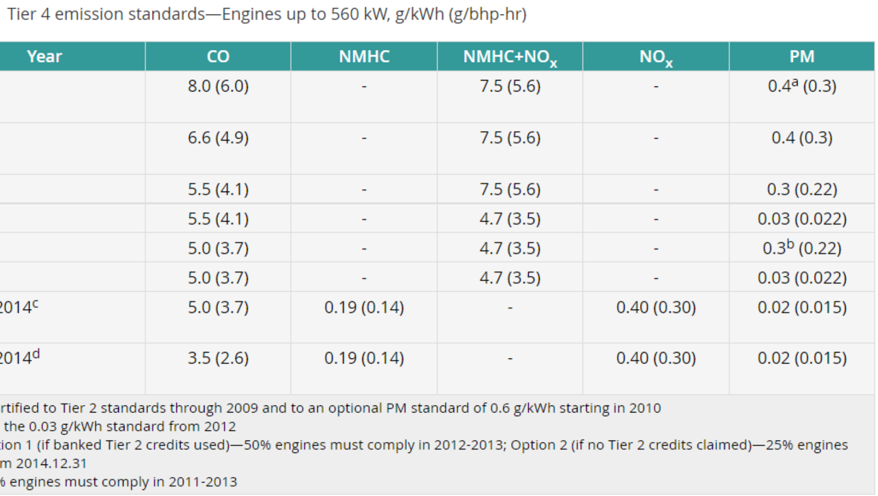
Figure 74 – MY 2027+ US EPA HDV emission standards [20]

4.3.2 USA Off-road vehicles

Differently from on-road vehicles engines case, US emissions standards for off-road engines are in most cases regulated by EPA only. California authority is limited for what concerns new farm and construction equipment under 175 hp to be subjected to an authorization request to federal EPA. Again, the important steps in time were [21]:

- In 1994 Tier 1 federal standards for nonroad diesel engines over 37 kW were introduced, to be adopted from 1996. In 1998 regulations were extended to engines under 37 kW power threshold limit.
- Still in 1998 Tier 2 and Tier 3 standards were scheduled to be applied from 2000 to 2008
- Tier 4 standards were signed in 2004 and phased-in from 2008 to 2015.
- In 2021 California Air Resources Board released first workshop on Tier 5 emission standards development, to further reduce NOx and PM emissions by 50-90% in 2028-2030.

For what applicability regards, non-road standards cover engine of several sizes, in application to a wide range of machineries, equipment and so on. According to EPA definition non-road engine includes all *engines installed on self-propelled equipment, on equipment that is propelled while* *performing its function, or on equipment that is portable or transportable, as indicated by the presence of wheels, skids, carrying handles, dolly, trailer, or platform* [21]. Separate EPA regulations regard engines used in railway locomotives, marine vessels, underground mining. Regulated applications are for example bulldozers, excavators, farm tractors etc. Tier 4 non-road engines emission standards are harmonized to EU ones. Tier 4 standards for engines up to 560 kW are listed in following table with metric SI and limits in g/kWh. A difference with respect corresponding non-road EU emission limits is that here there is variation according to engine power.



Tier 4 emission standards—Engines up to 560 kW, g/kWh (g/bhp-hr)

Engine Power	Year	CO	NMHC	NMHC+NO_x	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

a - hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
b - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
c - PM/CO: full compliance from 2012; NOx/HC: Option 1 (if banked Tier 2 credits used)—50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed)—25% engines must comply in 2012-2014, with full compliance from 2014.12.31
d - PM/CO: full compliance from 2011; NOx/HC: 50% engines must comply in 2011-2013

Figure 75 – US EPA Tier 4 off-road emission standards for engine up to 560 kW [21]

Previous Tier 1-3 standards were met almost without need of after-treatment systems usage. Tier 4 standards tight limits of PM and NOx of about 90%. Usage of ATS is so now needed, at a level similar to exhaust after-treatment of on-road engines. Also, for non-road Tier 4, in engines between 56 and 560 kW rated power NOx and HC standards were reached over some years period. Moreover, Tier 4 includes [21]:

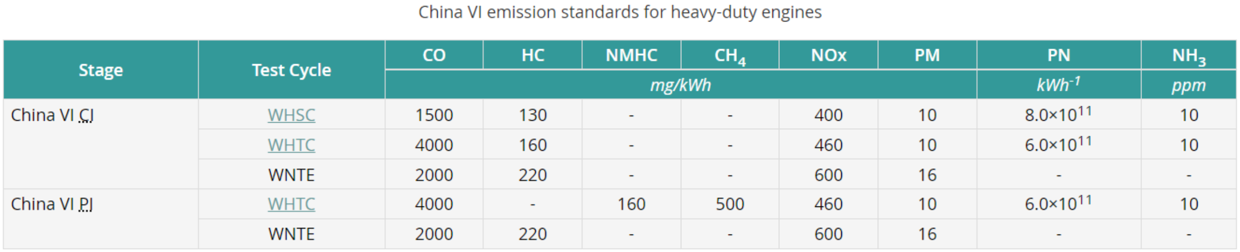
- Smoke opacity control
- Crankcase emissions measurement
- DEF refill interval definition for SCR equipped engines
- Ammonia slip emissions (10 ppm over test cycles)

Before Tier 4, no specification was valid for sulphur content in diesel fuels. Oil industry specification was aligned at 0,5% maximum weight factor, equivalent to 3,000 ppm of sulphur content. Tier 4 needs a technology enabler in low sulphur diesel fuel, and EPA made reduction of sulphur content in diesel oil mandatory till 15 ppm maximum acceptable in non-road, locomotive, and marine diesel fuels. Workshop for Tier 5 standards is going to consider a new cycle for type approval certification, OBD requirements, useful life extension of regulations and so on. However, EPA authorization over Californian proposal still will hold. For what testing requires, Tier 4 standards are based on both steady state and transient non-road test cycles (NRTC and NRSC), already seen in EU non-road standards. They are a global test procedure, internationally defined. Transient testing was introduced from MY 2011 in power rated engines between 130 and 560 kW, then extended to lower power levels. Engines over 560 kW are not tested over NRTC. Also, NTE standard are present in Tier 4, introduced at categories step from 2011. Here NTE standards are without a precise test schedule and differs for pollutants multiplication factors over regular standards (1,25 for all type of pollutants and 1,5 for PM and NOx engines certified below 0.07 g/kWh and 2.5 g/kWh respectively). NTE standards apply both at certification time as well as for useful life, preventing defeat device usage. According to EPA, when Tier 4 regulation was born, full non-road fleet engines replacement with Tier 4 spec engines meant a yearly emission reduction estimated in 738,000 tons of NOx and 129,000 tons of PM [21]. Additional technology cost needed to meet these mandatory standards was estimated in 1-3% fraction of total equipment price [21].

4.4 China legislation

4.4.1 China On-road vehicles

In China, most of standards for heavy-duty vehicles are based on European ones. Schedules and implementations are although different between Beijing, Shanghai, Guangzhou areas and nationwide. First China I implementation was in year 2000 for type approvals and in 2001 for all vehicles. The China III-V stages are based respectively on Euro III-V. They brought introduction of ESC+ELR and ETC cycles. We have seen that they were defined by different steady-state mode and prescriptions, as well as different transient driving cycles [22]. At previous China I and China II stages, tests were based on ECE R-49 9 modes cycle. Historically, a big step was represented by China IV-V steps. Supplemental requirements were asked to decrease NOx emissions in urban driving conditions. In this scenario the introduction of World Harmonized Transient Cycle (WHTC) and the PEMS testing represented a big step toward alignment and overtake with respect to European and United States standards. Both were at the beginning applied in Beijing only and then nationally. In fact, the Beijing authorities added in 2013 a supplemental standard to China IV and V regulations, then followed at national level to be implemented in 2015. The standard required, in addition to ETC, the adoption of WHTC tests. In Europe the WHTC test made it first appearance only with Euro VI, completely implemented just some months later. The WHTC additional requirement was fuel neutral in Beijing and for CI engines only nationally. The weighting factors of cold and hot start phases are a bit different than European and US ones, being of 14% and 86% respectively. For China IV/V limit values were aligned to respective WHTC European ones, except NOx limits, a little bit softer. PEMS testing were implemented in 2013 in Beijing and 2017 nationally in China V limits, providing that OEMs prove that real-world emissions are not in excess with respect type approval ones. Latter China VI standards were published in 2018 and are going to be phased-in till mid of 2023. Emission limits values could be found in below figure.



China VI emission standards for heavy-duty engines

Stage	Test Cycle	CO	HC	NMHC	CH_4	NOx	PM	PN	NH_3
		mg/kWh						kWh^{-1}	ppm
China VI CI	WHSC	1500	130	-	-	400	10	8.0×10^{11}	10
	WHTC	4000	160	-	-	460	10	6.0×10^{11}	10
	WNTE	2000	220	-	-	600	16	-	-
China VI PI	WHTC	4000	-	160	500	460	10	6.0×10^{11}	10
	WNTE	2000	220	-	-	600	16	-	-

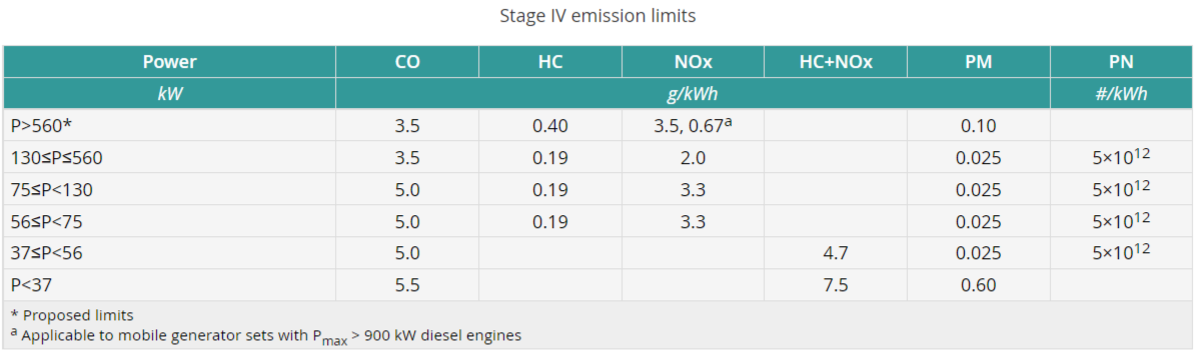
Figure 76 – China GBVI emission standards for HDV [22]

China VI is split into two phases: China VI-a and China VI-b. The latter introduces more tight requirements, for example a PN limit for the entire PEMS test duration, plus a remote emission monitoring system. PEMS testing are based on European PEMS regulations. Also, OBD requirements based on Euro VI ones are present, as well as emissions durability requirements.

For what the remote OBD regards, China VI asks for real engine data of all emission-related features, reported to regulatory agency. Moreover, retrofits of remote OBD till China IV type approved vehicles are encouraged [22].

4.4.2 China Off-road vehicles

China emission regulations for off-road engines are called Stage I,II…IV. Stage I/II standards were adopted in 2007, based on respectively European stages [23]. In addition, Chinese regulations also considered small displacement diesel engines, at the contrary of European one. To fill that empty space the US Tier 1 and 2 for non-road engines was taken as reference. In 2014 Stage III and IV standards were proposed, based on EU IIIA and IIB stages. Again, smallest and largest engines regulations were filled by referring to US Tier 2. Finally, Stage IV standards were modified in 2018, by adding a PN limit and a wall flow DPF requirement. Implementation date is by December 2022 for engines up to 560 kW [24], with in-service conformity tests asked as mandatory. Till Stage III, standards were based on a steady-state cycle with 8 mode tests. From Stage III durability requirements are added. Initially, Stage IV standard limits are summarized in figure 77 [23]:



Stage IV emission limits

Power	CO	HC	NOx	HC+NOx	PM	PN
kW	*g/kWh*					*#/kWh*
P>560*	3.5	0.40	3.5, 0.67^{a}		0.10	
130≤P≤560	3.5	0.19	2.0		0.025	5×10^{12}
75≤P<130	5.0	0.19	3.3		0.025	5×10^{12}
56≤P<75	5.0	0.19	3.3		0.025	5×10^{12}
37≤P<56	5.0			4.7	0.025	5×10^{12}
P<37	5.5			7.5	0.60	

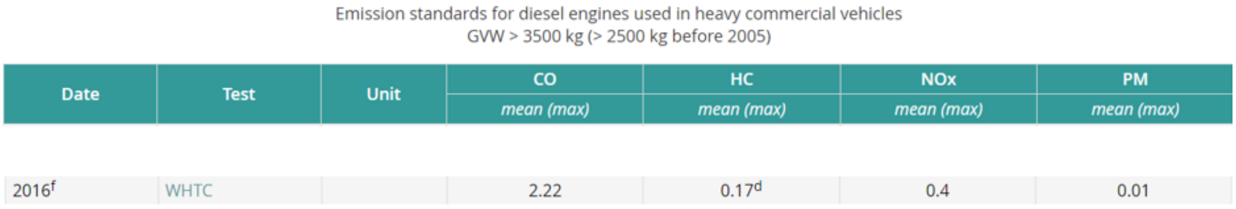
* Proposed limits
^{a} Applicable to mobile generator sets with P_{max} > 900 kW diesel engines

Figure 77 – Chinese Stage IV standard emission limits for off-road vehicles [23]

Variable speed engines are tested over transient NRTC cycle, while constant speed ones in steady-state NRSC. As said, a wall-flow DPF is mandatory, with PN limit fixed in $5\text{x}10^{12}$ #/kWh. Ammonia emissions must not be over 25 ppm for SCR engine equipped vehicles. Moreover, if SCR contains vanadium, it is needed to demonstrate that vanadium emissions would not occur over entire useful life and temperatures are kept below 500°C. For machineries with a rated power over 37 kW PEMS have to be used, with a conformity factor equal to 2.5 for CO and NOx, or CO and HC+NOx for machineries whose engine has from 37 to 56 kW. Multiplying factors equal to 2 apply for NTE limits. In-use smoke emission is checked with a specific opacity meter procedure. OBD requirements are also present, with control of telematics and all emission-related (including CO_2 and fuel consumption) data for NRMMs in 37-560 kW categories. Finally, a draft from 2018 proposed to OEMs to meet EU Stage V equivalent limits on voluntary basis [23].

4.5 Japan and India

Other two important areas in HDV and NRMMs markets are Japan and India. One is located in the Asia Pacific Market (APAC) and India is part of the new macro-economic-area called IMEA (India Middle East and Africa). In Japan, new diesel engines for heavy-duty vehicles are tested over the transient WHTC cycle. Actual (post 2016) mean permitted emission limits are reported in figure 78 in g/kWh



Emission standards for diesel engines used in heavy commercial vehicles
GVW > 3500 kg (> 2500 kg before 2005)

Date	Test	Unit	CO	HC	NOx	PM
			mean (max)	*mean (max)*	*mean (max)*	*mean (max)*
2016[f]	WHTC		2.22	0.17[d]	0.4	0.01

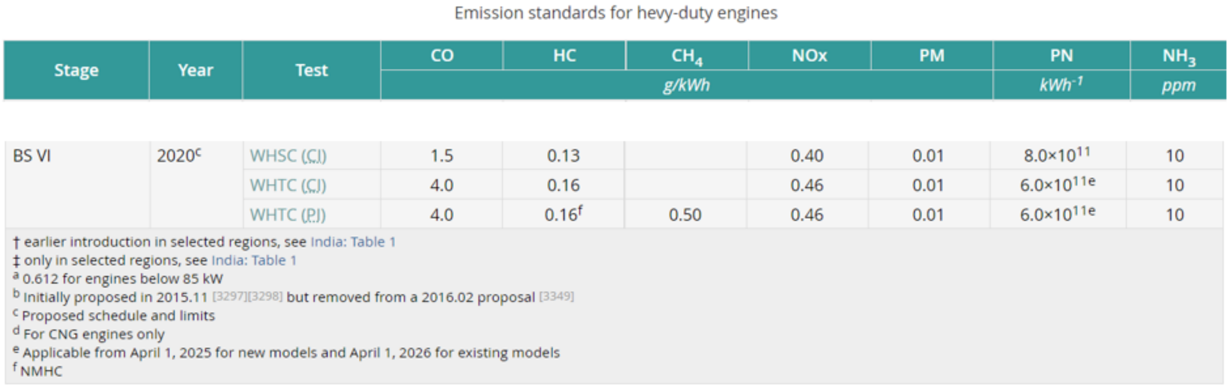
Figure 78 – Japan CI engines HDV emission standards legislation [25]

Like it happens in Europe, legislation is not fuel neutral, and for gasoline and LPG vehicles another set of standards actually holds, different in diesel one in type approval cycle (JE05) and implementation date. Japan non-road engine emission standards scenario is quite more complicate [26]. The standards are valid for engines which power rate is between 19 and 560 kW. They are divided based on typology of vehicles application

- Special motor vehicles – registered with license plate for operation on roads
- Nonroad motor vehicles – non registered off-road vehicles and machineries

However, emission limits are the same for both categories, being introduced and implemented at different times. Again, there is difference between diesel fuels and spark ignited engines. For diesels, from years 2015-2016, standards based on US Tier 4 and/or EU Stage IV are in charge. Limits of hydrocarbons were changed to NMHC, and the transient NRTC cycle is used along with a steady-state 8 mode test. SI engines emission limits are different, and measured over a 7 mode test cycle. Moreover, like it happened and happens in other legislations, OEMs may register their engines as *low emission engine* here just in the perimetry of the construction machinery. Useful life requirements are considered too.

For what India regards, HDV on-road engine regulations [27] are applicable to vehicle of GVW > 3500 kg. Over years limits have been tightening, starting from 'India 2000', passing through different BS till BS VI 2020 implementation, with a transition directly from BS IV to BS VI since BS V proposal was removed and updated. In figure 79 the actual emission limits:



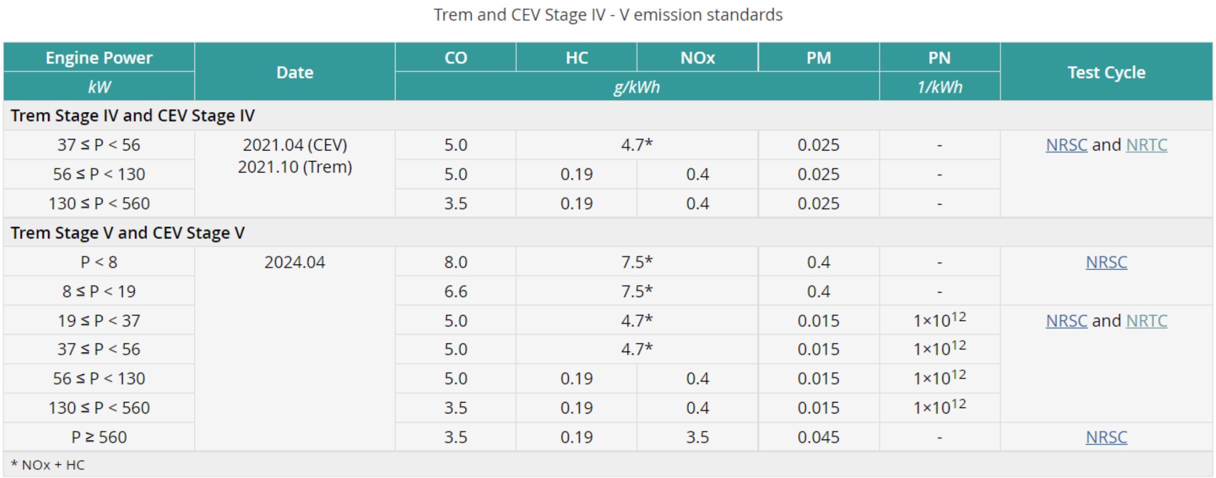
Emission standards for hevy-duty engines

Stage	Year	Test	CO	HC	CH_4	NOx	PM	PN	NH_3
			g/kWh					kWh^{-1}	ppm
BS VI	2020^c	WHSC (CI)	1.5	0.13		0.40	0.01	8.0×10^{11}	10
		WHTC (CI)	4.0	0.16		0.46	0.01	6.0×10^{11e}	10
		WHTC (PI)	4.0	0.16^f	0.50	0.46	0.01	6.0×10^{11e}	10

† earlier introduction in selected regions, see India: Table 1
‡ only in selected regions, see India: Table 1
[a] 0.612 for engines below 85 kW
[b] Initially proposed in 2015.11 [3297][3298] but removed from a 2016.02 proposal [3349]
[c] Proposed schedule and limits
[d] For CNG engines only
[e] Applicable from April 1, 2025 for new models and April 1, 2026 for existing models
[f] NMHC

Figure 79 – BS VI Indian emission standards for HDV engines [27]

Euro VI related BS VI are certified with E10 gasoline and B7 diesel. An in-use test conformity is performed, with a conformity factor for gaseous pollutant emissions. PEMS testing is also mandatory as well as NTE limits to meet. OBD requirements are aligned to European ones. Non-road first emission set of limits [28] were effective in 1999 with Bharat (Trem) Stage I for agricultural tractors only. Construction machinery sector had separate standards, born in 2006 with Bharat (CEV) Stage II-III. The first was harmonized to EU Stage I, with small engines part addition, and the second is based on US Tier 2/3. From Bharat Stage IIIA emission standards became aligned between agricultural tractors and construction machineries for almost all engine categories. In 2018 there was adoption of Bharat Stage IV and V, implementing them in 2021 and 2024. They are respectively harmonized to EU Stage IV and Stage V. Test cycles were based on 8 and 5-mode tests. With Stage IV and V introduction, switch to NRSC and NRTS cycles has been completed. Since the beginning, limit values apply for both type approval and conformity of production testing. In below figure Stage IV and V emission limits are showed. In 2020 nomenclature for the two main categories has been separated, calling Trem Stage IV and V standards for agricultural tractors and CEV Stage IV and V the ones for construction machineries.



Trem and CEV Stage IV - V emission standards

Engine Power	Date	CO	HC	NOx	PM	PN	Test Cycle
kW		g/kWh				1/kWh	
Trem Stage IV and CEV Stage IV							
37 ≤ P < 56	2021.04 (CEV) 2021.10 (Trem)	5.0	4.7*		0.025	-	NRSC and NRTC
56 ≤ P < 130		5.0	0.19	0.4	0.025	-	
130 ≤ P < 560		3.5	0.19	0.4	0.025	-	
Trem Stage V and CEV Stage V							
P < 8	2024.04	8.0	7.5*		0.4	-	NRSC
8 ≤ P < 19		6.6	7.5*		0.4	-	
19 ≤ P < 37		5.0	4.7*		0.015	1×10^{12}	NRSC and NRTC
37 ≤ P < 56		5.0	4.7*		0.015	1×10^{12}	
56 ≤ P < 130		5.0	0.19	0.4	0.015	1×10^{12}	
130 ≤ P < 560		3.5	0.19	0.4	0.015	1×10^{12}	
P ≥ 560		3.5	0.19	3.5	0.045	-	NRSC

* NOx + HC

Figure 80 – Indian Trem Stage IV and V emission standards for off-road vehicles [28]

While Stage V will be valid for all engine power rates, Stage IV is limited between 37 and 560 kW. Ammonia slip limit of 25 ppm is added for SCR provided engines, on a mean value over engine cycles. Useful life periods limit values are also valid, with deterioration factors applied to pollutants.

4.6 Worldwide scenario conclusions

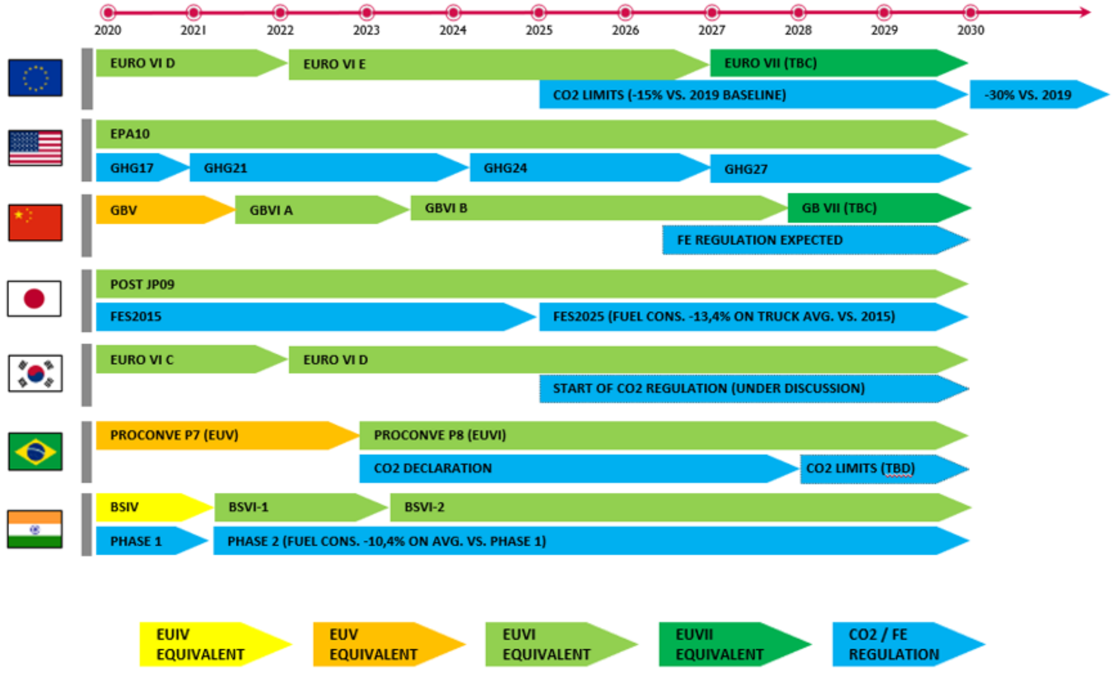


Figure 81 - Global on-road emission scenario [FPT Industrial]

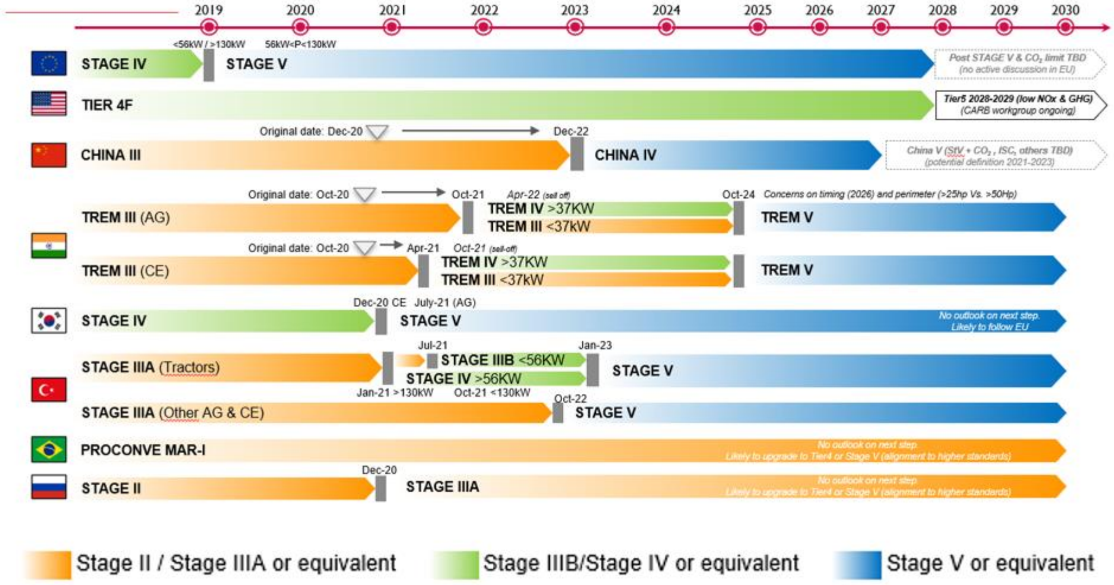


Figure 82 - Off-road global emission limits evolution [FPT Industrial]

We have seen main emission related standards for both on-road HDV and off-road NRMMs in the most important regulation areas. Type approval procedures, standards and regulations are ruled by authorities seeking for tightening in pollutant emission limits. OEM are often aligned in that, and often agreements are signed on voluntary basis in order to be coherent in near and far future threshold decisions. However, it could be important to get harmonization also in worldwide different authorities' standards scenarios. Alignment of limits, type approval procedures and test cycles as well as additional requirements are more than a simple nice to have. It allows the standardization of 'hardware' components for the after-treatment systems. It is an enabling factor for those manufacturers who operate in different economic regions, for those who will, and for the commercial agreements between manufacturers, suppliers and clients operating in different areas. In other words, a higher level of standardization is helpful to generate scale economics and reach a higher level of emissions regulation tightening, and a clearer situation on problems related to differences between type approval procedures and real life emission measurements. As we have seen, adoption of harmonized type-approval procedures and emission standards is now taking the lead over larger geographical and economic areas. Starting from the definitions of LD and HD worldwide harmonized transient and steady state cycles (the higher examples are the WLTC for passenger cars, WHTC, WHSC, NRTC, NRSC etc.), aligned emission standards could be set. It can be figured out that what was written in chapter 2 for CO_2 reduction strategies, about the need of a a framework capable of follow a unique strategy, is valid also in this field. It is clear how European and US regulations took the lead, and they take advantage of their large influence and their more than thirty-year experience on pollutant regulation field. Their standards are in this way diffused worldwide, with big developing economics countries like India following this path and adopting EU and US regulations. China is becoming a big market and player too, undergoing in decisions toward tightening of emission limits and alignment with European and US pollutants standard levels. Japan too introduced WHTC in both on-road and off-road engines emission standards. EU and US are aligned over certain decisions, especially in off-road engines standards, and still divergent in other ones. We noticed how NRTC and NRSC cycles are adopted in both EU and US off-road legislations, how

Stage V and Tier 4 are somehow similar, how level of Euro VI and MY 2010 standards are aligned. However, some structural differences hold in vehicle categories selection and fuel neutrality considerations (being Europe historically dividing engines in propulsion typology). The former difference is for sure due to different market structures and vehicle choice, more often narrowing in these years. The last figure well explains legislations split at global level and the trend in pollutant treatment. Euro VII expectations are on stricter limits on NOx, CO, PN and new limits introduction (for example on CH_4 and N_2O). For pollutant limits trend, we can notice how the common strategy pursued in both LD and HD sectors is to act against NOx, PM and PN. During first years of legislations, limits were concentrated on CO and HC emission levels. Being them today very low and near the threshold level represented by after treatment technologies, it is more appropriate to tight other health harmful compounds. With introduction of Euro 5-6, Euro V-VI, and various Stage V, Tier 4 and all their global-aligned standards, modifications implied setting of new limits of PN emissions also for gasoline and CNG engines, ammonia slip and lower NOx levels. This is still bringing introduction of enabling technologies like SCR and ammonia slip catalysts even in passenger cars, the introduction of wall flow DPF and SCR in agricultural tractor sectors and many non-roads, or SCRof for many different applications, or even CPF for gasoline and CNG engines. An overview on ATS layouts will follow in next chapter. In this scenario, as written also in chapter 2, the CO_2 emission levels became in latest years the higher concerns of authorities, due to its GHG harmful potential and the ongoing of the climate crisis. Being them a product of combustion, their effect would have a major impact on engine efficiency and propulsion typology. Still, we have seen how in the industrial market future forecasts the internal combustion engines will remain important, let say at least in next decade and with good possibilities of penetration in the following one. So, the emission regulations for ICEs will play an important role, and so will do the after-treatment systems. They will need enabling solutions for being efficient enough to reach present and future pollutant limits, as well as to stay competitive on the market and get effective cost reductions, in a picture of global continuous instabilities, energy and material shortages and cost changes. For these reasons it will be interesting to follow the technical and economical analysis of a particular solution, involving the latter washcoat zone coating design specification dedicated to a three-way catalyst for different families of CNG engines present in the study. For what the rest of the world regards, its picture gave us different results. Some countries tend to align to already studied procedures, others take their own paths. Just to take a brief overview, we can monitor situation in countries like Australia, south-American countries like Argentina and Brazil, Korea, Mexico and Canada, just to give a couple of examples. According to dieselnet.com, Australian emission standards are based on European regulations for light-duty and heavy-duty vehicles, with selection of certain US and Japanese standards. It is singular that in Australia standards do not apply for off-road engines, such as those used in construction or agricultural machinery, but are dedicated just to off-road passenger vehicles. From 2002 Australia adopted various European stages for passenger vehicles, buses and trucks selecting them by GVW. In South-America, Argentina started adoption of Euro stages in 2006, nowadays Euro V legislation is valid, implemented from 2016 to 2018. Brazil heavy-duty on-road emission legislations are called 'PROCONVE P-1…8' standards. The first set of standards were voluntary, and applicable also to light trucks. Then from PROCONVE P-5, Euro stages basement was introduced. PROCONVE P-8 standards, based on Euro VI, ran in 2018 with implementation from 2022 [*dieselnet.com*]. Tests are WHTC and WHSC, with PEMS additional tests requirements. Brazilian non-road diesel engines regulations came into effect in 2011, they are based on USA Tier 3 and EU Stage III A for nonroad diesel engine emissions, at first for some power rates only, then extended to other through years. In Korea, first heavy-duty engines emission standards were based on Japanese legislation, then, since 2003, Euro harmonization have been adopted. At the same time, Korean non-road engines standards have always been based on US Tier regulations. Construction equipment engines have been regulated since 2004. Agricultural machineries engines are meantime regulated since 2013. In Mexico HD regulation is not fuel neutral. HD Diesel engines first requirements were based on US EPA 1991, then updated through years. Since 2003 also European standards can be meet as alternative. Gasoline and gaseous fueled engines are tested over the FTP transient test and must meet the US EPA-based emission standards [*dieselnet.com*]. Natural gas engines can alternatively be tested over the European ETC test and meet the Euro IV/V-based emission standards [*dieselnet.com*].

Also Canadian standards were divided by diesel and Otto engines initially. Nowadays both diesel and gasoline engines standards are harmonized to US standards, with differences for phase-in time periods. For off-road engines there is harmonization with US authorities' standards too. It began in 2000 with Tier 1 alignment of a manufacturers voluntary agreement, and it is still valid today with Tier 4 standards introducing mandatory regulations.

Chapter 5 – Aftertreatment system architectures and components

5.1 Passenger cars aftertreatment architecture evolution

Vehicular after-treatment technologies have been diffused since the end of ‘90s and almost in same time there was the introduction of first European legislations over pollutant gaseous emissions. The after-treatment applications still undergo an evolution, in terms of components, architectures, materials, working principle etc. As we have seen, differences still hold based on vehicular application typology, kind of legislation and engine propulsion typology (whatever if the engine is spark or compression ignited, LPG, CNG etc.). We discussed on main components chemistry point of view, as well as mandatory legislations that make their introduction necessary. We will see how these components interact each other, the past and the future applications and architectures over both SI and CI engines for most important applications (PC, heavy-duty vehicles and NRMMs). It could be beneficial this time starting from passenger cars case, since the first regulations and technological applications were on this sector. Understanding PC components and architectures may be a solid basis to understand how they were then later transferred and modified in other sectors, due to some similar needs but also to structural differences.

5.1.1 SI engines architecture evolution

In SI engines for passenger cars, first important component to be developed was the TWC. Before its application, we have seen how dual bed catalyst concept was studied, without beneficial effects and implementations. Euro 1/2 standards so relied just on one or more underfloor TWC, depending on engine displacement and vehicle application. Different pollutant emission level reductions were achieved through different TWC number, dimension and PGM loading.

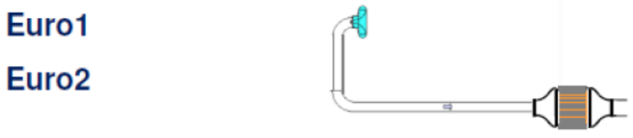


Figure 83 – SI Passenger cars Euro 1/2 after-treatments architecture [FPT Industrial]

The underfloor position caused high times to reach LOT, as the catalyst was quite far from engine. In Euro 2 standards, most of HC emissions are due to engine operating before the reaching of LOT. From Euro 3, type approval execution has been changed, without the 40s idling phase and the cold start emission records, not allowing any warm-up phase. A fast achievement of LOT so became crucial. The solution was to adopt a 'closed-coupled' catalyst (CCC) solution. In CCC configuration the catalyst is placed just downstream of the turbocharger turbine in engine bay compartment. Heat losses decreased, due to less distance that gases have to cover, and LOT could be reached faster. It allows to reach LOT temperature within 20s from the start of the type approval cycle. Moreover, it also reduces HC emissions in the range from 37% to 45% [11]

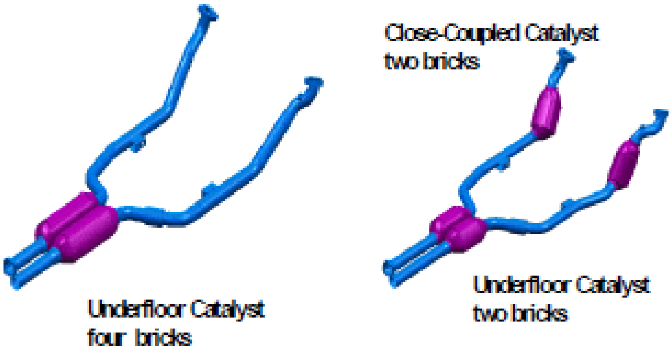


Fig 84 - Schematic of Euro 2 and Euro 3/4 of V6/V8 engines [11]

Anyway, some displacement constrictions could be present, in case of a bigger engine volume displacement (that mean also a bigger TWC volume). In these cases, for medium/large engine displacement vehicles, the solution adopted was to split the CCC catalyst in a 'cascade' configuration, or to have a 'pre-cat' followed by an underfloor main catalyst. Often the total catalyst numbers depend also upon number of engine cylinders.

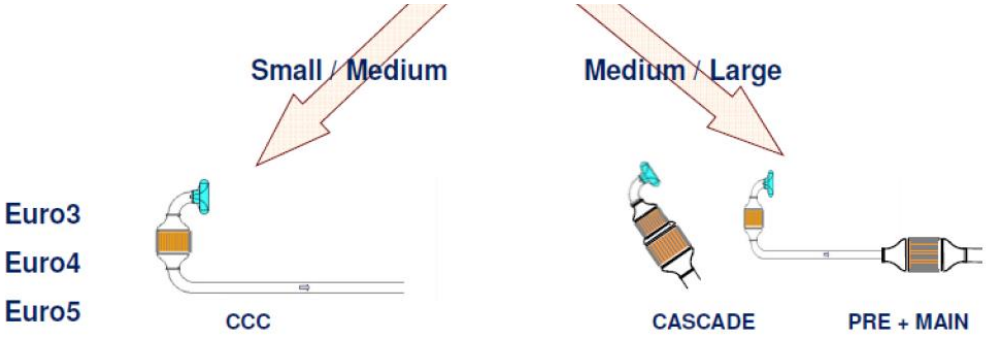


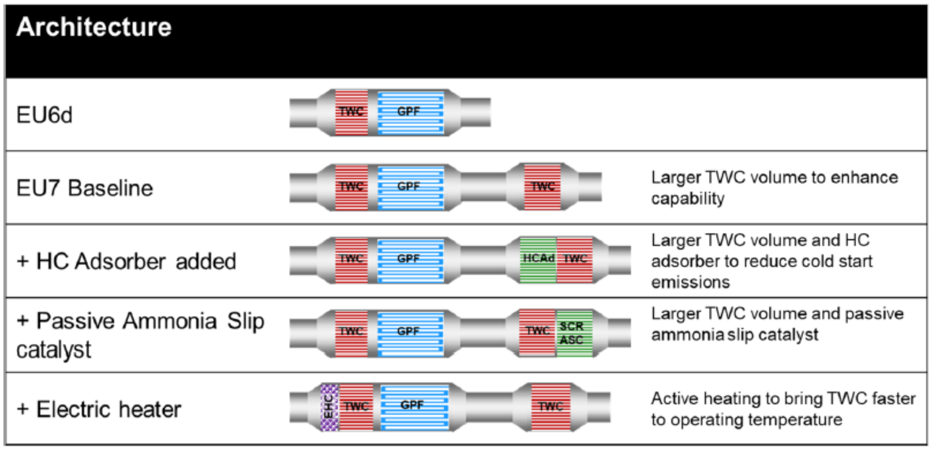
Figure 85 - SI Passenger cars Euro 3-4-5 after-treatments architecture [FPT Industrial]

Naturally, a CCC catalyst is exposed to higher stresses with respect to an underfloor one, often forcing to adoption of FeCr metallic catalysts instead of Cordierite ones. From Euro 6 standards we know that PN over cycle are limited. Moreover, steps toward actual Euro 6d standard led to RDE conditions limits and PEMS measurements. It led to definition of different strategies, the PN requirement in particular often need the adoption of a CPF (or GPF).

Figure 86 - Euro 6d architecture for passenger cars [29]

For what future scenario forecasts regards, according to a study promoted by Corning and presented in 2021 Aachen Colloquium of Sustainable Mobility, future Euro 7 (and aligned standards) are going to further expand the assessing of vehicle emissions [29]. Most probably, Euro 7 will be the first European legislation that is fuel neutral, as it is implemented in regions like US and China. Modifications over the conditions of RDE usage and the definition of a new RDE CF and the modification of the RDE cold start evaluation, toward more tight boundaries. Moreover, it is likely that besides traditional pollutants also new ones are going to be regulated [29], such as NH_3, HCHO, N_2O and CH_4. PN emissions measurement actual has a inferior limit cut-off set at 23 nm, that in future legislation should go down even to 10 nm, leading to an increase of PN emission measurement at exhaust up to 20-40% at same engine and ATS condition. The

TWC is the most mature after-treatment technology, and it will remain 'the hearth' of future after-treatment architectures. Its effectiveness can be optimised by the right PGM selection loading of Pt, Pd and Rh as well of substrates, as we will see. Expected cold start emission limits tightening could be controlled with higher PGM loading, but the cost increase of material should be careful monitored. Figure 87 address also the future scenario possibilities:



Architecture		
EU6d		
EU7 Baseline		Larger TWC volume to enhance capability
+ HC Adsorber added		Larger TWC volume and HC adsorber to reduce cold start emissions
+ Passive Ammonia Slip catalyst		Larger TWC volume and passive ammonia slip catalyst
+ Electric heater		Active heating to bring TWC faster to operating temperature

Figure 87 - Examples of potential EU7 gasoline aftertreatment architectures. [29]

A hypothesis is the utilisation of HC adsorbers, based on the concept of storing hydrocarbons (by using zeolites for example) during cold and/or lean operations and releasing it when warm-up phase is finished. Ammonia slip could be reduced by using passive SCR and ASC (Ammonia oxidation catalysts). Cold start performance could also be improved with addition of upstream active heaters components. It is not a very recent solution since it had already been developed during '90s. But today's electrification in passenger cars, with 48V or higher voltage system (from MHEV or full hybrid systems) could be a key for its implementation. Moreover, an improved efficiency GPF will be also utilised.

5.1.2 CI engines architecture evolution

We saw how compression ignition engines needs dedicated after-treatment features. It goes from Euro 3/4 DPF adoption till NOx filtration systems (mainly SCR and LNT in passenger cars, so dedicated components are present in diesel cars. Also for compression ignition engines, changes in legislation standards led to different architecture adoption over the years. Before Euro 3/4 DOC only was adopted, in different combinations and number depending on application. Then, between Euro 3/4 legislations, several OEMs adopted underfloor DPF downstream the DOCs, with the solution adopted in 100% of cases by end of Euro 4 legislation. Its presence led to the regeneration problem, with too narrow windows of regeneration, due to the low temperatures of diesel exhaust gases reaching DPF underfloor position, and the too invasive regeneration strategy, that often need too much post-injections fuel to waste. In order to decrease the time needed to reach regeneration temperatures window and decrease the regeneration control effort need, starting from Euro 5 the typical architecture was the one with DPF in closed-couple position, following the DOC just downstream the turbine exhaust. The evolution is underlined in figure 88. The advantages of the CCC solution of limiting heat losses and get a faster system response are though counter-measured by the volume limits in engine bay. Limiting DOC and DPF volumes may mean to have higher HC slip and DPF regeneration frequency.

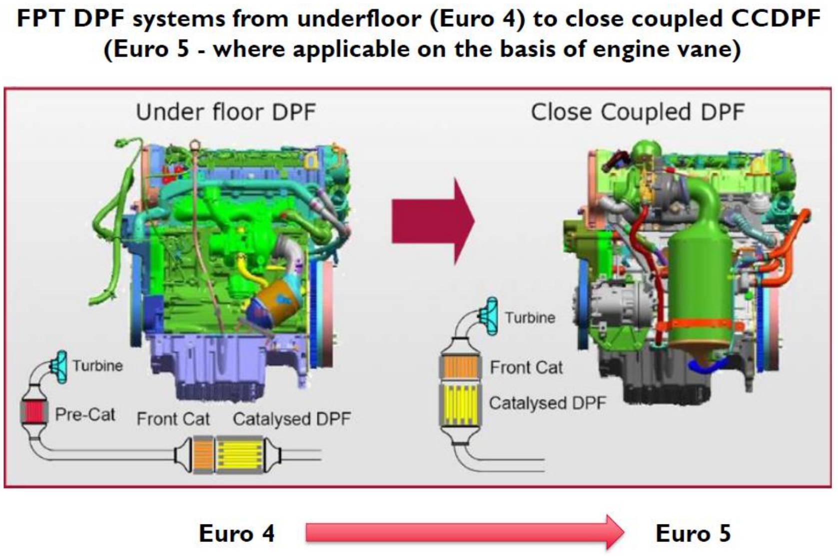


Figure 88 – FPT DPF position comparison between Euro 4/5 [FPT Industrial]

Euro 6 additional NOx requirements led to the definition of the actual architecture. LNT and SCR systems have been adopted. When the vehicles are equipped with LNT, they replace DOC and usually a CCC configuration coupled with DPF is chosen (most often on small displacement engines). In these cases, no SCR is implemented, and LNT converts HC/CO/NOx leaving the DPF the job for the particulate matters. But usually the Euro 6 'base scheme' is an adoption of a CCC DOC+DPF (the first for HC and CO and the second for PM) plus an SCR catalyst for NOx control, with all the subsequent DEF urea system dosing and supplying module and the mixer, to enhance SCR NOx reactions. Base scheme architecture could be found in below figure, applied on Euro 6 diesel

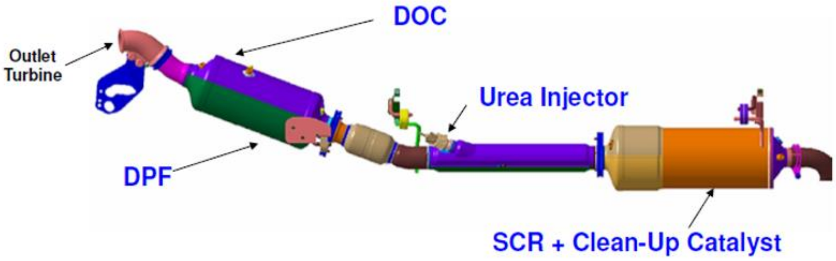


Figure 89 - Example of Euro 6 DOC + DPF + SCR system [FPT Industrial]

Recently SCRof adoption coupling DPF and SCR function is more and more diffused. SCRof has a light-off advantage and can sustain DPF-function regeneration. Current-like Euro 6 architecture is summarised in figure 90 and a temporal evolution of passenger cars diesel after-treatment architecture could be found in following figure

Figure 90 – CI Passenger cars current-like Euro 6 architecture [29]

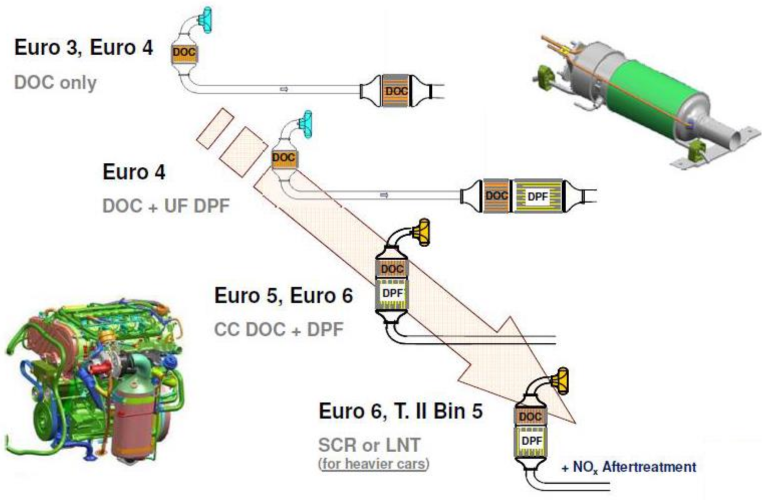


Figure 91 - Evolution of passenger cars diesel after-treatment [FPT Industrial]

While future Euro 7-like legislation could bring adoption of new components for gasoline passenger cars, for diesel applications less change is expected [29]. The Euro 6d typical layout seems to be robust [29]. The system will hold DOC catalyst (or partially formulation of lean NOx trap like in figure) with a SCR coated DPF (so a SCRof) in a CC position [29] followed by a larger SCR catalyst with Ammonia slip control. Dimensions of the substrates are expected to grow. Moreover, a second urea dosing module could be added to better manage urea dosing at different regimes [29]. We can get also an electric catalyst heater upstream of the overall system. The reason is that it is possible to inject urea only at temperatures above 180°. At cold start or low load engine operating point, highly efficient engine exhaust temperatures are often below this level [29]. Electric heater enhance the urea dosing.

