

Simulation Technology and Its Application to xEV Driving Control Development with AI Support

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Simulation Technologies for xEV Driving Control Development

3

Control Calibration Process Improvement by AI Support

① Engine Stop Control in xEVs

② Step 1: Optimal Control Derivation Using Reinforcement Learning

③ Step 2: Generalization Through Mechanism Analysis

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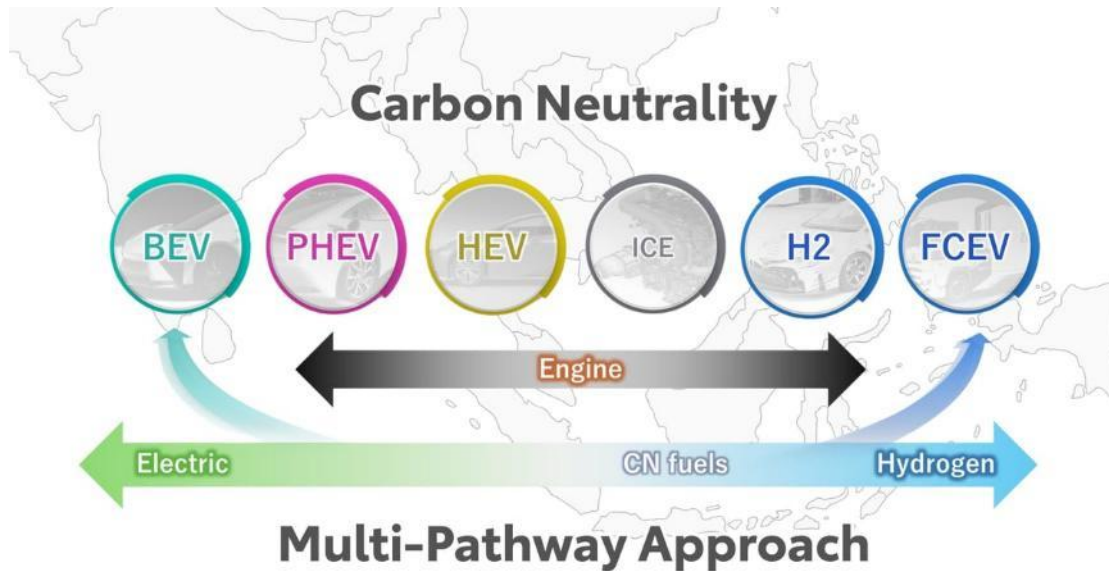
5

Conclusion

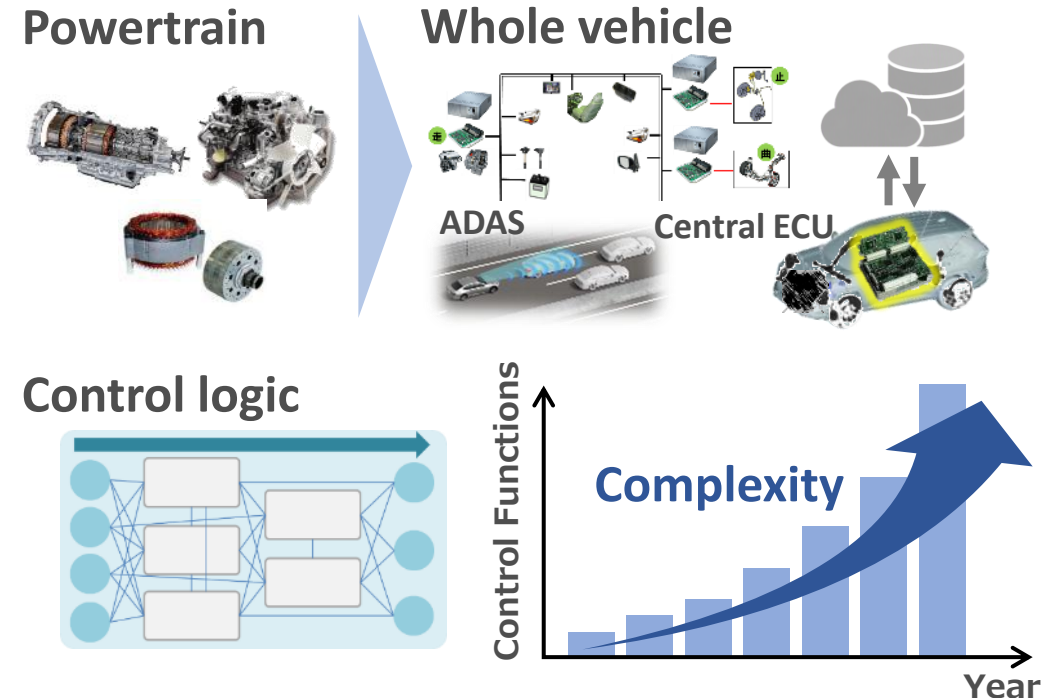
Introduction

Challenges in Vehicle Development

Expansion of Vehicle System Types



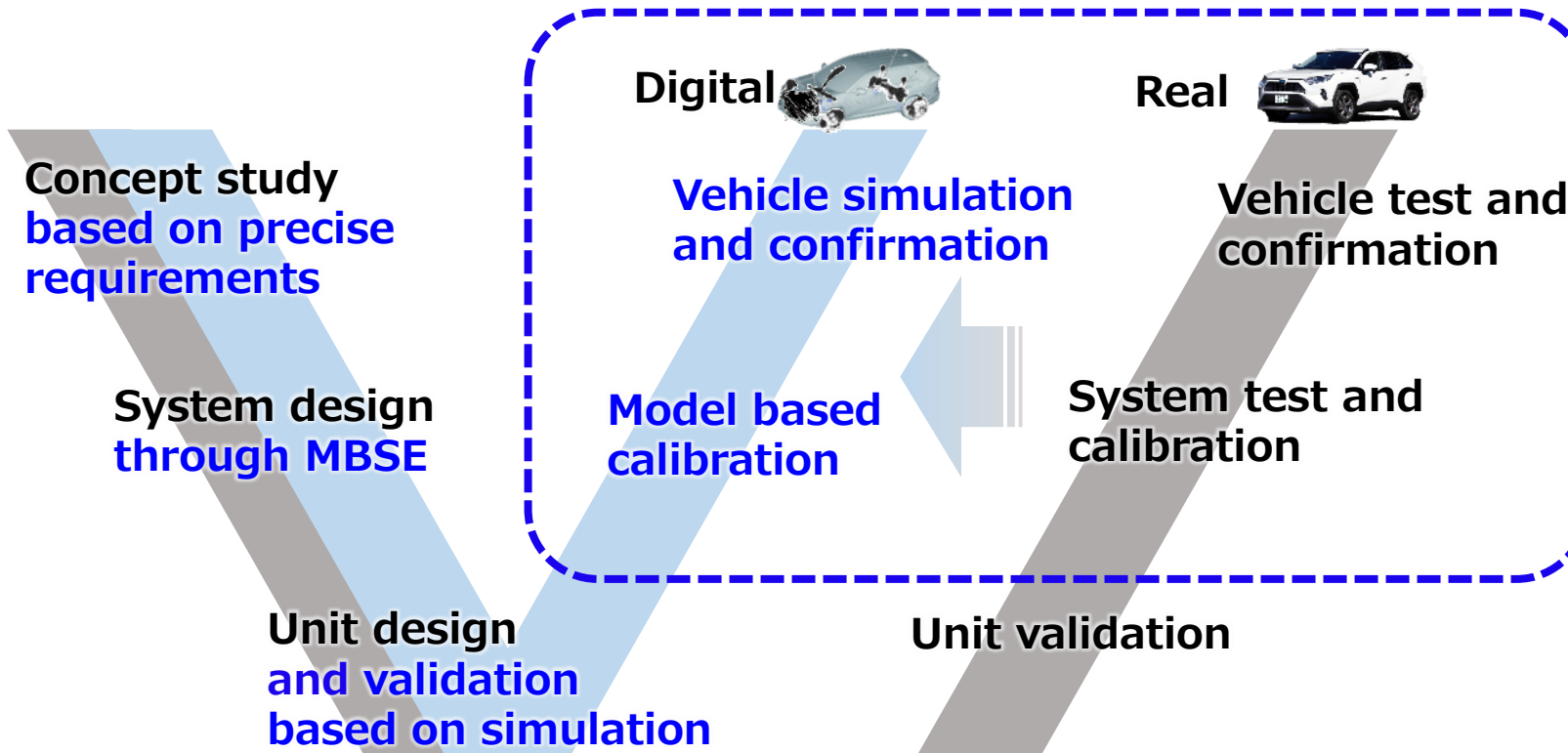
Expansion of Control Domains



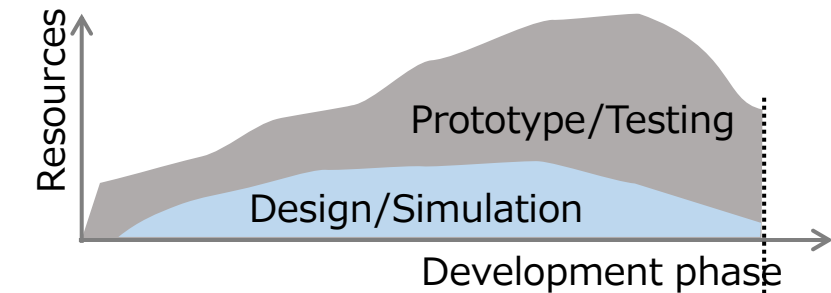
Both result in substantially increased development efforts and resource requirements

Model Based Control Development and Calibration (MBD/MBC)

