



泛亚汽车技术中心有限公司
Pan Asia Technical Automotive Center Co., Ltd.

基于多自由度虚拟整车模型的电动四驱控制算法开发

孔敬之, 泛亚汽车技术中心有限公司



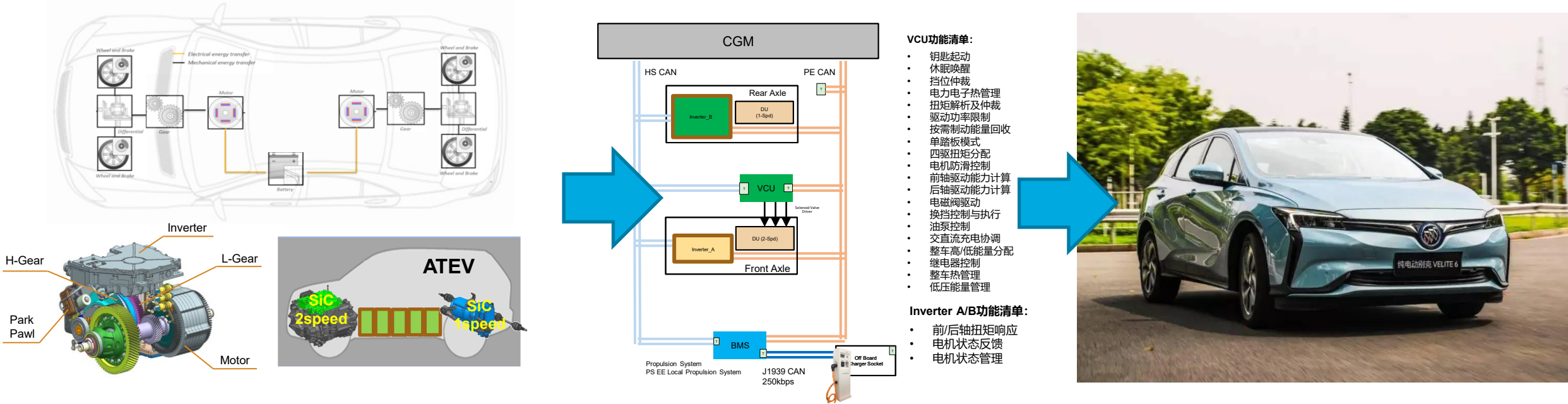
2022 MathWorks
中国汽车年会

目录

- 项目背景
- 性能四驱控制算法目标
- 性能四驱控制算法分解
- 控制器硬件方案
- MIL整车系统模型简介
- 驱动功能更新简介
- 仿真结果分析
- 下一步的工作

项目背景

- 一年一度的ATEV(Advance Technical Electrical Vehicle), 汇集了泛亚的新技术demo, 是一个技术创新和实践的平台
- 2022 ATEV基于2021 ATEV改造, 更换800V后电桥, 升级底盘结构, 今年在驱动功能上的创新在于尝试性能四驱
- 在α阶段, Inverter和VCU分别开发, 支持整车四驱功能及换挡控制; Inverter中预留集成整车驱动软件的空间, 并进行ECP_E相关硬件的开发;
- 在β阶段, 进行Inverter和ECP_E/S的集成开发, 适配集成VIP相关信号的数据库; TPIM/RPIM面向量产, VCU和BMS功能集成在VICM中;



驱动控制架构拓扑 (部分)

性能四驱控制算法目标

Grade Requirements

The gradeability requirements for eAWD system shall be as given below by the table



Traction ON

	GVW/RGAWR	
Feature Variant	Step CoLaunch	Slip CoLaunch
Base AWD	20%	12%
Premium AWD	20%	20%

Traction OFF

	GVW/RGAWR	
Feature Variant	Step CoLaunch	Slip CoLaunch
Base AWD	20%	na
Premium AWD	20%	12%

Traction Requirements

Low - Co launch performance shall adhere to the following table for FWD based AWD

Test	Base AWD t(0-3m) - Velocity or Acceleration	Premium AWD t(0-3m) - Velocity or Acceleration
Split Mu 30% pedal apply	< FWD w/TCS ON Red: <5kph 5kph<Yellow<14kph Green>14kph	<< AWD or = base AWD w TCS OFF Red: < 5 kph 5 kph <Yellow< 15kph Green>15kph
Split Mu 60% pedal apply	< FWD w/TCS ON Red: <5kph 5kph <Yellow<15kph Green>15kph	<< AWD or = base AWD w TCS OFF Red: < 5 kph 5 kph<Yellow<16 kph Green>16 kph
Split Mu WOT pedal apply	< FWD w/TCS ON Red: <5kph 5kph <Yellow<16kph Green>16kph	<< AWD or = base AWD w TCS OFF Red: <5kph 5kph <Yellow<16kph Green>16kph
Homogenous Low Mu	< FWD TBD	< AWD TBD
Acceleration on a 12% Grade	< FWD TBD	< AWD TBD
Acceleration on a 20% Grade	< FWD TBD	< AWD TBD

Low - Co launch performance shall adhere to the following table for RWD based AWD

Test	Base AWD t(0-3m) - Velocity or Acceleration	Premium AWD t(0-3m) - Velocity or Acceleration
Split Mu 30% pedal apply	< FWD	<< AWD
Split Mu 60% pedal apply	< FWD	<< AWD
Split Mu WOT pedal apply	< FWD	<< AWD
Homogenous Low Mu	< FWD	< AWD
Acceleration on a 12% Grade	< FWD	< AWD
Acceleration on a 20% Grade	< FWD	< AWD

Low Co acceleration performance shall adhere to the following table for RWD based AWD (Bigger rear Motor)

Test	Base AWD		Premium AWD	
	Average Acceleration or Velocity @ 120m (Traction VTS)	Acceleration Uniformity (+/- % or g)	Average Acceleration or Velocity @ 120m (Traction VTS)	Acceleration Uniformity (+/- % or g)
Split Mu 30% pedal apply	> FWD >69 kph	< FWD	>> AWD	<< AWD
Split Mu 60% pedal apply	> FWD >75kph	< FWD	>> AWD	<< AWD
Split Mu WOT pedal apply	> FWD >78kph	< FWD	>> AWD	<< AWD
Homogenous Low Mu	> FWD >3.41 m/s^2	< FWD	> AWD >3.41 m/s^2	< AWD
Acceleration on a 12% Grade	> FWD >3.36 m/s^2	< FWD	> AWD >3.63 m/s^2	< AWD
Acceleration on a 20% Grade	> FWD >2.48 m/s^2	< FWD	> AWD >2.48 m/s^2	< AWD



性能四驱控制算法目标

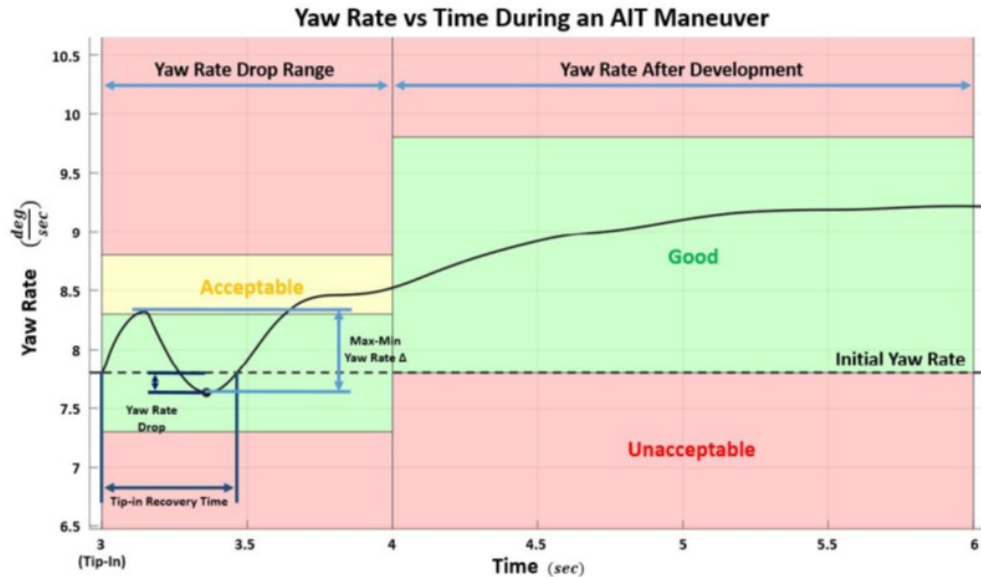
Yaw Requirements

Experimental Yaw metrics Derived from Acceleration In a Turn (AIT) maneuvers

Yaw rate response delta: initial Yaw Rate response after tip in, differentiates understeer v/s oversteer

Yaw rate recovery: yaw rate recovery towards initial yaw rate before tip in, relates to the initial feel of response by the user after tip in

Yaw rate growth: measures consistency of yaw rate response during acceleration prior to saturation/limit



RWD based AWD

Test	AIT - AWD Low Co			AIT - AWD Hi-Co	
	Yaw Response Delta Yaw Rate 0-1 sec	Yaw Rate Recovery sec	Yaw Rate Growth +1-4 sec	Yaw Response Delta Yaw Rate	Yaw Rate growth
AWD Assist	TBD	TBD	Yaw Gw > 0	Future Expansion - Performance Vehicles	
Base AWD	'+/- 0.1 deg/Sec	TBD	0 < Yaw Gw < +1 deg/sec		
Premium AWD	'+/- .5 deg/Sec	TBD	0 < Yaw Gw < +2 deg/sec		
Surface: < 0.35 Snow/Basalt			Surface: < 0.9 Hi-Co Road		

Yaw Assist Metrics

Experimental yaw assist metrics for asymmetrical torque capability - yaw moment spec

Yaw moment target based on speed range

Yaw moment must be scaled to system sizing (maybe use % based on maximum yaw moment capability)

Test	Max Yaw Moment (Nm)		
	< 10 kph	60 kph	100 kph
AWD Assist	na	na	na
Base AWD	na	na	na
Premium AWD	5700	4500	3400
Surface > 0.8 Hi Co			



性能四驱控制算法分解

车辆状态信息 (Vehicle Dynamic Core)

- 各个车轮上的扭矩
- 各个轮胎上的 F_x , F_y , F_z
- 车辆的参考车速（地速）
- 前，后轮的轮胎参数
- 估算地面摩擦系数 μ
- 前轮转角
- 车辆纵向加速度
- 车辆横向加速度
- 车辆的Intended Yaw, Actual Yaw, 及Yaw Error
- 各个车轮的轮速
- 正坡，侧坡信息

前后轴性能分配策略（AWDR）

- 基于预控的分配策略
 - 基于前后轮胎摩擦圆的分配[1]
 - 最大限度地使用各个轮胎的地面附着力
 - 根据驾驶员需求扭矩的分配[2]
 - 根据驾驶员的加速踏板增加量和扭矩增加量，以及方向盘转角，将前轴扭矩迁移到后轴
 - 分配补偿
 - 根据驾驶员选择模式，坡度， μ 信息，对[1]，[2]进行修正
- 车轮滑转控制
 - 使用目标滑转率对扭矩进行迁移及控制[3]
 - 分配补偿
 - 根据驾驶员选择模式，坡度， μ 信息，对[3]进行修正
- 车辆的Yaw控制
 - 基于Yaw Error Target的前后扭矩分配[4]
 - 基于Yaw Damping的前后扭矩分配修正[5]
 - 基于Yaw Error Target对驾驶员的总需求扭矩进行限制[6]
 - 分配补偿
 - 根据驾驶员选择模式，坡度， μ 信息，对[4]，[5]，[6]进行修正

