第二届世界内燃机大会

The 2nd World Congress on Internal Combustion Engines

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Development and Outlook of Artificial Intelligence Systems for Future Electrified Powertrains
未来电动化动力总成人工智能系统的发展与展望

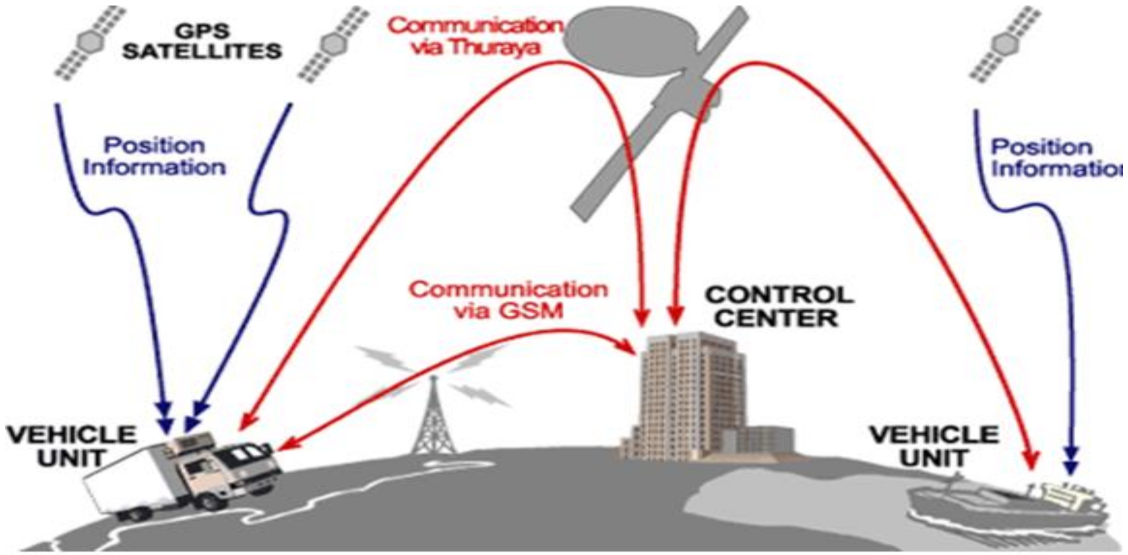
Professor Hongming Xu (徐宏明)

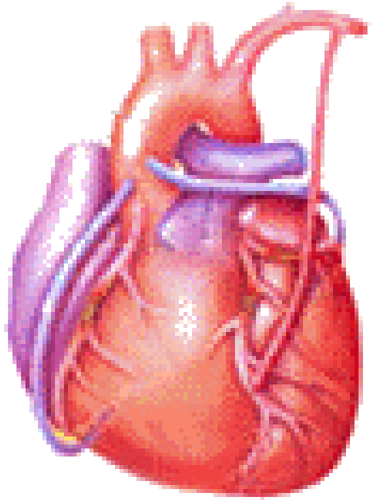
Vehicle and Engine Technology Research Centre
车辆与发动机技术研究中心

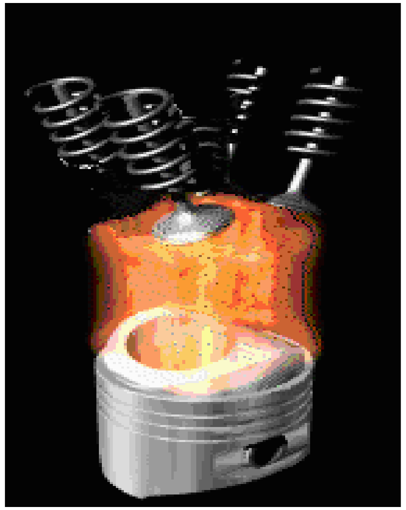
2nd World Congress of IC Engines
21-24 April 2021, Jinan

Presentation Outline

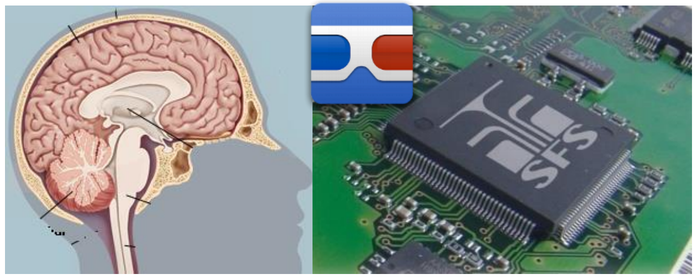
1 Future Vehicles/Engines on the Way







portal.ku.edu.tr/.../VEHICLE%20TRACKING%20SYSTEM.ppt



- Internal combustion engines are used in the environment facing CO_2 treats and energy issues but with tremendous information and powerful tools for the designers and users.
- 车用内燃机正在因为环境和能源问题受收到低碳化的要求而设计人员和用户可用的数据信息也更多和工具也更加强大。

1 Electrification of Vehicle Powertrain

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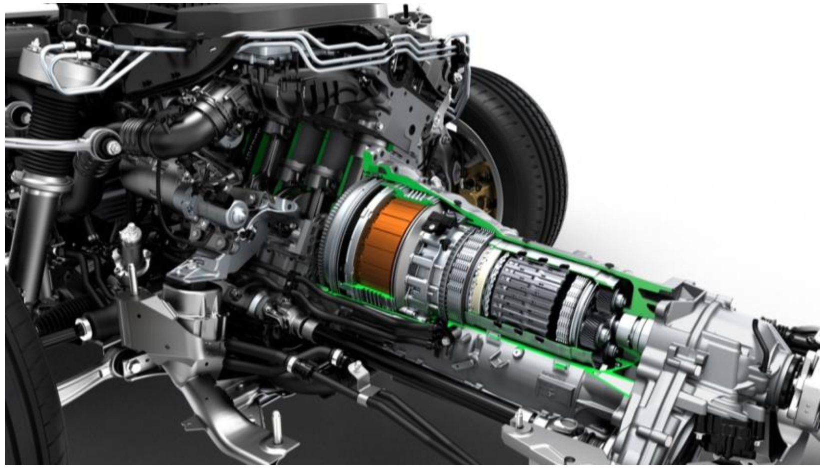
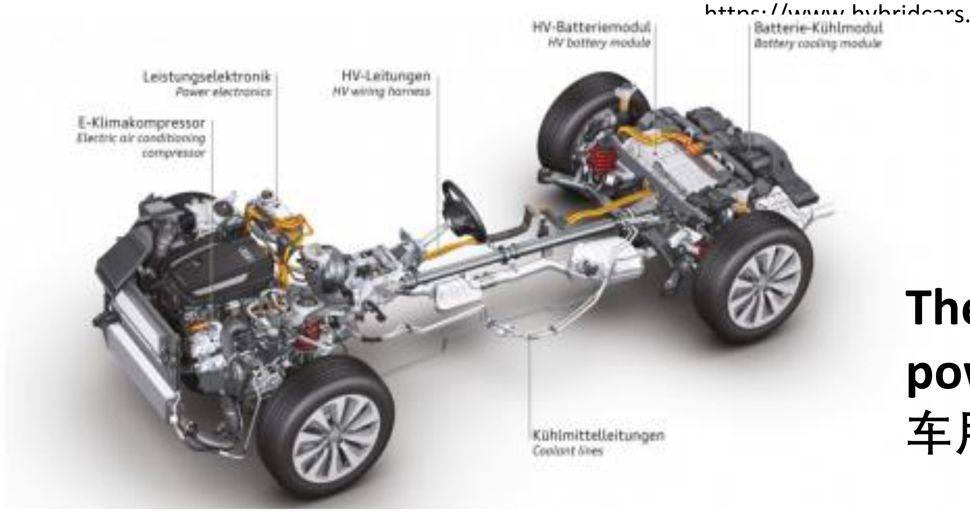
CASE	=	Connection 网联	+	Automation 智能	+	Sharing 共享	+	Electrification 电动化



https://www.hybridcars.c



The IC engine is no longer on its own anymore and the powertrain as well as the whole vehicle is being ‘electrified’
车用内燃机不再单独工作 – 动力总成以及整车都正在“电气化”

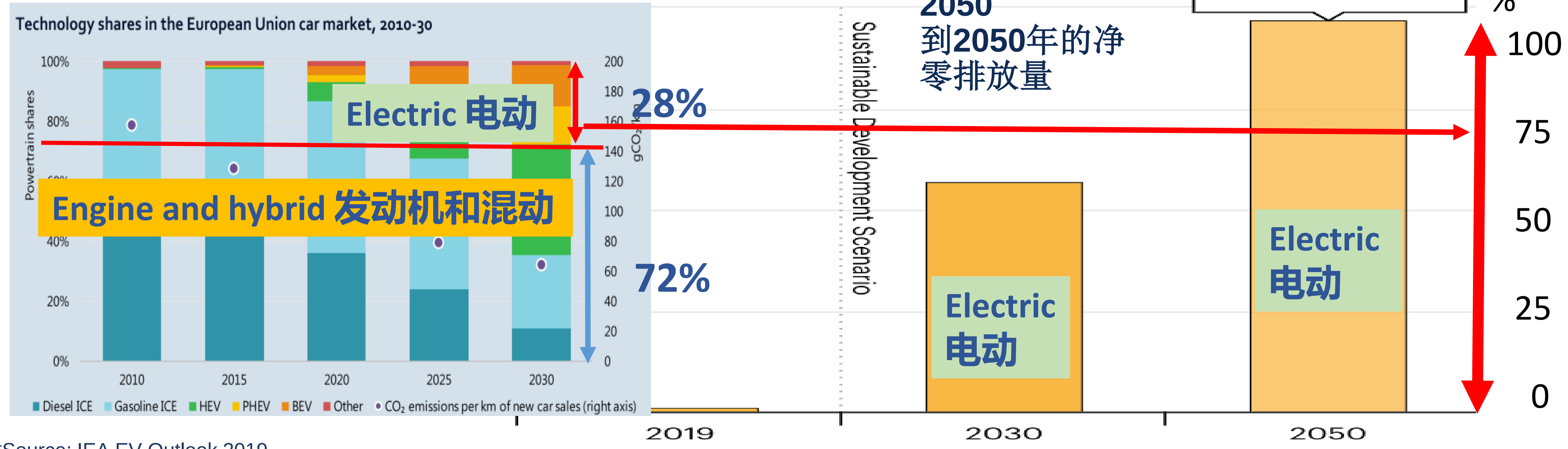
https://www.hybridcars.com

Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, Mehrdad Ehsani, et al

1 EU/IEA Positions of ICE in the Future

EV share in EU 在可持续发展情景中，欧盟汽车的电动汽车份额

Electric Vehicles 电动汽车 = PHEV 插电混动 + BEV 纯电动 + FCEV 燃料电池



*Source: IEA EV Outlook 2019

*Source: IEA Energy Outlook 2020

The electric vehicles include PHEVs using IC engines. The exact proportion of the IC engines by 2050 is defined yet.

