



2022年11月10日

JARIシンポジウム 2022

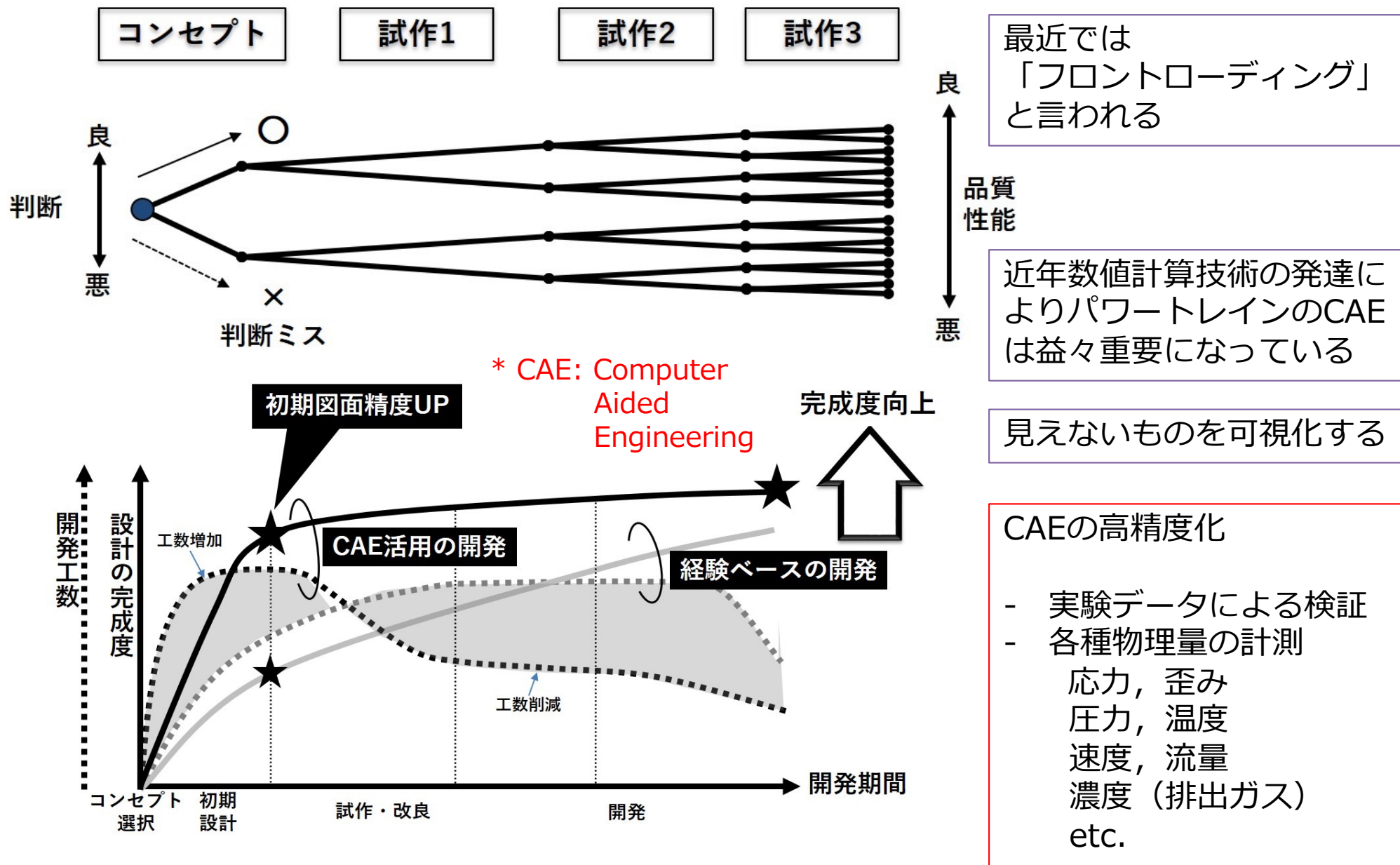
学におけるモデル開発とその活用事例
～ハイブリッドパワートレイン、エンジン及び触媒モデルの
連成による冷間始動エミッション改善～

早稲田大学大学院
創造理工学研究科総合機械工学専攻

草鹿 仁

<http://www.f.waseda.jp/jin.kusaka/>

開発初期におけるコンセプト創出の重要性*

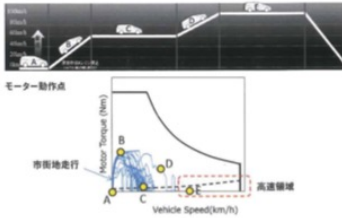


* 金子, 草鹿, 高林 他「基礎からわかる自動車エンジンのシミュレーション」, コロナ社

開発におけるデジタル活用

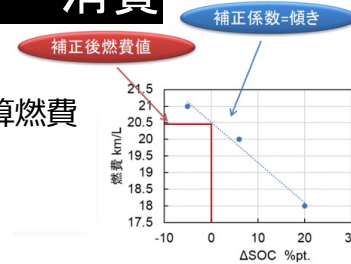
1Dシミュレーションにおけるコンセプトの検討

出力



エネルギー消費

ガソリン換算燃費



パワートレイン基本仕様の決定

HiLSによるシミュレーション

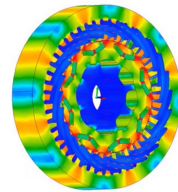
* Hardware in the loop Simulation

3Dシミュレーションにおけるパワートレイン構成要素の検討

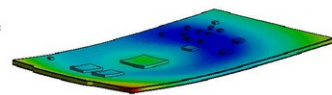
1Dシミュレーションにおけるシステム検討



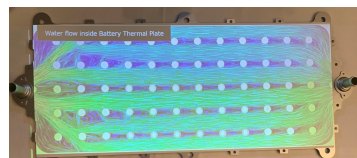
エンジンの高効率化



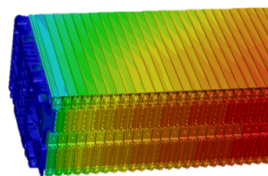
モーターの磁界解析



基板の応力、熱疲労

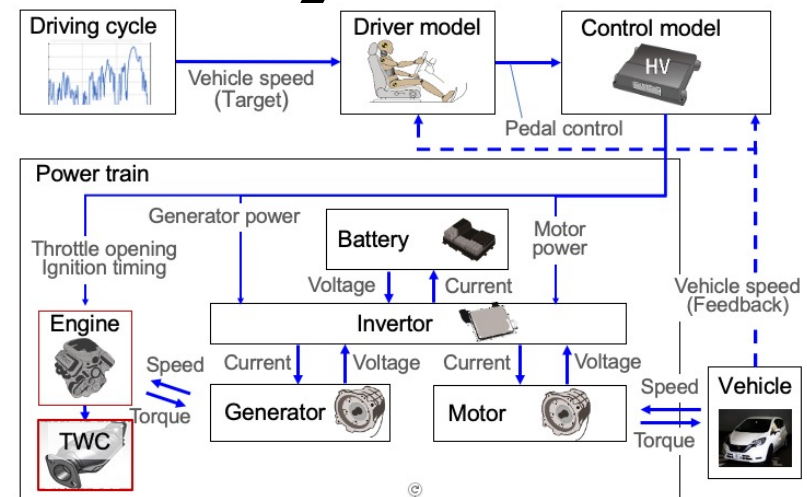


冷却プレートのCFD



バッテリー温度分布

構成要素の1次元モデル化 (リダクション)





Vehicle tests

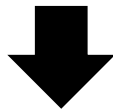
To acquire performance data of

- Each powertrain component
- Exhaust gas emissions on the chassis dynamometer

Parametric analysis

The effects of

- Engine control logic
- Electric Heating Catalyst on fuel consumption and emissions



Numerical model

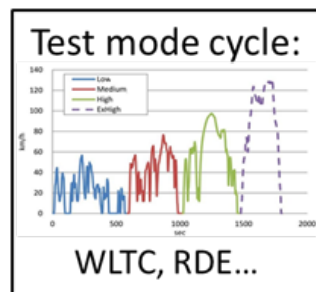
Vehicle model

+

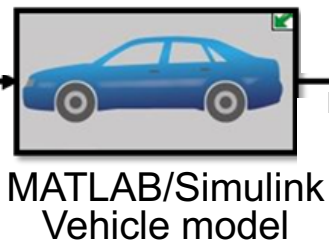
Engine model

+

TWC model



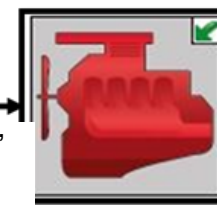
Vehicle speed,
Acceleration,
Required power, SOC