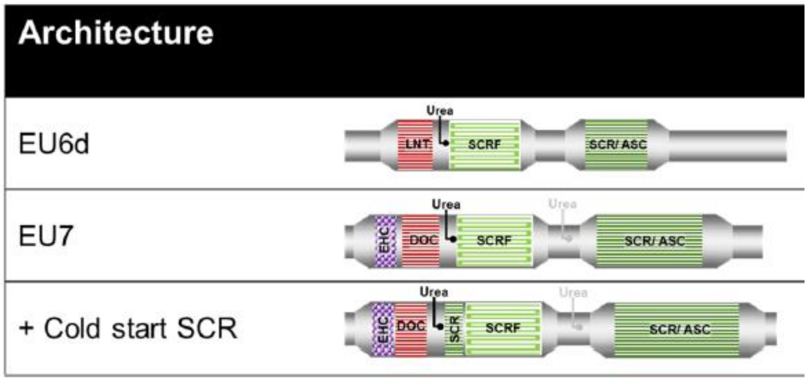
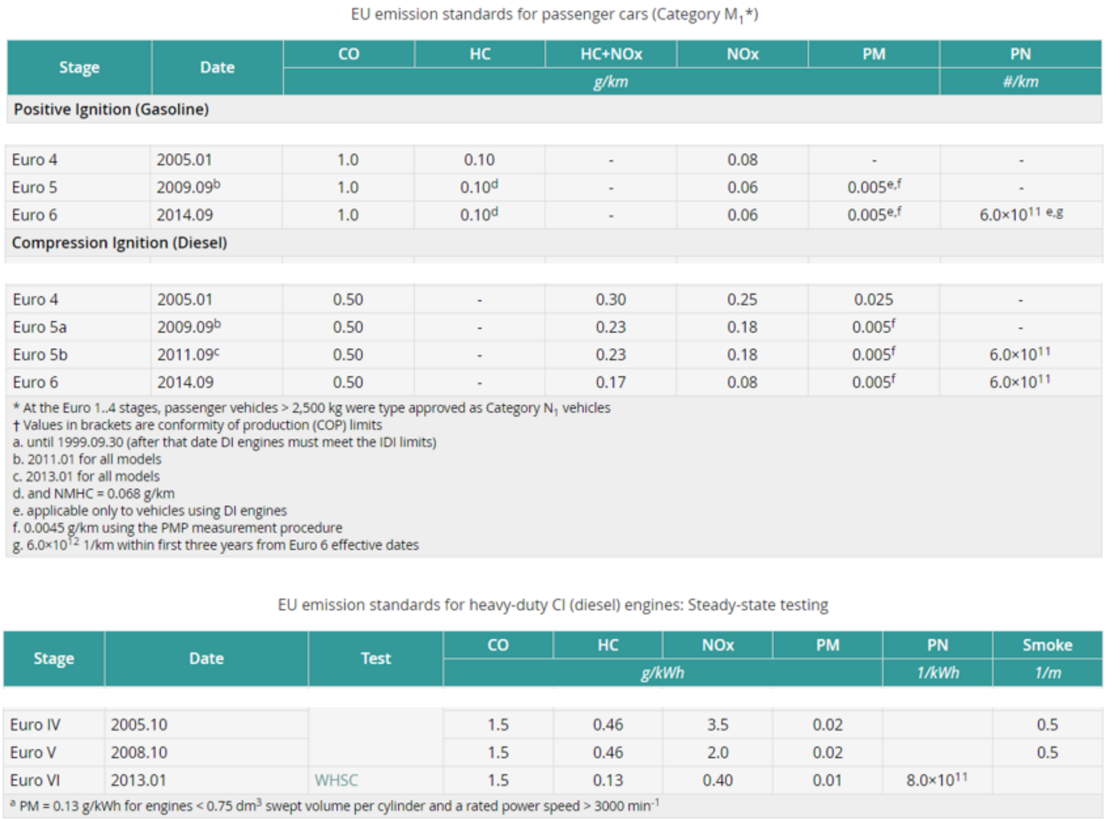


Figure 92 - Examples of potential EU7 diesel aftertreatment technologies [29]

An additional hypothesis foreseen the adoption of an additional short close-coupled SCR catalyst to have deNOx function at low temperatures, as highlighted in the figure.

5.2 On-road industrial vehicles aftertreatment architecture evolution

In last chapter the rate of change of different emission legislations has been analysed both in bigger regions and in a worldwide look. In Europe Euro IV, V and VI standards followed path created by LDV Euro 4, 5…6 standards. Obviously, differences are present in the absolute magnitude of limits. It is possible to notice that the attention was pointed toward PM, PN and NOx limits tightening for both LDV and HDV legislation. Herewith a comparison between LDV and HDV last European legislations, although they are taken on different type approval cycles.



EU emission standards for passenger cars (Category M_1*)

Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					#/km
Positive Ignition (Gasoline)							
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]
Compression Ignition (Diesel)							
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

EU emission standards for heavy-duty CI (diesel) engines: Steady-state testing

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				1/kWh	1/m
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	

[a] PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}

Figure 93 – Euro 4-5-6 and IV-V-VI over steady-state testing comparison [*Dieselnet.com*]

The result is that the after-treatment components adoption has seen the same evolution from passenger cars to heavy-duty sector, passing by light duty commercial vehicles and medium heavy-duty MHDV. So again, LPG engines are endowed with three-way catalysts (varying in dimensions, numbers and PGM loading based on application typology etc.) and from Euro VI step E2 the adoption of CPF is practically mandatory. All of that is usually implemented in a single big muffler. For CI engines more complexity is due to the need of reduce PM and NOx emissions. So DPF and SCR urea systems are mandatory to be consistent with emission legislation. The result is that Euro VI 'baseline' configuration is quite similar to passenger cars one. The difference is that in HDV we can find bigger components, parallel layouts then to be integrated again in a single silencer muffler unit, an insulating component containing in the order: a DOC followed by a particulate filter and usually two parallel SCR units and ammonia slip catalysts. In figure 94 we can find the typical Euro VI HDV architecture, accounting just the components flow. As obvious Euro VI-like standard emissions could be fulfilled with same after-treatment components implementation level.

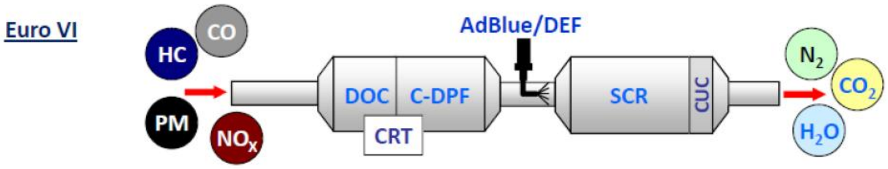


Figure 94 - Typical Euro VI layout [FPT Industrial]

For heavy duty vehicles "One box muffler" approach is the best solution to deal with vehicle constrains. The layout adopted in some engine case within FPT Industrial is the following one.

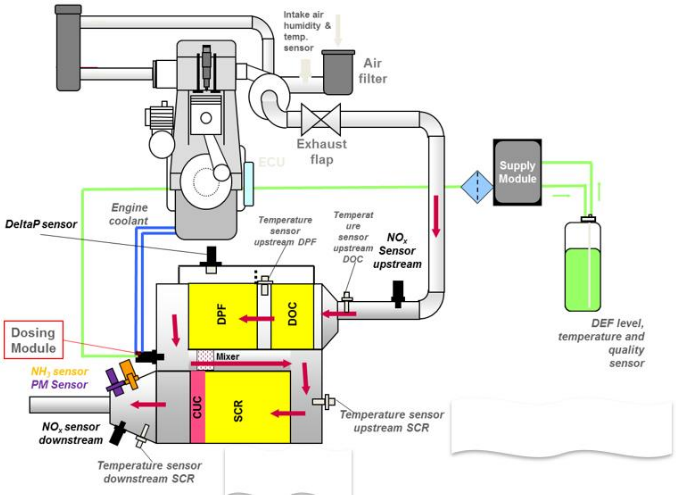


Figure 95 - Euro VI Step C system layout [FPT Industrial]

New contents have been implemented in the Eu VI A to C evolution minimizing the impact on muffler and installation. It is possible to spot several component typologies. All of them will be later discussed. We can see control and monitory sensors (temperature, NOx, delta pressure) and some of the SCR-related components (urea tank, Supply and Dosing modules). We can see that exhaust gases exit engine turbine and manifolds, they reach the muffler being processed at first by DOC. As we have seen, the oxidation of carbon monoxides and unburned hydrocarbons enhances the CRT® effect for NOx reduction and help the regeneration of the DPF, justifying its upstream position in the flow processing. Then the DPF presence together with two SCR guarantee the treatment of particulate matters and nitrogen oxides. The two SCR are integrated in the so-called SCRt box inside the muffler, and always inside the muffler a sort of internal mixing pipe and the mixer components presence efficiently create the suitable ammonia distribution in the selective catalysts just after the DEF urea injection, that happens in upstream position. Thanks to the urea injection in the dosing module, supported by the supply module that supply urea stored in tank to all seen components. In these two engine families cases the second SCR in the SCRt box is followed downstream by the clean-up-catalyst CUC, that avoids ammonia slip concerns and secure the fulfilment of the recently added ammonia slip emissions regulations over the test cycles. We can split so the components in three pots:

- SCRt muffler with integrated dosing module and DEF mixer (one box solution)
- DEF tank embedded of sender unit and level and temperature sensors
- deNOx system: Supply module and dosing module

As highlighted in the layout, the dosing module can be usually placed in the muffler along with the urea mixer. We can further have different vehicle muffler installation, with urea injection across mixing pipe feeding the supply module component. Clamps and heat shield or insulators are usually present in external skin of the muffler as well idoneous fastenings to the vehicle chassis. In passenger cars Euro 6 emission standards did realise the switch to SCR systems implementations due to lower NOx limits, meanwhile in HDV most manufacturers have been using urea-SCR for NOx aftertreatments since Euro IV [30]. Euro VI and aligned US 2010 standards uses more or less same architecture with urea-based SCR NOx reduction. But the difference lies in the fact that pre-Euro VI solutions were coupled to in-cylinder EGR NOx control, a solution that nowadays is reduced in use. In the past for some manufacturers the well know PM-NOx trade-off [5] with EGR usage was not a problem, as the PM-related caused by EGR presence was then controlled by DPF. In these cases the particulate filter is so needed to counterbalance the EGR usage, and from Euro VI is mandatory due to the PN limit [30]. In fact, prior to this limit introduction, some other technical solution adopted SCR only EGR-free solution [30]. An example was the Euro IV/V I FPT Industrial layout that can be found in fig 96 and 97

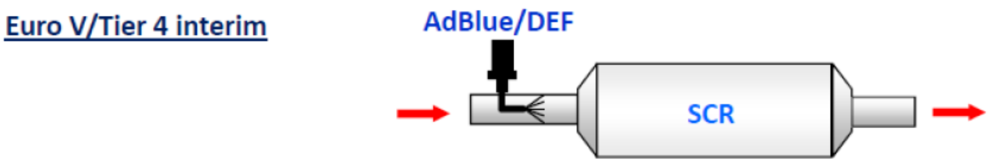


Figure 96 - Aftertreatment system architecture for MD/HD applications [FPT Industrial]

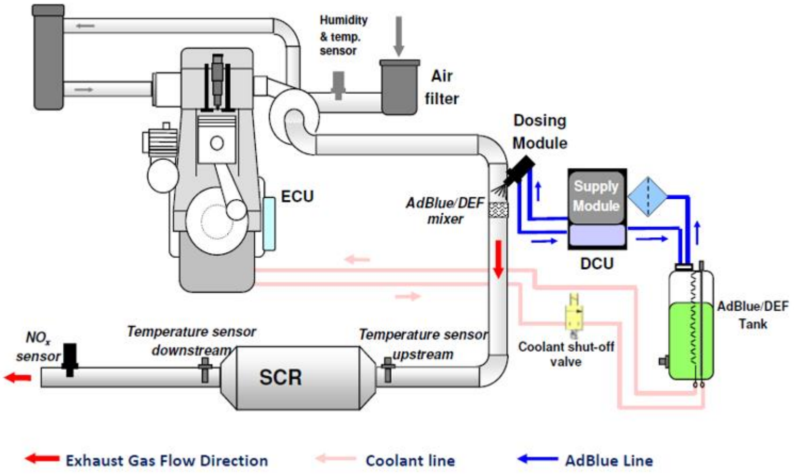
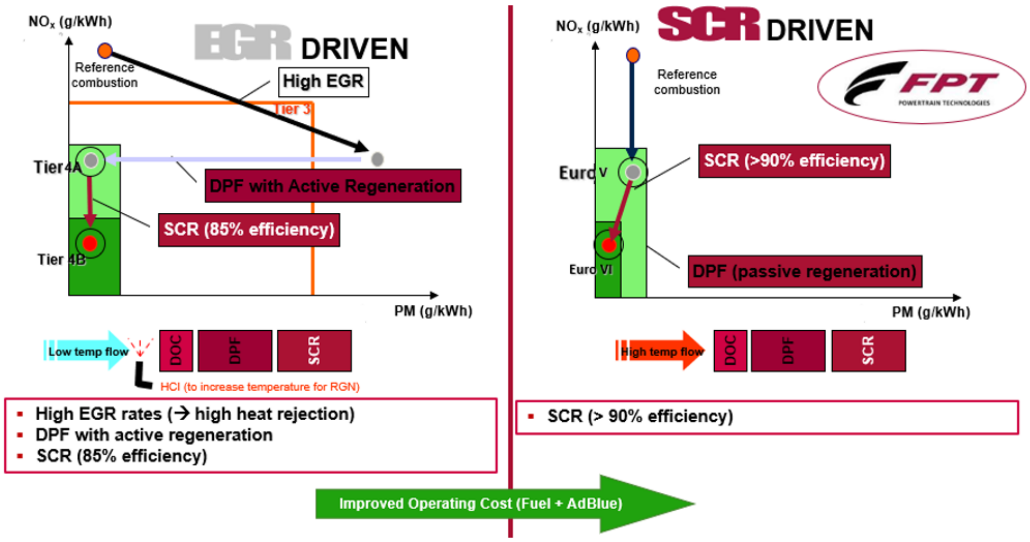


Figure 97 - Euro IV/V system architecture [FPT Industrial]

Sometimes in the past it was just a matter of fuel economy [30] as with SCR presence the engines could be calibrated for a higher engine-out NOx and higher efficiency. Meanwhile, as said, the coupling of SCR and EGR NOx control is not more feasible with Euro VI-like standards without a DPF, because of the PN limits [30]. With Euro VI, OEMs try to reduce or to completely eliminate EGR by adopting high efficiency SCR. Resuming, in the past the NOx reduction was through the usage of part-time and/or uncooled EGR [30]. The main strategies were:

- Cooled EGR + SCR,
- Hot (uncooled) EGR + SCR
- SCR only

Notice that Iveco and Scania solutions, often referred as 'SCR only' is referred to the NOx control (so absence of EGR). Nowadays these Euro VI solutions need however a DPF PM control. Do not confuse with past 'SCR only' applications that, as seen, could be also DPF-free. FPT Industrial choice was driven by the fact that EGR presence causes higher PM levels, a higher eventual DPF control with active regeneration that causes higher break specific fuel consumption. The regeneration temperatures limit the SCR efficiency, and the power loss due to EGR usage forces to adoption of bigger displacements or multi-stage turbochargers. It moreover impacts on engine cooling system. By the contrary, for SCR driven strategies optimised combustion leads to lower break specific fuel consumption values, good PM values controlled by a passive regeneration strategy that does not inhibit SCR efficiency. It remains feasible with current displacements and turbocharger technology. It is although true that more effort has to be spent for cold manoeuvres management for the SCR system, as it is not enhanced by DPF activity, a more precise urea dosing system is needed leading to NH_3 sensor introduction and more urea consumptions could be report. Figure 98 resumes technology drivers for Euro VI and NOx-PM trade-off shape of the two technologies.



- High EGR rates (→ high heat rejection)
- DPF with active regeneration
- SCR (85% efficiency)

- SCR (> 90% efficiency)

Figure 98 – EGR driven versus SCR driven strategies comparison [FPT Industrial]

The implementation of ATS hardware components architecture is in fact always related to engine-level strategy adoption (both at hardware and control level). Engine control strategies (EGR, spark advance or injection timings, turbulence control etc.) is off the scope of this study.

5.3 Off-road industrial vehicles aftertreatment architecture evolution

In past legislations set of standards for what regards Stage IIIA applications, engines were usually endowed with a cooled EGR system without any exhaust aftertreatment [*dieselnet.com*]. For Stage IV just an SCR system was used, referred to as 'SCR only' strategy. Latest years bigger change in NRMMs European emission standards is referred to the introduction of Stage V PN limits for several engines that so doing defined the implementation of DPF systems. [19]. However, NOx emissions limits also means that more efficient SCR technologies are needed, with overall increasing of complexities, size and costs [31]. As the main markets, like the European one, have this double goal on NOx and particulate matter/number reduction, the application of SCRof technology could relax OEMs constraints to implement a common solution for different applications range. It is worth to notice that emerging markets like India, China and Turkey are going to implement Stage V/Tier 5 compliant emissions limits [31]. Moreover, sometimes conflicting approaches could be spotted, like China and India that are currently favouring opposite paths toward respectively particulate filtering and NOx reduction [31]. So, implementing SCRof technology could be compliant for both the approaches.

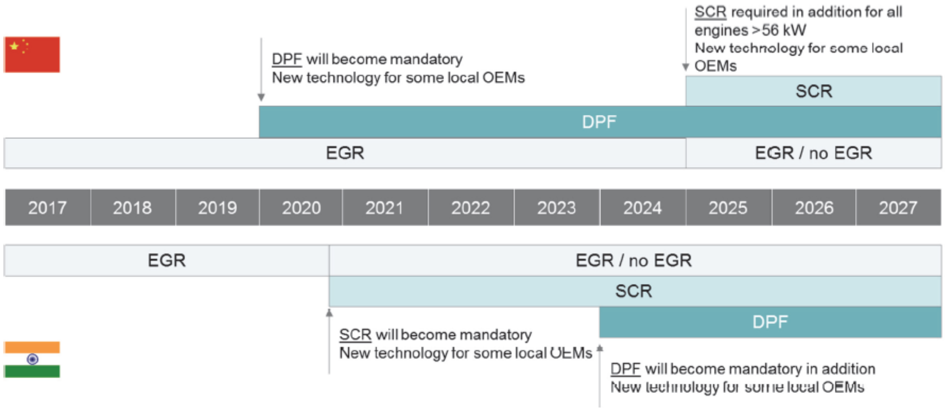


Figure 99 - China and India opposite paths toward over SCR and DPF implementation for off-road vehicles [31]

Across all the possible Stage V configurations, it is so interesting to stretch our attention on 'SCR on filter' technology usage. It could provide a more compact after-treatment overall package, of interest in many non-road applications as often they are limited by space constraints [31]. SCRof-based systems help to get more remote vehicle location and easier installation, with the reduced size that is requirement for applications where visibility is a key factor, like tractors. The differences with a 'SCR only' system, seen before in on-road HDV case and embedded in Stage IV and US Tier 4, starts with the piping between the turbine outlet and the SCR converter introducing the DOC system, and lies also on SCR housing differences to accommodate the additional SCRof. The differences are highlighted in following figure.

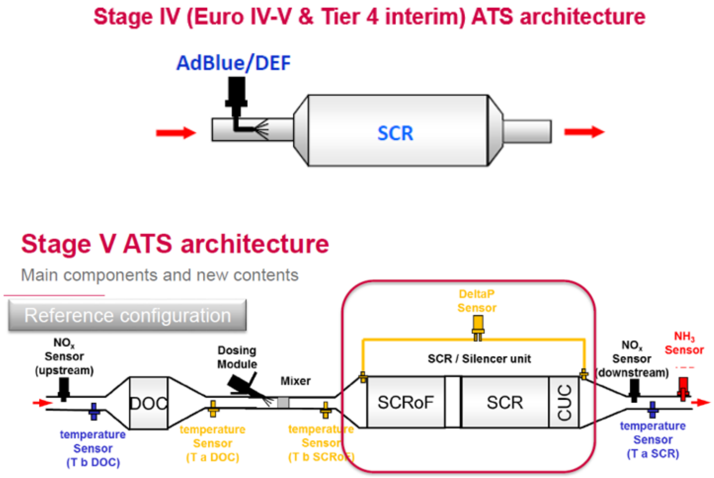


Figure 100 – Stage IV and Stage V European off-road after-treatment architectures [FPT]

The typical Stage V system architecture, like the one that endows FPT engines, includes a Pt/Pd oxidation catalyst, followed by urea injection using a dosing system, DPF coated with (vanadium) SCR catalyst and an additional vanadium-based SCR catalyst with an ammonia clean-up catalyst (CUC). Usually, the further SCR component that is added downstream the SCRof is to improve conversion efficiency during regeneration or at high temperatures [31]. It can be implemented either in the same can (more diffused and preferrable for packaging) or even in downstream/remote position. The latter will also need some thermal management effort. The overall system provides a high NOx reduction efficiency. It allows also for possible search for high NO_2 to PM ratios downstream of the DOC, enhancing passive DPF regeneration. The coupling of particulate filter and SCR elements need an increased effort of engineering and the implementation of the architecture over a big range of vehicles could bring to some challenges. The SCRof system is designed to meet Stage V compliance targets (NOx = 0.4 g/kWh, PN = 1×10^{12}

kWh^{-1}) with passive DPF regeneration on specific customer cycles and on NRTC. The SCR-on-filter technology was chosen due to its potential for the most compactness system and for the possibility of embed lower PGM amount. Challenges could arise in development for the co-existence of particulate filter and NOx-urea catalyst, for example the effects of the SCR catalyst on particulate filtration and pressure drops, the effect of ashes on the SCR catalyst and NOx reduction [31]. The passive regeneration of the particulate filter has to be favoured, with choice of regeneration strategy to fit the SCRof technology typology used. Vanadium systems are indicated for passive regeneration, while copper zeolite ones are good when active regeneration strategy is chosen [31]. Often, to enhance CRT® effect with high NO_2 content in DOC outlet helping soot filtering an increase in temperature is required, aimed to get an equivalent passive regeneration of the particulate filter and to get more NOx:PM ratio. The latter is also achieved via modification of engine outlet emissions. The balance of passive regeneration points and its temperatures are often difficult to achieve at low loads, because exhaust enthalpy is low. Some applications may need active regeneration intervals or even heaters. The active regeneration is achieved through additional injector in exhaust flow-stream or by post-injection [31]. For what regards the coating, its choice could influence the delta pressure across SCRof component. Implementation of SCRof with copper-zeolites coatings could generate backpressure as this kind of coating is characterised by low density, so it is capable of take lot of space within filter monoliths. Optimization either of the coating or of the substrate is so mandatory for some applications where backpressure must be monitored. Increase of the pore size and overall porosity can be an example of optimization. Playing with cells per square inch level and wall thickness could be beneficial, always looking at component durability. Working on coating uniformity and position is sometimes a method to optimize backpressure in soot emission compliance. The sizing also could affect backpressure, the lower it is the better the backpressure on component, but it has to be balanced also for regeneration interval and soot limit required. All of these aspects should be obviously tailored for each application typology and requirements, as it happens also for each component in the architecture of either on-road or off-road vehicles, but here the SCR NOx functions and the particulate filter ones should be properly balanced and matched. The experience that transport industry has on passenger cars SCRof is in that way going to be successfully applied to off-road markets and then extended also to heavy-duty future applications [31].

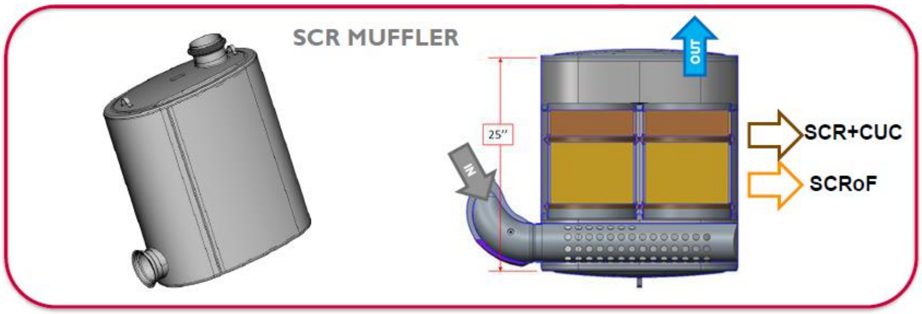


Figure 101 - Compactness of the SCR muffler for off-road Stage V applications [FPT Industrial]

It is worth to add that in this scenario evolution, the US EPA Tier 4 standards were phased in between 2008-2015 period in United States. For engines between 56 and 560 kW the initial 2008 phase-in standards, involving PM compliance, are sometimes referred as ‘interim Tier 4’ or ‘Tier 4i’ or even ‘Tier 4A’, while the additional 2012-2014 NOx/HC compliance led to definition of ‘final Tier 4’ or ‘Tier 4B’. Tier 4 interim ATS architecture layout and its strategy is the ‘SCR only’ equivalent we have seen for Euro IV-V heavy-duty applications and for off-road Stage IV. The solution was so EGR-free and DPF-free due to the lower PM emission levels gained by this strategy, with NOx control left to SCR [FPT Industrial].

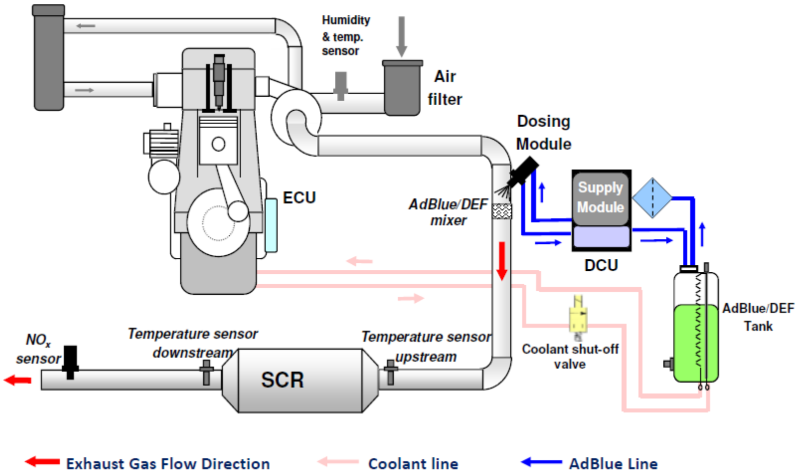


Figure 102 - Off-road Tier 4 interim layout with SCR only system illustration

The introduction of a second final phase of Tier 4 (characterised by tighter HC/CO and NOx limits) is translated in adoption of a 'final' typical layout. The difference to the SCR only layout is the addition of a diesel oxidation catalyst just upstream of the SCR unit. The DOC also incorporates the mixer for the urea necessary to run the SCR deNOx catalyst reactions. System is completed by urea tank and the supply module. Final US off-road FPT Tier 4 system is explicated in figure 103.

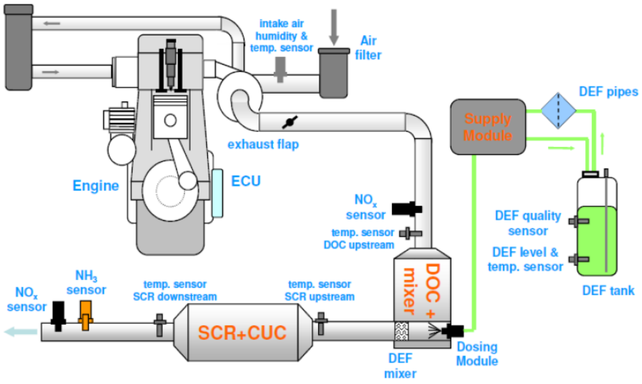


Figure 103 - Off-road Tier 4 final layout illustration

5.4 MD-HD and Off-road main others ATS components

After-treatment systems embed different technologic components. From the application of different catalysts and filters (the gasolines and diesel main catalysts, the DPF/GPF filters till the different NOx treatment components) the systems are coupled with numerous other sub-system components. Their dialogue make possible the complete functioning and processing of the exhaust flows, either from an 'hardware' point of view (that involves canning of the various monoliths and fixing of components) or for the control (and engine calibration) logic, making able the right exploitation of the after-treatment components and the check of their functionality with closed-loop control strategies involving as we have seen different sensors plus the vehicle ECU (Electronic Control Unit) and OBD (on-board diagnosis).

5.4.1 Mufflers and canning

Canning is the universal name for the installation of ceramic substrate in a metal housing. The monoliths are closed in a steel shell. It is important to avoid that the exhaust gas leaks in the space between the monolith and the external shell, it is so needed to seal this region with an insulating material. The concept of substrate canning is explicated in figure 104 and 105

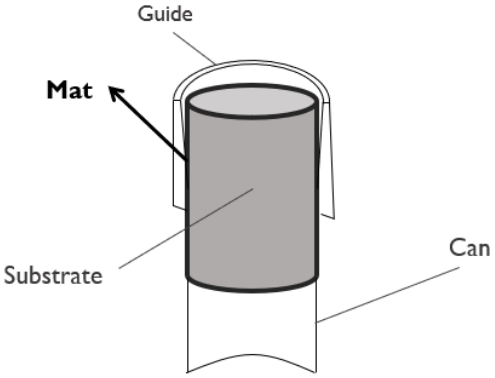


Figure 104 – Stuffing process in canning illustration

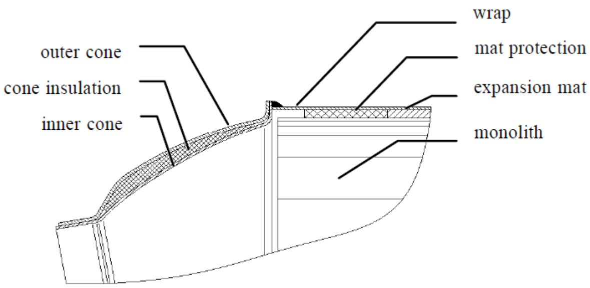


Figure 105 - Force controlled wrapping process canning [11]

The substrate is sleeved in a cylindrical support mat component. It is basically enclosed by this expansion mat. The mat has the aim of supply holding force to the substrate during operational lifetime, keep substrate in place during operation and also to thermal insulate the substrate [FPT Industrial]]. It moreover seals to prevent exhaust gas flow going around the substrate. Almost all support mats used today are made up of ceramic fibres or alumina fibres [FPT Industrial]. Several different canning methods have been developed. An example could be the stuffing process, stuffing is a canning method where the substrate is sleeved in a support mat and then pushed into a steel housing by using a stuffing cone [FPT Industrial]. Three types of support mats are commercially available

- Intumescent
- Non intumescent
- Hybrid

The intumescent mats have the peculiarity of expanding with increasing temperature. At the cooling down they will not shrink aiming to keep fixed the substrate inside the shell. Intumescent mats were the main support mat, firstly used in the early ‘90s for gasoline PC (passenger cars). They are made of vermiculite (45-60%), high temperature aluminosilicate fibres (30-45%) and organic binders (5-9%) [FPT Industrial]. Meanwhile, aluminium-silicate non-intumescent mats just rely entirely on the fibres displacement from the initial compression given by the canning process to hold the substrate in place. They have relatively low variation with temperatures, due to their lower conductivity that could be beneficial. Often, for relatively large and heavy substrates (like a DPF for example) knitted metal rings are used in the canning process, placed in the upstream and downstream face of the substrate in contact with the mat to prevent mat erosion and to supply additional holding force (since the heavier substrate). They are called wiremesh, an example was internally photographed for DOC&DPF visual inspection during failure mode analysis and ATS post-mortem analysis procedures.

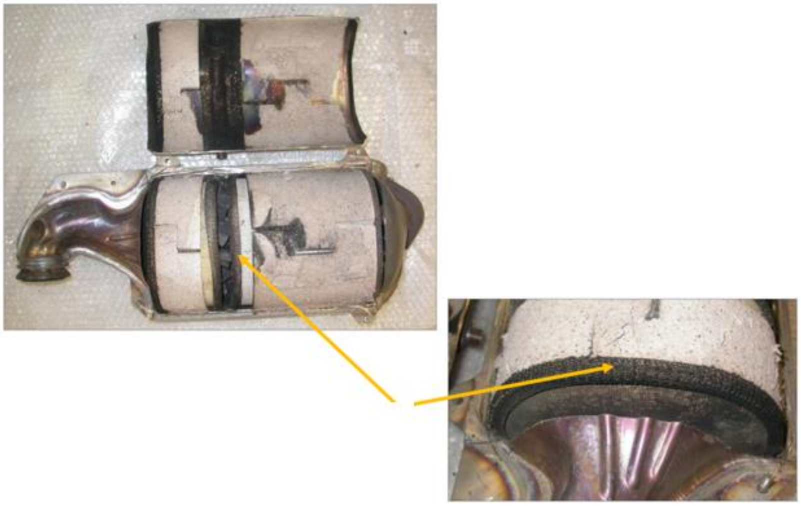


Figure 106 – Visual inspection DPF with wire-mesh elements highlighted

The canning ensures the good placing of the element inside the muffler. Differently from passenger cars applications, either for MD-HDV or for off-road vehicles, muffler are more than just acoustic chambers. Apart from their loud-reduction roles, in fact they will enclose all after-treatment elements, sometimes in a single brick unit. We saw example of Euro VI HDV system or SCRof off-road mufflers. They are basically integrated silencer in a compact unit that is insulated and can contains all various after-treatment systems and can hold all the bosses (cavities) necessary for the placing of various sensors needed for control and calibrating purposes.

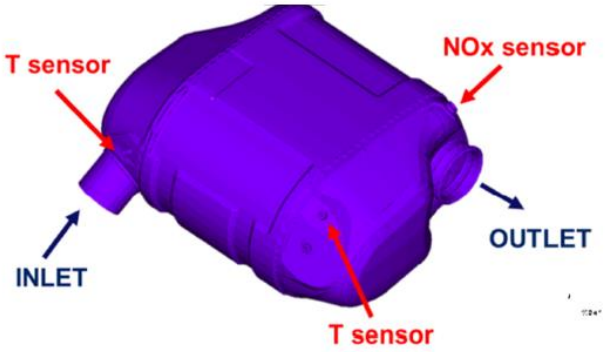


Figure 107 - SCR Muffler

5.4.2 SCR main components

In the SCR component, NH_3 is the reducing agent to convert various nitrogen oxides to non-harmful N_2 and H_2O [32]. Urea ($(NH_2)_2CO$) water-based solution is the reducing medium, it had been chosen for its properties of non-toxicity, for being non-corrosive and for being easily handled [32]. The management of this medium to get the right oxidation reduction inside the catalyst substrate brought to the definition of a complex system, made by different components. As we have seen AdBlue®/DEF water-32,5% weight urea need a specific storage tank. High temperatures hydrolysis reactions make the urea decompose into NH_3, so we need the solution to be properly supplied, injected and dosed, then finally properly mixed to get the right hydrolysis reactions upstream of the catalyst component substrate. Alongside this flow, the control system needs the right sensors to manage and to check the overall functionalities, also from a legislation point of view. In fact, vehicles may theoretically run also without any urea solution at disposal, but this would vanish the presence of the SCR and so various legislation standards ask for urea level control, mandatory refill interval windows and for engine stop procedure in case of missing DEF solution. All of this will translate in the presence of some component groups:

- Urea tank
- Supply module
- Dosing module

- Mixer

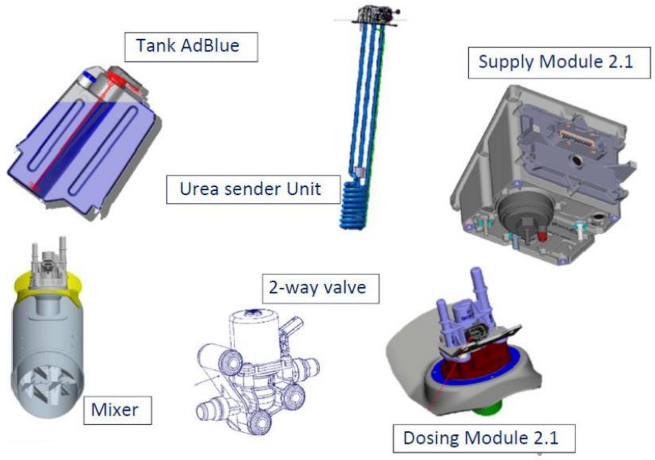


Figure 108 – SCR urea feeding main components [FPT Industrial]

The urea tank must be careful positioned in the vehicle, paying attention to tank inclination, possible damage positioning and fixing force levels. The tank is endowed with a filler cap, a free expansion volume and tank ventilation system.

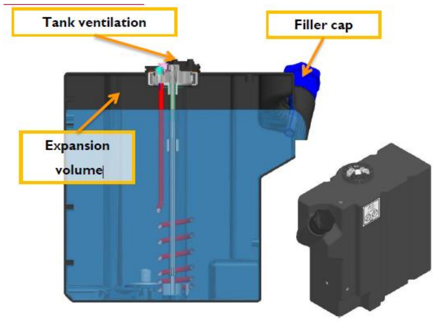


Figure 109 – Urea tank

The tank group is completed by a sender-unit, needed to send urea solution toward the supply module system, and the urea quality sensor UQS. The multifunction sender unit contains urea tank level sensor, temperature sensor, suction and return pipe. Eventual frozen DEF can be melted by means of a coolant heater coil, by means of engine coolant. A solenoid which is actuated by the DCU (Dosing Control Unit) – indicated in the previous picture - controls the engine coolant flow through the heater. Sometimes the tank unit is available also without heater coil, depending on vehicle operating conditions. The system is explicated in figure 110. We can see the heather coils and their connections, urea sender unit suction and return links.

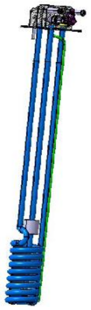


Figure 110 – Urea tank sender-unit

The urea quality sensor embeds an ultra-sonic sensor that sends a signal and measure the time to receive the reflected signal to detect the speed of sound, depending on liquid typology (quality) and temperature. The ultra-sonic sensor needs a minimum urea quantity level to proper work. Components lie on bottom of the tank bed fixed by a rubber foot. For what regards the supply module, DNOx SM system is showed in below picture. It is interesting to notice the coolant water connector for the heater, the AdBlue connectors and the water heater unit to supply heater coils.

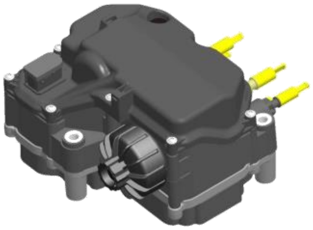


Figure 111 - DNOx Supply Module system [FPT Industrial]

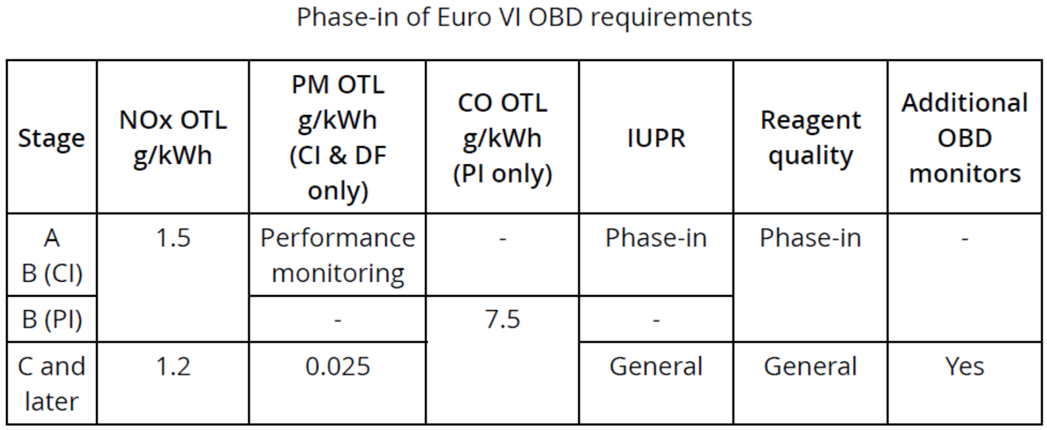
In supply module filter elements, inlet and outlet connectors (from tank and to dosing module) and respective inlet/outlet backflow connectors are present but hidden in this view. Meanwhile, the DNOx Dosing Module embeds coolant, urea and electrical connectors in order to accomplish its function of dosing and inject urea with the right quantity, spray angle and spray holes downstream toward the mixer and the SCR catalyst. Coolant and heat shield are important to lower thermal stress on component by exhaust gases.

5.4.3 Sensors and On-Board diagnosis

The On-Board diagnosis is a self-diagnostic functionality in engine and after-treatment control systems, aimed at identifying faults that could lead to higher emissions performance of the vehicles. OBD monitors performance of catalysts, particulate filter, evaporative control, ammonia slip etc. Exact requirements of the OBD system are specified in pertinent regulations. OBD requirements were for the first time introduced for LDV with Californian CARB first implementation in 1991 and extended in rest of US in 1994. In Europe EOBD regulation was introduced for light-duty sector in 2000 for gasoline cars and in 2003 for compression ignition passenger cars. For heavy-duty trucks, US OBD requirements were phased-in from 2005-2007 MY and in Europe in same years with the Directive 2005/55/EC [*dieselnet.com*]. For off-road vehicles, US Tier 5 is going to set OBD requirements. OBD aim is to detect and signal emissions fault, via the MIL (Malfunctioning Indicator Light). The following components or systems are typically subject to OBD monitoring [33]

- Emission aftertreatment devices
- Fuel system
- Engine misfire
- EGR system
- Evaporative system oxygen sensor (gasoline engines)

OBD ensures compliance of long-term emissions, as it is important that vehicle emissions increase stand within 'normal' increase and not abnormal. An example of OBD threshold limits (OTL) is below represented, with Euro VI HDV ones:



Phase-in of Euro VI OBD requirements

Stage	NOx OTL g/kWh	PM OTL g/kWh (CI & DF only)	CO OTL g/kWh (PI only)	IUPR	Reagent quality	Additional OBD monitors
A B (CI)	1.5	Performance monitoring	-	Phase-in	Phase-in	-
B (PI)		-	7.5	-		
C and later	1.2	0.025		General	General	Yes

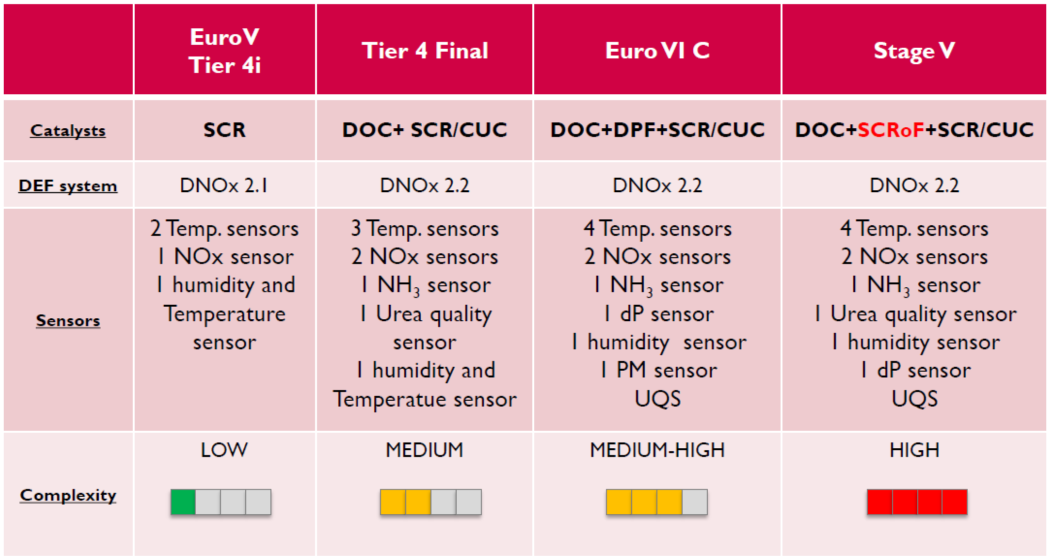
Table 12 – Euro VI OBD requirements emission standards for HDV [18]

Euro VI introduced several additional performance monitoring requirements for such components as EGR systems, boost pressure, malfunctioning injectors and emission after-treatment. For SI engines OBD must detect malfunctioning exceeding OTL paying attention of catalyst efficiency, lambda sensors functionality, misfiring conditions (that could increase HC and bring catalyst damage) and check all emissions-related components connected to ECU. Once a problem is detected, drives should be warned with MIL spy at instrument dashboard level and the relative error code should be stored to be detected in maintenance. For CI engines is more or less the same, with particular attention on DOC efficiency reduction, functionality and integrity of DPF and NOx catalysts, of the fuel-injection system electronics and emission-related powertrain components or systems (air mass flow rate, boost pressure, temperature etc.)

Engine management system is made up of:

- Sensors to monitor and measure engine working conditions;
- The engine control unit (ECU) that receives inputs from sensors and other units onboard and through calculations and maps provides commands to actuators;
- Actuators that convert into mechanical variables the electrical signals output by the ECU.

Sensors are so part of the main components of MD-HD and off-road vehicles ATS systems. They provide OBD thresholds compliance as well for in-life compliance of the emission limits, or they became also relevant for off-cycle compliance, a lot important in latest years. The complexity and the ATS architecture also lie in the addition of several sensor, in order to fulfil all the mandatory limits and all the calibration effort and checks needed, in relation of the component typology that added in the architecture (TWC, DOC, DPF etc.) In table 13 we can find a comparison over all the industrial ATS architecture we have seen in last chapter, and that are endowed in FPT Industrial systems.



