TONGJI UNIVERSITY

分布式驱动电动汽车控制系统研发与实践

Distributed Drive Electric Vehicle Control System Research, Development and Practice

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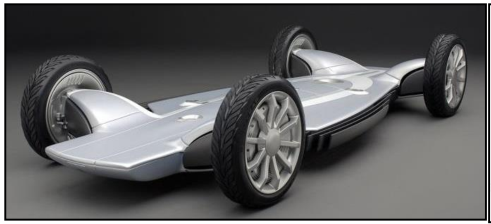
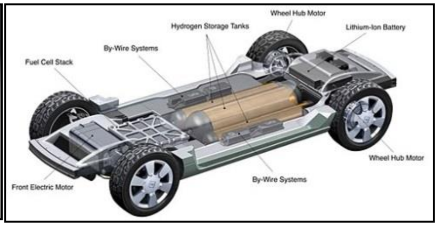
概述

OUTLINE

分布式驱动电动汽车/Distributed Drive Electric Vehicle





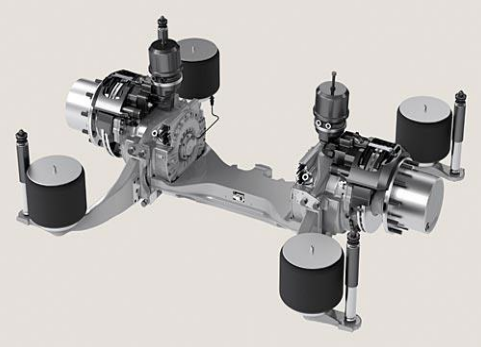
GM Autonomy, 2002 **GM Sequel, 2006** **Acura NSX,2016** **LVCHI Venera,2018**

乘用车 Passenger vehicle

大客车 Coach

特种车 Special vehicle

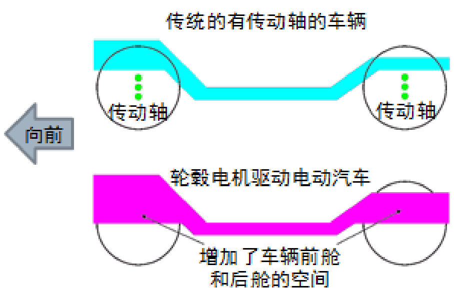
Protean PD18



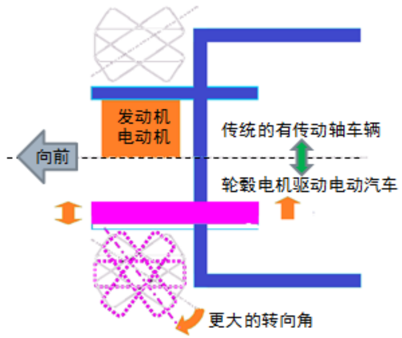
ZF AVE130

GM · Audi · TOYOTA · HYUNDAI · SCHAEFFLER (LUK, INA, FAG) · SIEMENS · ZF · HONDA · Protean ELECTRIC · MICHELIN · ECOMOVE · SIM-Drive

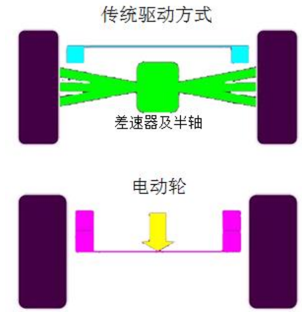
分布式驱动电动汽车/Distributed Drive Electric Vehicle



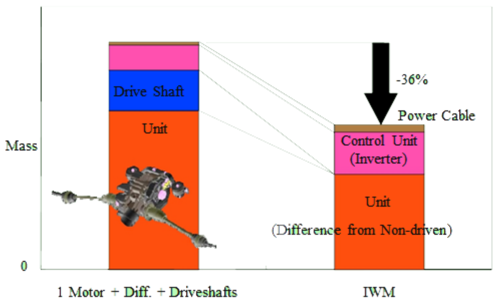
增加车内空间
Increase the interior space



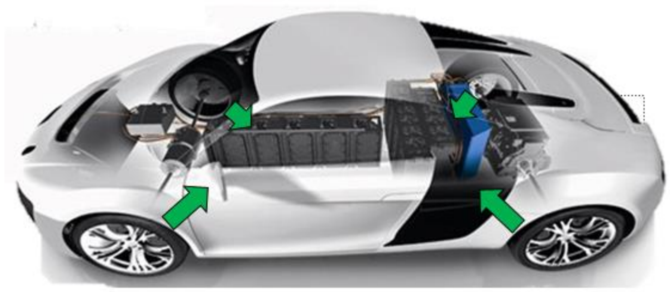
减小最小转弯半径
Reduce the minimum turning radius



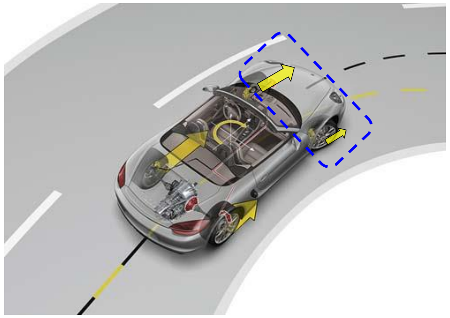
增加整车设计自由度
Increase vehicle design freedom



减轻整车质量
Reduce vehicle weight



能效优化
Optimize energy efficiency



先进动力学控制
Advanced dynamics control

- **主动安全**：基于直接横摆力矩控制的ESC产品，每年可挽救5000-8500个生命，减少30%正面碰撞，减少80%由侧滑引起的交通事故，减少50%交通事故。
- **Active Safety:** DYC based ESC products save 5000-8500 lives per year, reduce 30% direct impacts, 80% traffic accidents caused by lateral instability and 50% traffic accidents.
- **节能高效**：设计优越的分布式驱动电动汽车比传统汽油发动机车效率高155%，比传统的单电机集中驱动型电动汽车效率高19%-42%。
- **Economy:** Efficiency of well-designed DDEVs is 155% higher than ICVs, 19%-42% higher than centralized EVs.