扭矩仲裁

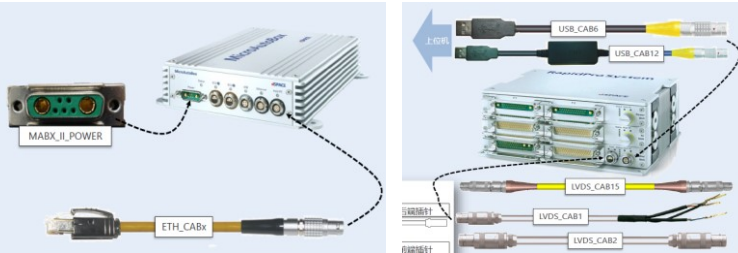
- 确定AWD的激活条件
- 根据预控，滑转和Yaw控制分配策略，对前后轴扭矩仲裁

前后轴经济性分配策略及外部干预仲裁

- 经济性分配策略
 - 存在一种经济性分配方法，可以使得车辆在各个工况下效率最高，设计时需考虑激活，和退出条件。
- 外部干预
 - Primary/Secondary Axle的状态，及能力
 - SOC信息
 - Motor信息
 - TCS, ESC, ABS干预标志

控制器硬件方案

由于样车前桥有一个双速变速箱，需要精确控制油压电磁阀以实现精确换挡，所以VCU升级方案使用了 MABXII + RapidPro + PGI + Dither Driver 方案



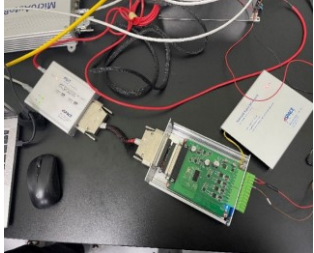
DS1511



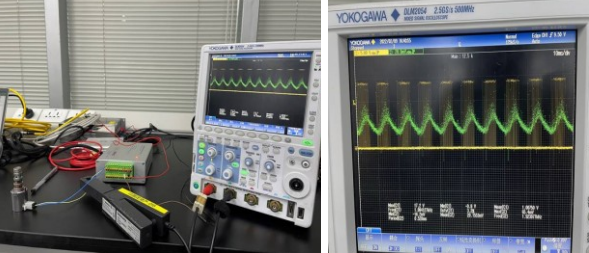
RapidPro(E-Stack)



PGI Dither Driver

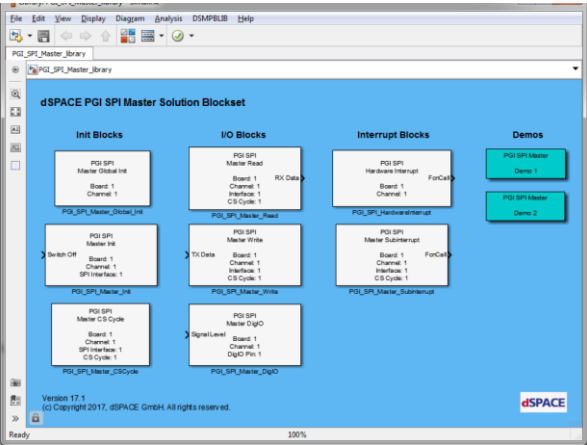


实际方案连接效果

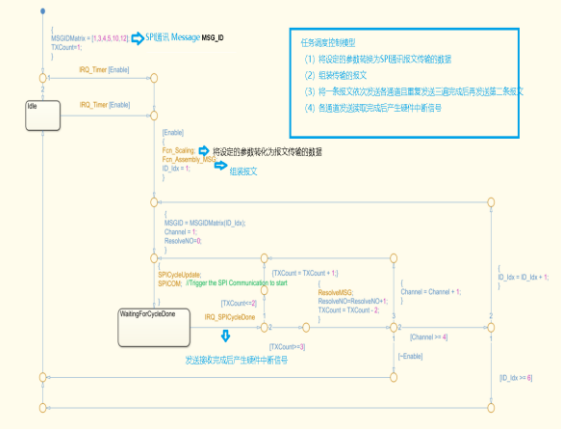


驱动波效果与仿真一致

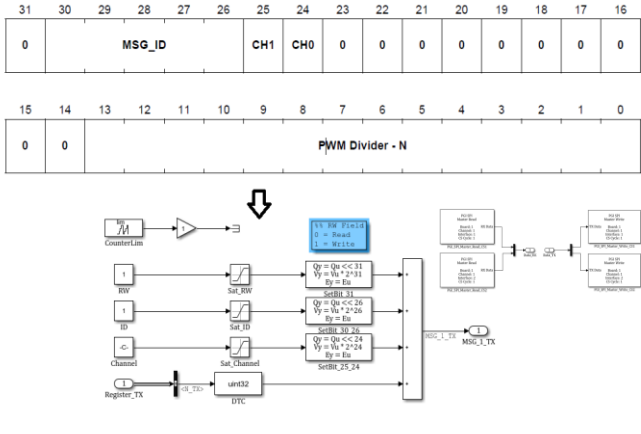
PGI扩展方案通过LDVS接口于MABX2的扩展ECU端口连接，将LDVS信号转换为SPI信号，驱动Dither芯片工作原理可参考论文[脉宽调制中的颤振算法]



PGI SPI Master Solution Library



SPI 发送及读取任务调度控制模型



驱动参数报文打包发送

Dither Algorithm in Pulse Width Modulation
 ZHU Yutian TANG Xinghua
 (College of Mechanical Engineering, Tongji University, Shanghai 201804)

Abstract: Pulse width modulation (PWM) has become the standard for electro-hydraulic proportion valve amplifiers for it is efficient, excite and anti-interference. Meanwhile, the dynamic characteristics of a proportional valve can be improved by superimposing fibers to the valve coil. Aiming at the two control parameters, the frequency and the duty ratio of the PWM, the algorithm of the parasitic dither in low frequency PWM is deduced. The result shows that the amplitude and frequency of the dither cannot be set independently. In a high frequency PWM, dither with independent frequency and amplitude can be generated separately by changing the duty ratio of the pulses. According to the current in inductive loads, the algorithms for two types of dither, one in sine wave envelop and another in triangle wave envelop, are deduced respectively. Numeric emulation agrees with the experiment result. The algorithm particularly suits for digital signal processing and control system.

Key words: Pulse width modulation (PWM) Parasitic dither Independent dither Algorithm

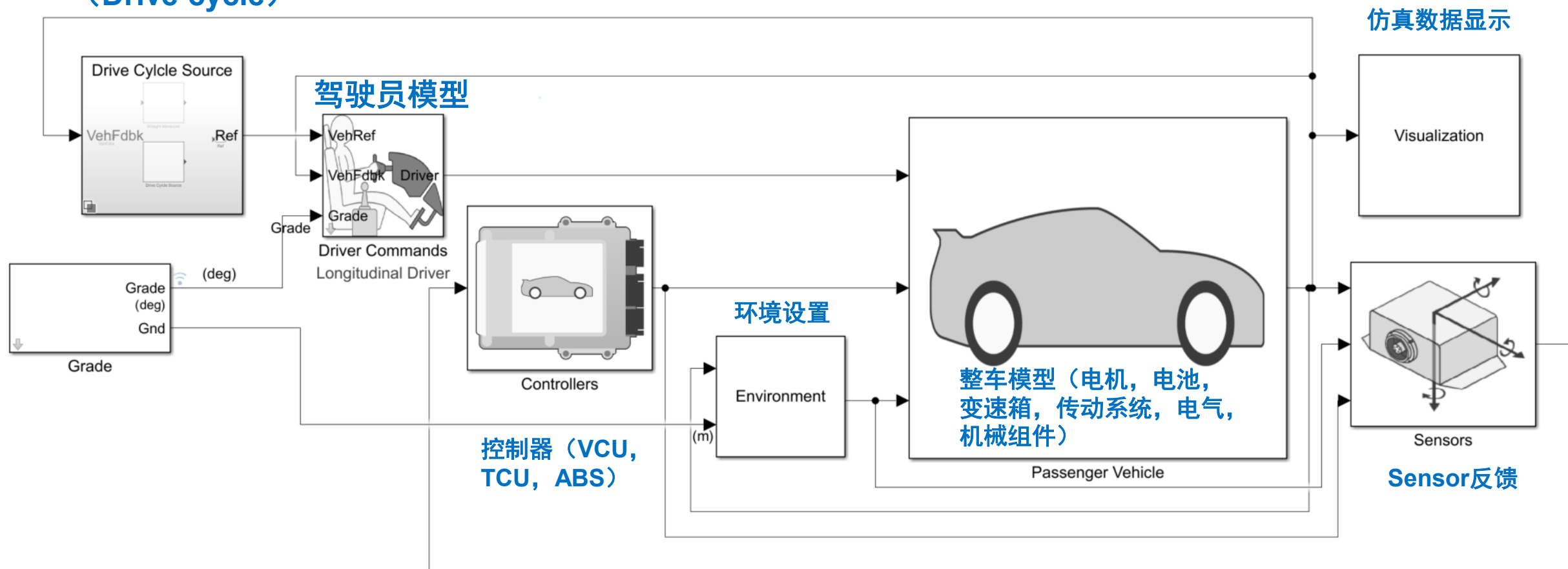
Dither Algorithm In Pulse Width Modulation

注：PGI方案不是dSPACE的标准方案，需额外购买。

MIL-整车系统模型简介

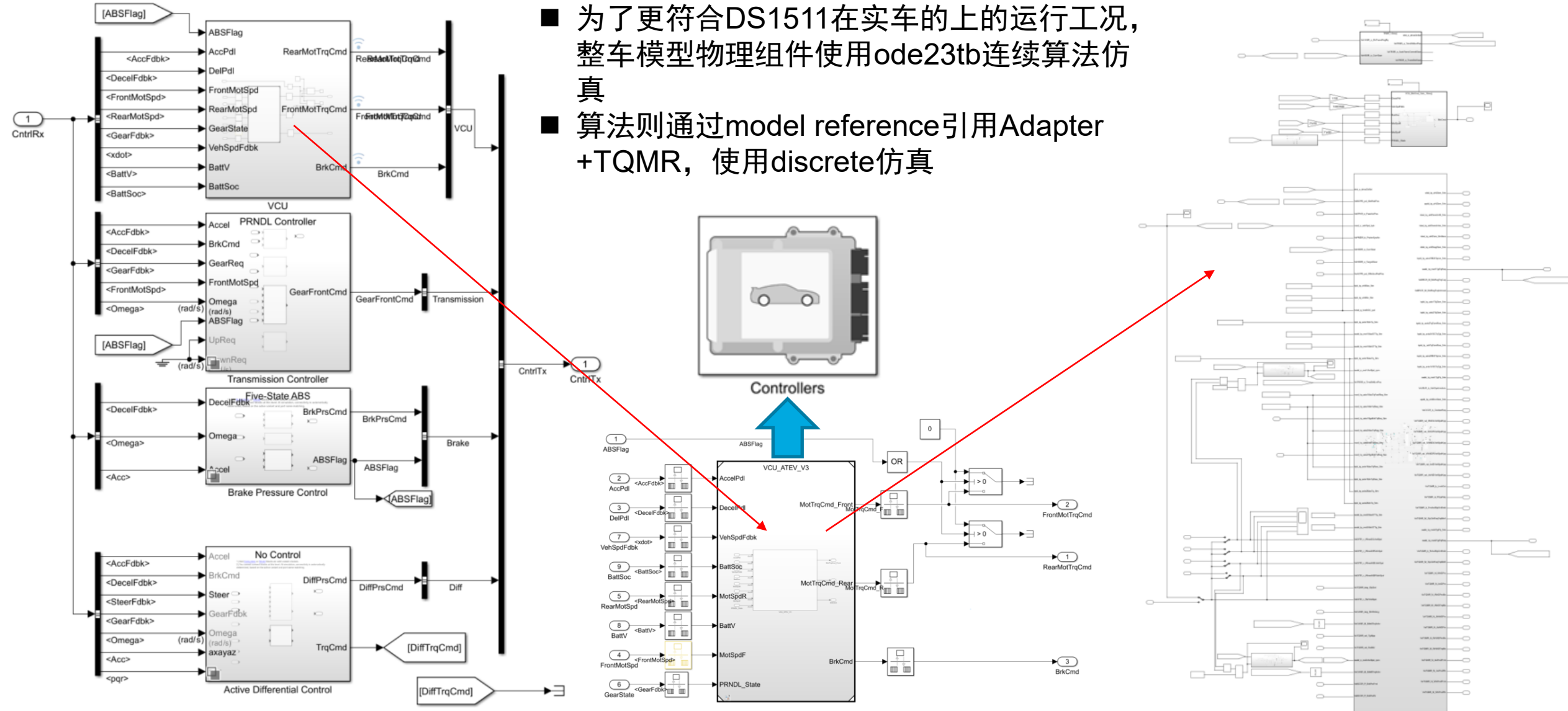
- 对于开发周期短资源不足的项目而言，多自由度虚拟整车模型非常重要。算法是否适用，取决于设计者对控制对象的了解
- 在此项目中，采用先搭建整车模型，再升级算法的方法进行开发，缩短开发周期