电动汽车包括使用内燃机的插电混合动力。到2050年时，全球插电混合动力的确切份额比例尚未确定。

1 UK APC Roadmap 2020

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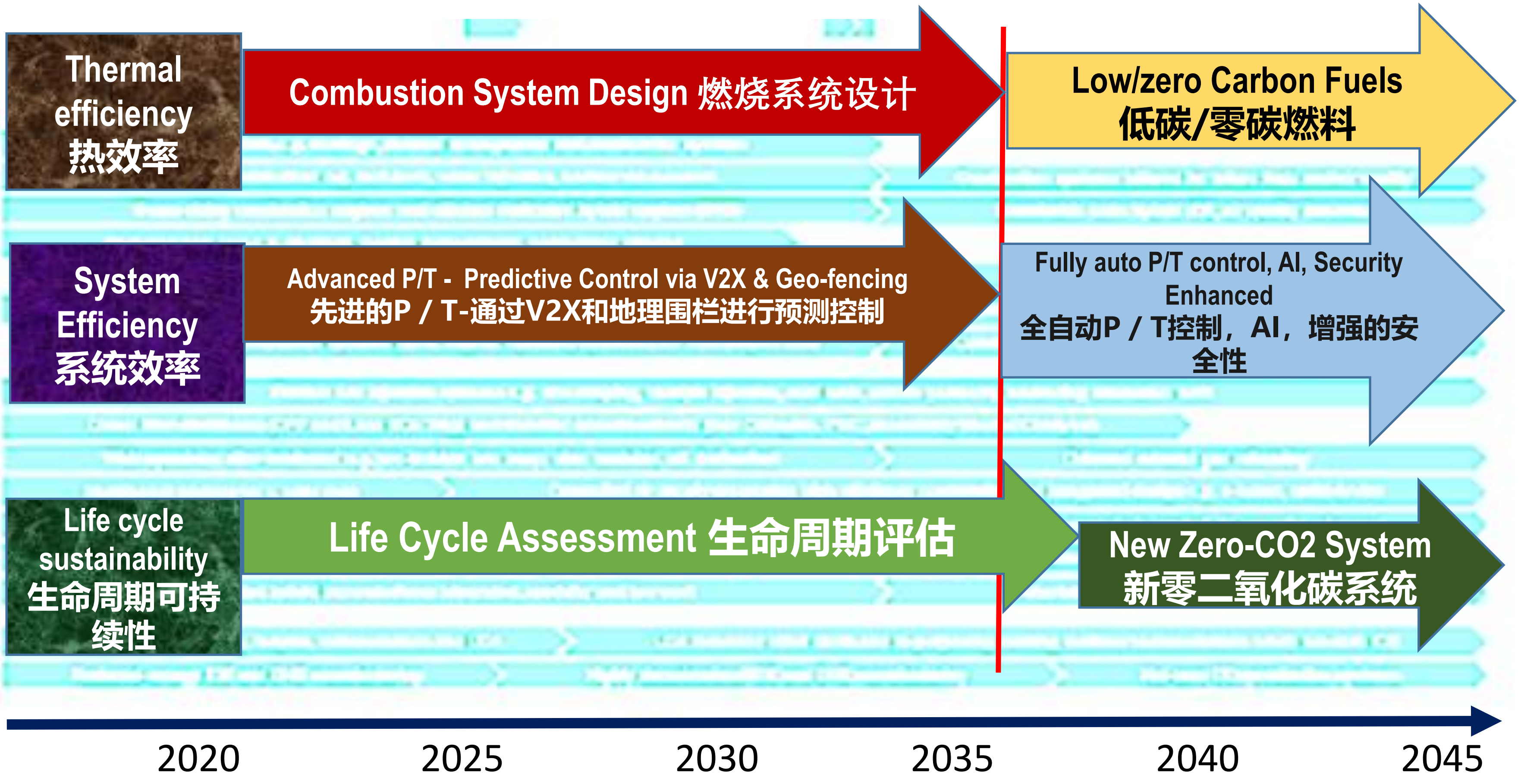
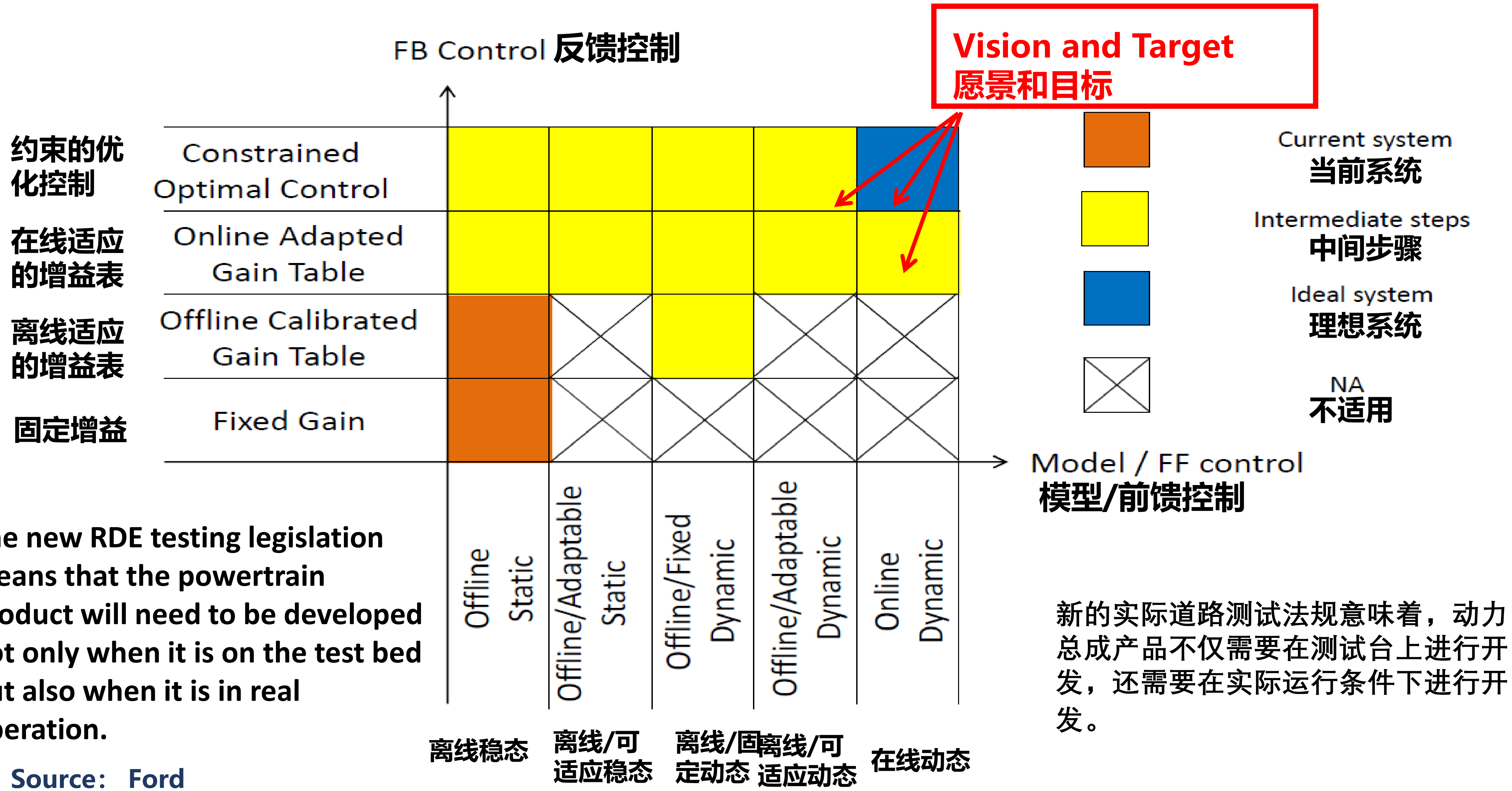
System control is one of the 3 main areas requiring development in the future roadmap.

在未来的技术路线图中，基于人工智能的系统控制是需要开发的三个主要领域之一



*Source: UK APC Roadmap 2020

1 In line with Vision at Industry



The new RDE testing legislation means that the powertrain product will need to be developed not only when it is on the test bed but also when it is in real operation.

新的实际道路测试法规意味着，动力总成产品不仅需要在测试台上进行开发，还需要在实际运行条件下进行开发。

Source: Ford

Presentation Outline

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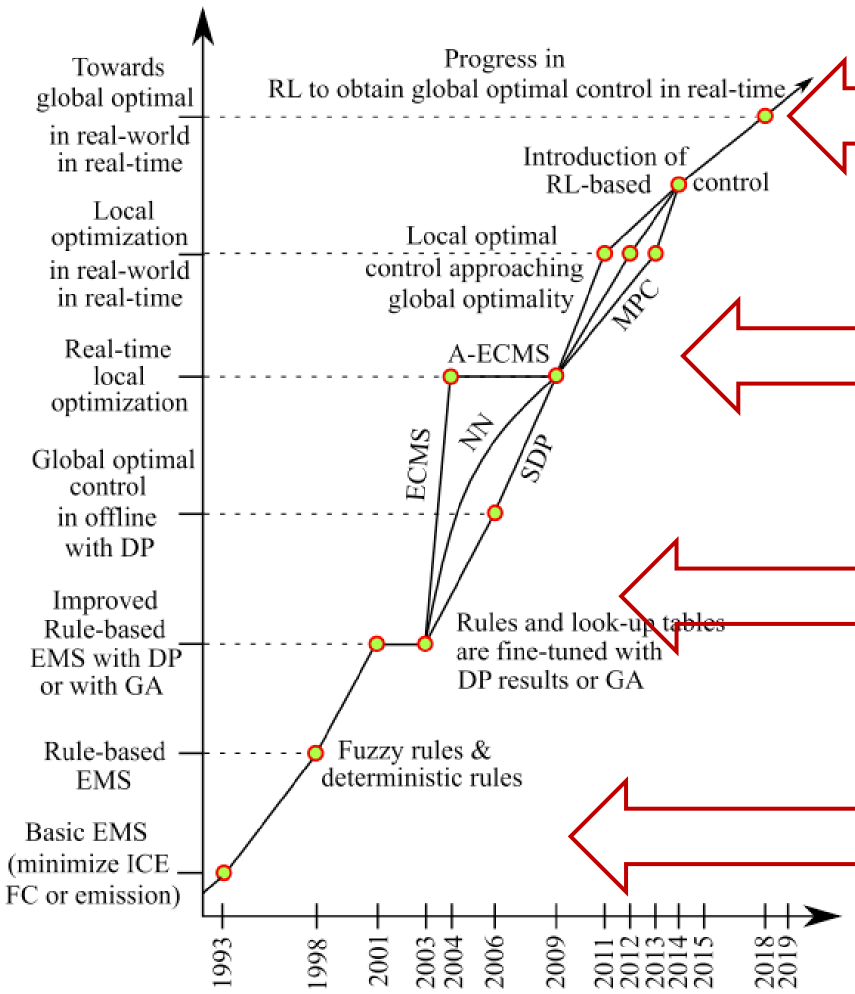
1	Introduction 引言
2	**Roles of AI 人工智能的角色**
3	Present development 当前进展
4	Outlook 展望
5	Summary 总结