同济大学在国内率先开展分布式驱动电动汽车研发工作
Tongji Achievements in DDEV R&D

Tongji Achievements in DDEV

春晖嘉乐 | 无人游览车 | 军用特种车 | SUV

春晖一号 | 春晖三号 | NVPG | 世博观光车 | 乘用车 | 大客车

研 发 与 示 范 | 企 业 应 用

2002 | 2007 | 2010 | 2013

研发春晖系列分布式驱动电动汽车

与蒂森克虏伯合作新一代电动汽车平台NVPG

ThyssenKrupp

EXPO 2010 SHANGHAI CHINA

universiade shenzhen 2011

嘉陵工业 JIALING

SAIC 上汽集团 SAIC MOTOR

BYD 比亚迪汽车 BYD AUTO

YUTONG 宇通客车

上海国际工博会“创新奖”

上海国际工博会“高校展区一等奖”

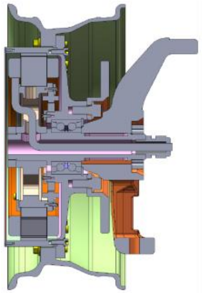
国内首次分布式驱动电动汽车百辆级示范

上海市科技进步一等奖

完成汽车领域唯一973计划项目

同济大学在国内率先开展分布式驱动电动汽车研发工作
Tongji Achievements in DDEV R&D

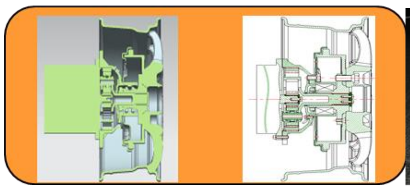
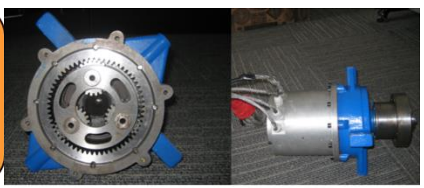
- **外转子轮毂电机系统 (2006-2008)**
- **Outer rotor in-wheel motor (2006-2008)**



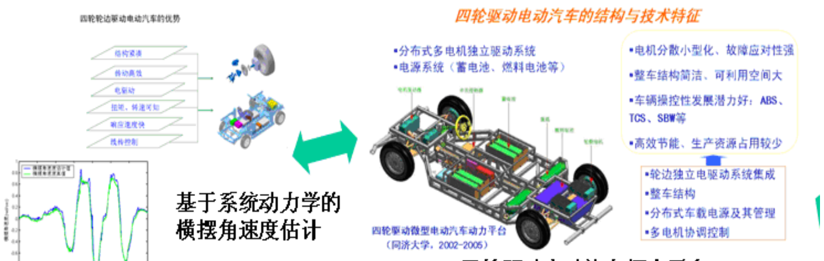
电动轮–悬架模块试制

- **整车及电动轮试验台 (2004-2010)**
- **Test bench for vehicle and motor(2004-2010)**


- **行星减速式轮毂驱动系统 (2007-2008)**
- **Planet reduction gear (2007-2008)**

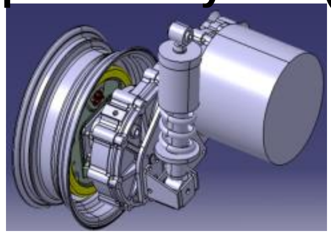



- **轮毂驱动电动汽车动力学控制研究（2005-)**
- **Research in dynamic control of in-wheel motor electric vehicles（2005-)**



四轮驱动电动汽车概念平台

- **电机-减速机构-悬架集成系统(2008-2015)**
- **Integration of motor –reduction gear-suspension system(2008-2015)**



自主开发的平台样车

代表性项目/ Main Programs

项目来源/ Resource	项目名称/ Program
国家973计划 National 973 Project	高性能分布式驱动电动汽车关键基础问题研究 Study on the Key Basic Problems of High Performance Distributed Drive Electric Vehicles
国家重点研发计划 National Key R&D Project	高效轻量化轮毂直驱电动轮总成关键技术研究与应用 Research and Application of Key Techniques for Efficient and Lightweight Wheel Direct Drive Electric Wheel Assembly
科技部国际合作项目 International Science & Technology Cooperation Program of China MOST	中德清洁能源汽车动力系统、电源和电机关键技术研发 Sino-German Clean Energy Vehicle Power System, Power Supply and Motor Key Technology Development
国家863计划 National 863 Project	四轮驱动电动汽车关键技术研究 Research on Key Technologies of Four-wheel Drive Electric Vehicles
国家863 计划 National 863 Project	轮边电驱动系统关键零部件及其底盘应用技术研究 Research on Key Components of Chassis Electric Drive System and Chassis Application Technology
国家科技支撑计划 National Key Technology Support Project	电动汽车分布式四轮驱动系统研发 Distributed Drive System Research and Development of Electric Vehicles
自然科学基金联合基金 China NSF	轮毂/轮边电驱动汽车电动化底盘系统优化设计及分布式协调控制 Wheel Hub/Wheel-side Electric Drive Vehicle Eclecticized Chassis System Optimization Design and Distributed Coordination Control

分布式驱动电动汽车动力学控制

Distributed Drive Electric Vehicle Dynamics Control

分布式驱动电动汽车整车动力学一体化协调控制
DDEV Integrated Control

分布式驱动电动汽车结构特点/ Structure features of DDEV

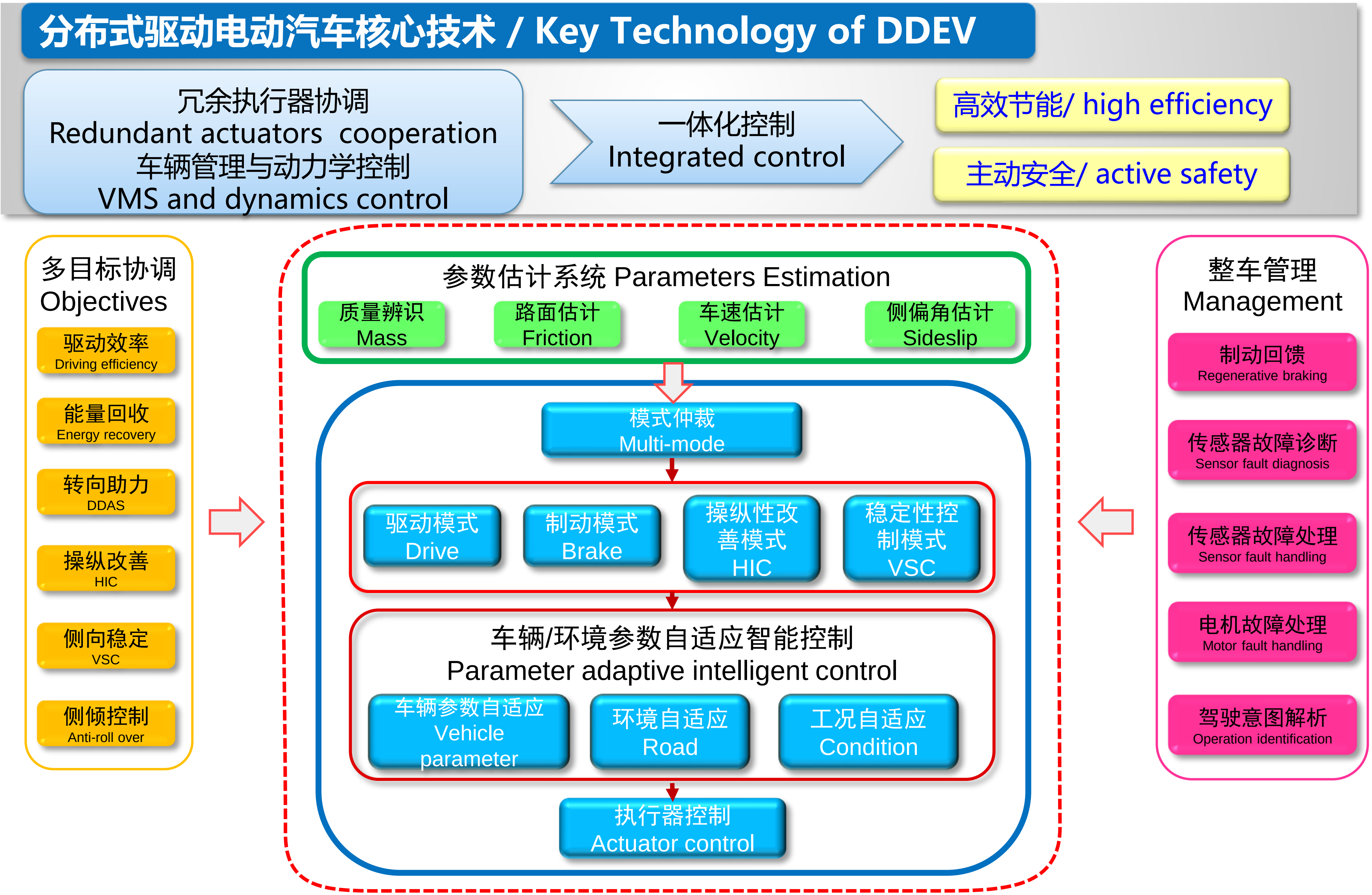
分布式电机、制动器
In-wheel / wheel-side motors, brakes