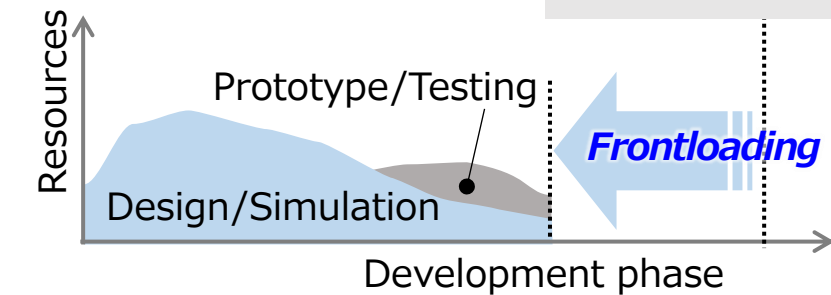
Scope of this study:



Before



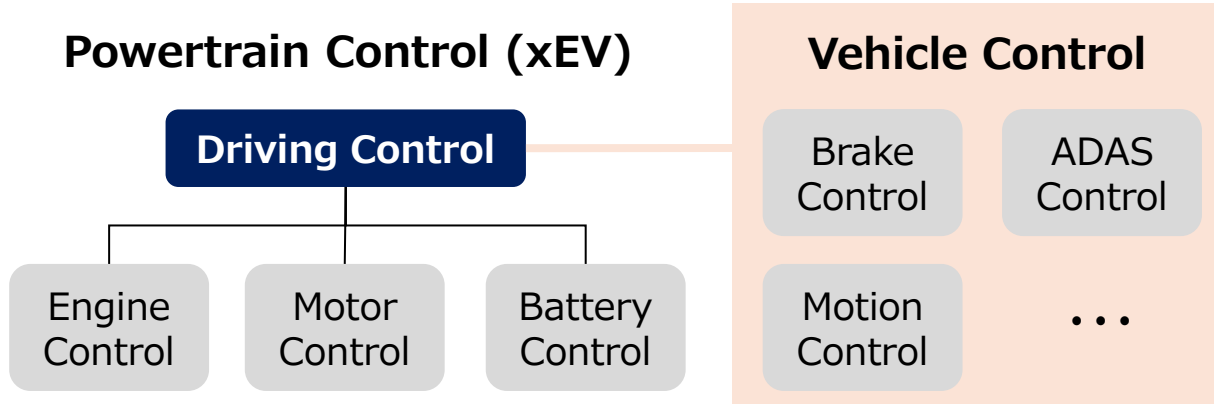
Target



Target: A fully digital development process through MBD/MBC on the right-hand side of the V

Introduction

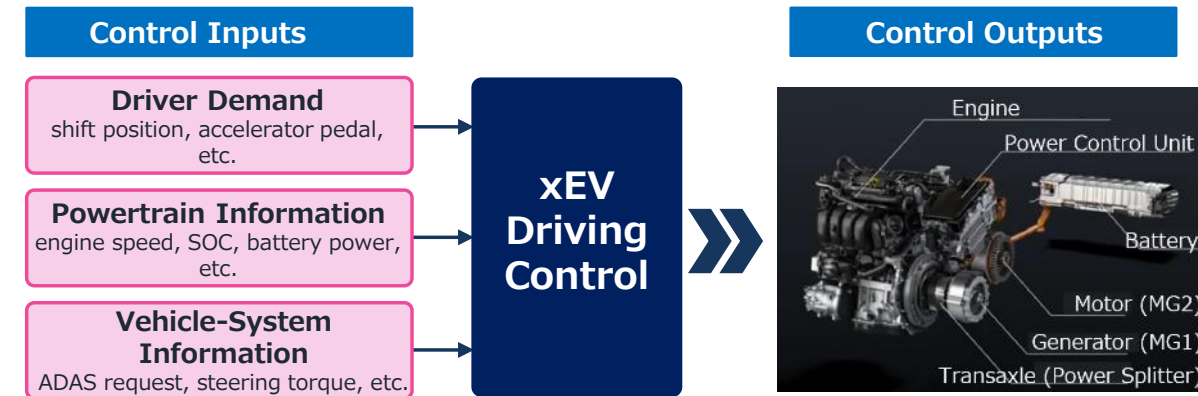
Driving Control of xEVs



Features of Driving Control

- Strongly coupled with powertrain and vehicle-level control
→ **Hundreds of interdependent control functions**
- Vehicle-level performance must be ensured
→ **Hardware or software changes require re-validation and recalibration**

Example : Toyota Hybrid System (THS)



Main Functions

- Satisfy driver demand
→ Driving performance and drivability (shock, hesitation, etc.)
- Respect unit operating constraints
→ Motor, inverter, battery, engine, etc.
- Operate each unit at high-efficiency points

Many factors affect the operating scenario

One of the largest vehicle control functions : High potential for development effort reduction

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Simulation Technologies

Key Requirements for xEV Driving Control Simulation at Toyota

Scalability

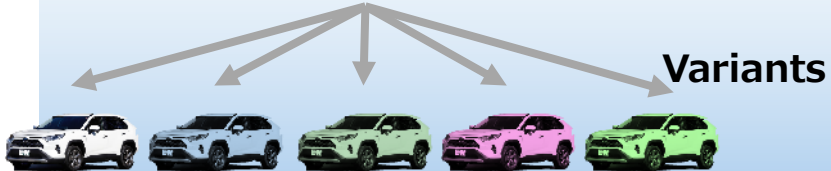
THS



Base System



Leading Vehicle



Variants

HEV, PHEV
SUV, Sedan, Minivan, etc...

Generality

Driving Control

Functions

Drivability

Engine Start and Stop

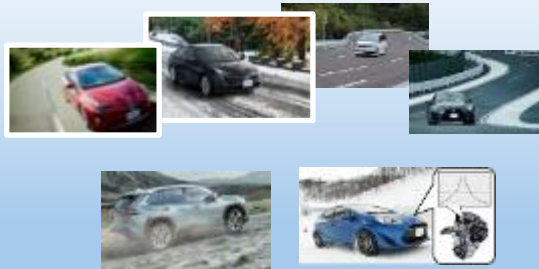
Operating point

NV

Power Management

etc...