Recent Advances in AI

Milestones of AI applications in powertrain control 动力总成控制中AI应用的里程碑



Evolution of powertrain control strategies
动力总成控制策略的演化

Stage 4: Autonomous AI decision making
阶段4：自主AI决策
e.g., reinforcement learning and online knowledge transfer

Stage 3: AI-driven model-based predictive control
阶段3：AI驱动的基于模型的预测控制
e.g., online solving of nonlinear predictive models

Stage 2: Meta-heuristic searching
阶段2：元启发式搜索
e.g., control parameter optimization/calibration using evolutionary algorithms, e.g., GA, PSO

Stage 1: AI-based modelling
阶段1：基于AI的建模
e.g., fuzzy inference of reversed relationship of the powertrain unit inputs/outputs; nonlinear modelling of the powertrain system using artificial neural networks

Role of AI in powertrain control
AI在动力总成控制中的作用

Source: Biswas, A., et al, (2019) ‘Energy Management Systems for Electrified Powertrains:

Early Work of Engine Control

人工智能的早期应用实例

960328

Artificial Intelligence for Combustion Engine Control

内燃机控制的人工智能

Ulrich Lenz and Dierk Schroeder
Technical University of Munich

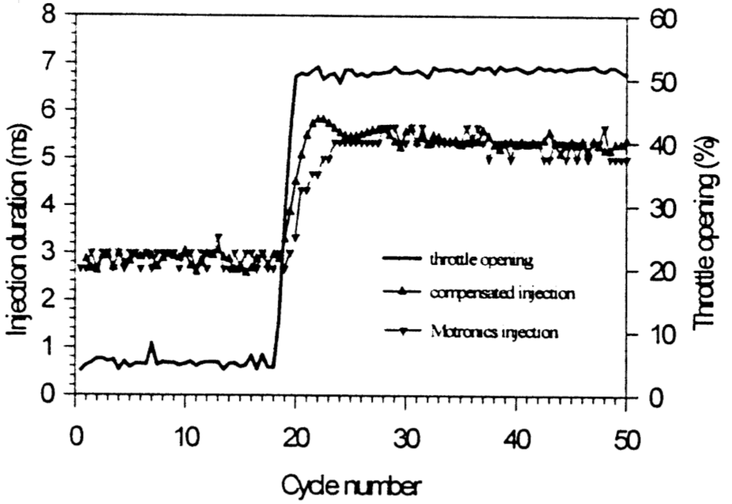
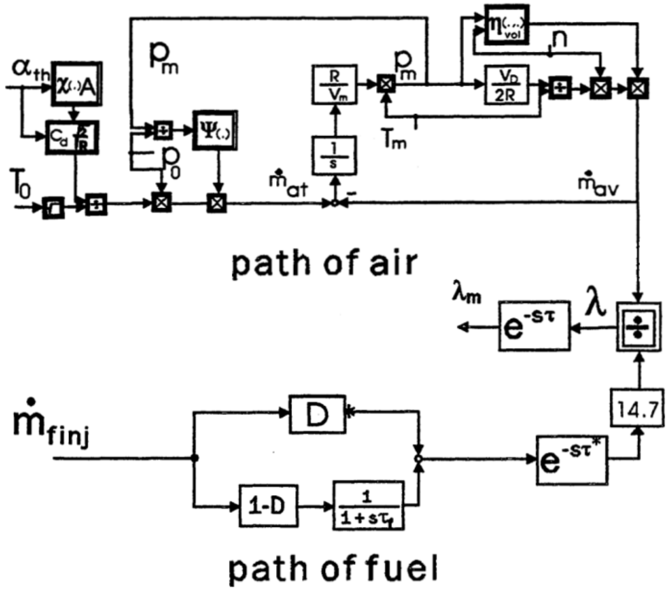


Figure 14. The required fuel injection strategy calculated using the Xu model for reducing the air-fuel ratio excursion with a load transient at 1400 rpm.



SAE TECHNICAL PAPER SERIES

1999-01-1484

Control of A/F Ratio During Engine Transients

发动机空燃比瞬态控制

Hongming Xu
Imperial College of Science, Technology and Medicine

Examples of AI application in IC engine controls

Start of real time engine modelling

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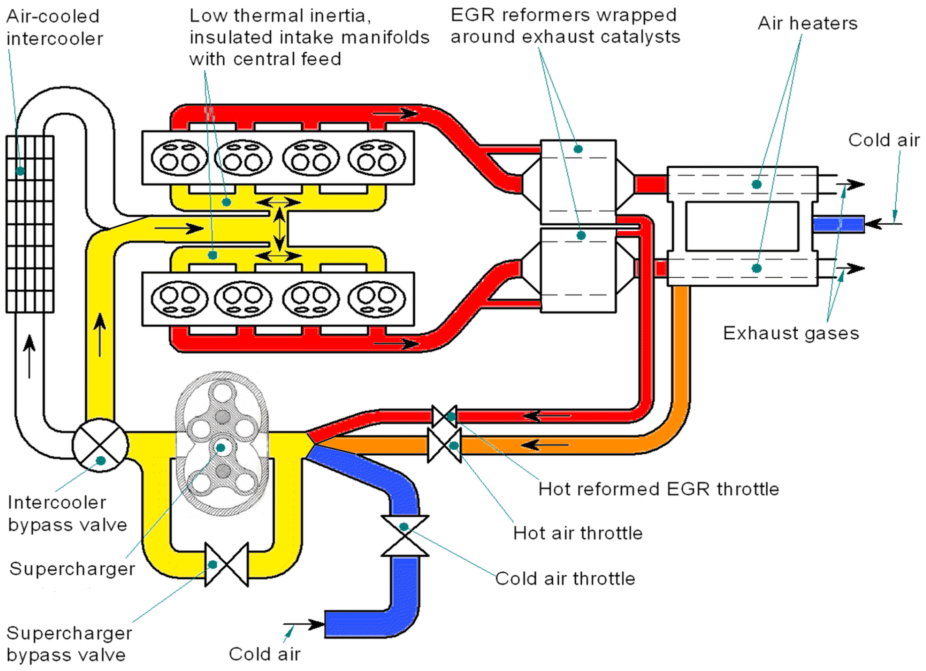

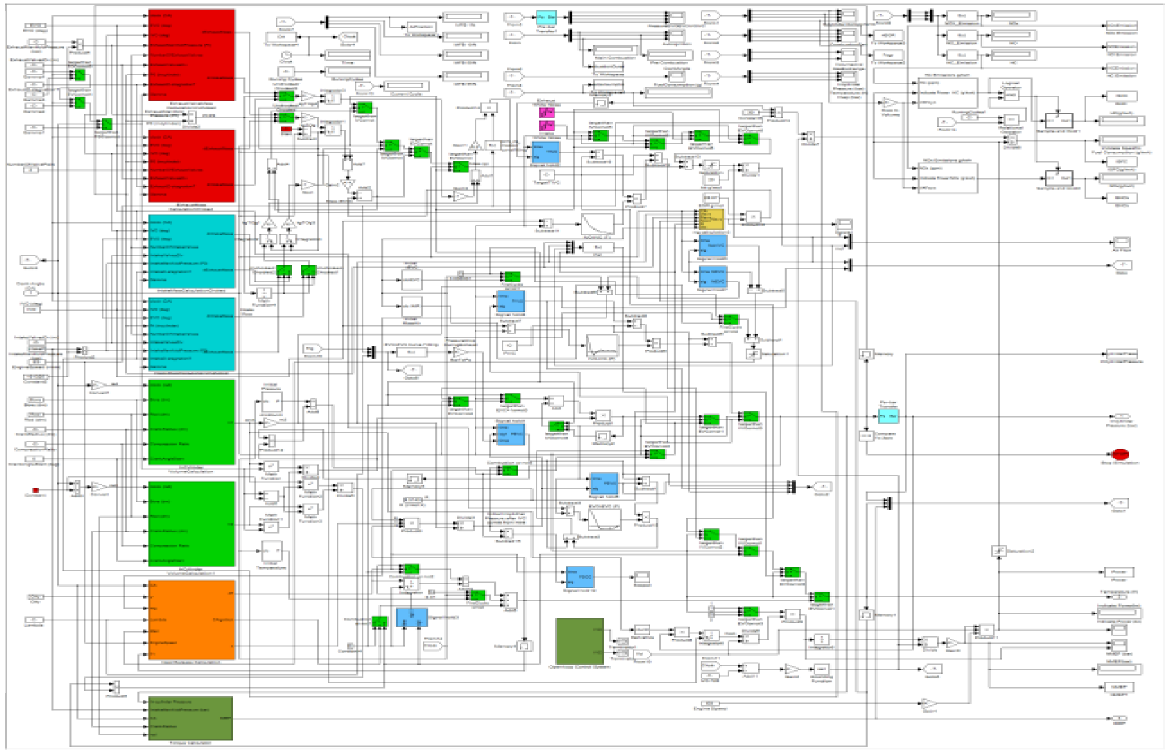

Real time model 实时模型

The first real-time HCCI engine control model. The engine management system is combined with the thermal management control model

第一个均质压燃发动机与热管理控制模型相结合的实时控制模型。这个实时发动机模型已经被发展成为火花点火发动机的实时控制模型

EPSRC Engineering and Physical Sciences Research Council

JAGUAR LAND ROVER Shell

Roles of AI in Engine R & D

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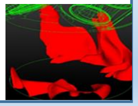
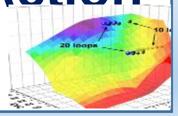
How can AI contribute to R&D of advanced ICE technology?人工智能如何助力先进发动机技术研发

R&D tasks 发动机研发任务	Perception 感知 	Decision/Action 决策 	Learning 学习 
Design 设计	AI based image/signal processing 智能图像/信号处理	AI based structure optimization 智能结构优化	Design evolution with digital twin 基于数字孪生的智能迭代
Control/Calibration 控制/标定		AI based engine control in transient operations 智能瞬态控制	AI based engine calibration 智能发动机标定
System integration 系统集成	AI based diagnosis 智能诊断	AI based component sizing 智能零部件匹配	AI based supervisory control 智能监督控制