车轮转矩、转速信号
Torque, Speed

多执行器
Multi-actuators

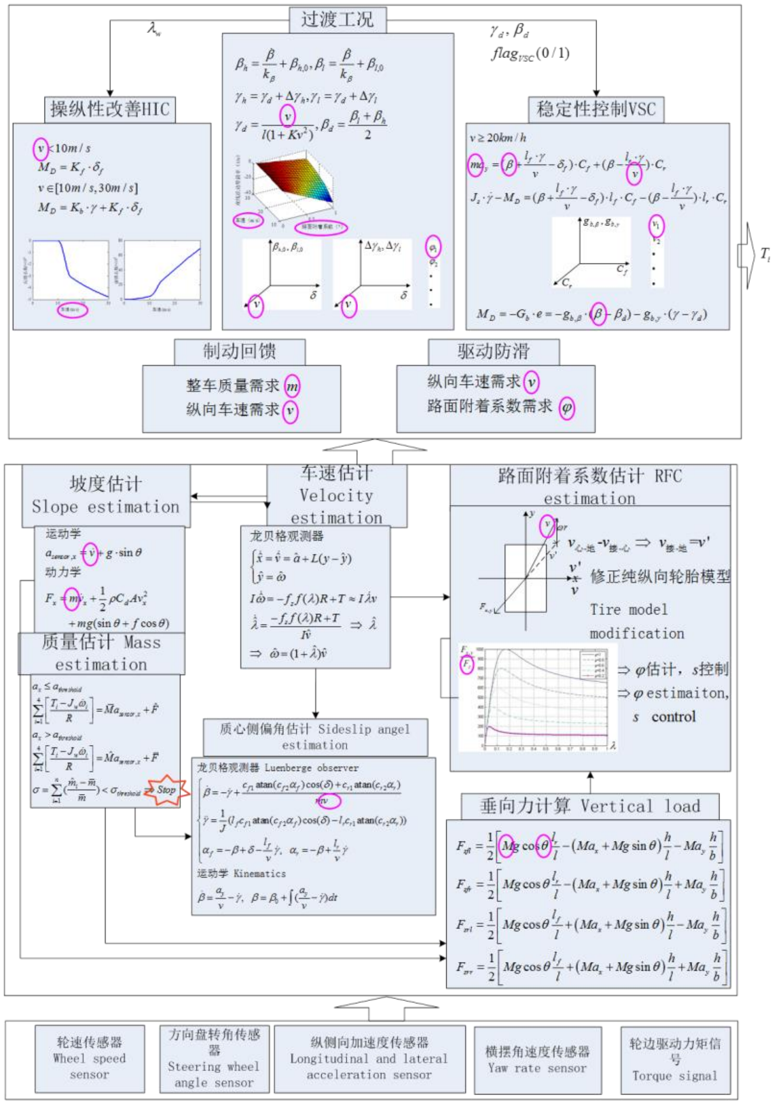
多信息源
Multi-information resources

分布式驱动电动汽车整车动力学一体化协调控制
DDEV Integrated Control



研究成果 / Research Results

一体化参数估计系统/ Integrated Parameter Estimation System



面向驱制动、操纵稳定动力学控制
以及能效优化控制
for driving/braking, handling and energy control

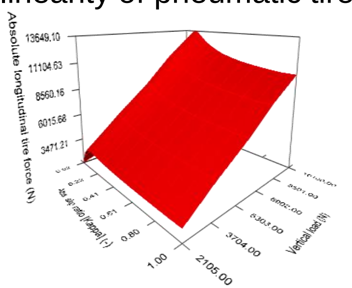
- ✓整车质量 / mass
- ✓行驶坡度 / slope
- ✓纵向车速 / longitudinal speed
- ✓路面附着系数 / tire-road friction
- ✓质心侧偏角 / sideslip angle

曲彤. 分布式驱动电动汽车动力学控制关键状态与参数一体化估计方法, 2015.（学位论文）
Yuan F, Lu X, Zhuoping Y U, et al. Recursive Least Square Vehicle Mass Estimation Based on Acceleration Partition[J]. Chinese Journal of Mechanical Engineering, 2014, 27(3):448-459.（SCI检索）
Xia X, Xiong L, Sun K, et al. Estimation of maximum road friction coefficient based on Lyapunov method[J]. International Journal of Automotive Technology, 2016, 17(6):991-1002.（SCI检索）