SURIAWASE 2.0

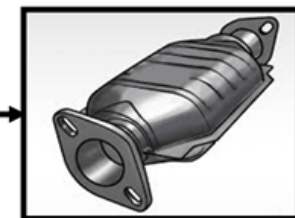


Engine speed,
Required torque,
EGR %



GT engine model

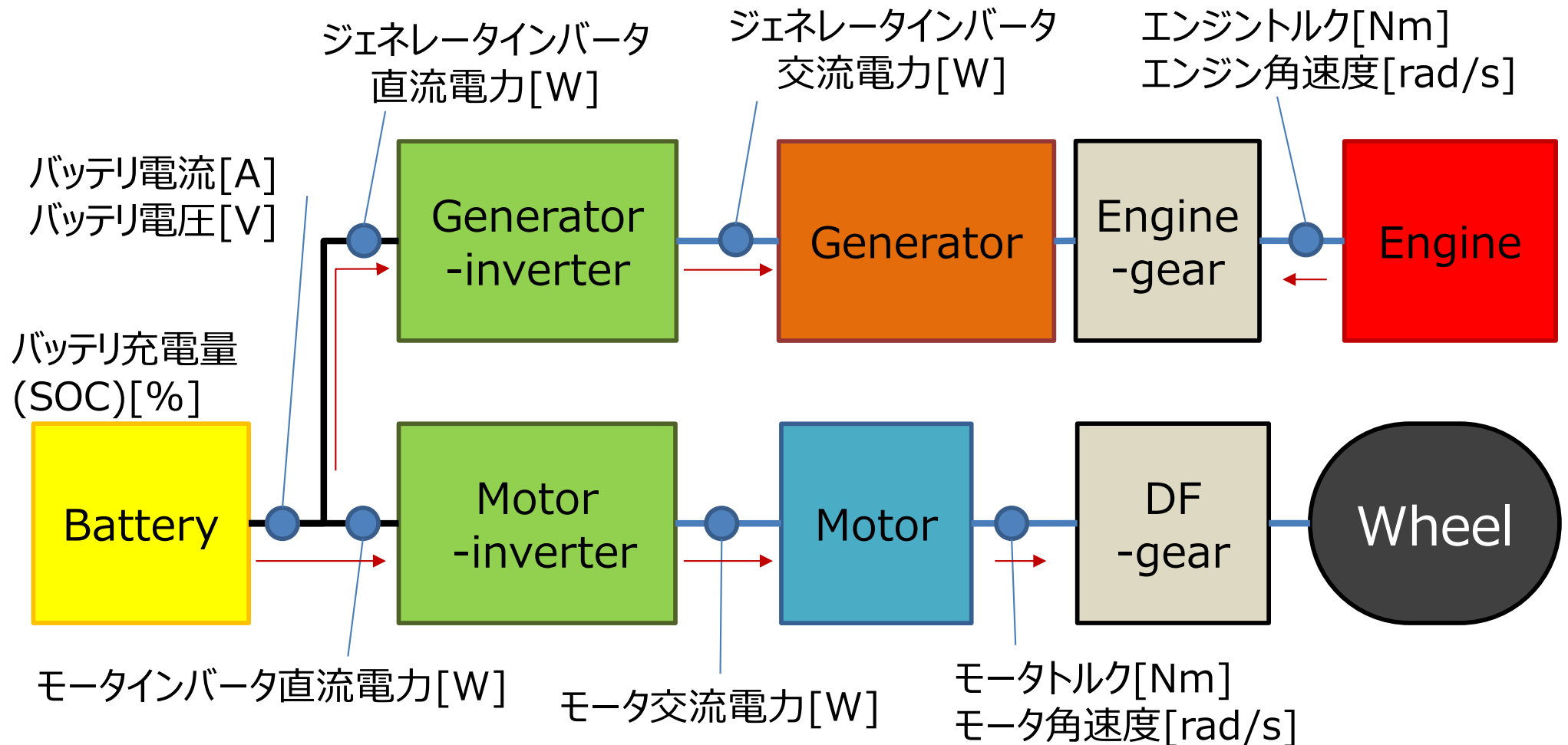
Engine out gas conc. SV



GT TWC model

Fuel economy and
emission evaluation

各種コンポーネントの結合





Overview of vehicle test bench

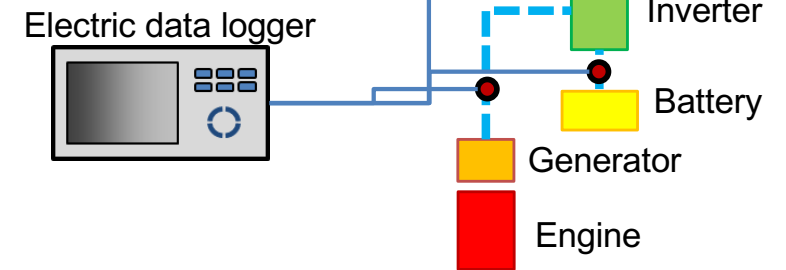
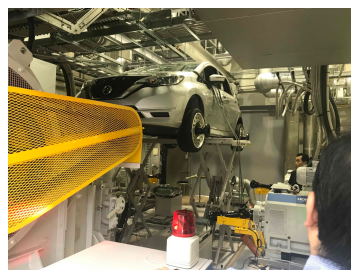
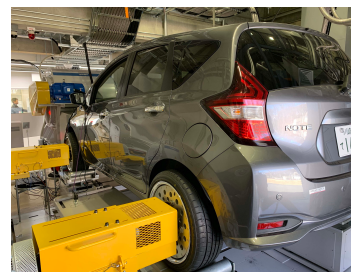
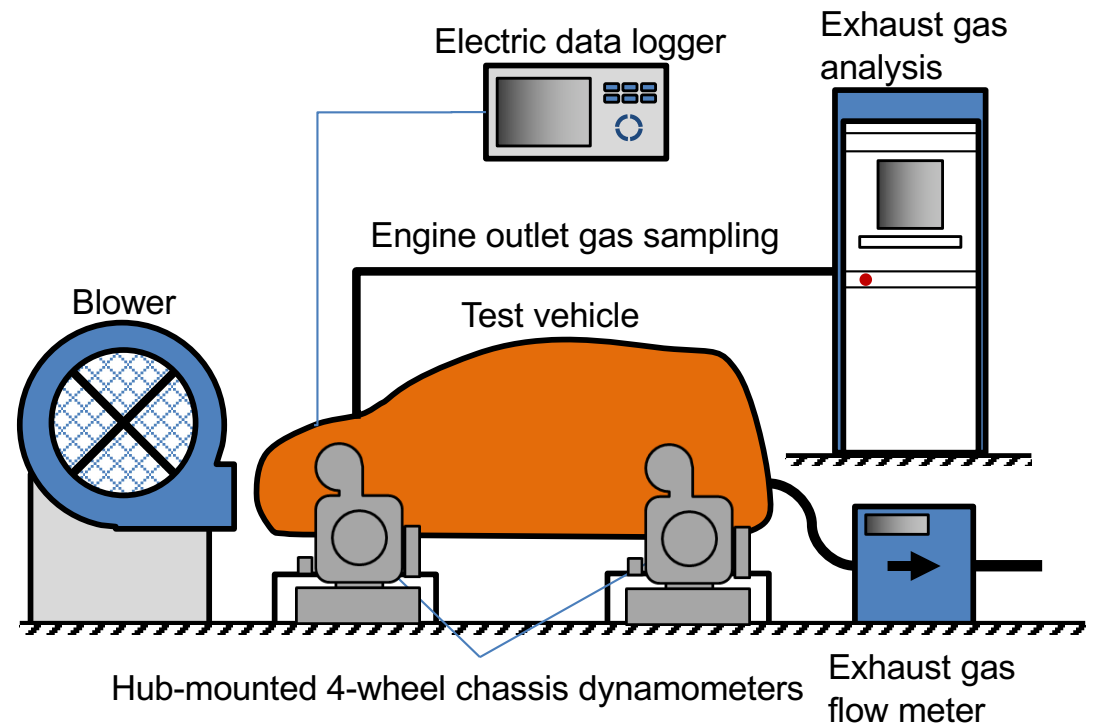
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Experimental conditions

Driving mode	WLTC/Steady state
Initial SOC %	60 / 70 / 80

Main measurement items

Engine	Speed
	Torque
Exhaust	Gas concentration
	Flow rate
Motor	Current
	Voltage
Generator	Current
	Voltage
Battery	SOC (State of charge)
	Current
Inverter	Voltage
	Frequency
	Current
	Voltage