Scenes



Explainability

Quality Assurance

Regulations,
Requirements

Control / Software
Development

Calibration & Testing

Results

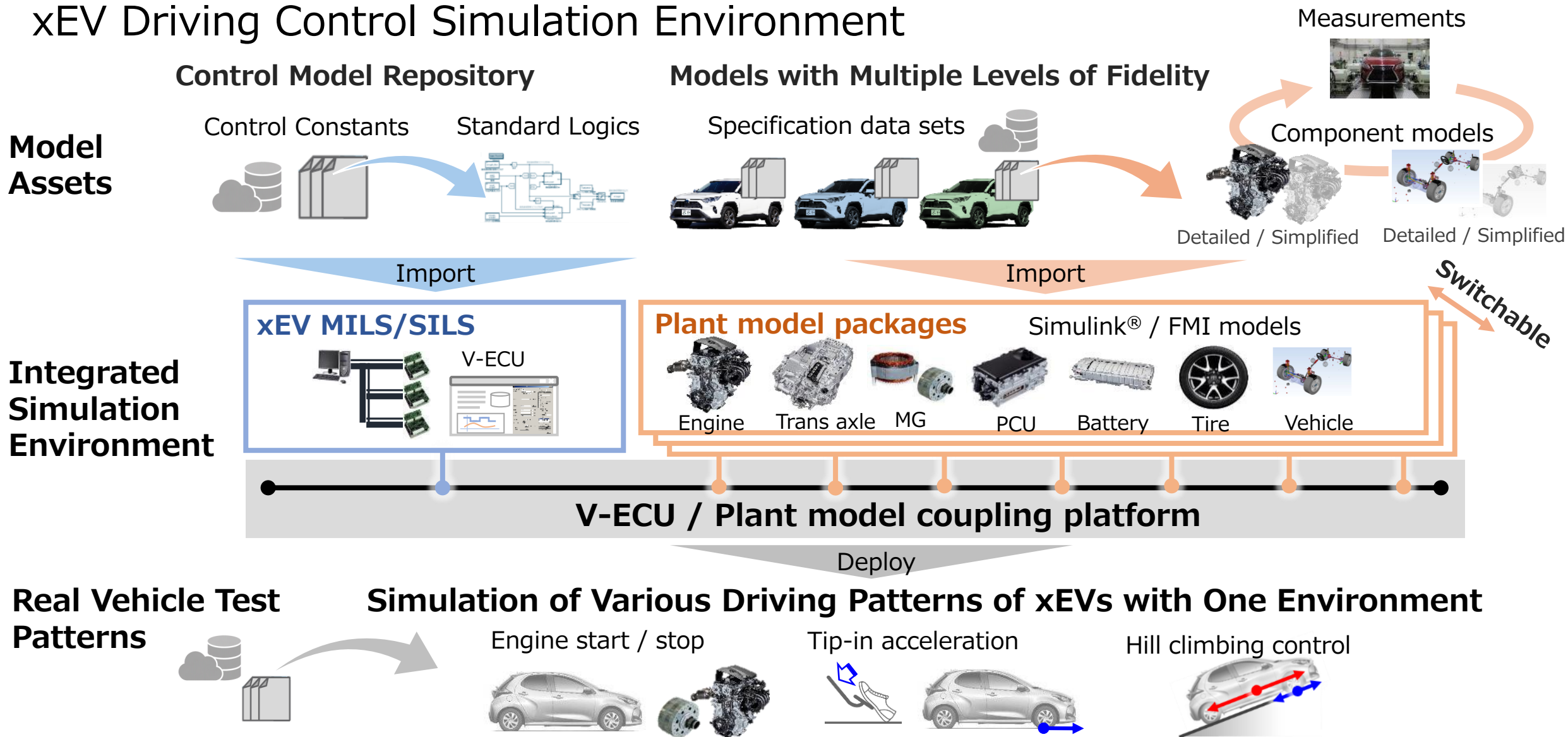
Traceable

One Standard Simulation Environment



Simulation Technologies

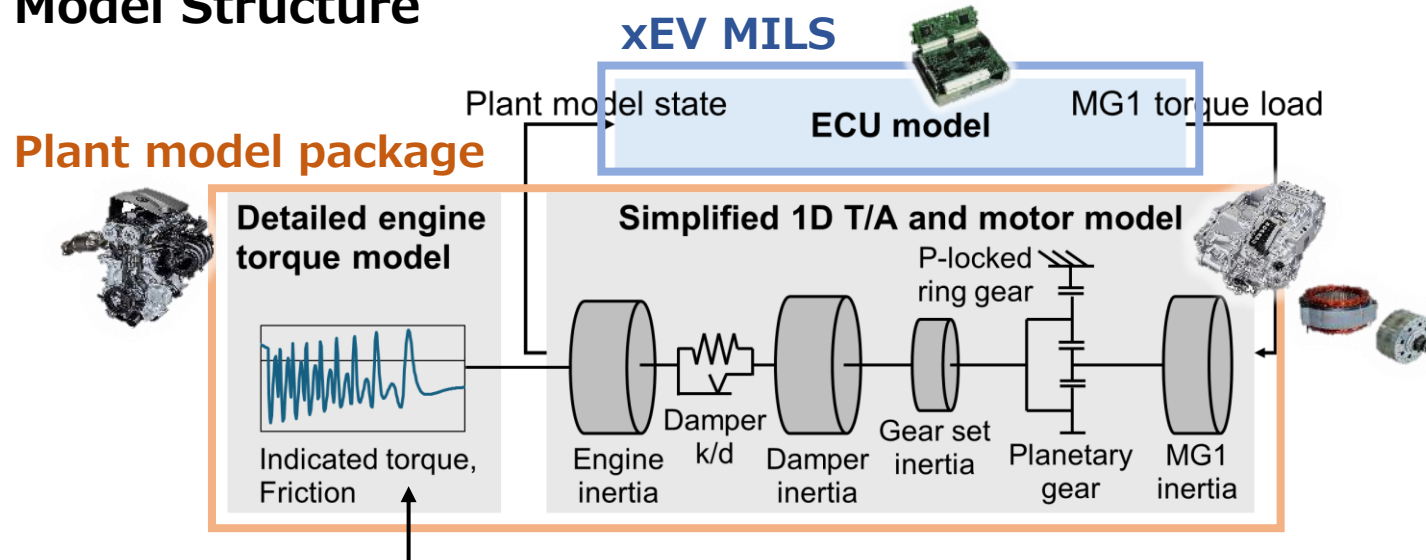
xEV Driving Control Simulation Environment



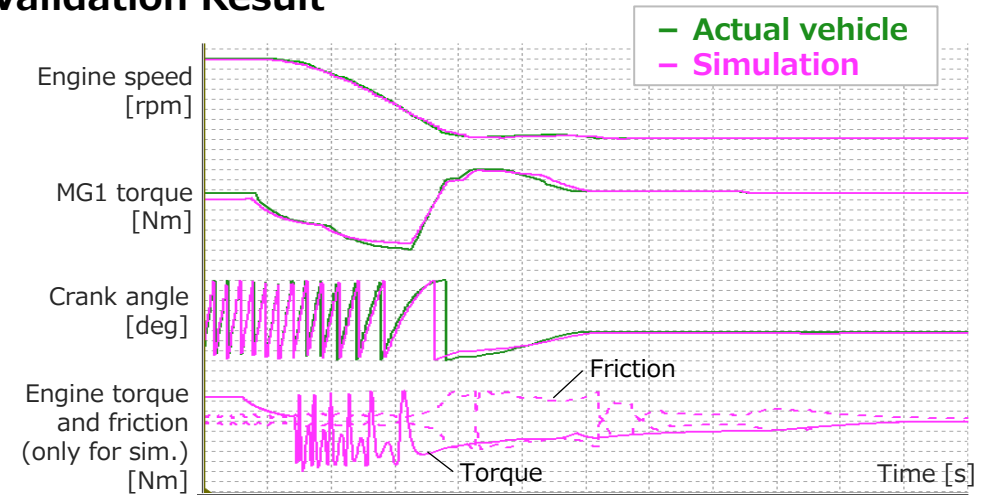
Example: Prediction of Engine Stop Control※ and Behavior in THS

※ Details of engine stop control will be discussed later

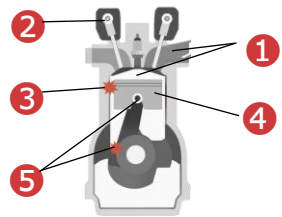
Model Structure



Validation Result



Engine torque balance in plant model



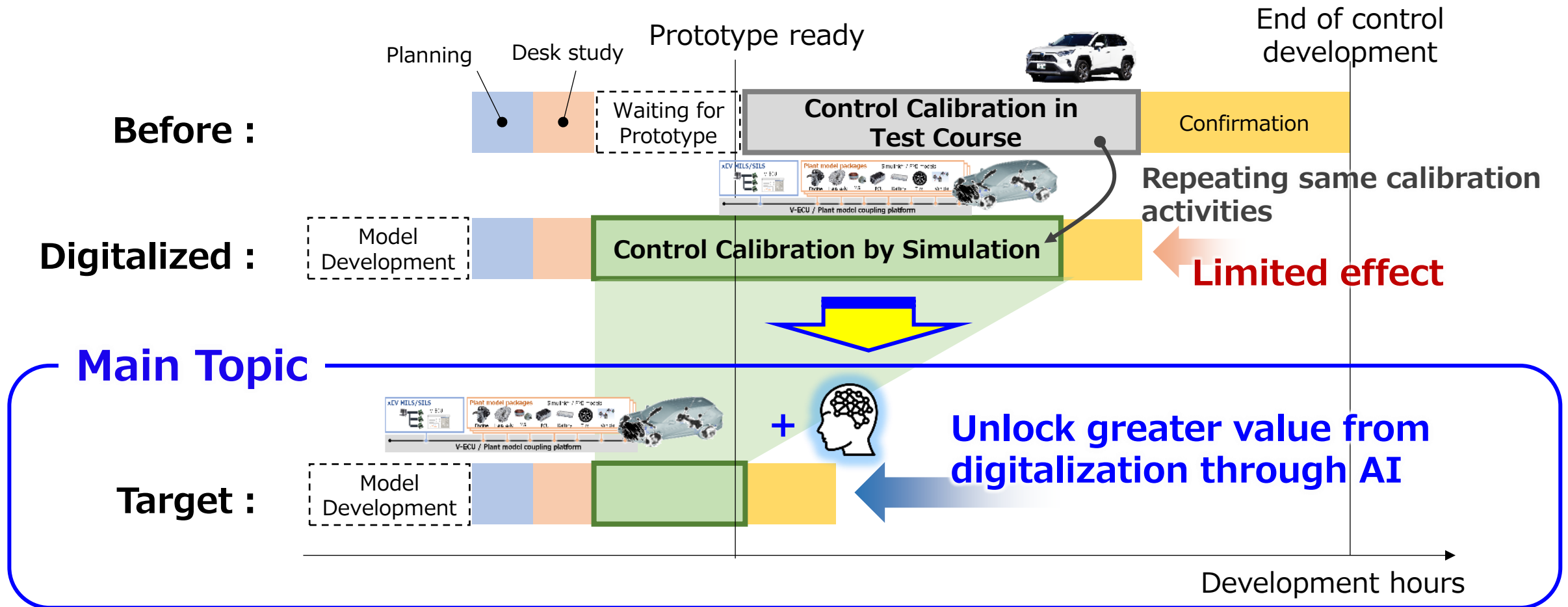
$$T_e(\omega_e, \theta) = T_{pres}(\omega_e, \theta) + T_{cam}(\omega_e, \theta) + T_{fpist}(\omega_e, \theta) + T_{iner}(\omega_e, \theta) + T_{frot}(\omega_e) \quad [\text{Nm}]$$

Total engine torque Indicated torque Cam torque Piston friction torque Inertia torque Rotational friction torque

The developed model can quantitatively reproduce actual vehicle behavior

Key Challenges in Simulation Utilization

Issue : Simulation alone cannot eliminate repetitive calibration activities



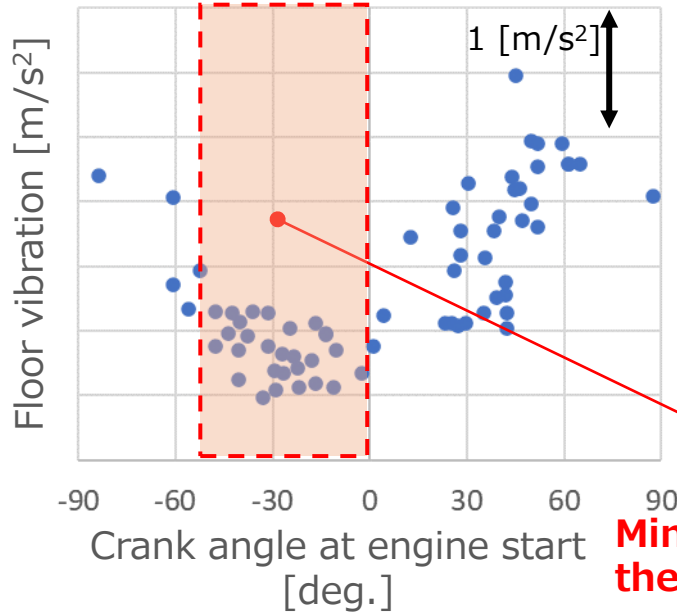
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① Engine Stop Control in THS