鲁棒自适应滑移率控制/ Robust adaptive SRC

充气轮胎非线性特性

Nonlinearity of pneumatic tire

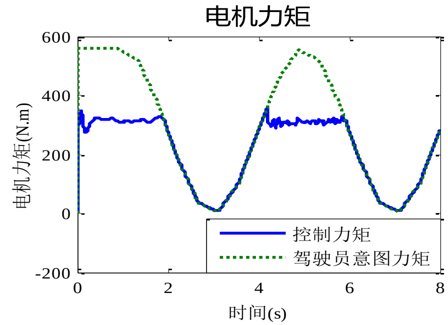


路面不确定性

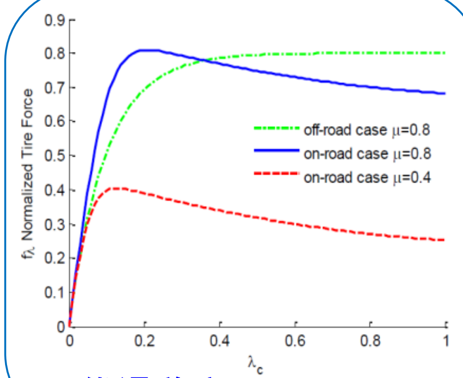
Road uncertainty

分配层转矩需求

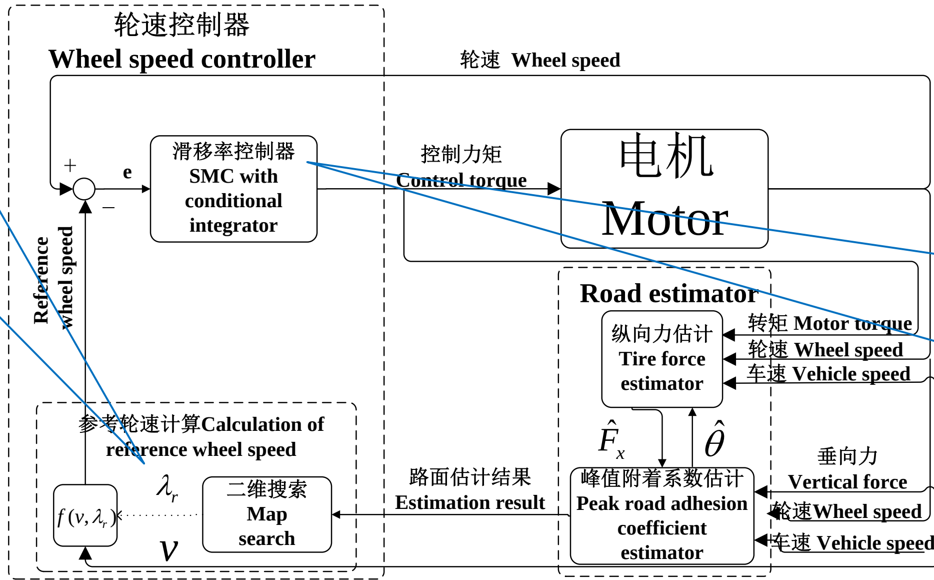
Torque request from DC

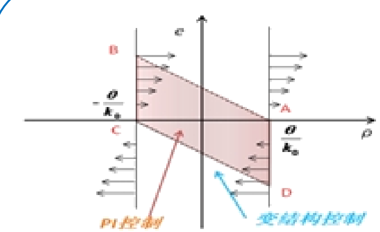


- 低附路面起步平均纵向加速度**提高33%**
- Average ax raised **33%** on low-μ road
- 对开路面起步平均纵向加速度**提高83%**
- Average ax raised **83%** on split-μ road
- 路面附着系数利用率**超过90%**
- Road friction usage rate over **90%**
- 滑移率收敛时间**小于0.3s**
- Slip rate convergence time less than **0.3s**



最优滑移率 optimum slip





鲁棒滑模控制

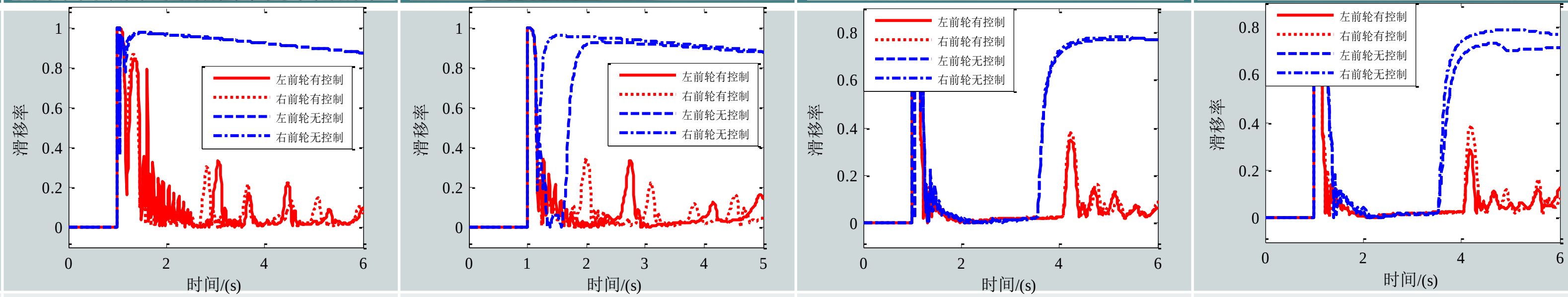
robust SM control

Yu, Z., Zhang, R., Lu, X., Jin, C., & Sun, K.. Robust adaptive anti-slip regulation controller for a distributed-drive electric vehicle considering the driver’ s intended driving torque. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, v 232, n 4, p 562-576, March 1, 2018. （SCI检索）

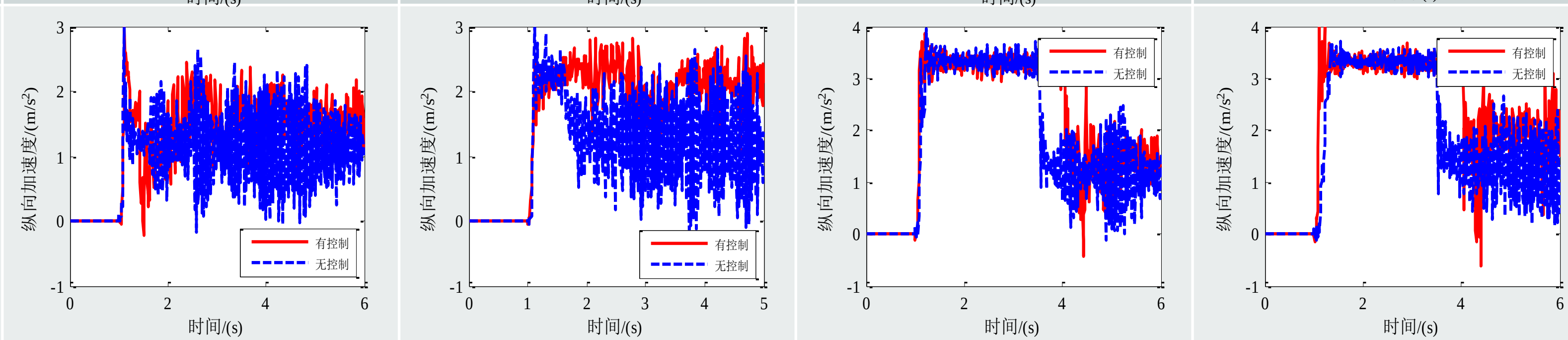
研究成果 / Research Results

鲁棒自适应滑移率控制/ Robust adaptive SRC

滑移率控制效果
SRC results



驱动效率改善效果
Driving efficiency improvement



低附路面起步平均纵向加速度提高33%，对开路面起步平均纵向加速度提高83%
33% acceleration improvement on low-μ road, 83% on split-μ road.