Overview of engine setup

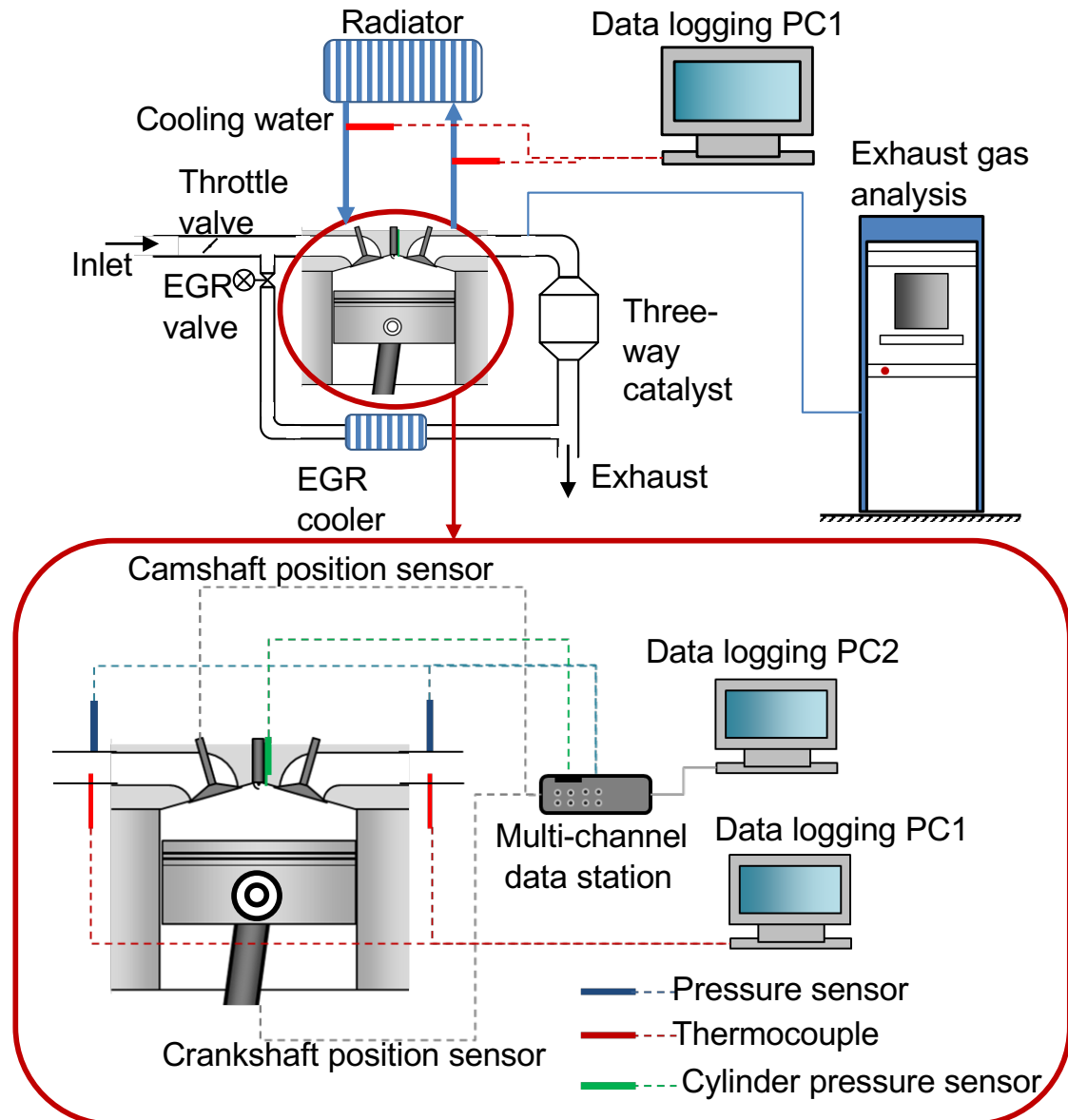
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Measurement items

Intake / Exhaust	Pressure
	Temperature
Cylinder	Pressure
Cooling water	Temperature

Engine specification

Type of engine	Multiport injection, 3 cylinders, 4-stroke-cycle
Displacement cc	1198
Bore × stroke mm	78.0 × 83.6
Compression ratio	12.0
IVO (Intake Valve Open) deg. BTDC	-12 ~ +26
IVC (Intake Valve Close) deg. ABDC	76 ~ 38
EVO (Exhaust Valve Open) deg. BBDC	34
EVC (Exhaust Valve Open) deg. ATDC	10
Maximum output kW / rpm	58 / 5400
Maximum torque Nm / rpm	103 / 3600 – 5200





1D engine model built in GT-Power

➤ TPA(Three pressure analysis)

- Require
- In-cylinder pressure
 - Intake pressure
 - Exhaust pressure
 - Boundary conditions
- Estimate
- Heat release rate
 - The trapping ratio
 - Residual fraction

➤ Steady state conditions

➤ Transient conditions

- Model identification with experimental data

Combustion model

➤ SI Wiebe

$$MBF(\theta) = 1 - \exp \left[-a \left(\frac{\theta - \theta_0}{\Delta\theta_{10-90}} \right)^{m+1} \right]$$

θ : Crank angle a, m : constant

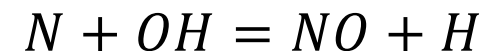
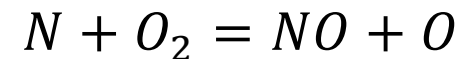
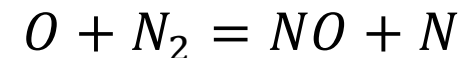
θ_0 : Crank angle at combustion starts

