The Influence of a Diesel Particulate Filter with Low-Temperature Regenerability on Diesel Engine Emissions

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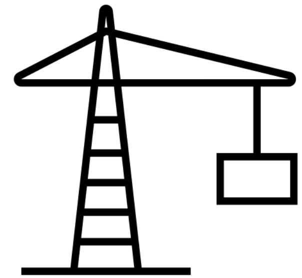
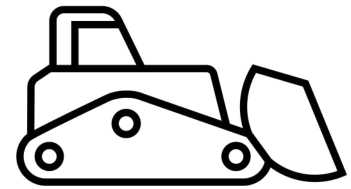
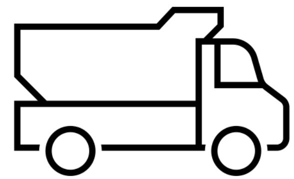
Emissions of diesel engines



- Diesel engines are emission sources for various pollutants, including nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and halogenated persistent organic pollutants (POPs).
- International Agency for Research on Cancer (IARC) identified diesel engine exhaust as a group 1 risk, due to the carcinogenic impact it can have on human health.



- The World Health Organization (WHO) ambient air PM2.5 guidelines (an annual mean of 5 μg/m^3 and a 24-h mean of 15 μg/m^3), and the increasingly strict air quality standards for PM2.5.



Reduce PM emissions from vehicular exhaust

- **Engine innovations-** still face many technical problems which are hardly satisfied with more stringent PM emission regulations (PN limits)
- **Cleaner fuels**
- **Aftertreatment devices**

Diesel particulate filters (DPFs), Gasoline particulate filters (GPFs), Particle Oxidation Catalyst (POC)

DPFs

- DPFs are currently the most effective way to reduce the PM emitted from diesel engines (PM capture efficiency is higher than 95%).
- The accumulation of PM leads to an increase of engine back pressure that adversely affects the engine fuel efficiency.
- The engine will ultimately cease to function if no action was applied to remove the accumulating PM.

Fang et al, (2019)

Regeneration

Soot ignition temperature T_{10} (at which soot conversion reaches 10%) >450 °C

- **Active regeneration**
  - fuel burner or electrical heater
  - to increase the DPF inlet temperature to 550 °C or higher for regeneration (Ko et al., 2016)
- **Passive regeneration**
  - Typical diesel engine exhaust temperatures during normal driving cycles fall within the 200–400 °C range. (Fino et al., 2016)
  - Fuel borne catalysts; **Diesel oxidation catalysts (DOC)**

Research Purposes

DOC+DPF Performance

- Cold start and hot start of the heavy-duty diesel engine with and without DOC+DPF deployment.

DPF Regeneration Ability

- Different Catalyst Proportions and Their Effects on Regeneration

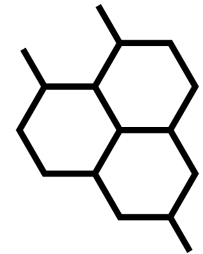
Influence of DPF conditions

Diesel engine emissions under the following conditions:

- New DPF
- During regeneration
- Post-regeneration

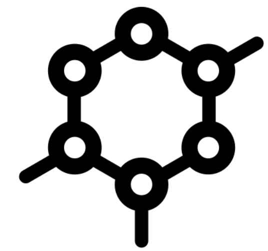
To reach the condition that the DPF needs to be regenerated, the engine idled for 30 hours to accumulate soot inside DOC+DPF

Target Pollutants

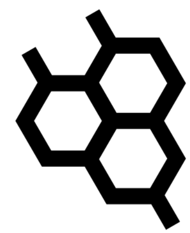


Traditional Pollutants

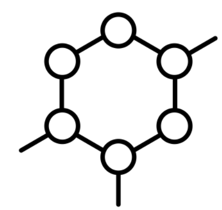
- $PM_{2.5}$
- CO_2, CO, HC, NOx, SO_2
- EC/OC



HAPs



- Heavy metals
- VOCs
- PAHs
- POPs (PCDDFs, PCBs, PBDDFs, PBDEs)