仿真场景设定 (Drive cycle)

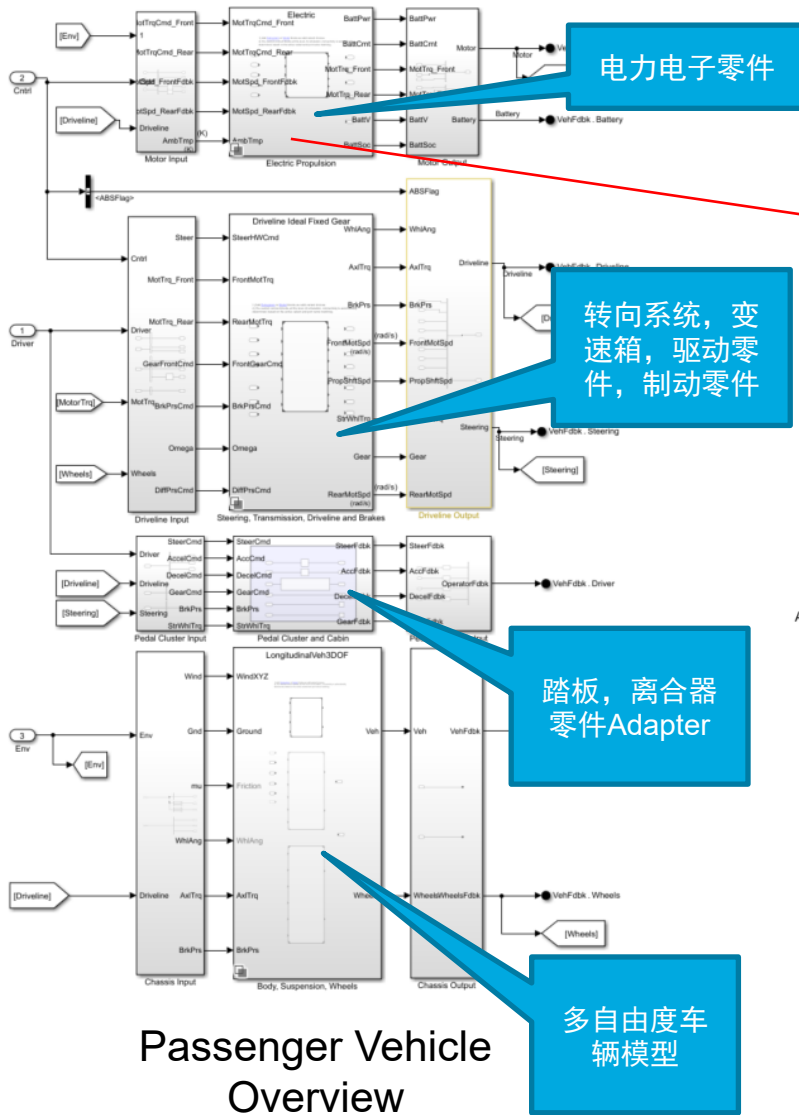


MIL-在Controllers中通过增加Adapter适配TQMR接口

- 为了更符合DS1511在实车的上的运行工况，整车模型物理组件使用ode23tb连续算法仿真
- 算法则通过model reference引用Adapter +TQMR，使用discrete仿真