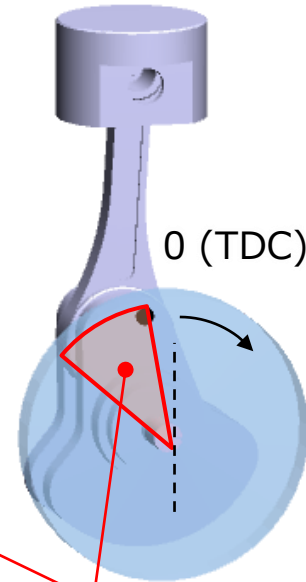
Objectives and Functional Requirements of Engine Stop Position Control

- Reduce stop shock and noise
- Reduce restart shock

Engine Start Crank Angle vs. Floor Vibration :

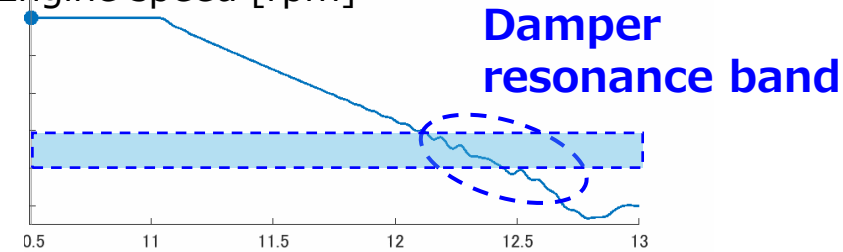


Control OFF

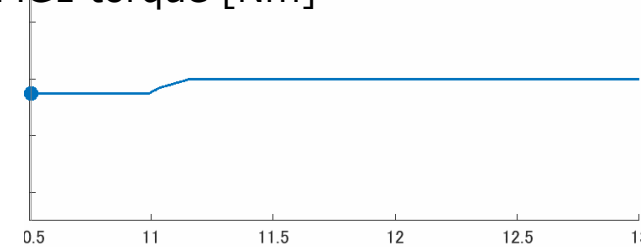


Minimize Vibration at the Next Engine Restart

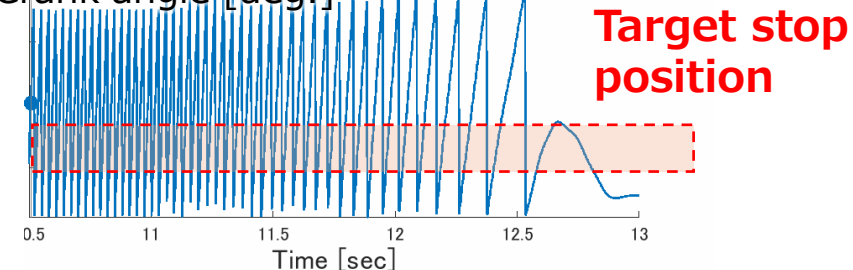
Engine speed [rpm]



MG1 torque [Nm]



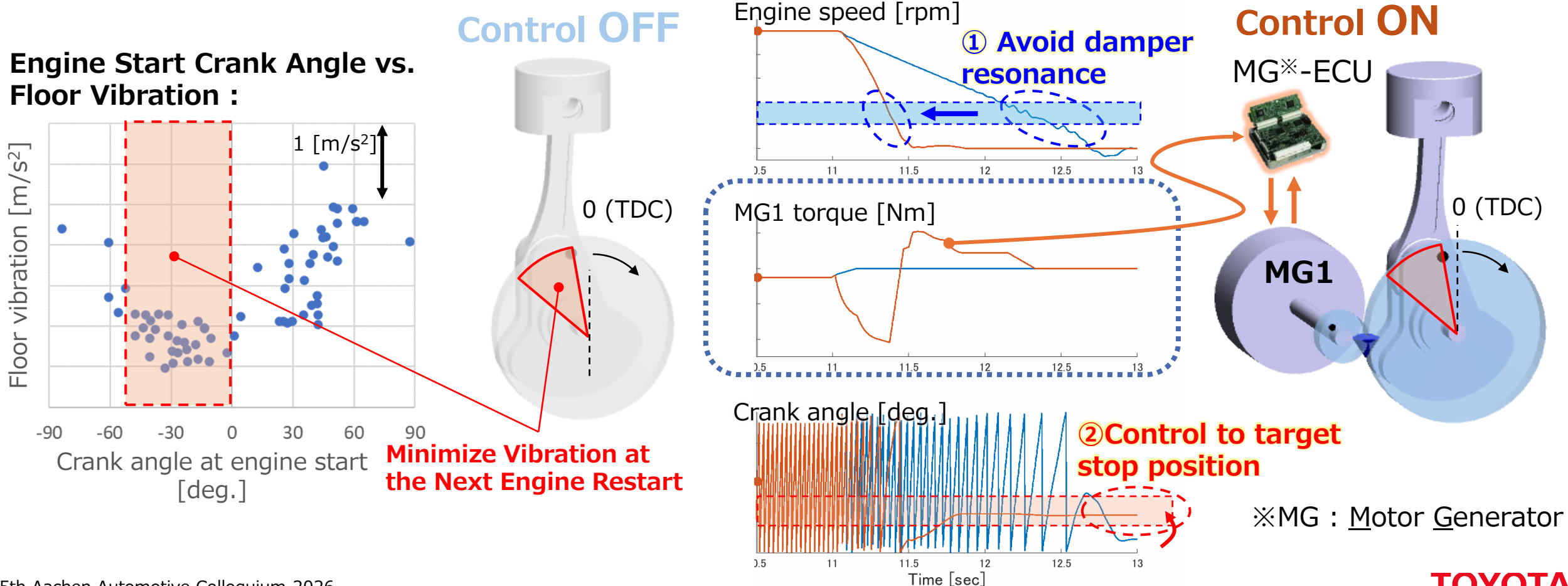
Crank angle [deg.]



① Engine Stop Control in THS

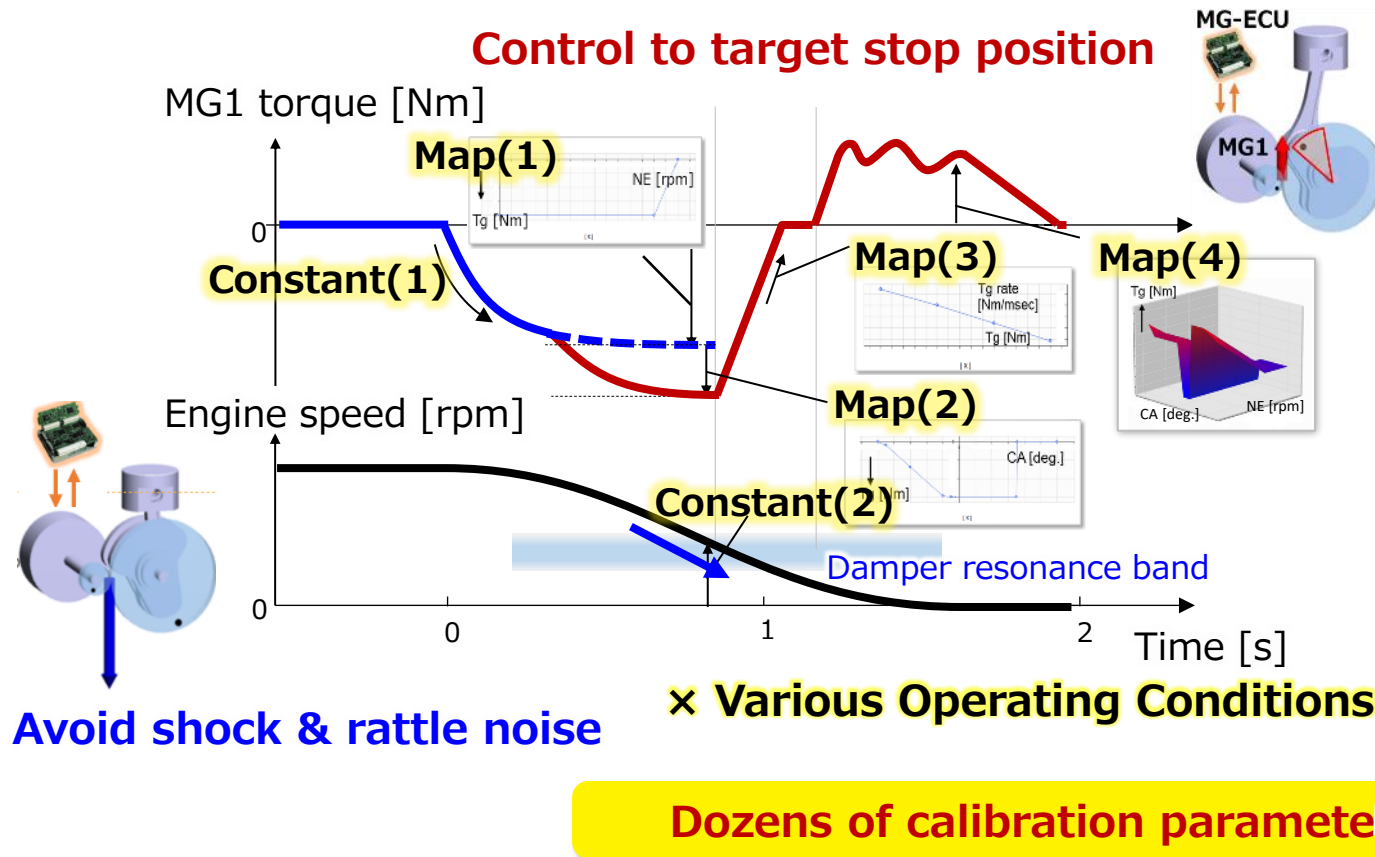
Objectives and Functional Requirements of Engine Stop Position Control

