

High-efficient and Cost-effective Three-Way Catalyst Substrate Design for Plug-in Hybrid Electric Vehicle

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01

Introduction

Emission legislation and PHEV emission-control technology

Introduction

Emission Legislation

USA
EPA Tier 4

- CO2 50% reduction by 2032 starting from 2027
- SFTP eliminated
- Fleet average NMOG + Nox 35→15mg/mi

Euro
2023/851
Euro 7

- CO2 50% and 55% reduction in 2030 for PV and LDV compared to 2021
- Same gaseous pollutant limit as Euro 6e
- PN emission 23nm→10nm

China
China 7

- introduce CO₂ standards
- Fleet average introduced
- NH3 introduction
- PN emission 23nm→10nm

PHEV Emission Technology upgrade

Higher engine thermal efficiency

- High efficiency zone
- Miller cycle
- ...

Electrification-related aspects

- Hybrid –specific transmission
- Intelligent power management
- Pure electric driving mode

CO2

CO2

gaseous
pollutant

gaseous
pollutant

Lower Engine out
emission

- Stable engine control
- Motor aided load reduction

Better TWC Technology

- Pt-Pd-Rh technology
- Lighter substrate
- higher mesh substrate

(SAE2025-01-8528)

02

Experiments and Methods

Test vehicle, aftertreatment samples and ageing protocol

Experiments and Methods

Test Vehicle PHEV [China6b]

- 175kW electric motor with a maximum torque of 320N·m
- an 18.99kW·h lithium iron phosphate battery
- a 1.5L naturally aspirated engine with an Atkinson cycle



Aftertreatment/Analysis system

- Temperature/Lambda/Gas analyzer

Ageing method

- Oven ageing - according to the TWC bed temperature of SRC
- Moderate Ageing & Harsh Ageing
- UF is also considered

Vehicle test

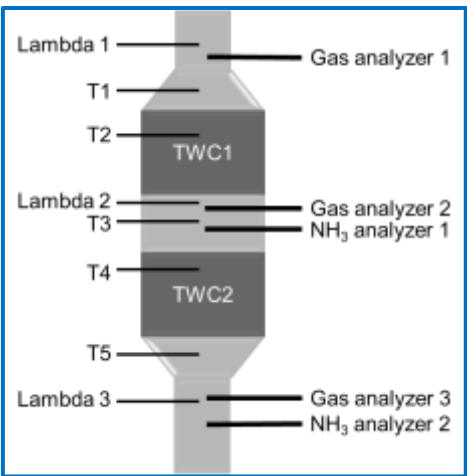
- Driving mode - CS mode BSOC-18.5%
- Pre-test – 4 high speed cycles + WLTC
- Test cycle - WLTC



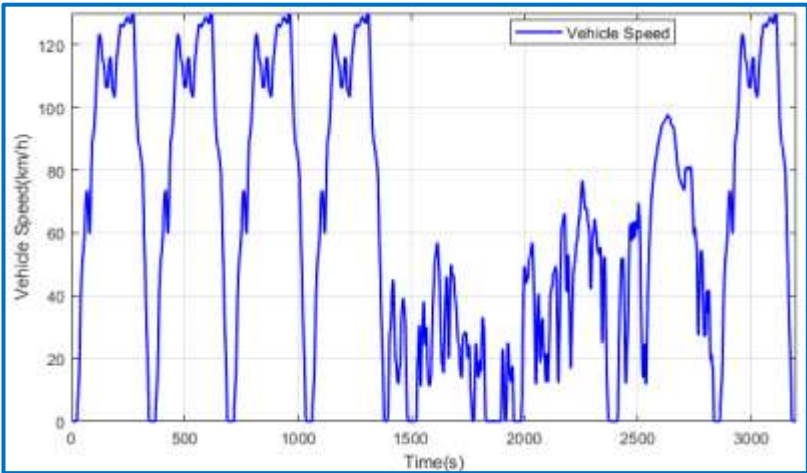
Aftertreatment system

TWC samples: Same PGM, Size: $a > b = d > c$, WCL

Systems	TWC1			TWC2		
	Diameter*Length(mm)	CPSI/wall thickness	Pt:Pd:Rh	Diameter*Length(mm)	CPSI/wall thickness	Pt:Rh
a	118.4*45	750/2	5.3:7.9:1	118.4*50	400/4	18.22:1
b	118.4*50	750/2	5.3:7.9:1	118.4*65	400/4	18.22:1
c	118.4*60	750/2	5.3:7.9:1	118.4*80	400/4	18.22:1
d	118.4*50	900/2	5.3:7.9:1	118.4*65	400/4	18.22:1