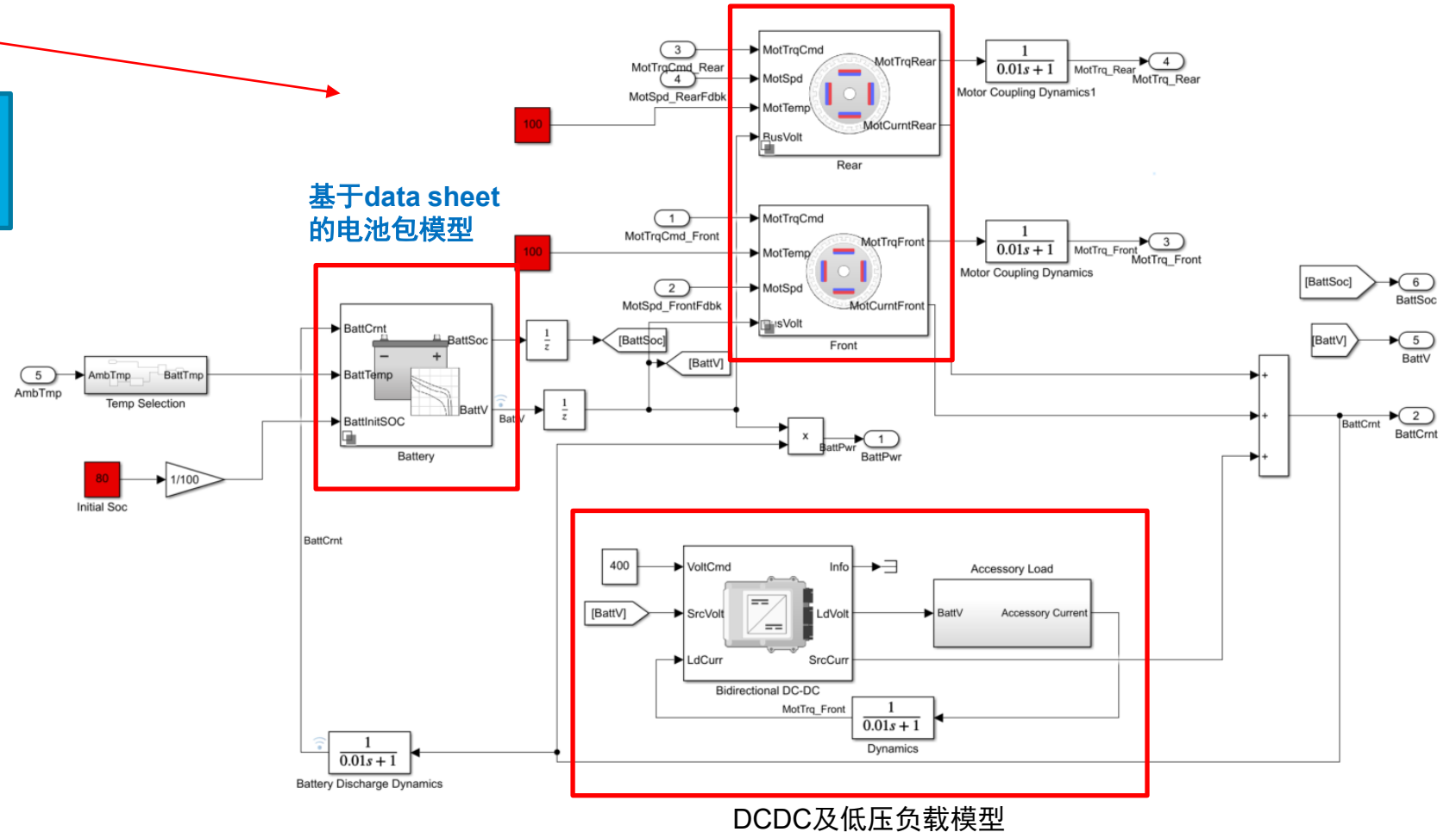


MIL-Passenger Vehicle. Electric Propulsion

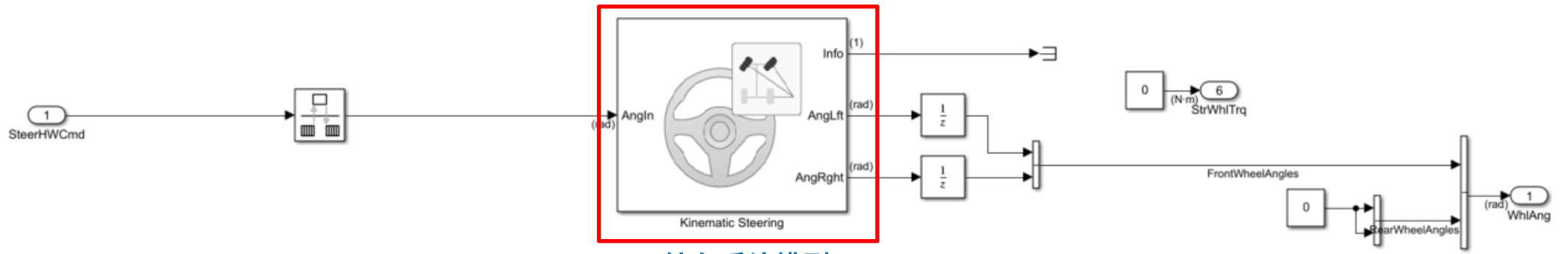


基于Mapped的前后电机模型

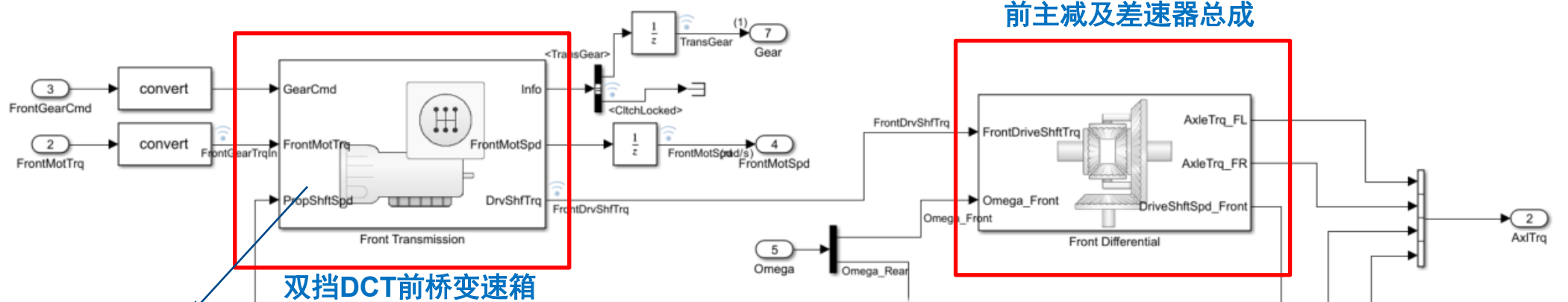
基于data sheet的电池包模型



MIL-Passenger Vehicle. Steering, Transmission, Driveline and Brakes

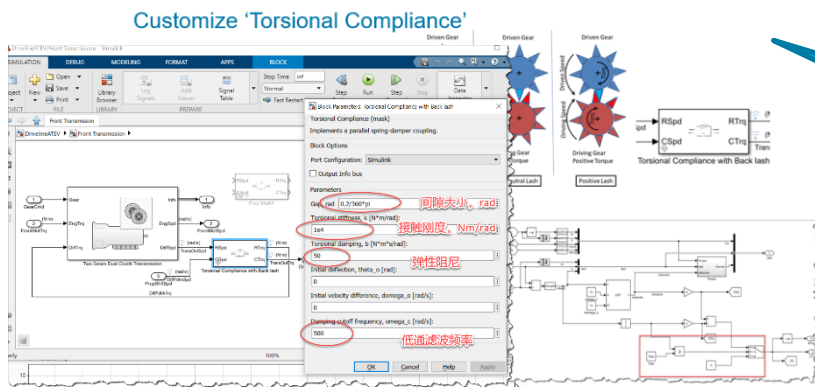


转向系统模型

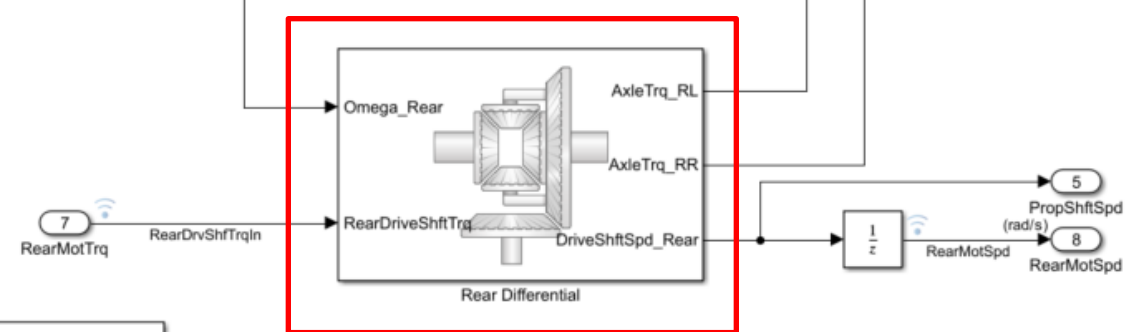


双挡DCT前桥变速箱

前主减及差速器总成



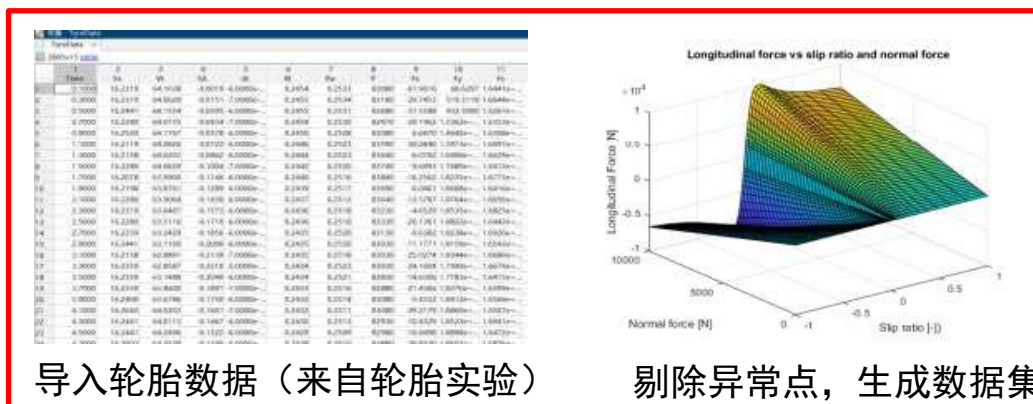
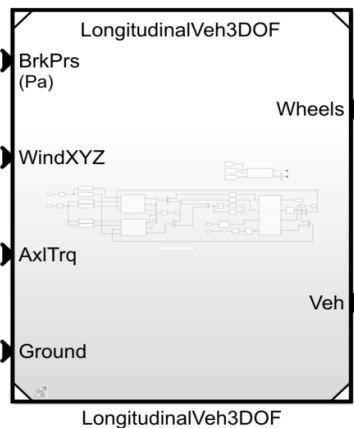
传动齿轮包含 back lash模拟



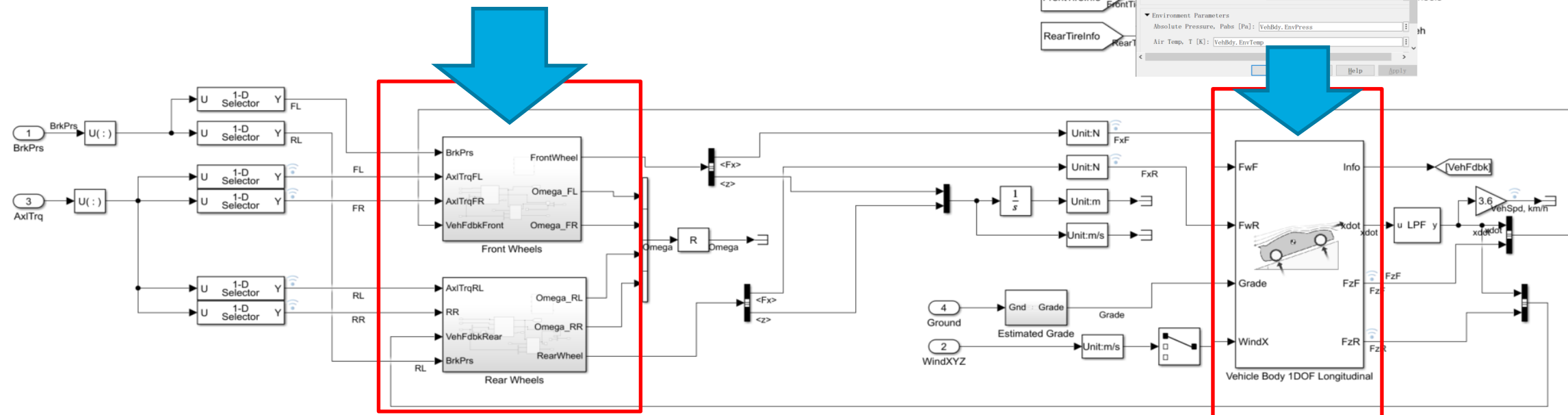
后主减及差速器总成

MIL-Passenger Vehicle. Body, Suspension, Wheels (Longitudinal 3DOF)

- 该模型用于评估车辆纵向动力学控制算法



导入车辆参数

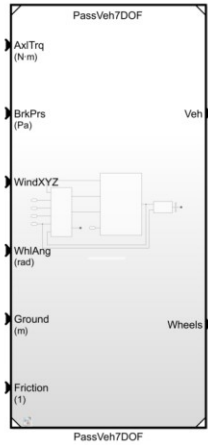


基于Map特性的1DOF轮胎模型

1DOF车身模型

MIL-Passenger Vehicle. Body, Suspension, Wheels (7DOF)

- 该模型用于评估车辆横向动力学控制算法（不考虑悬挂因素）

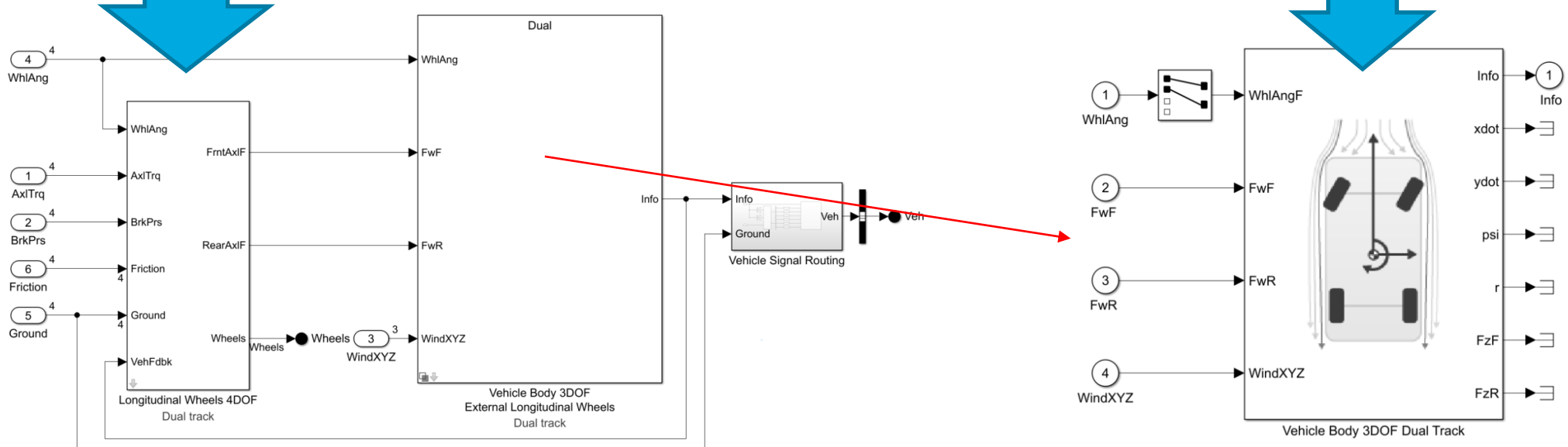


导入轮胎数据（来自轮胎实验）

生成响应曲面

导入轮胎模型

导入
车辆
参数



MIL-车辆工况选择

- 选择驾驶循环进行经济性仿真
- 选择WOT进行动力性仿真

Drive Cycle Source
.mat, .xls, .xlsx or .txt file (1800 seconds)

RefSpd (m/s)

3.6 Vref, km/h

Unit:m
AccelZero

1 Ref

Block Parameters: Drive Cycle Source

Drive Cycle Source (mask) (link)
Generates a standard or user-specified longitudinal drive cycle. The block output is the vehicle longitudinal speed. You can import drive cycles from:

- Predefined sources
- Workspace variables, including arrays and time series objects
- mat, xls, xlsx, or txt files

Use the fault tracking parameters to identify drive cycle faults within specified speed and time tolerances.

Cycle Setup Fault Tracking

Drive cycle source: .mat, .xls, .xlsx or .txt file

Drive cycle source file: D:\model\R_0509\ATEV20220509\01_ATEV\Data\CATC_mps.mat

Specify variable Select file

Install additional drive cycles

Repeat cyclically Output acceleration

Units and sample period

Source velocity units (

Output velocity units (e.g., m/s, km/h, mph):

m/s

Output sample period (0 for continuous), dt [s]: 0

Update simulation time Plot drive cycle

OK Cancel Help Apply

Block Parameters: Drive Cycle Source

Drive Cycle Source (mask) (link)
Generates a standard or user-specified longitudinal drive cycle. The block output is the vehicle longitudinal speed. You can import drive cycles from:

- Predefined sources
- Workspace variables, including arrays and time series objects
- mat, xls, xlsx, or txt files

Use the fault tracking parameters to identify drive cycle faults within specified speed and time tolerances.