研究成果 / Research Results

鲁棒自适应滑移率控制/ Robust adaptive SRC

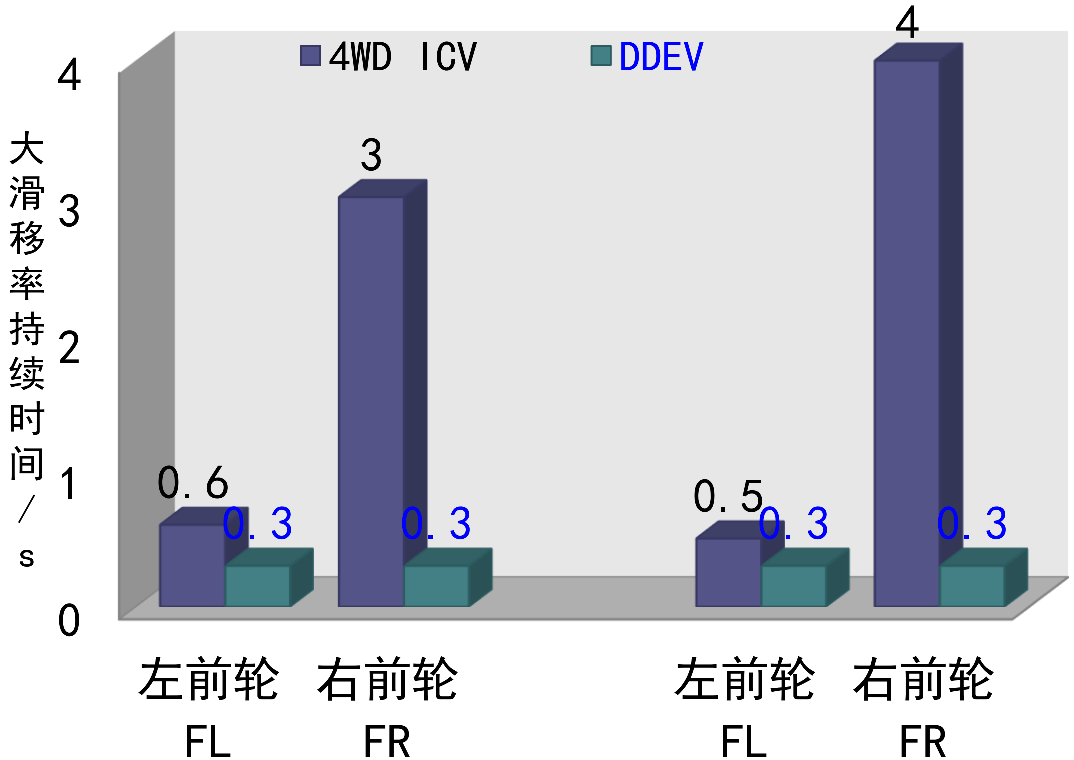
同济大学嘉定校区试验场
Proving ground in Tongji University

江苏玛吉斯试车场
MAXXIS proving ground，Jiangsu

中汽中心呼伦贝尔冬季试车场
CATARC Hulunbeier winter proving ground

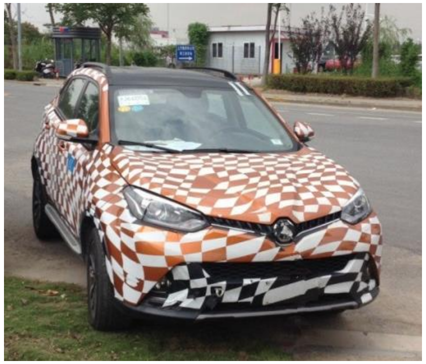
冰面起步Start on icy road

鲁棒自适应滑移率控制/ Robust adaptive SRC



对开路面起步 高附→对开

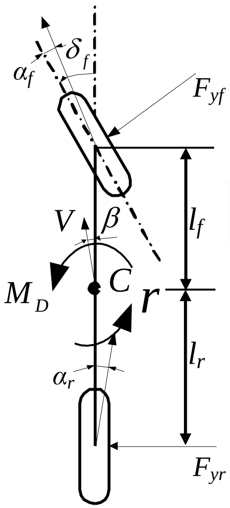
split μ high μ to split μ



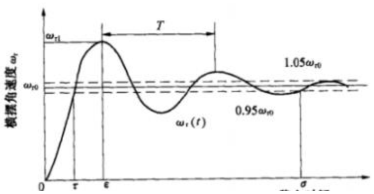
施加控制车辆滑移率峰值的持续时间仅0.3秒，控制精确，路面附着系数利用率高，相比于传统四驱车增加了50%的优化效果。

Slip rate convergence time of DDEV is only 0.3s, much less than ICV.

多目标优化的操纵性改善控制 Multi-objective handling improvement control



优化目标/ Optimization targets



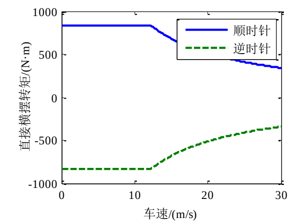
横摆角速度响应
Yaw rate response

上升时间
Rise time $t_r = \dfrac{(\pi - \arccos\zeta)}{\omega_n\sqrt{1-\zeta^2}}$

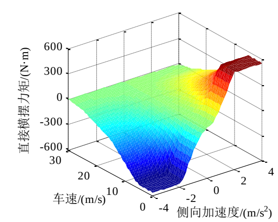
超调量
Overshoot $M_p = \exp(-\pi\zeta / \sqrt{1-\zeta^2})$

助力力矩
Assist torque $f(v,\delta_f,T_h,\mu)$

约束条件/ Constraints



电机能力
motor capability



助力特性
Assist characteristic

多目标优化确定反馈系数
Multi-objective optimization feedback gain

$$J(V,K_b) = w_{tr}\left(\frac{t_r(V,K_b)}{t_r(V,0)}\right)^2 + w_{mp}\left(\frac{M_p(V,K_b)}{M_p(V,0)}\right)^2 + w_{kb}\left(\frac{K_b}{5000}\right)^2$$

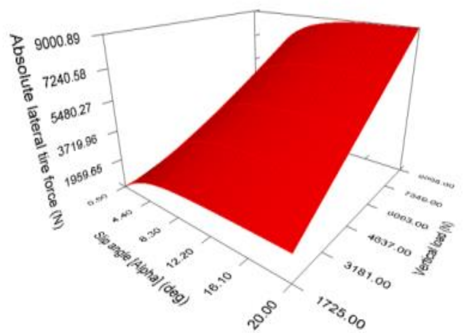
综合助力、稳态、瞬态性能确定前馈系数
Feed-forward gain concerning power-assist, steady/transient performance

$$K_f \le \left.\frac{\gamma}{\delta_f}\right)_s \cdot \frac{V_a}{a_y}\left[M_{D,f}(a_y) + 2M_{w,\max}\cdot i_s - K_b\frac{a_y}{V_a}\right]$$