$\Delta\theta_{10-90}$: Combustion duration

Emissions model

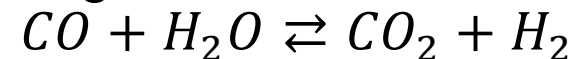
➤ NOx

Extended Zeldovich mechanism



➤ CO

Water gas shift reaction



➤ THC

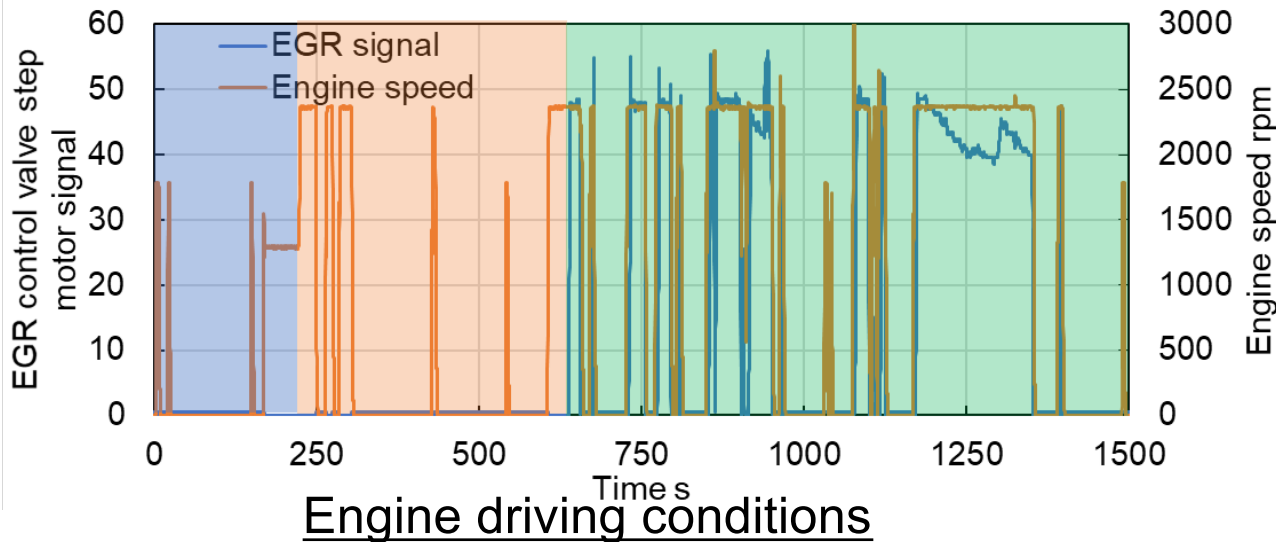
Unburned fuel components



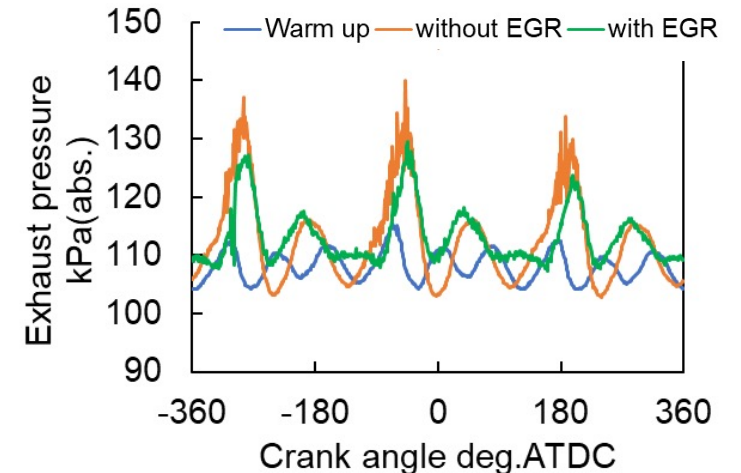
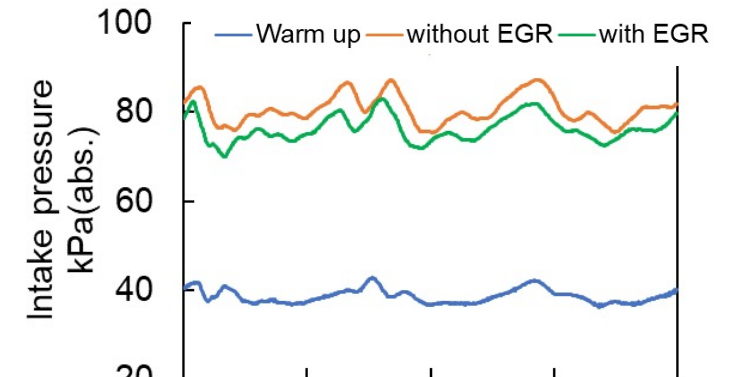
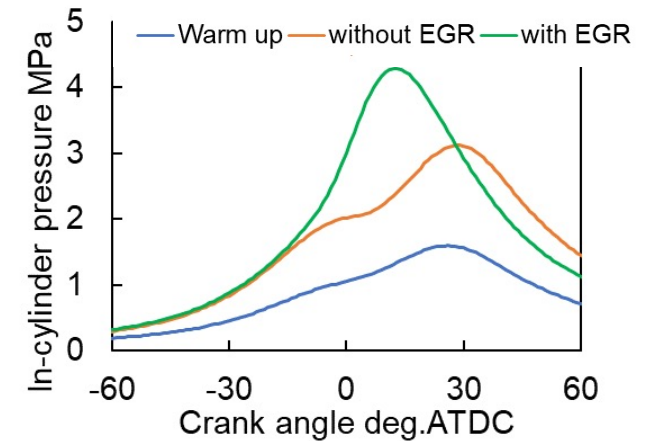
Results of vehicle tests

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WLTC cold Initial SOC 60%



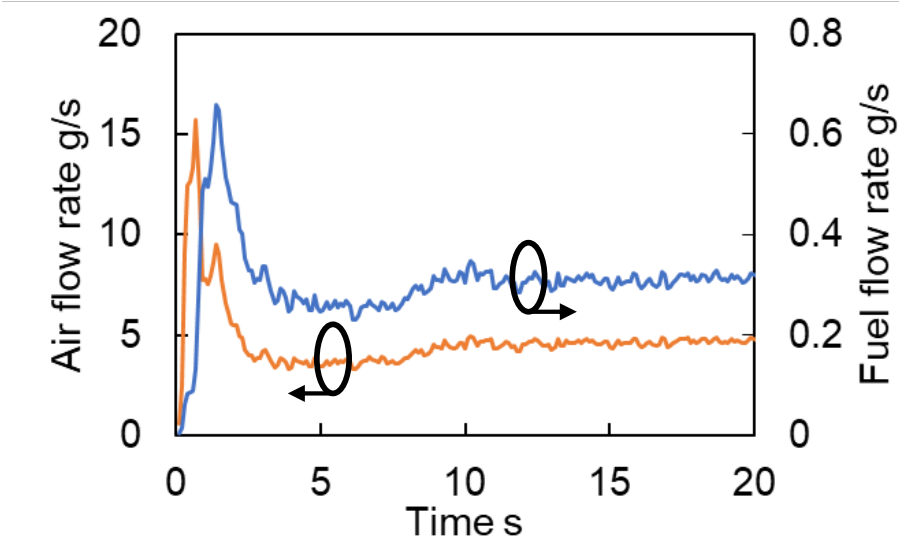
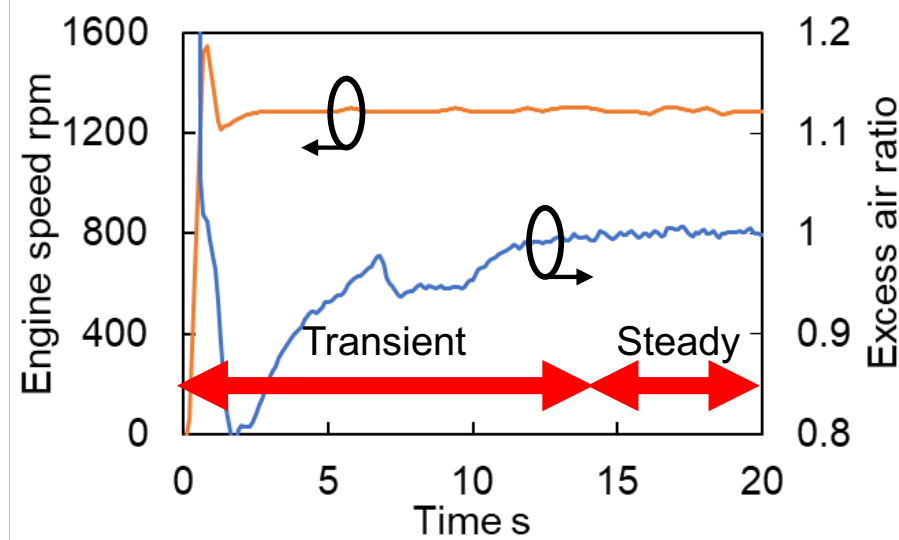
	Warm up	without EGR	with EGR
Engine speed rpm	1300	2370	2370
Engine torque Nm	34.5	79.5	72.0
EGR rate %	0	0	13
A/F	14.7	14.7	14.7
Fuel flow g/s	0.383	1.27	1.11
Intake air flow g/s	5.82	19.1	17.0
CO ppm	4010	5081	4121
NO ppm	187.0	1038	400.1
THC ppm	3265	3444	2330



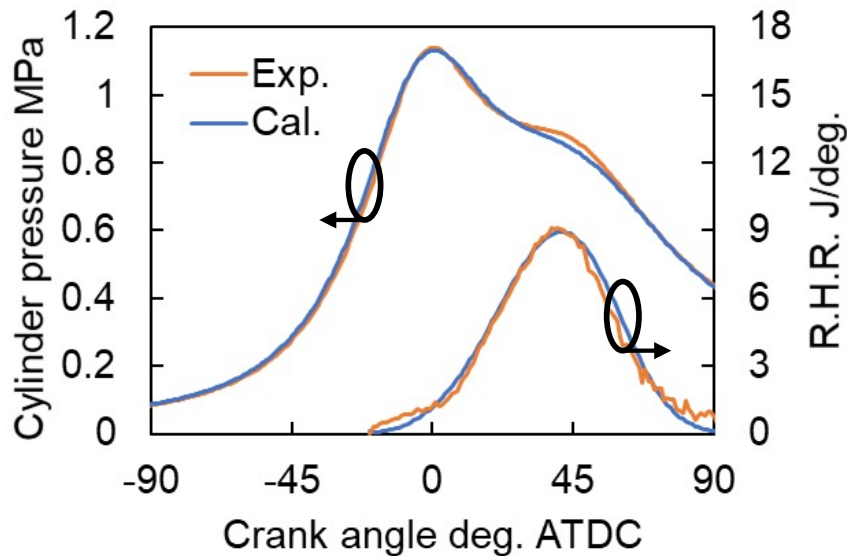


Result validations : Steady state

Input (cold start)



Results at steady condition



Comparison between exp. and cal.