Analysis system



Pre-test cycle

03

Results and Discussion

Gaseous pollutant emissions under moderate

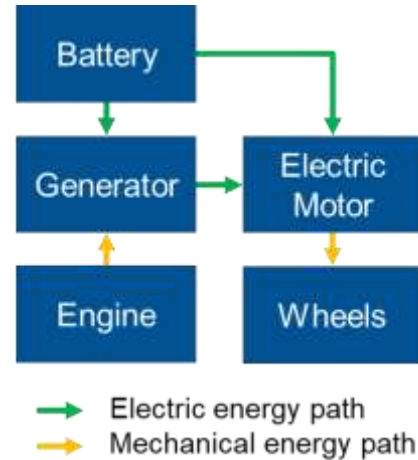
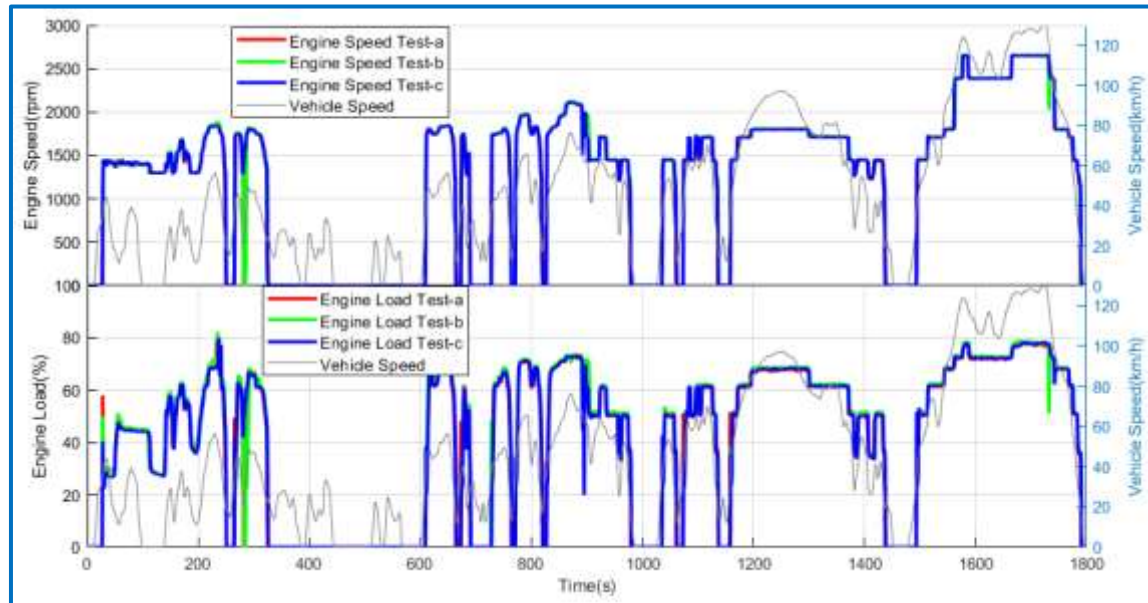
Moderate Ageing: Oven TWC1 980°C/20hrs+TWC2 900°C/20hrs

Harsh Ageing: Oven TWC1 1000°C/20hrs+TWC2 980°C/20hrs

Results and Discussion

PHEV engine operating conditions

- Stable engine condition
- Lower than 80% engine load
- 1400rpm & lower than 60% load during cold start
- No significant differences among different tests.

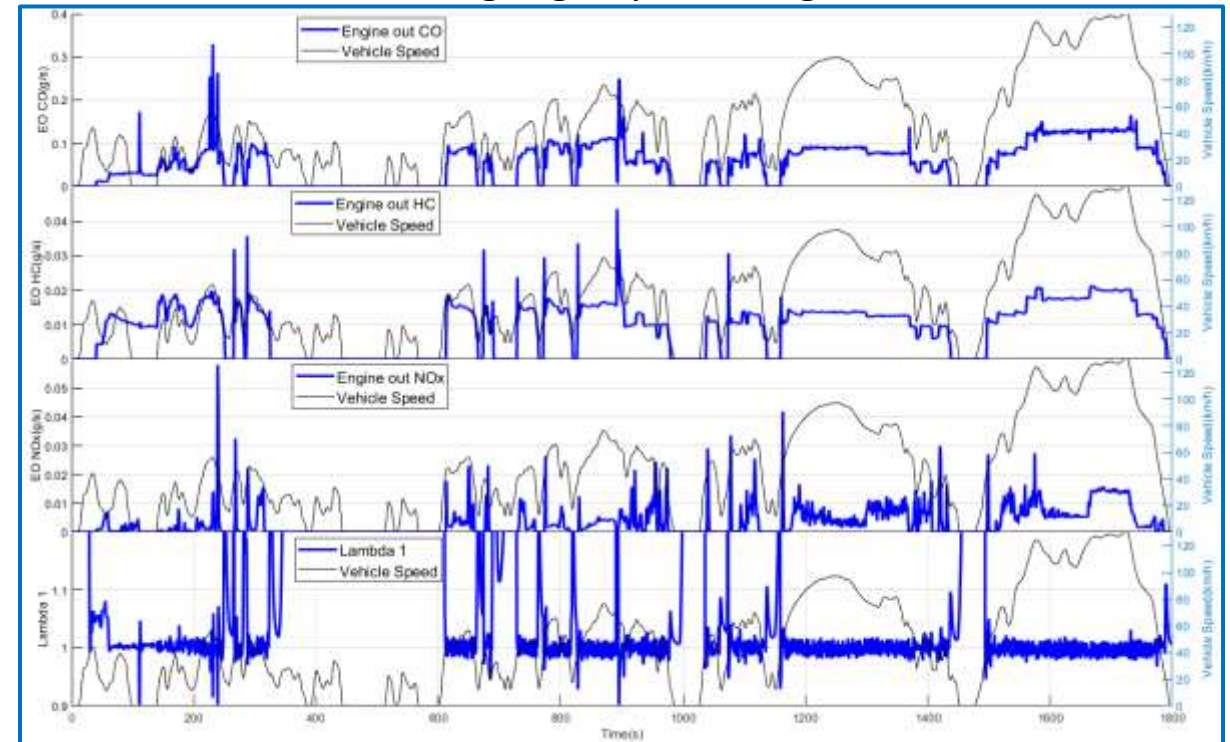


ATS: **TWC1 750/2**:Dia:118.4mm, Length(mm): a=45, b/d=50, c=60, ***d-Flora(900/2F)**,