- **Reduce stop shock and noise** : Avoid damper resonance and gear rattle during engine stop
- **Reduce restart shock** : Control crank angle position at engine stop



① Engine Stop Control in THS

Control Parameters and Maps Requiring Calibration



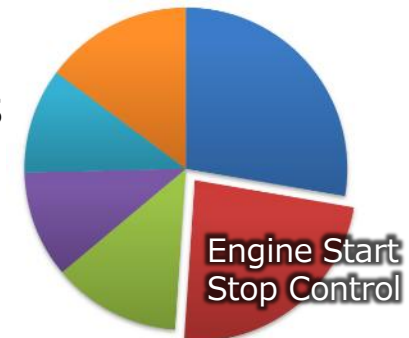
Strengths

- Proven reliability through long-term production use
- Performance guaranteed across diverse operating conditions

Challenges

- **High calibration effort due to numerous maps and complexity**

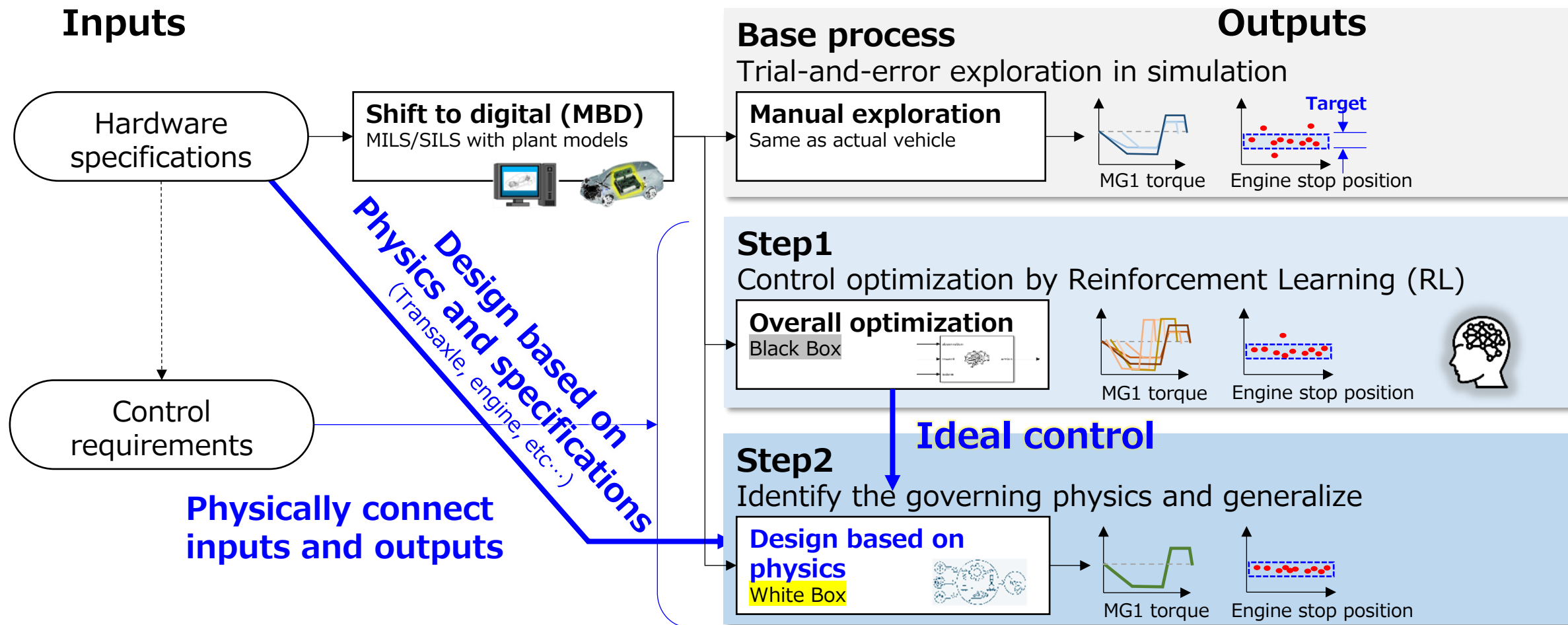
Effort Distribution Across THS Drive Control Calibration :



Focus : Leverage AI to address the challenges while preserving the strengths

① Engine Stop Control in THS

AI-Guided Refinement of Baseline Control Logic

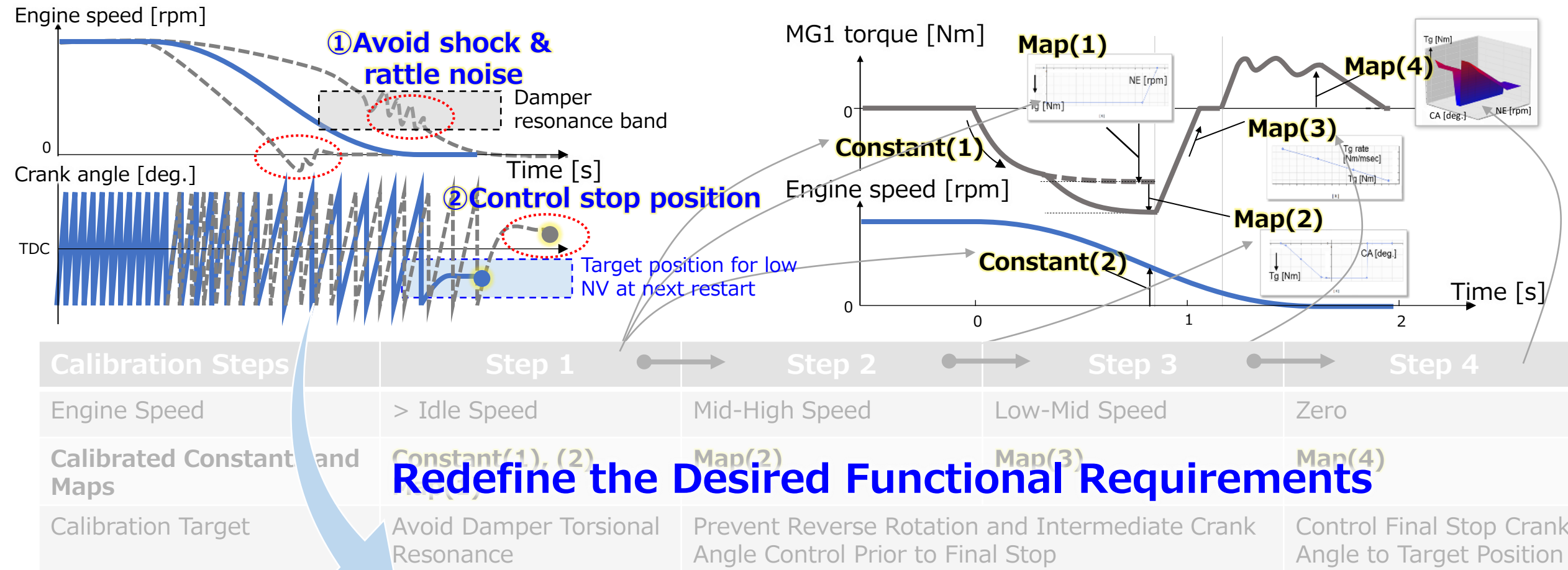


Develop a mechanism-based calibration methodology using simulation and AI

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② Step 1: Optimal Control Derivation Using RL

Current Calibration Approach and Functional Requirements



Redefine the Desired Functional Requirements

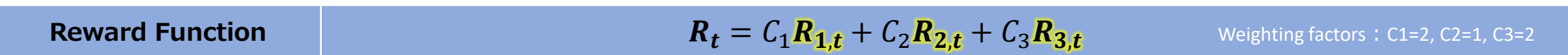
Overall Requirements

Minimize Damper Resonance $\wedge$ Minimize Gear Rattle $\wedge$ Maximize Stop Position Accuracy



Based on: “AI Based Controller for HEV Engine Stop Control”,
Jeroen De Smet, Toyota Motor Europe, CTI Symposium 2023

Minimize Damper Resonance $\wedge$ Minimize Gear Rattle $\wedge$ Maximize Stop Position Accuracy

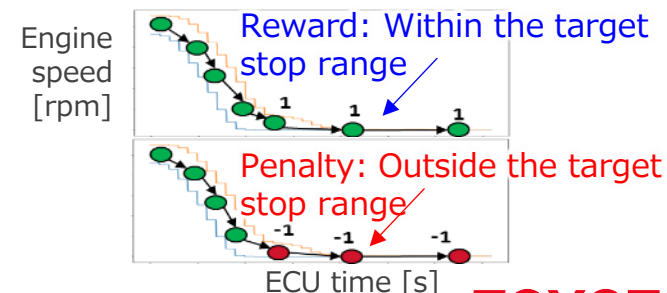


$R_{3,t}$: Stop Position Accuracy

Lower and upper boundaries of target stop position

$$R_{3,t} = \begin{cases} 1 & (\theta_{stop,lb} \leq \theta_{stop,fin} \leq \theta_{stop,ub}) \\ 0 & (otherwise) \end{cases}$$