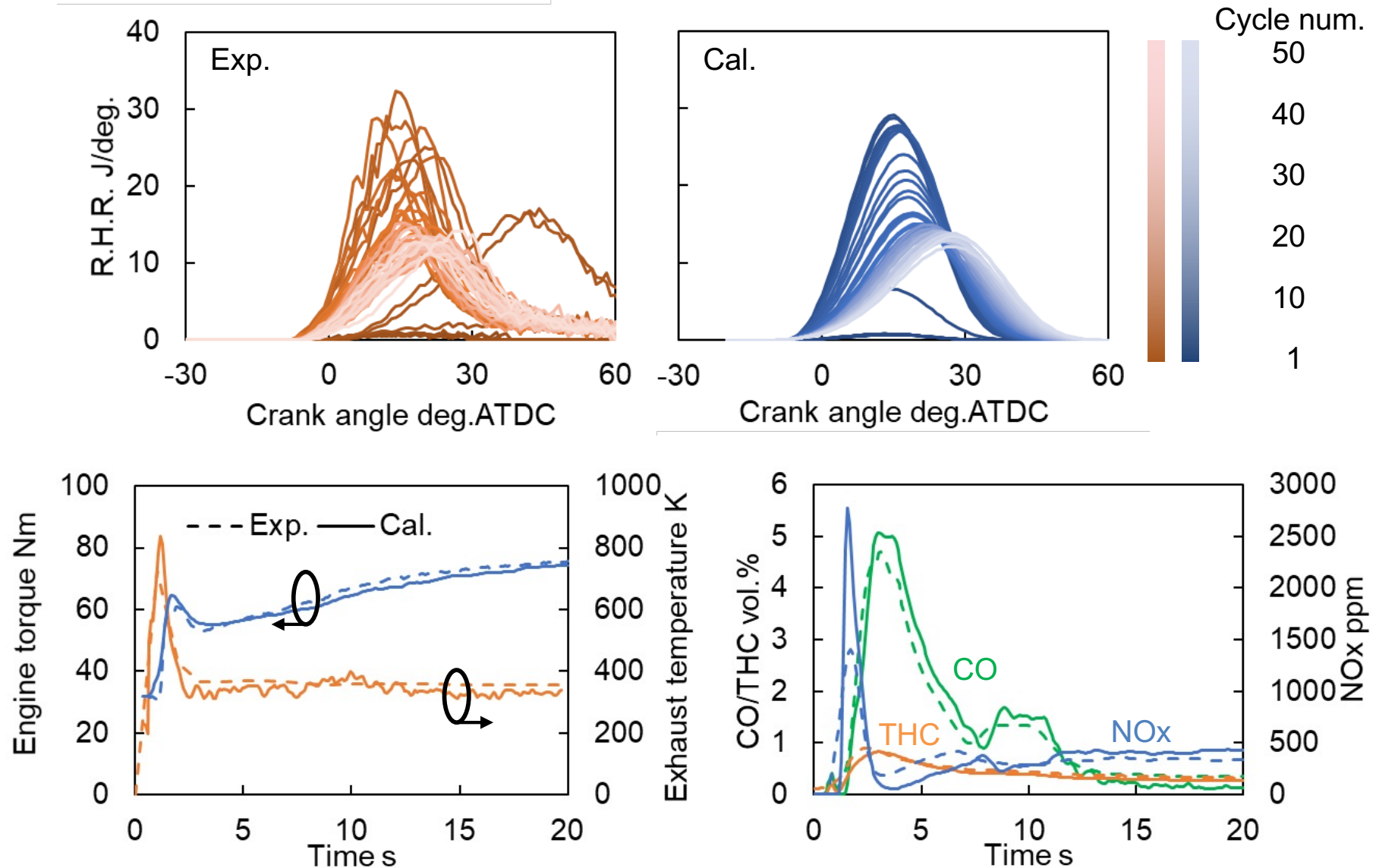
	Exp.	Cal.
Torque Nm	35.5	32.7
Exhaust temp. K	734.6	743.8
NOx ppm	454.7	412.5
CO vol.%	3.403	1.467
THC vol.%	3.175	2.729



Result validation : Transient

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Results at transient condition (cold start)