	Euro V Tier 4i	**Tier 4 Final**	**Euro VI C**	**Stage V**
Catalysts	**SCR**	**DOC+ SCR/CUC**	**DOC+DPF+SCR/CUC**	**DOC+SCRoF+SCR/CUC**
DEF system	DNOx 2.1	DNOx 2.2	DNOx 2.2	DNOx 2.2
Sensors	2 Temp. sensors 1 NOx sensor 1 humidity and Temperature sensor	3 Temp. sensors 2 NOx sensors 1 NH_3 sensor 1 Urea quality sensor 1 humidity and Temperatue sensor	4 Temp. sensors 2 NOx sensors 1 NH_3 sensor 1 dP sensor 1 humidity sensor 1 PM sensor UQS	4 Temp. sensors 2 NOx sensors 1 NH_3 sensor 1 Urea quality sensor 1 humidity sensor 1 dP sensor UQS
Complexity	LOW 🟩⬜⬜⬜	MEDIUM 🟨🟨⬜⬜	MEDIUM-HIGH 🟨🟨🟨⬜	HIGH 🟥🟥🟥🟥

Table 13 – Comparison of on-road and off-road last after-treatment architectures

The Euro 6 after-treatment gives us a good example of typical sensors implementation. DOC and TWC are usually oxygen-level (lambda sensor) and temperature controlled. The first for obvious chemical reason (to check catalyst efficiency and OSC, plus the closed loop monitoring lambda upstream and downstream of the catalyst) and the second for controlling catalyst temperatures (that may also damage a lambda sensor itself). The DPF functionality (and so the SCRof) is checked via delta-pressure control, as it is trivial to understand the relation with pressure difference across DPF and its efficiency, its capability of filter soot and to properly regenerate. The SCR are temperature controlled (remember that nitrogen oxides reduction oxidations are temperature dependent and ammonia hydrolysis is too), and urea system bring the introduction of additional urea quality, level and temperature sensor (plus all the urea tank/supplying/dosing module we have seen so far). Latest introduction of newest regulations on PN and ammonia slip limits also make necessary to adopt PM sensor and NH_3 sensor (Euro VI and Stage V/Tier 4 final). They are introduced downstream SCR and ammonia slip catalyst. To close the loop, latest legislations compliant vehicles (always Euro VI-Stage V/Tier 4 final) adopt two NOx sensors, placed upstream and downstream all components in closed-loop. In figure 112 the scheme and explanation of what said. Sometimes implementation could vary, and the closed-loop strategies allow to arrange differently the sensors order thanks also to the presence of a multitude of systems. It is what happens for some Euro VI case, that seen the delta pressure sensors not across DPF as usually but between the DOC+DPF couple, so the total pressure drop is measured.

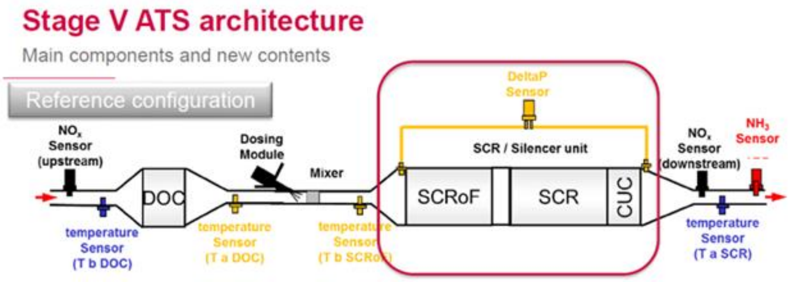


Figure 112 - Stage V after-treatment architecture

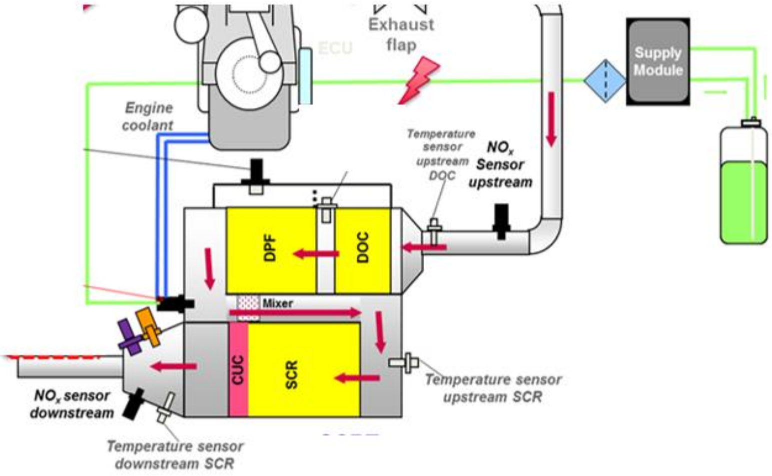


Figure 113 - Euro VI after-treatment architecture

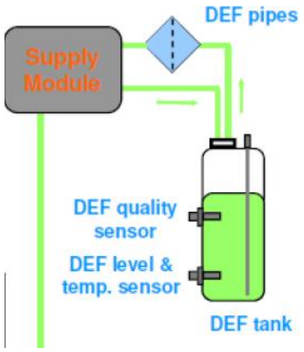


Figure 113 – Urea tank and supply module SCR urea feeding system scheme [FPT Industrial]

Resuming, the main component sensors used in OBD monitoring are [from FPT Industrial]:

- Lambda sensors: they are used to evaluate the actual air/fuel ratio. They compare the oxygen residual content in the exhaust gas with the oxygen content in the atmosphere and indicates whether a rich ($\lambda < 1$) or lean ($\lambda > 1$) air-fuel mixture is present in the exhaust gas. Only two output values are available, due to the abrupt change in the residual oxygen. The most widespread lambda sensor is usually called HEGO (Heated air-fuel ratio Exhaust Gas Oxygen analyser) In case of a rich mixture the output voltages reaches 800 to 1000 mV, while for a lean mixture only less than 100 mV. For closed-loop strategies this sensor is used only to correct drifts of the sensors upstream of the catalyst, with the swinging of the A/F ratio around the stoichiometric value
- Temperature sensors must be installed directly on muffler. Installation bosses exist on specific housings, located in a position representative for the DOC/DPF and SCR temperature. Sensor element is a Platinum thin film on Al_2O_3 substrate, their temperature Range is continuous from 40° C to 900° C with peak at 1000° C.
- For NOx sensors, the most common technology relies on Y-stabilized ZrO_2 electrochemical sensing element. NOx sensor is very sensitive with regards to water. Ceramic part could crack and/or the sensor cell may be poisoned. Therefore, any contact with water due to rain or washing has to be avoided.
- Delta-pressure measures the DPF pressure drop, which is the difference in the exhaust gas static pressure upstream and downstream of the DPF.

- NH_3 sensors make direct control of urea dosing based on ammonia slip levels, optimised levels of urea storage on the SCR catalyst are then possible and NOx conversion can be maximized. The sensing element utilizes co-fired zirconia and alumina layers with a Pt reference electrode and an integrated heater circuit. The sensor is designed to detect ammonia in the range from 0 to 100 ppm. It was reported to be relatively insensitive to interferences from pollutants like NOx, N_2O, CO and HC.
- Particulate matter sensor is a new content of Eu VI step C system. It Is located at mufflers outlet, in the exhaust pipe and open to the gas flow. The sensing element consists in a pair of flat electrodes affixed to a ceramic carrier. As soot particles are deposited onto and between them, conductive pathways are formed resulting in an increase of electric current (sensor signal).
- Humidity & temperature sensor instead is to be installed on suitable place with high air velocity (no dead zones) after air filter.

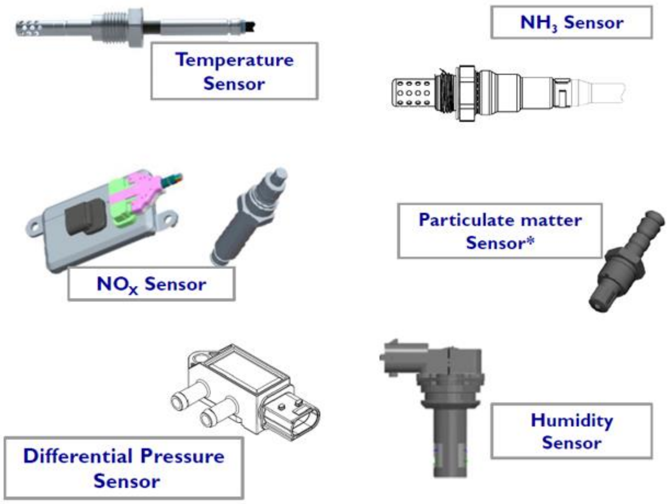


Figure 114 - Different sensor elements illustration [FPT Industrial]

Chapter 6 - Project implementation within FPT Industrial: the ATS Platform

In this chapter it will be showed how actually Iveco and FPT Industrial implement modifications on after-treatment systems architectures for both Captive and Non-Captive applications. It is all handled within a dedicated platform within the FPT Industrial company, called 'ATS Platform'. For Captive vehicular applications (Iveco) it collaborates with commodity and buyer personalities of Iveco. ATS Platform is the platform within which the present study has been conducted in this experience. The role in which the author was dedicated is the Advance Purchasing Development (often called 'PD' for Purchasing Development and its Manager is called PU or PDP), and all the data shared in study are collected within Purchasing Development team or shared by ATS Platform. Other main personalities within the platform are:

- *ACE* – Assistant Chief Engineer
- *PE* – Product Engineer
- *CE* - Cost Engineer
- *CM* - Customer Manager
- *DPE* – Design Project Engineer
- *Sales*
- *PLT* – Platform Manager
- *LM* – Launch Manager
- *SQE* – Supply Quality Engineer
- *Logistics*
- *PM* - Program Manager

They form a sort of board, the Change Review Board (CRB) within which all new product launches, modifications, customer requests, change of tooling, change of logistics etc. are handled via a tool and/or form named Change Request Form (CRF).

6.1 The Purchasing Development Product team

The team in which the author of the study was dedicated and all related activities were conducted is the Purchasing Product Development team. After-treatment systems Platform within FPT Industrial is in charge of following all ATS related components design, manufacturing, sales, modification etc. Among all teams composing the Platform, the Purchasing is the one dedicated to different responsibilities. The team manage strategies in supplier selection, start the sourcing, supervise compliance with deadlines of the project and its specifications. It moreover follows the product development, buying parts from the alpha-phase till the SOP (Start of Production), passing by other project timing milestones, like the PPAP (Production Part Approval Process, a process used to guarantee customer homologation together with their processes of production and components) certification of the supplier component production process. So, the Purchasing team takes care of supplier relationship, and it is in charge of manage the sourcing process as well as of send the RfQ (Request for Quotation) – an economical quotation for the ATS part in object. Once the quotation is received, team hold the commercial negotiation with the supplier, basing on internal Cost Engineering target quotation. So, resuming, Purchasing team functions involve:

- Activate sourcing process by keeping into account economics and timing. Purchasing checks technical and economical documentation, supplier bid list, RfQ, technical review, manufacturing processes and toolings
- initiates RfQ's
- prototype purchase orders
- Commercial negotiation with suppliers
- Identify and involve suppliers according to technical, temporal and economical milestones of the project
- Support business case definition and analysis
- Support new product launch
- Support possible cost reductions activities
- Verify consistency of market prices versus expected target costs, especially for new products and new technical solution
- Support communication among Cross-Functional teams in company

Sourcing is an activity often needed for the selection of the right supplier for a new product technology, but it could be also due to a supplier dismission to product non-conformity, modification or to direct customer request. Purchasing follow these procedures also for technical modification and cost reductions activities that took place in Platform and that are ongoing on the product. The figure of the PDP Manager is in charge of coordinate the group of PDP specialists, that often support the Manager in new programs definition and deployment in line with management request.

6.1.1 The Supplier management

We have seen that the Purchasing team is in charge of manage various aspects of the supplier-company relationship in order to satisfy the customers and have the better product, as design specifications. Being a single ATS muffler a complex overall item, made by a lot of components and sub-components, a purchasing stream is necessary. In order to do that, the purchasing flow is organised between various supplier companies as follow:

- Tier 3: Supplier that produces substrates.
- Tier 2: Supplier that makes the coating of washcoat. It is called *coater*
- Tier 1: Supplier that performs the canning of the coated monoliths. They produce the final muffler form.
- Other components suppliers (electrical components and wirings, pipes, sensors, clamps etc.)

An example of catalyst manufacturing flow for heavy-duty or off-road industrial after treatment systems is in below figure.

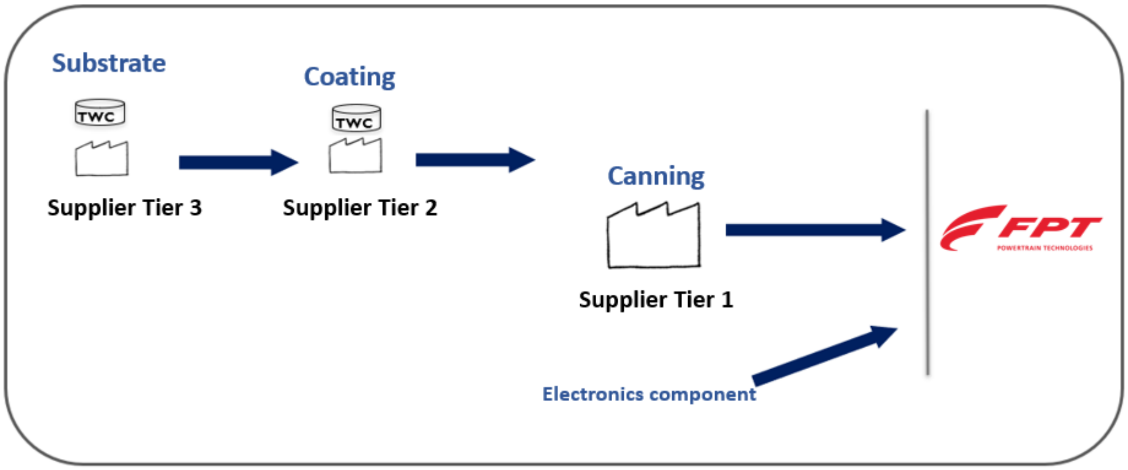


Figure 115 - Catalyst manufacturing flow

The mechanism is regulated through a sort of chain pulled by customer and FPT Industrial. The payment chain is regulated through the supplier Tier *n-1* paying directly supplier *n* (for example the coater Tier 2 buys substrates pieces from Tier 3 for FPT Industrial side, it is not FPT Industrial pushing the stream from the bottom buying the substrates and passing them to Tier 2). In fact, FPT Industrial does not relate exclusively to Tier 1 canning by buying directly the final muffler form. Instead, being the ATS complex on technical and legislation point of view and being the solution to be implemented and tailored for specific customer different applications, it has to be designed or co-designed with the direct FPT Industrial supervision to be matched with the engine and to be validated then internally. For some other smaller components (a sensor etc.) is instead easier to buying them directly from supplier company and having less relationships with sub-suppliers. For ATS main components, being this nature of stream and being the suppliers buying from other companies specific components (that often fit and are designed specific for FPT Industrial and Iveco solutions) by FPT Industrial account, the stream sees some payment voices call Handling Charges that will be addressed by each company while selling its product to take account the financial and logistics risk of buying such items. They will be later explained and added in the chapter related to the economic aspects.

6.2 Product and project implementation

6.2.1 CRF (Change Request Form) approval

Product and project implementation is managed within FPT Industrial with a powerful instrument: the CRF. CRF stands for Change Request Form, it is used to manage any variation that leads to:

- A new component production
- Modification of production component
- Cost variations (due to change in manufacturing volumes or technical changes)
- Modification to productive systems (logistics changes etc.)

Any variation on product or process must be accomplished through the CRF, in order to get the final approval of the Platform Manager. CRF approval is so a duty of the Platform Manager, that is supported and works with a team called CRB (Change Review Board). CRB meeting updates weekly to verify that current open Change Request Forms are compliant with

- emissions and safety legislations
- technical targets
- quality and process targets
- eventual cost reduction targets
- timing

CRB organizes CRFs, but the technical management is left to the Product Engineering (PE). PE implement CRF by releasing the so-called CID, acronym for Italian *Comunicazione di Inoltro Documentazione* (Documentation Forwarding Notification), that releases the prototypes or components drawings. Before the implementation, the Assistant Chief Engineer defines the technical feasibility of the product modification/variation. Later on, Program Manager and CRB monitors all states of CRF flow, implemented finally with actuation through the Launch Manager. For the component/modification in object, any possible client impact or application must be screened. Any refusal/acceptance or proposal from the clients must be verified. When a design or process modification involves customer request, it is necessary to inform the client and figure out a possible agreement. This role is proper of the Customer Manager. CRF management follows a precise flow, with specific responsibilities and duties. Flow procedures are processed within an IT system called Engineering Suite.

6.2.2 CRF Flow of approval

Change Request Form passes different status level flow, from initial State '10', representing an opening request, till State '200', the closure.

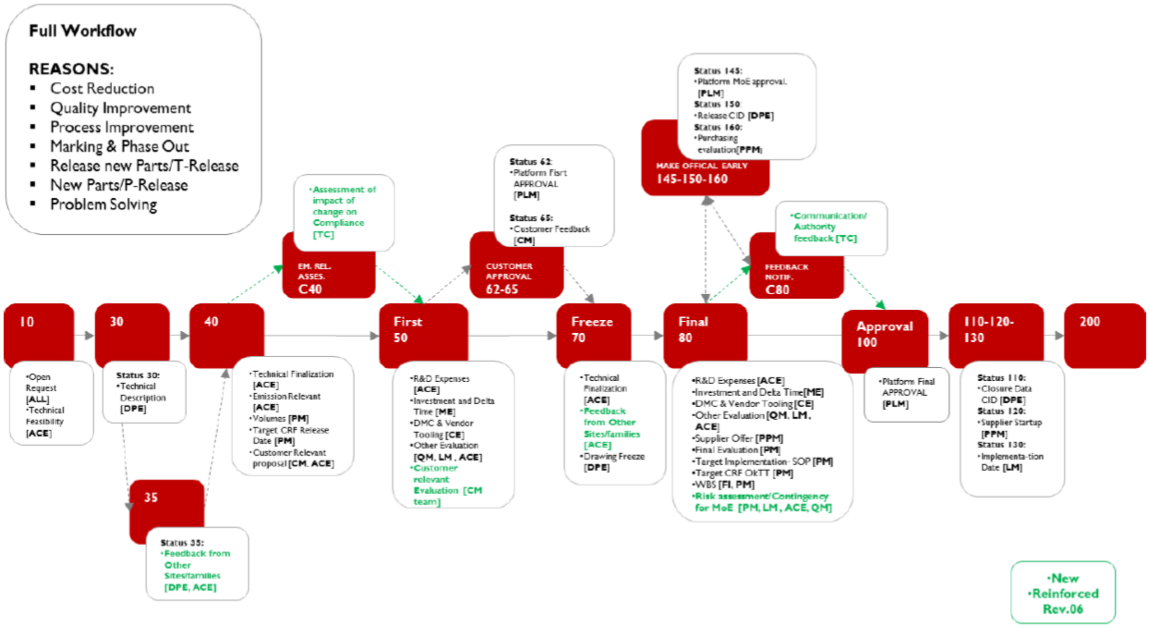


Figure 116 - Full flow of CRF

First milestone of CRF is its opening, represented by State 10. Figures of the company that may ask for the request opening are various: it is duty of the Quality Manager, the ACE (Assistant Chief Engineer), the Launch Manager, Program Manager and the Purchasing Program Manager. Each requester should formalise the proposal via CRF Engineering-suite system with the relative form, including

- Type of requests (internal request or external request as customer, Supplier… etc.)
- Reason for change
- Phase

For CRFs with an impact on the product, the ACE checks the reasons and preliminary technical feasibility, filters the proposals and push forward the feasible ones only. Once State 10 is finished, it is officially passed at State 30. Here the DPE (Design Project Engineers) define the CRF under the technical point of view. They fill the form with the list of components part numbers code involved, attaching drafts of drawings and/or studies. They explicit the impacts on all product families/production sites/all economic market regions (EMEA, LATAM etc.). Within the components involved, the part that is the more relevant in terms of emission is flagged as 'Part Level C'. In State 40 ACE confirms the reason of change request and checks the technical completeness of the information, including preliminary technical feedback from other engines families (if impacted by the modification, often called State '35'). Moreover, he indicates a target data within preliminary evaluations for the CRF presentation to the CRB should be provided, evaluates if CRF is emission relevant or not. Meanwhile, the Program Manager verifies the reason of the change request, its phase, and includes a preliminary forecast of volumes impacted. A middle State of the flow is there present, called '40C', useful to the Technical Certification to check if the CRF emission relevant or not and if needed evaluate certification authority involvement.

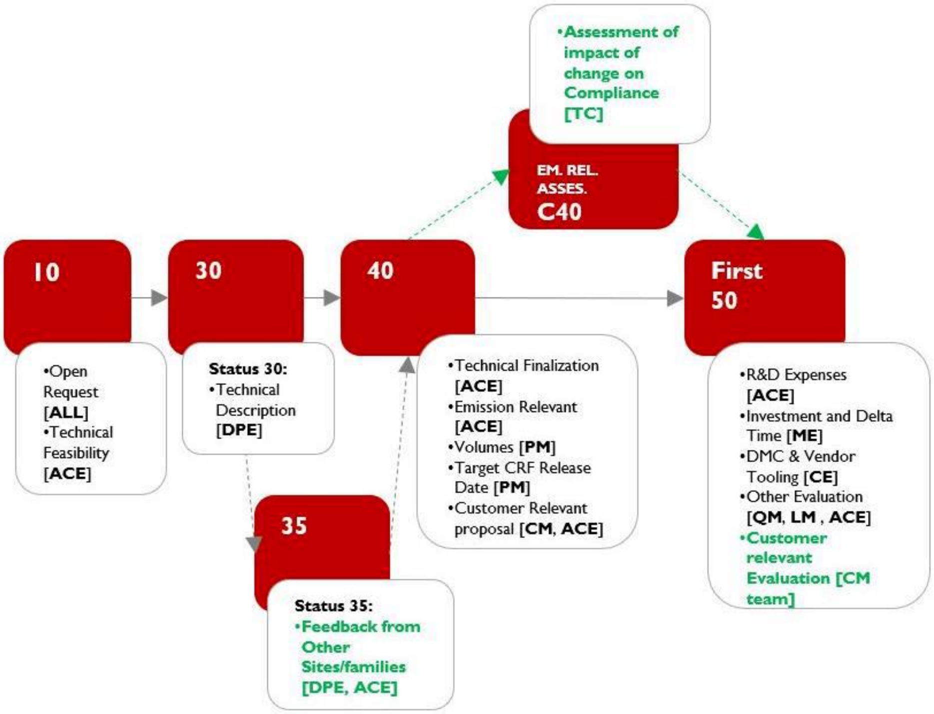


Figure 117 - Flow of CRF between State 10 and 50

Following step is the state '50'. It is an evaluation phase where the CRF should be evaluated by all actors of the CRB meeting. They have to fill their own sections into the Engineering suite (E-suite) system, according to their functional requirements control. Cost Engineer evaluate and report into the CRF the cost of the material, called Direct Material Cost (DMC), and eventual investments in terms of tooling machines (that is nominated Vendor Tooling VT). New Product Launch evaluates internal resources and investments. The Assistant Chief Engineer fill the R&D expenses part. The Customer Manager and the customer relevant team select in the CRF (by a YES/NOT switch) whether the opened request is customer relevant or not. Quality Management, Logistic Management and Launch Management (QM/LM) give other evaluations. At this state, the CRF proposal is analyzed and discussed during the CRB meeting, the CRB decision can be:

- Proposal rejected → CRF passage in state '999
- Request of revision or completion in case of missing data
- Approval to continue with development of request processing.

The outputs of the CRB meeting are evaluated, elaborated and sent to involved people by email, often in a form equal to a sort of 'minute' of the meeting (MoM). This report should contain the following information at least:

- identification number of discussed CRFs and its status
- brief description
- any approval date
- actions and those responsible for
- Emission relevant: YES/NO
- Customer relevant: YES/NO

In the case of a CRF which impact process only, the need for a new PPAP level setting must be evaluated in accordance with the PPAP guides, unless there is an exemption formally expressed by the customer involved. Output of this phase is the passage in state '65' if the CRF is customer relevant, or in '70' otherwise. A CRF is defined as customer relevant if it involves components thar are emission relevant, under FPT technical responsibility but purchased and assembled directly by the customer, base engines or transmission components (i.e. purchased and assembled at FPT Plant) with an impact on the form and function (including performance, durability, emissions) of the product and on any customer requirements (appearance, packaging, traceability etc.). Before passing to next step, in the case of technical impacts the Customer Manager should inform the customer requesting technical approval of contents, times and possible need for a new PPAP, if present. Always the Customer Manager should manage economic impacts, asking for economic approval to the client. In case of customer emission relevant changes approved by CRB, CM must provide updated customer drawing to ACE/DPE (Design Project Engineer) to be released in FPT Bill of Material. Feedback from the customer is then registered, attached to CRF and if it is positive next step passage happens, otherwise CRF is rejected in state 999. In State 70:

- DPE prepares drawings
- ACE releases RDAs part procurement if a prototype is needed
- ACE request experimental and/or virtual tests

RDA stands for Italian *Richiesta di Acquisto (*Purchase Request). It involves a request for prototype purchasing activity. It is duty of the Purchase department to send request of quotation to the supplier. Once the quotation is back from the supplier, ACE releases RDA. Once the RDA is released, it is duty of the Purchase department proceed with the proper prototype buying activity, within GPP/SAP internal IT system. Then according to the ongoing tests, if the results are negative a proposal for CRF cancellation is given to CRB team, while if only partially passed contents of the CRF should be reviewed. In case of passed tests the ACE verifies the technical completeness of the information according to engineering standards and to technical feedback of all players impacted by modification/request object. Then, the DPE prepares the definitive technical configuration of the CRF, attaches the definitive drawings and confirms variations of Part Numbers (PN) involved in request. State 80 is a sort of a centre of gravity point of the request procedure represented by CRF. It is again an evaluation phase, covered by all functions in the Platform that revise the technical final solution and will then end with the final approval. All functional standards and CRB target must be met. Almost all Platform players must complete and formalize the evaluation in their own form into the E-Suite IT system. In particular:

- Cost Engineer: Direct Material Cost & Vendor Tooling Evaluations
- New Product Launch: Internal Investments and Manpower
- Purchasing Program Manager: Supplier identification and final offer request, final negotiation on technical and commercial basis
- ACE: R&D expenses
- ACE: CRF ready for FINAL states: confirmation of technical solution (e.g.: positive outcome of experimental tests)
- ACE/ Product Engineer: confirmation to proceed (e.g.: positive feedback of Authority)
- Program Manager: confirmation or updating volumes estimation
- Quality Manager /Launch Manager/ logistics: other specific evaluations

The CRF is then left to the final approval from CRB team. Decisions can be of an OK to proceed, a rejected state due to negative feedback from emission authorities or if there are not positive technical/economical evaluations, if far from the targets. In case of missing data, request of revision is possible. The Program Manager, on indication of Purchasing Program Manager, **formalizes the (selected if result of sourcing) supplier**. Still in this approval phase and the end of 80 State, the PM also formalizes the economic closure values, the approved WBS (an economical budget basket) and the PPAP level. The implementation date is formalized. If the change exceeds the approved expense authority assigned to the Platform Manager or contingency fund is required, the Platform Responsible Leader (Engines/Transmissions) approval shall be requested giving the right documentation. CRFs with customer impacts (customer relevant) can only be discussed for Final Approval after customer feedback. In case of CRF approval, the customer must be notified about the implementation target date. In the case of cancellation, for CRFs requested by the customer, the cancellation reasons must be notified to all actors of the CRB. Final approval is in correspondence of State ‘100’ and it is in charge of the Platform Manager.

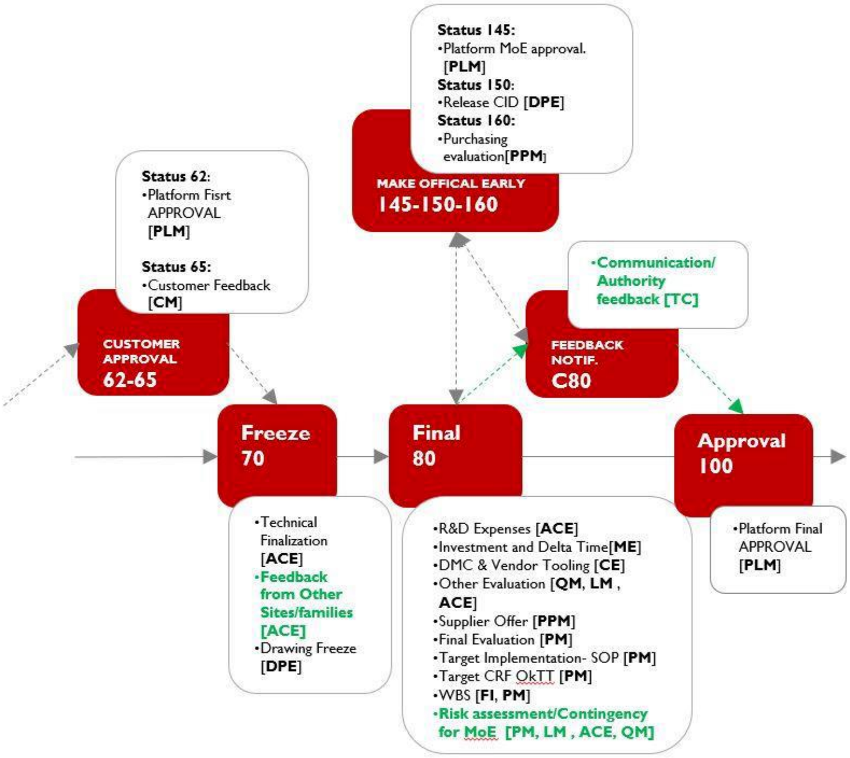


Figure 118 – Flow of CRF between state 65 and 100

Once the CRF is approved, it is in State '110' and it is duty of the Design Project Engineer to implement and make available the CID and its drawings. All is charged in E-Suite. DPE will end State 110 by indicating CID number and its release date. In '120' the Purchasing team is the protagonist. Having both economical WBS and technical CID drawings, the team can proceed selecting and launching the supplier. Purchasing team write and send to the supplier the Kick-off-letter, approved and signed by PPM. It is a letter of intent of legal concerns, that defines at the end of the negotiation the obligations from both sides, defines parts, volumes, DMC, Tooling, logistics and payments (and currency) terms. In this letter, all actors of the CRB team involved are reported. With this letter in attachment, the supplier is invited by e-mail to start production of the new or modified component. Once the e-mail is sent, the Purchasing team update the CRF to state '130'. In this State Launch Manager update information with the forecast date of implementation, if the request is customer relevant the client is aligned by Customer Hub. Once all of that is done, CRF will be moved to State '200' that defines the work-flow conclusion.

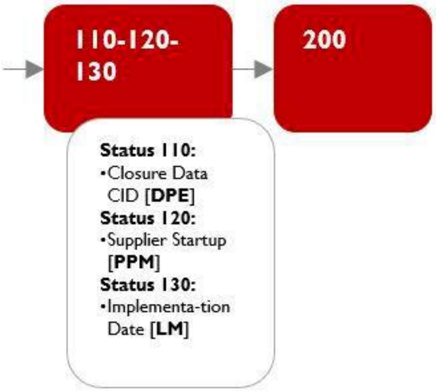
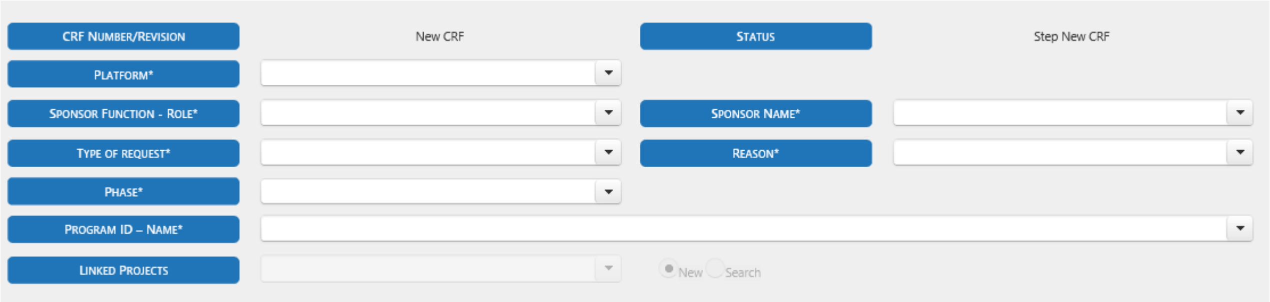


Figure 119 – Last passages of the Change Request Flow

6.2.3 CRF application to Three-way catalyst CNG Zone coating

The development of a zone coating three-way catalyst technology for CNG engines is an activity ongoing in FPT Industrial and the sourced suppliers. The Start of Production targeted is in 2023 or 2024 for Euro VI E2 vehicles. The activity could be classified under the 'cost-reduction' pot, because as we will see it is a technology that could couple, in front of initial investments, direct material cost reduction and technological gain. It is so obvious that also this specific implementation have been managing via the CRF instrument. Actually, it required the open of a CRF for each engine that will receive the zone coated TWC. This activity will interest in first side, at different level of the flow, the Purchasing function of the ATS Platform, so it will be of Advanced Purchasing department competence. Every time a new CRF is opened, some request form must be filled in the first page:



CRF Number/Revision	New CRF	Status	Step New CRF
Platform*			
Sponsor Function - Role*		Sponsor Name*	
Type of Request*		Reason*	
Phase*			
Program ID – Name*			
Linked Projects		● New ○ Search	

Figure 120 - Open Request CRF

Number of CRF is made of two parts: the first indicates the year of opening, the second one is the indicative number, in progression once the CRF are created. Initial Status set is '10'. Among all fields to fill there are:

- Platform: Engine family typology involved
- 'Sponsor function' and 'Sponsor Name' → Name of people in charge of require opening
- Type of request: Internal, or 'external' with proper supplier name if it is relative to external purchasing of components
- Program ID: code of identification for the project

The second passage is the 'Change Description' section fulfilment. This section explains the activity by briefly describing the CRF and by answering the questions 'What', 'Why' and 'How'.

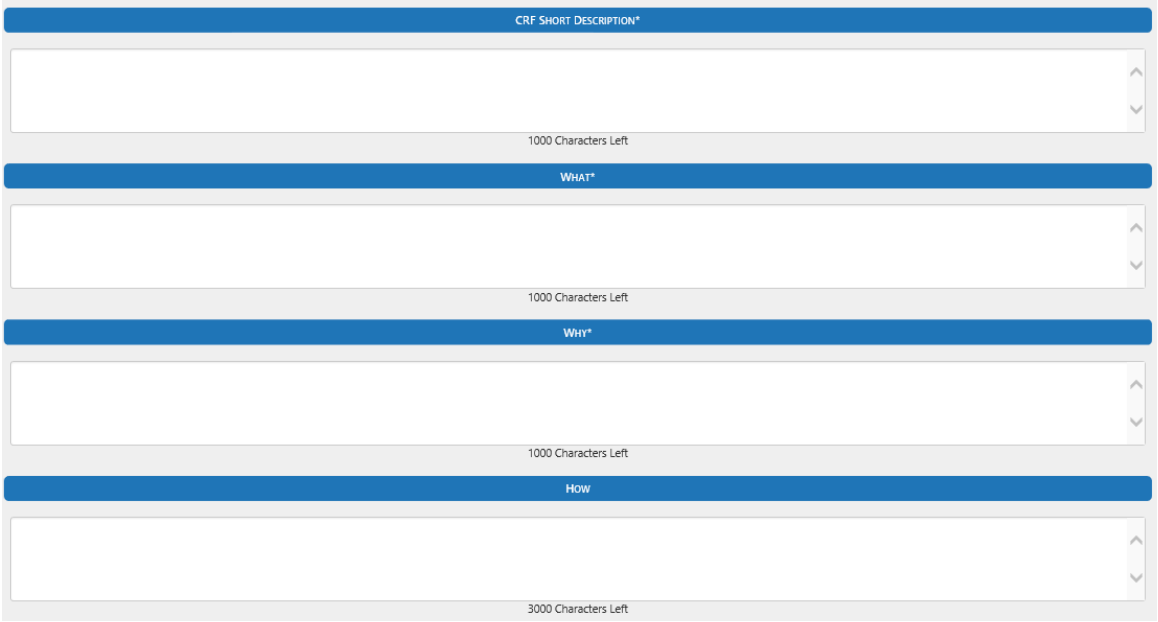


Figure 121 – Change Description section view

The first page is composed of different sections, the already seen open request and change description, plus details of timing, CRB team components names and a final section of summary to submit in approval phase. Other pages of the CRF are listed in following figure.

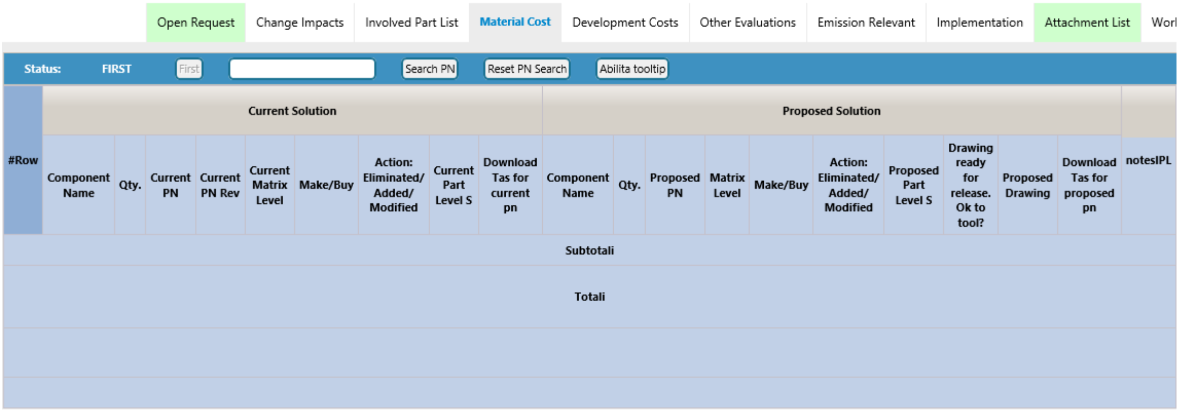
CUSTOMER RELEVANT: Yes

EMISSION RELEVANT: Yes

COMPONENT READINESS: Yes

Figure 122 – CRF main menu pages

Change impacts page enlist forecast volumes and engine platform, among supplier and clients that are involved in the modification. The PNs of the cost-reduction activity will be listed in the Involved part list section, and they will automatically figure in Material cost section. In the case of this zone-coating activity, the TWC PN will be associated to the CPF, as the cost-reduction activity involve the coupling of the zone-coated TWC with a (bare) CPF. The Material cost is the most important page section, particularly crucial for Purchasing team and to process the request in State 80. The PNs are shown in a sort of Bill of Material structure. For any PN row there is a column showing its component name, level number of the BOM, quantities number of components in BOM, actual PN (before modification), indication whatever the PN is a component 'make' or 'buy' (bought from suppliers). Other columns specify if the CRF was opened for that specific PN modification, addition or elimination (for example when the CRF is for an overall ATS kit), or if it is new. Finally, the TAS column, that is nothing different from the technical drawing of the component, that is released via the internal IT TAS system.



Status: FIRST

#Row	Current Solution									Proposed Solution										
	Component Name	Qty.	Current PN	Current PN Rev	Current Matrix Level	Make/Buy	Action: Eliminated/ Added/ Modified	Current Part Level S	Download Tas for current pn	Component Name	Qty.	Proposed PN	Matrix Level	Make/Buy	Action: Eliminated/ Added/ Modified	Proposed Part Level S	Drawing ready for release. Ok to tool?	Proposed Drawing	Download Tas for proposed pn	notesIPL
Subtotali																				
Totali																				

Figure 123 – Material cost section of CRF in Engineering Suite

We will have two more sections within the Material Cost page. The first yellow one is dedicated to the Cost Engineering estimations and the pink one to the supplier offers and quotations received from Purchasing team. The Purchasing team will insert information related to current and selected supplier and the component cost (Material Cost over each component unit and for each engine unit). Tooling presence and eventual delta of material cost for a component modification could be also added in the appropriate cases. Then there is a column reserved for the attachment of the documentation (for example e-mail of offer confirmation from the supplier).

Cost Engineering estimation copiaCostiCE							Purchasing Offer copiaCEPU								
Current Material Cost (€/Unit)	Current Material Cost (€/Engine)	External Investment (€)	Proposed Material Cost (€/Unit)	Proposed Material Cost (€/Engine)	Delta DMC	Notes	Current Supplier	Proposed Supplier	External Investment (€)	Material Cost (€/Unit)	Proposed Material Cost (€/Engine)	Delta DMC	startupTimes	Attachment	Notes
0,00	0,00	0,00	0,00	0,00	0,00		Subtotali		0,00	0,00	0,00	0,00			
0,00	0,00	0,00	0,00	0,00	0,00	Salva Completa	Totali		0,00	0,00	0,00	0,00			Salva Completa

Figure 124 – Cost Engineering estimation vs Purchasing Offer sections

Always within the Material cost page, Program Manager will confirm the evaluations made by Purchasing team. Sporadically there is also a column section reserved to the evaluations of the Manufacturing. Other pages could show development costs (with ramp-up volumes evaluated), other evaluations (Training, Manpower costs etc.), emission relevant and implementation form. Final pages resume the attachment list and the work-flow. The E-Suite system allow to download in a compressed folder various *.xlx* format pages of the CRF, or the technical drawings present in the CRF. As we have seen, only once the CRF is in State 120 it is possible for the Purchasing team to proceed then with the formulation of the Kick-off letter.

Chapter 7: Zone Coating in Three-way catalysts and the FPT Industrial CNG zone coating cost reduction program

7.1 The three-way catalyst zone coating

During last decades the emission regulations have been tightening, in coherence with the awareness of global pollution and environmental problems concerns. In addition to this, there is also the situation regarding the increase over exhaustion and shortages of natural resources, that matches (and it is cause of) the rising material costs and continuing fluctuation over the prices of precious metals of PGM group that endow vehicular ATS. For these reasons, OEMs, starting from LD applications, began to search for alternative solutions allowing to develop three-way catalysts that can both satisfy emission regulations required but also reduce the amount of precious metals usage, within a scenario of high catalytic performance. The application of technology involving zone coating and/or washcoat carrier degradation control are the key to reduce PGM amount in three way catalysts [34]. The zone coating is the different PGM and carrier coating formulation of the different zones of the catalyst monolith substrate. Different zones of the monolith could be coated by respective coating different formulations [12]. Most of applications involve a front and rear zone coating lengths, over the axial catalyst direction. Initially similar applications approaches were provided of two separate substrates coated with respective catalyst and placed one downstream the other. Nowadays, with the zone coating two axial different coating zones for the same substrate monolith could replace the application of two distinct substrates [12]. Also, radial zone coating is possible by putting more loading of PGM in central zone, involving the channels where flow rate of exhaust gases is higher [12]. Figure 125 from *dieselnet.com* shows the two zone-coating concepts.

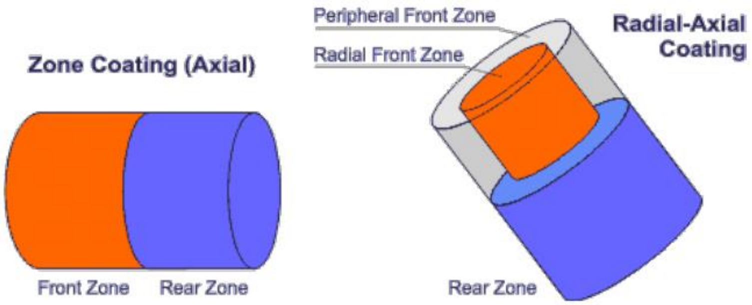


Figure 125 Axial and radial zone coating [12]

Axial zone coating can be done by dosing less slurry than needed for an entire homogeneous case. Differently from the manufacturing coating process overviewed for the standard catalyst, a specific apparatus is designed for the zone coating case. The part is partially dipped in the slurry (or washcoat solution or water-based solution) from the top, filling a zone of the catalyst called 'dip pan'. Then the coating slurry is forced to enter in substrate channels combining effects of capillary forces and vacuum, applied from the top of the monolith unit.

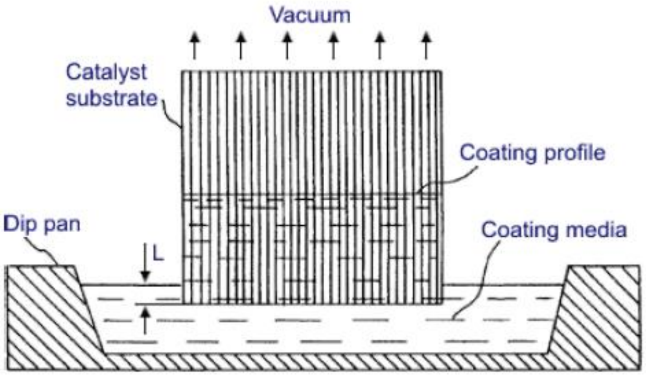


Figure 126 - General zone coating process overview [12]

The depth L (dip pan) is of few millimetres and guarantee first coating drawing up by capillary actions, then enforced by top-vacuum pulses. The zone coating is achieved by coating at first one end (at the right axial distance designed, for example in the middle or 60/40 or 40/60 ratio depending on design choices and specifications) then following drying and oven calcination. Then, once dried, the catalyst is turned and coating and calcination are repeated. It is obvious that, if the monolith is axially zone coated, it must be dipped in the coating media bath by longitudinal profile. For what regards carrier degradation control, it is coupled and implemented in zone coated catalysts to control of the interactions between catalyst precious metals and carriers. It was firstly studied and exploited alone as solution. In fact, if the aim is to keep high efficiency of catalyst emissions reduction while implementing less PGMs, it is necessary to suppress the degradation (sintering, deactivation phenomena) of the metals inside the carriers, as much as possible, that make possible to lower PGM content safely. In this manner aging phenomena will not damage catalytic performance. This could be done at chemical level, with right addition of selected Rare-earth-Oxides (ReO) and Alumina diffusion barrier. In addition, coupling this solution with the zone-coating (largely implemented in a second moment) it could be advantageous for exploiting the beneficial effects of zone coating both at chemical, OSC and degradation suppression levels [12]. The zone coating so enhances the improvement of HC and NOx conversion reactions, as well as the oxygen storage capacity reactions. It will do that by also by optimising the catalyst structure, directing the exhaust flow in a catalyst-controlled environment. In last decade several examples of zone coating in automotive LD applications are present, adopting a technology with less Rh in comparison with a conventional TWC and/or adopting a better Pd/Pt/Rh ratio, in terms of costs and quantities. The first literature studies and applications were diffused during first years of 2010s, just after the evaluations of the application of the washcoat double-layer technology. Double-layered three way catalysts are far from the zone coating concept, being coated with an homogeneous coating over all catalyst length. However, the first idea was to transform the coating in a homogeneous double layers coating of Pt (or Pd eventually) and Rh, with dedicated developed Pt and Rh supports respectively, in order to suppress Pt-Rh alloying, grain growth and sintering. The final result aim was in this way similar to zone coating, leading to lowering the amount of needed PGM by 40% and keeping the same catalyst efficiency. The difference is in the induced decrease of OSC due to the double layer presence, that must be properly counter-measured. Successive development of zone coating technology enhanced the OSC and the catalytic efficiency of the TWC. For this reason, after the LDV sector exploitation, also Industrial one is going to introduce this technology for three-way catalyst in next years. OEMs will study formulations, according to benchmarking activites. FPT Industrial selected suppliers and chose with them a technology that brings several innovations and peculiarities among the zone coated three-way catalysts of actual production. The project was driven in an optic of cost reduction and efficiency improvement for HDV on-road CNG engines. It is the best answer to implement a solution that is compliant with recent Euro VI E2 requirements (among all the NH_3 slip limit) without adding additional after-treatment systems components (like the ASC downstream the already present TWC and CPF) that could bring more complexities and costs, but instead by reducing raw material and get substantial savings.