2

Framework for PT Control Development

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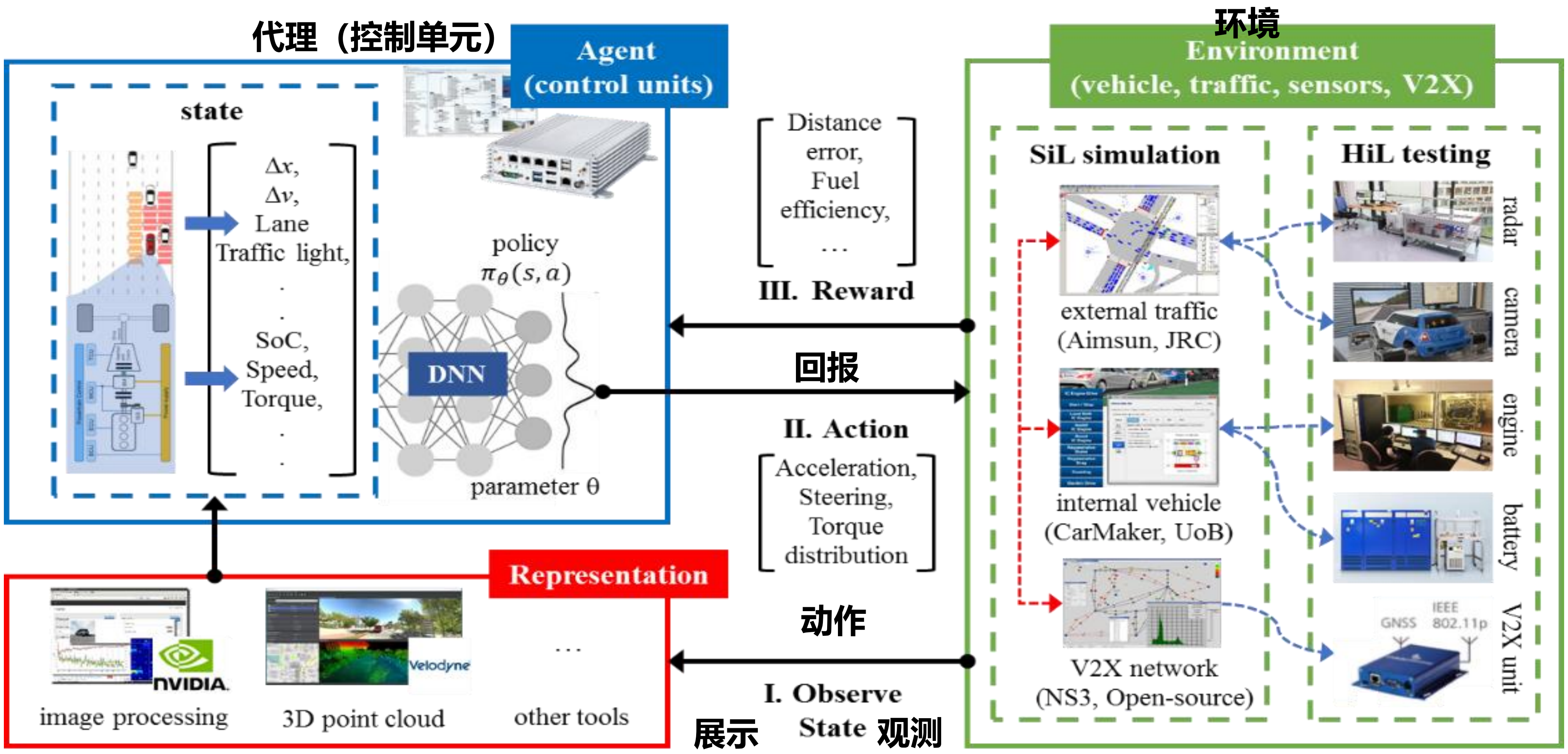

RD using AI for HEVs is highly interdisciplinary and this is different from the traditional research of engine technology which is more focused on the engine itself.

使用AI进行混合动力汽车研发是高度跨学科的，这与传统的发动机技术研究（仅专注于发动机本身）不同

2 Present Work on AI Based EMS

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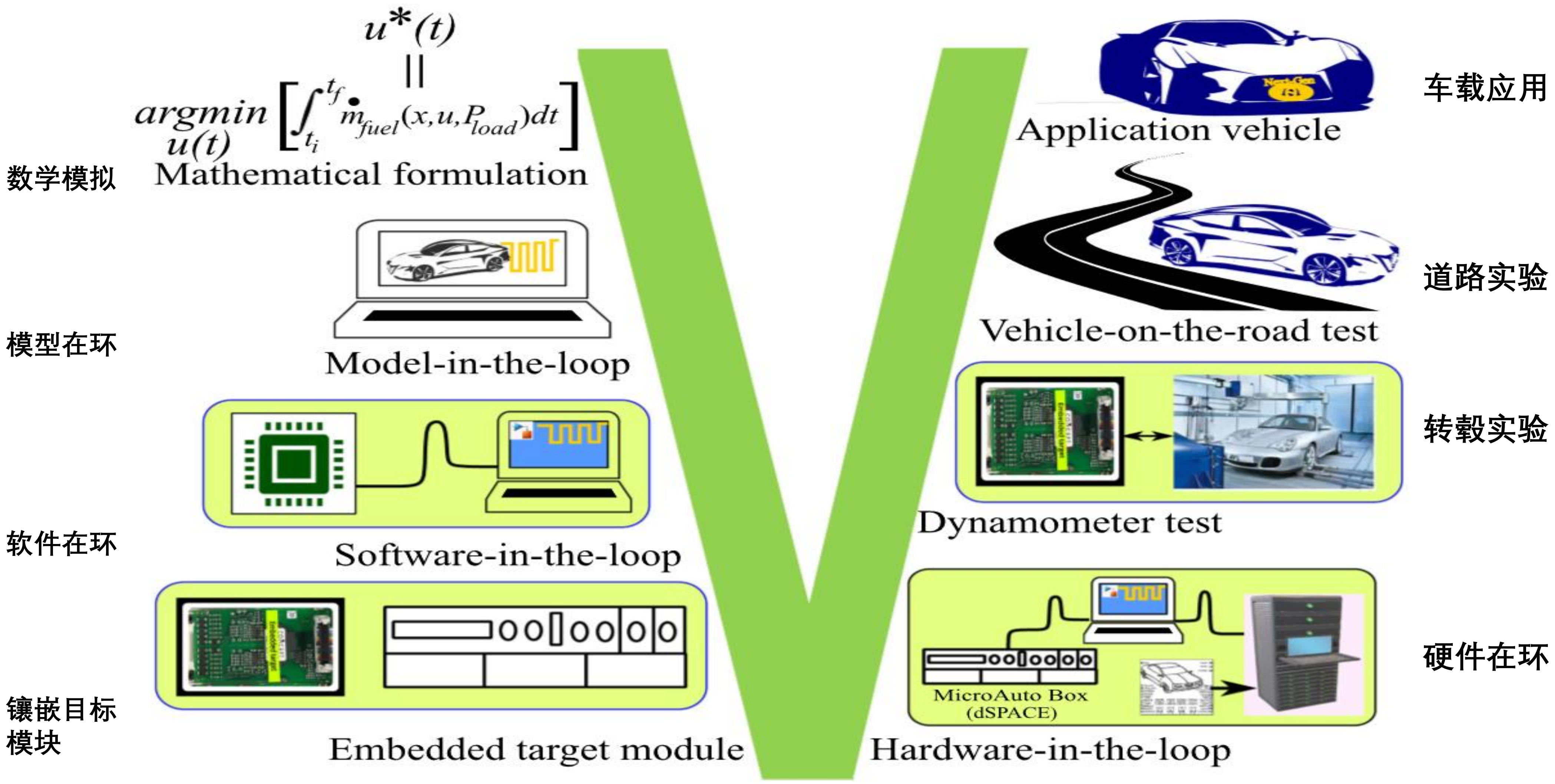

Steps of EMS development 能量管理系统的开发步骤

IEEE Transactions on Vehicular Technology, vol. 68, no. 7, 2019

Presentation Outline

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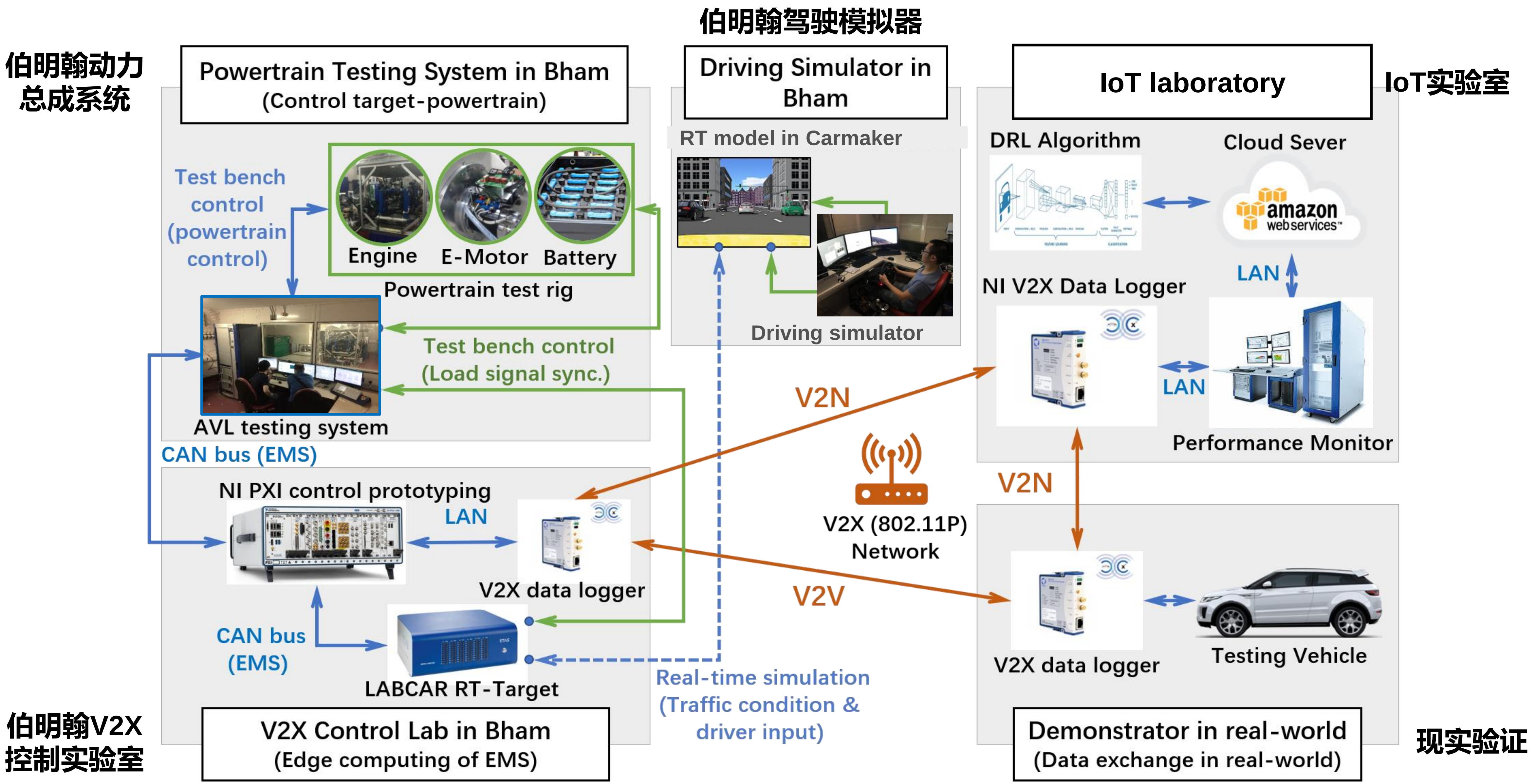
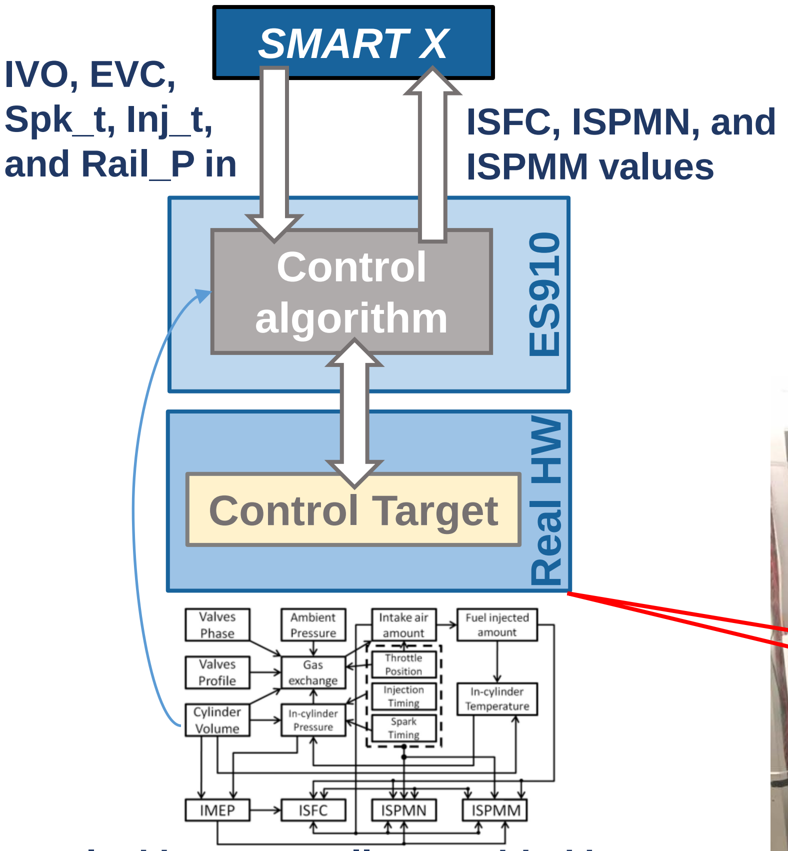
3 AI Based Research Facilities