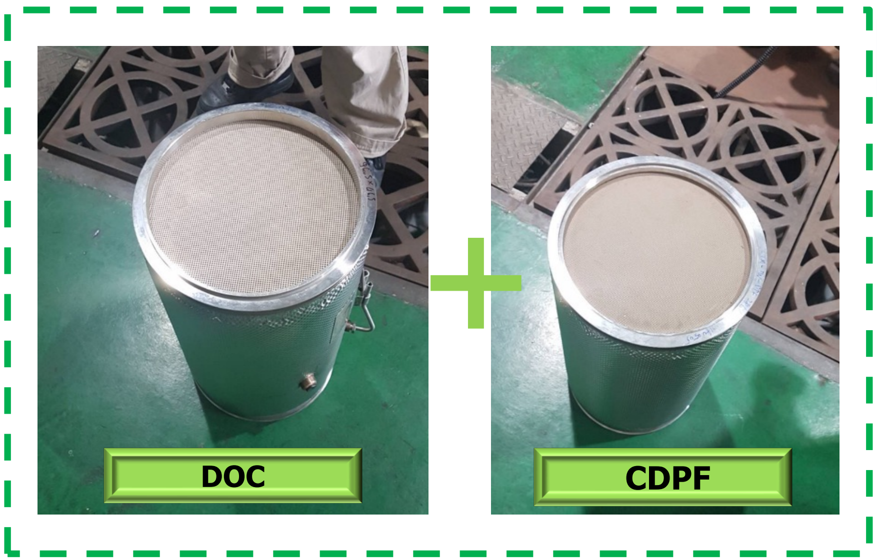
Samplings and measurement

- Diesel Engine Dynamometer
- Real-Driving Emissions (RDE)
- Real-Driving Durability Test

Diesel Engine Dynamometer Test

Engine mounted on dynamometer

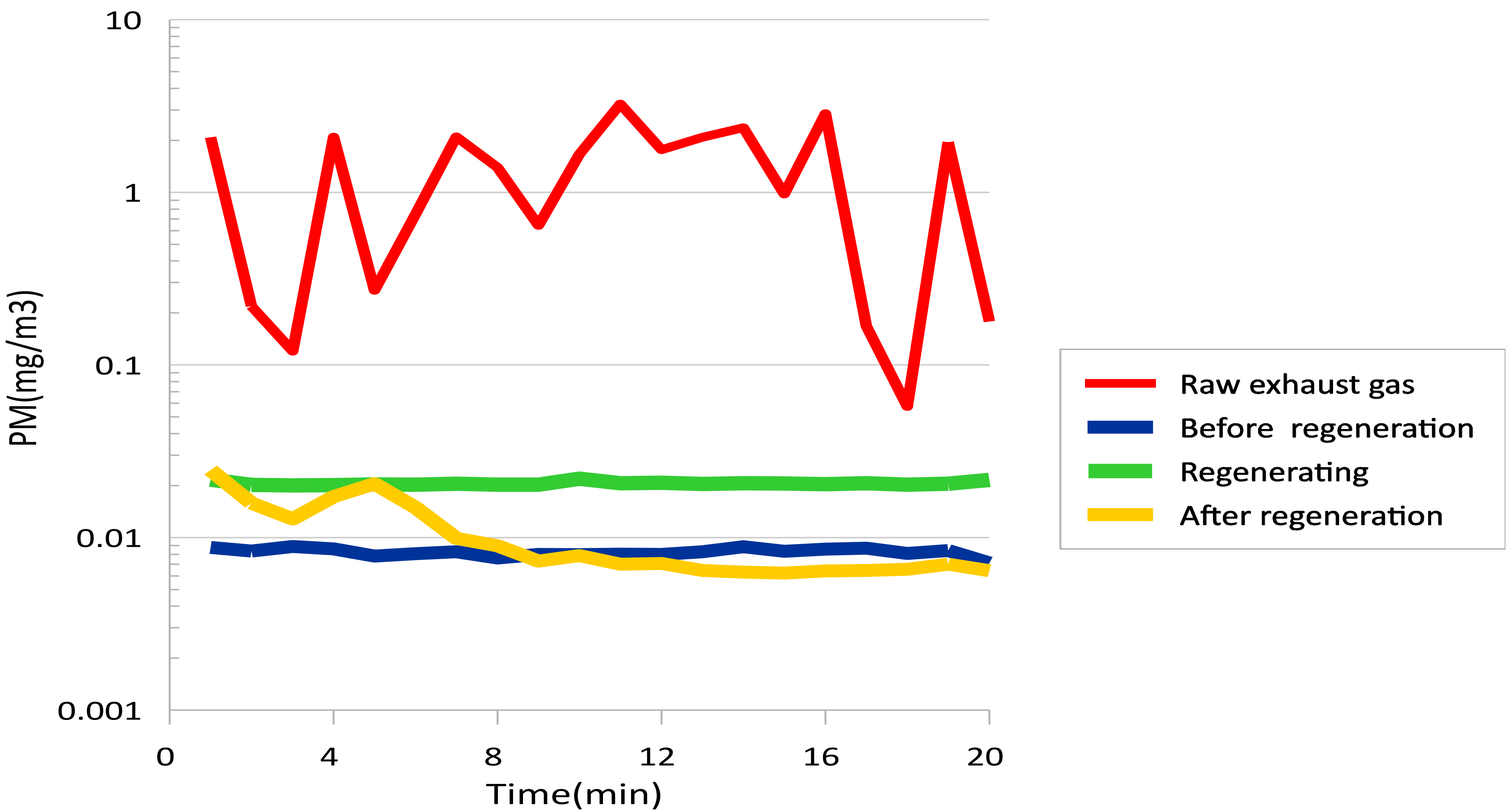
- The tested engine is Cummins ISC 315 (Euro III).
- The engine was mounted and operated with a dynamometer to provide the testing power and torque.
- The testing followed the US EPA Federal Transient Cycle Procedure (FTP Transient Cycle).