Cycle Setup Fault Tracking

Drive cycle source: Wide Open Throttle (WOT)

Drive cycle source file: D:\model\R_0509\ATEV20220509\01_ATEV\Data\CATC_mps.mat

Specify variable Select file

Repeat cyclically Output acceleration

WOT Parameters

Start time, t_wot1 [s]: 5

Initial reference speed, xdot_woto []: 0

Nominal reference speed, xdot_wot1 []: 120/3.6

Time to start deceleration, t_wot2 [s]: 50

Final reference speed, xdot_wot2 []: 0

WOT simulation time, t_wotend []: 1000

Units and sample period

Source velocity units (e.g., m/s, km/h, mph): m/s

Output velocity units (e.g., m/s, km/h, mph): m/s

Output sample period (0 for continuous), dt [s]: 0

Update simulation time Plot drive cycle

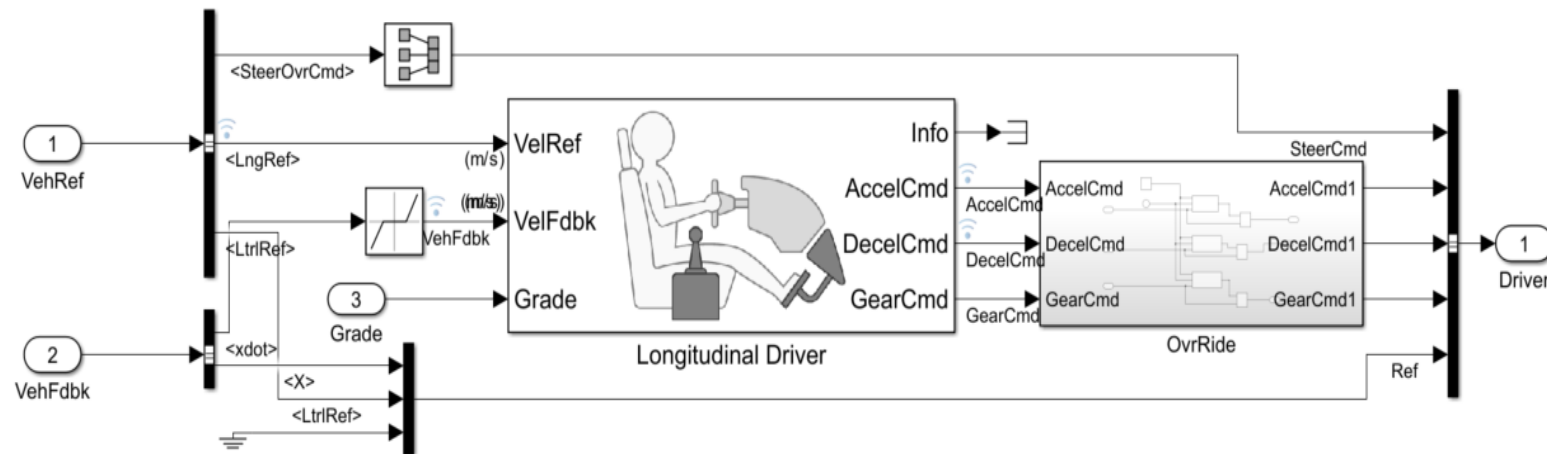
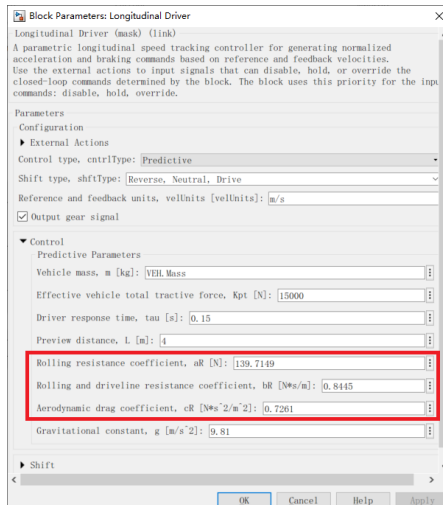
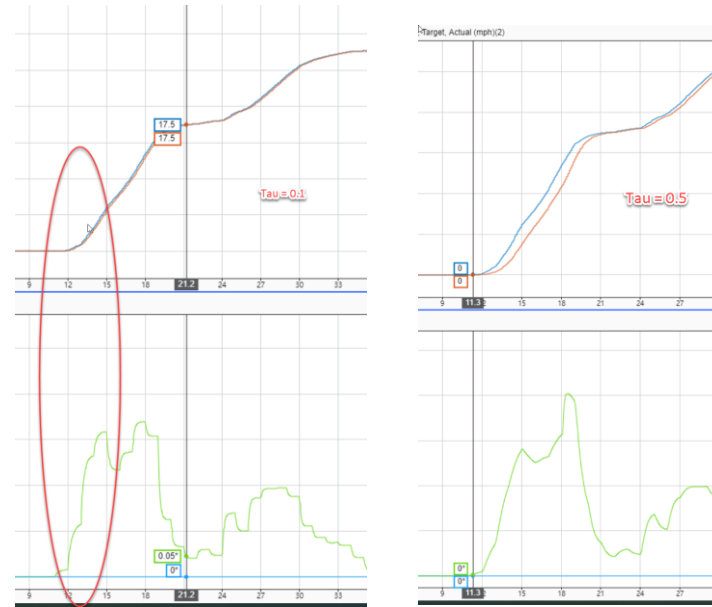
OK Cancel Help Apply

选择自定义工况

WOT参数设定

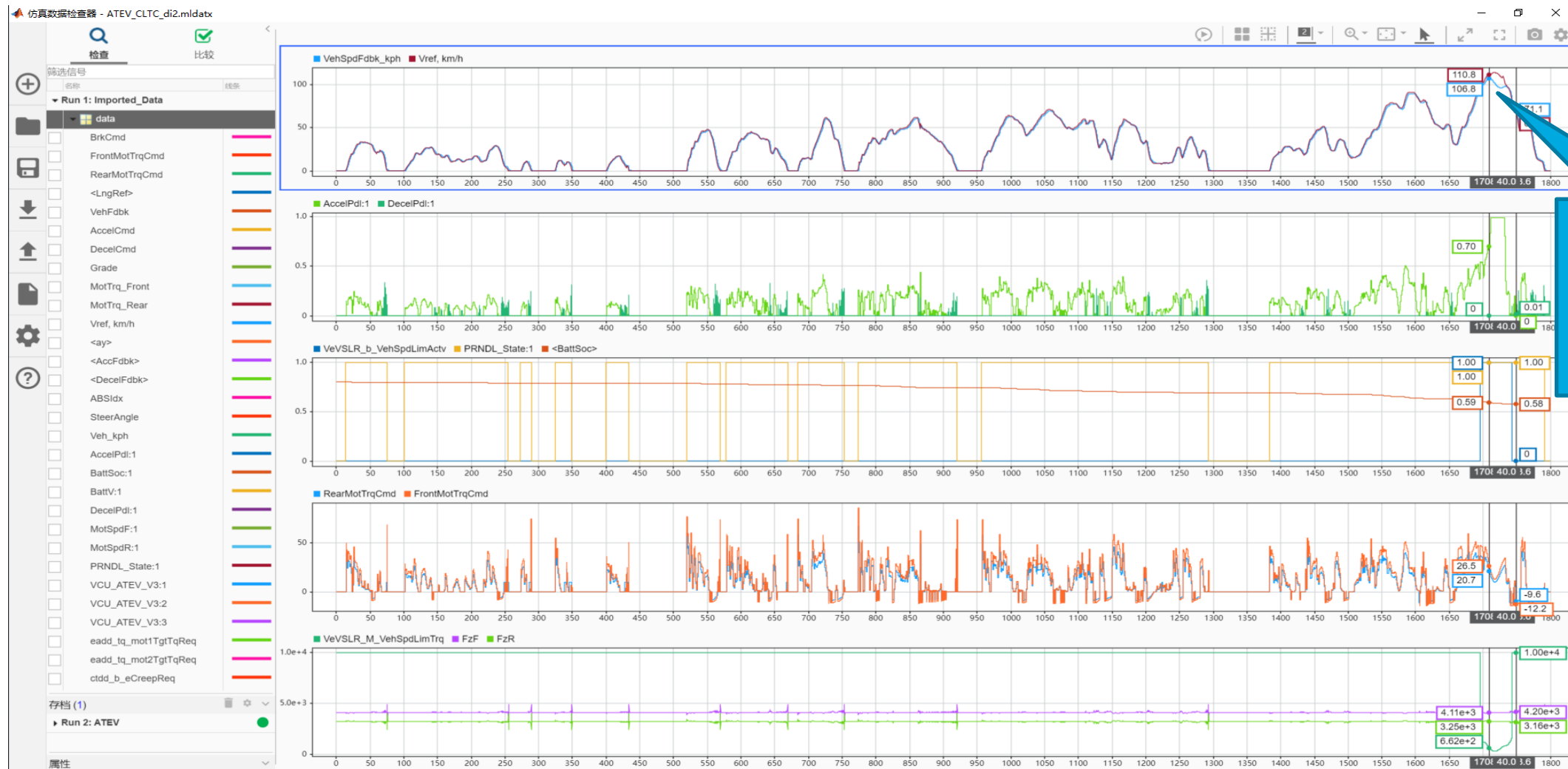
MIL-驾驶员模型标定 (Predictive)

- Step 1: 根据模型实际整车参数设置
 - 滑行阻力系数: a, b, c , 由滑行阻力曲线进行二阶多项式拟合获得;
 - 整备质量
 - 有效整车总牵引力
- Step 2: 调驾驶员响应参数 τ, L
 - 影响驾驶员模型响应效果的参数:
 - Preview distance, $L(m)$* : 影响高速部分, typical value 1~7m
 - Driver response time, $\tau(s)$* : τ : 影响低速
- L/v 和 τ 取小值
 - 当车速 v 大时, L/v 值小, 起作用的时 L 参数;
 - 当车速 v 低时, L/v 值大, 如果大于 τ 值, 则起作用的是 τ 。
- 方法:
 - 根据实际曲线响应情况, 去调整 L, τ , 直到获得满意曲线形态为止。