ATS: **TWC2 400/4**:Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

Engine out emission: TP (TWC+TWC2)

- Lean lambda cold start
- Low CO and NO_x during warm up stage
- Rich lambda at engine start leads to a high HC
- Stable CO/HC during high-speed stage

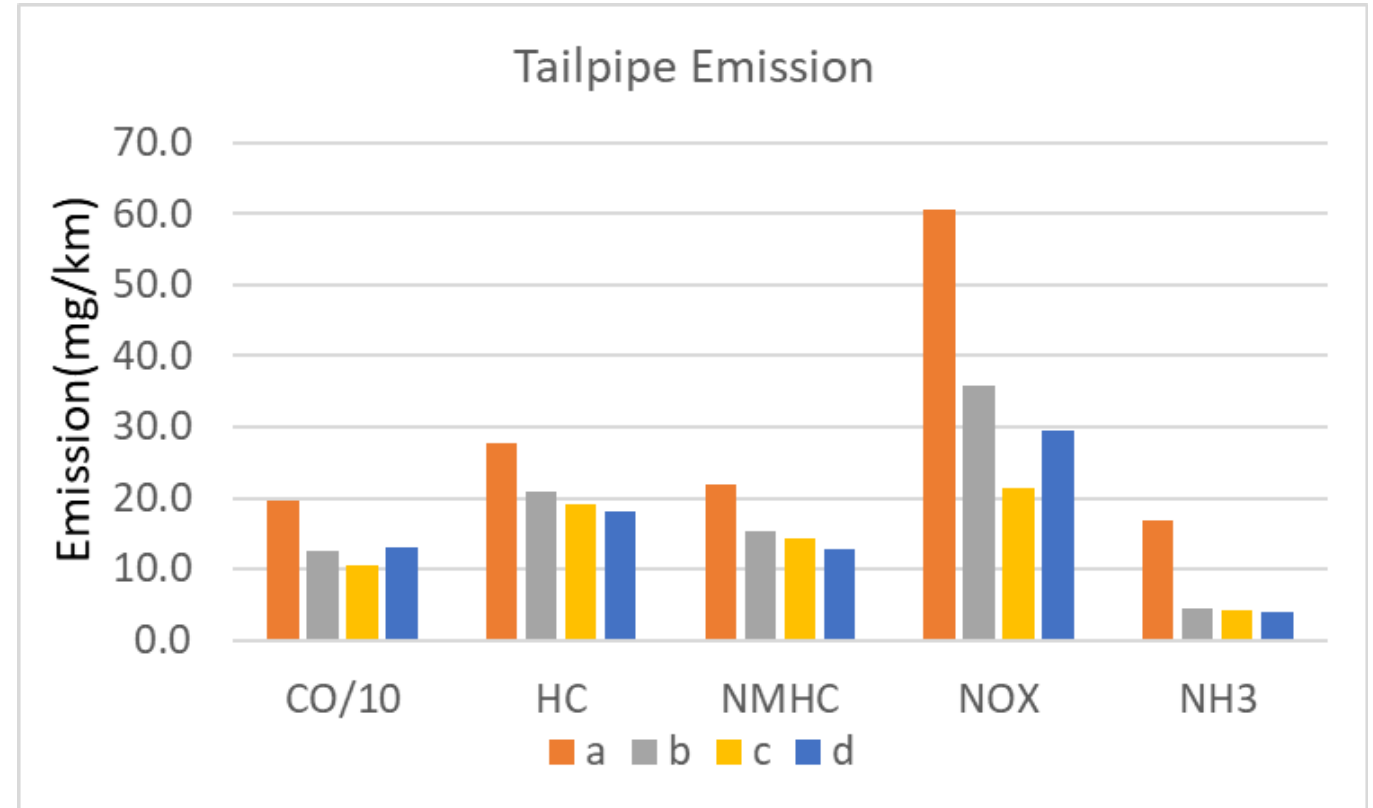


Results and Discussion:

Moderate Ageing: Oven TWC1 980°C/20hrs+TWC2 900°C/20hrs

Tail pipe: Gaseous Emission

- Longer substrate length → lower emission
 - Substrate size $c > b = d > a$
- Flora substrate show a better emission compared to same size substrate design.
 - System “b” CC1 TWC → 750/2
 - System “d” CC1 TWC → 900/2 Flora
- NO_x is the main concern, which requires more reaction time. A larger system volume would result in a significantly higher conversion efficiency.
- NH₃ emission is ~5mg/km except system a caused by a higher concentration of CO and NO_x in TWC2.