Pollutant Reduction emitted by the engine under different conditions

Conditions	CO (g/bhp-hr)	THC (g/bhp-hr)	NO_X (g/bhp-hr)	PM (g/bhp-hr)	Smoke (m^{-1})
Raw Exhaust	1.38	0.213	3.29	0.108	0.64
	⇩ 91.2%	⇩ 100%	⇩	⇩ 96.9%	⇩ 100%
New DPF	0.122	0	3.11	0.0033	0.00
During Regeneration	0.165	0.004	3.12	0.0054	-
Post-Regeneration	0.0966	0.004	3.12	0.0023	-

Real-time PM emissions of heavy-duty diesel engines under different DOC+DPF conditions



Impact of high soot-loaded and regenerated diesel particulate filters on POP emissions from a diesel engine fueled with waste cooking oil-based biodiesel

	B2			**B10**			**B20**		
	Before DOC+A-DPF	**After DOC+A-DPF**	**ratio**	**Before DOC+A-DPF**	**After DOC+A-DPF**	**ratio**	**Before DOC+A-DPF**	**After DOC+A-DPF**	**ratio**
$PM_{2.5}$ (mg/L)	122	19.6	0.16	155	17.5	0.11	133	9.61	0.07
PAHs (μg BaP_{eq}/L)	1.70	0.363	0.21	1.62	0.198	0.12	0.922	0.277	0.30
PCDD/Fs (pg WHO-TEQ/L)	17.3	45.5	2.6	10.3	15.2	1.5	4.59	7.67	1.7
PCBs (pg WHO-TEQ/L)	1.89	5.97	3.2	1.88	1.15	0.61	0.665	0.407	0.61
PBDD/Fs (pg WHO-TEQ/L)	6.26	7.05	1.1	3.78	2.17	0.57	2.56	1.64	0.64
PBDEs Mass (ng/L)	87.3	104	1.2	61.1	31.1	0.51	34.7	28.5	0.82

Chen, Wang* *et al., Appl. Energy* (2017)

Highly Cited Paper

POPs於DPF前後之氣固相分布

$$\overline{C_{1,p}} = \frac{C_{1,DOC} \times W_{1,p}}{V_1}$$ (particle-phase POP concentrations before DOC+DPF)

$$\overline{C_{1,g}} = \frac{P_{1,g} + (P_{1,p} - \overline{C_{1,p}} \times V_1)}{V_1}$$ (gas-phase POP concentrations before DOC+DPF)

$$\overline{C_{2,p}} = \frac{C_{2,DPF} \times W_{2,p}}{V_2}$$ (particle-phase POP concentrations after DOC+DPF)

$$\overline{C_{2,g}} = \frac{P_{2,g} + (P_{2,p} - \overline{C_{2,p}} \times V_2)}{V_2}$$ (gas-phase POP concentrations after DOC+DPF)