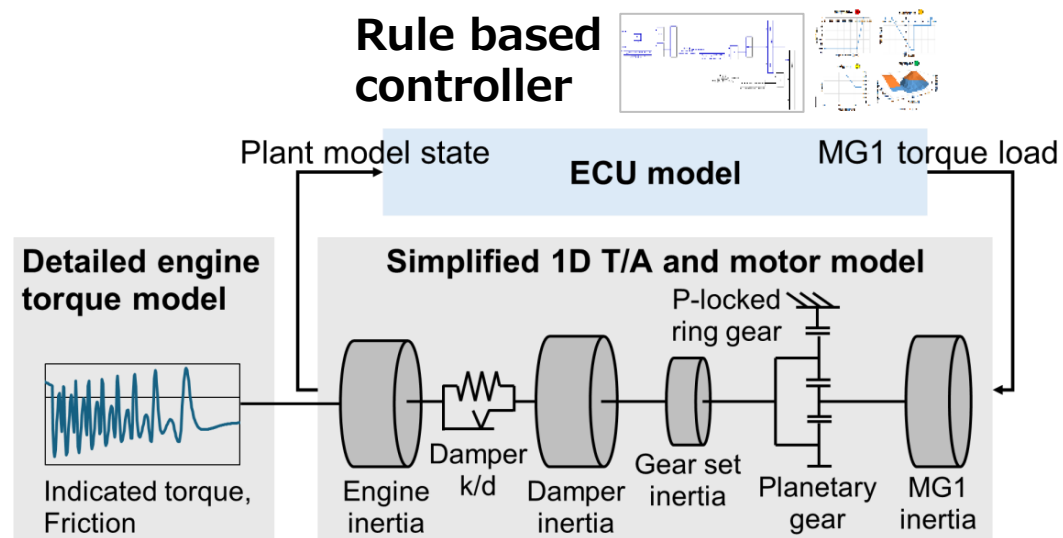
Final stop position



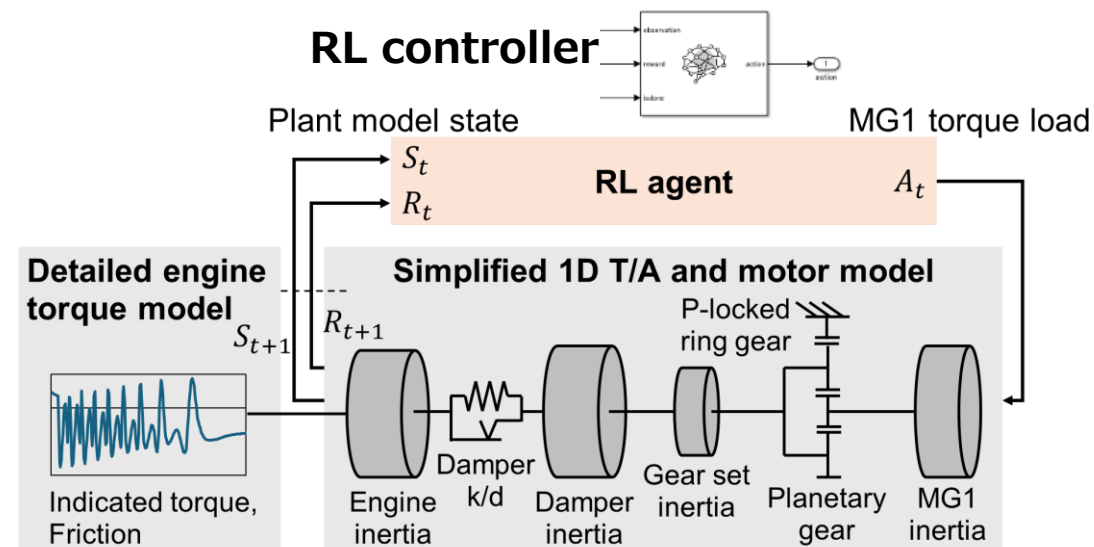
② Step 1: Optimal Control Derivation Using RL

Learning Environment

Control parameter design environment (MILS)



Reinforcement Learning environment



Offline learning was conducted within a model-based simulation environment for calibration design

② Step 1: Optimal Control Derivation Using RL

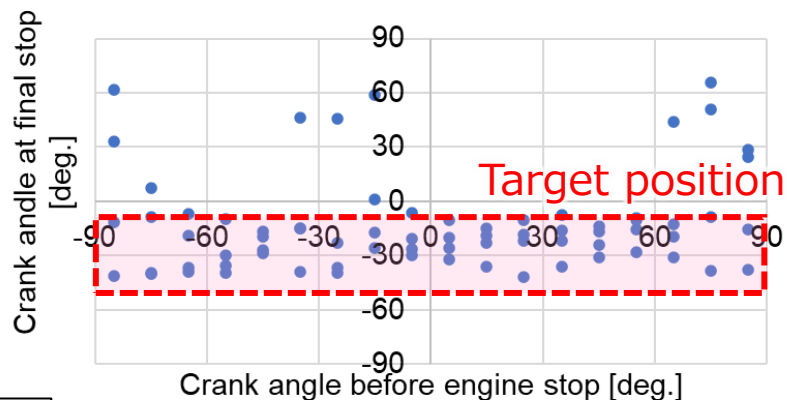
Simulation Results of RL

Method studied vehicle : 1.8L-THS-HEV

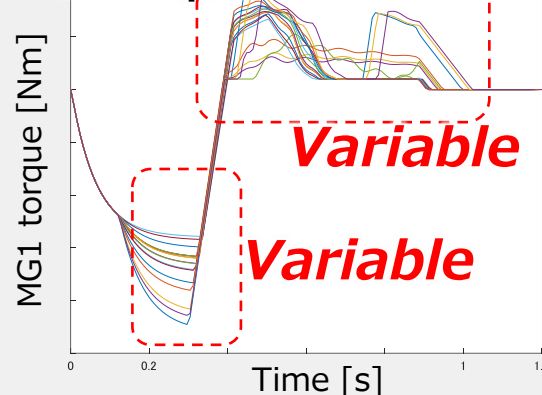


Base control

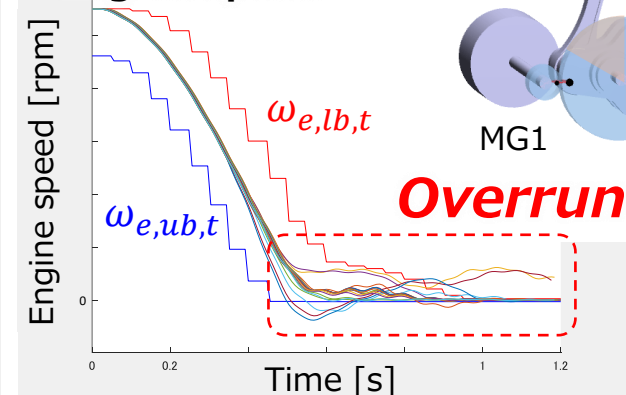
Engine stop positions



MG1 torque

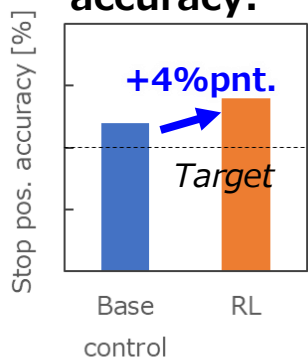


Engine speed

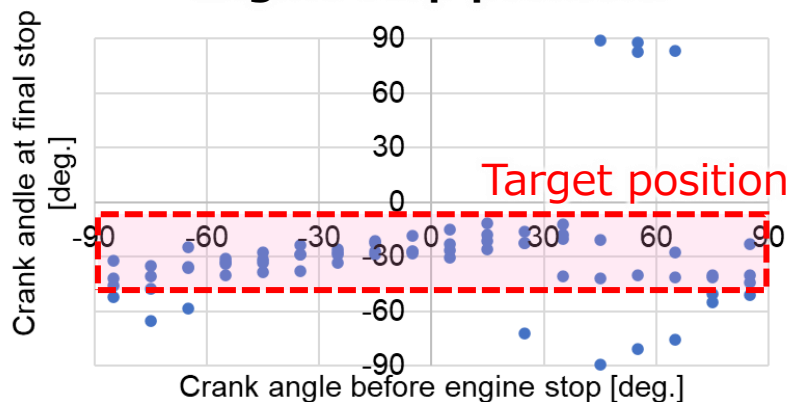


RL control

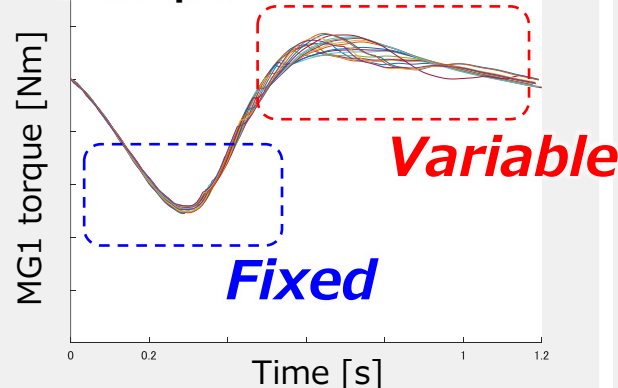
Stop position accuracy:



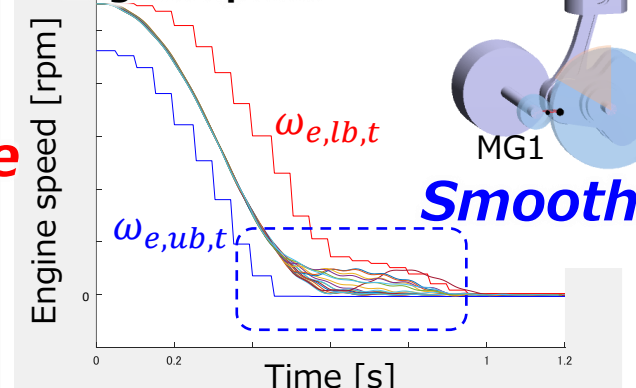
Engine stop positions



MG1 torque



Engine speed



A simpler control strategy was demonstrated with accuracy comparable to or better than the baseline control

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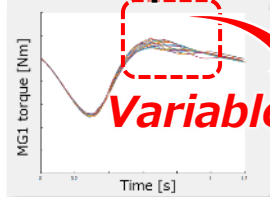
③ Step 2: Generalization Through Mechanism Analysis ²³