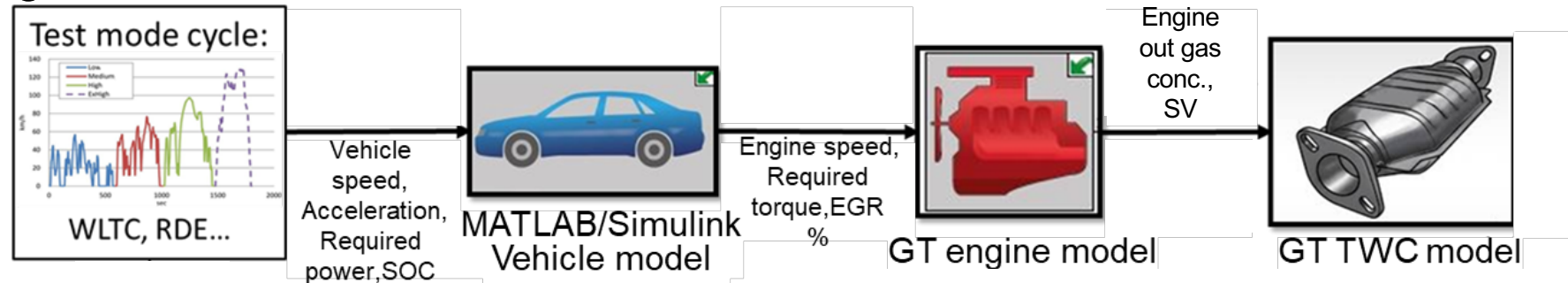




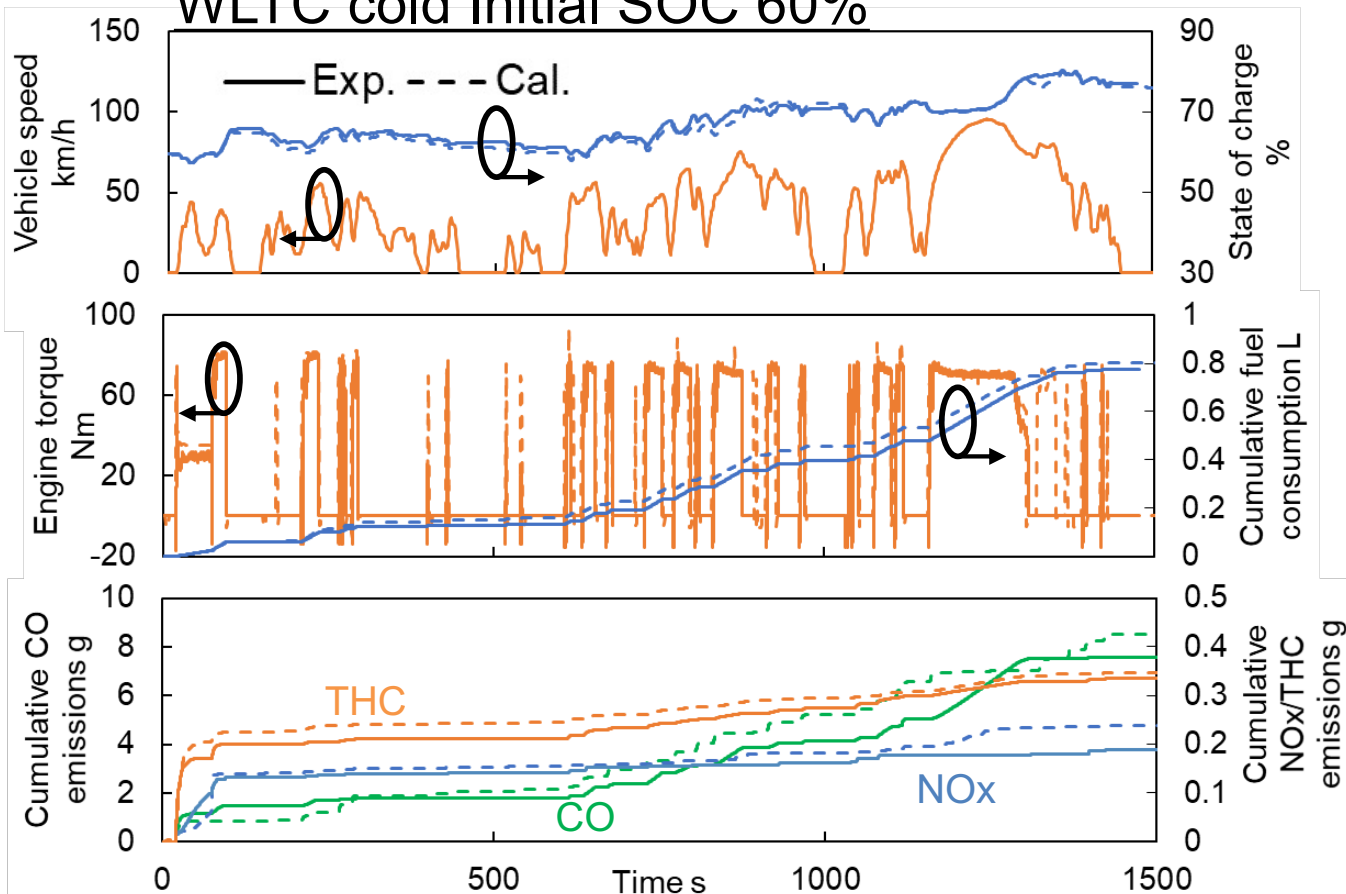
Validation results of integrated model

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Integrated vehicle model



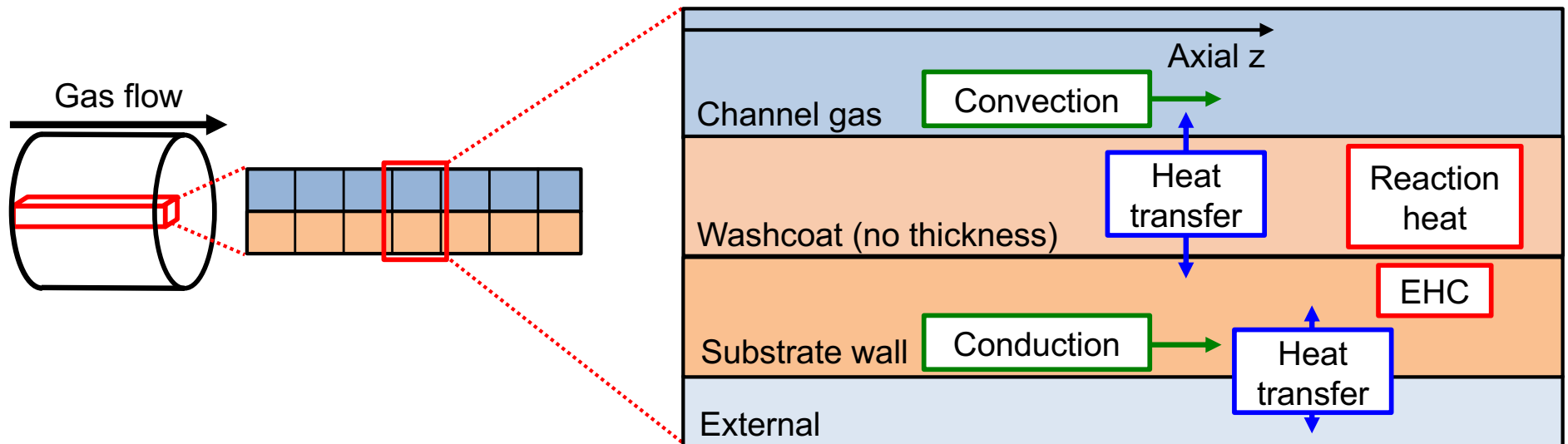
WLTC cold Initial SOC 60%



- ✓ Integrated model has a good agreement with experiment.
- ✓ Fuel economy and emissions are predictable.



➤ Energy balance



Gas phase

$$\varepsilon_v \rho_g C_{p,g} S \frac{\partial T_g}{\partial t} = -\rho_g v C_{p,g} \frac{\partial T_g}{\partial z} - hS(T_g - T_s)$$

Solid phase

$$\psi_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \left(f_{sb} \lambda_{sb} \frac{\partial T_s}{\partial z} \right) + hS(T_g - T_s) - \sum_{j=1}^{n_{rct}} \Delta H_j r_j + \dot{s}_{power} + h_x S_x (T_x - T_s)$$

➤ Reaction rate

$$r_j = k_j [A]^a [B]^b, k_j = A_j \exp \left(\frac{-E_j}{RT_s} \right)$$



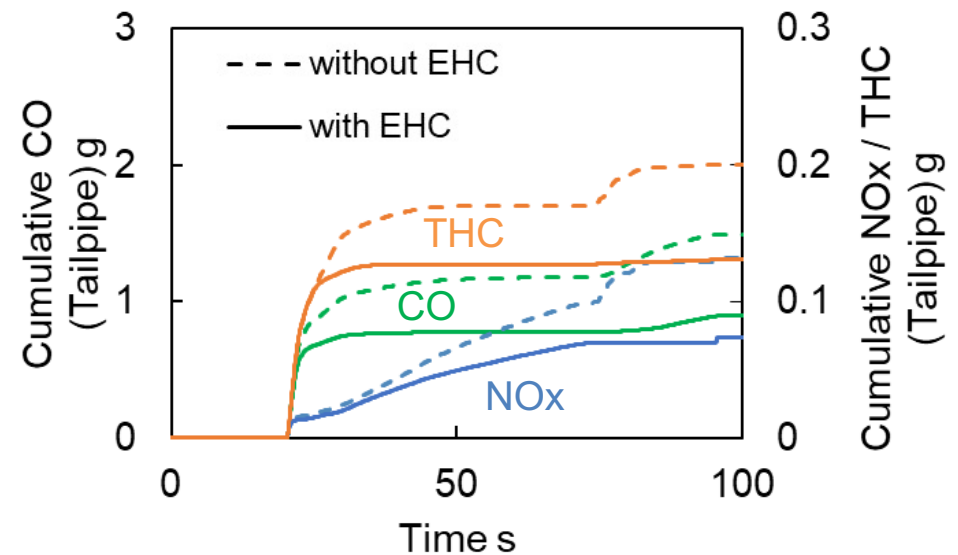
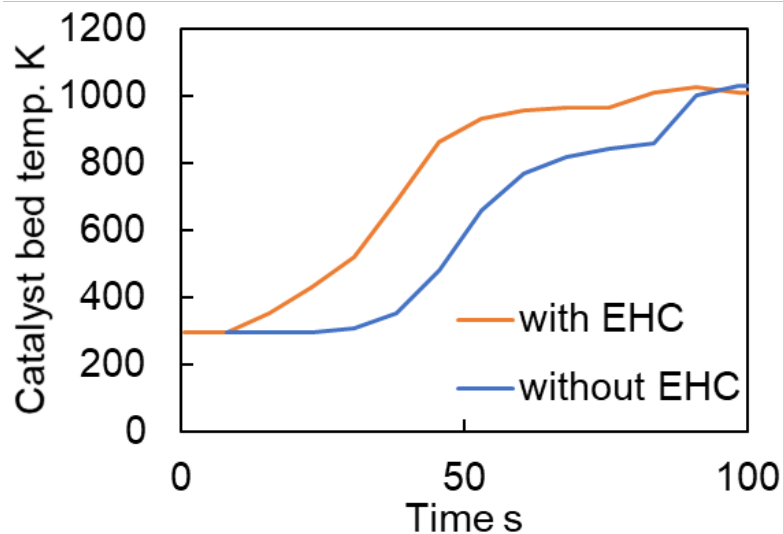
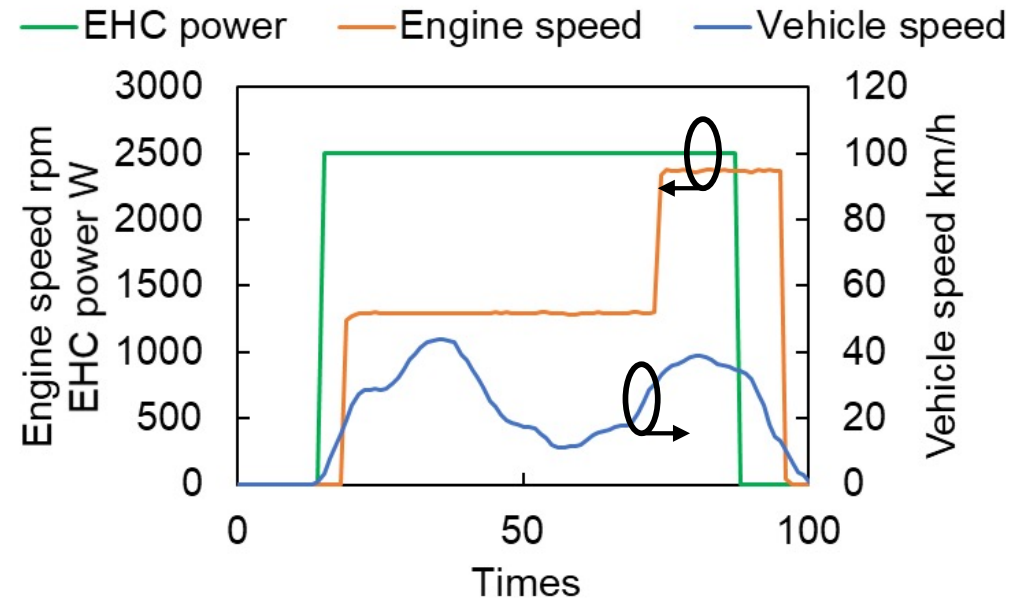
Effect of EHC on emissions and fuel consumption under cold start

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➤ EHC performance prediction under cold start