ATS: TWC1 750/2: Dia:118.4mm, Length(mm): a=45, b/d=50, c=60, *d-Flora(900/2F),

ATS: TWC2 400/4: Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

Results and Discussion

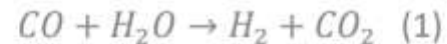
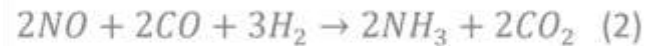
Moderate Ageing: Oven TWC1 980°C/20hrs+TWC2 900°C/20hrs

Mid-emission

- System “c” shows quite lower emissions especially during high - speed stage.
- System “a” show a better emission during cold start stage but higher emission after that.

NH3 emission

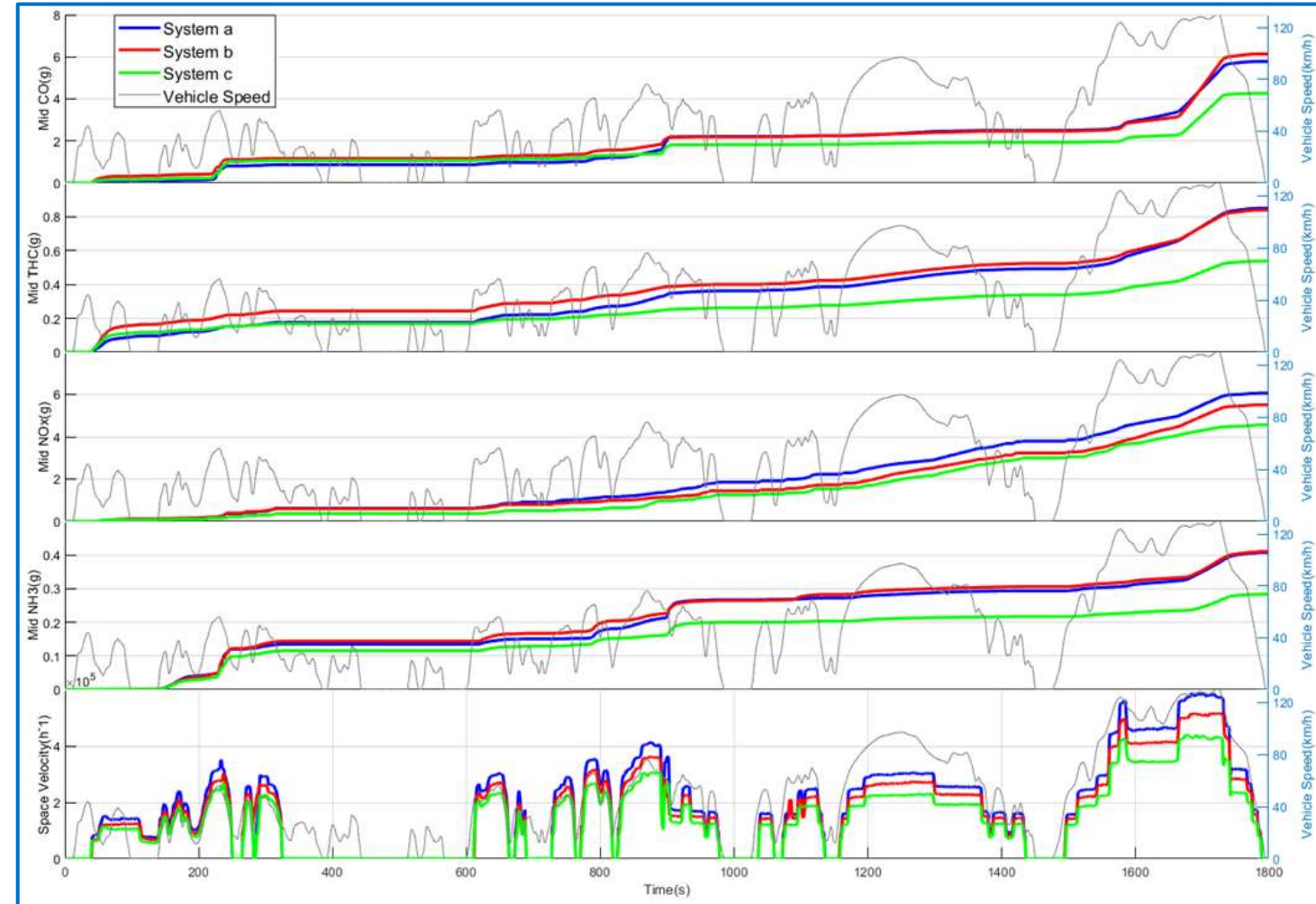
- 140s to 300s, the rate of NH3 generation exceeds the oxidation → a high concentration of NH3.
- system “a” exhibits the NH3 emission slightly lower than the mid-emissions



ATS: **TWC1 750/2**:Dia:118.4mm, Length(mm): a=45, b/d=50, c=60, ***d-Flora(900/2F)**,

ATS: **TWC2 400/4**:Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

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Results and Discussion

Moderate Ageing: Oven TWC1 980°C/20hrs+TWC2 900°C/20hrs

ATS: System b; TWC1(750/2) + TWC2 (400/4)