7.1.1 Segregated washcoat and the double layer coating: chemical and fluids-dynamic reasons

In a conventional three-way catalyst, noble metals PGM group loading is made on the support carrier materials. In a Pt/Rh catalyst Al_2O_3 washcoat surface is matched with support materials: Pt support enhance oxygen storage capacity (OSC) with CeO_2-ZrO_2 oxides compounds, while Rh support does the same via ZrO_2 [9]. This separate loading of the catalytic noble metals on respective different support materials is often done to let the metals be in an optimal support. By doing that, catalytic activity is improved. It is done mainly because noble metals may react with each other or with washcoat component, especially in aging conditions, leading to deactivation phenomena (masking, fouling, sintering etc.) may occur, producing catalytically inactive compounds, that are undesired. To avoid that and to keep a good level of catalyst out efficiency (in terms of pollutant) often a bigger amount of PGM load is so dispersed. The matching of noble metals with separate coating support is often called ‘segregated washcoat’. Segregated washcoat physically separates PGMs by fixing them on a chosen metal oxide of the washcoat composition, before it is actually applied to the monolith substrate. An example is visible in figure 127

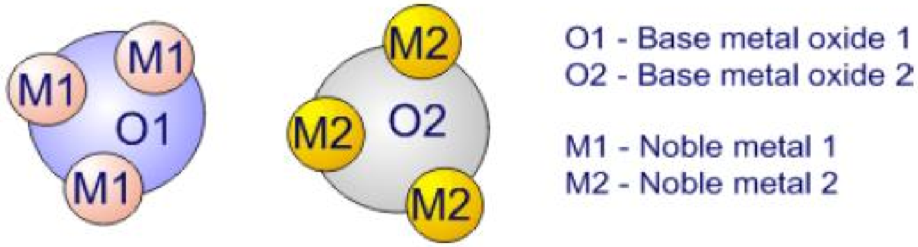


Fig 127 – Segregated washcoat explicated [dieselnet.com]

However, after a durability test (Aoki et al. observed via TEM images a catalyst submitted to a 1.000°C bed temperature using an actual engine exhaust stream) Pt and Rh could be found as Pt-Rh alloy grains also for segregated coated catalysts. Noble metals tend in fact to diffuse between supports. NOx conversion efficiency drops down [9]. It suggests that alloying mostly affect Rh. To get lower emissions is important to carefully control alloying of Pt and Rh. The segregated washcoat in conventional catalyst, that is made by supporting Pt and Rh in dedicated supports, seems that could be not efficient enough. A dedicated double-layer coating that separates the Pt and Rh layers has been developed. Before the zone coating introduction, it was the ultimate strategy to get cost reduction while improving the efficiency performance of Pt (or Pd) and Rh metals even after ageing condition [9]. The double layer solution involves a separated components of the catalytic system using washcoat layers with different oxides and/or noble metals. It was designed with the aim of reduce Rh amount via the limitation of Rh and Pt (or Pd) in conditions of high temperatures oxidation. The Rh layer support was on top whilst the Pt catalyst on the bottom, near the substrate. The cross-sectional view of a double-later Pt/Rh catalyst is showed:

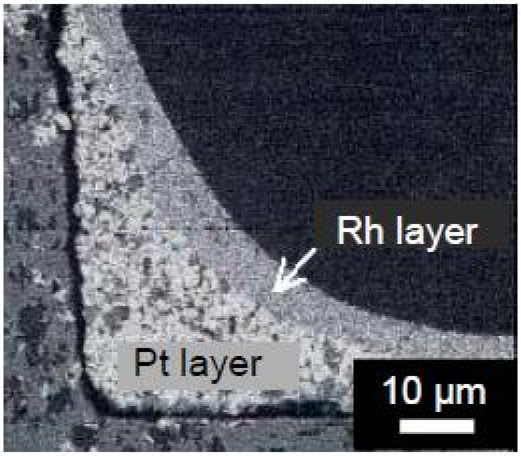


Figure 128 – SEM of a cross-sectional view of a double-later Pt/Rh catalyst [9]

After the same durability tests, the alloying of noble metals drops down consistently, thanks to the double-layer configuration. It is thought that alloying can be monitored by increasing distance between Pt and Rh [9]. If in single-layered catalyst the NOx efficiency decreases, here the double-layer configuration makes possible to maintain high efficiency in rich conditions after ageing. The downside is that OSC performance seems to decrease. The decrease of oxygen storage capacity is imputable to the presence of a thicker double metals layer, that makes the diffusion of exhaust gas flow to OSC enhancing material to be slower. In fact, this enhancing material is only present in the bottom layer, in contact with the substrate. The presence of this kind of double layer makes the distance higher (or thicker) and more difficult to be crossed by diffusing molecules of compounds composing exhaust gases. By conceptually dividing the catalyst coating layer in three layers (bottom, middle and top), Aoki&Toshitaka et al. discovered that OSC decreases proportionally with the distance from base surface of coating. Figure 129 shows how with the increasing of distance, the OSC performance drops down due to a worst exploitation of OSC enhancing chemical components present in the basement washcoat slurry composition.

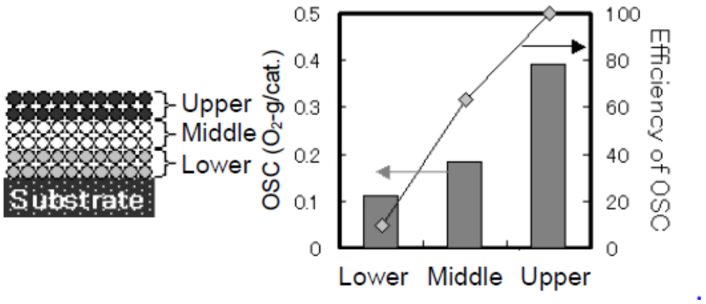


Figure 129 – OSC performance at variation of the coating distance from substrate [9]

The overall achieved performances are visible in fig 130, in terms both of NOx conversion efficiency gain versus the single layer solution, and also in terms of oxygen storage capacity of the catalyst endowing the solutions.

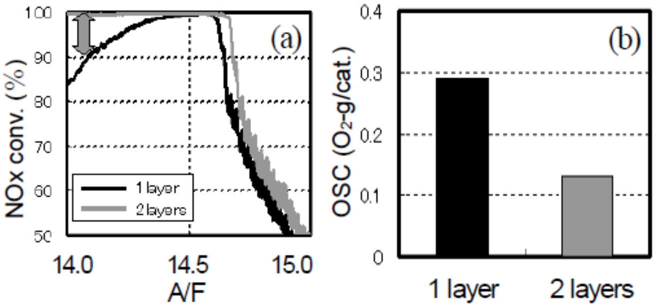


Figure 130 – Single layer vs double layer NOx conversion efficiency and OSC results [9]

Therefore, it seems that with this technology there is an effort needed to achieve a trade-off between the achievement of good performance in durability conditions and the overall OSC. To achieve both the target characteristics could be important. In order to do that solutions were studied [9] :

- Improving gas diffusion in Rh layer
- Adding better CeO_2/ZrO_2 ratio to flavour the top Rh layer support
- Try to limit as much as possible Pt grain growth in bottom layer and so maintaining OSC in ageing.

First solution involves the improvement of diffusion by pore distribution control, the second one also adds the optimisation of the CeO_2/ZrO_2 ratio. This optimisation must be done to flavour both OSC performance and enhancing Rh catalytic activity. In first solution pores diameter and volume of top Rh layer support were increased. By doing that, the diffusion velocity of gases increases, improving gas diffusion. For the second method, it has been smartly kept into account that OSC performance relies on CeO_2 to ZrO_2 ratio [10]. Testing different ratios situations, it was discovered that a CeO_2/ZrO_2 ratio equal to 0.25 for a ZrO_2-CeO_2 Rh support offers the achievement of both high OSC and catalyst performance [9]. At the same manner, bottom layer Pt growth to enable OSC in ageing can be controlled via optimal amount Pt presence in CeO_2-ZrO_2 compound oxides presence in support. It was discovered that OSC performance depends upon Pt dispersions. Behaviours improved for Pt=0,5%wt for tests conducted by Toshitaka et al. Finally, the study stressed-out a developed double-layered TWC that with the usage of 40% less noble metals achieved much lower NOx emissions, keeping more or less same OSC performances in LA#4 mode test [9]. Results were reported in figure 131.

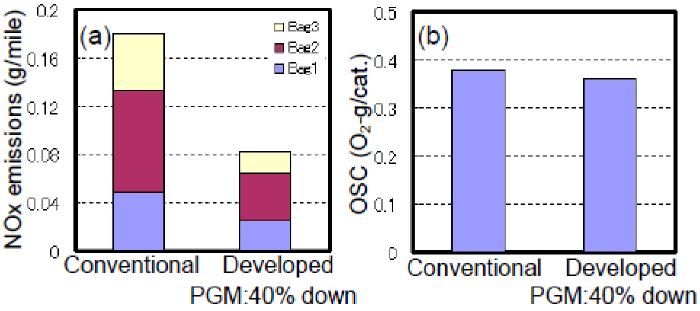


Figure 131 – Developed Double layer NOx and OSC performances [9]

7.2 Zone coating introduction: chemical and fluids-dynamics reasons

It is clear the need for a catalyst technological solution that is enabling factor for the reduction of amount of precious metals loading in usage, without impacting the TWC performance but being instead capable to comply with most recent and stringent legislations. Previous researches focused on application of anti-degradation features to be implemented in carrier and/or through improvement of catalyst structure (for example controlling the porosity of the substrate). It is vital to keep under control the conversion degradation reactions, by trying to suppress the degradation and the ageing effect that could arise especially with high temperatures applications. The usage of a zone-coated three-way catalyst could lead to beneficial effects, either from a direct effect point of view or also by indirect enhancing the noble metals catalyst deactivation suppression, helping the carrier able to suppress degradation thanks to its particular coating layout. Aoki et al. [34] performed test on zone-coated TWC that was previously aged with real-engine exhaust gases. Real-engine exhaust flow was also used for catalyst performance test. Particular attention was pointed on warm-up characteristics and OSC performance, the latter by monitoring lambda O_2 sensor behaviour in a situation of air-fuel ratio swinging from 14.1 to 15.1 or vice versa. Degradation is studied at research level with TEM (Transmission electron microscopy), x-ray analysis and powder diffraction for chemical identification [34]. The primary tests were conducted on HC conversion efficiency level. Unburned hydrocarbons are indicative of oxidation reactions typology in TWC, mostly managed with Pd or Pt [34]. Unburned hydrocarbons are also mostly discharged at cold start condition, during engine warm-up. A rapid activation of catalytic activity is important. It happens thanks to heat from exhaust gases, reaching the proper operating temperatures. It was noticed that during the phases of warm-up of the catalyst there are big temperatures gradient between each zone of the bed catalyst substrate [34]. In LA-4 mode, after first 20 seconds of engine start the front zone of the catalyst axial length can reach a temperature of 400°C, whilst the rear downstream zone cannot even reach half that temperature [34]. Result is in follow figure:

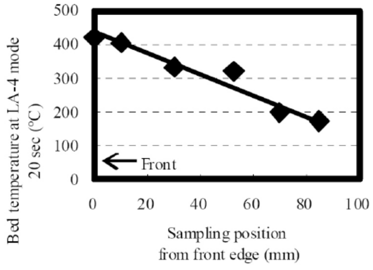


Figure 132 – Bed catalyst temperature vs sampling position from front edge [34]

It is not wrong so to search for a solution that allows the front portion of the TWC, that heat-up earlier, to activate earlier. In less words, a solution that endows more PGM loading in the front axial zone of the catalyst, at least for the noble metals accounting for the treatment of those pollutant compounds which are particularly temperature sensitive. This is a key concept to fix to understand three-way catalyst zone coating implementation. Therefore, in the study cases like this one, the front zone of the catalyst was coated with the amount of precious metal equivalent to the required for the homogeneous solution over whole length for the HC pollutants. Pd was used in Aoki et al. study [34], testing different alternatives scenario, with coating lengths of front zone from 10% to 53% of the length of substrate, starting from front axial edge. The scenarios were created because there was concern about the possibility that the coating length ratio of the zoning could interfere with the performance efficiency. Therefore, an optimal length should be found and set. Obviously tests on aged catalyst of different zoned length have been performed with same typology and amount of coating support material and Pd. Once collected results, it has been discovered that the shorter the length of catalyst layer, the shorter the amount of time to reach 50% efficiency of conversion [34]. The peak around 10% shows that for front coating lower than this percentage (over the whole substrate length), the 50% efficiency conversion time is going to increase [34]. The result is clear in figure 133.

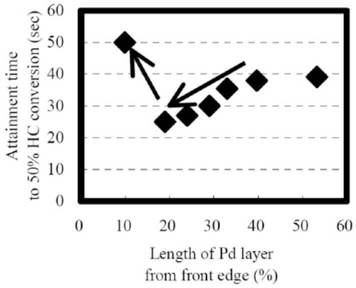


Figure 133 - Length of Pd layer from fronte edge and 50% HC efficiency conversion time [34]

The increase of performance in warm-up with the diminishing of front load length is due to the improvement of heating characteristics of the catalyst layer in front portion [34]. However, the peak increase of attained 50% HC conversion time in correspondence of 10% or lower coating lengths is due to the fact that even if there is such improvement, at same time diminishing the front-loaded length means to makes the space velocity faster. With a faster space velocity, 'residence times' of gases on catalytic active sites diminish and utilisation efficiency of catalyst will decay [34]. Figure 134 shows CSV increases. Space velocity is related to the catalyst active volume (at denominator in its definition). It is obvious that a decrease of catalytic volume (by decreasing coating front length) will make the CSV higher, for the same gas flow rate. Higher CSV means lower time in which catalytic reactions take place, ruining catalyst efficiency, LOT or 50% HC conversion attained time. So, it is clear that an optimal coating length is present. The space velocity relation with catalyst volume (front zoning length dependant) is visible in following figure for the equivalent test procedure

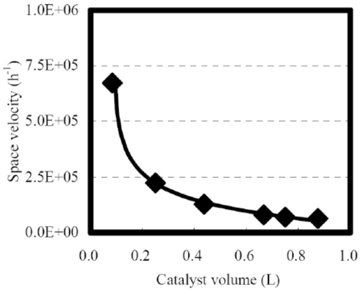


Figure 134 – Space Velocity relationship with catalyst volume [34]

Then, after the establishment of a front zone coating related to the concept of (HC) cold warm-up efficiency, and the right Pd/Pt oxidant PGM amount, the coating has to be completed with the downstream rear zone. The Rhodium rear zone will complete the picture of zoning but also of emission reducing function, taking care in this way of NOx reduction, once engine has warmed up [34]. Although, as we have seen the NOx emissions depend upon temperatures but also A/F ratio, and final level of emissions will be based on fluctuations of the air-fuel ratio around a reference stoichiometric value. It is so needed to achieve good oxygen storage capacity levels, thus assuring good and robust catalyst performances. The properties of compounds like CeO_2 and ZrO_2 have been largely explained, and in the same manner are well known during a development process of a new zone coated TWC. It is also well known that overall OSC depends also upon their ratio (of CeO_2/ZrO_2). Aoki et al. [34] underlined how the balance between the speed of oxygen release and the amount of oxygen release changes on the CeO_2/ZrO_2 ratio basis and how this property is a lot useful applied in a zone coated catalyst case. In fact, the smaller the CeO_2/ZrO_2 ratio and the faster the oxygen release. Vice versa, the larger it is the ratio and the more is the level of oxygen released. Thereby, the need of exploit both the characteristics well match with the zone coating layout of the catalyst. In fact, two different supports with different stabilizers ratio and OSC enhancing materials could be arranged in respective zones of the catalyst coating, adding optimisation of the support materials typology based on loading typology and needs. In front position was placed a materials ratio that can release bigger amount of oxygen, while fast OSC reacting adder ratio was implemented in downstream zone. Then, tests on this particular layout and comparison with single coated solution were able to show the potential of this particular stabilizers configuration in zone coating. The catalyst that received materials zoning based on their characteristics showed higher oxygen storage capacity with respect to single homogeneous coating catalyst [34]. In addition, theoretically speaking it seems to be more appropriate to choose this layout (high CeO_2/ZrO_2 at front with high amount of oxygen release and low CeO_2/ZrO_2 at rear with faster release of oxygen) than the way around. The reason is that test evidence shows that concentration of emissions and A/F amplitudes are higher in front portion, so it is good to match in that zone a materials ratio that may release more oxygen level. At the contrary, the concentration of pollutants is measured lower at rear portion and so a fast-reacting OSC support materials enablers are thought to be more appropriate. It is evident how the zone coating architecture helps to exploit possible chemical and flow-dynamic solutions and interaction, enhancing degradation control and conversion reaction improvements without increasing the precious metal loading but instead balancing and reducing it. Another effect of the different coating over axial length zones of the catalyst is the suppression of Rh degradation (in rear zone for the zoned catalyst) thanks to the control of Rh poisoning in aging condition. As we known, the material suiting for NOx reduction is Rh. The same relationship between conversion efficiency and space velocity will hold for Rh too. To get a lower space velocity and better efficiencies it is needed to have a longer length of the Rh catalyst (being in evident trade-off with Pd zone length so being careful at not enlarge it too much and ruining first zone performance). However, the increase of Rh length is stopped not only by the need of having a Pd zone bigger than 10% over total length, but also from the fact that there could be influence of poisoning on the front zone of the catalyst that makes Rh performance decay. We know that Phosphorous (P) coming from engine oil may influence the catalytic activity, poisoning the TWC. Aoki et al. [34] did study aged catalyst chemistry and analyse zones where P deposited. It was discovered that higher amounts of P can be found in front portion of catalyst. Phosphorous compounds like $CePO_4$ were found on catalyst bed. $CePO_4$ may react with CeO_2 of the catalyst support. Also $Ca_3(PO_4)_2$ could be found by reactions with Ca of engine oil. This latter compound as we known inhibits the diffusion of exhaust gases [FPT Industrial - 5] and hinder PGM. Therefore, also for the poisoning effect there must be found a trade-off and/or a right zone length balance to guarantee performances. To exploit this concept, the same study made additional tests with a fixed amount of Rh quantity on the rear catalyst layer. Zoning was then applied in different lengths, starting from the rear edge, from 50% to 100% of the monolith length. After-aged tests were then compared. Conceptually, it holds that the shorter the Rh layer and the lower are NOx conversion efficiency, and by contest the longer the Rh layer and the better the conversion efficiency of NOx. However, from tests is clear that higher conversion NOx performance is around 80% of coating length. This is due to the fact that with this coating length from the rear edge, we get Rh being removed from the front one, where poisoning effect is a lot. This would enhance Rh utilisation rate and suppress its degradation. All of this is well matching the zone coating characteristics, as well as the first zone of oxidant precious metals needs. Experimental evidence are in figure 135

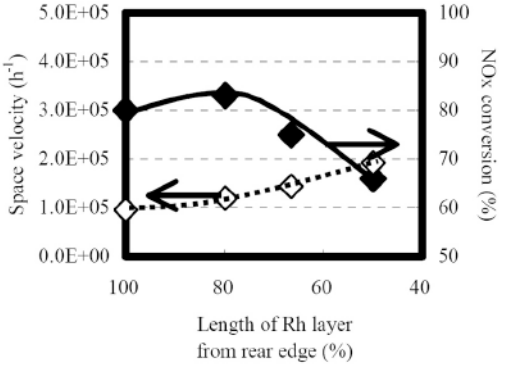


Figure 135 – Space Velocity relationship with length of Rh layer from rear edge [34]

This last anti-poisoning property well match with the high OSC capacity that could be attained with zone coating layout, by acting on supports materials. High NOx reduction could be thus achieved. Comparative tests in same study showed how Rh grains growth was suppressed in all axial length position with respect a homogeneous coated catalyst case. This is helpful especially when bigger A/F ratio fluctuations are present in the exhaust stream, that due to their higher concentrations of oxidation and reductant gas flow could cause higher Rh grain growth. Moreover, Rh sintering could be also suppressed through some other carrier improvement. In fact, by adding Nd_2O_3, a rich Nd layer could be created. The latter could form a strong interaction with Rh on the carrier surface. Neodymium could create a sort of 'anchor' effect on Rh and therefore suppress Rh sintering. The Rh dispersion level depend on Nd enrichment amount (added in carrier as Nd_2O_3 as mentioned). An improvement of dispersion degree of Rh have been detected in the tests for Nd_2O_3 surface enrichment between 1%wt and 3%wt. [34]. Over that level, the dispersion degree would decrease. Another improvement could be perceived with the suppression of CeO_2-ZrO_2 (inserted as carrier stabilizer) compounds sintering through alumina diffusion barrier introduction. As the literature known, suppression of the stabilizers compounds could be achieved through the introduction of Al_2O_3 diffusion barrier into their compounds [34]. In figure 136 it is highlighted the difference between ZrO_2 grain growth behaviour after aged environment either for alumina diffusion barrier presence case or not.

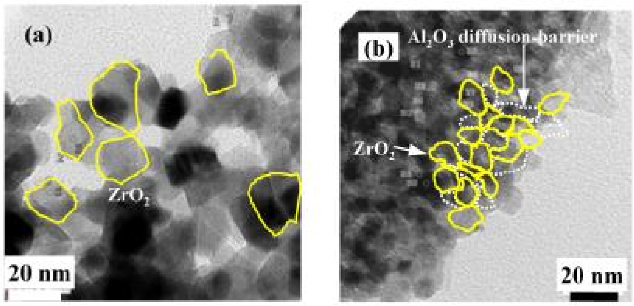


Figure 136 - TEM Images and particle size of ZrO_2 Support with (righ) and without (left) Al_2O_3 Diffusion Barrier [34]

In right case, with the alumina diffusion barrier, the particle sizes of ZrO_2 are much smaller : grain growth suppression is so achieved. The carrier improvement methods could be also studied to be superimposed. The latter two, involving Nd enrichment and alumina diffusion barrier addition, could be for example considered. What happens, and what is explained in next figure, is that a Nd_2O_3 enriched layer is formed on primary particle surface of the ReO stabilized ZrO_2 carrier. Rh sintering is suppressed via Nd enrichment, but in addition to that an alumina diffusion barrier decreases the sintering of outer primary ZrO_2 particles.

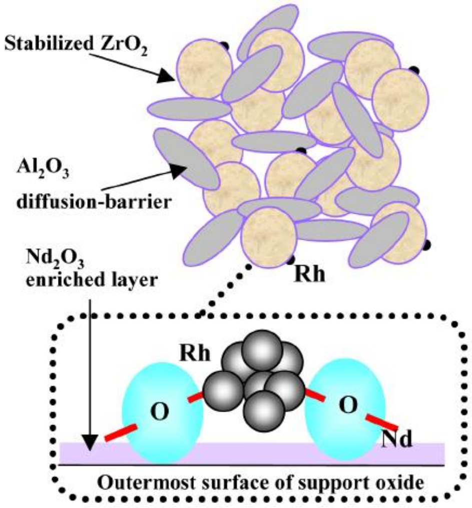


Figure 137 - Conceptual of developed support oxide structure for supported Rh Catalyst [34]

Starting from an improved developed Rh carrier baseline case, additional Al_2O_3 diffusion barrier and Nd_2O_3 surface enrichment could lead to a next 10% increase in Rh dispersion. It is trivial that Rh dispersion increase and grain growth suppression improvement is the strategic key toward a big reduction of the Rh used in the carrier. These two last carrier improvement methods could be exploited also in a single coated catalysts too, leading to good results of precious metal loading need. However, being implemented in a zone coating could represent a powerful tool of cost reduction and efficiency increase. At the end of the cited study, a catalyst model with integrated zone coating design and improvement carrier policies was build and implemented in a light-duty vehicle (for both closed-coupled and under-floor positioned catalysts). Relative emissions were compared on same LA-4 mode for conventional case and two new-build solutions that endow either the same amount of precious metals loading of the conventional (developed catalyst 1) or a lower one (developed catalyst 2). Amount of precious metals loading was classified in g/L (0.3 g/L of first two vs 0.16 g/L of new zone-coated developed catalyst 2 solution). Catalysts with same PGM loading comparison showed a big reduction of NMH, CO and NOx emissions in the new-build new carrier & zone-coated case [34]. Moreover, the developed new-build catalyst 2 kept higher emission performances with respect conventional catalyst, but with a 46% reduction of Rh quantity [34].

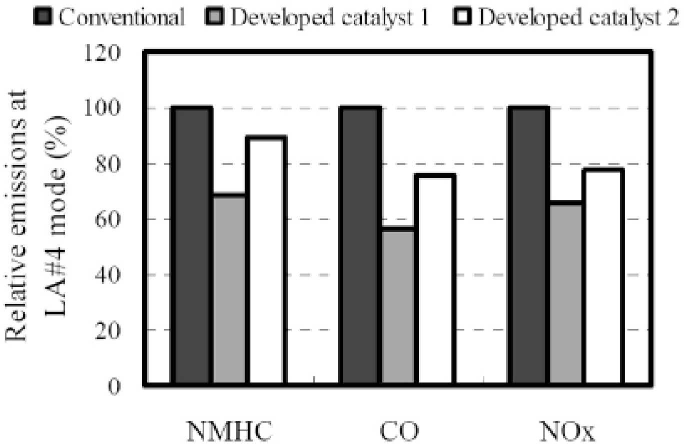


Figure 138 - Relative Emissions (NMHC, CO, NOx) of Conventional and Developed (-47% Rh layer) Catalysts in LA-4 Mode [34]

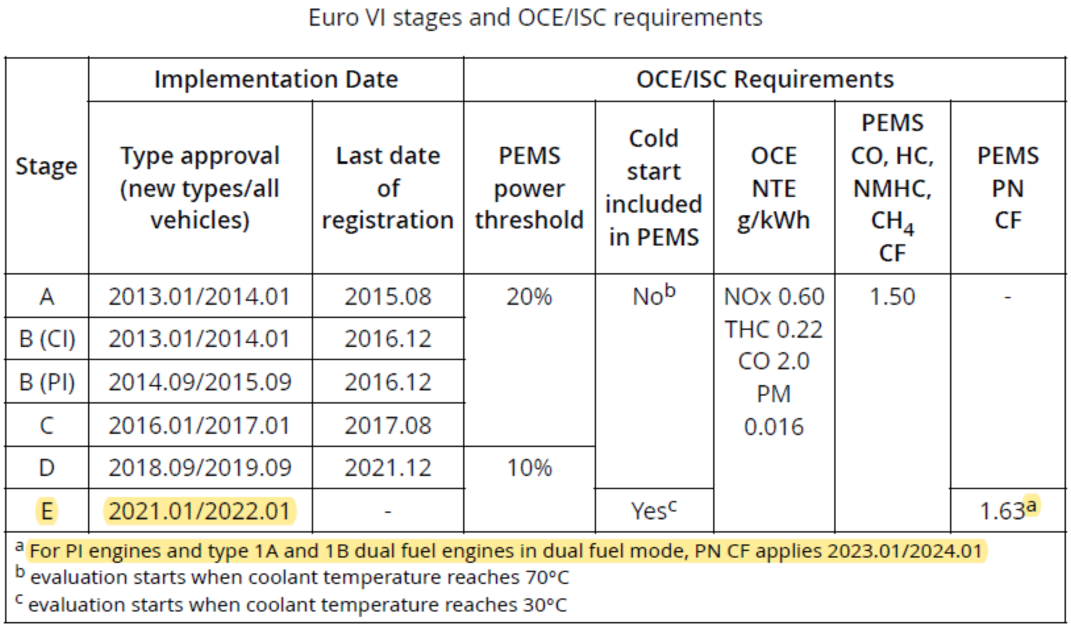
This is the final and application proof that three-way catalysts axial zone coating of catalytic layer and improved carrier technologies are capable of reduce emissions and reduce amount of precious metals loading.

7.3 FPT Industrial TWC zone coating cost reduction program in CNG engines

The particularity and innovative side of the zone coating cost reduction program for CNG Euro VI step E2 engines within Iveco group is that it is intended to be fitted for

a) CNG engines
b) Industrial applications

As we know Iveco group offers for its on-road vehicles several CNG engines solution, starting from light-duty and passing to medium and heavy-duty vehicles sectors. Moreover, FPT Industrial offers these CNG engines family's solutions also to Non-Captive client brands and Pivot engines (including also several off-road vehicles) and not only all internal Iveco applications. The zone coating is a cost reduction activity in introduction reserved for on-road Euro VI step E medium and heavy application families. Recalling back the legislation framework, Euro VI various step A,B,C… etc. are different on OCE/ISC basis. Euro VI step E has tighter PEMS power thresholds that includes cold start also and lower multiplication coefficient for NMHC, CH_4 and PN emissions. As resumed in below figure, Step E 1 Legislation Target (from January '22) is to satisfy Conformity Factor (CF) of 1.5 on NOx in Cold Start (CS) condition during PEMS, while Step E 2 Legislation Target (January 2024) is to satisfy, on top of Step E1, a Conformity Factor (CF) of 1.63 on Particulate Number (PN) during PEMS.



Euro VI stages and OCE/ISC requirements

Stage	Implementation Date		OCE/ISC Requirements				
	Type approval (new types/all vehicles)	Last date of registration	PEMS power threshold	Cold start included in PEMS	OCE NTE g/kWh	PEMS CO, HC, NMHC, CH_4 CF	PEMS PN CF
A	2013.01/2014.01	2015.08	20%	No[b]	NOx 0.60 THC 0.22 CO 2.0 PM 0.016	1.50	-
B (CI)	2013.01/2014.01	2016.12					
B (PI)	2014.09/2015.09	2016.12					
C	2016.01/2017.01	2017.08					
D	2018.09/2019.09	2021.12	10%				
E	2021.01/2022.01	-		Yes[c]			1.63[a]

[a] For PI engines and type 1A and 1B dual fuel engines in dual fuel mode, PN CF applies 2023.01/2024.01

[b] evaluation starts when coolant temperature reaches 70°C

[c] evaluation starts when coolant temperature reaches 30°C

Figure 139 - Euro VI stages with step E due dates [18]

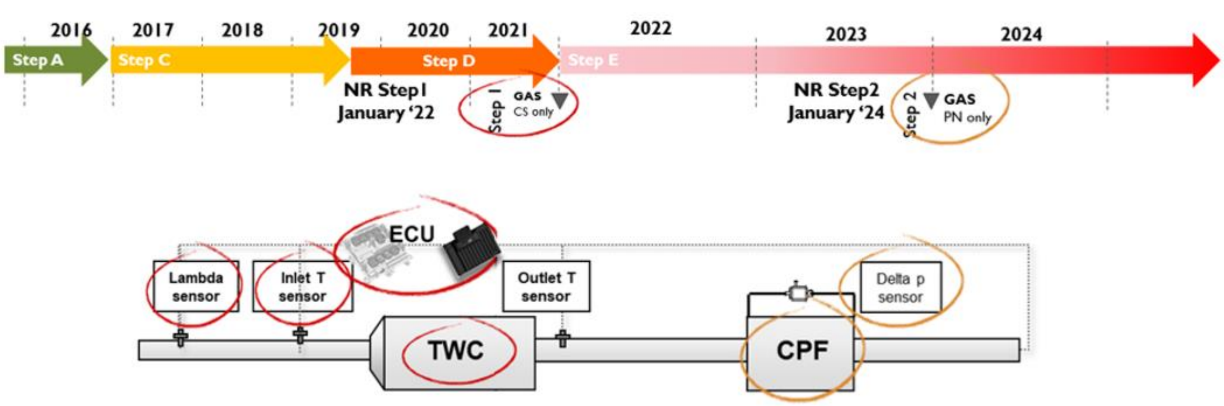


Figure 140 – HDV Euro VI step E1 and E2 architecture components [FPT Industrial]

As explicated by yellow circles, with E2 implementation, additional substrate to trap the particulates is needed. Implementations involve:

- New CNG particulate filter (CPF) with Delta pressure sensor
- Review ATS canning, exhaust pipe and tailpipe to cope with the packaging changes
- New Engine Control Unit software and calibration to handle the new substrate module

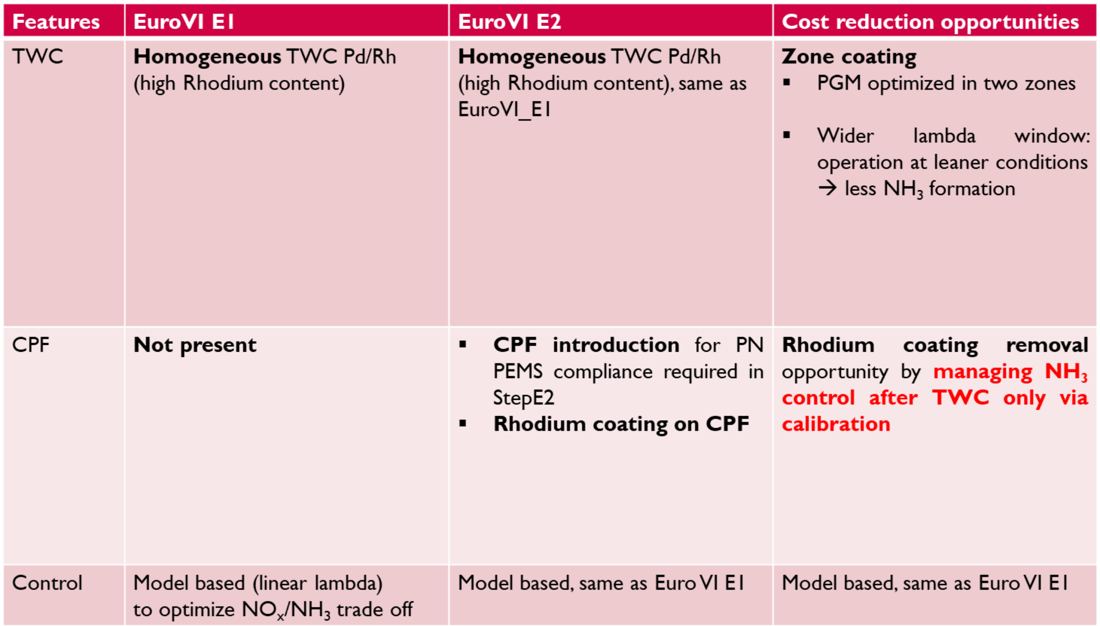
For CNG engines, the new PEMS Particle Number CF applies from 01.2024 in New Registrations. PN limit for CNG engines is postponed 2 years (1st Jan 2023 for New Approvals, 1st Jan 2024 for New Registrations), and in the period between 1st January 2021/22 and 31st December 2022/23 the PN CF will be only monitored (without mandatory limitation). In this implementation, to better understand the cost reduction program, it is helpful to start saying zone coating was evaluated between different cost reduction alternatives, with different scenarios and evaluating benchmark (with respect other OEMs) on hardware and PGM trend. Starting with previous Euro VI D, FPT Industrial adopted a solution with a single Three-way catalyst architecture. No EGR strategy had been implemented, with an on-off lambda sensor and stoichiometric engine feeding. In the below table a benchmark activity over Euro VI D HD scenario is explicated. For confidentiality reasons suppliers and other manufacturers name has been omitted, as well as for the FPT Industrial Heavy Duty engine case in study, that from now on will be taken as base case example to explain zone coating technical implementation. The cost reduction program involving zone coating, in fact, is dedicated to different engines across On-road CNG engine range today available. For sake of simplicity, the technical and economical analysis will be conducted in this paper on a single case only. The case was chosen as the most representative for volumes, applications, technical specifications, and economical values. However, with the right proportions due to ATS dimensions and PGM mass presence, the results have same significance. In the following we are going to find

- Engine 1
- Engine 2
- Engine case of study, from now on *ENGINE CASE STUDY*

As said, in next Step E2 legislation for heavy-duty Euro VI, the PEMS PN emissions test introduction made mandatory the CPF introduction. Potential Step E2 FPT Industrial hardware cost reduction started from assumptions:

- Potential introduction of new catalyst concept (Zone coating vs. Homogeneous) in order to move from bi-metallic Rh/Pd to tri-metallic Pt/Rh/Pd and reduce Rh/Pd dependency
- All OEMs in Europe are planning to implement CPF in 2024 driven by PN PEMS legislation requirement (currently PN controlled only via engine HW / management)

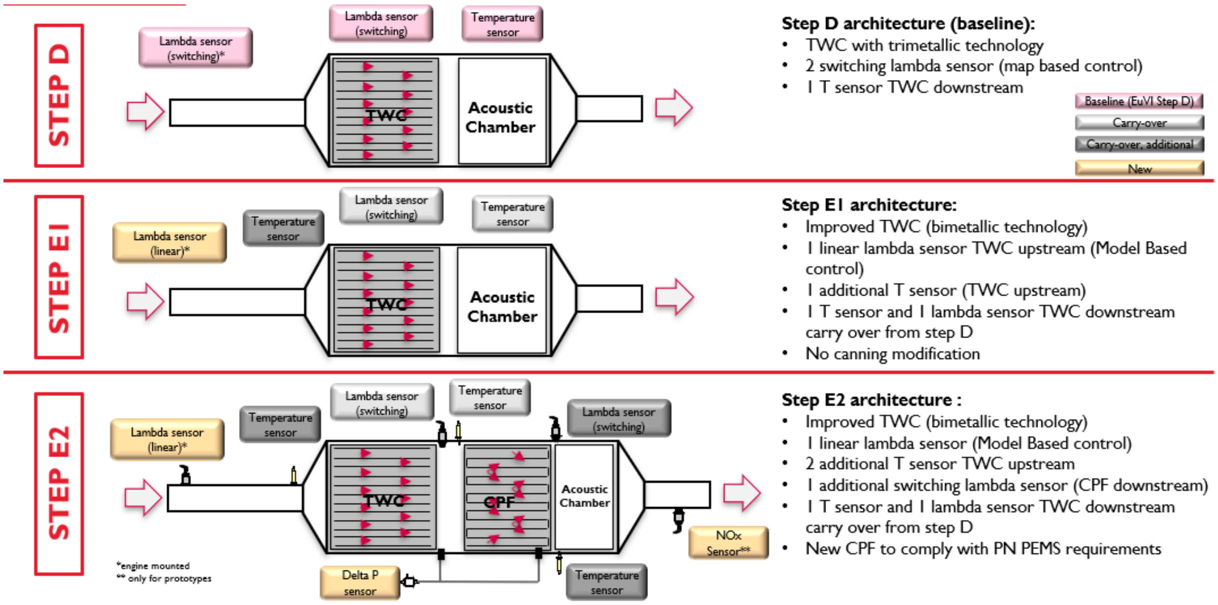
We will concentrate on proper TWC zone-coating technology, then seeing a brief overview on how it can interact and can be coupled with different CPF cost reduction program activities. Initially, NG Step E phase 1-2 were approved with baseline ATS homogeneous TWC (Rh/Pd) plus a coated CPF with Rh in later E2 introduction. Then, with the introduction of cost reduction scenarios, the zone coating cost reduction activity was selected as the best option, and it is foreseen to be start produced between the middle of 2023 and beginning of 2024, depending on engine application. Notice that the zone coating is both acting as a technological enabler (for step E2 of Euro VI) but in an environment of a cost reduction activity. In fact, by anticipating its implementation in 2023, further costs saving could be achieved with respect the implementation in 2024 just for new legislation need. Moreover as explained before, different layout alternatives and CPF implementation have been studied between E1 and E2 phase introduction, and so it must be checked in both technical and economical analysis. In the ATS Platform, the activity was seen a cost reduction, and so a complete sourcing did not start as it would be for a new product launch. Selected suppliers were chosen to develop the technology and the project with all its phases and timeline milestones. A summary of the option considered in the platform at the beginning of step E2 activities is given in below table:



Features	EuroVI E1	EuroVI E2	Cost reduction opportunities
TWC	**Homogeneous** TWC Pd/Rh (high Rhodium content)	**Homogeneous** TWC Pd/Rh (high Rhodium content), same as EuroVI_E1	**Zone coating** ▪ PGM optimized in two zones ▪ Wider lambda window: operation at leaner conditions → less NH$_3$ formation
CPF	**Not present**	▪ **CPF introduction** for PN PEMS compliance required in StepE2 ▪ **Rhodium coating on CPF**	**Rhodium coating removal** opportunity by **managing NH$_3$ control after TWC only via calibration**
Control	Model based (linear lambda) to optimize NO$_x$/NH$_3$ trade off	Model based, same as Euro VI E1	Model based, same as Euro VI E1

Table 14 – Possible program implementation strategies

Initial E1 step was thought to be implemented with conventional homogeneous Pd/Rh TWC Pd/Rh. Conventional TWC is endowed with high Rhodium content to increase selectivity of NOx towards N_2 against NH_3 formation. We will see reactions details in technical evaluation phase. CPF is not present. Passage in step E2 was thought to be handled with same conventional TWC but implementing Rh coated CPF introduction. Rhodium coating on CPF is to unbalance control towards rich calibration (higher NO_x conversion but higher NH_3 produced by TWC, depleted on CPF). The zone coating cost reduction base concept is to exploit phenomena already seen in literature, moreover in this application case the idea was to have PGM optimized in two zones: front zone optimized for CH_4 conversion, rear zone optimized for NOx reduction and NH_3 control. The zone coating implementation also makes possible to adopt a wider lambda window calibration: with better OSC control and NOx conversion efficiency, a leaner exhaust flow condition is possible, creating a good environment for NH_3 management and so by consequence getting the opportunity to remove the Rh coating from CPF! In the middle, a ‘quick win’ solution based on conventional TWC and CPF bare without any Rh coating was studied too. Moreover, in late 2019 also a solution with a passive **SCR/ASC** after homogeneous TWC was evaluated, to reduce high level of NH_3 slip from in field tests. Zone coating implementation helps to **avoid** these two lasts kind of product complexities and costs increase to be compliant with limits. So, at the end, ATS CNG engines architecture roadmap is explained in following figure:



Step D architecture (baseline):

- TWC with trimetallic technology
- 2 switching lambda sensor (map based control)
- 1 T sensor TWC downstream

Step E1 architecture:

- Improved TWC (bimetallic technology)
- 1 linear lambda sensor TWC upstream (Model Based control)
- 1 additional T sensor (TWC upstream)
- 1 T sensor and 1 lambda sensor TWC downstream carry over from step D
- No canning modification

Step E2 architecture :

- Improved TWC (bimetallic technology)
- 1 linear lambda sensor (Model Based control)
- 2 additional T sensor TWC upstream
- 1 additional switching lambda sensor (CPF downstream)
- 1 T sensor and 1 lambda sensor TWC downstream carry over from step D
- New CPF to comply with PN PEMS requirements

Figure 141 – CNG ATS Architecture evolution from Step D to Step E2 [FPT Industrial]

An example of implementation over Iveco S-Way CNG version is herewith showed, with the single muffler containing both TWC and CPF, the downpipe from engine exhaust system and the tailpipe

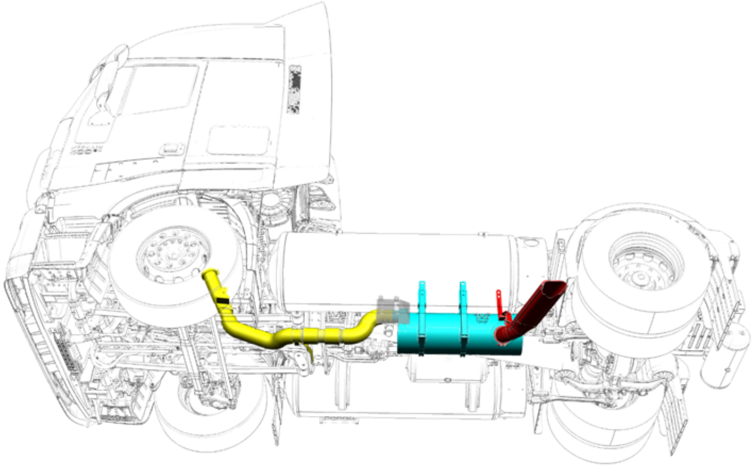


Figure 142 – CNG Euro VI muffler vehicular installation

A summary of the activity in start of cost reduction hypothesis till current scenario is underneath given:

- Precious Grade Material (Rhodium / Palladium) cost increase started from 2020 and foreseen for coming years: this fluctuation has strong impact on CNG after-treatments
- to reduce PGM noble material dependency it was needed to review Coating technology as cost reduction opportunity for future product facing 2023/2024 SOP
- Innovation activities were in place to evaluate a new technology feasibility (TWC Zone coating vs Homogeneous)
- Coater supplier process improved to reduce PGM impact with tolerance range reduction on existing NG ATS
- New technologies are under development, after first phases with two main NG coater supplier discussions and selection among one of two.
- Cost reduction scenario proposals were, including CPF Rhodium removal on **Engine 1, Engine 2, Engine case study**:

  a) "quick win" solution in short term: based on actual homogeneous Catalyst technologies and CPF bare.

  b) New-catalyst concept (Zone coating) and CPF bare, medium-term implementation 2023, developed on Truck & Bus Step E2 application facing Iveco milestone

7.4 FPT Industrial TWC zone coating cost reduction program in CNG engines: technical overview

For Euro VI Step E phase 1, due to concern about NH_3 slip in field, FPT Industrial and the supplier selected to increase Rh to improve NH_3 suppression, implementing in Pd/Rh homogeneous coating the highest possible Rh-ratio content:

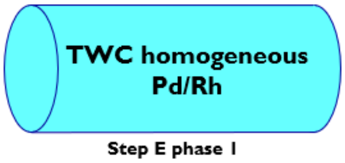


Figure 143 – Pd/Rh homogeneous Euro VI E1 three-way catalyst

In late 2019, to compensate the huge increase in PGM market prices and treat ammonia slip, innovative options to reduce noble metals usage without impacting tailpipe emissions have been investigated:

- Zone Coating: average trimetallic coating made of 2 bimetallic zones
- passive SCR / CUC after TWC
- Rh-coated CPF

In late 2020 **Zone Coating** concept with **same** average of PGM total density content (of the homogeneous case) has been selected for alpha-phase development, offering the best performance/durability trade-off:

- 1st zone, NO_x / CH_4 / CO conversion → Pd/Rh bimetallic
- 2nd zone, Rh-rich for NH_3 suppression → Pt/Rh bimetallic

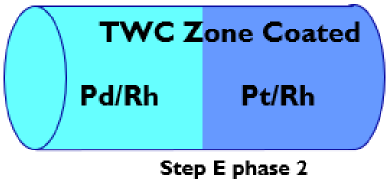


Figure 144 – Pt/Pd/Rh trimetallic axial zone coated Euro VI E2 three-way catalyst

The averaged total PGM density (the same of homogeneous case) is obtained through an arithmetic average between first and rear zone densities weighted for the respective length of the catalyst zone. In this case for the selected technology the zoned length ratio is 50:50 and the catalyst volume is the same of homogeneous case. The mass of PGM can be obtained by multiplying the PGM density by the catalyst volume (of each zone or overall averaged one). We got:

- 1st zone: Pd in less quantity with respect homogeneous case and Rh in small content
- 2nd zone: Pt introduction and Rh relative rich zone, but still less in quantity with respect homogeneous total content

For a total of

	Pt	**Pd**	**Rh**
Δ PGM %	**+ 20% ***	**-18,48 %**	**-37,5%**

* *The Pt variation is computed on total homogeneous PGM content base*

Table 15 – Relative PGM variation of new zone coated catalyst with respect homogeneous

We can notice an overall 18,48% Pd quantity decrease with respect previous bimetallic optimised homogeneous solution. The Pd decrease is in part absorbed by Pt* introduction (whose price is the lower among the three PGMs for catalyst usage), but the big difference is made by Rh content decrease. Even if it can be seen as a low reduction in terms of overall grams it is a sensible percentage decrease (37,5%) with respect previous Rh quantity embedded in homogeneous solution, and it has a big impact in cost reduction due to the big Rh price increase from third quarter of 2020. More economical evidence will be given in following analysis. The Pt percentage variation (in addition) is computed with respect total PGM mass of homogeneous case.