EHC conditions

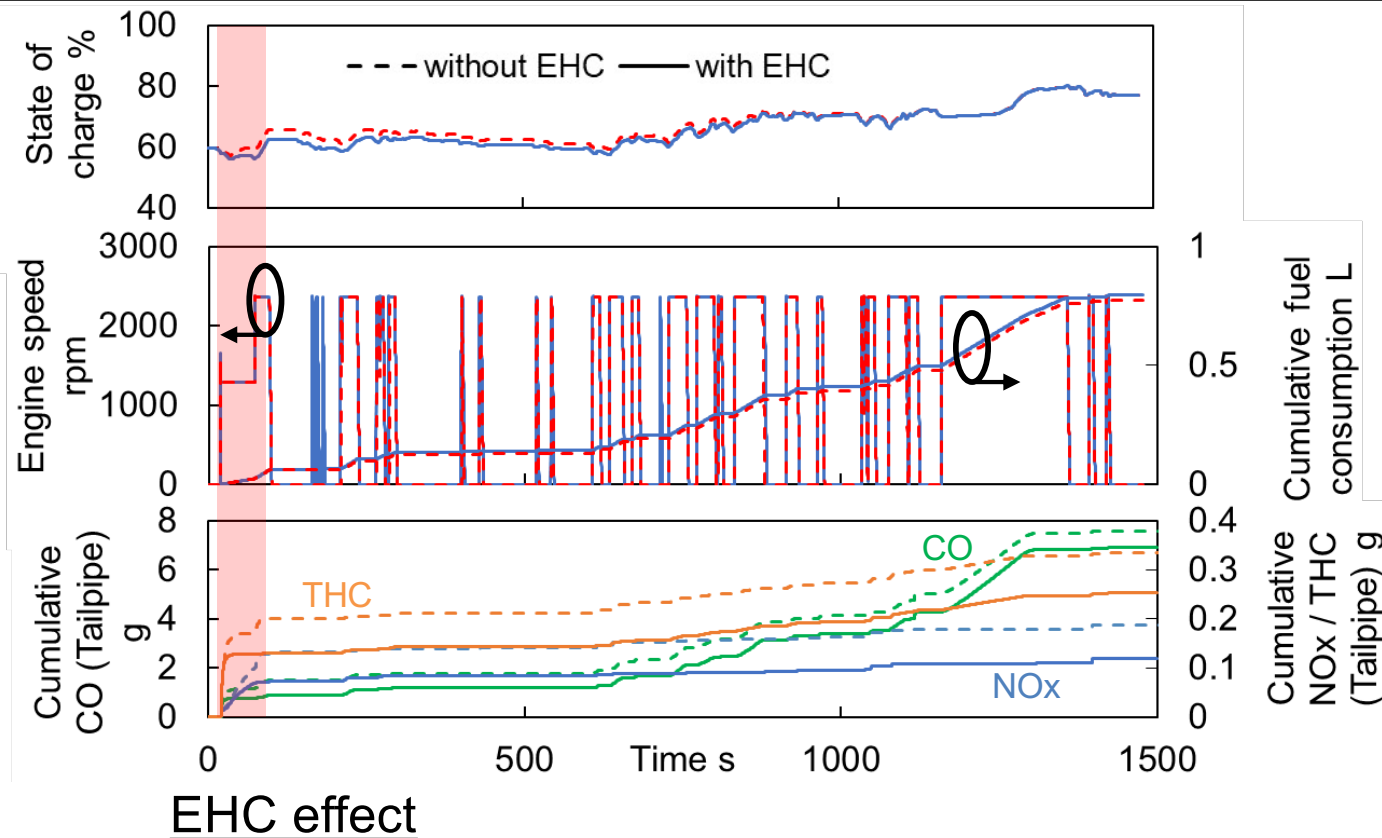
Input power kW	2.5
Input duration s	72
Input energy kJ	180
Timing	Driving start





Effect of EHC on emissions and fuel consumption under WLTC

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EHC effect

	without EHC	with EHC	Reduction %
Fuel consumption L	0.775	0.795	-2.66
CO emissions g	7.59	6.90	9.02
NOx emissions g	0.188	0.119	36.8
THC emissions g	0.335	0.253	24.4

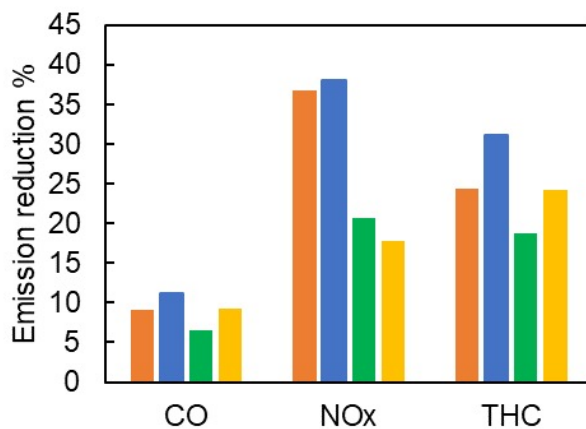
- ✓ Emissions can be reduced effectively during cold-start.
- ✓ Fuel consumption increased due to the increased number of engine start as the battery charge reduction.



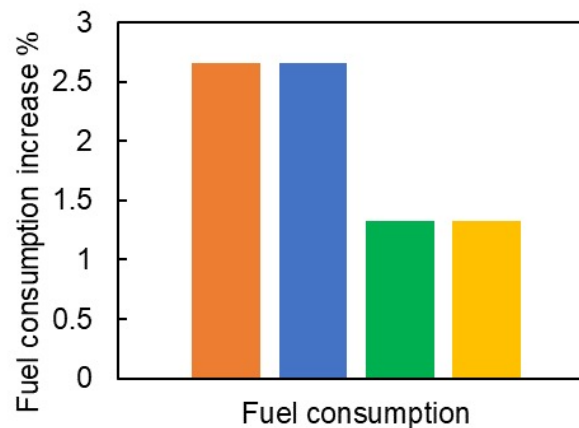
➤ Verification of effect of EHC input timing and duration

EHC conditions

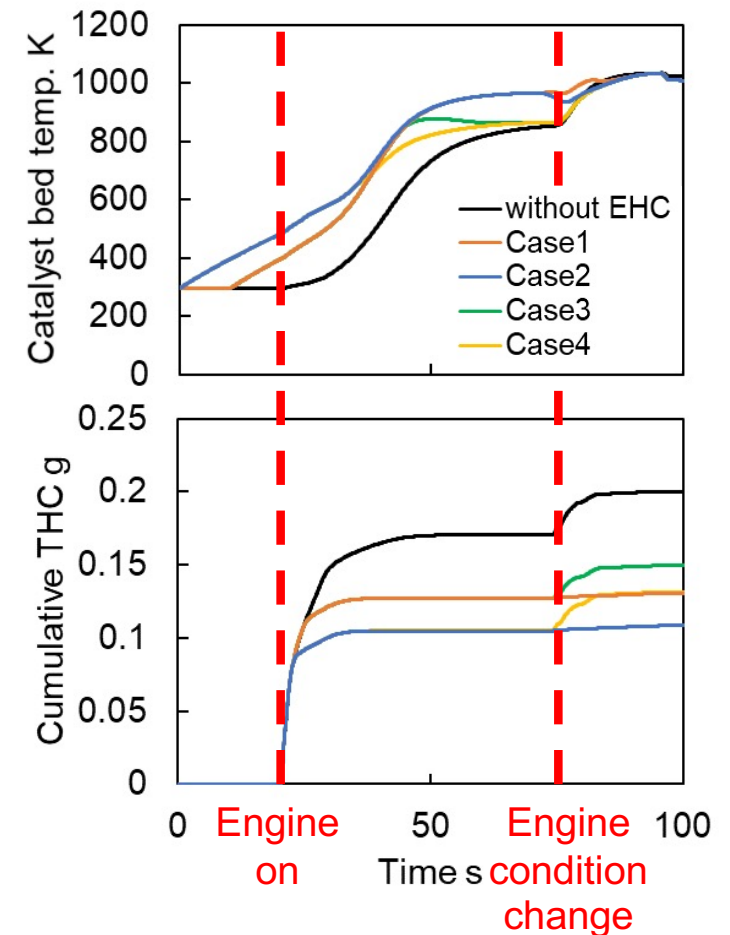
Case num.	1	2	3	4
Input power kW	2.5	2.5	2.5	2.5
Input duration s	72	72	35	35
Input energy kJ	180	180	87.5	87.5
Timing	Driving start	Switch on	Driving start	Switch on