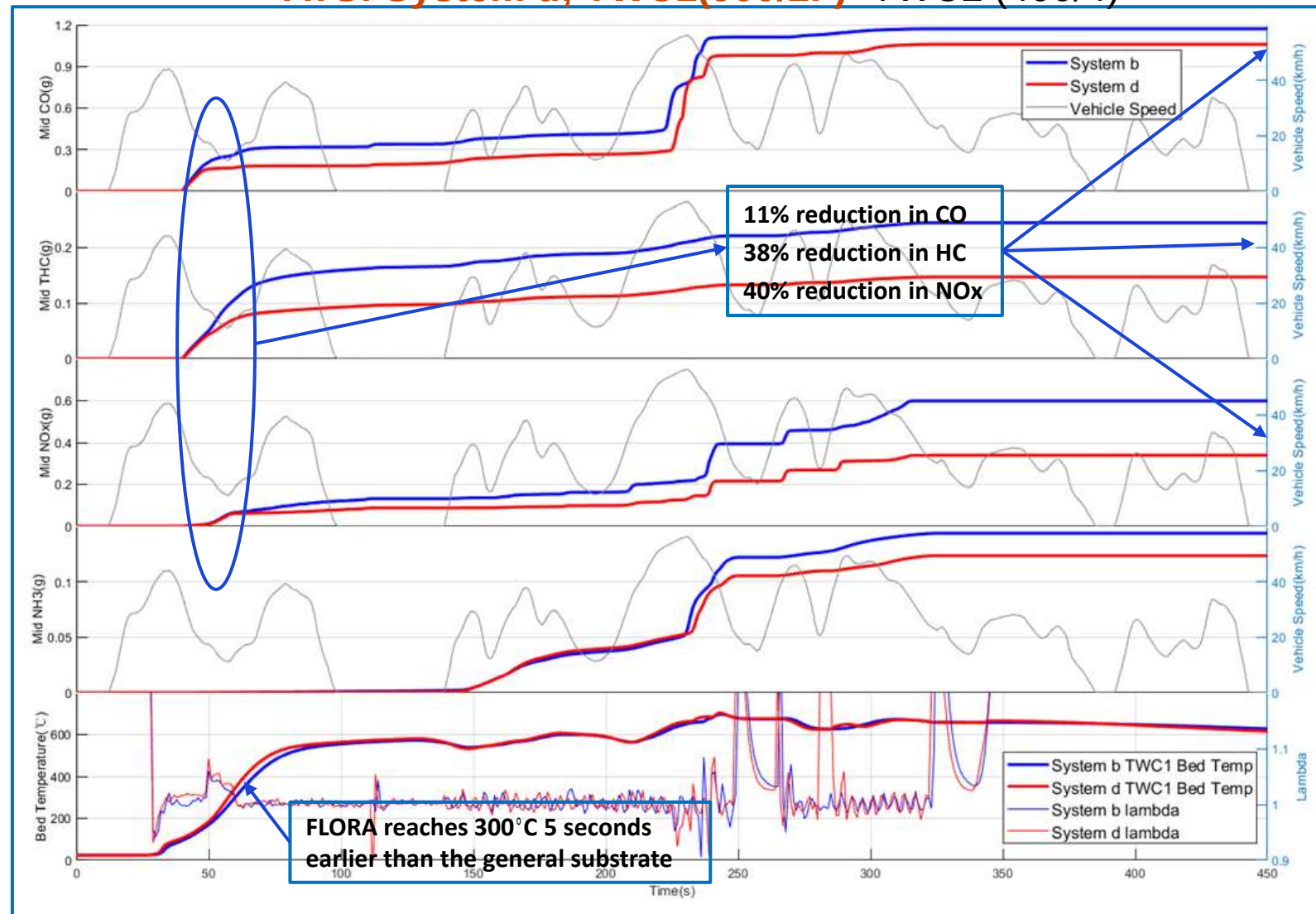
ATS: System d; TWC1(900/2F)+TWC2 (400/4)

Flora substrate (CC1 of system “d”)

- **Geometric surface area** - enhance the contact between exhaust gas and the catalyst

$$GSA(in^2/in^3) = 4 \times CPSI \times \left(\frac{1}{\sqrt{CPSI}} - WT \right) \quad (5)$$

- The GSA of TWC1 in system “d” is calculated to be 2.41m², which is higher than that of TWC1 in system “b” (2.21m²) despite having the same size.
- **Porosity** - Compared to a general substrate with 28% porosity, the FLORA substrate used in system “d” has a porosity of 55%. This results in TWC1 of system “d” (262g) being 15% lighter than the TWC1 of system “b” (307g) after coating → better light off