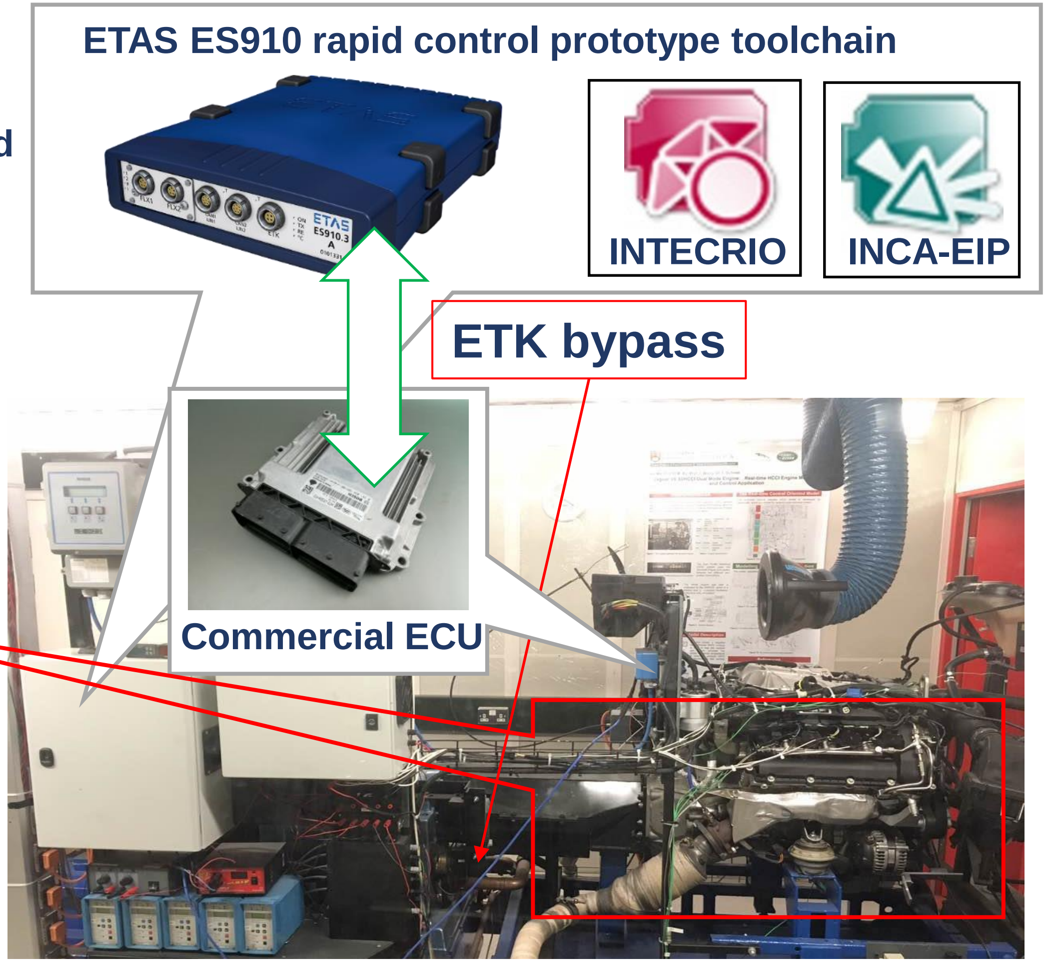


AI Based Optimization at the Engine Level

Workflow of steady state calibration – ECU bypass
稳态校准的工作流程– ECU旁路



Blackbox controller provided by JLR
捷豹路虎提供的黑盒控制器



Reference

1. Ma H, Li Z, Tayarani M, Lu G, Xu H, Yao X. Model-based computational intelligence multi-objective optimization for gasoline direct injection engine calibration. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2018 Jun 4. https://doi.org/10.1177/0954407018776743

AI Based Engine Calibration

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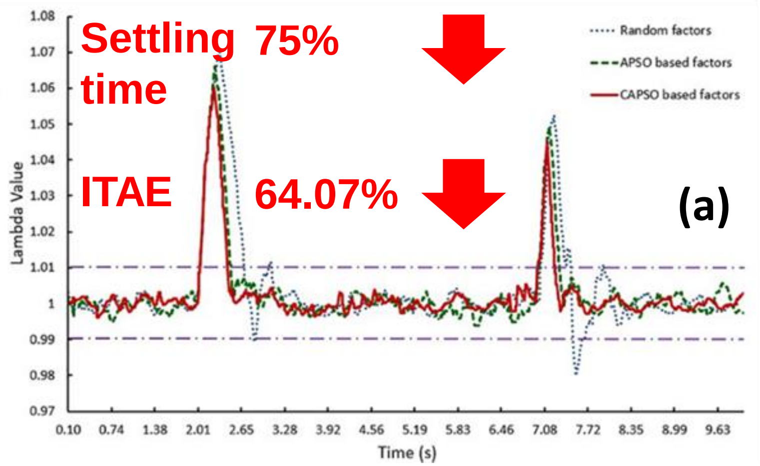
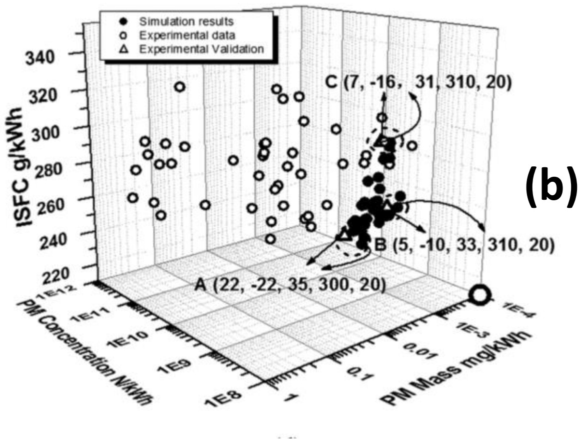
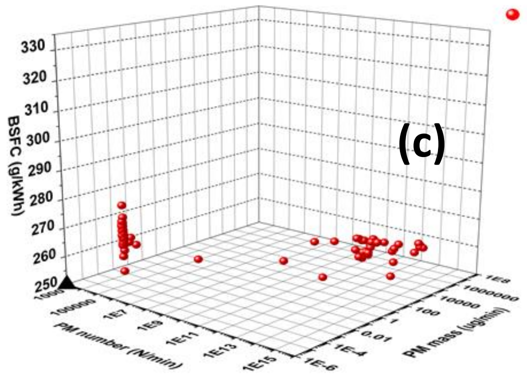
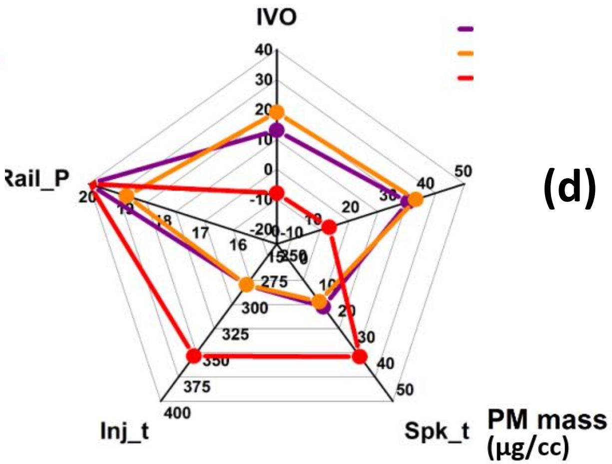
Comparison of the results of the engine calibration using the commercial and AI based calibration software
使用现有的商业发动机标定软件和基于AI标定软件的发动机标定结果比较。

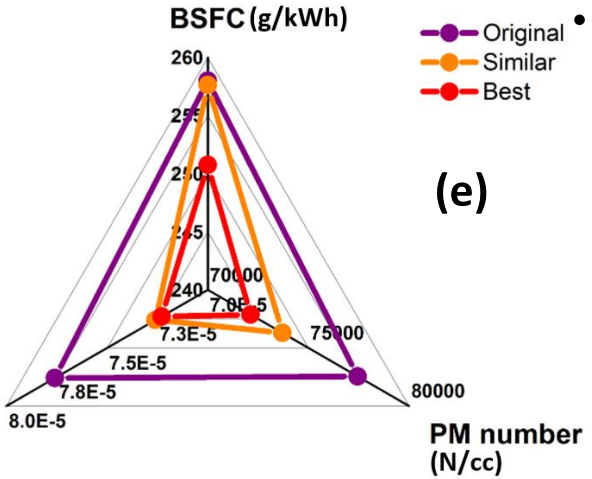




- **Open ECU or rapid control prototype is required.**
- **AI based engine control policy is developed by using either model based or non-model-based methods and the programme is then uploaded to the prototype controller.**
- 需要使用开放式ECU或快速控制原型
- 通过使用基于模型的方法或基于非模型的方法来开发基于AI的发动机控制策略，然后将程序上载到发动机原型控制器。







BSFC 3.1% ↓
PMn 6.8% ↓
PMm 6.9% ↓

Ma H, Li Z, Tayarani M, Lu G, Xu H, Yao X (2018)

Ma, H., Li, Z., Tayarani, M., Lu, G., Xu, H*., & Yao, X. (2018).