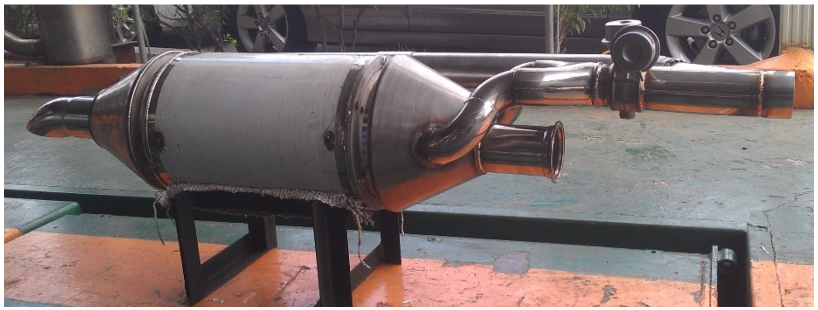
The corrected gas- and particle-phase partitioning of PCDD/Fs and PBDEs in the raw and treated exhausts.

PCDD/Fs homologues		A-DPF trial				R-DPF trial			
		Before DOC+A-DPF		After DOC+A-DPF		Before DOC+R-DPF		After DOC+R-DPF	
		Particle	Gas	Particle	Gas	Particle	Gas	Particle	Gas
TeCDD	%	2.6	97.4	3.9	96.1	2.2	97.8	0.5	99.5
PeCDD	%	2.6	97.4	0.4	99.6	3.4	96.6	0.0	100
HxCDD	%	3.0	97.0	8.1	91.9	1.3	98.7	0.3	99.7
HpCDD	%	3.2	96.8	3.3	96.7	2.3	97.7	0.4	99.6
OCDD	%	3.2	96.8	3.1	96.9	2.5	97.5	0.3	99.7
TeCDF	%	2.8	97.2	10.3	89.7	2.7	97.3	0.4	99.6
PeCDF	%	2.8	97.2	8.4	91.6	1.0	99.0	0.1	99.9
HxCDF	%	3.0	97.0	5.7	94.3	1.4	98.6	0.4	99.6
HpCDF	%	3.0	97.0	2.3	97.7	1.9	98.1	0.1	99.9
OCDF	%	3.3	96.7	5.9	94.1	1.9	98.1	0.6	99.4

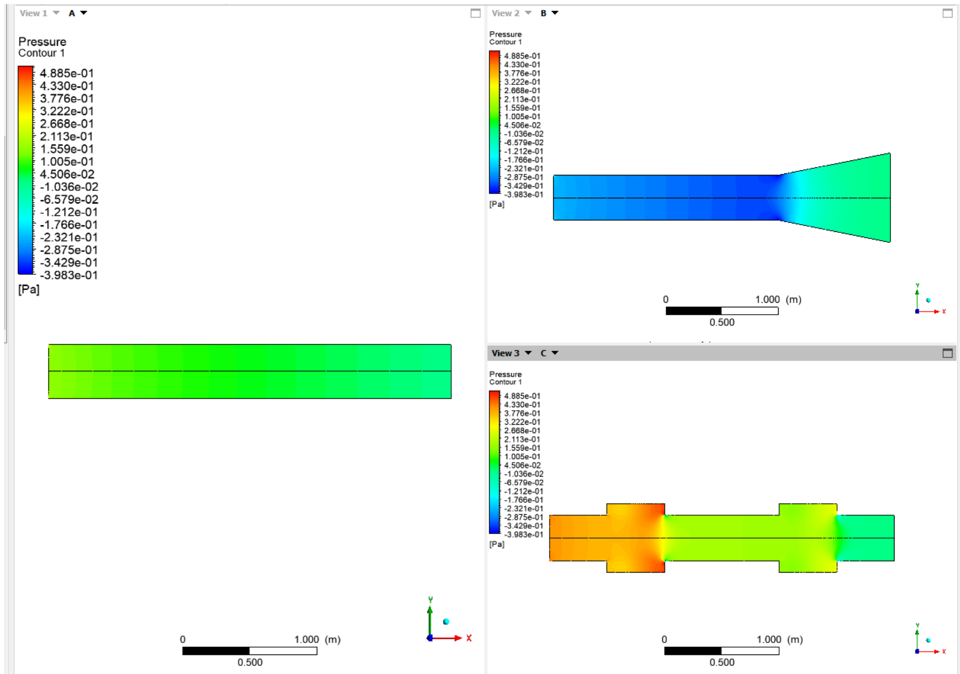
- Formation mechanism of POPs in diesel engines is mainly through homogeneous gas-phase formation
- Heterogeneous precursor pathway and de novo synthesis occurred, when exhausts passed through DPF.