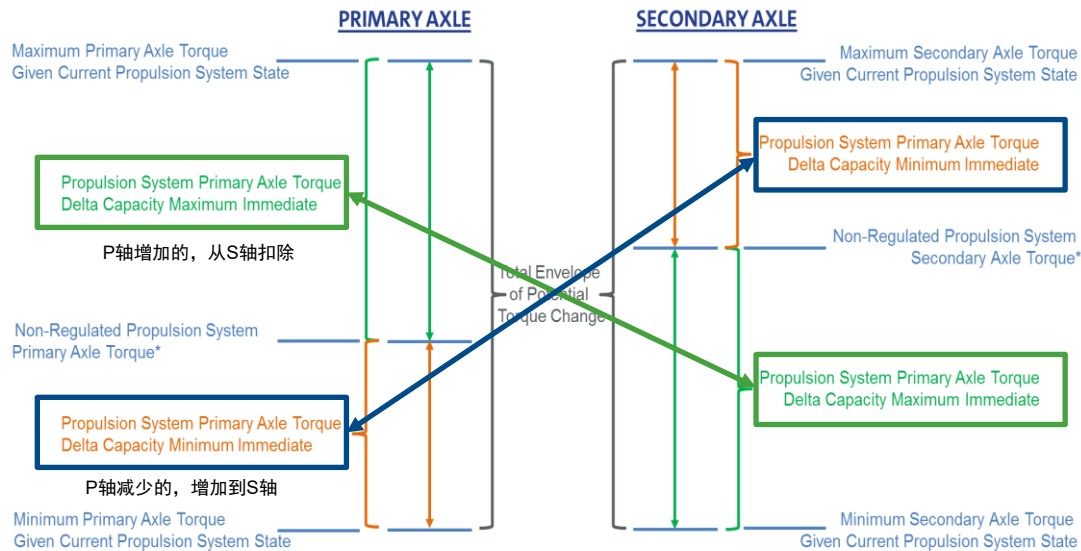
MIL-仿真及结果分析

- 通过simulation data inspector查看信号是否达到性能指标要求，并进行参数调整
- 如果信号水平异常，则应回到单元设计步骤对功能进行调整

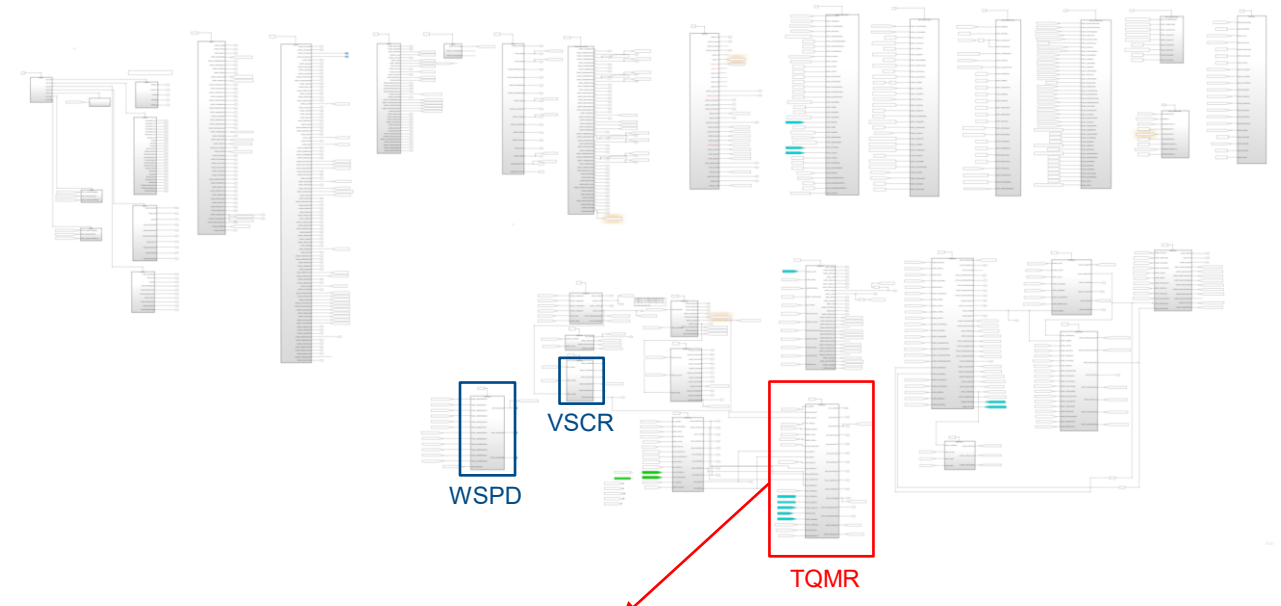


发现车速无法跟随，
分析发现是车速限制
模块启动，调整限制
车速后，问题解决

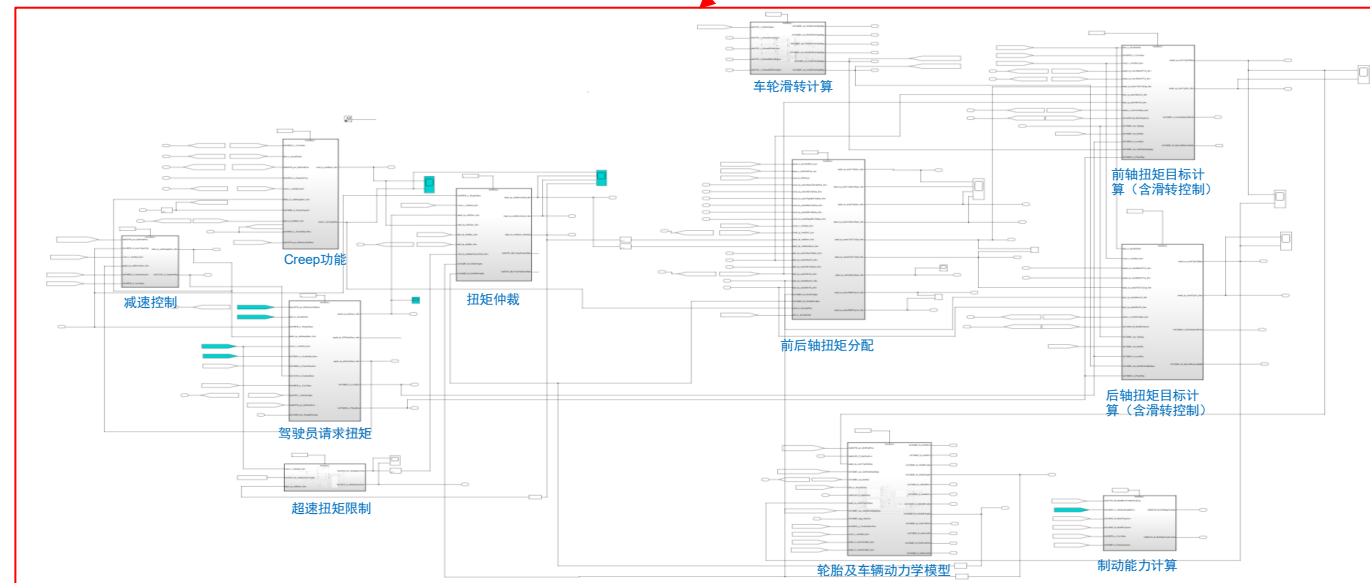
驱动功能更新简介 - VCU驱动功能在模型中所处的位置



* Non-Regulated Propulsion System Primary/Secondary Axle Torques are the amount of torque the propulsion system would command to each axle without any intervention from eAWD Vehicle Dynamics Feature
 Note: All of this is based on the assumption that torque is just getting shifted between axles without significantly changing the driver's torque request

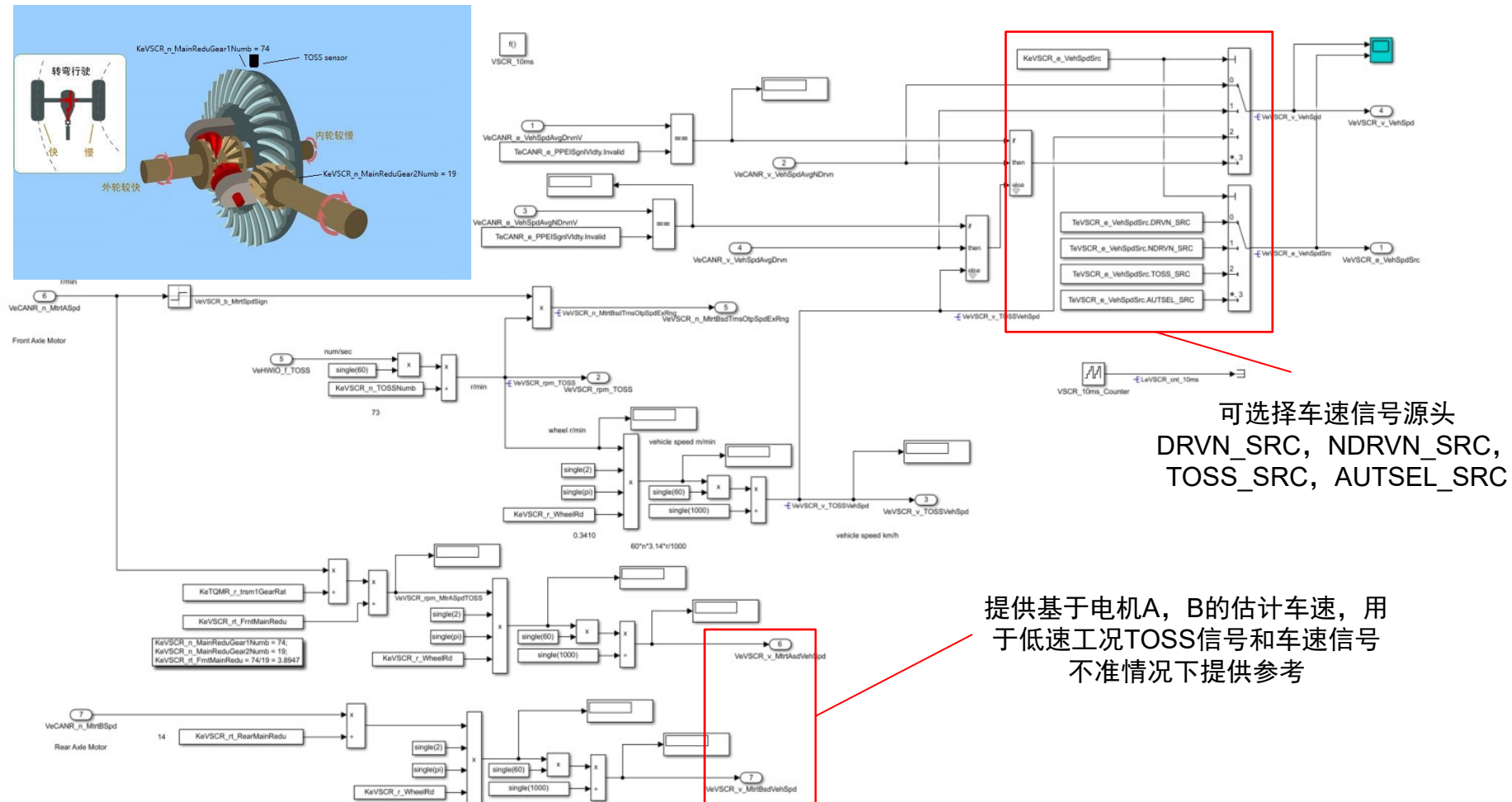


TQMR2子功能	功能描述	更改等级
DTD_DecelerationControl	减速控制	Low
CTD_CreepDemand	Creep功能	Medium
APD_DriverDemand	驾驶员请求扭矩	Medium
VSLR	超速扭矩限制	New
TDA_TorqueDemandsArbitration	扭矩仲裁	Medium
Calc_Wheel_Kappa	车轮滑转计算	New
TQD_TorqueDistribution	前后轴扭矩分配	Medium
Lngtdnl_Veh_Dynmc	轮胎及车辆动力学模型	New
EAD_TargetTorqueControlMot1	前轴扭矩目标计算 (含滑转控制)	Medium
EAD_TargetTorqueControlMot2	后轴扭矩目标计算 (含滑转控制)	Medium
BRCR_BrkReg	制动能力计算	None