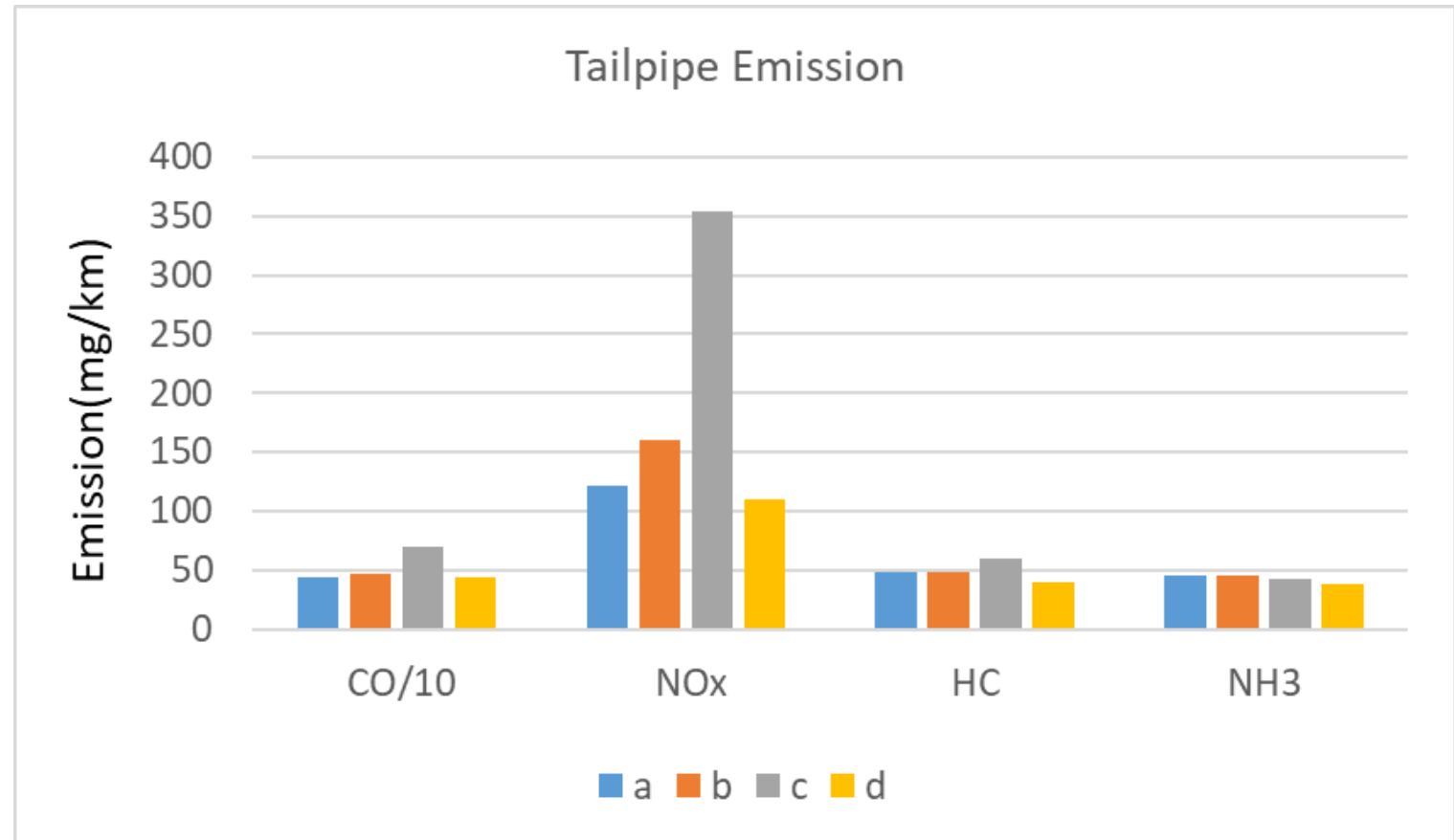


Results and Discussion

Harsh Ageing: Oven WC1 1000°C/20hrs+TWC2 980°C/20hrs

Gaseous Emission

- Shorter substrate length → lower emission
 - Substrate size $c > b = d > a$
 - A higher PGM concentration, exhibits higher resistance to harsh ageing and thus higher emission rate
- Flora substrate show a better emission compared to all substrate design.
 - System “b” CC1 TWC→750/2
 - System “d” CC1 TWC→900/2
- Similar NH_3 emissions are found to be $\sim 40\text{mg/km}$ due to high NO_x and CO concentration in the catalyst.



ATS: **TWC1 750/2**:Dia:118.4mm, Length(mm): a=45, b/d=50, c=60, ***d-Flora(900/2F)**,