DOC + DPF with Low-Temperature Regenerability

- Catalyst type and ratio, catalyst coating method, DPF structure

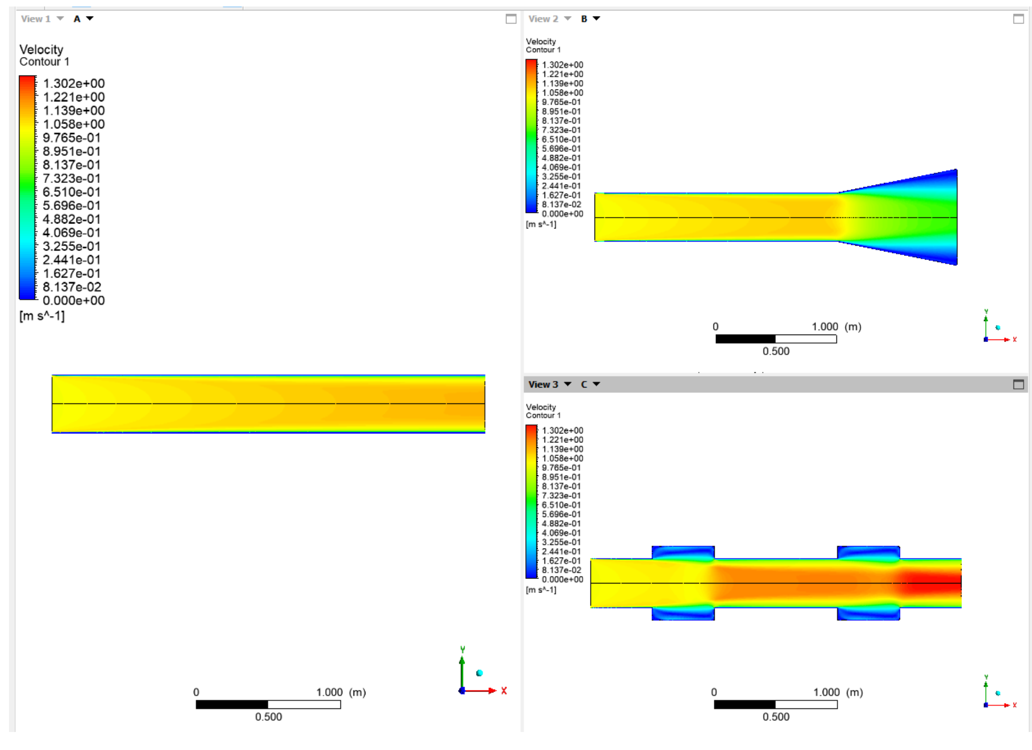


Computational Fluid Dynamics (CFD) Simulation



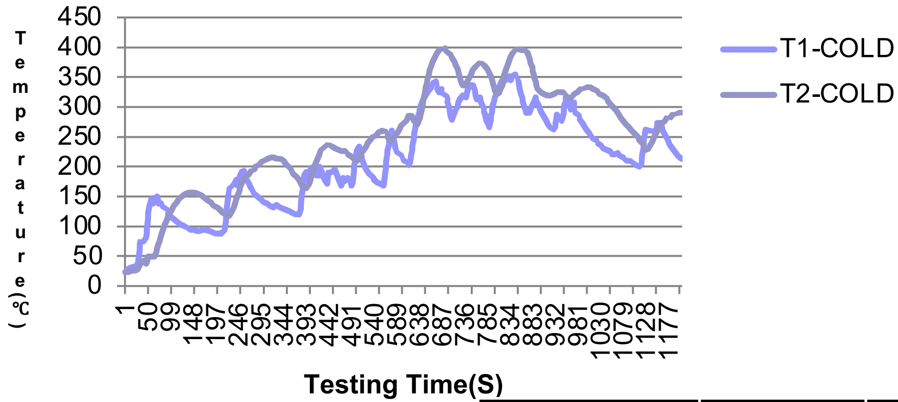
Pressure

Exhaust Flow Rate

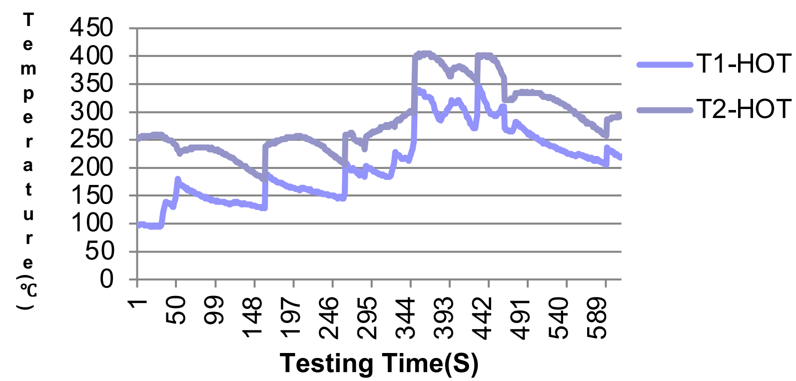


Reduction efficiency of DPF on PCDD/Fs

DPF	DPF#1				DPF#2			
Conditions	New DPF		After regeneration		New DPF		After Regeneration	
	Cold start	Hot start	Cold start	Hot start	Cold start	Hot start	Cold start	Hot start
Total PCDD/F WHO-TEQ	-0.2%	84.8%	18.9%	64.8%	86.6%	74.3%	88.0%	75.4%



Condition	Time	(%)
T>220°C	763	63.27%
T2-T1>30°C	767	63.60%