Case1 Case2 Case3 Case4



Case1 Case2 Case3 Case4



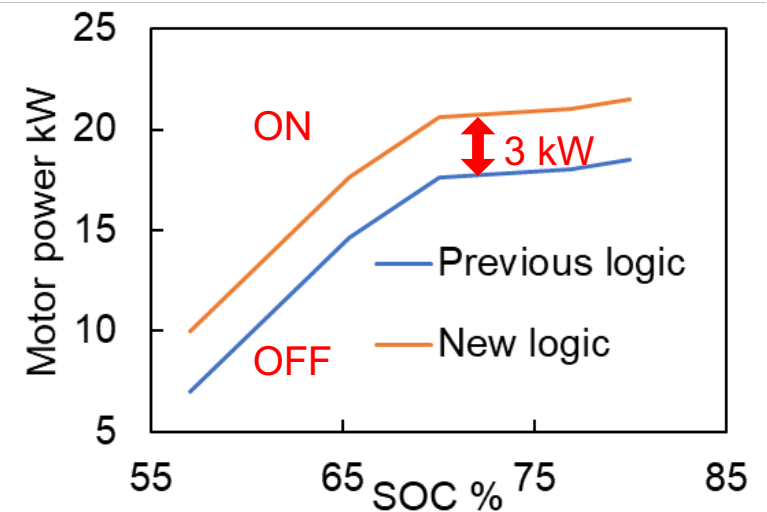
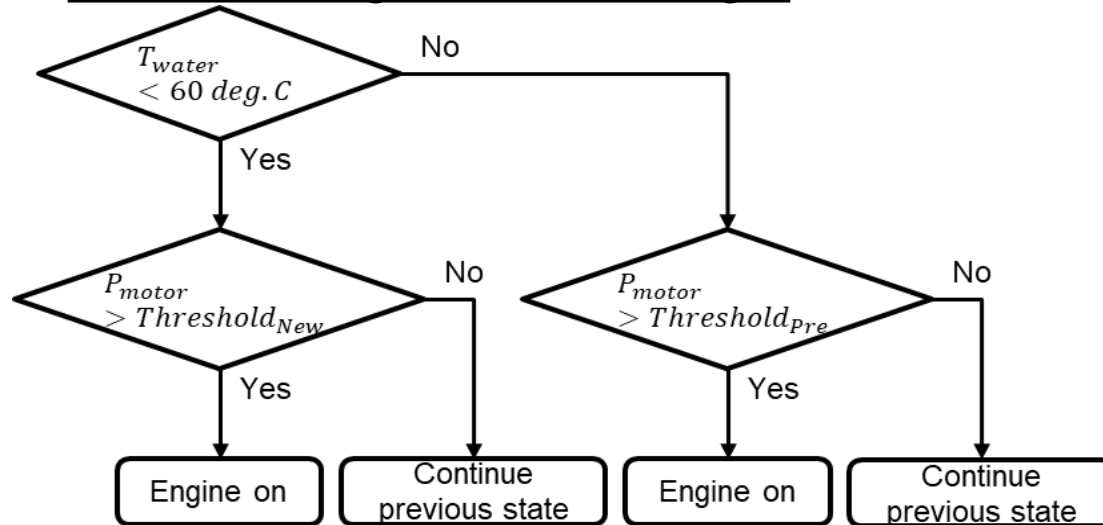
- Higher temperature by earlier input timing at engine on can help reduce emissions.
- Temperature can be maintained at high level by long duration.



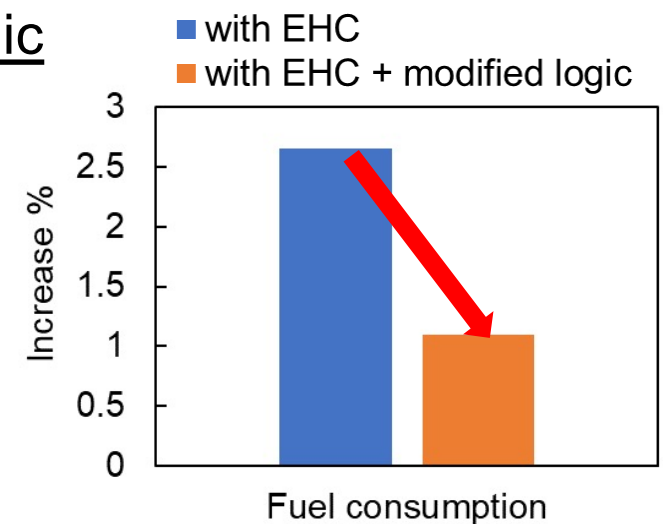
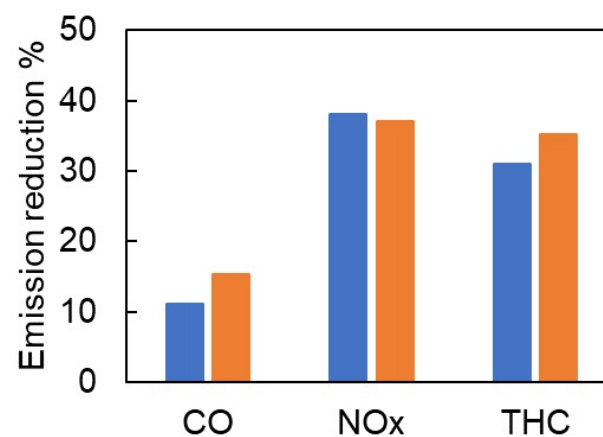
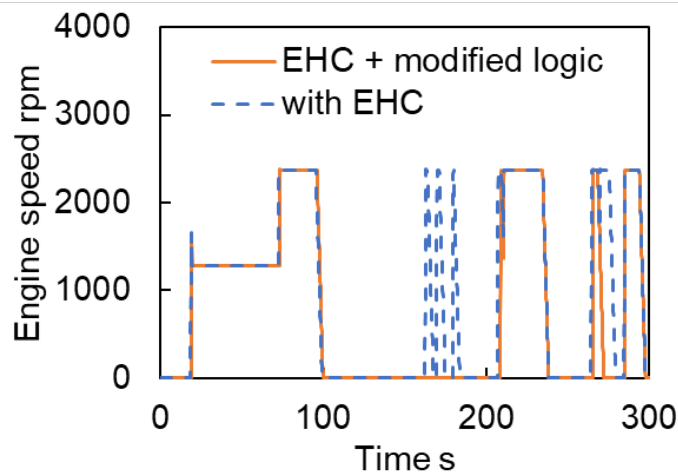
Effect of EHC and engine control logic

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➤ Modified engine control logic



➤ The effect by EHC + Modified engine control logic



✓ Fuel consumption could be improved without deteriorating emission performance



過渡条件を高精度に再現可能な統合シミュレーションモデルの構築，燃焼消費量および排出ガス浄化性能の同時改善を目的として，実車試験で取得したデータをもとにモデルを構築し，EHCとエンジン制御による燃料消費量および排出ガス浄化性能についての評価を行い，以下の知見を得た．

- 実車試験で取得したデータをもとに構築したエンジンモデルによってエンジンの出力および排出ガスを概ね再現した．
- エンジンモデル，車両モデル，三元触媒モデルの連成によって構築した統合シミュレーションモデルは燃料消費量と排出ガスを高精度に評価し，各構成要素の挙動・状態を予測可能である．
- EHCの適用によって三元触媒の早期暖機・活性化が可能である．
- EHCをより早期からより長時間適用することによって，燃費は悪化するが排出ガス浄化性能は大幅に向上する．
- EHCを適用する際，冷間始動時のみエンジン制御を変更することで燃費の悪化を最小限に抑制しつつの排出ガス浄化性能が向上する可能性が示された．

車両全体を考慮した電動車両DX開発

～MBDを活用した手戻りの少ない自動車開発プロセス 第二ステージ～

外部情報

道路, 地形 (勾配), 渋滞, 気温, 実路走行

パワートレイン

補機類

サーマルマネジメント

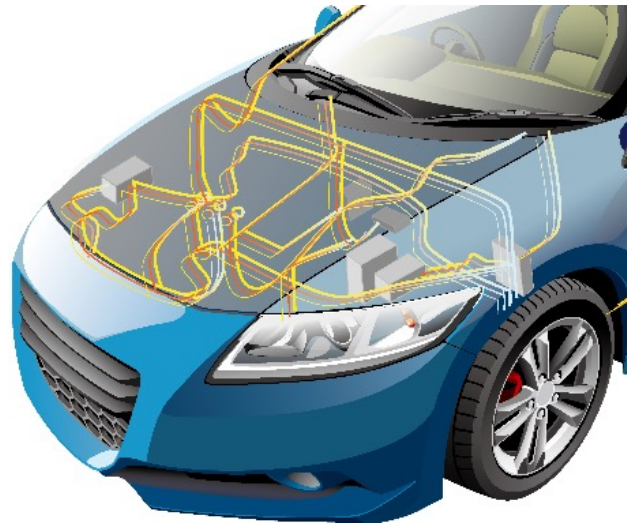
エアコン

ビークルダイナミクス

ボディ設計

NVH

Noise Vibration
Harshness





本講演の内容の一部は, エヌ・イー・ケムキャット株式会社及びAZAPA株式会社との共同研究の成果によるものです. ここに記して謝意を表します.