3 Benchmarking of AI Based SMART X

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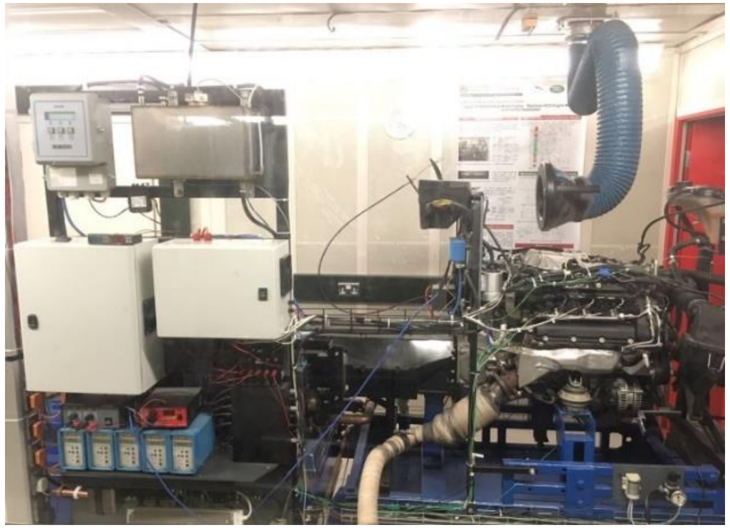

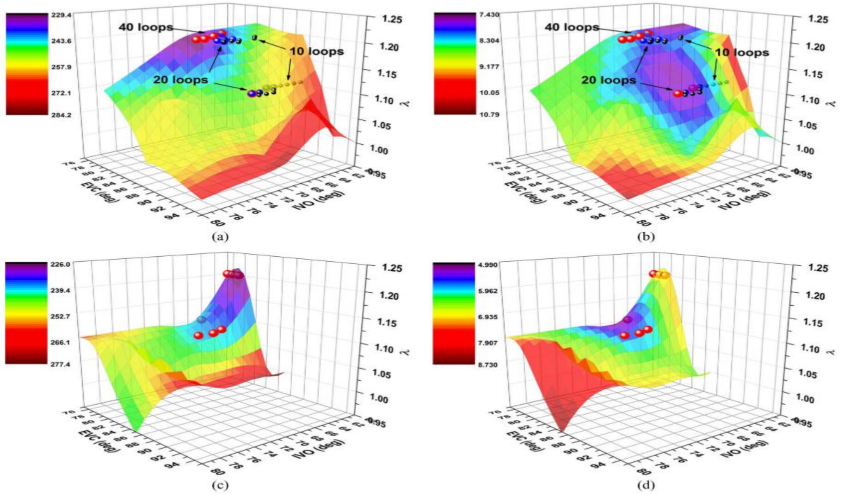

Engine calibration test bench and result with Smart X
发动机校准测试台和Smart X的结果

	Benchmark toolbox	SMART X
Concept 概念	Model-based calibration 基于模型的标定	**Model-free calibration 基于无模型的标定**
Core function 核心功能	Parameter calibration by engineers 工程师参数标定	Calibration **by AI 人工智能标定**
DoE 实验设计	Manual DoE 人工实验设计	**Evolutionary DOE 进化实验设计**
Deliverable of DoE 交付成果	Data-driven model for offline optimisation 数据驱动模型	**Calibration result via online optimisation 标定结果**
Offline modelling 离线建模	Polynomial curve fitting 多项式拟合	**N.A. 不适用**
Optimisation method 优化方法	• Linear programming 线性规划 • GA 遗传算法 • Single objective 单目标 • Multi-objective 多目标	• Swarm intelligence 群智能 • Computational intelligence 计算智能 • Multi-objective multi-variable optimisation 多目标多参数优化 • Online transient and steady state calibration 在线瞬稳态标定

3 AI Workflow of Transient Calibration

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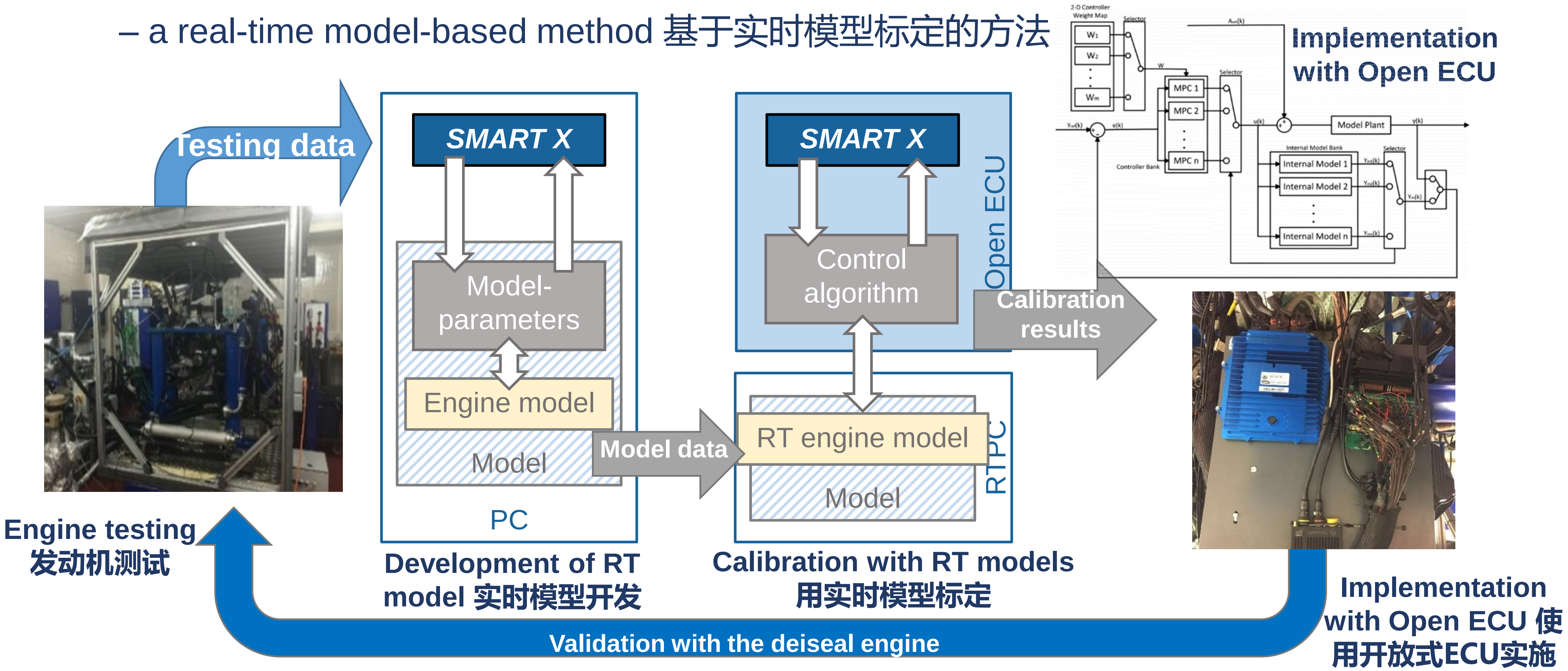
– a real-time model-based method 基于实时模型标定的方法



1. Zhang, Yunfan, et al. "Intelligent transient calibration of a dual-loop EGR diesel engine using chaos-enhanced accelerated particle swarm optimization algorithm." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 233.7 (2019): 1698-1711.

3 Validation of the Calibrated EGR Control

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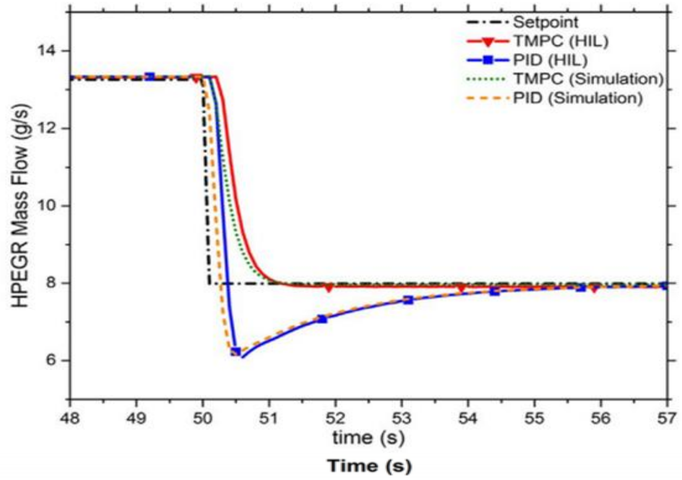
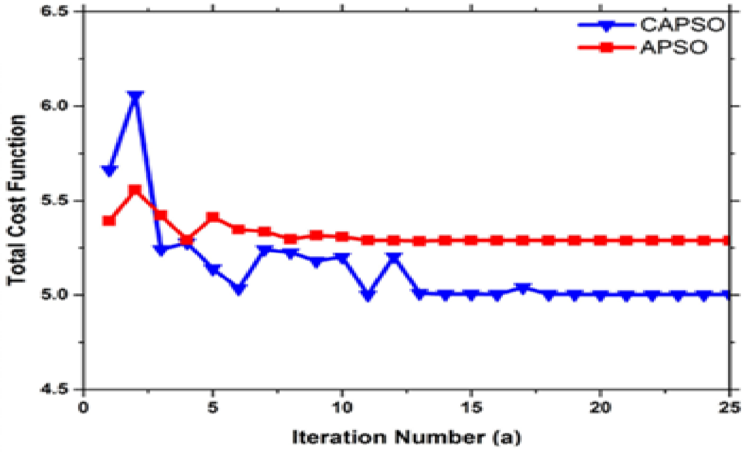
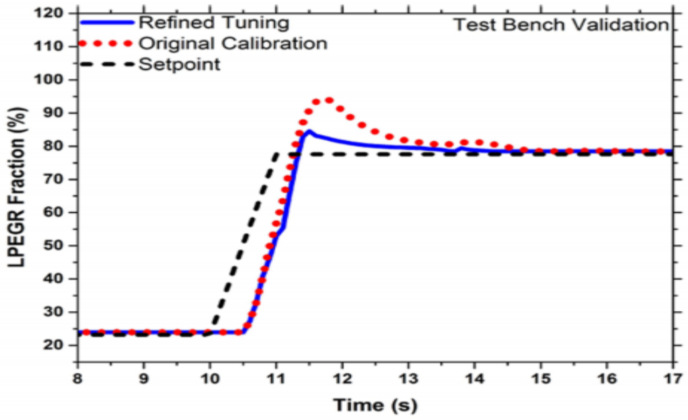
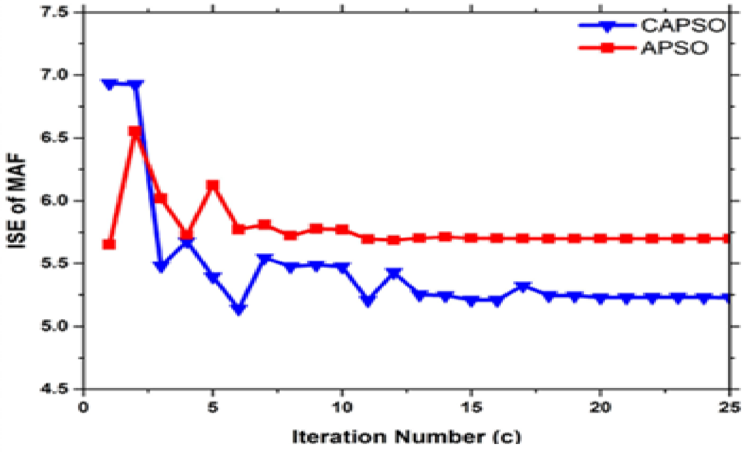
Proposed TMPC vs traditional PID: smoother and more responsive engine EGR control
智能TMPC与传统PID比较：更平稳，更响应的发动机EGR控制