T2-T1>50°C	501	41.54%



Condition	Time	(%)
T>220°C	1045	86.65%
T2-T1>30°C	855	70.90%
T2-T1>50°C	620	51.41%

Opacity and Power

Method and procedure for testing opacity of black smoke emission from diesel vehicles

HORIBA-600S
Opacimeter

Opacity and Power

Raw Exhaust (without DOC+DPF)

Power Ratio					
Test Load	Engine Torque	1	2	Max Value	Power Ratio
100%	2100 rpm	2089 rpm	2092 rpm	261.7 kW	93%
		261.7 kW	261.1 kW		

Exhaust Opacity				
Run	1	2	3	Average
Results	1.33 m^{-1}	1.36 m^{-1}	1.36 m^{-1}	**1.3 m^{-1}**
	2555 rpm	2561 rpm	2554 rpm	

Phase 3 Standard: 1.2 m^{-1}

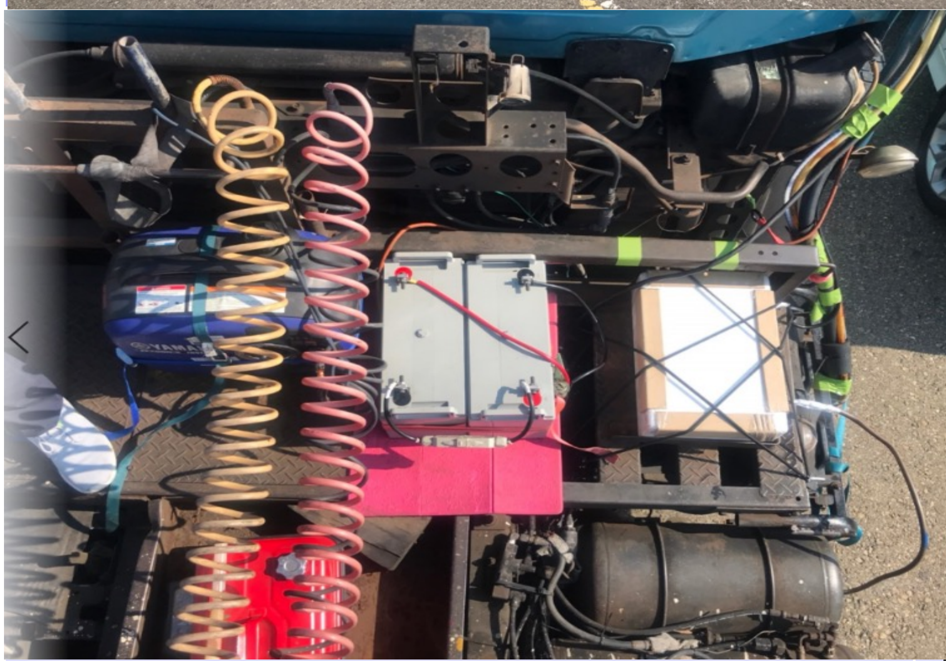
Treated Exhaust (with DOC+DPF)