Dominant Factor Identification Using Multiple Regression Analysis

Dependent Variable:

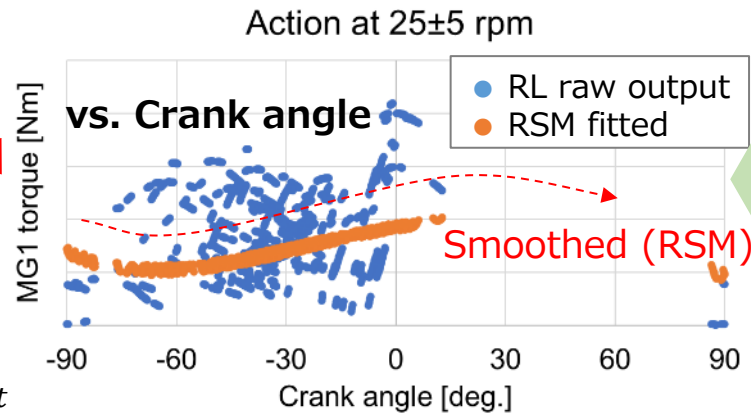
Ideal MG1 Torque Output (from RL Results)

MG1 torque



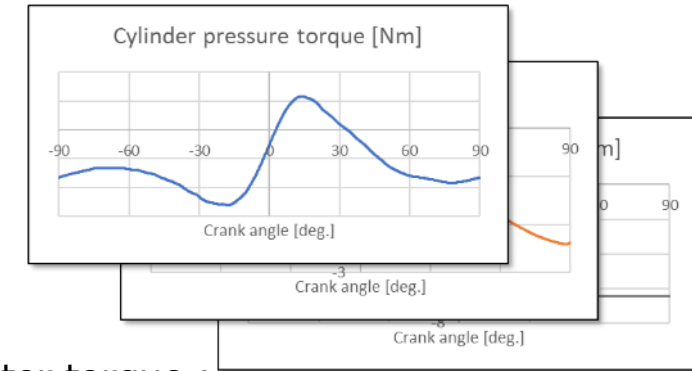
Action of RL

$$A_t = T_{MG1rate,t}$$



Explanatory Variables :

Crank-Angle-Dependent Intermediate Quantities

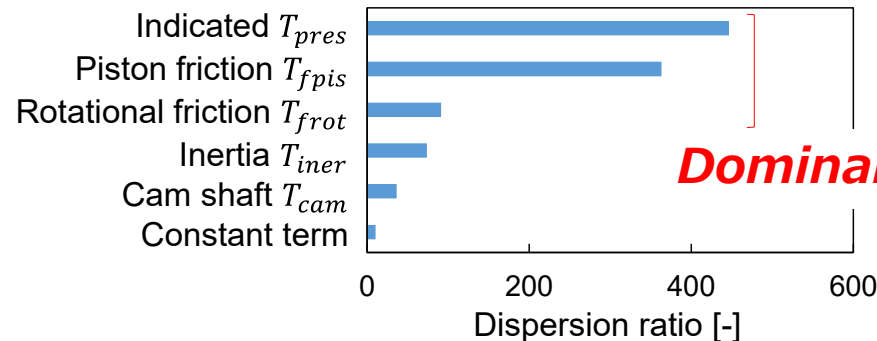


Engine counter torque :

$$T_{loss}(\omega_e, \theta) = T_{pres}(\omega_e, \theta) + T_{cam}(\omega_e, \theta) + T_{fpist}(\omega_e, \theta) \dots + T_{iner}(\omega_e, \theta) + T_{frot}(\omega_e)$$

Identification of Dominant Factors

Variance Contribution of Dominant Physical Factors :



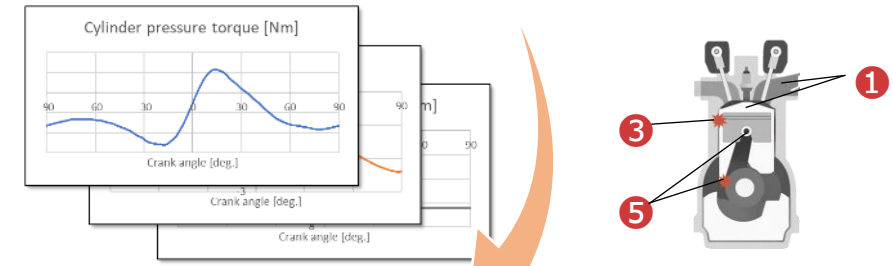
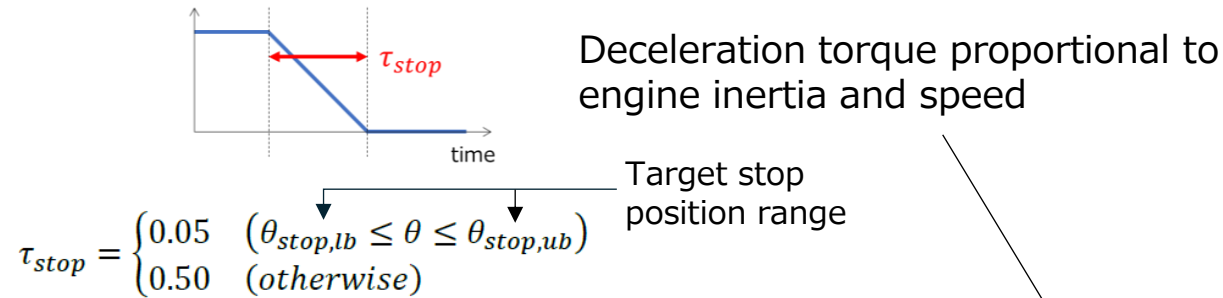
→ Ideal MG1 Torque Can Be Explained by a Small Set of Intermediate Physical Factors

The rationale behind the RL actions can be explained by the engine torque balance

③ Step 2: Generalization Through Mechanism Analysis ²⁴

Physics-Based Formulation of MG1 Torque Design

**IN : Engine counter torque
(Intermediate states in the model)**



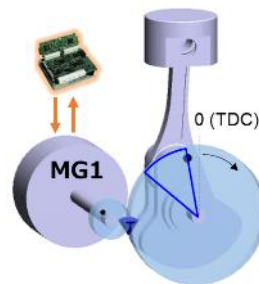
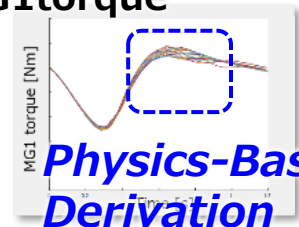
Required MG1 torque :

$$T_{MG1}(\omega_e, \theta) = \frac{1}{1 + \rho} \left[-\frac{I \omega_e}{\tau_{stop}} + \overset{1}{T_{pres}(\omega_e, \theta)} + \overset{3}{T_{fpist}(\omega_e, \theta)} + \overset{5}{T_{frot}(\omega_e)} \right]$$

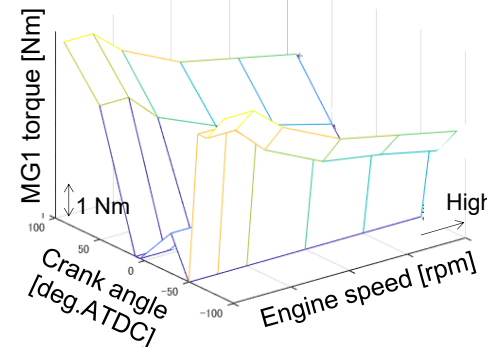
Planetary ratio Indicated torque Piston friction Rotational friction

OUT : Control parameter for MG1

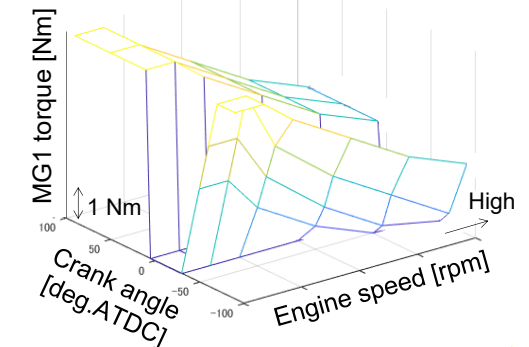
MG1torque



Physically designed map



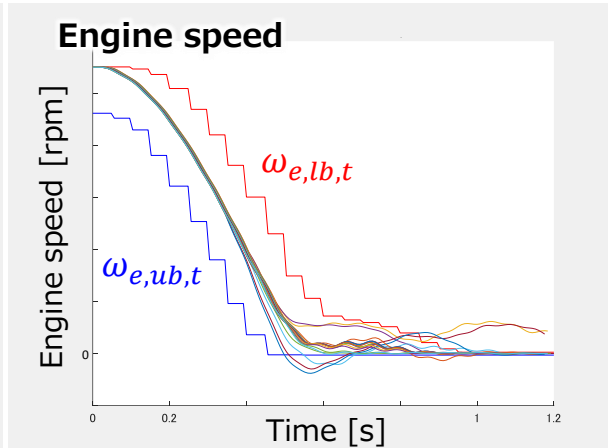
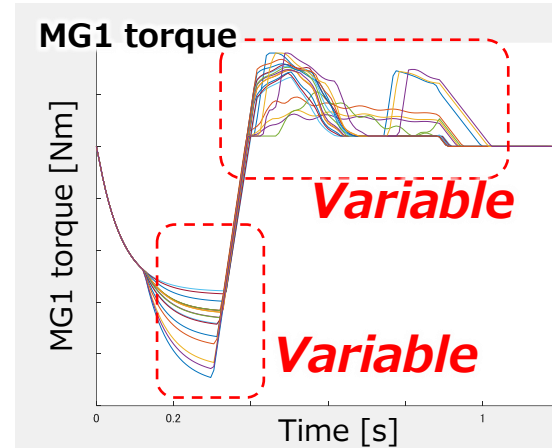
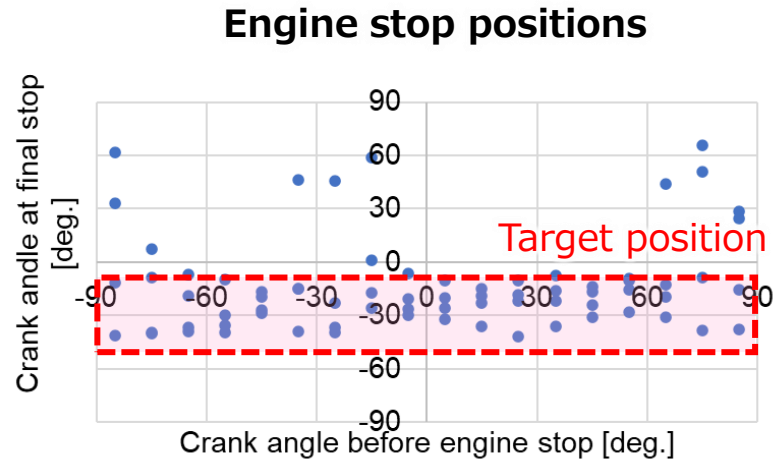
Base map