- **A tuneable model predictive control (TMPC) controller based on the AI tool SMART-X is used for Dual EGR control.**
- **The average overshoot and settling time of the engine MAP are reduced by 1.2% and 5.7 s respectively.**

- **基于AI的可调谐模型预测控制（TMPC）SMART-X优化的控制模型，用于高低压双回路废气再循环系统控制。**
- **发动机MAP的平均过冲和稳定时间分别减少了1.2%和5.7 s。**

Zhang, Yunfan et al. Tuneable model predictive control of a turbocharged diesel engine with dual loop exhaust gas recirculation. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2017

Zhang, Yunfan, et al. "Intelligent transient calibration of a dual-loop EGR diesel engine using chaos-enhanced accelerated particle swarm optimization algorithm." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 233.7 (2019):

Intelligent Sizing of P/T Components

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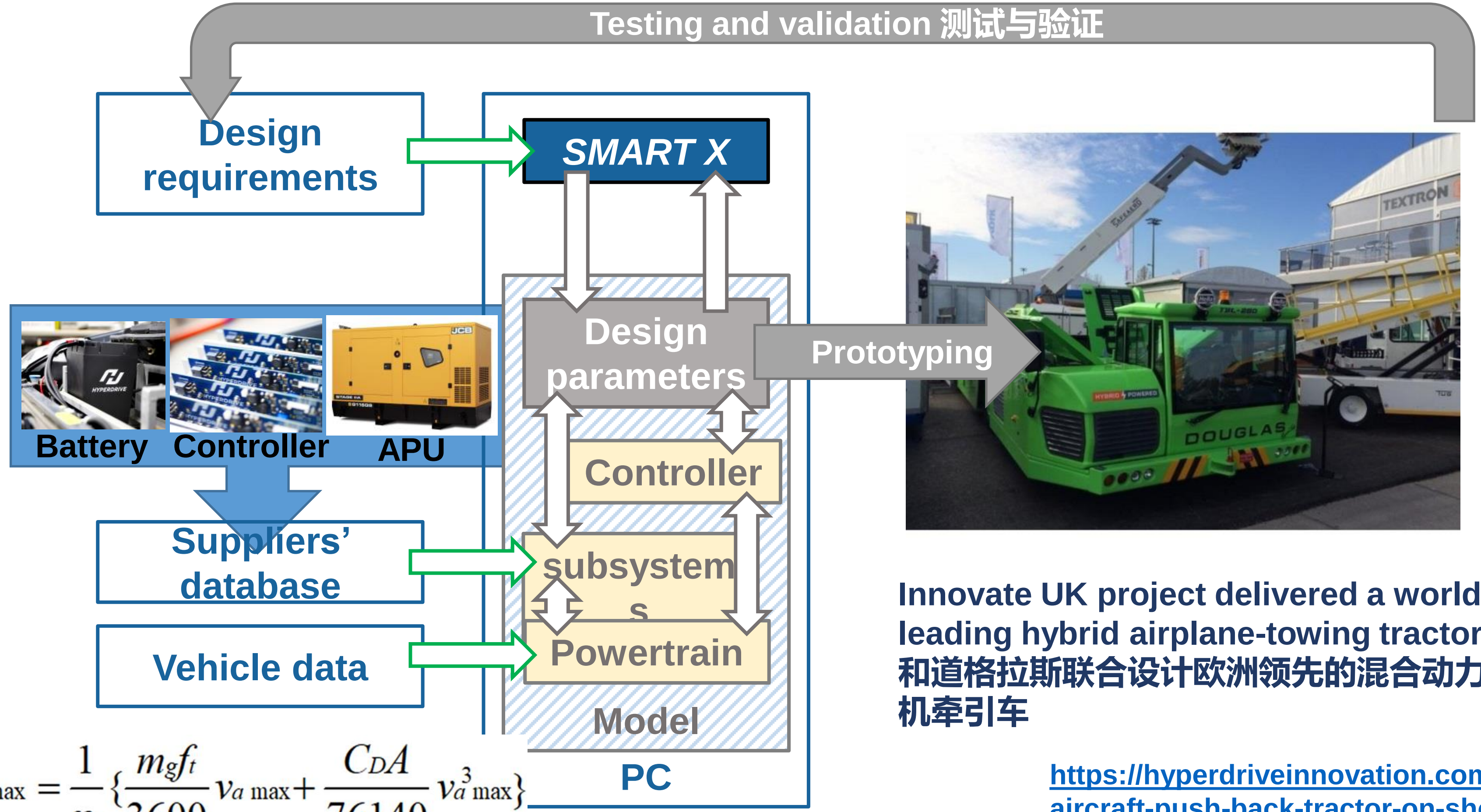
Workflow of intelligent modular design – a knowledge integrated method
智能模块化设计的工作流程–一种知识整合的方法



$$P_{max} = \frac{1}{\eta_t}\left\{\frac{m g f_t}{3600} v_{a\,max} + \frac{C_D A}{76140} v_{a\,max}^3\right\}$$

Innovate UK project delivered a world-leading hybrid airplane-towing tractor
和道格拉斯联合设计欧洲领先的混合动力飞机牵引车

https://hyperdriveinnovation.com/insights/news/new-hybrid-aircraft-push-back-tractor-on-show-at-inter-airport-europe-exhibition/

Each subsystem has different sizes for different combinations – intelligent sizing design is required for the Hybrid powertrain.

每个子系统针对不同的组合具有不同的尺寸。

混合动力总成需要智能化的优化尺寸设计。

Zhou, Quan et al., "Intelligent sizing of a series hybrid electric power-train system based on Chaos-enhanced accelerated particle swarm optimization." Applied Energy 189 (2017)

Reinforcement Learning for Energy Management

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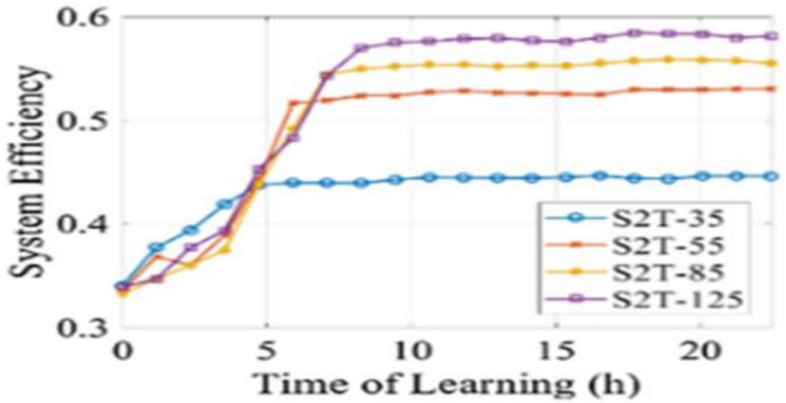
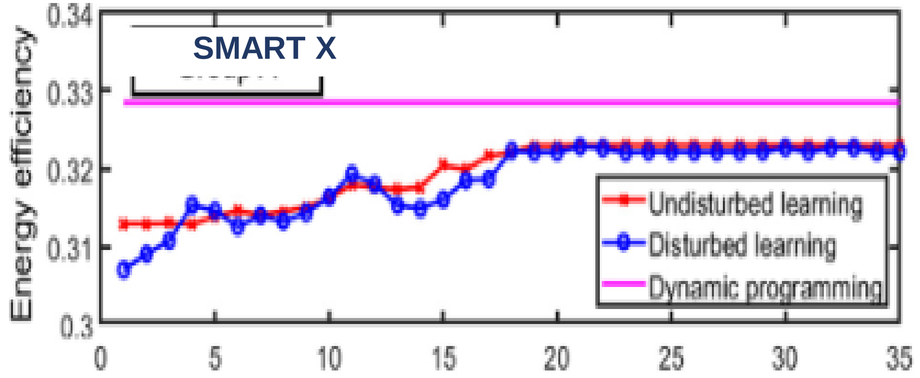
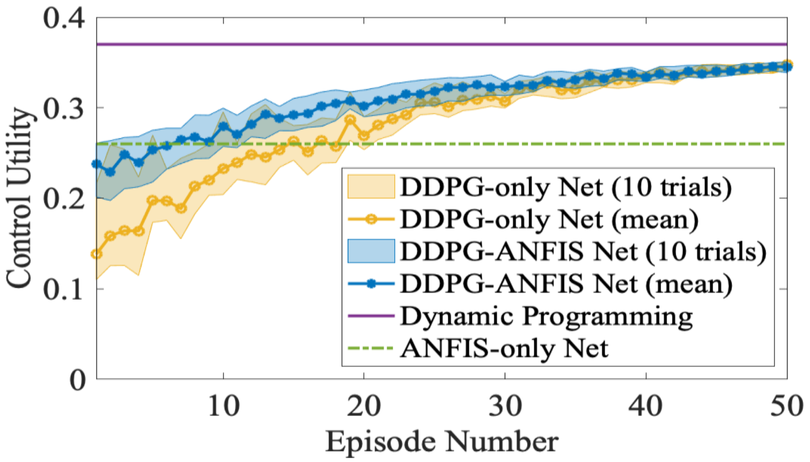
Improvement of vehicle system efficiency in real-world driving 在实际驾驶中提高车辆系统的能量使用效率







Capability for transfer learning
迁移学习的能力

For the real-world driving conditions at the airport, this hybrid vehicle will reach optimal energy efficiency after 15 hours of operation when learning from scratch

对于机场的实际驾驶条件，从头开始学习时，这款混合动力牵引车在运行15小时后可以达到最佳能量使用效率

SMART-X has robust learning in disturbed and undisturbed scenarios
具有在受干扰和不受干扰的情况下进行稳健的学习的能力

1. Zhou, Quan, et al. "Multi-step reinforcement learning for model-free predictive energy management of an electrified off-highway vehicle." Applied Energy 255 (2019): 113755.
2. Shuai, Bin, et al. "Heuristic action execution for energy efficient charge-sustaining control of connected hybrid vehicles with model-free double Q-learning." Applied Energy 267 (2020): 114900