Power Ratio					
Test Load	Engine Torque	1	2	Max Value	Power Ratio
100%	2100 rpm	2134 rpm	2118 rpm	260.2 kW	93%
		259.3 kW	260.3 kW		

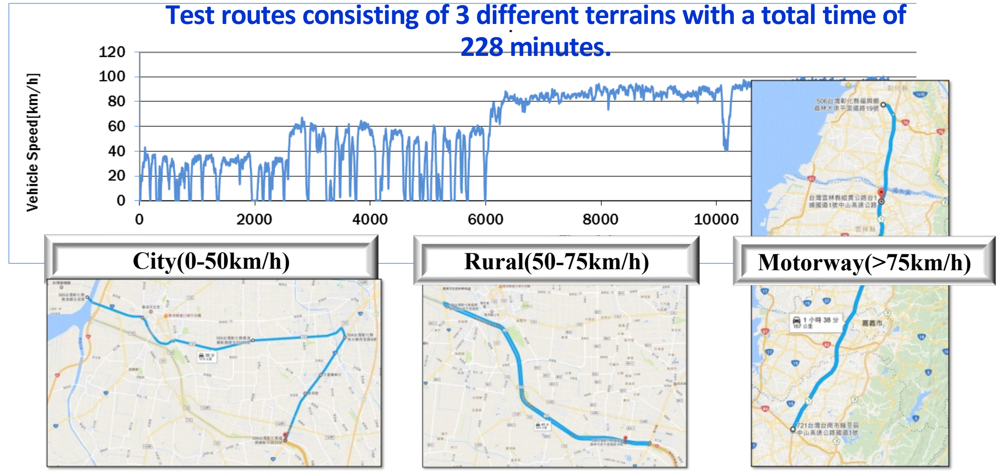
Exhaust Opacity				
Run	1	2	3	Average
Results	0.03 m^{-1}	0.04 m^{-1}	0.04 m^{-1}	**0.0 m^{-1}**
	2552 rpm	2553 rpm	2548 rpm	

Phase 5 Standard: 0.6 m^{-1}

Real-Driving Emissions (RDE)



Portable Emission Measurement Systems (PEMS) Monitoring



According to Euro VI-C regulations, test routes should include urban, rural, and motorway drivings differentiated by vehicle speed.

- City <50 km/hr
- Rural 50~75km/hr
- Motorway >75 km/hr

The total mileage is 216 kilometers (about 3 hours driving)

		Raw exhaust	Treated	
PM	mg/m^3	18.8	0.0583	99.7%
THC	g/km	0.36	0.03	91.7%
CO	g/km	3.09	1.35	56.3%
CO_2	g/km	751.09	781.59	
NOx	g/km	13.79	14.41	

Real-Driving Durability Test

15,000km (~ 3 months of driving)

Test Points	Driving Time	Opacity	Power ratio
Before installation	0	1.3 m^{-1}	93%
After installation	0	0 m^{-1}	93%
10,000 km travelled	2 months	0 m^{-1}	96%
15,000km travelled	~3 months	0 m^{-1}	98%

Conclusion

- The DOC+DPF with low-temperature regenerability developed in this research has no effect on the horsepower of heavy-duty diesel engines, and has great reduction on CO, THC, particulate matter and opacity, regardless of dynamometer or real-driving test.
- Passive regeneration can be started at 180°C, and more than 60% of the time, the DPF was in regeneration. This effectively inhibit the formation potential of PCDD/Fs, and further reduce 74.3%-88.0% of PCDD/F emissions.
- The durability test showed that the exhaust opacity of heavy-duty diesel vehicle deployed with the DOC+DPF was still 0 m^{-1} after 15,000 kilometers of driving.

Thank you for your time.