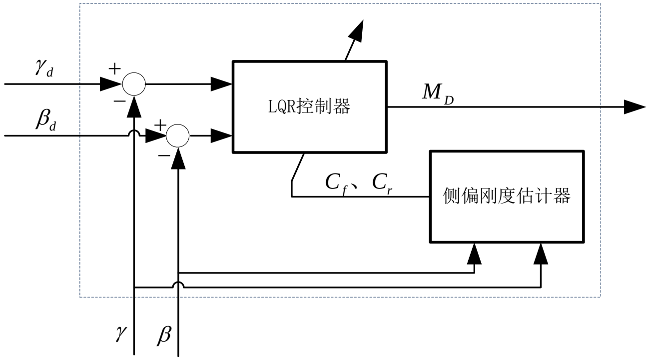
- 蛇行试验方向盘转角**降低15%**以上，方向盘转矩**降低10%-20%**
- Slalom test steering wheel angle has been reduced by **15%,**steering wheel torque has been reduced by **10%-20%**
- 稳态圆周试验横摆角速度响应时间**减少10%**以上
- Steady circle test yaw rate response time has been reduced by more than **10%**

Zhuoping YU, Bo LENG, Lu XIONG, et al. Direct Yaw Moment Control for Distributed Drive Electric Vehicle Handling Performance Improvement[J]. Chinese Journal of Mechanical Engineering, 2016, 29(3):486-497. （SCI检索）

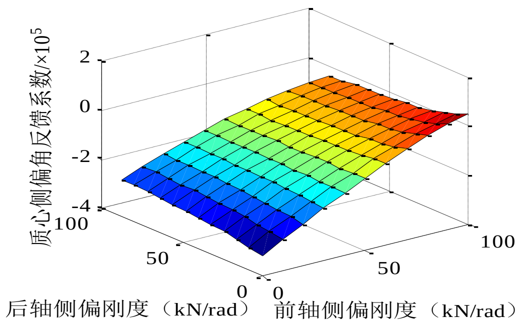
轮胎侧偏刚度自校正的稳定性控制
Tire cornering stiffness adaptive based stability control



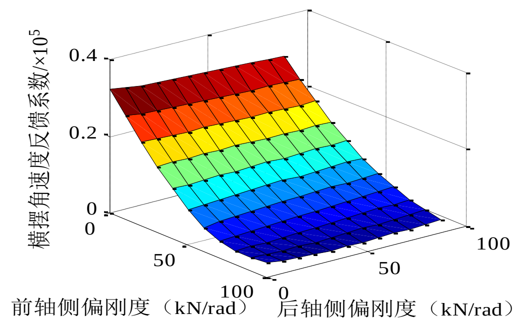
轮胎侧偏刚度非线性特性
Tire cornering stiffness nonlinear characteristic



自适应二次型最优调节器
Adaptive LQR controller

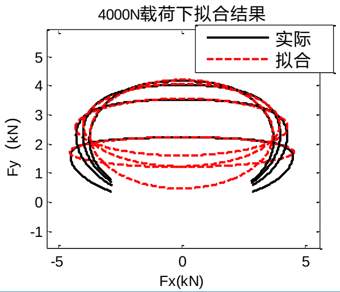


质心侧偏角误差反馈系数
Side slip angle error feedback gain



横摆角速度误差反馈系数
Yaw rate error feedback gain

轮胎侧偏刚度自校正的稳定性控制
Tire cornering stiffness adaptive based stability control



轮胎力纵侧耦合特性
Tire force coupling

$$M_{zx}(T+\Delta T) = M_{zx}(T) + \Delta M_{zx}$$

$$\Delta M_{zx} = B_{zx}\Delta F_x + B_{zy}\Delta F_y$$

$$B_{zx} = [-\frac{b}{2} \quad \frac{b}{2} \quad -\frac{b}{2} \quad \frac{b}{2}]$$

$$B_{zy} = \left[l_f \quad l_f \quad -l_r \quad -l_r\right]$$

$$\Delta F_y = \nabla f_{yx}^{\alpha}(\Delta F_x)$$

轮胎力纵侧耦合

Tire force coupling

$$\Delta M_{zx} = \left(B_{zx} + B_{zy}\nabla f_{yx}^{\alpha}\right)\Delta F_x$$

动态效率矩阵：
Dynamic efficiency matrix:

$$B = \begin{bmatrix} B_x \\ B_{zx} + B_{zy}\nabla f_{yx}^{\alpha} \end{bmatrix}$$

- 低附紧急避障最高通过车速**提高10%-15%**，稳定性裕度优于配备ESC的传统四驱车。
- Low adhesion road emergency obstacle avoidance test: maximum passing velocity increased **10%-15%**, stability margin better than traditional 4WD vehicle with ESC

LuXiong, ZhuopingYu, YangWang, et al. Vehicle dynamics control of four in-wheel motor drive electric vehicle using gain scheduling based on tyre cornering stiffness estimation[J]. Vehicle System Dynamics, 2012, 50(6):831-846. （SCI检索）
Leng B, Xiong L, Yu Z, et al. Allocation control algorithms design and comparison based on distributed drive electric vehicles[J]. International Journal of Automotive Technology, 2018, 19(1):55-62.（SCI检索）

操纵稳定性控制/ Handling and stability control

蛇行工况，无控制
Slalom without control

操纵稳定性控制/ Handling and stability control

蛇行工况，有控制
Slalom with control

操纵稳定性控制/ Handling and stability control

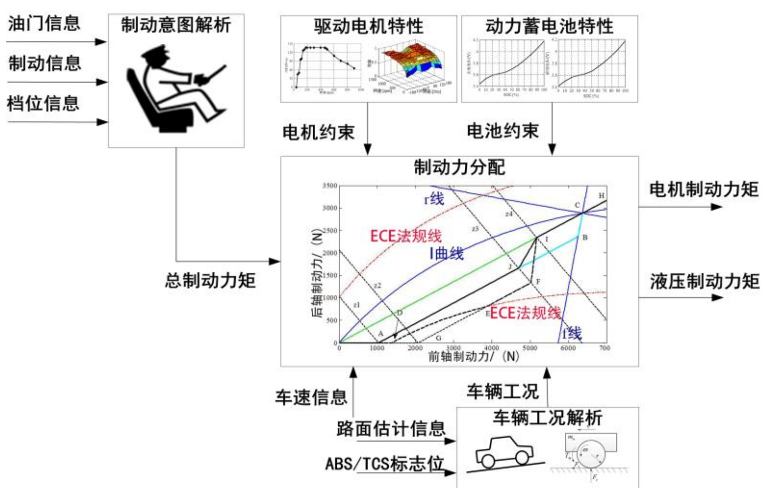
紧急避障工况，无控制
Obstacle avoidance without control