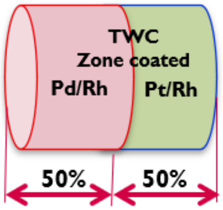


Figure 145 – Axial zoning length ratio of zone coated catalyst

The reason for the selection of these precious metals and the loading level is given by the application typology (Natural Gas engines) and the precious metals interaction, that makes possible to achieve the emissions reduction target. From Homogeneous to Zone coating:

- Pd is concentrated in first TWC zone to achieve high CH_4 /CO oxidation.
- Pt substitutes Pd in second TWC zone, being good enough to complete CH_4/CO oxidation.
- Rh is kept at adequate low level in first zone to abate NOx, then increased in second zone to complete NOx reduction & consume formed NH_3.

In this way we found theoretical path explained in PGM catalyst function. For low molecular weight unburned hydrocarbons and carbon monoxides, in fact, Pd is much way more active than Pt. For higher molecular weight HC the opposite held, and Pt is more active. In fact, in diesel engines Pt is used instead of Pd. Generally, Pt and Pd are better for oxidation reactions of CO and HC. For NO reduction Rh is preferrable. Between FPT Industrial and supplier partner it has been noticed that for the specific application, three-way formulation needs to mix all 3 noble metals to get best performance. For CNG engines Pd has the best performance for CH_4 oxidation, Pt has the best performer for CO conversion and Rh is the best in terms of NOx selectivity. The Pt substitution in second zone helps to keep cost decreasing, since PGM actual values quotation. In the past Pt was more expensive than Pd and the second was the most preferred solution for efficiency and cost [8]. Nowadays Pd is more expensive. However, it is not possible to replace completely Rh and Pd. The zone coating is implemented on a porous carrier with nano-dispersion of Alumina and Ceria fine metal compounds. As we have seen from literature overview, it is the key to have good OSC levels and to inhibit Rh sintering and degradation, thus consenting also to better exploit the axial zone coating layout characteristics and so achieve good Rh reduction levels (here of 37% with respect homogeneous Rh quantity, perfectly aligned with state of art numbers already seen).

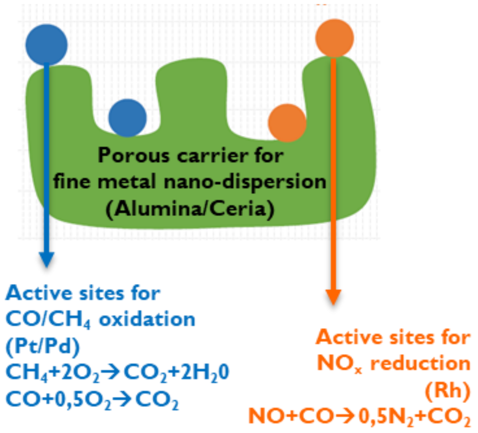


Figure 146 – Three-way catalyst porous sites for CNG pollutant oxidation and reduction reactions over CNG engines

Oxidation reactions of CH_4 and CO are showed in above figure. Their conversion efficiency shape curve with respect temperature shows that Pd has the best performance for Methane reduction, while CO reduction is anyway similar and good between Pt and Pd (with Platinum slight faster in achieve better conversion levels). In below figure the conversion efficiency % with respect temperatures curve shapes for each metal:

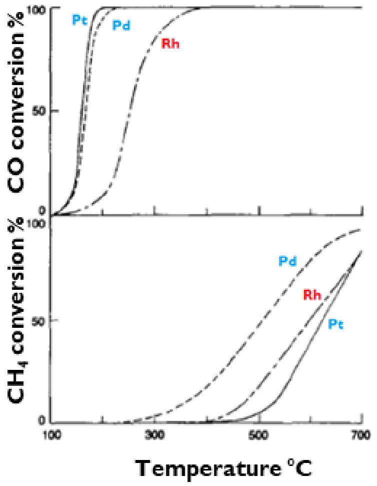
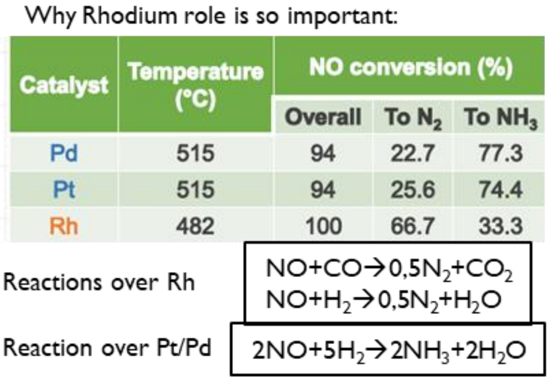


Figure 147 – Methane and CO conversion efficiency over temperature

For what NOx reduction regards, it is good to start saying that for CNG engines almost all NOx emissions are composed by NO only. It is difficult to decompose NO back to Nitrogen and

Oxygen. The Oxygen extracted must be somehow used. Hydrogen and CO products from exhaust flow are the most used methods. We said that Rh is preferrable with respect other PGMs, being the ranking Rh > Pd > Pt. The reason is that NOx reduction over Rh is selective to N_2 whereas over Pt and Pd mainly results in NH_3 (which is undesired). Table 15 shows Rh, Pd and Pt temperatures activity and NOx reduction reactions.



Why Rhodium role is so important:

Catalyst	Temperature (°C)	NO conversion (%)		
		Overall	To N_2	To NH_3
Pd	515	94	22.7	77.3
Pt	515	94	25.6	74.4
Rh	482	100	66.7	33.3

Reactions over Rh

$NO+CO \rightarrow 0{,}5N_2+CO_2$

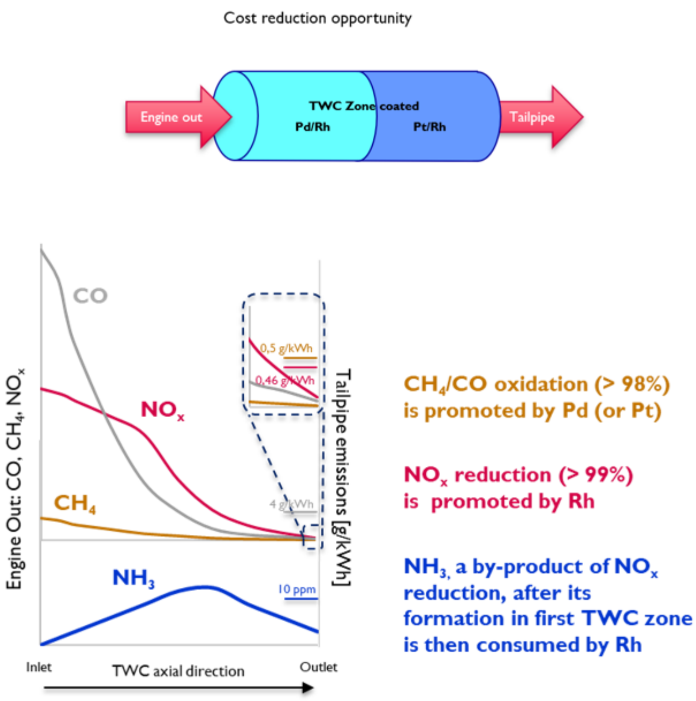
$NO+H_2 \rightarrow 0{,}5N_2+H_2O$

Reaction over Pt/Pd

$2NO+5H_2 \rightarrow 2NH_3+2H_2O$

Table 15 – Rhodium role over temperature for NH_3 limiting in NO conversion [FPT Industrial]

It is clear that Pd and Pt lead to higher NH_3 formations, while Rh is more efficient in reducing NO in higher N_2 percentages. That is the reason why highest quantity of Rh is embedded in rear section, to limit the NH_3 slip generated in first Pd axial zone. If we think at homogeneous architecture, Pd presence over the whole length generates NH_3 slip that has to be somehow treated. The zone coating manages it with its architecture characteristics with less overall Rh content. It is true that the idea of a Rh CPF coated after the Pd/Rh TWC makes possible to use a richer calibration of the engine, thus achieving higher NOx reduction via Pd and then managing NH_3 slip with higher Rh content and the Rh coating in CPF. However, it is far from being cost-efficient. The situation could be even worst on cost point of view with application of an SCR/ASC after the TWC. With the zone coating, it is possible to eliminate the Rh CPF need, by managing NH_3 with rear TWC Rh rich zone and without exploiting so the mixture enrichment, but instead using a bigger A/F window coupled with good NOx emission performance of the zoned catalyst. The zoned catalyst endows less PGMs and a bare CPF will control PN requirements without exploiting any additional PGM loading on it. The saving seems to be consistent and will be thus economical evaluated. Engine out and tailpipes emissions could be so then evaluated, from alpha-phase FPT Industrial experimentally found:



CH_4/CO oxidation (> 98%) is promoted by Pd (or Pt)

NO_x reduction (> 99%) is promoted by Rh

NH_3, a by-product of NO_x reduction, after its formation in first TWC zone is then consumed by Rh

Figure 148 – Engine out and tailpipe pollutants reduction over zone coated three-way

We got the same emissions abatement but using less Rh (-37,5%) and having cheaper Pt partially substituting Pd. The only problem is represented by thermal ageing. It is higher for NG engines due to the higher exhaust temperatures (with respect a conventional diesel case for example). PGM deactivation and resistance to ageing must be thus studied in alpha, beta and gamma phases of the project development. We can see also that Rh temperature of conversion is lower. The challenge of Zone coating technology, which has been firstly developed for passenger cars, is thermal durability. Tests are on-going to demonstrate suitability to Heavy-Duty applications. For what regards the needed PGM dispersion in ageing, we have seen that the lower is the size of PGM particles on the surface, the higher are the active sites available for gaseous pollutants abatement. Sintering and degradation must be avoided.

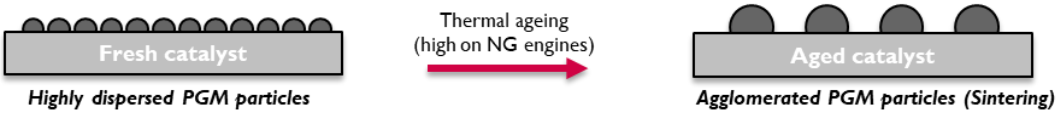


Figure 149 – Thermal loading ageing in three-way catalysts

Someone can wonder why Rh is embedded in small quantities also in first zone, leaving to Pd only the NOx reduction and avoiding first zone edge Rh possible poisoning [34], it is because high NOx reduction efficiency is anyway needed (it is not possible to completely substitute Pd and Rh) and coating process can be so improved. Different Rh loadings in the two zones, with higher Rh only when NH$_3$ suppression is needed (after NH$_3$ formation in front zone in rich window conditions). To complete the scenario, the trimetallic solution is achieved through the Pd substitution with Pt in rear zone. It is economically helpful, but it is also obtained thanks to lower temperatures in rear zones (as we previously have seen) and S-trapped by Pd coated layer in front zone, that prevent poisoning effects. The structure of the substrate (in cordierite) and the washcoat support layer with the precious metals loading is below drawn:

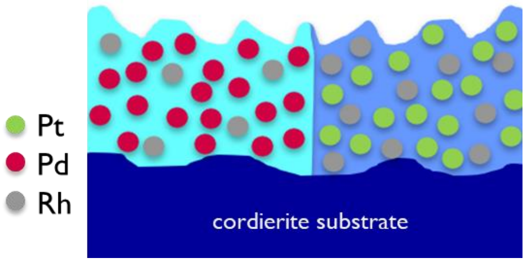
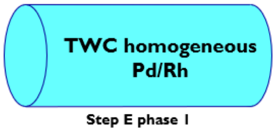


Figure 150 – Pt/Pd/Rh layout in zone coated slurry over catalyst substrate

By highlighting step E2 zone coating differences with respect homogeneous E1:

- Same total PGM density:
- Pd substitution with Pt in rear zone
- Rh total reduction



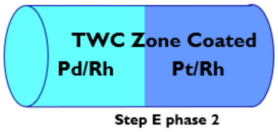


Figure 151 – Homogeneous and zone coated catalysts illustrations

First results show that:

I. Pt/Pd/Rh are not as thermally stable than Pd/Rh for aging temperatures higher than 900°C

II. The architecture concept shows 100°C better CH_4 light off than Pt/Pd/Rh

III. The architecture concept allows cost saving on PGM cost compared to Pd/Rh reference

IV. The architecture concept always shows the better NOx conversion

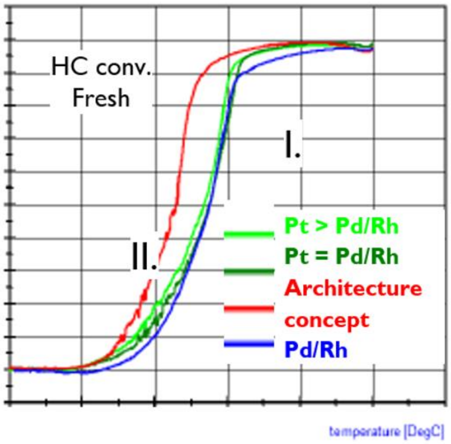


Figure 152 - HC conversion efficiency % at varying temperature

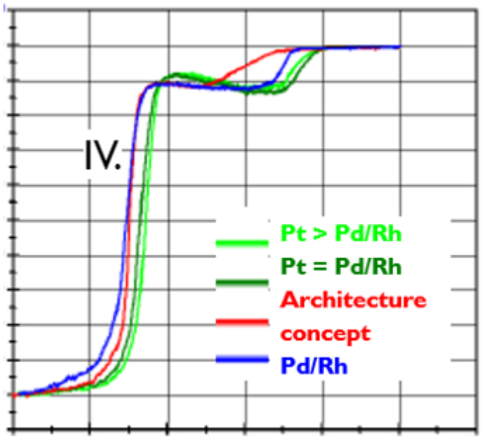


Figure 153 - NOx conversion efficiency % at varying temperature

7.5 FPT Industrial TWC zone coating cost reduction program in CNG engines: the coating process principle

Till now it was easier to justify main TWC costs due to PGM loading and materials. It for sure remains the biggest part, but in order to deeply understand the TWC component and its cost (as it will deployed in following chapters) it could be necessary to stress out the manufacturing process part of the coating. The study will report the technical discussion summary held within FPT Industrial through the supplier reports. It will influence the coating fee that suppliers usually address on clients. During three-way catalyst study it is common to find coating process explanation centrally focused on the word 'wash-coat'. The word itself explain the method of support carrier application. The process is often called also 'impregnation'. The impregnation method consists of depositing carrier (usually high surface Al_2O_3) by submerging the catalyst in a liquid carrier solution and then calcinating (through an oven passage) and quenching it [12]. In a homogeneous coated catalyst, the coating process is managed normally through the application of washcoat solution in all length of the substrate. Number of coating solutions and/or segregated/layered washcoats passages are created over the length, adding for each the respective precious metals and so deciding the better solution of carrier and stabilizers. For a zone coating solution, the situation might be different, with the necessity to have more coating passages but also a different manufacturing coating process involving just a partial dipping of the substrate, to respect the right axial zoned coating ratio. The complexity of the new technology is due to the featuring of a four zones coating process, while today's process is based on two uniform coating steps only: the new technology is doubling set-up and the process times. According to supplier* data, homogeneous catalyst coating is made by 2 uniform coating steps with full dipping of the substrate, while the new process consists in 4 different zoned coating steps and partial dipping. But there is not only the concern about doubling of the process number, each coating step needs in fact a careful set up of the coating unit aimed to determine the right amount of wash-coat and coating length on a specific length of the substrate. It is based on the zone coating length ratio. This set-up must be repeated four times in the zone coating case. Moreover, as said each coating step is featuring a different kind of wash-coat and PGM loading, which is causing an additional complexity in the chemical part of our process and on the set-up of the coating units. The complexity will also impact on energetic and time point of view considerations. More in the detail the coating scheme of the homogeneous Pd/Rh TWC is subsequent:

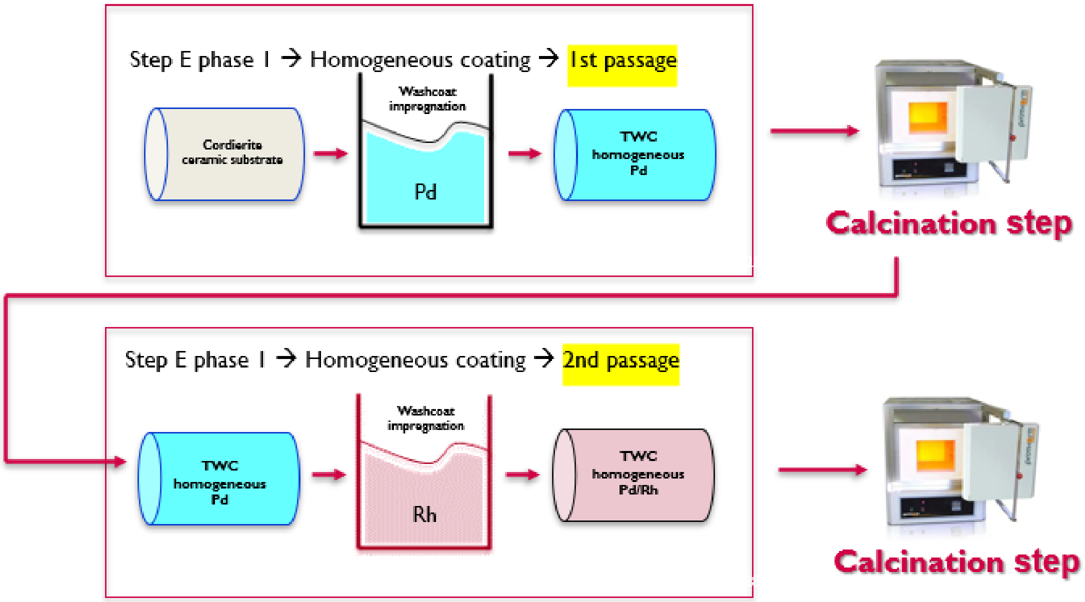


Figure 154 – Homogeneous catalyst coating manufacturing process illustration

Following the colours of the scheme we can see that the 'virgin' substrate monolith enters in the first washcoat 'bath', containing the Pd precious metals liquid solution. Being homogeneous, the piece will be submerged for its entirety, with full dipping methodology. Once the monolith has been calcinated in oven and quenched, it will be a simple Pd coated TWC. To be completed, a second Rh bath with right amount of Rh loading follows. The monolith is now correctly PGM loaded and will take its final form after calcination step. It is worth to notice that Pd and Rh coating are not taken in a single bath because we are speaking of a precious metal dedicated to the oxidation reactions (Pd) and one for reduction (Rh). Carrier formulations will be so different and poisoning effects are avoided. Moreover PGM densities could be different. In case of a hypothetical trimetallic solution Pt/Pd/Rh or a bimetallic Pd/Pt alone, it is possible to couple the oxidant precious metal in same bath and carrier washcoat composition. The same cannot be done in Rh reductor presence. Meanwhile, in the zone coating process scheme we got:

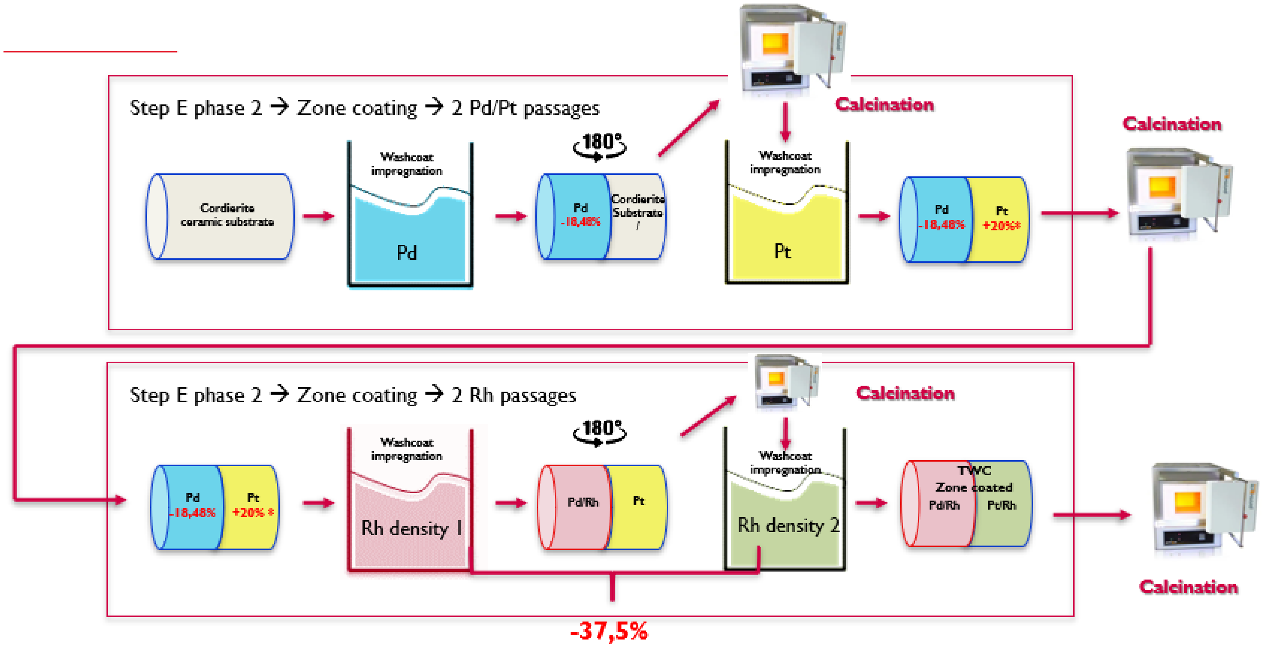
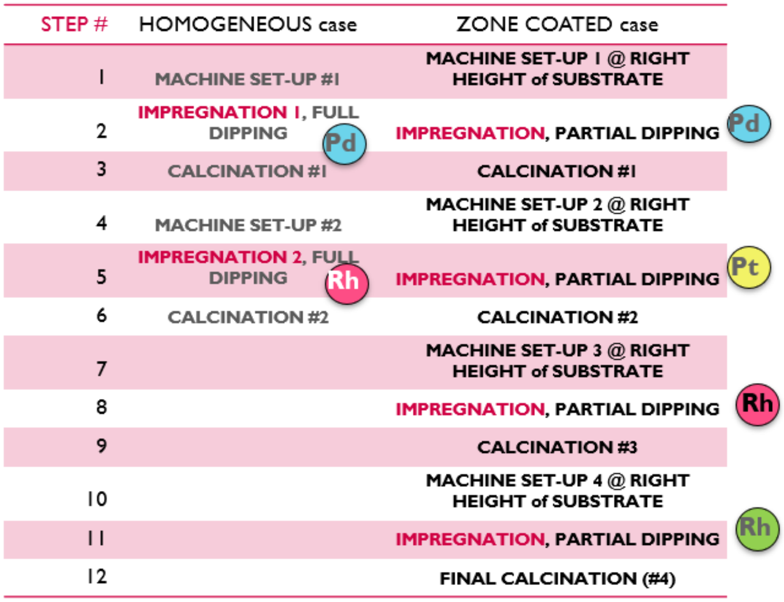


Figure 155 – Homogeneous catalyst coating manufacturing process illustration

In this case the empty cordierite monolith is washcoated in a way to guarantee the two zones splitting so that in first zone half Pd/Rh loading is obtaining and in second rear half Pt/Rh, getting an overall trimetallic catalyst. The substrate enters in first Pd bath in partial dipping methodology, till the selected first zone length. Then it is calcinated, and before entering the second zone Pt bath it is 180° flipped, or better it is assured that the right half is partial submerged. Notice that, according to the supplier* information data, a full 50:50 zone coating is not applied, but a small safety volume is left free between first and second zone. It is a volume that is some millimetres axially long, it is inert and so it does not impact on emission reduction performance and being small it does not impact too much on exhaust gas space velocities. It is done for safety reasons (to not merge different coating zones at the middle border edge of the two zones) and so doing to avoid possible poison effect on catalyst. After second calcination step, TWC is zoned in front and rear by Pd/Pt oxidant precious metals. It is then time to Rh adding. Here it comes the particularity of the developed technology. The Rh double loading characteristics along the axial substrate length are fundamental for the control of NOx and NH_3 slip emissions, as we have seen. However, the presence of two different Rh loading solutions lead to more process complexity. Chosen Rh formulations are different between first front zone and rear one in terms of loading density in g/ft^3. First half zone is embedding a certain g/ft^3 Rh solution, while the second one a double Rh layer density. Being the axial length of the two zones the same (50:50 ratio of zoning) the first one is endowing half the Rh loading in term of mass (in grams) with respect the rear zone, with 20,8% and 41,7% respectively with respect previous homogeneous total Rh loading. The two densities zones have to be created with two different washcoat baths embedding appropriate solution density of the precious metal. It is evident how choice of zone coating ratio, choice of PGM loading and where to put it and choice of PGM densities are all linked. It is necessary to study the best dataset to have the desired emission reduction performances and desired PGM loading quantity in the right catalyst zone. As we have seen in this case, the choice could not only impact the catalyst loading structure but also the coating manufacturing process. Since the two Rh washcoat baths for the impregnation submerging are of different solution and Rhodium loading, a single full dipping impregnation passage is here impossible to accomplish. So again, the substrate (hence coated partially with Pd and Pt in the two zones) have to be partially dipped in the first washcoat bath from the right front edge till the selected zoned length. Then again it is calcinated, flipped and inserted in the second Rh rich bath for the rear zone. Then, fourth and final calcination step for the Rh rear coating zone ends the overall manufacturing coating passages needed. In below table all passages are enlisted for both homogeneous and new developed trimetallic zone coated technology, to have a comparison.



STEP #	HOMOGENEOUS case	ZONE COATED case
1	MACHINE SET-UP #1	MACHINE SET-UP 1 @ RIGHT HEIGHT of SUBSTRATE
2	IMPREGNATION 1, FULL DIPPING Pd	IMPREGNATION, PARTIAL DIPPING Pd
3	CALCINATION #1	CALCINATION #1
4	MACHINE SET-UP #2	MACHINE SET-UP 2 @ RIGHT HEIGHT of SUBSTRATE
5	IMPREGNATION 2, FULL DIPPING Rh	IMPREGNATION, PARTIAL DIPPING Pt
6	CALCINATION #2	CALCINATION #2
7		MACHINE SET-UP 3 @ RIGHT HEIGHT of SUBSTRATE
8		IMPREGNATION, PARTIAL DIPPING Rh
9		CALCINATION #3
10		MACHINE SET-UP 4 @ RIGHT HEIGHT of SUBSTRATE
11		IMPREGNATION, PARTIAL DIPPING Rh
12		FINAL CALCINATION (#4)

Table 16 – Homogeneous vs zone coated catalysts coating steps

It is clear that the major outcome of the coating process change due to zone loading is the complexity. It will create energy and process cost increases. As said, the set-up time is approximatively doubled. For each coating passage (of four totals) the substrate must be well collocated, the partial dipping and the right loading length must be selected. Moreover, between each passage the substrate piece must be put in oven for calcination, doubling handling times and calcination steps. Moreover, between each passage the quality checks are doubled, and it must be taken into account that before launching the production of the full batch, this set-up process is inevitably generating some scrap. Scrap rates will increase with respect a normal homogeneous coating case, according to supplier and FPT Industrial shared evidence. The coating manufacturing process complexity increase will impact on total OHC (Over-Head-Costs), in which percentages of machinery tooling usage and amortization, quality costs etc. are present and hence here influenced. Manufacturing process cost increases, affecting coating fees, must be monitored and evaluated in the cost reduction program, checking that they remain low. Moreover, in addition raw material, energy and logistics could be affected by a step increase, like it happened in the last months. They have to be monitored. The technology however has big potentials to keep delivering meaningful cost saving, compared to the current technologies.

7.6 FPT Industrial TWC zone coating cost reduction program in CNG engines: the loading alternatives hypothesis

As we have seen in technical analysis, the selection of zoning is dictated by emission reduction targets both in terms of reduction reactions and chemical characteristics. Enhancing the rear Rh rich NOx treatment and NH_3 suppression needs a bigger amount of Rh in rear part, and by exploiting the zone coating characteristics a less overall Rh quantity can be embedded with respect to a homogeneous overall Rh rich case. However, playing with the selection of appropriate zoning length ratio and the PGM loading density over the catalyst volume, big impact both on manufacturing coating process and on catalytic activity could be generated. For this reason, it could be hypothesize and study, accompanied by suppliers, different solutions to pick among a series of TWC alternatives for future engine updates. From now on we will refer as 'baseline' the 50:50 ratio trimetallic zone coated TWC, and from this latter different possible little 'hardware' changes could be evaluated, called 'alternatives'. Being this chapter fruit of the hypothesis, and being the FPT Industrial E2 CNG zone coated program on HDV the only one to be implemented, the technical and economical analysis will remain focused on baseline case, for which more data are available, and only few hints will be given on the additional innovations possibility. All of that could testimony how zone coating is not a technological concept related to a fix formulation, but optimisation and innovation is possible, as we are seeing on the difference from the literature and the case study. The starting idea, is to have a zone coated TWC with less total amount of PGM loading at overall level (with respect the homogeneous one), and not equal like the baseline formulation. As we have seen from literature, also a decrease of overall quantity could guarantee the emission reduction target achievement [33 - 34]. While doing this, additional zoning ratios could be studied. The alternatives three-way may have a minor loading density over the whole volume, so changing it and changing the length ratios, also the local densities will be different, and all of that will be directly linked with each zone PGM loading amount in terms of grams. We start evaluating different scenarios:

Description	**Baseline**	**Alternative 1**	**Alternative 2**	
PGM loading density	SAME 50:50 zoned	MED (LESS) =/= 50:50	LOW (LESS) =/= 50:50	g/ft^3
PGM	68,7	TBD	TBD	g
Pt	+20% *	TBD	TBD	g
Pd	-18,48%	TBD	TBD	g
Rh	-37,5%	TBD	TBD	g

Table 17 – Few alternative hypothetic possibilities

Starting from the alternative 1: It charges less PGM total grams, and a different zoning axial length ratio. Also, different volumes could be studied reducing overall PGM quantity for aligned loading density. For all of them a full validation activity should then be need. Another possible difference is that the catalyst could be implemented as still trimetallic, but with a different composition and/or formulation. For example implementing front zone Pt/Pd/Rh loading instead of baseline Pd/Rh only. Decrease overall Pd layer inserting little Pt portion (cheaper), achieving Pt-for-Pd substitution, that will we later see, could be beneficial for economic aspects. It is interesting because composition change could have effect on respective coating process passages. The bigger difference is in fact that Rh coating between the two zones, even if it is still respecting the different loading zones structure, now could be ideally designed as homogeneous in terms of density between the two zones. The consequences of the choice are so on coating process. Even if the first zone sees an introduction of Pt it could be handled in the same Pd bath, because Platinum and Palladium are both oxidant metals and they could be impregnated in same washcoat slurry with same stabilizers. They will not suffer of poisoning effect. So the first zone is partially dipped up to a certain % of total axial length of the catalyst. Then there is the calcination step, and the second rear oxidant zone bath of Pt impregnation. A 'free zone' is left empty again, and a second calcination step is necessary. Here in the Rh coating could lie the big difference between baseline zone coating case defined for the study in object. The alternative cases with possible homogeneous Rh density impregnation choice between the two zones makes possible to save one coating passage. The coating passages will be three instead of four, and so the calcination steps needed decrease to three too. It will lead to less complexity of the coating process, less energetic and less time consuming manufacturing process, and to the enlighting of all added costs related to the process complexity increase, gaining more economics advantages. The overall structure could keep the same performances of the baseline case and the same concept, with the advantage of a single homogeneous Rh slurry in terms of densities. The latter, coupled unbalanced zoned ratio, leads to a different Rh mass in the two zones anyway. In the below figure we can find the coating passages:

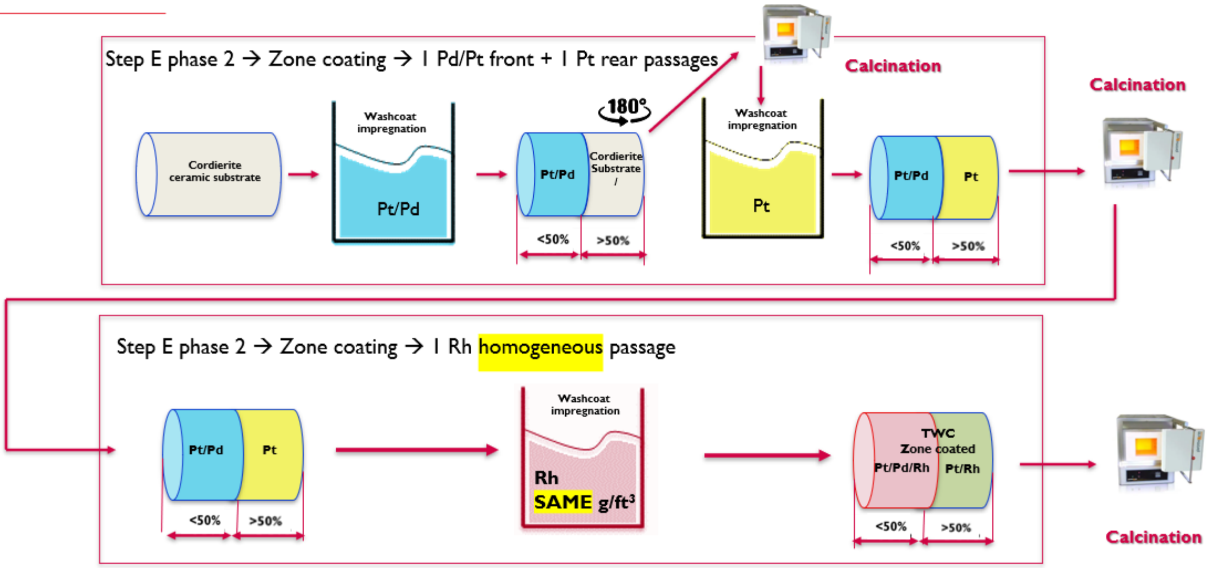


Figure 156 – Manufacturing coating passages for alternative Pt/Pd/Rh zone coating formulations

Another difference with respect the baseline case is that with third Rh impregnation passage, the catalyst is full dipped. It is for sure an advantage, again in coating process complexity decrease. But it will lead to the Rh coating of the small empty un-coated volume that was left in previous passages. However, it should not represent a problem on chemical point of view, being very small and only Rh-coated.

7.7 FPT Industrial TWC zone coating cost reduction program in CNG engines: preliminary results, timing steps and coupling with CPF

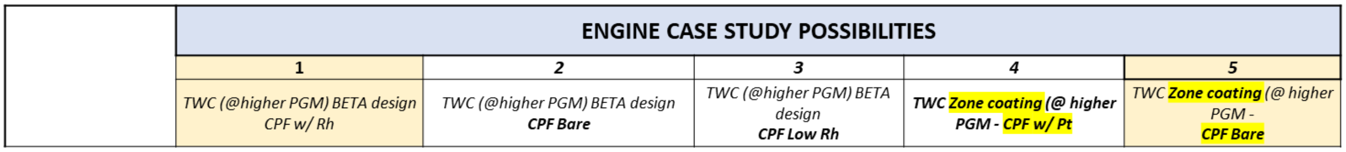
In FPT Industrial, the cost reduction activity follows some temporal milestones paths, in agreement with platforms activities explained in chapter 5. Moreover, integration with engineering and the engine platform activities must be performed, in particular with engine calibration activities. As explicated in previous chapters, before selecting actual zone coating cost reduction activity as the road to follow and implement in after-treatments, different layout solutions for different engine case studies were compared. Then for the selected one the technology validation is performed within time dictated by temporal milestones shared with customers to achieve start of production. In this optic, different transient tests for calibration development were performed for each engine involved in the zone coating cost reduction program and for each viable solution. For our engine case in study, they were performed at the very beginning of the timing steps schedule. We will concentrate on these first transient cycle test that were made at preliminary level on ATS layouts, by comparing

- Step D three-way (homogeneous)
- Step E1 three-way (homogeneous and Rh rich)
- Step E2 initial layout (homogeneous TWC and coated CPF)

Preliminary tests involved just step D, homogeneous E1 and zone coating solution (with E2 configuration and consequently CPF influence. At this preliminary level, the study were limited on TWC and a coated CPF with Rh level. The data were at preliminary level and to be not mature enough, so without tests on:

- Intermediate various solution of step E2
- Final solution of step E2 zone coated TWC and bare CPF, that finally was selected as the one to implement

For a total of



	ENGINE CASE STUDY POSSIBILITIES				
	1	**2**	**3**	**4**	**5**
	TWC (@higher PGM) BETA design CPF w/ Rh	*TWC (@higher PGM) BETA design* ***CPF Bare***	*TWC (@higher PGM) BETA design* ***CPF Low Rh***	***TWC Zone coating (@ higher PGM - CPF w/ Pt***	*TWC* ***Zone coating*** *(@ higher PGM -* ***CPF Bare***

Table 18 – Architectures hypothesis for *ENGINE CASE STUDY*

However, the preliminary test comparing D-E1-E2 first solution (1 in table) were a good starting evaluation and comparison that was done before the choice of optimised zone coated solution and its relative tests, calibration and validation activities. Obviously once chosen the final fifth solution it has to later be implemented in temporal milestones like specific ATS devices Ok-to-Tool (OKTT), PPAP level and Start of Production for this best solution individuated. In this scenario preliminary tests were on WHTC transient weighted averaged results during calibration development of step E2 solutions. The comparison is with the homogeneous catalyst, in both fresh and aged. NOx and NH_3 emissions are monitored. First E2 **initial layout** tests data evidence showed that emission levels are under engineering target, as well as their trade-off. At the same time, it is visible that with E2 aged ATS, emissions are **under engineering target** and NH_3 under legal limit. The reason is for the Rh coating ATS improvement, thanks to Rh implementation in CPF. Further tests data are on-going within FPT Industrial for reference '5' layout, with TWC zone coating (so with overall total PGM loading equal to previous homogeneous one, as said) and bared CPF. Tests are performed for WHTC on test bench/bed cells. PPAP batches and various homologations are waited to come in future within the start of production ranged between start of 2023 and 2024 based on engine typology. Meanwhile, first tests seem to be:

- Good in limits compliance for both fresh ad aged ATS parts.

In samples some level change (always within legal limits) are under evaluation. Different root causes are taken into account, for example the differences in canning design between versions, sensors positions and the presence of insulating layer. Temperature difference is also taken into account. All of that is useful to understand how tests are managed in time from the very early alpha prototypes phases till start of production. Activities of calibration are followed by **OBD** activities and **PEMS** on vehicles.

In parallel, based on engine bench assessment, CPF requirement was monitored since the first weeks of 'brainstorming' and layout evaluations, that lead to the definition of layout nr. 5 matched with the zone coating cost reduction activity. Based onto engine bench assessment, CPF seems to be required on almost all engines in step E2. The question is of big importance since step

E2 will have PEMS PN conformity factor implementation from January 2024. At first benchmarking activities marked the intention of heavy-duty sector to consider CPF introduction for Euro VI E2 legislation. The question is whether the CPF has to be coated or not, of if in its absence the regeneration (active or passive) is good enough to not generate oil consumption and contamination management problems. It could moreover be coupled with zone coating trend, to reduce volume and optimise PGM values. The focus seems to be not only on generic CPF presence, but it is on the need of a system compliant with step E2 PN PEMS requirements. Investigations on which kind of engine CPF is necessary, and on which filtration efficiency basis, were performed in FPT Industrial. Checks on CPF performances, maintenance and regeneration are mandatory, since as explained in below figure there are new Step E contents later explained:

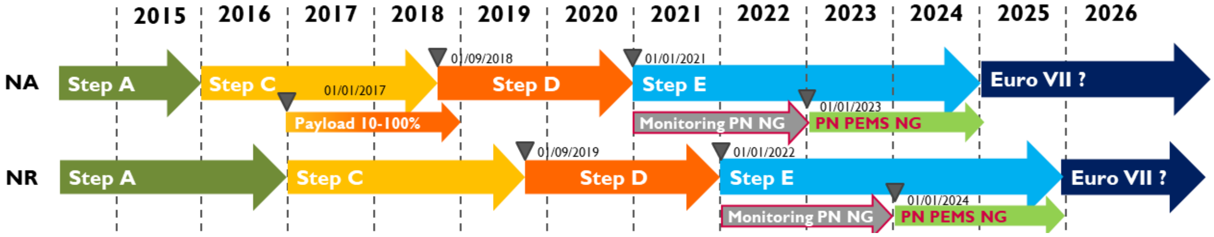


Figure 157 – Illustration of Euro VI steps due date in legislation

- New procedure for the PEMS Cold Start and PN inclusion, based on the calculation of 2 separated Conformity Factors (CF): CF for the Cold phase and CF for Hot phase. Cold phase is the portion of the PEMS test with Coolant Temp within 30 and 70°C, the Hot phase the portion beyond 70 °C.
- Conformity Factors are the same as today (CF = 1,5) for all pollutants, except for PN, where CF is 1.63
- PN limit for CNG engines is postponed 2 years (1st Jan 2023 for New Type Approval, 1st Jan 2024 for New Registrations), in the period between 1st January 2021/22 and 31st December 2022/23 the PN CF will be only monitored (without mandatory limitation)

Is the CPF needed to comply with PN PEMS requirements? By considering three different MD/HD engine families, among which our engine case study is present, we could strike that in some cases legal compliance are not met without CPF, in others CPF may be required depending on ageing and evolution factor effect. For what regards the engine case in study, here are reported some PEMS tests. Values were hidden for confidentiality reasons.

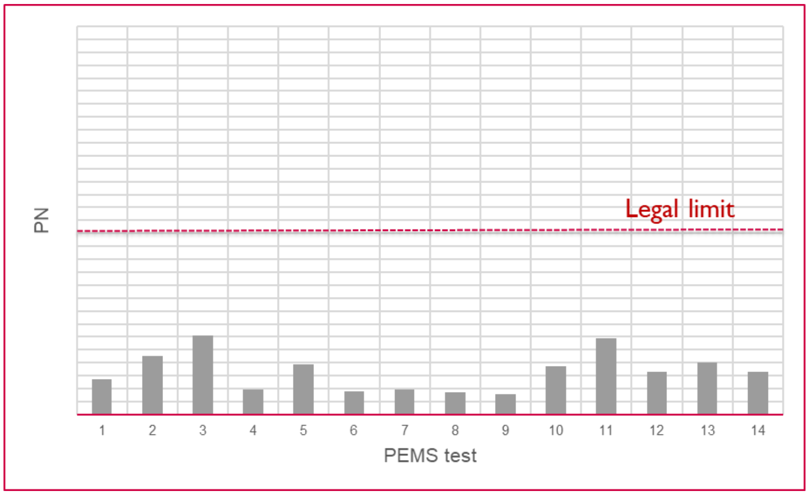


Figure 158 – PN PEMS tests **values hidden for confidentiality*

The emissions seems to be in specification limits. The CPF removal possibility was studied for each of the engine into consideration. However, potential for CPF removal for the engine case in study only need ATS hardware modification, that is in fact a sort of impact. It in fact needs a new acoustic chamber, completely reviewed. Structural performances are so modified and must be revised, and the NVH level could be reviewed. CPF removal also need engine hardware modifications, as alluded before. Modifications are at combustion and calibration level, but also on chamber parts and tolerances accepted in several components. It is trivial that investments at both engine and ATS levels are needed. Moreover, eventual cost saving is limited, especially in case of bare CPF utilisation, where no PGM saving could be accounted. For this reason, the '5' final layout solution seemed to be even more strong. The zone coating technology, in this case, can be seen also as a sort of enabler, to assure PN limits compliance with CPF presence coupling and to choose a single cost reduction that is in this way useful for its own perspective (being pollutants and NOx/NH_3 compliant with less PGM and cost impacts) but also to give an answer to whether CPF removal for this engine alon perspective could be advantageous. The latter became in this way useless. Additionally, new acoustic chamber or alternative monolith must be considered as additional costs to compensate for CPF removal. Based on the evidence above, CPF removal appear as not recommended. The decision seems to be important to trace actual Euro VI ATS layout for CNG engines. Fresh and aged backpressure are monitored as well as NH_3 slip suppression. Maintenance level and emission compliance useful life must be appropriate depending on engine/vehicle application and typology. Ash load model provides for information about CPF maintenance at service (for cleaning or replacement). OBD warns on CPF removal, even if the PM control is not mandatory in OBD for SI engines. CPF is not OBD relevant in terms of NOx. For what packaging regards, CPF max dimensions and best aspect ratio have to be selected to fit vehicle packaging constraints. Inside-chassis or side-chassis usually chosen on HD and MD respectively. For safety reasons CPF canning skin temperature must be below Customers' and relevant regulation requirements, and CPF backpressure must be below dangerous levels for engine reliability.

7.8 The zone coating in different catalysts: literature overview

The technical discussion could not come at an end without assessing the zone coating possibility of implementation for other automotive/industrial catalyst technologies that differ from the classical three-way application. As we know different catalyst are present apart from spark ignited or CNG three-way applications. TWC concept is properly transferred to diesel engines output through proper metallic selection, creating the Diesel Oxidation Catalyst. A range of NOx reducing catalyst are present, either in form of lean traps or with urea dosing system. Finally, particulate traps for both diesel and gasoline applications are often endowed with coating to enhance pollutants treatment and particle filtration efficiency. As we know, the zone coating formulation concept finds its roots in explication of thermodynamic, chemical and space velocities principles. The exploitation of different temperatures axial zones and their chemical metals loading, together with OSC enhancing capacities and properties of stabilizers of the washcoat slurry composition, plus the interaction between front zone and rear zone features, form the overall zone coated package catalyst characteristics. The axial lengths and the coating metals loading should be then controlled for space velocities and chemical and manufacturing process reasons, and last but not least for economical ones. Their interactions with carrier and stabilizers should be also obviously matched. We could strike that all of that is obviously proper of the three way catalyst, the first among after-treatment systems to appeared on market, with a history of more 40 years and many application typologies, but also to any flow-through or wall-through ceramic or metallic substrate that can be loaded with precious metals in a carrier slurry. It can be done either it is called TWC and endows certain typologies of PGM ratios, or if it is a DOC for diesel engines destination, rather than also for coated filters. They can enhance the same properties we saw for the three-way. Obviously, the main application studies started from 1990s in automotive light-duty sector for three-way only [12], with more literature in-depth analysis and following in-vehicles applications from 2010s, after limits tightening and some small PGM price oscillations. Oscillations that became stronger, as we will see, in the latest years, leading to studies and first applications approach also in heavy duty and industrial sector in overall. Since that, there are in recent years also different feasibility analyses considering DOC and GPF zoning. Main results from most important studies will be enlisted and highlighted. It is worth no notice that it is true that any substrate with precious metals coating could theoretically enhance the zone coating properties, but the chemical aspect must be considered too, to not going toward a direction that could simply deviate from the specific component purpose. It is the case of NOx post-treatment systems. For them, the mandatory presence of Barium or lanthanum oxides for LNTs, and NH_3 from urea hydrolysis in SCR, could complicate things in coating formulation. Moreover, being their aim the NOx reduction, Rh and Pt are mostly embedded, so a more sensible cost reduction activity could be on loading quantities, typologies (leading and pushing toward Pt as less expensive metal) and overall dimensions, rather than zone-coating. For these reasons, less studies are present on these components, and analysis will remain at DOC and CPF level, whose implementation and function in engine outlet could accomplish for zone coating properties similar to the three-way ones.