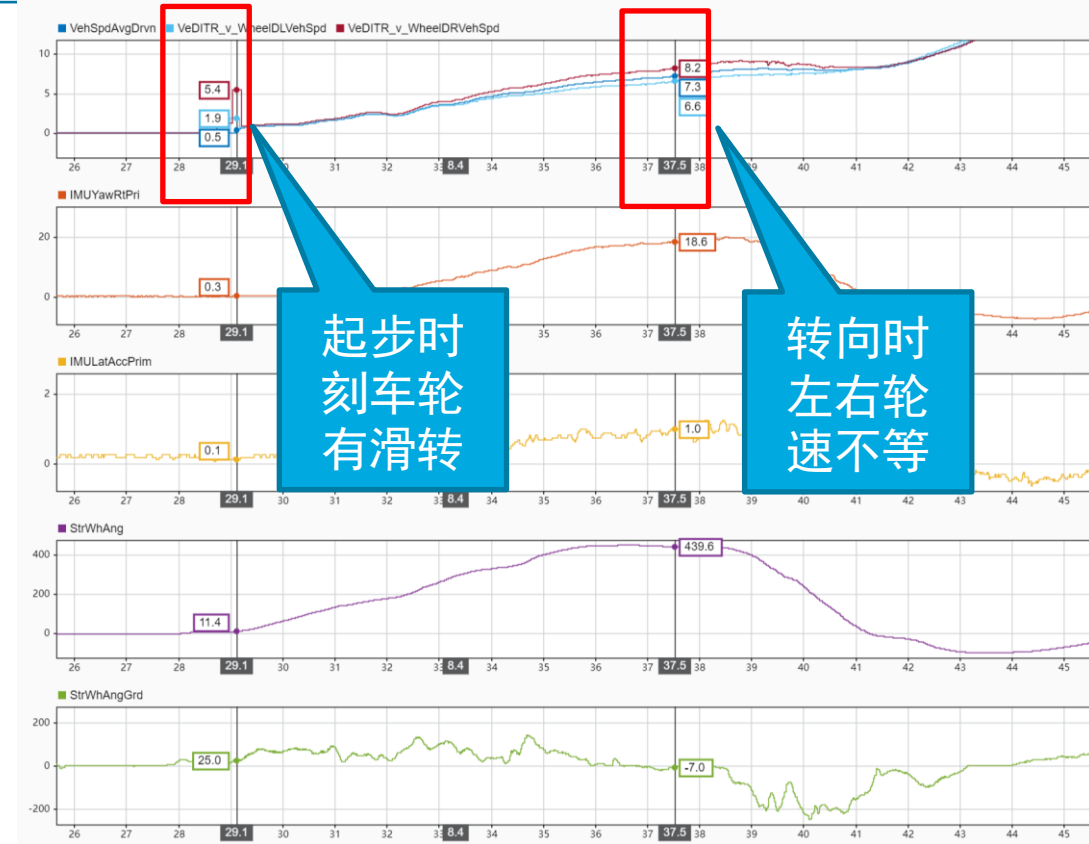
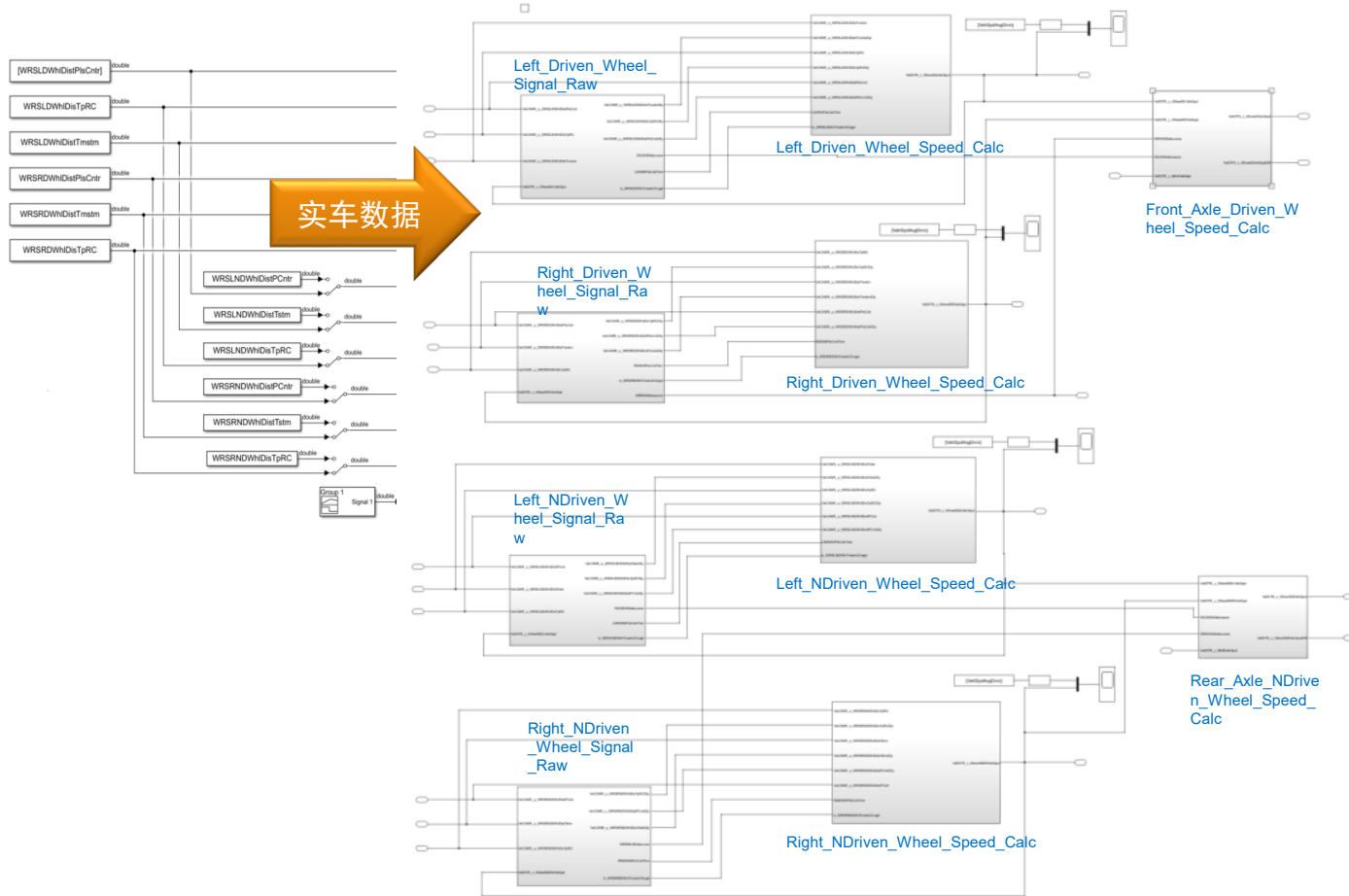
驱动功能更新简介 - 前置模块Vehicle Speed Calculation (VSCR)

- 提供多种源头的车速信号适配不同应用场景的算法模块



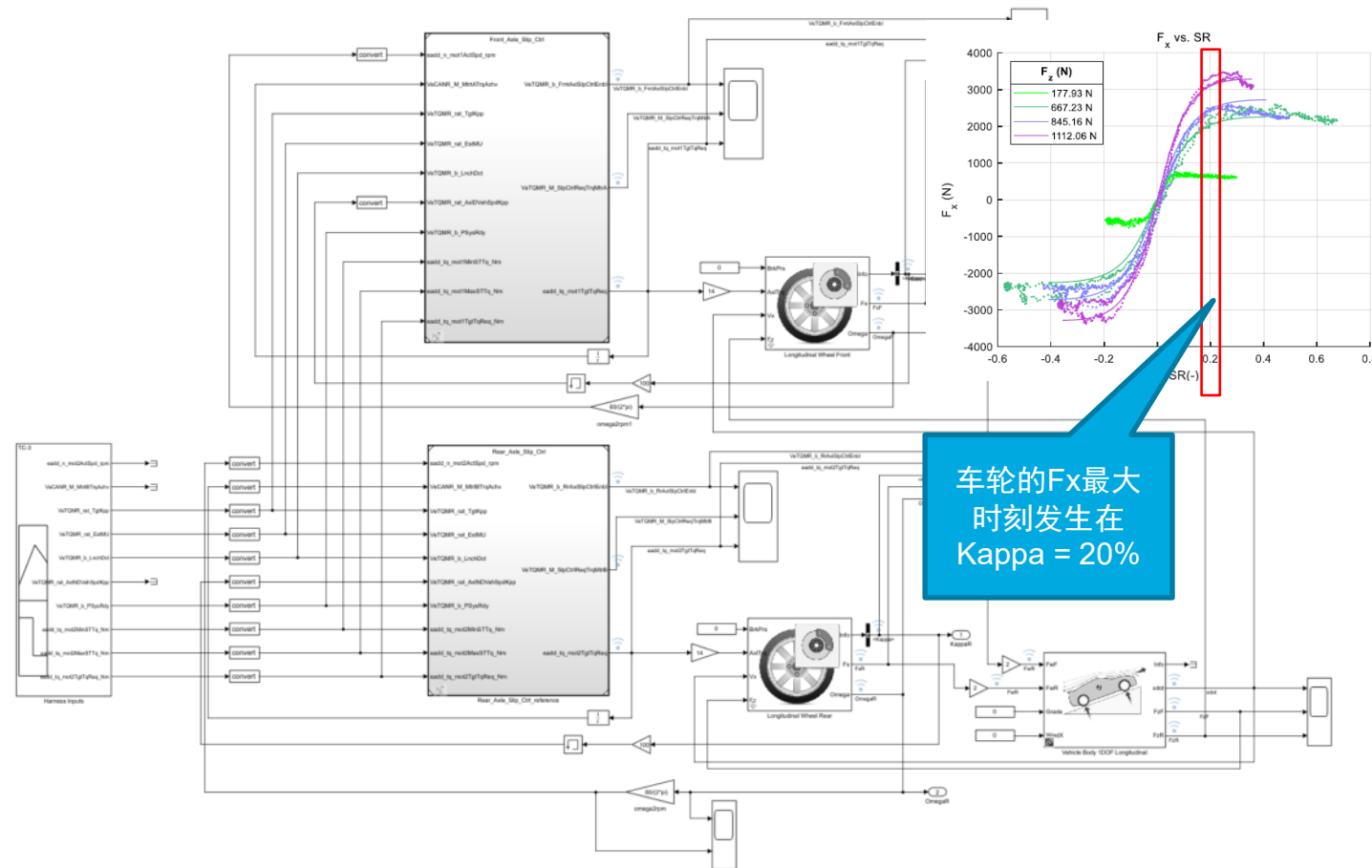
驱动功能更新简介 - 前置模块Wheel Speed Calculation(WSPD)

- 处理各个Wheel的Distance Pulse Counter, Pulse reset counter, Distance Time stamp, 计算得到各个车轮的速度
- 根据车速得到各个驱动轴的轴速
- 使用采集的真实信号注入, 准确还原车轮速度状态