操纵稳定性控制/ Handling and stability control

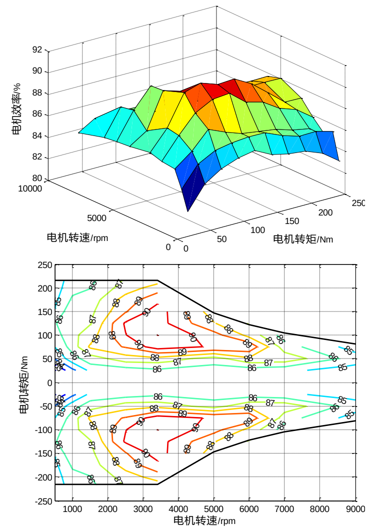
紧急避障工况，有控制
Obstacle avoidance with control

能耗优化策略/ Energy consumption optimization strategy

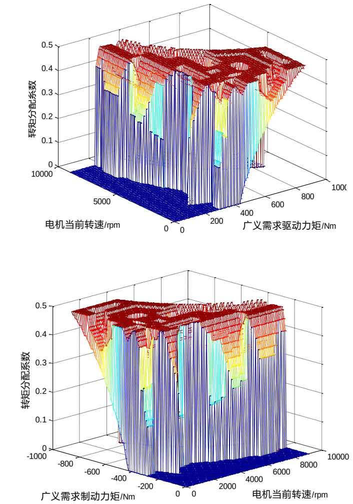
技术原理：综合考虑**ECE法规要求、驱动电机效率特性与动力电池特性**，提出包含驱动转矩优化分配和复合制动分配的能耗优化策略。
Driving torque distribution strategy and hybrid brake strategy were designed for energy saving based on ECE laws, motor efficiency and battery characteristics.



多目标优化的复合制动分配策略框图
Diagram of multi-objective hybrid brake strategy



电机效率场
Motor efficiency field

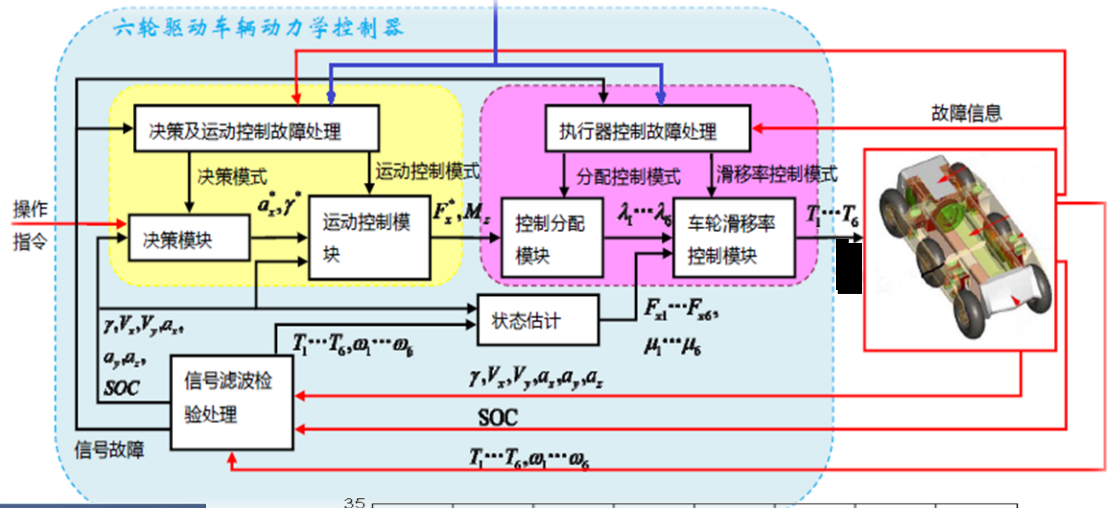


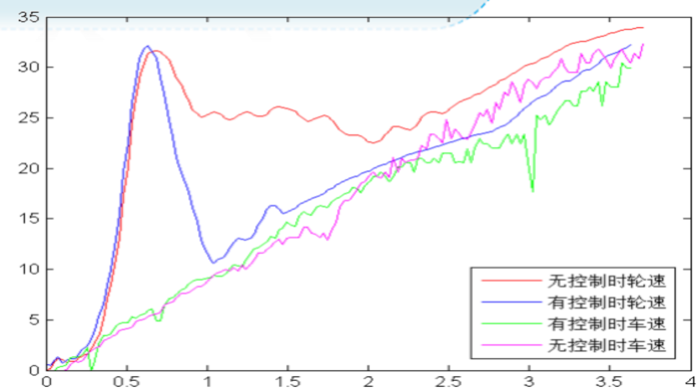
驱/制动里分配系数
Drive/brake torque distribution factor

应用效果：应用该项目成果的上汽荣威E50纯电动轿车综合工况**能量消耗率**在原车基础上进一步**降低8.3%**，分布式驱动客车**NEDC工况百公里电耗**在原车基础上进一步**降低5%**。
Energy consumption rate was decreased by 8.3% in a ROEWE E50 and 5% in a distributed bus.

研究成果 / Research Results

差动转向车辆动力学控制/ Skid steering vehicle dynamics control





应用效果：应用该项目成果的差动转向特种车辆可实现轨迹跟踪（无人驾驶模式），全路况行驶，**低附路面车轮滑移率收敛时间**较无控制车辆**减少50%以上。**

The skid steering special vehicle can follow designed trajectory, all road drive; and the convergence time of wheel slip rate on low-μ road can be reduced by more than 50% compared with the uncontrolled vehicle.

成果应用

APPLICATIONS

成果应用/ Applications

2010年上海世博会国内**首次示范**运行**分布式驱动**电动观光车，并获得上海世博会先进集体荣誉称号。

In 2010 Expo Shanghai, Tongji University realized DDEVs' first demonstration operation in China and won the award from the Chinese government.