7.8.1 The zone coating in different catalysts: the Gasoline Particulate Filter, DOC and DPF

As we know, introduction of step E in Euro VI heavy-duty legislation, bring the introduction of PEMS requirements for PN. In near future it could become even tighter, and target gasoline and diesel engines without distinguish. From 01/2024 in fact, all new type registrations of CNG and

SI engines, must fall within PEMS PN limits with a Conformity Factor of 1.63. For this reason, the implementation of a particulate filter for industrial heavy-duty gasoline engines too became crucial to be compliant with above limits. Usually the choice stands between a 'bare' filter or a coated one. The first is also called 'adding-type' because of it bared nature, that will not lead to any other after-treatment component substitution. The coated one is often referred as 'replaceable', thanks to its coating precious metals layer that could also enhance pollutants treatment, and so the GPF might replace standard components (like the TWC, for example) [35]. Obviously, it can be done on *theoretical* point of view, but vehicular applications on on-road heavy-duty sector are very seldom. It is not in our interest for what regards the specific FPT Industrial applications for on-road engine families, where different solutions were studied but never with a single coated GPF in substitution of the TWC brick. Moreover, the more innovative cost reduction layouts are based on the bare GPF typology, by exploiting the characteristics of the zone coated TWC. But it could be of interest to at least have an overview at literature level for the coating of the GPF, to have a comparison and an extension of what studied for the three-way. Coated GPF adoption could be effective in reduce the substrates costs (if replacing the TWC only, otherwise we get additional PGM costs) and reducing the pressure drop in exhaust system. The possible three-way replacement could lead also the volume and space saving for the exhaust after-treatment. Coated replaceable GPF applications pursue the improvement of catalytic performances, the lowering of pressure drop across the filter and obviously the PN filtration efficiency improvement. The implementation of zone coating technology and the choice of coating process typology ('in the wall' vs 'on the wall) are the items through which the three coated GPF requirements could be matched [35]. The zone coating can be effective to improve the three-way catalytic performance at the same manner of the three-way, with the optimisation of precious metals arrangement in order to get a better warming up of the catalyst. Inoda et al. [35] studied two samples, with the same substrate size and same amount of washcoat slurry and PGM loading usage. We fall under a well known case, seen either in literature or application field, with two comparable catalysts on dimensional/carrier/loading point of view but with different axial zone coating specifications. Both the particulate filters were aged on engine bench with the same intensity. The different axial coating zones exploit the thermodynamic activity of the exhaust gas, that differ in parts especially for what regards concentrations and temperatures. The frontal upstream part is heated for first and first activated. Right OSC control can be implemented in right part, to get downstream part purification. Suppression of sintering and degradation is so enhanced in the rear portion. The deterioration of the downstream zone of the catalyst is lowered, and performances are increased, especially in light-off terms [35]. The study of Inoda et al. pushed on this direction for GPF only case, and testimony how the technology can be implemented on different substrates and filters that embed classical trimetallic Pt/Pd/Rh plus carrier catalyst activity. Again, NOx and HC light-off performances were evaluated on steady state engine emissions tests [35]. The results clearly indicate that zone-coated GPF has a better light-off with respect to homogeneous coated one, both in terms of HC and NOx. The results are below showed:

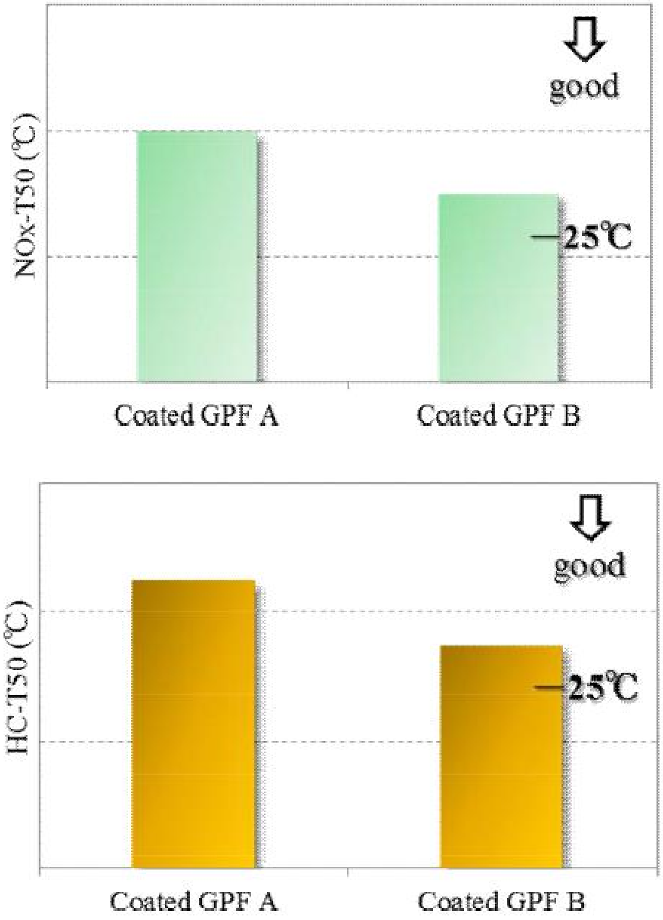


Figure 159 – Zone coated GPF vs homogeneous NOx and HC T50 [35]

The results show that it is possible to enhance different coating of particulate filters in specific axial zones and that it is someway effective to improve NOx and HC light-off efficiency.

Furthermore, according to a study of Koltsakis et al. [36] multiple layers and zones loading are applicable to both DOCs and DPFs. The study promoted a virtual modelling techniques to substitute real-life laboratories experiments. Indeed, the developed methodology can be used in this way to design new coatings (among which the zoned ones) by optimising emission control.

Chapter 8 - Platinum Group Materials: mining, manufacturing process, sustainability and market trends

8.1 Review of PGM mining and processing

The Platinum Group is composed by six metals with almost similar physical and chemical properties [37]. It is made by Platinum (Pt), Palladium (Pd), Rhodium (Rh), Iridium (Ir), Osmium (Os), and Ruthenium (Ru). They could be divided according to their density in heavy density category (Pt, Ir, Os) and a group of light density material (Pd, Rh, Ru). Moreover, due to characteristics of corrosion and oxidation resistance, also Au and silver are generally classified as noble metals too [37]. They are considered as noble also for the scarcity amount at disposal on earth. In literature we can find abbreviations like ‘4E’ or ‘6E’ indicating respectively the families Pt+Pd+Rh+Au or Pt+Pd+Rh+Ru+Ir+Au. The applications of PGMs are wide. Half of yearly demand of PGMs is from automotive sector, for catalytic converters. From a quarter to 30% of annual demand is dedicated to jewellery sector, then in electrical ones, in a wide range of industrial and medical applications, pharmaceutical, dental (crown and bridges) and medical treatments [38]. PGMs are used also in Biomedic healthcare, in devices such as pacemakers, defibrillators and catheters in human body, devices to treat Parkinson’s disease and loss of hearing. As industrial catalyst, PGMs are used to produce ammonia, nitric acids and a lot of chemicals compounds like polyester, nylon, fertilizer and synthetic rubber. Platinum-group rhenium catalysts are important for the naphtha reforming to produce gasoline blending with high octane numbers. Moreover, glass manufacturing and financial and investments sectors are involved too. Implementation of fuel cell technologies are a demand source for PGMs too. Figure 160 shows a PGM usage per sector in 2010, while following figure historically trace the Pt usage between 1975 and 2008 according to *Johnson Matthey*.

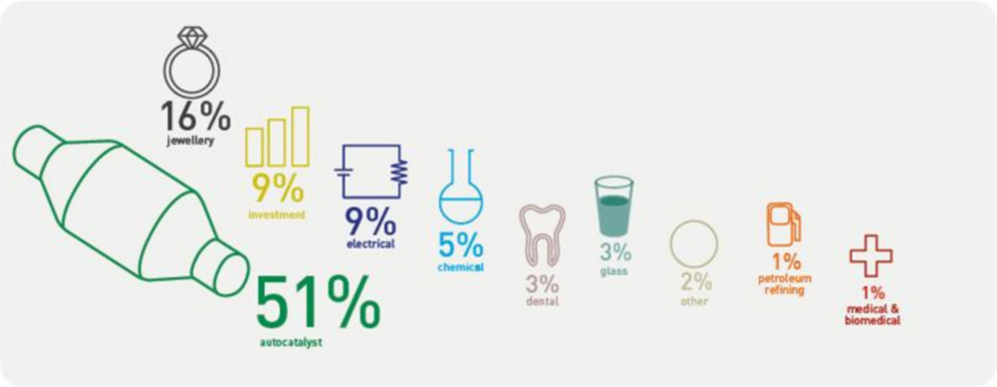


Figure 160 – PGM application typologies [38]

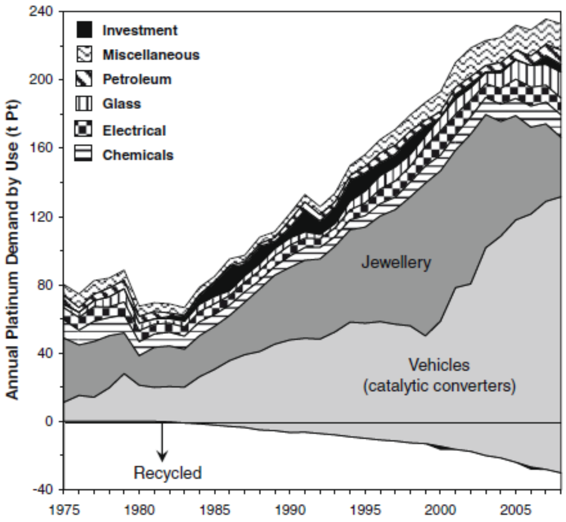


Figure 161 - Pt demand by usage, 1975-2008 [37]

In 2007 PGM production was of 509t [37]. The world's largest PGM reserve is in the Bushveld Complex in South Africa, which covers for more of 80% of global reserves [37]. Other countries involved in PGM mining and trade are Russia, Canada, United States and Zimbabwe. For what regards the extraction and concentration of ore containing PGM, a study attested that on average, concentrations of about 5g of PGM could be found in a tonne (1000kg) of ore and can be so sent direclty to precious metals refinery [39]. Then, the rest has to face the process of PGM recovery through concentration process. Both mining and concentration operations are environmentally challenges. They may undergo land transformations, they could chemically affect surface and ground water and several wastes could be generated [39]. Airborne and waterborne emissions could affects local communities, affecting water, livestock, fauna and flora [39]. The first PGM ore process operation is mining. The mining of ores is via underground or open-cut techniques [37]. Mining underground operations are made through different techniques using winches, air loaders, blasting, drilling machineries etc. It involves different energy resources, and it is economically expensive.

Figure 162 - Open Pit mine [from *Wikipedia.org*]

Once ore PGMs grade are sent to precious metals refinery, the ore concentration process could start. Ore mined undergo separation of valuable contents. Grinding and gravity-based (or density) separation methods are the most used. Crushing, milling and wet screening are accounted, to get a slurry which contains the precious metals [39]. Then precious metals content has to be separated through flotation cells, where some chemical reagents are added to get compounds with high-grade PGM [39]. The ore concentration process is accountable for airborne and waterborne emissions too [39] According to Bonnie J. et al. [37] there are four mains PGM ores:

- Stratiform deposits: mafic or ultramafic layered deposits, good in size and grades
- Norite intrusions: from meteoritic impact
- Ni-Cu bearing sills
- Alluvial sedimentary

8.2 PGM Sustainability reports

Since mining and concentration operations of ores containing PGMs seem to be energetic consuming and impacting on water and air local pollution, in past two decades lot of sustainable reports had been generated, often directly from mining companies on voluntary basis. Moreover, being the mining areas big over local area, also effects on local communities are listed. Sustainability reports regards environmental, economic and social effects of a company. Some companies started to release yearly environmental reports in the mid of 1990s, evolving till the form of sustainable report from 2000s. The Global Reporting Initiative (GRI) was set from 1997, it is a protocol on voluntary basis ad acts as tool for the mining companies [37]. Reports include economic, environmental, labour practices, human rights and social aspects. Indicators, both quantitative and qualitative can be both core and voluntary. Examples of core indicators taken in Bonnie J. et al. study are:

- EN3/EN4 – direct/indirect energy consumption by primary energy source
- EN8 – total water withdrawal by source
- EN16 – total direct and indirect greenhouse gas emissions by weight
- EN21 – total water discharge by quality and destination
- EN22 – total weight of waste by type and disposal method.

While on voluntary basis

- EN9 – Water sources significantly affected by withdrawal of water
- EN10 – Percentage and total volume of water recycled and reused.

It is possible also to account the equivalent carbon dioxide emitted for each stage of PGM processing and total one. It can be done through a Life Cycle Inventory Analysis, by developing a process tree or a flow-material chart of the processes involved and using an appropriate software tool (like the 'Umberto for carbon footprint' embedded in Mabiza et al. study [39]) that maps all input/output of each flow-chart process that impacts at carbon footprint level, accounting emissions, disposal, treatment, waste recycle etc. According to this study, the mining operations only have a total equivalent carbon dioxide emission of about 481.89 $kgCO_{2eq}$ for each tonne of ore mined. Mining only involves underground or open pit operations, drilling/blasting/hauling processes, energy required, the ore transportation and the dust at the mining reserve. Highest impacts are from rock broken and wastewater. For the ore concentration, the flow-chart involves much more operations, briefly described before. The total equivalent carbon dioxide emitted, according to the study, is about 1,574.96 $kgCO_{2eq}$ for one tonne of ore by concentration. Again, the most emission are from wastewater. However, emissions are from usage of a big amount of energy, most of it from indirect coal-fired power electricity generators or from direct consumption of energy resources as coal, petrol, diesel and LPG. It has a big impact on emissions of CO_2 in atmosphere. The dominance of electricity in energy consumption is however an opportunity to implement the usage of renewable energy technology, according to literature taken in account [37] and so reduce GHGs emissions. Some literature studies link the data on wastes, energy consume, water emissions and GHG emissions in relation to PGM production [37]. The ore grade seems to be constant around 3-5g/t [37]. Water consumption versus throughput seems to not show a link between water efficiency gain and production, so larger scales projects (and ore grades) are not said to be water efficient. Water consumed in milling is about 0.56-2.33 m^3/t. Saving of water is site specific and project specific. The same can be said for unit energy efficiency. Study was conducted over a variety of PGM mining sites. The indirect energy seems to be dominant, with a bigger effect of energy being used in underground mining. Other study [39] with LCA computations found about 72% of final cost value that can attribute to mining only operation. One of the biggest companies operating in South Africa, reported almost the same concept [37]. According to this, split in energy cost between mining, milling, smelting and refining showed dominance of the first three out the four stages of PGM production. The studies seem to be coherent for the energetic request that mining process requires. It can be also accounted while considering the mining typology site, with a trade-off between energy consumption (underground mining) and solid wastes production (open-cut mining). Meanwhile, a little relationship was found between ore grade and GHGs, as in evidence in following figure. The more the ore grade, the less the unit GHG emissions.

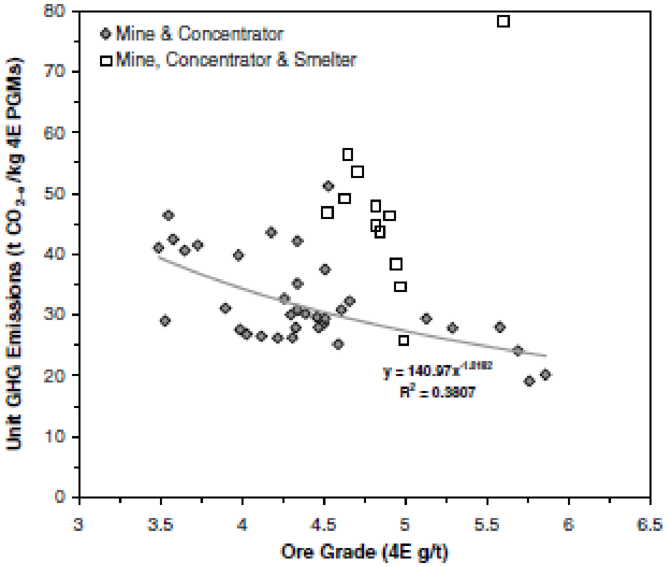


Figure 163 – Unit GHG emissions (tons CO_{2eq}) vs ore grade concentration [37]

However, the GHGs emissions growth due to production increases could be greater than savings due to efficiency improvement. It is important to notice that rate of PGMs production can be constrained by demand fluctuation [37]. Moreover, solid wastes need to be considered too. They need additional efforts and management. We could mainly found tailings, wastes of solid typology after the metal had been extracted, and waste rocks without metals in them. Slags from concentration smelters are important too. Companies rarely report amount of total mine wastes. According to study cited in [37] mining industry is the largest yearly producer of global solid wastes. In PGM more than 99.99% of ores becomes solid waste. It could bring dam failures, disposal of tailings in sea, acid and metalliferous drainage at land etc. However, in GRI reports they are often reported at discretion. Literature reports provided that PGMs environmental costs are slightly higher in energy, lower in water and a little higher in GHGs with respect to Au ores, for which grade is similar but they are processed differently (mostly in underground instead open cut). As said, voluntary reports on sustainability by companies treat social, economic and environmental aspect. They could bring a picture of the sustainability situation for PGMs processing but by their voluntary basis nature sometimes the full picture is not represented, as claimed and contested by ActionAid study in South Africa area. For sake of completeness, a Socio-

Economic report from IPA [38], a non-profit organisation representing 80% of the mining, production and fabrication companies in PGM industry, will be reported too alongside. According to IPA report, PGM mining companies provide their staff training, housing, health and care and create opportunities for local economy in South Africa. Moreover, labour plans include improvements of roads, schools, buildings and water supplies. Educational and skills programmes are enhanced [38]. Socio-Economic Development programmes involve also housing, with house building and conversion of hostels in family units. According to IPA report, in 2013 510,000 out 14.9 million of South African employees are in mining sector whole. PGM operations alone had 191,000 employees in 2013, with 1.9 million people benefitting due to the fact that each employed supports 10 family members [38]. Moreover, many indirect services and jobs are supported. The picture is completed with the social benefits coming from PGM wide application usage, as anticipated at the beginning of the chapter. IPA also claims that in recent years financial pressure have seen a growth due to declining of the ore grades, and it is confirmed by data collected by literature studies. Capital costs and energetic costs increases make the business less profitable for the company. In this scenario, labour cost increase is to account too. According from these companies investigations, strike activities are dangerous for the local communities on economical terms, especially if for long times and in big areas, with big loss of incomes for mineworker households and other related implications on health, nutrition, turnover times etc [38]. At the same time, in the past (2007) ActionAid realised a report based on villagers interviews and local authorities [40]. The reports revealed a different situation in South Africa area. The report claimed a situation in which villagers lost their agricultural land, homes relocations were not effective, mining activities were intrusive and water pollution from the mining activities was a serious issue, as well as for the already seen solid wastes. Voluntary basis companies reports were not aligned to that to complete the whole picture. Moreover, water and electricity cut off were experienced. Strikes and protests were often repressed with violence, as it happens in 2012 in the South African Marikana tragedy during an unprotected strike. One of 2007 ActionAid recommendations was that consumers of PGMs should ask that PGM supply is extracted so that social and economic sustainability and human rights are guaranteed. Annual reports should be improved to get an available and publicly full scenario of PGM supply overall impacts. For example we can relate to data that *Dieselnet.com* reported for non-road engines Tier 4 US regulations: if older engines are substituted by Tier 4 engines, annual emission cut-off are computes with 738,000 tons of NOx less and 129,000 tons of PM less from date of implementation within 2030, 12.000 yearly premature deaths would be prevented due to the implementation of the proposed standards [21]. They are referred to the non-road sector only for US market only. We can spot the benefits of right PGM embedding in automotive and industrial sector. Sector that alone accounts for 50% of yearly PGMs production. Benefits of PGM supply cover also wide areas of human activities, from healthcare, to medical and chemical sector and various technology [37-38]. However, a price must be paid off in terms of impacts that can be GHGs related. Bonnie J. et al. made a model that taking into account past PGM production and ore reserves compute the PGM production curve in time for two different models and their related GHGs emissions. In 2010 71,000t of PGMs reserves were known, with an annual production of 509t and a cumulative production of more than 12,000 tonnes from 1900 to 2007 [37]. According to data collected in literature a further 80,000t were estimated in reserve base [37]. Moreover, deeper mining in South African sites only is estimated to enhance higher reserves. So, the sustainable problem is not about the resource availability in the future but are the environmental costs. Considering unit 39.4 tons of $CO_{2\text{-eq}}$ per each kg of PGM, in 2007 level of GHGs related to PGM production was about 25 Mt $CO_{2\text{-eq}}$/year [37]. Obviously, being a CO_2 (equivalent) emission, this number cannot be directly related and compared to automotive catalyst benefits, as it was done by estimating ideal NOx and PM cut-off with a new legislation implementation on old engines. However, it must be considered in case of demand increase, especially while world major efforts are to cut GHG emissions. It has to be considered in the implementation of new technologies too. The zone coating again makes a perfect match of technical, legislation and environmental feasibility (pollutant reduction), cost reduction activities due to recent market trends that shake PGM unit prices, and also theoretically helps to go toward a direction of production and supply control and sustainability. However, it is difficult to link its massive theoretically installation on automotive sector and effects on market trends, especially considering the superimposition of effects with other technologies/legislations implementation over market trends (like fuel-cells that endows PGMs and tighter regulations that theoretically need more precious metals) and additional external factors. For this reasons, actual market trend will be studied in the following chapter, giving evidence of how it has been a major factor for the passage to zone coating technologies for a lot of automotive and industrial players, including FPT Industrial.

8.3 PGM Market trend

2020 for PGM supply will be remembered for the dramatic fall in both supply and demand, mainly driven to Covid-19 pandemic and its several related effects. Eventual expectations and hypothesis of a rise-back to pre-pandemic business conditions sadly seemed to be wrong and optimistic [41]. The following year was in fact conditioned by shortages and supply-chain disruptions, in particular way for the automotive and industrial sector. Additionally, the impact of semiconductor shortages was superimposed to new up-coming technologies, both due to legislations changes as well as new consumer preferences. Hybrid, battery electric vehicles and FCEVs have seen a surprising growing in the last three years, divided in two by the pandemic scenario. Moreover, in early months of 2021 PGM supplies suffered plant outages, particularly in South Africa area [41]. What happened then was a strange continuing of mismatch between demand and offer. In early stages of the year the demand was higher due to recover after the pandemic, but the incremented 2020 backlogs and the outages kept offer too low. Once the outages were solved and backlogs eliminated, the fallen of demand caused by semiconductor shortages and supply chain issues left a low demand for higher offer with PGM surplus for the rest of the year [41]. In 2021, these mismatches between supply and demand caused PGM price shakes. The direct consequence was that during the early part of 2021 low availability and good demand level set prices really highs, just before the following increase of supply and the demand falling brought prices downwards.

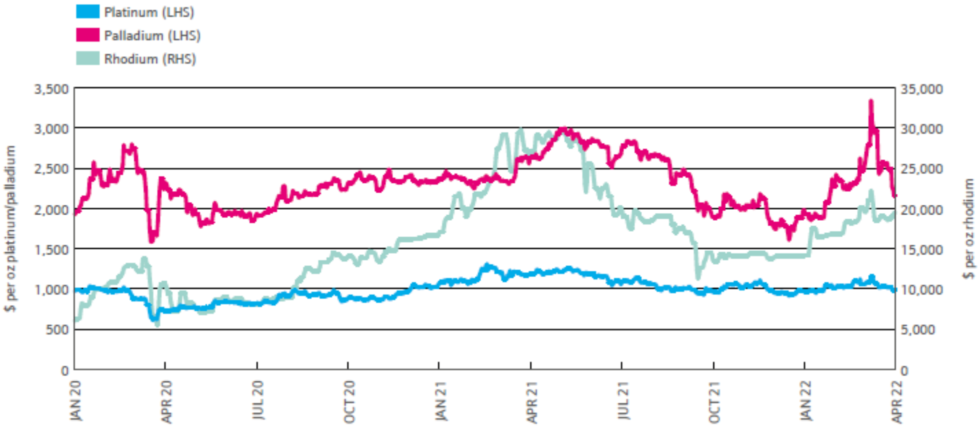


Figure 164 - Pt, Pd and Rh prices in $/oz over 2020 and mid of 2022 period [41]

According to Johnson Matthey's PGM market research, during the first four months of 2021, all the PGM except platinum were traded well above historical levels. Rhodium got the highest price increase, reaching peaks between 30,000$-35,000$ per once [41]. Notice that one once is 28,35 grams approximatively (and one once troy is equivalent to 31,1034768 grams), the last cited peak of 30,000$/oz correspond to around 1,050€/g! The price reflected shortages in some plants in 2020, that created a consistent backlog. Platinum and Palladium supply issues were limited by their absence of dependence from a single geographical supply, as it instead happens for Rh dominated by South Africa extractions [41]. Palladium was someway hit too in early 2021 up to 3,000$/oz (about 105€/g) due to worries about production capacity. Platinum was the more stable of the three, thanks to its largest market among different sectors and thanks to less suffering from outages and disruptions in plants (eventual floodings, incidents etc.). Anyway, it reached 1,300$/oz, equivalent to 45,5€/g. Second half of 2021 have seen demand decrease and backlog recovery, sending PGM prices hardly downwards. Rhodium touched briefly $11,000/oz stabilizing then at 14,000$/oz (490€/g) [41]. Palladium fell 1,600$/oz (56€/g) and Platinum went to pre-pandemic levels. It is worth to notice that OEMs and/or coater suppliers are (often) purchasing precious metals by periodic (monthly o yearly etc.) contracts. It is usual to have also some stocks: this could also impact the report computations of the demand dedicated to automotive sector while trying to report PGM market. Other sectors are more stable on this point of view. For what regards each sector level of involvement, according to Johnson Matthey PGM purchasing began to fall as ICE vehicle production slid lower and Chinese automakers thrifted PGM loadings. High PGM prices also limited industrial consumption, not giving credits to post-lockdown rising expectations [41]. However, industrial demand decrease is not valid for Platinum only, that instead have seen an increase, thanks to glass industry. Three-metals combined three-way catalyst and new formulation technologies (like the zone coating embedding) also helped to pursue Platinum for Palladium substitution, mainly on gasoline substrates (Platinum were already highly utilised for diesel oxidation catalysts). Only sector that hit Platinum was jewellery [41]. Shortages also created PGM secondary supply source (mainly represented by autocatalyst recycling) decrease. With the automotive market stuck, price and demand for used vehicle rose. Consequently, older cars were kept longer with less recycling possibility, stopping the previous rising in processing due also to 2020 accumulation of scrapping. An analysis on automotive demand says that the sector still remains as the major single contributor to PGM applications and demand. Implementations of tighter legislations also should boost PGM implementations theoretically. In 2020 vehicle sales were however affected by Covid and plant closures. The recovery expected by 2022 was not attended, mainly due to shortages of micro-chips semiconductors. Meanwhile battery electric vehicle grew their market share almost globally, at exception of 'Rest of the World' region, according to Johnson Matthey. The HDV sector was less affected, and China VI new heavy-duty legislations required a demand increase in PGM loading, helping for Pt demand rise in particular [41]. However, the report noticed how there was a PGM thrifting in China, forwarding for more efficient engines, and also an average Palladium and Rhodium implementation decrease, with technical cost reduction programmes like the zone coating one or in some way similar. According to the report, gasoline Tri-metals formulations implementation, moving away from classical Pd/Rh substrates and with platinum for palladium substitution are likely to be implemented after 2022 [41]. The picture of demand and offer in the actual scenario for the current year is meanwhile characterised by new events and players coming into action. Johnson Matthey reported uncertainties for PGM supplies from Russia because of Ukraine war. Palladium peaked about 3,300$/oz in March 2022 (115€/g) and then retained back at 2,200$/oz. Platinum slight increased too, and now is navigating around

1,000$/oz (35€/g). Fears about Rhodium supply (like it happened in 2020) made it growing after end of 2021 price flexion, reporting then it back at around 20,000$/oz (700€/g). Plant maintenance in South Africa also contributed to the diminish of supply availability. Also, secondary PGM supplies (i.e. by recycling) are forecasted to be in contraction also for 2022. Johnson Matthey's forecast about automotive PGM requirements says that a slight increase is expected, as reported in following table on thousands of ounces base, even if the scenario may evolve differently due to instabilities (post-pandemic, war, high inflation).

Gross demand '000 oz	2020	2021	2022
Europe	2,791	2,716	2,956
Japan	1,091	1,071	1,131
North America	2,082	2,219	2,521
China	3,227	2,896	2,627
Rest of World	2,316	2,737	2,958
Total	**11,507**	**11,639**	**12,193**

Table 19 – Gross demand of PGM over world regions [41]

Average PGM content is expected to remain stable [41] balancing the thrifting of PGM with the increase of loading due to legislation needs. In HDV sector it is the Chinese legislation that drives for a sensible increase of average precious metals loading content per vehicle [41]. Notice that diesel heavy duty trucks are almost platinum rich, while in light-medium and heavy-duty gasoline applications substitutions of Palladium with Platinum can hold, meaning that use of Platinum is likely to outperform Palladium and Rhodium [41]. In other industrial sectors, high prices are impacting on Pd and Rh only, with Pt keeping its demand at good levels.

8.3.1 Platinum

In 2021 the platinum market entered into a surplus state, as supplies promptly recovered from Covid disruption and processing outages, while demand fells off due mainly to shortages first and conflict/inflation situations. However, heavy-duty demand increase and platinum for palladium exchange in gasoline/CNG substrates was beneficial for Platinum demand too. Recovery in supplies were almost due to South Africa Platinum contribution, and previous 2020 Covid backlogs were recovered in 2021 [41]. Additionally, a small amount of Platinum was stocked too, passing in a situation of surplus.

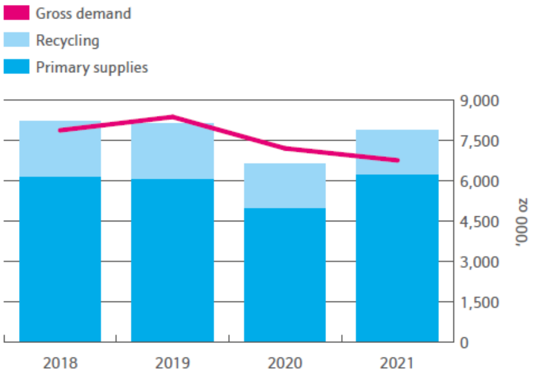


Figure 165 - Platinum supply and demand 2018-2021 [41]

It is worth to notice that even if the Platinum fought overall automotive demand vehicles decrease thanks to already cited platinum-for-palladium substitution, heavy-duty vehicles higher requests, tighter legislations and so on, it is important also to add that there was a continuing slide-down of diesel car output in recent two years. [41+ The result and combination of all these factors is the red shape curve traced between 2020 and 2021, where the expected demand increase was disattended. Automotive numbers collected in Johnson Matthey's report also considered LDV and HDV of fuel-cell typology, with a demand doubled in 2021, for the first time also in HDV sector.

8.3.2 Palladium

Also for Palladium, availability improved in 2021 as supplies sources in South Africa recovered outages from previous year. Vehicular production was then constrained by shortages, but OEMs shifted resources in BEV production for Pd. The overall demand slid just by 2% [41]. In the figure the flat trend in last two years is visible, after pandemic fall, and availability returned to normal level

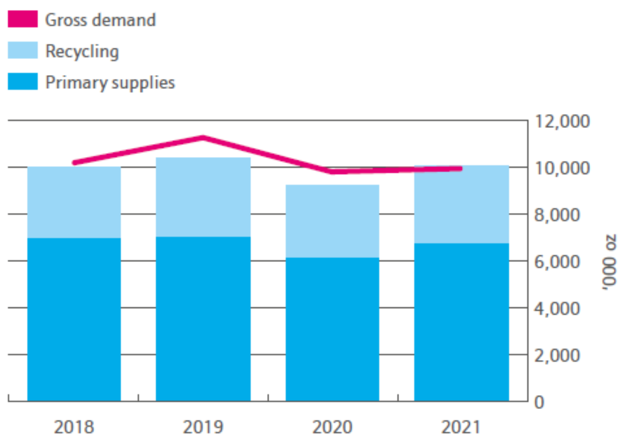


Figure 166 - Palladium supply and demand match 2018-2021

Recycling level increased too (up to a certain point of 2021) and it is quite visible from the graph. This is due to 2020 high prices and recover of backlog, that encouraged scrapping and recovering. However, used car market peaks prices and new sales drops in second part of 2021 stopped the recycling contribution, that had the potentials to be even bigger without the stop. Automotive demand declined by 2%, after the 2020 12% reduction. Even if world gasoline vehicle sold rose a bit, the average palladium loading per vehicle decreased due to efficiency improvement and thrifting in China, utilisation of Platinum and tri-metallics formulations for gasoline catalysts. Industrial demand saw a modest recovery too [41].

8.3.3 Rhodium

Rhodium case is the most emblematic among the PGM metals. A combination of pandemic, disruptions, mining disruptions and supplies were fatal to availability and price shakes in 2020. At the contrary, combination of primary and recycling rose up strongly in 2021. The backlog in South Africa (where main Rhodium is produced) was recovered and recycling saw increase. However, consumption fell slightly, due to simultaneous combination of automotive production, thrifting of PGM loadings, and changes in the composition in industrial sectors.

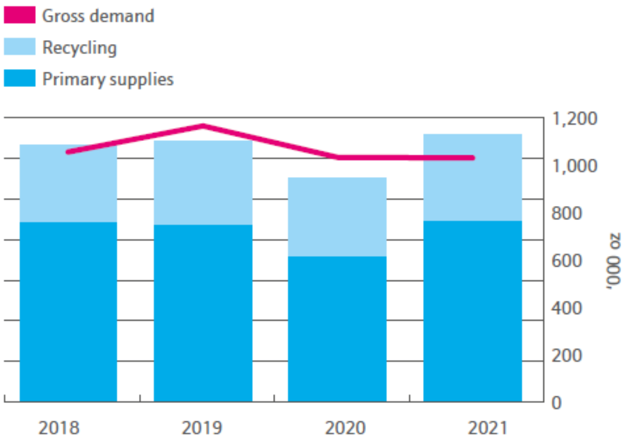


Figure 167 – Rhodium supply and demand 2018-2021 [41]

In the beginning of 2021, demand overcome supply, as vehicle production saw a little recovery before the shortages, and primary supply were still stuck in mining disruptions. Price rose at its maximum in March [41]. Then prices were falling back due to demand decrease and supply shortages problem resolution. However, at historical level the prices were still high and still they are remaining high in 2022. A Rhodium price outlook in historical basis is given in following figure, based on Johnson Matthey base price.

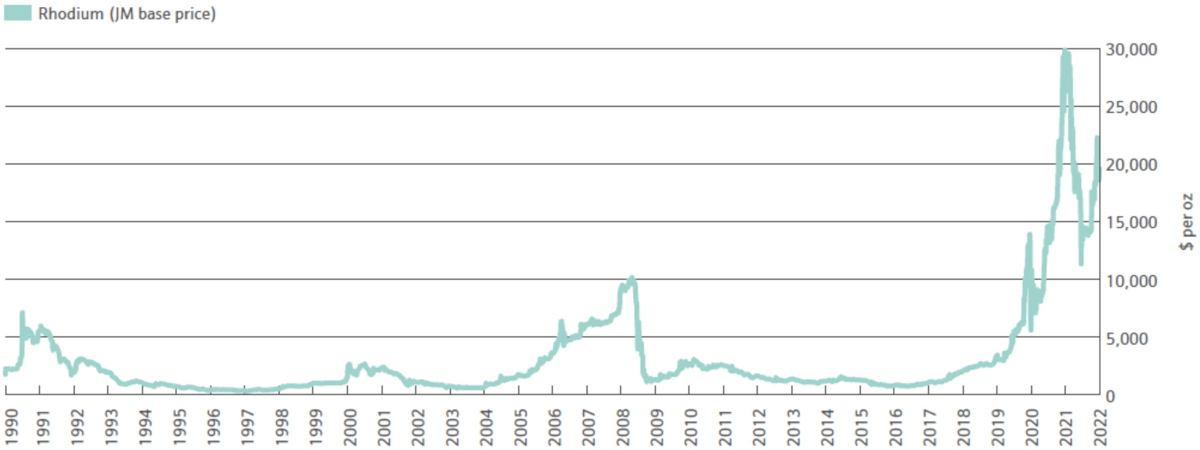


Figure 168 – Historical Rh price trend [41]

In the case of Rhodium, shortages in second 2021 part are not the only main protagonist of demand decrease, for automotive and other sectors. High prices represented a negative impact while deciding Rhodium introduction in a technology, process or business. According to the report, being the historical price shape of the Rhodium, and being it inelastic, it is embedded in applications in which there are not practical alternatives only. Autocatalysts dominate consumption, because as we have seen Rhodium is beneficial in treating NOx emissions more than any other precious metal. It guarantees high degree of NOx suppression, catalytic activity enhancing and less NH_3 formation. The rest of the applications and demand are form process catalysts and glass sector. Even past 1990-91 and 2007-2008 peaks enhanced new technical solution with less Rhodium too. It is not a case that in previous studies on chapter 7 it had been written that zone coating was first studied by 1990s, and then first literature studies were in first 2010s for light vehicles for gasoline, passing at last on heavy duty sector with different solutions, even the one to be embedded on CNG engines too like FPT Industrial case. The challenge is to do it efficiently and keeping degree of pollutants reduction high enough to cope with legislations tightening. In past two years Rh prices reached peaks that are way higher than past ones, and even if the trend decreased in 2021, it is not so decreased at historical level. Glass industry adjusted Rh content too. Last year automotive demand for Rhodium fell by 1% according to the report [41]. Thrifting of PGM content outweighed tightening of emissions in Europe and North America [41]. In particular, being Rhodium important for NOx reductions, it is important to notice that NOx limits have been tightened in all major economical area of automotive markets. Moreover, RDE emissions with different and harsher Conformity Factors are actual in evolution. It is not a case that North America and Europe demand is still not so decreased. According to Johnson Matthey collected data, thrifting Rh content was more effective again in China, for certifications reasons for which less time is needed to introduce new catalysts and for their certification.

8.3.4 FPT Industrial and literature insights

Having its business with Platinum Group Metals manufactured components, FPT Industrial monitors the situation of costs on every-day base and periodically updates its forecasts and insights, also having advice from third parties. We can see that the situation is quite aligned from the one presented by reports like the one cited for the upcoming years. In particular:

- Pt is forecasted to continue stay stable and strong, considering that is the one between the three that could diversify range of utilization. Substitution Platinum-for-Palladium on three-way augments demand, but the increase is smoother than the one Pd & Rh had along 2020/21 biennium due to the ground stocks and investment holdings which could counteract potential future market deficits.
- Pd previse is that it starts to decline since it’s primarily used in autocatalyst applications and could be largely substituted by Platinum in the upcoming developments. Output from mining operations is expected to be restored completely in few month.
- Rh is expected to remain strong: its adoption in autocatalyst applications can’t be avoided (no chance for substitution) and the tighter emission regulations to come are increasing the deficit along the next decade. In the meantime South African supplies are expected to decline over the forecast period as conventional mines begin to shutter. Prices to remain in the highest path of the recent trend.

The trends could found confirmation on *matthey.com* site of Johnson Matthey. In last 3 years, for Platinum we got:

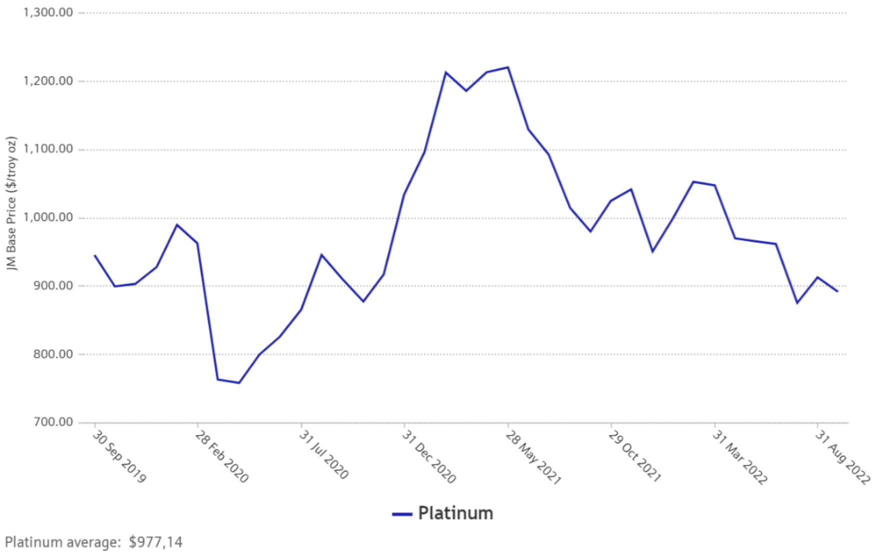


Figure 169 – 2019-2022 Platinum price trend [from *matthey.com*]

With a trend almost stable from end of 2021. Even the conflict in Ukraine did not lead to big peaks. The average is of about 34 €/g. For Palladium instead we have a decreasing trend, for the reasons explicated before, except a short period of uncertainty due to begin of war, that still makes its prices high. Lastly, the Rh is tended to remain high in next years. It will augment the economic impact of a technology like the zone coating one. Last two trends are highlighted in next figures:

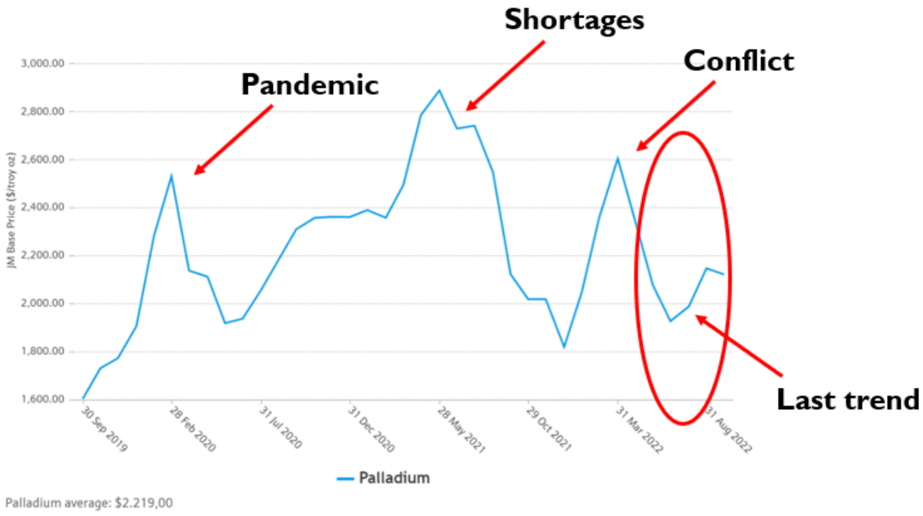


Figure 170 – 2019-2022 Palladium price trend [from *matthey.com*]

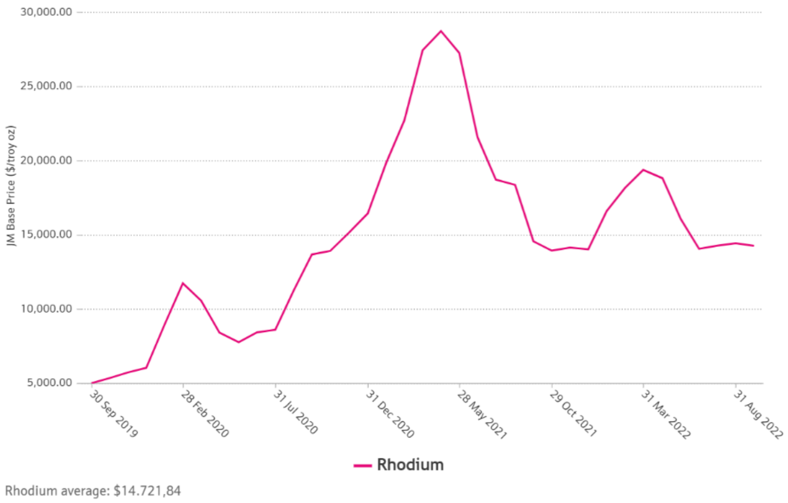


Figure 171 – 2019-2022 Rhodium price trend [from *matthey.com*]

Future PGM costs forecasts as such can be not 100% accurate or being subjected to external events and so change their behaviour. It is however important for OEMs to follow their trends and to be the most accurate possible in order to trace and follow a clear road on technology and manufacturing investments.

Chapter 9: Economical analysis of the FPT Industrial zone coating application for a Euro VI E2 CNG engine

9.1 The economical analysis within the FPT Industrial Purchasing Development team.

The first sensible impact of zone coating implementation is, as it has been underlined in chapter 6 for the technical analysis, the precious metals loading content decrease and/or ratio change. It is the core of the cost reduction activity, for which the technology has been proposed and it started in 2021. It was my concern in the company, with my colleagues, to evaluate technically and economically the feasibility of the cost reduction program, as well as to bring the discussion with the suppliers. As explained in the chapter relative to the ATS Platform, my role as Purchasing Development brought me to follow last part of supplier discussions process for the zone coating implementation in on-road heavy-duty Euro VI E2 CNG engines. While supplier selection proceeded and once supplier's scorecard and choice process ended, the Purchasing Development team with which I worked for also followed cost reduction activity process ongoing, in particular by initiating various RfQ's, ordering prototypes, and deal with commercial negotiation with suppliers. In this scenario, the updated technical impacts of cost reduction activities were evaluated on economical point of view and the results shared with all ATS Platform and its major actors (Platform Manager, Program Manager and the Assistant Chief Engineer in particular). The results will be presented as per their pertinence, relevance and highlighting the features impacting the economical evaluation and Business case only. Results highlighted in following pages are results of everyday work within Purchasing team in FPT Industrial (and from talks with suppliers) for what the technology in study regards, and underline the considerations made by the author with the team itself and the platform sharing and discussion. It is worth to notice that all the results are from an economic analysis within the Purchasing team that has some limitations:

- It is not indicative of the real muffler price, as sensor elements and sub-components will be not considered

- For confidentiality reasons, some voices are hided to protect FPT Industrial commercial agreement with suppliers
- The computations are a good cost **estimation** for coated substrates units and final mufflers elements, but they are subjected to changes due to shakes in price of PGM, subcomponents
- Due to confidentiality reasons, it is not possible to show real supplier offer but taking a picture of a scenario of PGM with data aligned with various supplier talks. Taking them fixed, it is possible to argue on other economics impact items. At the contrary by changing the PGM prices we could see the impact of zone coating program at variation of PGM costs. Both activities will be conducted.
- Due to above reasons, the prices herewith computed could be considered aligned to implementation and good indicators. The comparison between the homogeneous architecture and the zone coated one still gives a good measurement of zone coated program economical impact.

Impact evaluation may ideally start on basis of delta of PGM price in catalyst between homogeneous TWC embedded for CNG Euro VI step E1 and the new zone coating implementation for same engine and model line but for successive step E2 homologation. The engine chosen for the technical and economical evaluation has been labelled as 'case study' within this paper for confidentiality reasons, and it has been chosen among on-road CNG FPT Industrial engine families list because it is the most important in the on-road line applications and because it well represent technical implementations of the new technologies. It is so a good metre of economic impacts, we will briefly see how alone it weight most of overall cost reduction activity. Before starting with evaluations, it could be helpful to recap the concept of Tier 1/Tier 2/Tier 3 suppliers:

- Tier 3: Supplier that produces substrates.
- Tier 2: Supplier that makes the coating of washcoat of the monolith element. It is called *coater* internally

- Tier 1: Supplier that takes the coated monolith element and performs the canning of these monoliths. It gives to FPT Industrial the final muffler form, that is then endowed in final ATS of the vehicle.