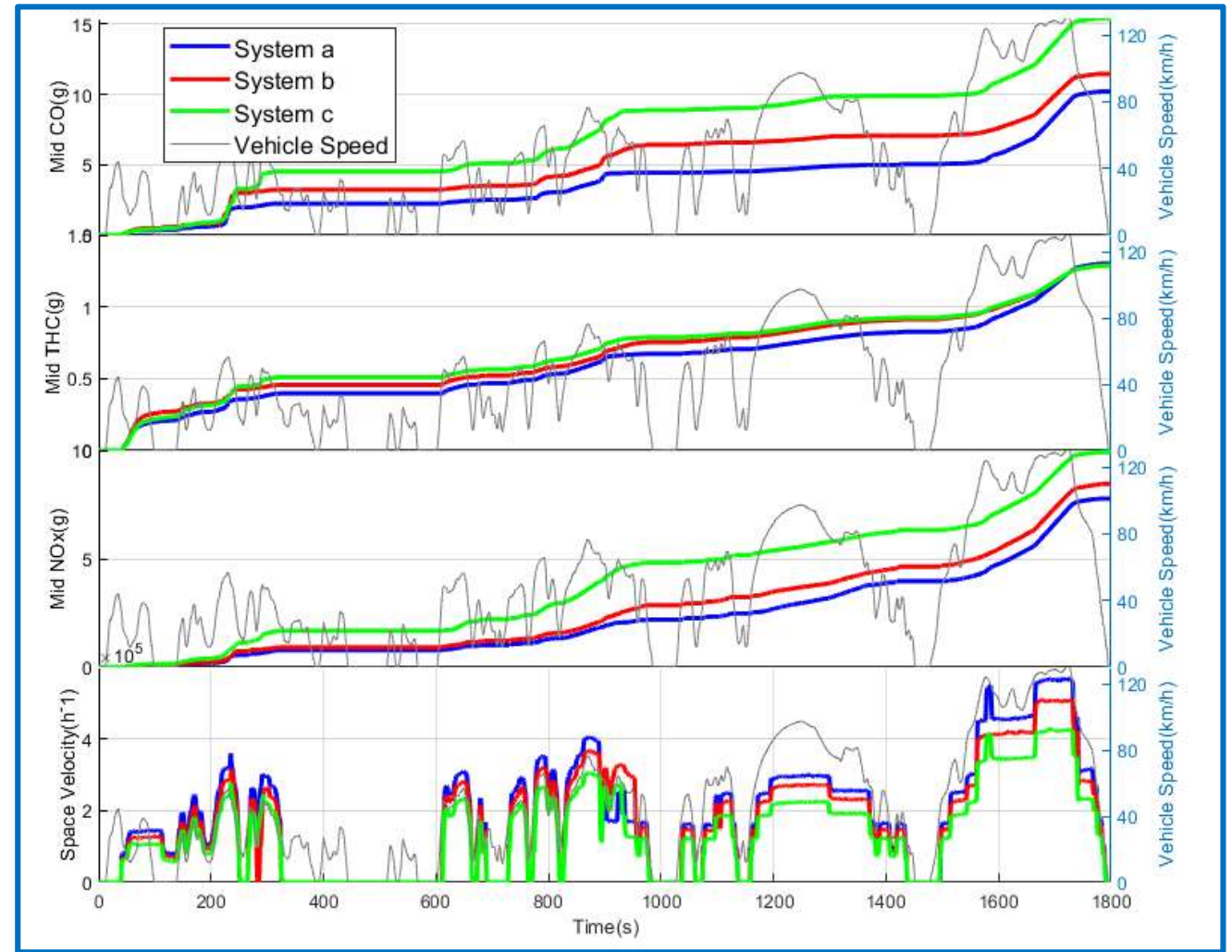
ATS: **TWC2 400/4**:Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

Results and Discussion

Harsh Ageing: Oven WC1 1000°C/20hrs+TWC2 980°C/20hrs

Mid-emission

- The harsh ageing emissions are much higher than moderate ageing emissions(2-3 times)
- The mid emission has a similar trend with tailpipe emission
- CO and NO_x emissions are very low due to the low engine out emission.
- System “c” show a better emission during high-speed stage; System “a” show a much better CO emission during cold start stage.



ATS: **TWC1 750/2**:Dia:118.4mm, Length(mm): a=45, b/d=50, c=60, ***d-Flora(900/2F)**,

ATS: **TWC2 400/4**:Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

Results and Discussion

Harsh Ageing: Oven WC1 1000°C/20hrs+TWC2 980°C/20hrs

ATS: System b; TWC1(750/2) + TWC2 (400/4)