③ Step 2: Generalization Through Mechanism Analysis ²⁵

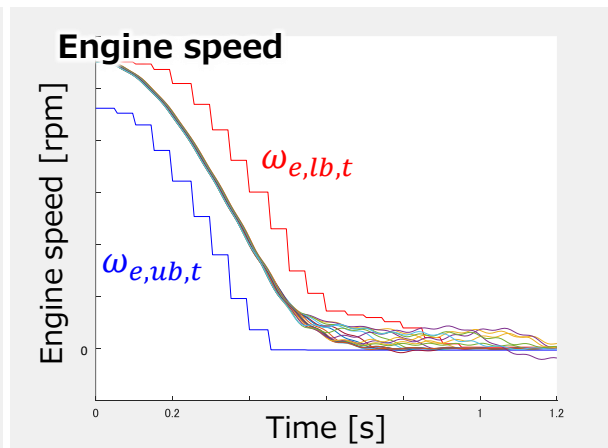
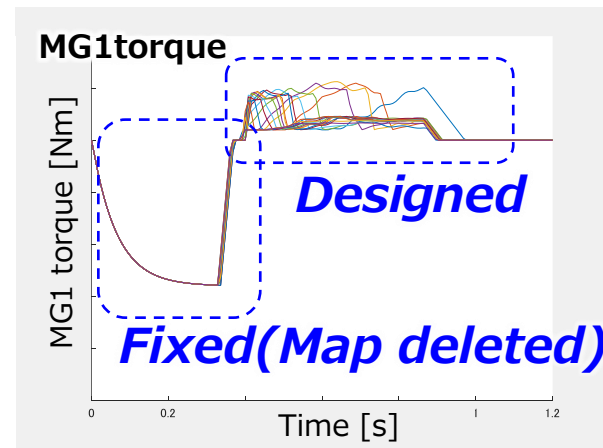
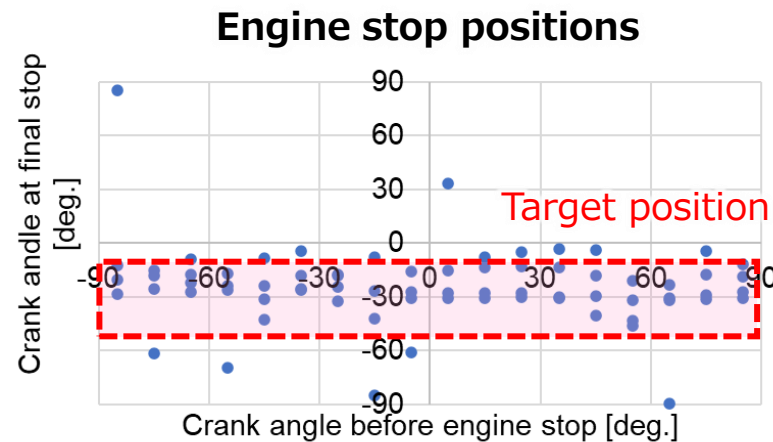
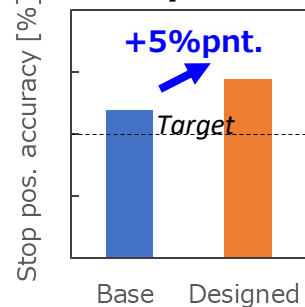
Physics-Based Formulation of MG1 Torque Design

Base
Constants



Designed
Constants

Stop position
accuracy:



Stop position accuracy comparable to or better than the baseline calibration was demonstrated

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Application to Vehicle Development

Deployment to a New Vehicle

Method developed vehicle :
1.8L-THS-HEV



Confirmed vehicle :
2.5L-THS-PHEV

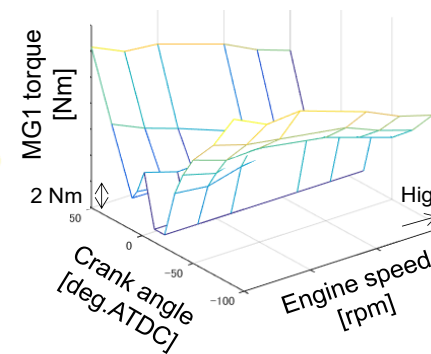


**Derived from the
New Vehicle Specifications**

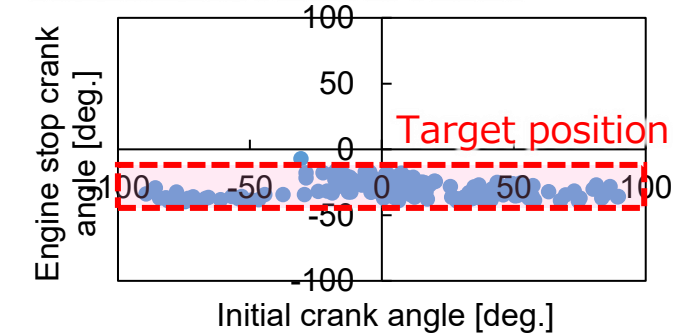
**Required MG1
torque :**

$$T_{MG1}(\omega_e, \theta) = \frac{1}{1 + \rho} \left[-\frac{I\omega_e}{\tau_{stop}} + T_{pres}(\omega_e, \theta) + T_{fpist}(\omega_e, \theta) + T_{frot}(\omega_e) \right]$$

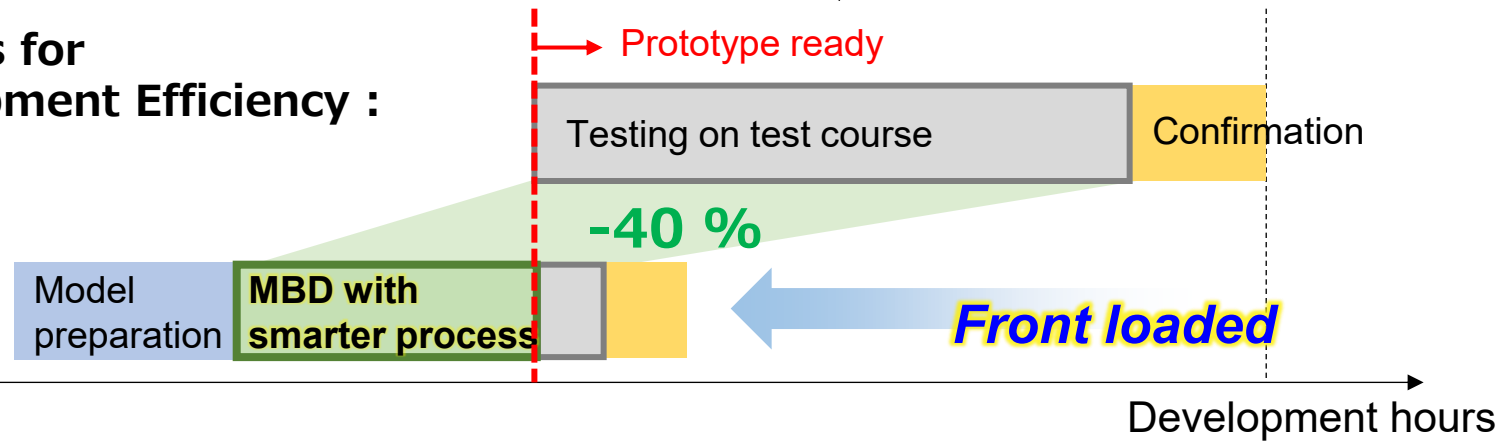
Physically designed map



Confirmation result in vehicle



**Benefits for
Development Efficiency :**



Demonstrated cross-vehicle applicability, enabling front-loaded and accelerated development

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Conclusions

For engine stop control in THS, a new simulation-driven calibration process utilizing Reinforcement Learning (RL) was developed.

1. Optimal Control Solution Derivation by RL

- RL successfully derived an optimal engine stop control strategy from the functional requirements.
- A simpler MG1 torque profile was found to satisfy the functional requirements while maintaining the baseline calibrated performance.

2. Mechanism-Based Generalization and Application to Base Logic Calibration

- Physics-based interpretation of RL results identified the key factors governing MG1 torque.
- A generalized control formulation was established using physically meaningful variables.
- The established formulation was successfully deployed across vehicles with different specifications.

The proposed approach enabled simulation-driven front-loading of driving control calibration through MBD with high scalability

Acknowledgment

The authors would like to thank **Jeroen De Smet (Toyota Motor Europe)** for his valuable technical discussions and support.

Thank you very much for your attention.