An example of catalyst manufacturing flow for heavy-duty Euro VI step E1 after treatments is in below figure:

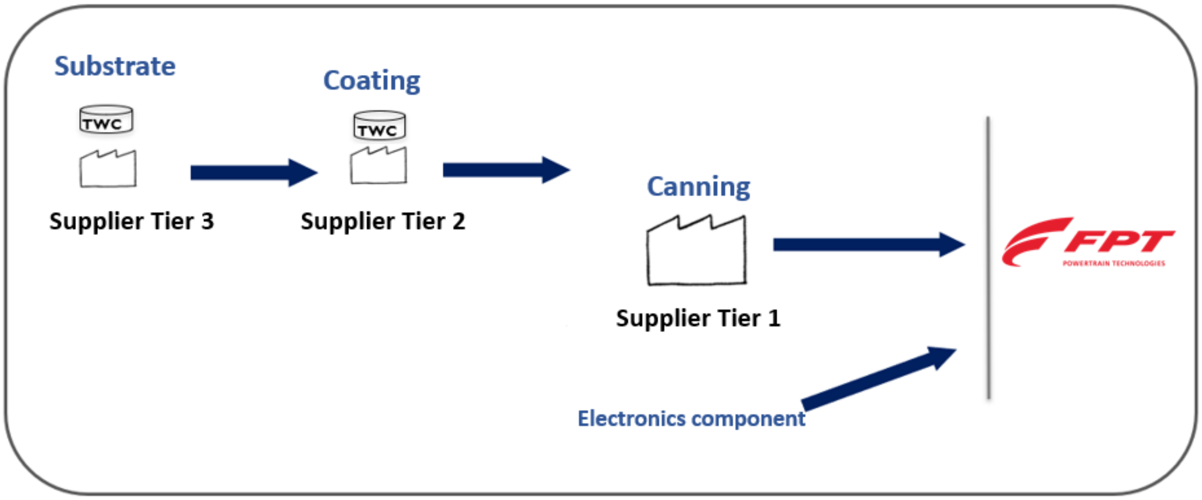


Figure 172 – Catalyst manufacturing flow

While, as it will be later explained, the muffler production flow for Euro VI step E2 CNG applications is a little bit different, with the presence of the CPF that being bare is directly shipped from Tier 3 supplier producing it to canning operations at Tier 1 supplier.

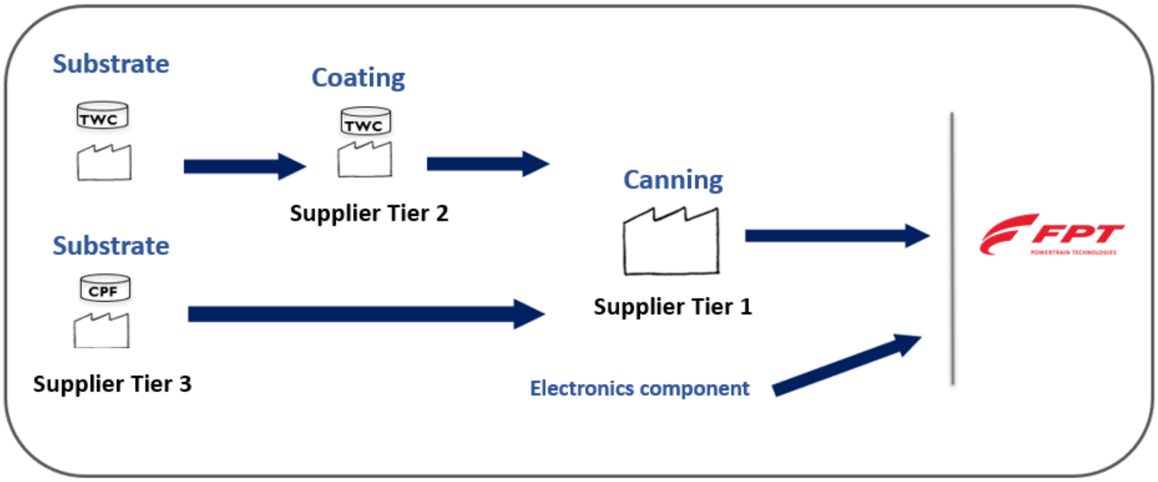


Figure 173 – Catalyst manufacturing flow for Euro VI E2 CNG architecture

In following chapters will be explained also how the stream of purchasing works and the financial agreements. With these three main suppliers, FPT Industrial has a strict relationship, controlling and sharing design activities and starting sourcing process. Other strict relationships are present toward urea tank assemblies. If a component is single (like could be a clamp, a sensor etc.) the relationship is *usually* more direct toward the supplier trading the component itself. The economical flow is streamed by:

- FPT Industrial recognising a price to Tier 1 canning supplier
- Tier 1 canning supplier paying for coated-ready material at Tier 2
- Tier 2 supplier paying for monoliths elements at Tier 3

The mechanism is regulated through some payment voices, call Handling Charges, later explained. The first impact of the PGM price studied here is related to a picture quite reliable of the last headquarter of 2022, when request for quotation was forwarded at supplier and relative offer and negotiation took place for the PPAP batches. Later PGM future market effects will be analysed

9.2 Impact of zone coating: PGM price delta with respect homogeneous Euro VI E1

In order to have back a recall on what zone coating cost reduction concern, a summary on catalyst substrates coats comparison is necessary. For the engine case in study, the CNG Euro VI E1 configuration in on-road application was selected to be endowed with a homogeneous catalyst coating. The Rh content was increased at highest possible level to get good ammonia slip reduction performances.

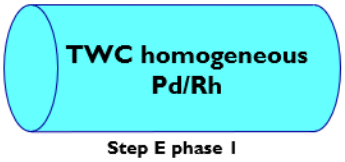


Figure 174 – Homogeneous coated Three-way catalyst for Euro VI E1 vehicles

The specifications show how a Rh rich formulation has been chosen. To get the mass of each precious metal over the catalyst, each precious metal density ratio (g/ft³ or g/m³) must be multiplied for the volume of the substrate for the respective right unit of measurement. The sum of each density ratio gives the total PGM density over the catalyst volume. We get the final presence in mass of Pt, Pd and Rh respectively. It has been already discussed how the step E1 homogeneous formulation is a classical Pd/Rh, with absence of Platinum. At the same time, the passage to zone coating involved different solution in studying. The selected one for the engine case of study was a catalyst whose zoned length ratio is 50:50. The total PGM density is the same of homogeneous, but averaged on the two 50:50 zones. The same computations give zone coated catalyst specifications as:

- 1st zone, NOx / CH4 / CO conversion → Pd/Rh bimetallic
- 2nd zone, Rh-rich for NH_3 suppression → Pt/Rh bimetallic

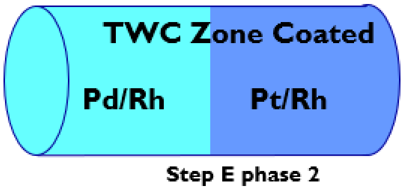


Figure 175 –Zone coated Three-way catalyst for Euro VI E1 vehicles

We can have a direct comparison of the PGM reduction occurring in zone coating

- 1st zone: Pd in less quantity with respect homogeneous case and Rh in small content
- 2nd zone: Pt introduction and Rh relative reach zone, but still less in quantity with respect homogeneous total content

For a total of

	Pt	**Pd**	**Rh**
Δ PGM %	**+ 20% ***	**-18,48 %**	**-37,5%**

* *The Pt variation is computed on total homogeneous PGM content base*

Table 20 – Relative PGM variation with respect homogeneous coated catalyst

As said, we can notice an overall 18,48% grams Pd quantity decrease with respect previous homogeneous solution. The Palladium decrease is counteracted by Pt introduction (whose price became now the lower among the three PGMs for catalyst usage), but the big difference should be made by Rh content decrease (whose price is the higher among the three autocatalyst PGMs). Obviously, the consequence of PGM load redefinition is the change of economical voice of PGM price of the catalyst. It could be accounted by multiplying each precious metal price by respective quantity present in the catalyst washcoat composition coated in the substrate. We must refer to PGM price list. As anticipated in the discussion relative to PGM market prices, OEMs and/or coater suppliers are usual to purchase PGMs by periodic (monthly o yearly etc.) contracts. Often, they make stocks, which made difficult to properly calculate demand by automotive sector while trying to report PGM market. However, the interesting effect is that we could keep consider for an amount of time a fixed PGM price for each of the three metals, or we can consider the supplier temporary offer value of the PGM. The last cannot be clearly showed for confidentiality. In next steps business case scenarios evaluating evolution of PGM forecast in next years for the cost reduction activity and their economical effect will be later discussed. For the moment, to consider properly the PGM market for homogeneous and zone coating comparison related to 2022 (actual) prices we could refer to *Johnson Matthey* website indications between 1st January 2022 and 1st September 2022. In that period the price trend is as follow:

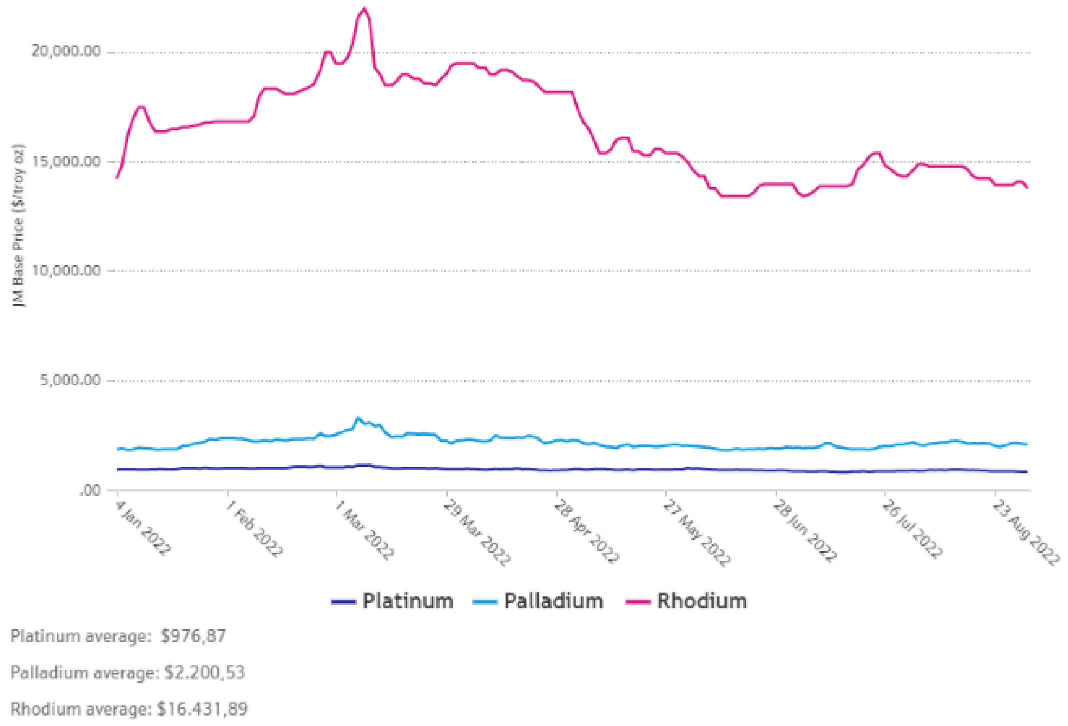


Figure 176 – Pt/Pd/Rh price trend over 1/01 ÷ 1/09 of 2022 [from *matthey.com*]

The averaged values are showed in the figure in $/troy oz (per each troy ounce $979,87 for Pt, $2.200,53 for Pd and $16.431,89 for Rh. We do remember that one troy oz is equivalent to 31,1034768 grams. In the same temporal length, the change US dollars ($) with euro (€) stated between around 1,14 (1,14€ for 1$) and 0,99 (0,99€ for 1$) with an evident decreasing trend of euro value with respect dollar from August 2022 [*yahoo finance*]. We can take an average of 1,0735€ for 1$. Translating and rounding, it is a price trio of:

Pt	**Pd**	**Rh**
31 €/g	**70€/g**	**528 €/g**

Table 21 – Computed PGM value for economic analysis

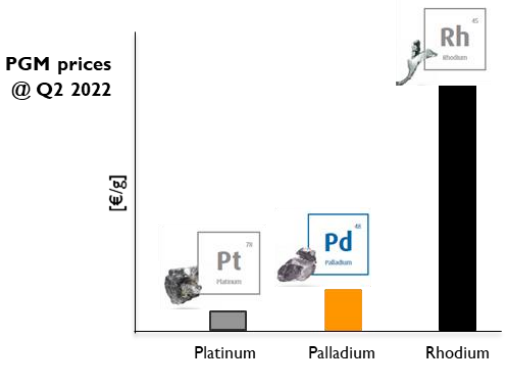


Figure 177 - PGM prices computed in 2022 for economic analysis

It is so trivial to understand that the price delta (difference) due to PGM load difference between the two solutions (homogeneous and zoned) is the difference between each solution PGM price herewith computed:

$$Pt_{HOMOGENEOUS}\,[€/pc] = COST_{Pt}\,[€/g] \times QUANTITY_{Pt\ HOMOGENEOUS}[g]$$

$$Pd_{HOMOGENEOUS}\,[€/pc] = COST_{Pd}\,[€/g] \times QUANTITY_{Pd\ HOMOGENEOUS}[g]$$

$$Rh_{HOMOGENEOUS}\,[€/pc] = COST_{Rh}\,[€/g] \times QUANTITY_{Rh\ HOMOGENEOUS}[g]$$

$$PGM(TOT)_{HOMOGENEOUS} = Pt_{HOMOGENEOUS} + Pd_{HOMOGENEOUS} + Rh_{HOMOGENEOUS}$$

The value of Pt cost for the homogeneous catalyst will be obviously nihil. At the same manner for the zone coated TWC:

$$Pt_{zone\ coated}[€/pc] = COST_{Pt}\,[€/g] \times QUANTITY_{Pt\ zone\ coated}[g]$$

$$Pd_{zone\ coated}\,[€/pc] = COST_{Pd}\,[€/g] \times QUANTITY_{Pd\ zone\ coated}[g]$$

$$Rh_{zone\ coated}\,[€/pc] = COST_{Rh}\,[€/g] \times QUANTITY_{Rh\ zone\ coted}[g]$$

$$PGM(TOT)_{zone\ coated} = Pt_{zone\ coated} + Pd_{zone\ coated} + Rh_{zone\ coated}$$

For the zone coated data has been calculated by considering the sum of each zone:

		Pt €/pc	**Pd €/pc**	**Rh €/pc**	**Total PGM €/pc**
ZONE COATED E2	Front	**-**	Pd_{front}	Rh_{front}	$\sum front$
	Rear	Pt_{rear}	-	Rh_{rear}	$\sum rear$
	Total	$Pt_{zone\ coated}$	$Pd_{zone\ coated}$	$Rh_{zone\ coated}$	$\sum Pt + Pd + Rh$

Table 22 – Zone coated total PGM cost computation

Consequently, the difference of PGM costs between homogeneous and zone coated catalyst will be:

$$\Delta_{PGM} = PGM(TOT)_{HOMOGENEOUS} - PGM(TOT)_{zone\ coated} = \mathbf{1480\ €}$$

For each catalyst the decrease of cost is around 1.480,00€. To get a percentage view, we got a cut that can be estimated around of 18-22% of the total PGM costs for an average catalyst piece of this kind (of dimensions and specifications similar to engine case of study). It is a substantial saving. It is a good result considering the fact that total PGM load in term of total mass and density is actual the same (although some solutions with alternative less loads could be explored, as said in chapter 6) but we have a total 37% of Rh quantity decrease for the zone coated catalyst with respect to the homogeneous one. The Rh decrease accounts for a big portion of the total PGM costs decrease.

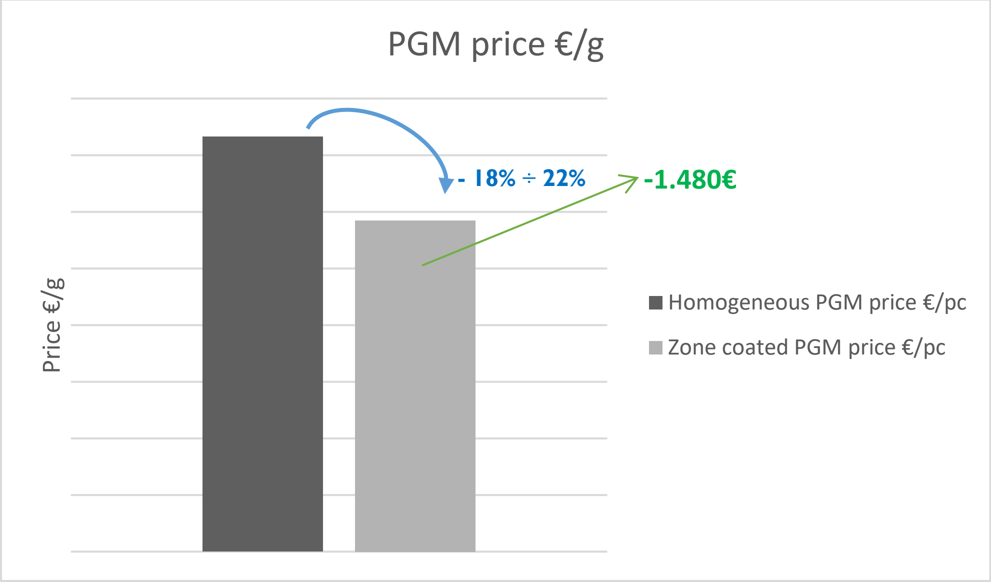


Figure 178 – PGM price difference between homogeneous and zone coated catalyst

Also, the massive (-18,48%) Pd decrease accounts for valuable save for each catalyst piece. However, the overall saving is counteracted by Pt introduction in rear axial zone of the catalyst. Still, with the total mass balancing, the operation remains of advantage because of relative cost differences between Pt, Pd and Rh. Pt introduction is the relative highest mass change, but with an impact limited to around -25% of the total PGM saving. The reason is that in recent years Pt became the cheapest precious metal among PGMs, and its price is around 31 €/g in our economic consideration (that could slight differ in values with respect to values in the offer between supplier and FPT Industrial for a certain amount of time). This last is the reason for which, after many years of gasoline TWC embedding bimetallic Pd/Rh solution, now the trend is toward the already seen Platinum-for-Palladium substitution, getting similar chemical reduction performances.

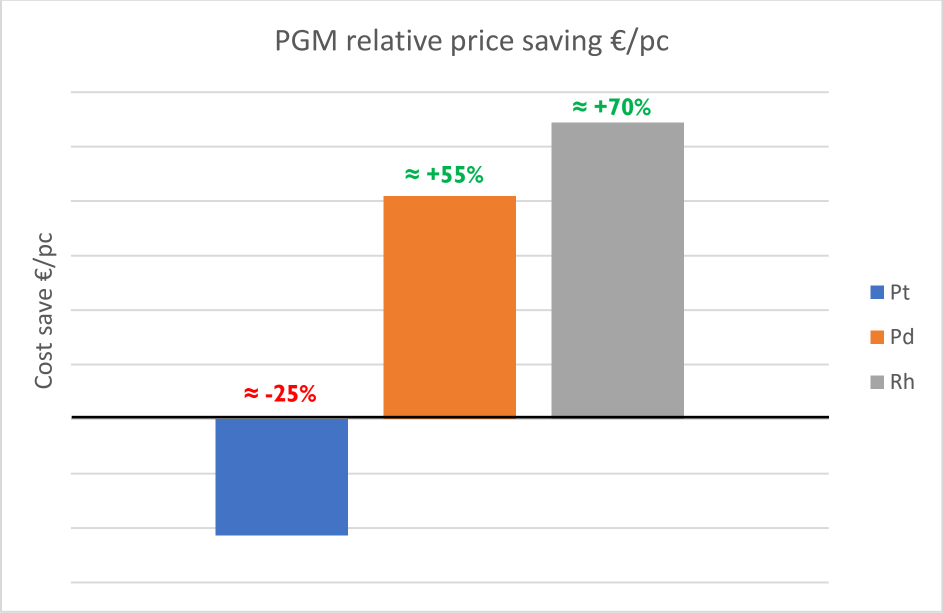


Figure 179 – PGM relative price saving for each precious metal

9.3 Impact of zone coating: TWC price delta with respect homogeneous Euro VI E1

We have seen the price difference of the PGM loading for the zone coating, with respect the previous homogeneous solution. However, the price of the precious metals endowing three-way catalyst is just a voice among others, to form final coated TWC unit price. Being the PGM considered for a 2022-like picture, also the TWC unit price here calculated will be aligned at this time frame. Enlisting it has been considered:

- Substrate price (€/pc) from Tier 3 supplier - S
- Handling Charge for Substrate purchasing to recognise at Tier 2 supplier (€/pc or %) - HC_{S}
- Total PGM value (€/pc) - PGM
- Handling Charge for PGM purchase by Tier 2 (€/pc or %) – HC_{PGM}
- Coating Fee to recognise at Tier 2 coater supplier (€/pc) - CF

Moreover, we should consider that to get the final muffler form we need canning, and so

- Handling Charge to recognise at Tier 1 canner to purchase the coated TWC substrate from coater (€/pc or %) - HC_{TWC}
- Canning unit price to recognise at canner Tier 1 (€/pc) - CAN

However, the two solutions are different in canning, because the canned element of Euro VI E2 version also embeds a bare CPF. Being its nature bare, FPT Industrial Purchasing team agreed with suppliers that is not necessary to ship the part (bared substrate) from production at Tier 3 supplier to coater (Tier 2) and then canner (Tier 1). A direct shipping to canner is instead preferred. In this way FPT Industrial, as client, must guarantee to canner additional:

- CPF unit price (€/pc) - CPF
- Handling Charge of CPF for CPF purchasing, of the same % of TWC – HC_{CPF}

Apart from the trivial unit prices, it could be helpful to analyse other voices. Handling Charges are fees that Tier *n* suppliers ask for purchasing items from Tier *n+1* sub-suppliers. Notice that are not always present, but just in case like in a ATS system in which FPT Industrial control, co-design, select and choice all stream of suppliers, from the one that produce and trade the complete final system (the so-called Tier 1, canner in our case) till the one that trades the basic elements (Tier 3 making substrates). However, the price is recognised once and just to the canner company. The stream is then accomplished by canner paying for coated elements (ready to be then canned) at the coater and coater itself buying substrates. The demand is however driven by FPT Industrial according to its needs (obviously within contract terms). Quotations and offers are obviously shared on volumes basis. Handling Charges (HC) must so be considered in each purchase flow passage, and account about few percentages of the item being bought. The reasons why suppliers ask them and oblige to recognise them is that buying batch of components require financial effort, could represent a financial risk and may represent a logistics problem. About logistics, Incoterms are shared between companies and are included in these prices. The coating fee is instead the fee due to manufacturing washcoating process that coater perform on virgin (or bared) substrate. These redundant voices someway explain how prices and complexity grow by adding more elements in after-treatment systems. The problem is whenever we want to get a direct comparison between the two final values of solutions, it is impossible to do it because of the CPF voices presence for Euro VI E2. Moreover, the zone coating program implementation gave right to re-discuss Handling Charges and canning unit price, opening the discussion to other canner suppliers. It would be all considered later, but for the moment the impossibility to make the direct comparison between homogeneous and zone coated solution made mandatory to cut-off voices related to canning. It could be also interesting to have a passage of comparisons dedicated to the coated three-way only. Thereby, the formula used to compute the TWC unit price is:

$$TWC = S + HC_S + PGM + HC_{PGM} + CF$$

In an eye-sight scheme is as below, we can see the items flow:

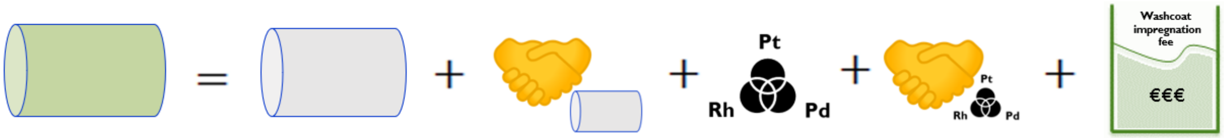


Figure 180 – Three-way catalyst unit price economic contributions illustration

If the Healing Charges are considered as % of relative item purchasing, the formula become:

$$TWC = S + (S * HC_{S\%}) + PGM + (PGM * HC_{PGM\%}) + CF$$

As consequence, we could strike a comparison of TWC unit price (at Tier 2 output and ready to be canned, paid by canner Tier 1 and then worked). The comparison was monitored in time by the Purchasing team as indicator in relation of different offers and engineering activities. It is a key indicator as the TWC unit price will influence final ATS muffler cost (also via Tier 1 HC costs). The main three temporal versions of the TWC evaluated in this work are enlisted as:

- Architecture concept – Sensitivity of 2021
- Definitive offer from coater supplier – June 2022
- Closure of the economic negotiations – September 2022

All of them were for sure compared with the homogeneous three-way, but the evolution of cost voices and final prices were taken under control. Starting with sensitivity activity with supplier, with gave a first price indication analysis, the architecture concept analysis computations:

- **Homogeneous case**

By substituting the PGM value previously computed:

$$TWC_{HOMOGENEOUS} = S + HC_S + PGM(TOT)_{HOMOGENEOUS} + HC_{PGM} + CF$$

For the zone coated case also we implement the computational structure:

- **Zone coated Concept 2021**

	Pt (g)	**Pd (g)**	**Rh (g)**	**CF % increase**
Front	-	-18,48%	-37,5%	+30%
Rear	+20%*	-		
** The Pt variation is computed on total homogeneous Pt content base*				

Table 23 – *zone coated sensitivity levels*

$$TWC_{ZC-SENSITIVITY} = S + HC_S + PGM(TOT)_{zone\ coated} + HC_{PGM} + CF$$

$$\Delta_{TWC} = TWC_{HOMOGENEOUS} - TWC_{zone\ coated} = \mathbf{1500\ €}$$

We got a first analysis on final TWC unit price cut of about 1.500€. It is a big save, again aligned about 18% ÷ 22% of the total estimated initial TWC unit cost for a coated three-way in this category. The costs were calculated considering:

- S (Substrate unit price) agreed with supplier selected for substrate production
- HC_S (% on substrate price to add)
- PGM – PGM costs that coater face
- HC_{PGM} – (% on PGM costs to add)
- CF – Coating fees for coating process to recognise ad coater, including in Tier 2 offer

For sensitive and confidentiality reasons the prices of these voices could not be showed but statistically treated, over which some considerations could be done. It is important to notice that

➔ Both HC voices remain equal for the two configurations respectively
➔ Substrate unit price remains the same for both
➔ CF changes due to coating process change

Commercially, HC percentage costs can go from 2,5% to not more than 4,5%. Three-way Substrate unit price in these cases account for really low values with respect TWC unit price. We could see that almost all delta of the TWC unit price (98,7% of it) is guaranteed by PGM cost reduction (mainly due to Rh content decrease and Platinum-for-Palladium substitution). In evaluating the new zone coated TWC unit price feasibility all information were considered. Being the cost fixed by technical specifications (PGM) or shared between the two E1 homogeneous and zoned E2 (various HC and Substrate price) the negotiation and evaluation activities focused on Coating Fee request. Coating Fee voices could vary a lot. Coating Fee could seem not influent because of the large PGM reduction delta quota within the total TWC unit delta. However, it could be quite influent on TWC unit price, and it should be remembered that on top of TWC unit price there are canning costs. Moreover, all of that will be projected on all volumes of the ATS to be build. As anticipated, being in a new project, with another manufacturing process, the implementation of zone coating gave right to Coating Fee re-discussion. For the first architecture concept sensitivity, the selected coater supplier hypothesized a “safety” adder of +30% on top of the prices for the homogeneous Coating Fee. It was done because of the projected increase of washcoating complexity (explained in chapter 6) but also because of still (at time) no precise indication from supplier R&D and Industrialization Teams. So, we could update last voice as:

➔ $CF_{Zone\_Coated} = +30\%$ of $CF_{Homogeneous}$

It is a substantial increase. Still, even if there is this increase, the final TWC unit price cut of 1.500€ between the two solution is higher with respect the consideration of the PGM cost difference alone (1.480€), with last voice representing almost all cost decrease as said. The reason is simple, and it is in HC influence on top of the PGM costs. Less PGM costs will lead to less HC related costs. A large PGM cost decrease also enhance a sensible HC_{PGM} cost decrease. The saving will overcome the net Coating Fee increase, and so the total cost saving remains higher. This shows how could be important also to negotiate low HC percentages together with net savings. Once project milestones went ahead, the precise PGM formulation was then refine and the new discussed offer have seen an update in coating fee.

ZONE COATED. JUNE 2022 - like scenario

	Pt (g)	Pd (g)	Rh (g)	CF % increase
Front	-	-18,48%	-37,5%	+69,23%
Rear	+20%*	-		

* *The Pt variation is computed on total homogeneous PGM content base*

Table 24 – ***zone coated 2022 economic scenario***

The update is quite far from first indications given by supplier and sensitivity analysis taken out the year before. A further increase of Coating Fee voice was registered for a total 69,23% coating fee increase with respect homogeneous case.

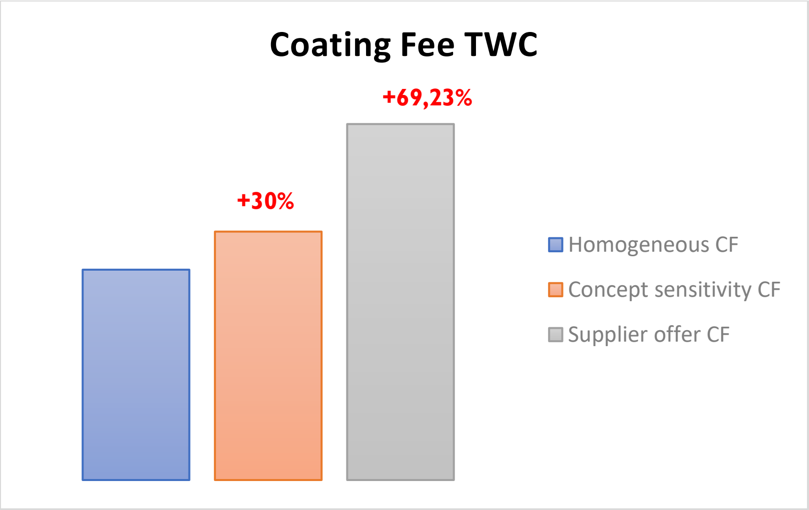


Figure 181 – Coating Fee increase over time

As said in previous chapters, for zone coating solution the process of coating situation is different, with the necessity to have more coating passages but also partial dipping of the substrate, with respect the right axial zoned coating ratio. Total of four zones of coating process are embedded, while homogeneous process is based on two uniform coating steps only: the new technology is doubling set-up and the process times. Moreover, each coating step needs in fact a careful set up of the coating unit. The complexity will also impact on energetic and time point of view considerations. In the zone coating process scheme we have:

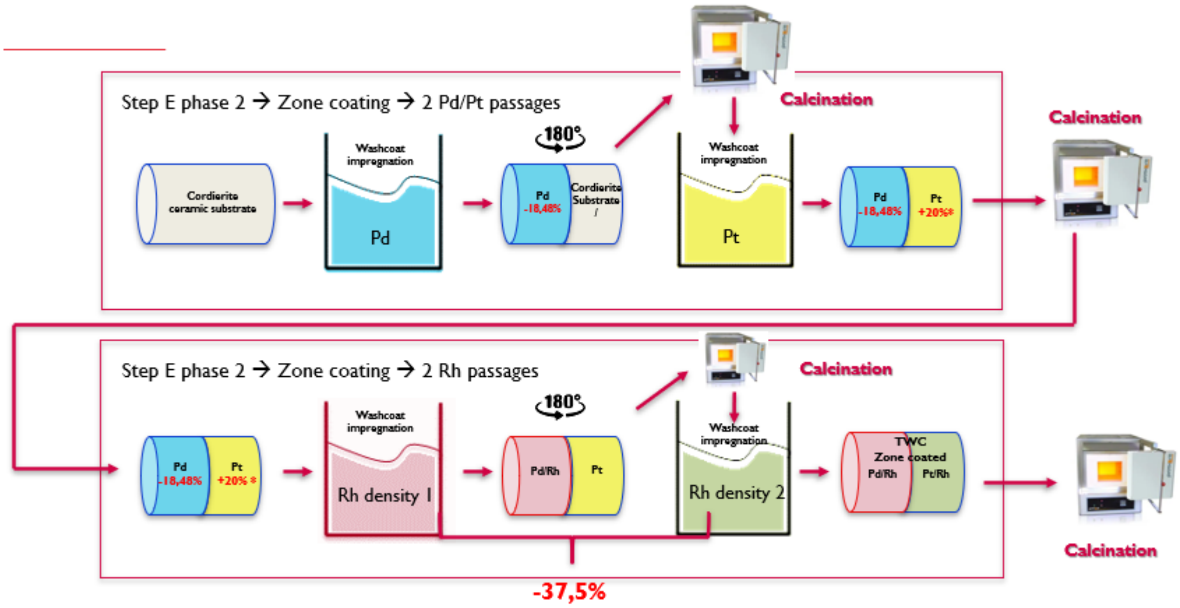


Figure 182 – Coating Manufacturing process illustration overview

The Coating Fee offer quotation was quite concerning in Purchasing team because it could erode the advantages taken out from zone coating program. FPT Industrial and supplier were aware of processing complexities in initial evaluation phases, but the actual scenario of shortages, raw material cost increases, transport cost increases and energy cost increases needed a deeper analysis. For these reasons, within the Purchasing team it was decided to ask to supplier to a quotation breakdown. Asking for quotation breakdown is something that it is often done at negotiation table, although suppliers could retain some confidentialities. According to the supplier:

	CF (€/pc)				**Process cost increase (including energy)**	**Material cost increase**	**Transport cost increase**
	Current homogeneous (A)	**Sensitivity (B)**	**Quotation (C)**	**Δ (C-B)**	**% of Δ**	**% of Δ**	**% of Δ**
ENGINE case study	X	A + 30%	A + 69,23%	**- %**	**82,47%**	**16,35%**	**1,18%**

Table 25 – Coating Fee percentage breakdown

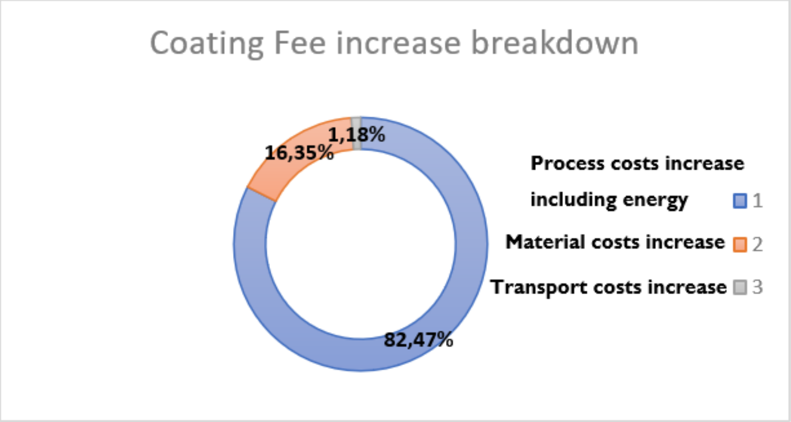


Figure 183 – Coating Fee increase breakdown

We can notice how process impacts almost on all increase of Coating fee, with marginal material costs effect and a tiny part related to transport. We further asked to try to quantify energy costs weight and split the voice from process one. What we got is an indication of energy share within process increase considerations, in which energy general cost increase is furthermore based on 70% Electricity and 30% Gas split at that time (June 2022). The breakdown analysis was the basis for the subsequent economical discussion both in internal (platform) and with supplier, they were basically the base on to which start the negotiations with suppliers. We can notice how energy quota data alone and unbundled from process gives a 13% contribute to the previous overall process including energy increase effect.

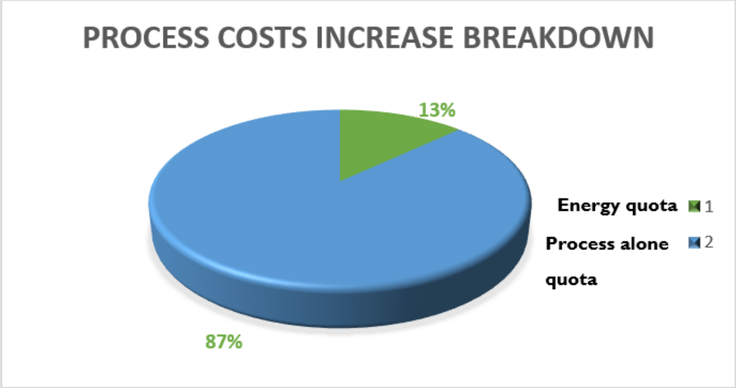


Figure 184 – Process costs increase breakdown

While proceeding with alpha and beta phase of the project, the contacts with Tier 2 coating supplier continued. They brought to the definition of some costs, for which some values cannot be show for confidentiality reasons. By substituting the already seen PGM market trend estimation we got a situation a little bit different. By indicating the Coating Fee increase with CF_{2022} we shall compute the consequent TWC unit price with the same previous formula, the result is herewith indicated as TWC_{2022}

$$TWC_{2022} = S + HC_S + PGM(TOT)_{zone\ coated} + HC_{PGM} + CF_{2022}$$

The difference with respect the homogeneous case will so be

$$\Delta_{TWC_{2022}} = TWC_{HOMOGENEOUS} - TWC_{2022} = \mathbf{1380€}$$

As we can see from the final catalyst price, the delta of 1.380€ is less with respect the previous value. The difference is due to the CF increase, so it is a process problem. Discussions and computations of its effect occurred in platform, as well as breakdown request to supplier and negotiation. The negotiation with the supplier usually bring to the final agreement. The values agreed will be launched and/or kicked-off with supplier launch management letter once the CRF passes the 100 and 120 states, and Advance Purchasing will send the above cited letter. It is the duty of the team within which this study has been conducted. In the final scenario after negotiation:

ZONE COATED. FINAL SEPTEMBER 2022 - like scenario

	Pt (g)	Pd (g)	Rh (g)	CF % increase
Front	-	-18,48%	-37,5%	< 69,23%
Rear	+20%*	-		

** The Pt variation is computed on total homogeneous Pt content base*

Table 26 – *final zone coated 2022 economic scenario*

The PGM values are obviously the same, but the Coating Fee passed from an increase of 69,23% with respect homogeneous CF to a slight less value, thanks to negotiations activities. Considering that in our cost reduction program the engine case in study is forecasted to be built for a certain number of annual volume, the saving thanks to negotiation may have an impact on yearly base. For the moment it could be helpful to see how the final-like values (after negotiation) impacts on final catalyst unit price that coating supplier address and that FPT Industrial will pay adding canner Handling Charges. Indicating the new Coating Fee value as CF_{FINAL}

$$TWC_{FINAL} = S + HC_S + PGM(TOT)_{zone\ coated} + HC_{PGM} + CF_{FINAL}$$

The difference with respect the homogeneous case will change toward:

$$\Delta_{TWC_{FINAL}} = TWC_{HOMOGENEOUS} - TWC_{FINAL} = \mathbf{1395\ €}$$

As it is understood, PGM price and its delta is not affected, but just the final TWC unit price for which Coating Fee has effective influence. The final saving is less than one obtained for the saving related to PGM expenses only because of Coating Fees increase. The Handling Charges savings on PGM are not enough to overcome this increase, even with the negotiation. The range of savings on TWC unit prices fell to 16% ÷ 20%.

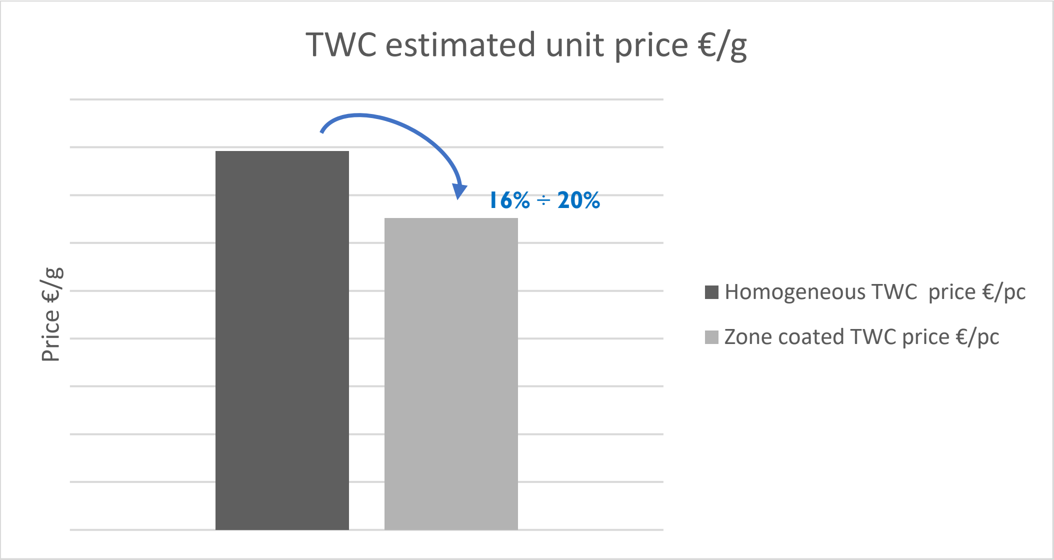


Figure 185 – TWC unit difference costs

9.4 Economics Implementation of zone coating: Impact of CPF presence in Euro VI E2 and final Muffler unit cost delta

As anticipated, the direct comparison of muffler final costs cannot be performed without considering the implementation of Gasoline Particulate Filter due to new Euro VI step E2 regulations. In chapter 6 it has been discussed the CPF implementation, with a bare substrate. It is the realisation of the new catalyst concept (Zone coating) and CPF bare. Figure 186 resumes European heavy-duty legislation trend and consequent hardware implementations:

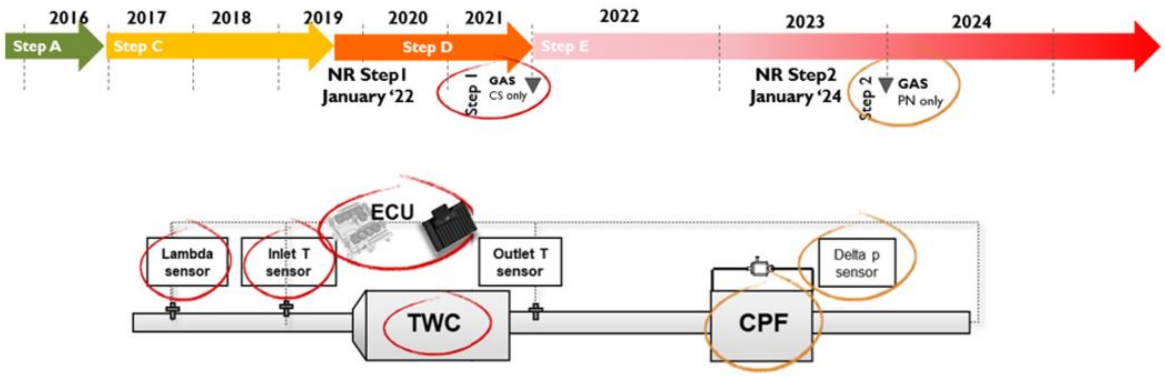


Figure 186 – Euro VI E2 architecture implementation

In red the implementations present in step E1 of Euro VI and in yellow the ones brought by step E2. With the:

- Handling Charge to recognise at Tier 1 canner to purchase the coated TWC substrate from coater (€/pc or %) - HC_{TWC}
- Canning unit price to recognise at canner Tier 1 (€/pc) - *CAN*

The full formula for Euro VI E1 becomes

$$MUFFLER_{E1} = TWC + HC_{TWC} + CAN$$

And recap final costs at Tier 1. In schematic view:

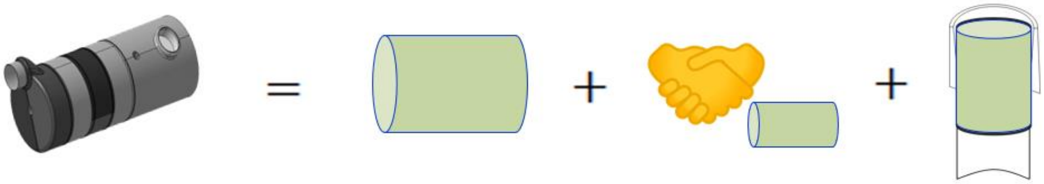


Figure 187 - Three-way catalyst muffler unit price economic contributions illustration

And substituting coated three-way unit price flow:

$$MUFFLER_{E1} = S + HC_S + PGM + HC_{PGM} + CF + HC_{TWC} + CAN$$

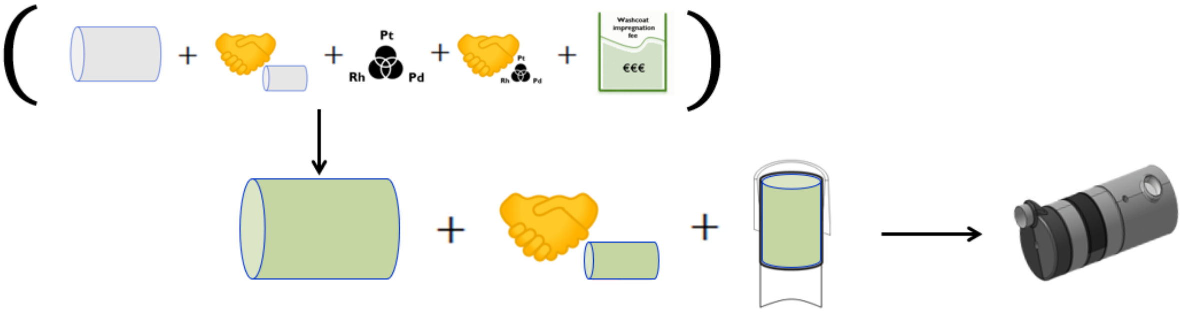


Figure 188 - Three-way catalyst substrate and complete muffler unit price economic contributions illustration

While for Step E2 we got the presence of CPF, so it would become:

$$MUFFLER_{E2} = (TWC + CPF) + HC_{(TWC+CPF)} + CAN$$

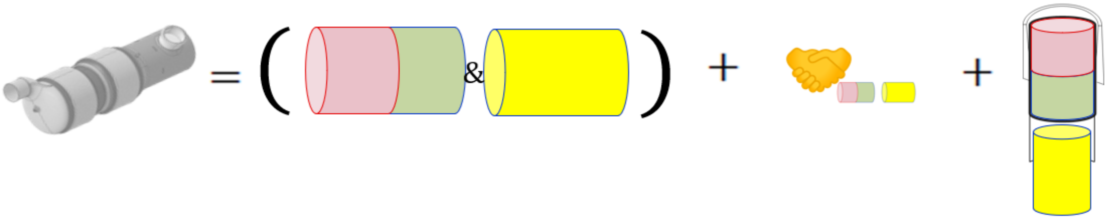


Figure 189 - Muffler unit price economic contributions illustration for step E2 mufflers

Or:

$$MUFFLER_{E2} = [\,(S + HC_S + PGM + HC_{PGM} + CF) + CPF] + HC_{(TWC+CPF)} + CAN$$

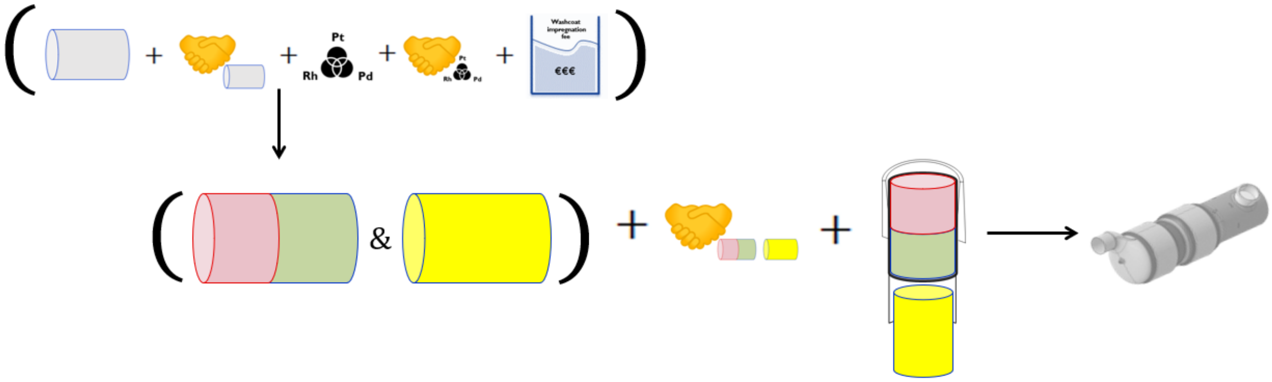


Figure 190 - Substrate and complete muffler unit price economic contributions illustration for step E2 mufflers