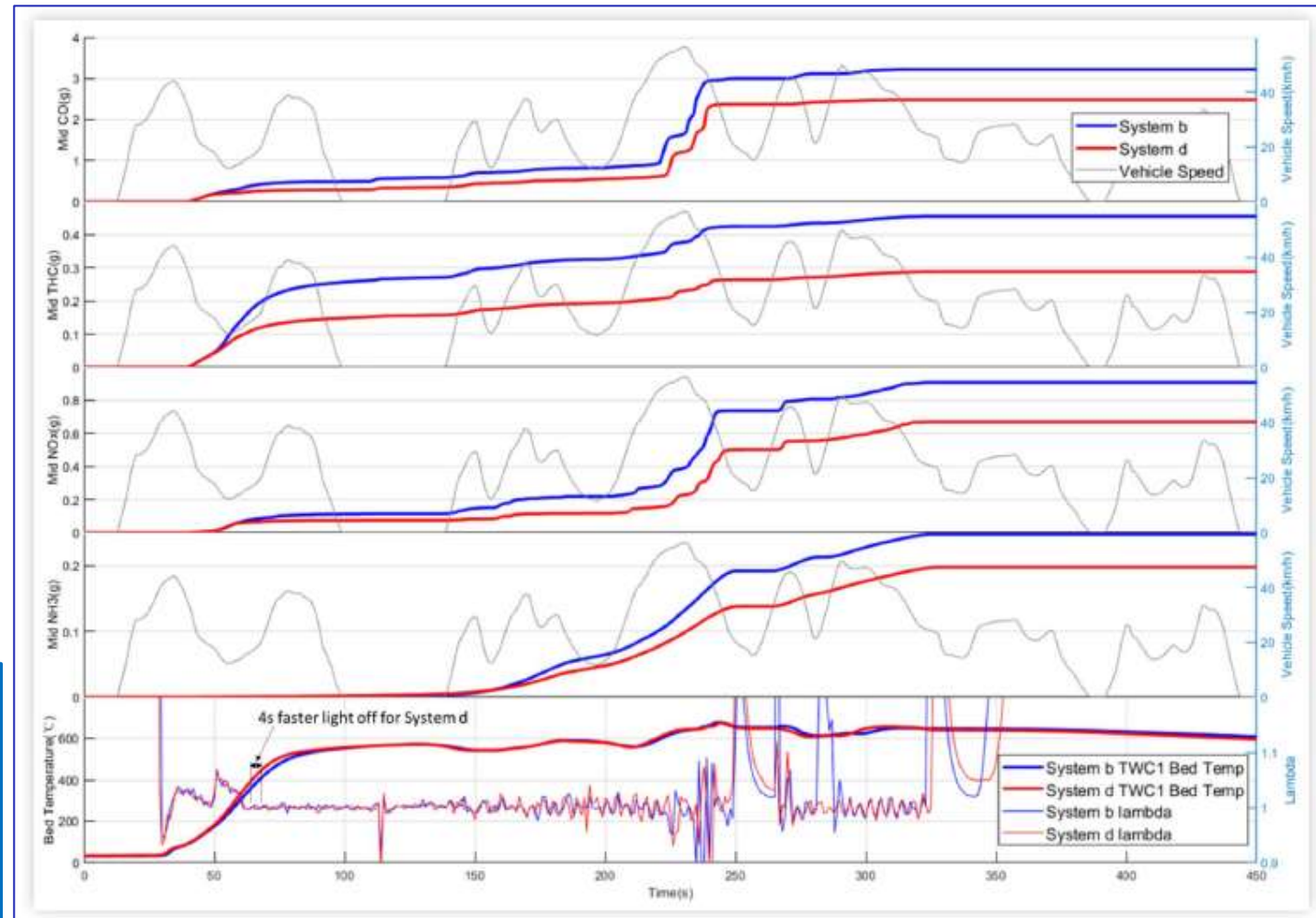
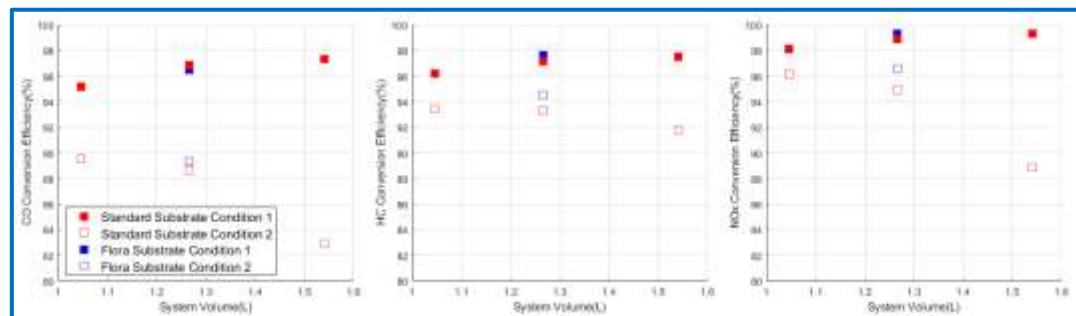
ATS: System d; TWC1(900/2F)+TWC2 (400/4)

Flora substrate emission (Mid Emission)

- It exhibits significant reductions → NO_x/HC/CO/NH₃
- the FLORA substrate performs better in maintaining higher conversion rates during lambda fluctuation
- Faster light off → lower HC/CO/ NO_x during cold start

The conversion efficiency between 2 ageing methods

- As the volume of the catalyst increases, the conversion efficiency of the catalyst under the two ageing conditions also increases
- Considering harsher aging conditions, an aftertreatment system with a higher PGM concentration and a larger volume is needed



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ATS: TWC2 400/4: Dia:118.4mm, Length(mm): a=50, b/d=65, c=80, d=65

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Conclusion

Key findings and the FLORA substrate advantage

Conclusion

1. **Stable engine-out emissions** — In the WLTC, a PHEV decouples the engine and the wheel, allowing the engine to operate at a stable engine load and speed, resulting in more stable engine-out emissions. The tailpipe emissions are focused more on the high-speed stage.
2. **Ageing methods**— Two different ageing conditions, moderate and harsh, were used to simulate the 200,000km deterioration of the catalyst under regular and abnormal driving conditions with UF=0.5.
3. **Substrate volume vs. PGM concentration** — Under moderate ageing, a longer substrate design proves advantageous in achieving lower emissions with the same total PGM content. However, under harsh ageing, a higher PGM concentration significantly enhances the catalyst's resistance to thermal ageing, exerting a greater impact on the conversion efficiency than the substrate volume.
4. **NH₃ formation** — The generation of NH₃ is closely related to the conversion rates of CO and NO_x. Under moderate ageing, a longer substrate is beneficial for conversion, resulting in emissions as low as 5mg/km. However, under harsher ageing conditions, NH₃ emissions increase significantly.
5. **FLORA substrate advantage** — Corning's new FLORA substrate, characterized by high porosity and high cell density, effectively accelerates catalyst light-off and reduces emissions during the cold start phase. With this FLORA substrate, a shorter substrate design can be adopted while maintaining comparable gaseous pollutant conversion efficiency, combined with lower NH₃ emissions.

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175
YEARS