分布式驱动世博观光车（12座）
Expo DDEV tour bus (12 Seats)

分布式驱动世博观光车（4座）
Expo DDEV tour bus (4 Seats)

EXPO
SHANGHAI CHINA

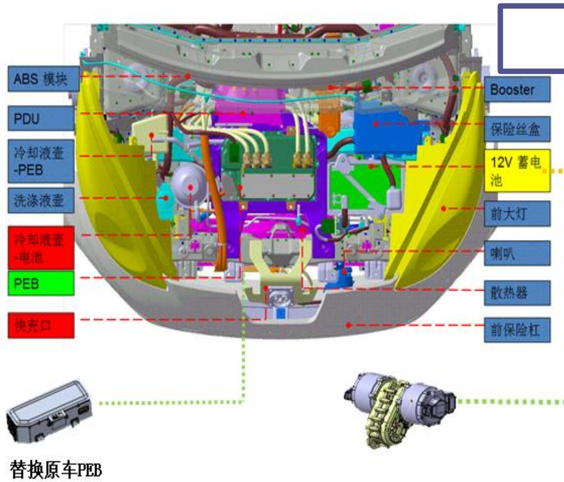
成果应用/ Applications

- 4轮边电机驱动
4 by-wheel motor driving
- 低地板大空间
Low floor, large space
- 驱动防滑
ASR
- 操纵性改善
Controllability improvement
- 稳定性控制
Stability control

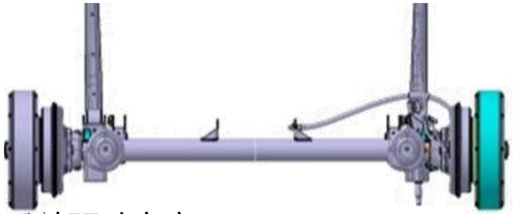
实车试验结果显示 Vehicle tests results：

- ➢ 低附着路面驱动效率显著提高
- ➢ Obvious improvement of drive efficiency under low-μ ground
- ➢ 车辆过多转向特性得到改善，主客观评分提高
- ➢ Oversteer character is improved, subjective/objective score is improved
- ➢ 能耗降低约5%，经济性得到改善
- ➢ Power consumption decreases about 5%, economical efficiency is improved

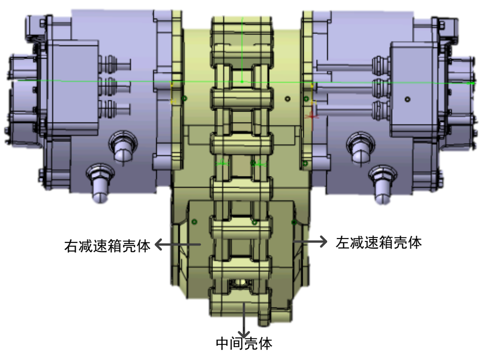
成果应用/ Applications



动力电池
Power battery

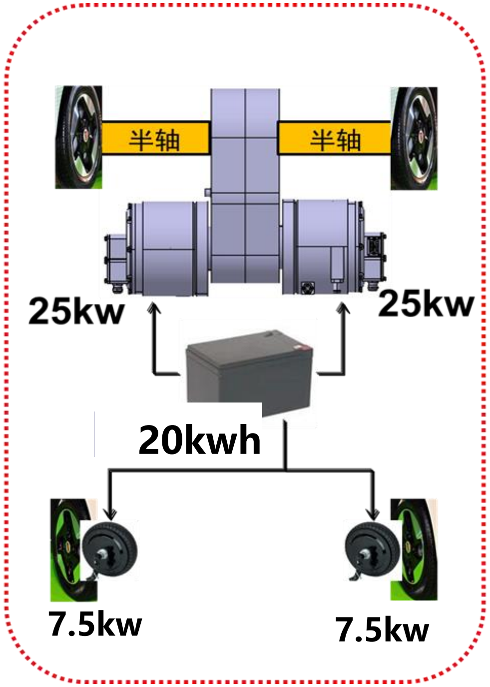


后轴驱动方案 Rear wheel brake



前轴驱动方案 Front wheel drive

参数Parameter	荣威E50 ROEWE E50	分布式平台 Platform
整车整备质量(kg) Curb weight(kg)	1260	1380
轮胎型号 Tire type	175/60 R13	185/55 R15
电机功率（kw） Motor power(kw)	52	65
电池电量（kwh） Battery (kwh)	18	20
最高车速(km/h) Max speed(km/h)	130	145
最大爬坡度 Max climb level	25%	30%



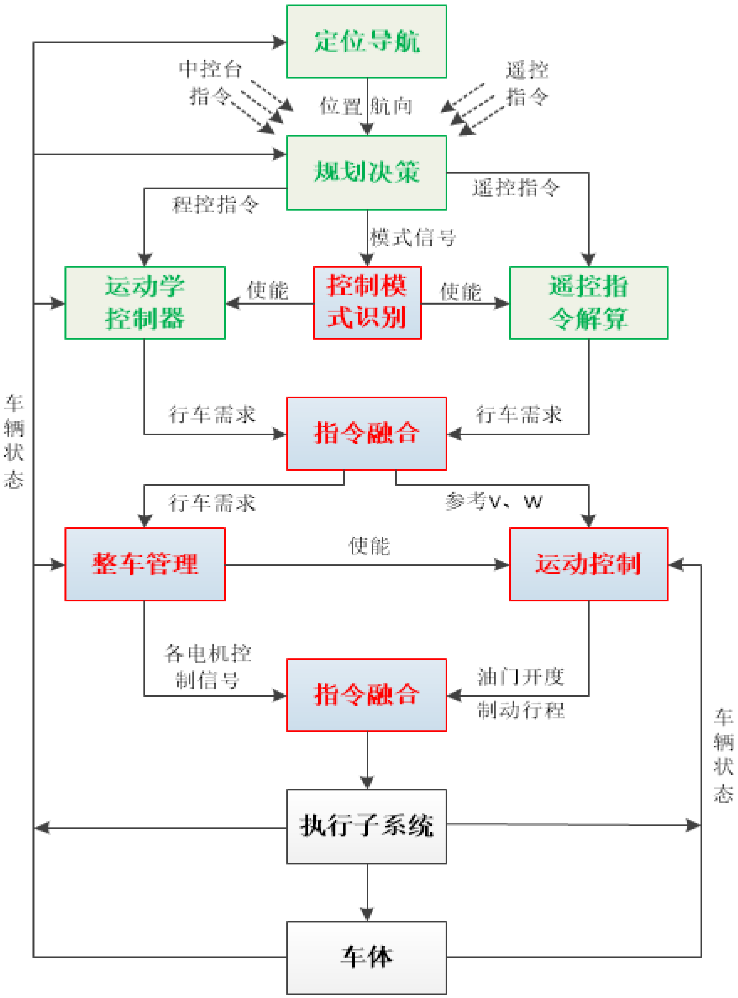
整车驱动系统 Vehicle driving system

成果应用/ Applications

4轮独立驱动纯电动乘用车
Four-wheel independent drive electric car

- 一体化参数估计Integrated estimation
- 驱动防滑 ASR
- 操纵性改善 Handling improvement
- 稳定性控制 Stability control
- 能耗优化策略 Consumption optimization

成果应用/ Applications



车辆控制系统架构
Vehicle Controller Diagram

TONGJI
UNIVERSITY

谢 谢！

THANKS FOR YOUR ATTENTION！

iiV TJU
同濟大學 智能汽车研究所
TONGJI UNIVERSITY Institute of Intelligent Vehicles