Notice the difference of streams for the coated three-way versus the un-coated (bare) CPF. Moreover, it must be considered that with the passage from step E1 to step E2 FPT Industrial decided to open a sourcing selecting procedure for the selection of supplier that trades canning elements. It is so changed, changing consequently the HC values and the canning unit price. For reasons of confidentiality names and values cannot be showed, but indications of final mufflers unit values will be compared for these PGM values. We can for sure say that with new supplier a big saving will be earn for what regard:

- Handling Charge of the new TWC + CPF unit $HC_{(TWC+CPF)}$ with respect the percentage of Healing Charge given to previous canning supplier for TWC only
- Canning unit price (reduction although a more complex canning due to CPF presence) CAN'

The change of Tier 1 supplier can be considered as part of a sort of cost reduction activity parallel to the zone coating concept implementation. The two united will form a substantial saving on yearly basis. Based on these assumptions, we can compute:

1. **Muffler Step E1 unit price indication – Homogeneous case**

$$MUFFLER_{E1} = TWC_{HOMOGENEOUS} + HC_{TWC} + CAN$$

At the same manner:

2. **Muffler Step E2 unit price indication – Zone coated case**

$$MUFFLER_{E2} = (TWC_{FINAL} + CPF) + HC_{(TWC+CPF)} + CAN'$$

So the differences with previous case are:

$$\Delta_{MUFFLER} = \ MUFFLER_{E1} - \ MUFFLER_{E2} = \mathbf{2425\ €}$$

In the previous formula it was accounted:

$$\Delta_{CAN} = \ CAN - \ CAN' = \mathbf{1140€}$$

And below we can report:

	Δ TWC only (€/pc)	**Δ at Tier 1 (TWC coated + CPF)**	**Δ Handling Charge Tier 1: E1 supplier vs E2 supplier (€/pc)**	**Δ Canning Tier 1: E1 supplier vs E2 supplier (€/pc)**	**Δ Muffler step E2 vs E1 (€/pc)**
Euro VI E2 – CNG – ENGINE CASE STUDY	**-1395€/pc**	HIDDEN	HIDDEN	**-1140 €/pc**	**-2425 €/pc**

Table 27 – ***Delta Muffler price and contributions across it***

So, considering the final muffler overall package, Euro VI E2 vs Euro VI E1 costs comparison with these specifications would have a final saving of € 2.425 per each ATS unit! The gain obtained with zone coating implementation, including manufacturing process complexity influencing Coating Fee increase, is contributing for more than half of the total final muffler saving (1.395 € of 2.425€). Notice that new Tier 1 supplier have to pay for the TWC coated unit price (whose delta between homogeneous and zone coated solutions have been explicated in previous chapter) and the CPF, that being bare comes directly from Tier 3 supplier. So, to the difference of the two TWC unit price of the solutions in comparison, we have to add CPF unit price (without the need of any coating process cost). The difference at Tier 1 of the two solutions have so to include the CPF cost. The delta will be so lower, but here it is hidden to not let understand CPF price and commercial agreement between FPT Industrial and CPF Tier 3 supplier, and protect so their confidentiality. The same has been done for Handling Charges (both in value and/or percentage) and Canning unit prices. Only deltas have been computed (either in value or percentage)

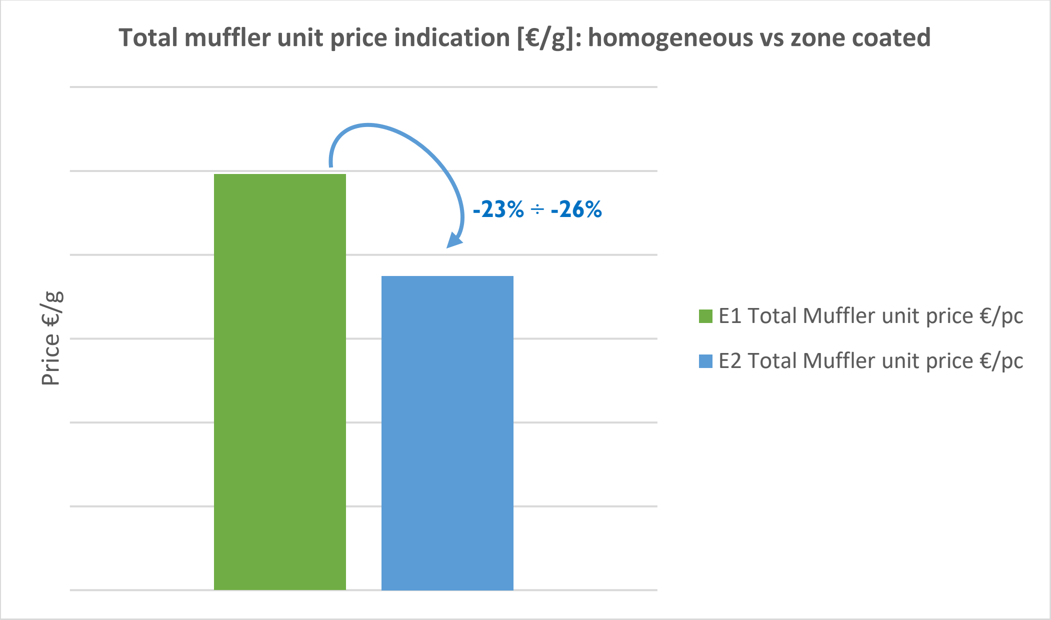


Figure 191 – Price indications of total muffler for homogeneous E1 and zone coated E2

9.5 Economical analysis of zone coating

Now that we computed the indication on muffler price difference between new Euro VI E2 muffler implementation and actual homogeneous step E1 case, it could be interesting to consider impact of the CPF implementation and all set of data regarding the change of the Tier 1 supplier, we can at least try to separate these data by not considering them in order to understand what is the real impact of zone coating implementation for a balanced situation, with all boundaries conditions at the same levels. We would re-consider the previous computations within a hypothetical situation without:

- Supplier change (with its savings on Canning unit price and change of Handling Charges)
- CPF implementation

All of that will be done in order to catch-out which could be the *theoretical* final impact of a zone coating implementation technology like the one presented here, considering an even situation for what regard Tier 1 costs, and so final costs. If we remember in chapter 8.3 we compared the homogeneous and zone coated TWC unit price (that Tier 1 pays at Tier 2) in two similar scenarios, with all the boundaries at the same values (except the Coating Fee due to coating change). To repeat the same operation for muffler comparison, we should consider Tier 1 level costs. We did it in last chapter by seeing the indications of the E2 architecture price difference with respect actual E1. But to properly compare a zone coated muffler with respect a homogeneous one, and so have a theoretical situation of even Tier 1 costs for homogeneous and zone coated, we consider:

- Ideal case of no CPF implementation & same HC percentage and Canning fees as previous Tier 1 supplier

The number that will be exploited will be then useful on volume base computations. Notice that the previous passages were however very good to evaluate activity done in FPT Industrial during the implementation of these cost reductions. So, showing ideal case indications:

3. Muffler without CPF implementation and Tier 1 change

Description	**TWC unit price (€/pc)**	**CPF unit price (€/pc)**	**Total unit price (TWC + no CPF)**	**Handling Charge ex-Tier 1 supplier (€/pc)**	**Canning unit price Ex-Tier1 (€/pc)**	**Total Muffler unit price (€/pc)**
Euro VI E2 – CNG – ENGINE X CASE STUDY	$\mathbf{TWC_{FINAL}}$	**0,00€**	$\mathbf{TWC_{FINAL}}$	$HC_{(TWC+\cancel{CPF})}$	CAN′ = CAN	$\mathbf{MUFFLER_{E2'}}$

Table 28 – ***Muffler price and its contributions without CPF adding and Canning fee change***

In this way the formula becomes:

$$MUFFLER_{E2'} = (TWC_{FINAL} + CPF) + HC_{(TWC+\cancel{CPF})} + CAN$$

Now we can evaluate the deltas in this theoretical ideal situation for which no price differences are present in relation of canning fee and handling charge percentage change due to the change of supplier. In the following table we can thus find the values:

	Δ TWC only (€/pc)	**Δ at Tier 1 (TWC coated + no CPF)**	**Δ Handling Charge at Tier 1 (€/pc)**	**Δ Canning at Tier 1 (€/pc)**	**Δ Muffler zone coated vs homogeneous (€/pc)**
Euro VI E2 – CNG - ENGINE X CASE STUDY	-1395€/pc	-1395 €/pc	-40 €/pc	**-0,00€/pc**	**-1435 €/pc**

Table 29 – ***Delta on Muffler and its contributions without CPF adding and Canning fee change***

With

$$\Delta_{MUFFLER}{}' = MUFFLER_{E1} - MUFFLER_{E2'} = \mathbf{1435\ €}$$

Notice here how the delta in canning is obviously nihil, but we got a small difference in Handling Charge due to saving in coated TWC unit cost at Tier 1, as happened before for PGM Handling Charges. We got the proper unit muffler saving due to zone coating, it is almost the same of the TWC unit saving. We said that on general TWC unit base, the zone coating saving was about the from 16% to 20%. The net saving on total muffler cost due to zone coating impacting only could be instead from 10% to 15% for a typical muffler of these dimensions. Notice how it is less with respect the saving reached in real FPT Industrial step E2 program implementation case. We could strike how big is the impact also of the Tier 1 supplier change, along with the zone coating, adding a further 10% save although the presence of the CPF.

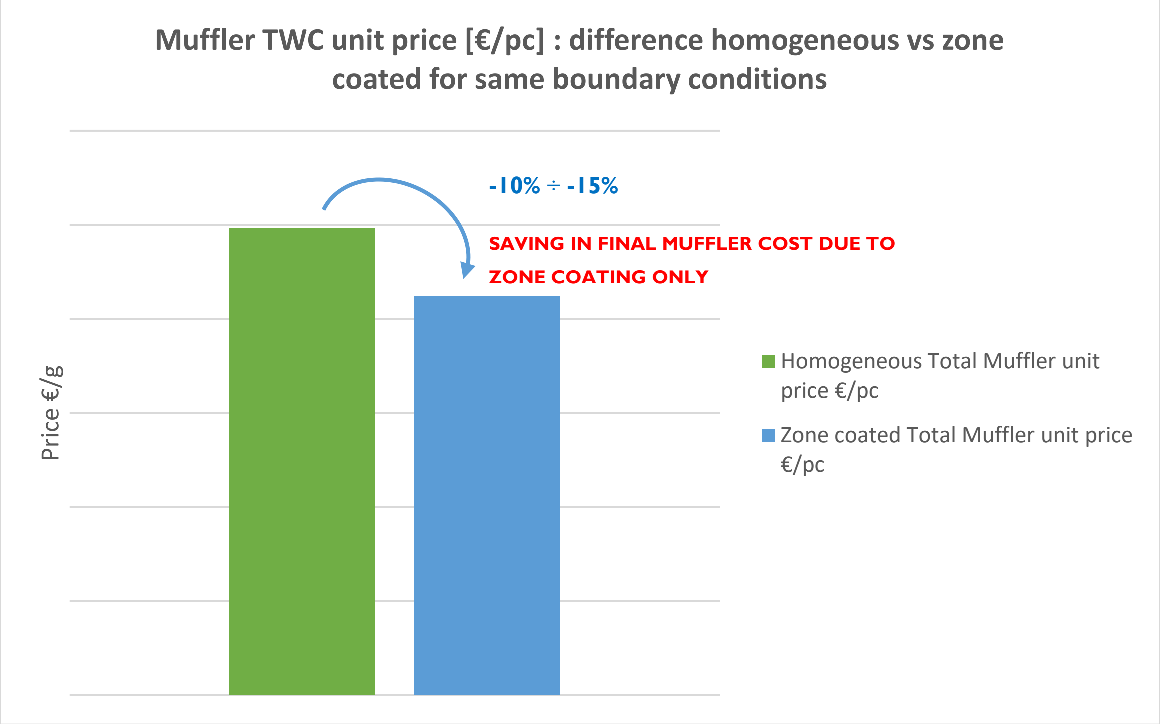
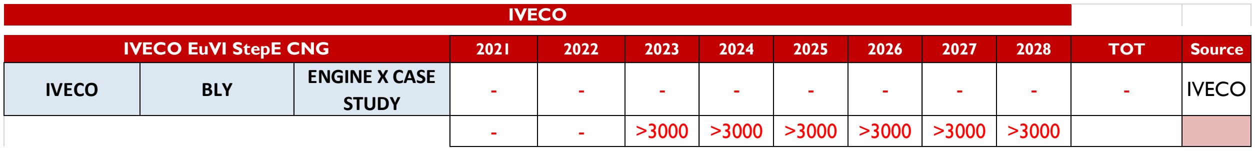


Figure 192 – Muffler unit price : difference homogeneous vs zone coated for same boundary conditions

In following, all the three cases will be considered with Annual Product per Volume (APV) costs, getting so a business case on yearly basis computation.

9.5.1 Economical analysis of zone coating: the Annual Product Volume impact

The following computations will indications based on hypothesized data but by showing the how forecasts are organised by FPT Industrial inter-functionals Platforms. Forecasts are made for each engine, both for Captive (Iveco) and Non-Captive (external customers) and for each engine family and typology (CNG or Diesel). What we are going to study is the one related to CNG Euro VI step E (from E1 → E2) applications for the engine in case of study. Forecasts are made on last year demand trend, new products ramp-up, customers request and survey activities. The volumes forecast are handled by Sales platform of the company.

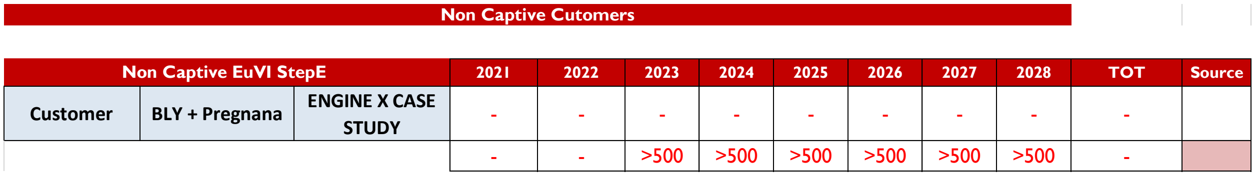


IVECO

IVECO EuVI StepE CNG			2021	2022	2023	2024	2025	2026	2027	2028	TOT	Source
IVECO	BLY	ENGINE X CASE STUDY	-	-	-	-	-	-	-	-	-	IVECO
			-	-	>3000	>3000	>3000	>3000	>3000	>3000		

Figure 193 – Yearly volumes forecast scheme layout

After a ramp-up period, demand is forecasted to stabilize with data projecting within 2028. For confidentiality reasons data accounted in the following economic analysis will be **not the actual forecasts** made by Sales department, but a solution came up within the Purchasing team with which this study was conducted. It was **hypothesized** a 3500 yearly unit demand in total between Non-Captive and Captive customers for the engine case in study. The CNG program in which embed zone coating solution is then completed by other two engine families. The number we came up with is a solution that can be either conservative in some scenario or also optimal. Next years market for CNG engines is in fact going to depend a lot from CNG and energy costs, advance of new technologies and legislations. For what regards Non-Captive Customers, demand will be related to a demand restricted to:

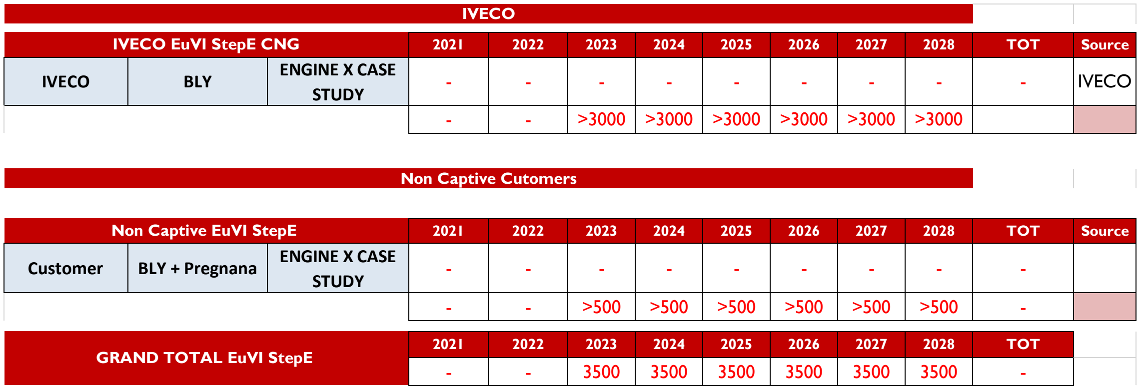


Non Captive Cutomers

Non Captive EuVI StepE			2021	2022	2023	2024	2025	2026	2027	2028	TOT	Source
Customer	BLY + Pregnana	ENGINE X CASE STUDY	-	-	-	-	-	-	-	-	-	
			-	-	>500	>500	>500	>500	>500	>500	-	

Figure 194 – Yearly volumes forecast scheme layout

BLY are the initials for Bourbon-Lancy (a French Iveco factory) and Pregnana stands for Pregnana Milanese (another factory indication). The total indication view in our files, that Purchase team then share with the suppliers during the request for quotation in order to get the offers is like the figure below:



IVECO

IVECO EuVI StepE CNG			2021	2022	2023	2024	2025	2026	2027	2028	TOT	Source
IVECO	BLY	ENGINE X CASE STUDY	-	-	-	-	-	-	-	-	-	IVECO
			-	-	>3000	>3000	>3000	>3000	>3000	>3000		

Non Captive Cutomers

Non Captive EuVI StepE			2021	2022	2023	2024	2025	2026	2027	2028	TOT	Source
Customer	BLY + Pregnana	ENGINE X CASE STUDY	-	-	-	-	-	-	-	-	-	
			-	-	>500	>500	>500	>500	>500	>500	-	

GRAND TOTAL EuVI StepE	2021	2022	2023	2024	2025	2026	2027	2028	TOT
	-	-	3500	3500	3500	3500	3500	3500	-

Figure 195 – Yearly volumes forecast scheme layout

It is interesting to remember that the volumes could be affected from time-to-time to **revision** and adjustments, as they are just a forecast base. The various European crisis- and the momentaneous dimmish of interest toward LPG/CNG applications due to high Methane and energy costs could lead to an adjustment toward lower numbers. Furthermore, the precise trend could change year by year. However, in initial phases it is common to consider an average yearly unit demand. For this reason, it was retained as reasonable to hypothesize and position the forecasted average to **3500 u/y**. We will refer to this averaged Annual Product Volume to compute the yearly saving of zone coating cost reduction program. First, we are going to start from the natural implementation occurring in ATS Platform, with the PGM load ratio change due to the new coating technology application and the change of canning supplier. It is necessary in every-day work to evaluate the effect of the implementation. Then, as it was done in previous chapter, we are going to come out with the zone coating effect only, in a theoretical implementation where the boundary conditions (CPF presence, other costs) are almost the same. It could be less interesting on applicable level, but it is a better kind of reference to understand the magnitude of a zone coating technology impact. The computations of all the gains thanks to the zone coating will be made keeping in mind the differences in each cost voice with respect the actual E1 homogeneous case. So, recapping:

- **Homogeneous case**

$$PGM(TOT)_{HOMOGENEOUS} = Pt_{\,HOMOGENEOUS} + Pd_{\,HOMOGENEOUS} + Rh_{HOMOGENEOUS}$$

$$TWC_{HOMOGENEOUS} = S + HC_S + PGM(TOT)_{HOMOGENEOUS} + HC_{PGM} + CF$$

$$MUFFLER_{E1} = TWC_{HOMOGENEOUS} + HC_{TWC} + CAN$$

- **Zone coated case**

ZONE COATED. FINAL SEPTEMBER 2022 - like scenario

	Pt (g)	Pd (g)	Rh (g)	CF % increase
Front	-	-18,48%	-37,5%	< 69,23%
Rear	+20%*	-		

* *The Pt variation is computed on total homogeneous Pt content base*

Table 30 – ***final zone coated 2022 economic scenario***

Again starting with the PGM costs

$$PGM(TOT)_{zone\ coated} = Pt_{\ zone\ coated} + Pd_{\ zone\ coated} + Rh_{\ zone\ coated}$$

$$\Delta_{PGM} = PGM(TOT)_{HOMOGENEOUS} - PGM(TOT)_{zone\ coated} = \mathbf{1480\ €}$$

$$TWC_{FINAL} = S + HC_S + PGM(TOT)_{\ zone\ coated} + HC_{PGM} + CF_{FINAL}$$

By comparing three-way costs

$$\Delta_{TWC_{FINAL}} = TWC_{HOMOGENEOUS} - TWC_{\ FINAL} = \mathbf{1395\ €}$$

And passing to muffler:

$$MUFFLER_{E2} = (TWC_{FINAL} + CPF) + HC_{(TWC+CPF)} + CAN'$$

The final muffler differences with previous case were reported as:

$$\Delta_{MUFFLER} = MUFFLER_{E1} - MUFFLER_{E2} = \mathbf{2425\ €}$$

Transferring the computations in table

	**Δ TWC only at Tier 1 (€/pc)**	**Δ at Tier 1 (TWC coated + CPF)**	**Δ Handling Charge Tier 1: E1 supplier vs E2 supplier (€/pc)**	**Δ Canning Tier 1: E1 supplier vs E2 supplier (€/pc)**	**Δ Muffler step E2 vs E1 (€/pc)**
	-1.395 €/pc	HIDDEN	HIDDEN	HIDDEN	-2.425 €/pc

Table 31 – ***Delta on Muffler and its contributions***

Now to compute the gain of each main voice related to yearly volumes, it occurs to refer to last row, which explicates delta of main components (TWC unit, Handling Charge change, Canning fee unit change). We got, by multiplications of each value for an average of 3500 u/y:

	TWC ONLY	HANDLING CHARGE	CANNING	TOT
DELTA APV	**≈ -4.885.000 €**	**Hidden**	**Hidden**	**≈ - 8.490.000 €**

Table 32 – ***Indication on economical impact of zone coating program for FPT case study***

From this important result we can tract some first conclusions:

- Even a not punctual and maybe optimum scenario (for 3500 u/y) total gain is consistent for the program implementation, for almost 8 million and a half (8,49 for sake of completeness) € per year!
- A big part of the total gain is given from the Canning cost changes and the relative change of the Handling Charge.
- The share of total yearly savings reflects obviously the share of unit price savings
- The total saving is the sum of the ones from: substrates at Tier 1 (with negative influence of CPF) + Handling Charge savings + Canning
- In 3 years plan it corresponds to a save of **25,47 million €!**
- Between 2023 and 2026, hypothesizing a ramp-up of 1200 u/y for 2023 and 3500 u/y in other years, it corresponds to a save of **28,39 million €!**

Projected in 5 years plan it would be a save of about 42,4 million €. Furthermore, as we did in previous chapter for unit costs, it is necessary to take out the data related to zone coating only. Taking the computations of point 3 of chapter 9.5 (Muffler without CPF implementation and Tier 1 change)

	**Δ TWC only (€/pc)**	**Δ at Tier 1 (TWC coated + no CPF)**	**Δ Handling Charge at Tier 1 (€/pc)**	**Δ Canning at Tier 1 (€/pc)**	**Δ Muffler zone coated vs homogeneous (€/pc)**
	-1.395€/pc	-1.395 €/pc	-40 €/pc	**-0.00€/pc**	**-1.435 €/pc**

Table 33 – ***Delta on Muffler and its contributions without CPF adding and Canning fee change***

Again, once the deltas were extracted, by considering the average yearly volumes we can assume:

	TWC	HANDLING CHARGE	CANNING	**TOTAL ZONE COATING**
DELTA APV	**≈ -4.885.000 €**	**≈ - 145.000 €**	**-0.00 €**	**≈ - 5.000.000 €**

Table 34 – ***Indication on economical impact of this zone coating program for FPT case study without any parallel program and with all boundary conditions***

This, according to our study indications, ideally represents the total overall impact of zone coating with respect the homogeneous case by just implementing the three-way catalyst in same canning. It is a quite big save. Projected in 4 years plan (in a scenario of flat PGM prices for all the years and stopping at the expected beginning of Euro VII, although search must be done to understand whether zone coating can be Euro VII ready) it would be a saving of 20,1 million €!

9.6 Economical analysis of zone coating program in FPT Industrial: the PGM Market trend impact

As it was explained in the chapter related to the PGM and in the current one dedicated to economics, often OEMs or suppliers are used to purchase their precious metals through regular monthly contracts, or at least periodic (could be of some months, headquarters etc.). It has been studied the zone coating technology large adoption as the direct result of PGM market trend shakes. Platinum-for-Palladium substitution for example is the result of recent years Palladium overcome of costs with respect Platinum. Rhodium content decrease is pushed because of its price peaks in recent periods. The zone coating formulation cost reduction program feasibility was studied in 2020 and 2021 period, with proper PGMs price forecasts for the SOP period and following periods, and consequently with proper economics effects. While the project advanced, the forecasts (as happened for the volumes) were properly adjusted based on latest PGM market trends insights. In the previous chapters of the economical analysis, as reported, it has been showed the indicative prices and the how supplier quotation offer and the computations are formulated. Following price adjustments will be due to PGM price adjustments and could impact the magnitude of the project gains and economical evaluations. Notice that although it can be said that the cost reduction activity could be affected by precious metals further changes, in general FPT Industrial studies, insights and sources, as well as the literature, are aligned and clear on fact that it is not likely that PGM prices will return to pre-pandemic (2019) situation. At the contrary we have seen how the situation may evolve in the future. Thereby, it is safe to assume that the activity brings a big cost reduction while passing to the next homologation step. Anticipating it in 2023 is a further saving with respect a case in which the old homogeneous solution is kept till 31st December 2023. In the same way as it was done an Annual Product Volume analysis with the 2022 PGM aligned prices, the present work will try to sketch a list of possible scenarios for different future precious metals costs, till considering a conservative situation, to give reference to the possible magnitude ranges of the technology implementation. It is very important because from the final costs point of view in previous chapters we investigated how the activity runs around the delta of PGM costs. It represents the heart of the cost reduction activity (although it has been associated to Tier 1 change) and it represents the starting reason why the paper is investigating the other E2 architecture cost differences with respect homogeneous E1. We previous weighted the impact of PGM price difference on TWC unit delta price and on overall muffler price difference. For the coated TWC cost at Tier 1 arrival level, PGM cost decrease represent almost all costs savings. Actually, the big PGM costs delta makes the

Handling Charges saves counteract the Coating Fee increase expenses. For what regards the entire muffler in E2 architecture, the PGM saves are more difficult to be accounted because other coating costs on top before arriving at Tier 1. But the 1.480€ PGM cost delta is more than half (60%) of the total muffler unit cost difference (2.425€). So, based on that, in order to compute economic results for different future precious metals costs we will consider a balanced/conservative scenario. The first analysis will be related to a hypothetic situation of PGM price trend over 2023 and 2024. The second one will be stretched over time till 2026. Trend within 2024 only will be initially studied because for the following years they would lose accuracy, PGM prices considered will be reported here below:

- **PGM price trend**

The PGM values herewith reports an increasing PGM price trend

	Pt (€/g)	Pd (€/g)	Rh (€/g)
2022	31	70	528
2023	31	62	650
2024	34	60	700
2025	37	55	800
2026	40	55	800

Table 35 – ***Study PGM price forecast from literature***

Take note that it is indicate as 'increasing' trend because two over the three precious metals are actually increasing their value for one gram. It is a trend that is first of all possible, as we have seen in previous chapter with almost stable and slight increase Pt, stable and slight decrease Pd, and overall big increasing Rh. It is moreover also impacting on catalyst price and on the delta with the adoption of the new zone coating three-way. The opposite trends of Pt and Pd in 2023 and 2024 diminish the advantage of Pt-for-Pd substitution, as the homogeneous three-way has no Pt, while the zone coated embeds Pt in rear zone. However, the possible big continuing step increase of Rh price at gram makes the Rh decrease in zone coating favourable. It will be interesting to monitor how both the homogeneous and three-way catalyst would change, and consequently the impact of the cost reduction activity based on PGM market. It will be clear that the activity is 'solid' from an economic point of view. The computations showed below are the summary of the same made in previous considerations. They are based on same computations made on last suppliers offers, with all spending voices considered (Substrates, Coating Fees, Handling Charges, Handling Charges variation with Tier 1 change, CPF presence etc.) that are obviously exactly the same of those already considered. What here represent the variables changing are only the three PGM values, evaluated in proper timing. For 2022 (price indications for eventual PPAP), 2023 (prices indications for SOP) and 2024 we would get a trend like:

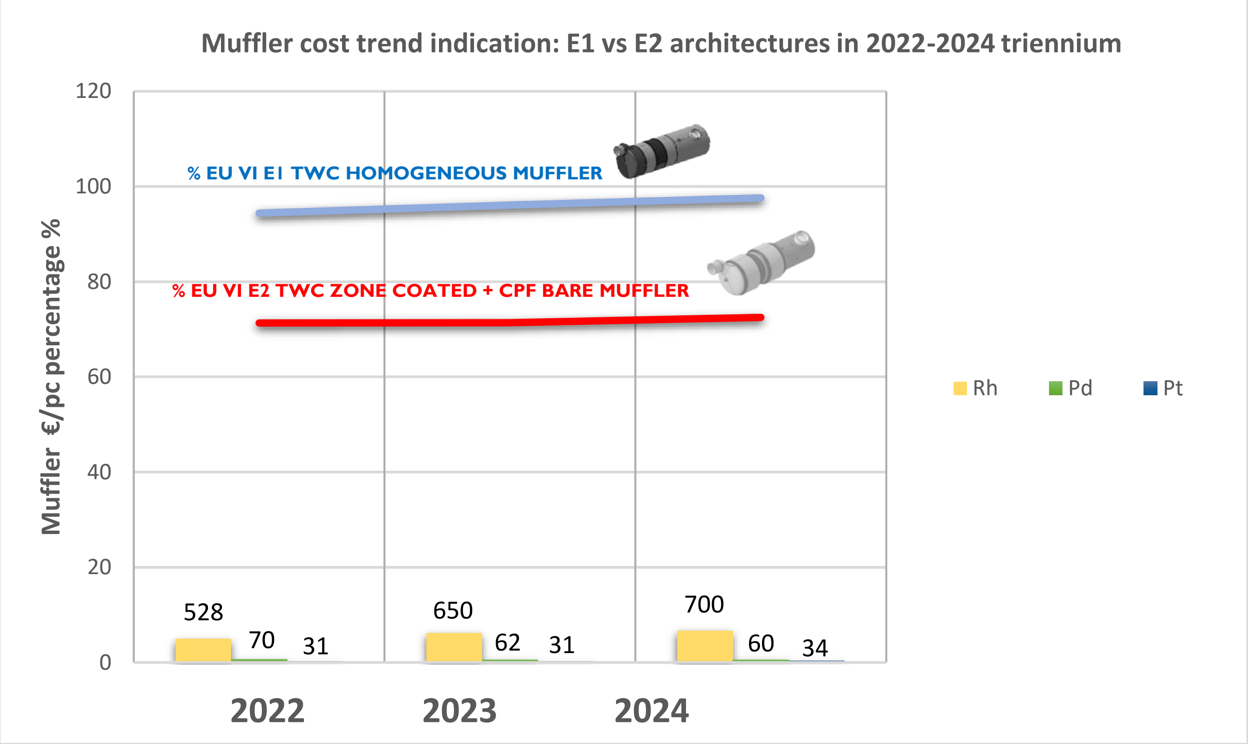


Figure 196 – Muffler percentage cost trend indication in 2022-2024 triennium

The percentage basis is here computed take as reference the peak reached in 2026 with 2026 PGM values in the table. The time range is of particular interest because it starts from 2022 prices till 2024. The first date represents the possible launch of PPAP batch activities of zone coating. The last one represents the year of last possible homologation (1/2024) of E1 CNG After-treatments. It is evident that there is an evident increasing trend, with theoretical 2024 E1 muffler 16% more expensive with respect 2022 base. The increase is however not step, the 2023 represents an intermediate passage. It reflects the increasing PGM trends described. The big Rh increase will make convenient to adopt zone coating, the final deltas between homogeneous and E2 zone coated muffler (with particulate filter) will increase accordingly (from around 2.400 €/pc till more than 2.600 €/pc). The benefit is from the Rh content decrease, and the opposite trend expected for Pt and Pd prices with respect lates years is not enough to ruin zone coated economical performances of this tri-metallic solution, also considering that it is still valid that Pt is much cheaper than Pd. In the following, the trend of two solutions mufflers difference is highlighted.

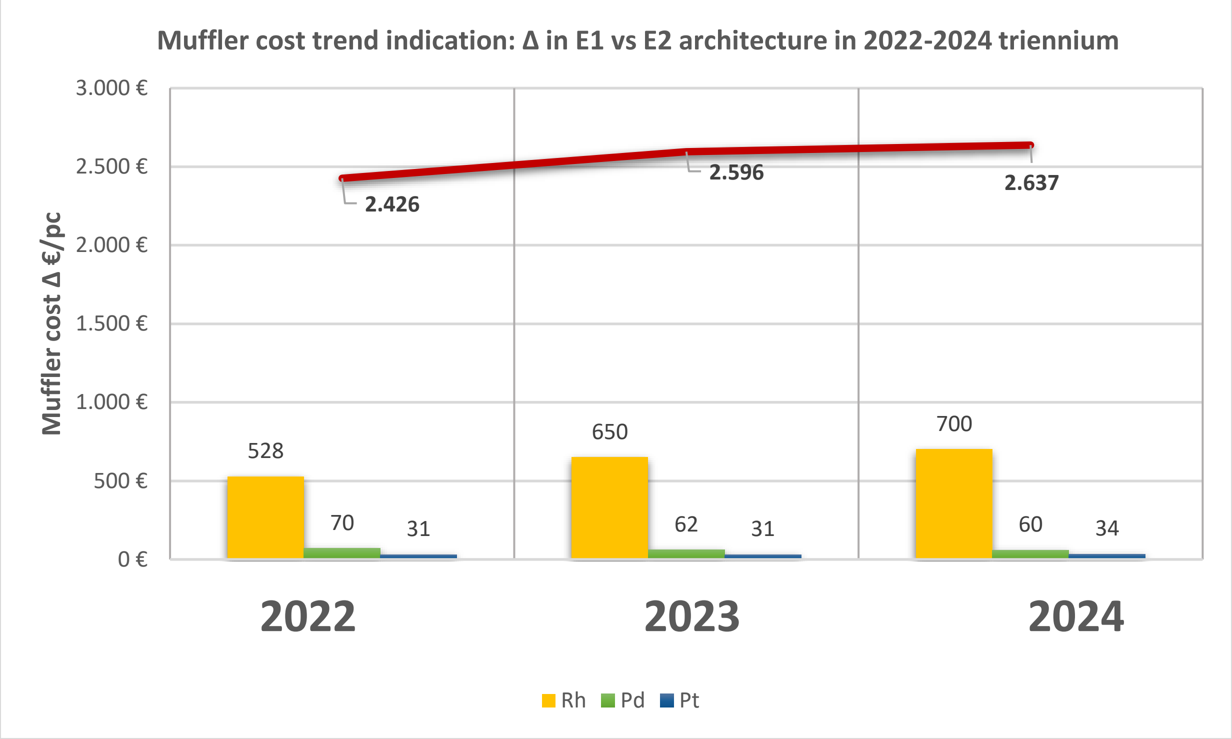


Figure 197 – Delta indication trend in muffler cost for 2022-2024 triennium

By considering these values, projected over the already considered 3500 units/year the save on 2023-2024 two years base (considering 3500 u/y for 2024 and SOP in 2023 with consequently ramp-up volumes **hypothesized** at **1200 u/y**) is around 12,34 million €!

Muffler indications	2023	2024	TOT
Δ E1 vs E2	**2.596 €/pc**	**2.637 €/pc**	
Volumes	1200 u/y	3500 u/y	
Saving	**≈ 3.115.000 €**	**≈ 9.230.000€**	**≈ 12.345.000 €**

Table 36 – ***Program saving indication over 2023-23 biennium***

We limited at considering 2023 and 2024. For 2025 and 2026 forecasts are less accurate. It could be also interesting to have comparison with pre-pandemic data and have a look on price trends for the ATS mufflers for a bigger range of time. It was done for this PGM increasing scenario,.The dashed lines indicate whether the solution can be not homologated (after 1/2024 for E1 homogeneous TWC without any hypothetical modification) or was not still running (from end of 2022 for the E2 zone coated TWC in end of beta phase). The results are really important and someway big in magnitude, but not surprising. Over the 2019-2024 period the price of an industrial muffler **more than doubled**, and between end of 2019 and 2021 (years related to pandemic and shortages) the trend of the prices had a big increase. A Euro VI E1 homogeneous three-way coated and canned was **102%** more expensive in 2021 with respect 2019! And the increasing scenario trend will bring a further increase shape in the trend within 2024. The following data are again normalized based on peak reached in 2026 with 2026 PGM values in the table, the PGM data are taken from external literature average values of previous years and the table forecast

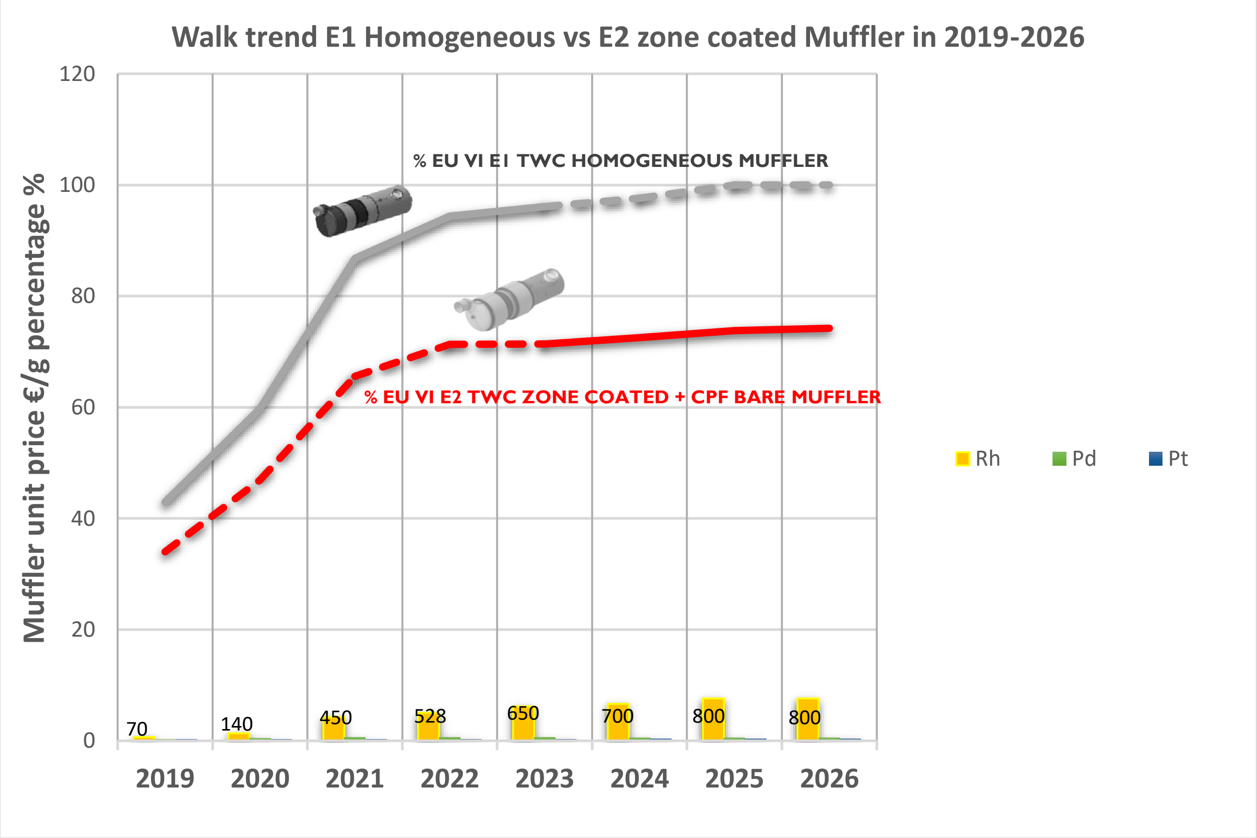


Figure 198 – E1 homogeneous vs E2 zone coated architecture prices walk trend 2019-2026

The deltas are showed in following

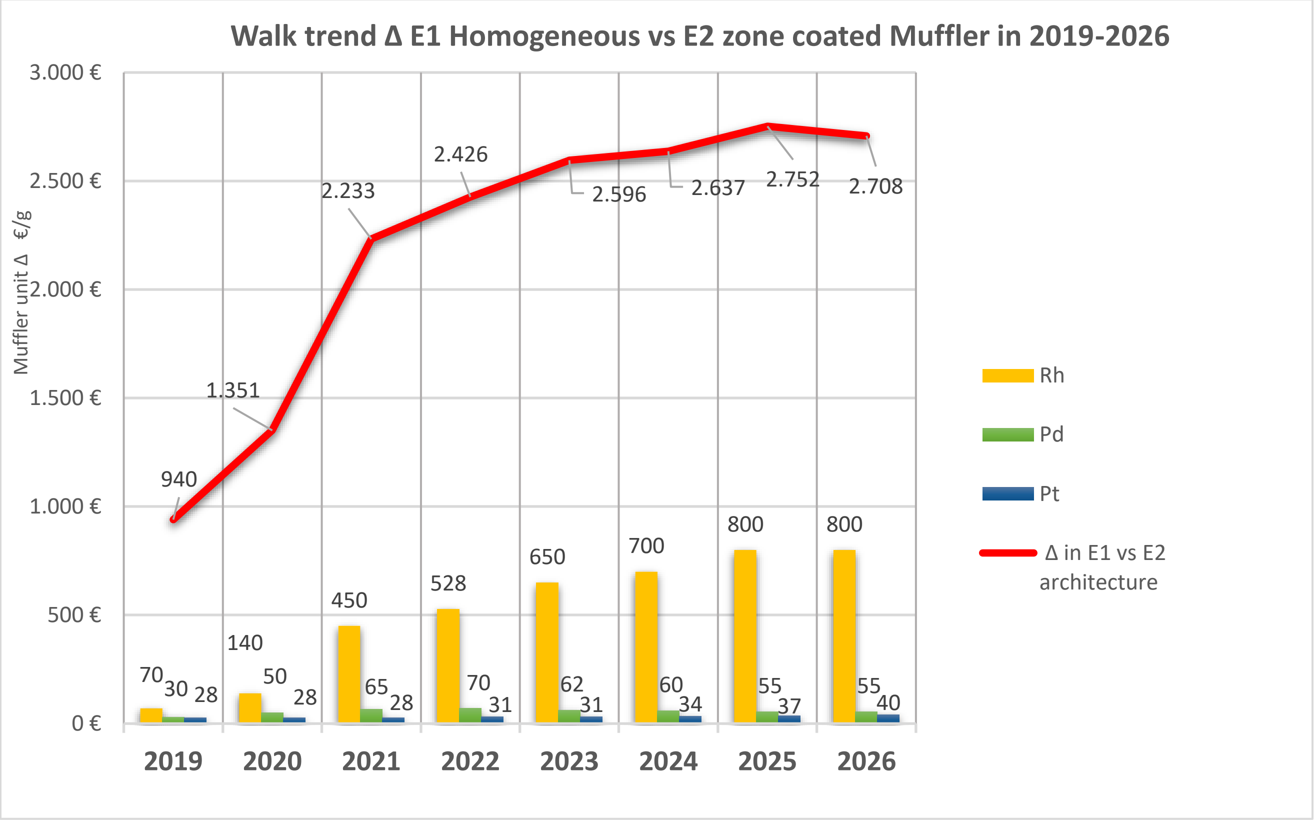


Figure 199 – E1 homogeneous vs E2 zone coated architecture delta prices walk trend 2019-2026

Bring to:

PGM increasing	2023	2024	2025	2026	TOT
Δ in E1 vs E2 architectures	2.596 €/pc	2.637 €/pc	2.752 €/pc	2.708 €/pc	
Volumes	1200 u/y	3500 u/y	3500 u/y	3500 u/y	
Saving	≈ 3.115.000 €	≈ 9.230.000 €	≈ 9.630.000€	≈9.480.000 €	≈31.460.000€

Table 37 – *Program saving indication over 2023-23 biennium*

A saving of 31,46 million € for the single engine case in study for the projected 4 years. We can see how it is not far to the projections made with PGM values fixed at last headquarter of 2022 (in chapter 8.5.1 it was about 28,39 million €). It is for sure higher due to the increasing trend of saving per unit price in the homogeneous versus zone coated comparison, due to the increase of PGM costs that further jeopardize homogeneous economical performances, except at the 2025-2026 biennium where the Pd decrease and Pt increase counteract the gaining. The last is however a prediction that has to be yet confirmed. It states that the new technology is capable of being competitive in almost all scenarios and takes major advantages to counteract a scenario of increasing costs (especially of Rh and Pd) and where it is almost mandatory to keep costs of ATS solution not too high. In 2019 the difference between a homogeneous three-way and a zone coated one would have been slightly more than 1,000€ (at the net of CPF). Maybe not enough to justify R&D and other expenses, especially for low volumes vehicles. The bimetallic Rh rich solution was so preferred. In late 2021 the difference was around 2,200€ (more than doubled) and it is intended to increase in next years, especially in the showed increasing scenario. This is also the reason why Iveco group is pushing hard to have this solution before 1/2024 data threshold of change of legislation. With this scenario, it is important to consider that the deltas after 2024 are not so accurate. They are affected by the introduction of step E2 legislation. They are made considering that a theoretical homogeneous E2 solution would somehow keep same price of actual E1 with that PGM content. Actually, it is lot more reasonable to think that to be compliant with step E2 legislation a homogeneous three-way would

- Need more PGM

And/or

- Need a coated CPF

The zone coating technology is so cost reduction activity while or in proximity of a change of legislation (step E2 of heavy-duty Euro VI), but it is also a kind of technology enabler of it. This is why it is able to match the need of cost reducing activity (for millions of euros in a four or five-years range), being environmental sustainable (in the cases where less density or overall amount of precious metals are embedded) and also keeping reducing the pollutant emissions of industrial internal combustion engines while pursuing latest legislations tightening, in a scenario where new technologies are now developing but ICEs will still be crucial in future decades .

10. Conclusions

The last chapter is a good indication of the economic impact of the technology studied in this thesis. It is far to claims itself as a proper business case, as lot of voices (like all the investments and expenses from the company) have not been deep analysed. Moreover, the computations had as base the aligned company values costs (hidden for confidentialities) but not the proper supplier-offers PGM values. The analysis is however a good indication of a possible magnitude of saving costs of both complete muffler unit prices together with some of their subcomponents plus the complete cost reduction activity magnitude. This economic aspects in the study will close the circle initiated with the technical evaluation of the zone coating technology. From the recent years literature coming from the automotive world studies, till the proper explanation of the technology in object implemented in FPT Industrial, that has the particularity to be embedded for industrial CNG internal combustion engines. The picture has been completed in an optic of legislation framework and an evolving technology scenario, where the climate crisis and the new CO_2 legislations pick the question whether has to be the share of internal combustion engine in industrial sector. Indeed, being it still important for next decades and being also the anti-pollutant needs and regulations evolving, a technology enabler like the one in object which is capable of match the need of reducing costs (in a panoramic of global shortages, pandemic, conflict etc.) and keeping reducing the emissions of industrial internal combustion engines is likely to be more and more implemented. It is likely that in short future heavy-duty industrial manufacturers will move into this solution, starting by next 12 months. The zone coated technology turned out to be less costly, more efficient and a possible solution to get rid of coating in CPF while continuing to treat ammonia slip. It is a technology through which full cost reduction activities will take place in industrial sector in the same way it has been for the automotive. In this standpoint, it has been very inspiring to get the chance of seeing in first hand both the technical and economical evaluation of such project.

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