Presentation Outline

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4 Digital Twin with AI

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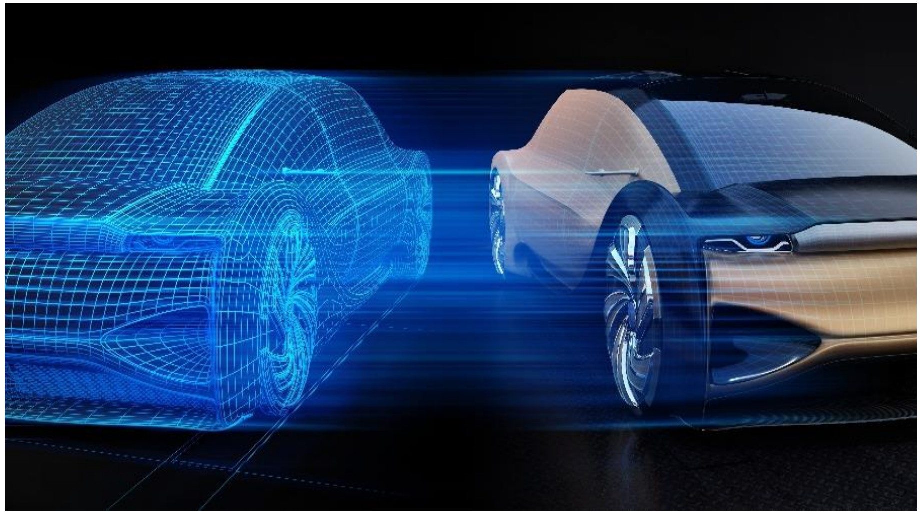
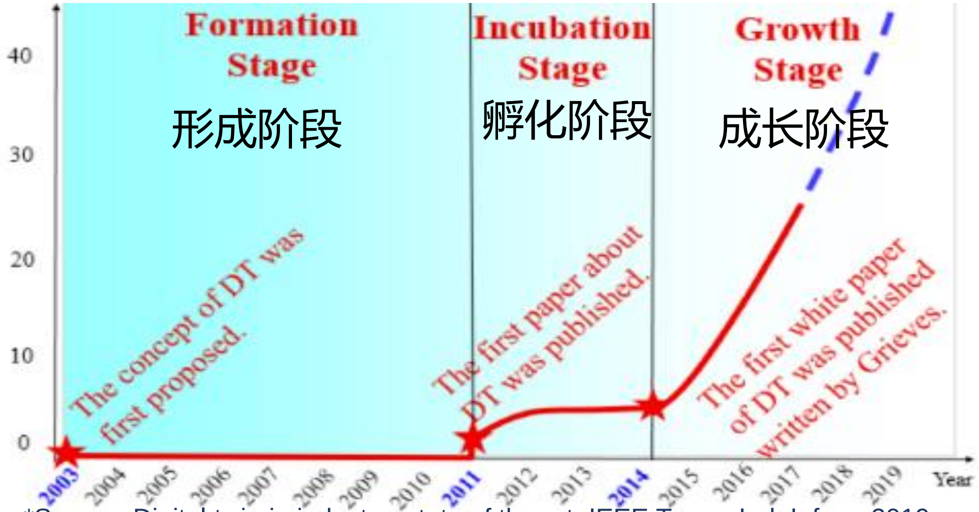
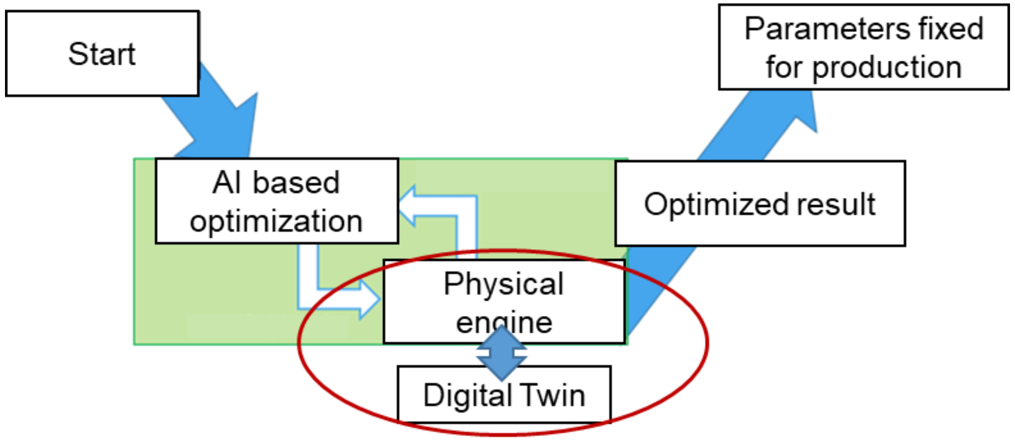


- A virtual real-time model 虚拟实时模型
- Commission of a product virtually before manufacturing 在制造之前，产品虚拟委托
- information which can be stored in the Cloud or remote locations. 可以存储在云或远程位置中的信息。

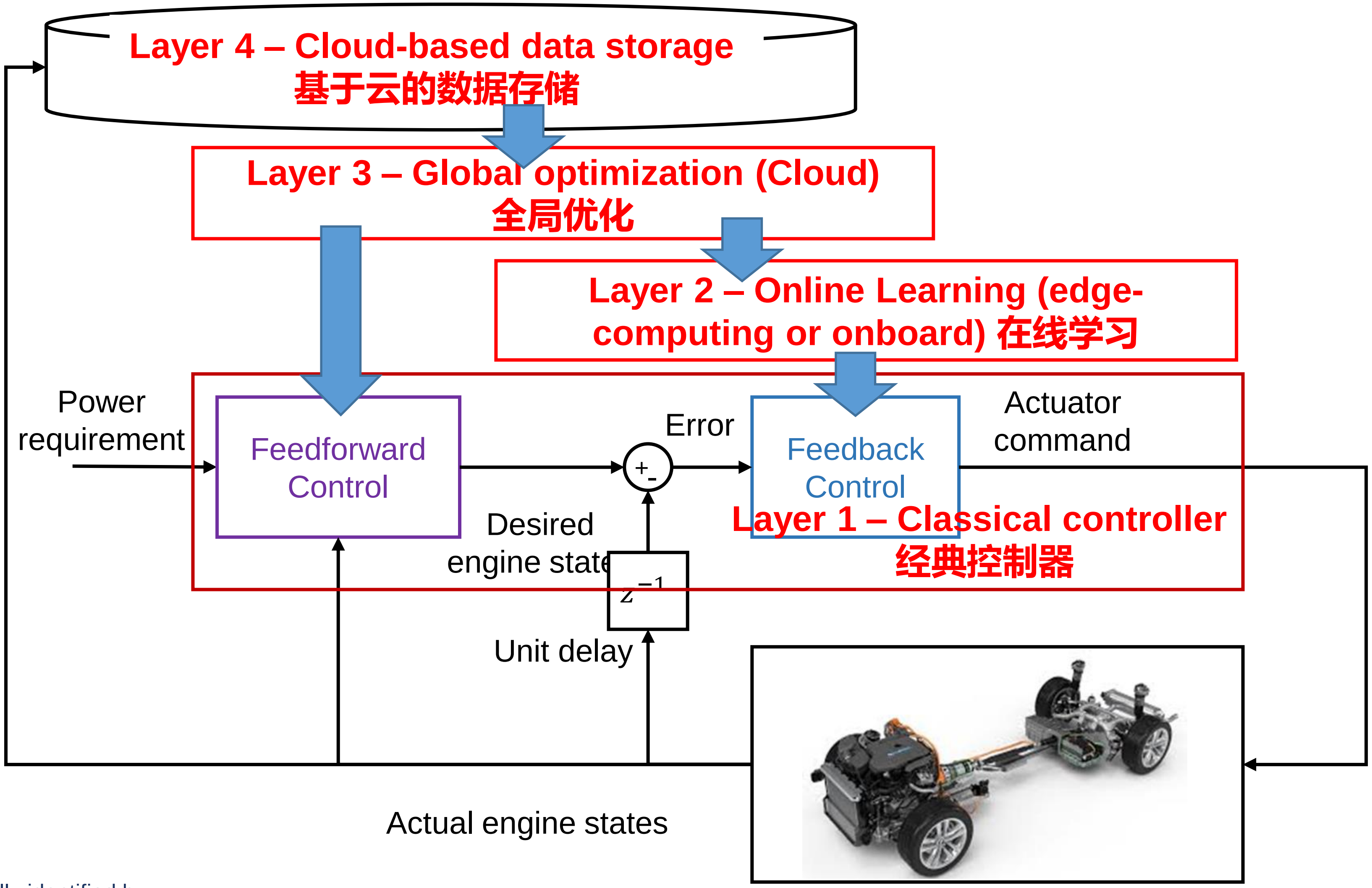


*Source: Digital twin in industry: state of the art, IEEE Trans. Ind. Infom. 2019



AI involved cyber-physical system

Layered Powertrain Control System



* Requirement originally identified by Ford and solutions proposed by UoB

4

Key Drives and Enabling Technology

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Key Drives 驱动力	Key Enablers 促成因素	Future Trend 未来趋势
Innovation & Optimisation 革新和优化		**Multiple source data fusion and predictive control 数据融合和预测控制**
Cost and Speed 减少成本 提高速度		**Merging of cyber and physical Systems** 信息物理系统合并
Revolution& Breakthrough 革命和突破		**Merging of classical optimisation with online AI learning 传统优化加智能学习**

Presentation Outline

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5 Summary

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1

The electric powertrain system with the IC engine must be designed to achieve the best and optimized performance and efficiency for all operating conditions at constrained cost. This requirement cannot be met by using conventional engineering practice.
基于发动机的电动化动力总成系统必须在不断减少成本和时间的条件下通过智能化设计使之在所有工况下整体达到最佳和优化的性能和效率。这个需求无法通过使用传统工程方法满足。

2

Intelligent control systems are required for future electrified powertrain systems which is adaptive and eventually able to be self-learning. This control task will involve layered subsystems at different levels involving the power unit, powertrain, vehicle and environment although it can finally be integrated.
未来的电动动力总成系统需要智能控制系统，该系统必须具有自适应性并最终能够进行自学习。尽管最终可以集成，但此控制任务将涉及不同级别的分层子系统，其中涉及动力单元，动力总成，车辆和环境。

3

The key enablers of the furfure control system will be the more advanced hardware, big data and artificial intelligence. AI based digital twin technology will change the process of product development and life-cycle performance of the electrified powertrain namely the new propulsion system.
未来控制系统的关键推动力将是更先进的硬件，大数据和人工智能。 基于AI的数字孪生技术将改变动力推进系统的产品开发过程和生命周期性能。

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Advantage West Midlands UK
European Regional Development

Contributions from

PhD research students and research fellows

Recent Publications

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Thank you!

Prof Hongming Xu

School of Engineering
The University of Birmingham
Email: h.m.xu@bham.ac.uk
Website: https://www.birmingham.ac.uk/staff/profiles/mechanical/xu-hongming.aspx