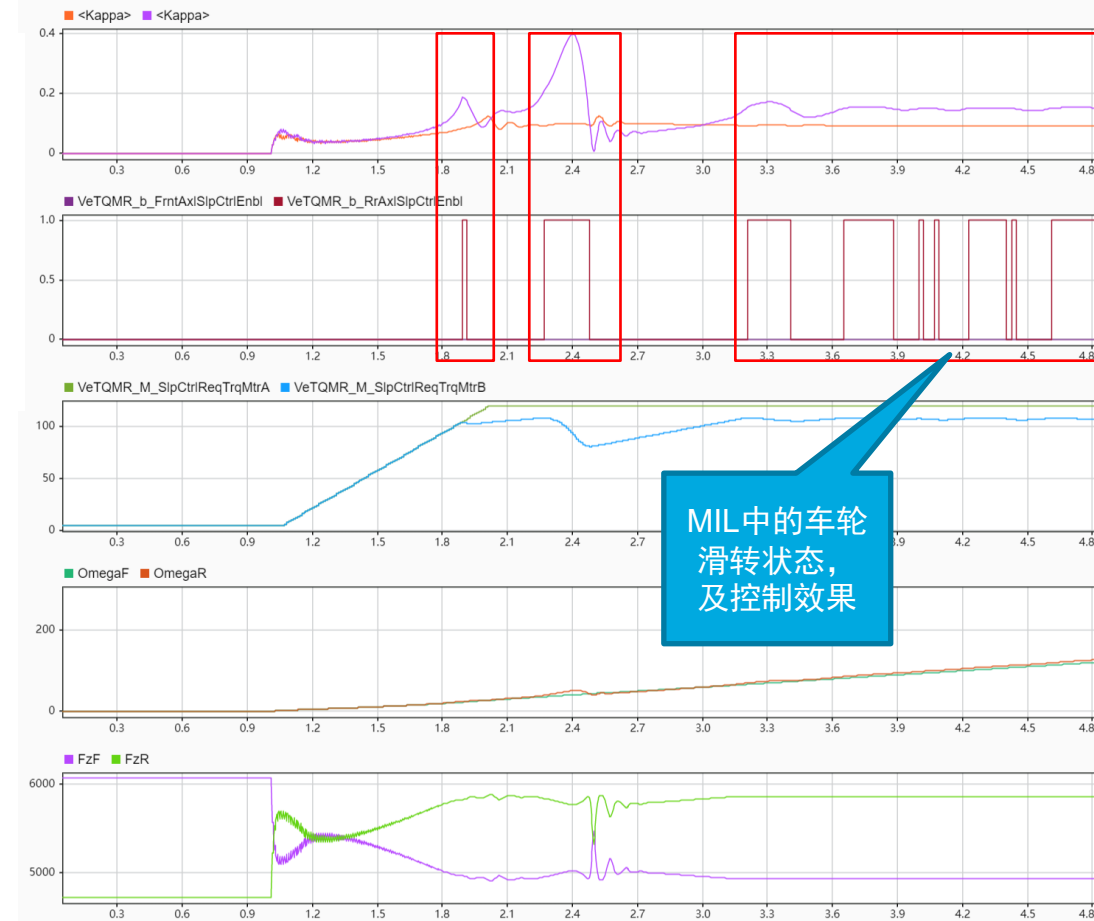
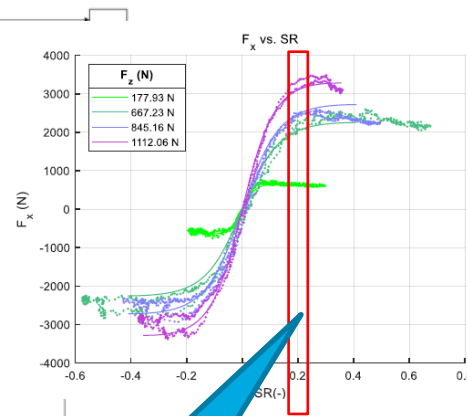


驱动功能更新简介 - 基于动力学分配 (纵向) 车轮滑转率控制

- 由前置模块WSPD和VSCR得到的信号，将用于每个车轮滑转率的计算
- 根据轮胎特性，20%的滑转率可以得到最大的Fx，则可以允许的起步时刻滑转率最大值为20%，也可通过标定调整
- 每个驱动桥的控制，都有单独的滑转率控制算法，算法中可以预判Kappa趋势，提前介入保证控制品质



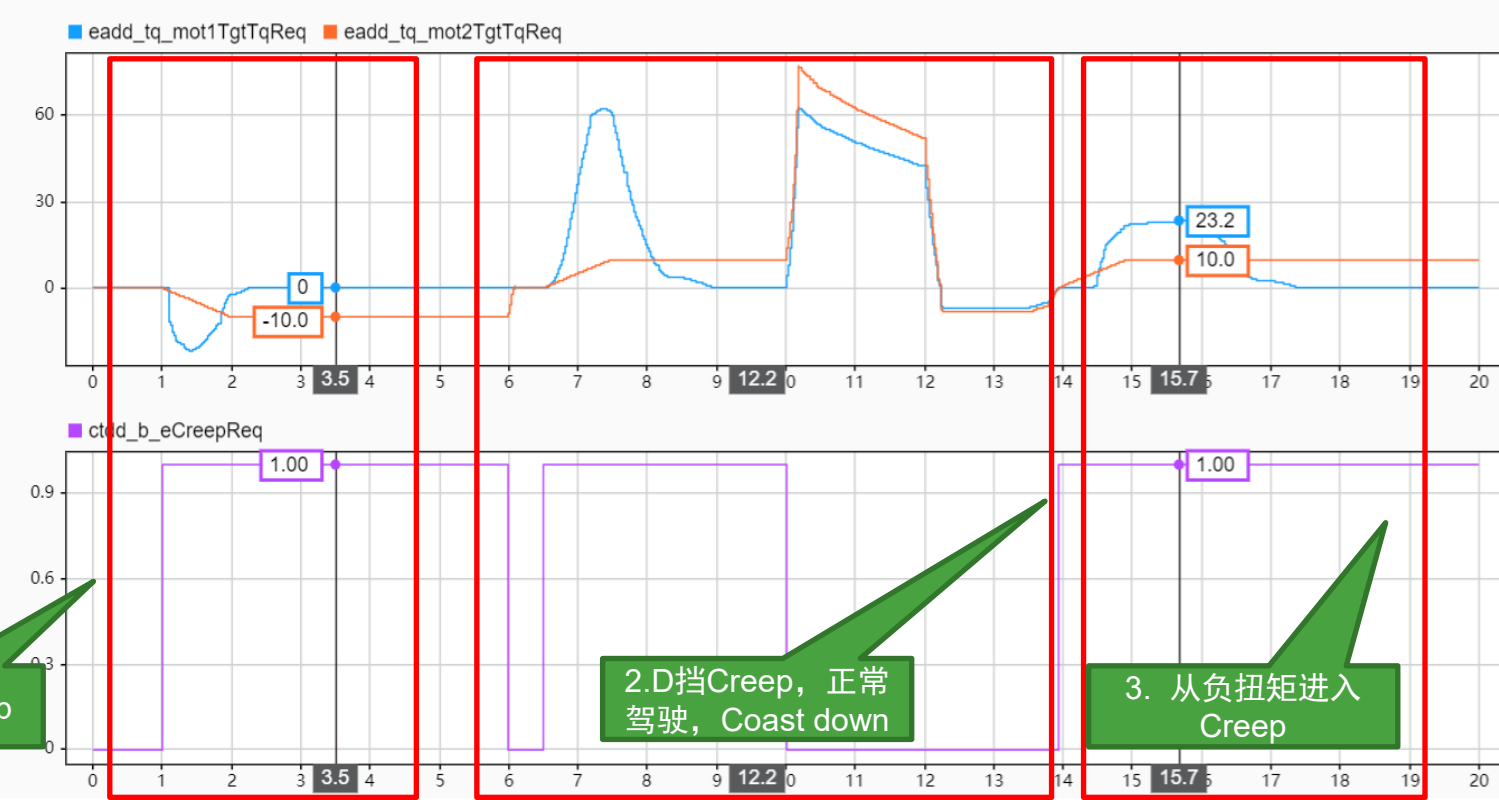
车轮的Fx最大
时刻发生在
Kappa = 20%



MIL中的车轮
滑转状态，
及控制效果

驱动功能更新简介 - 改良Creep策略

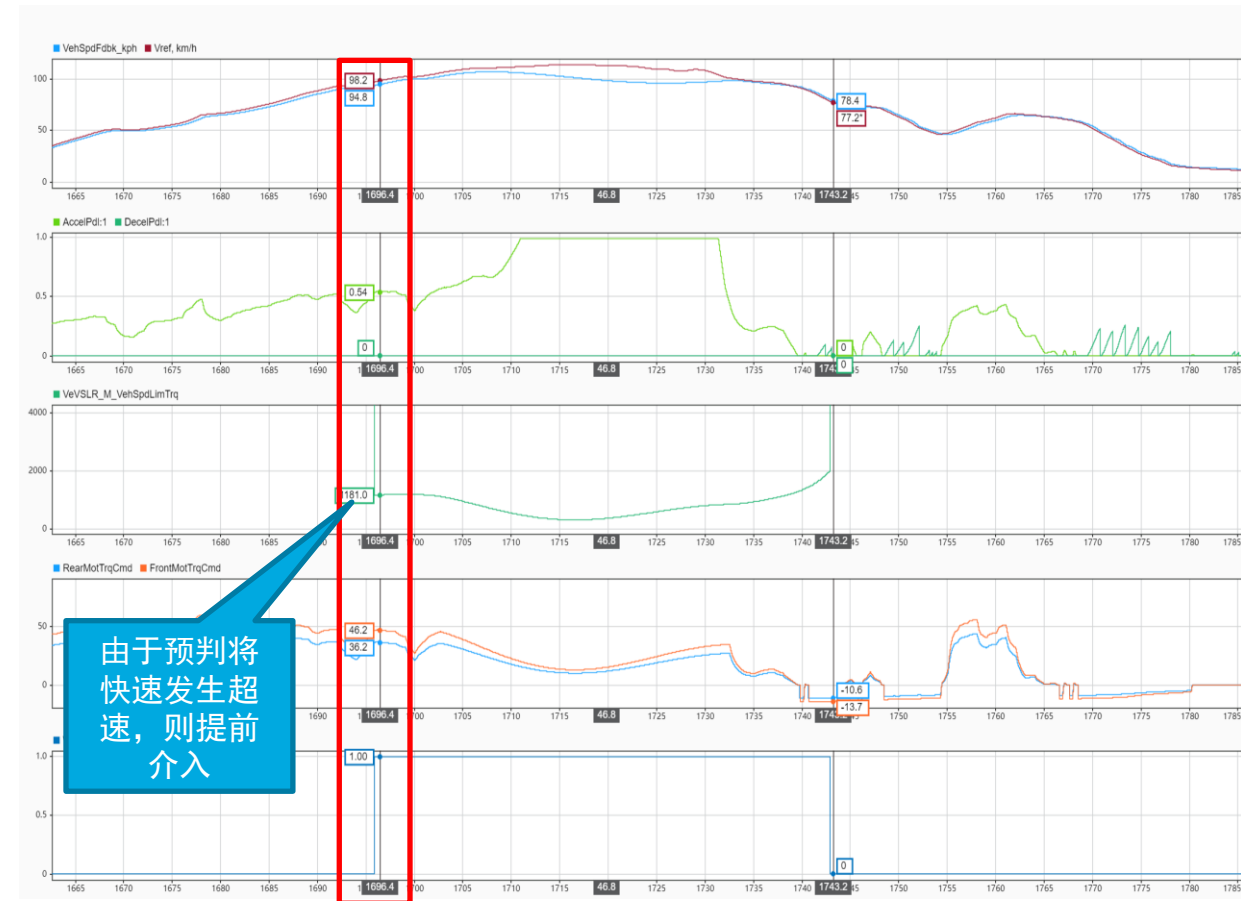
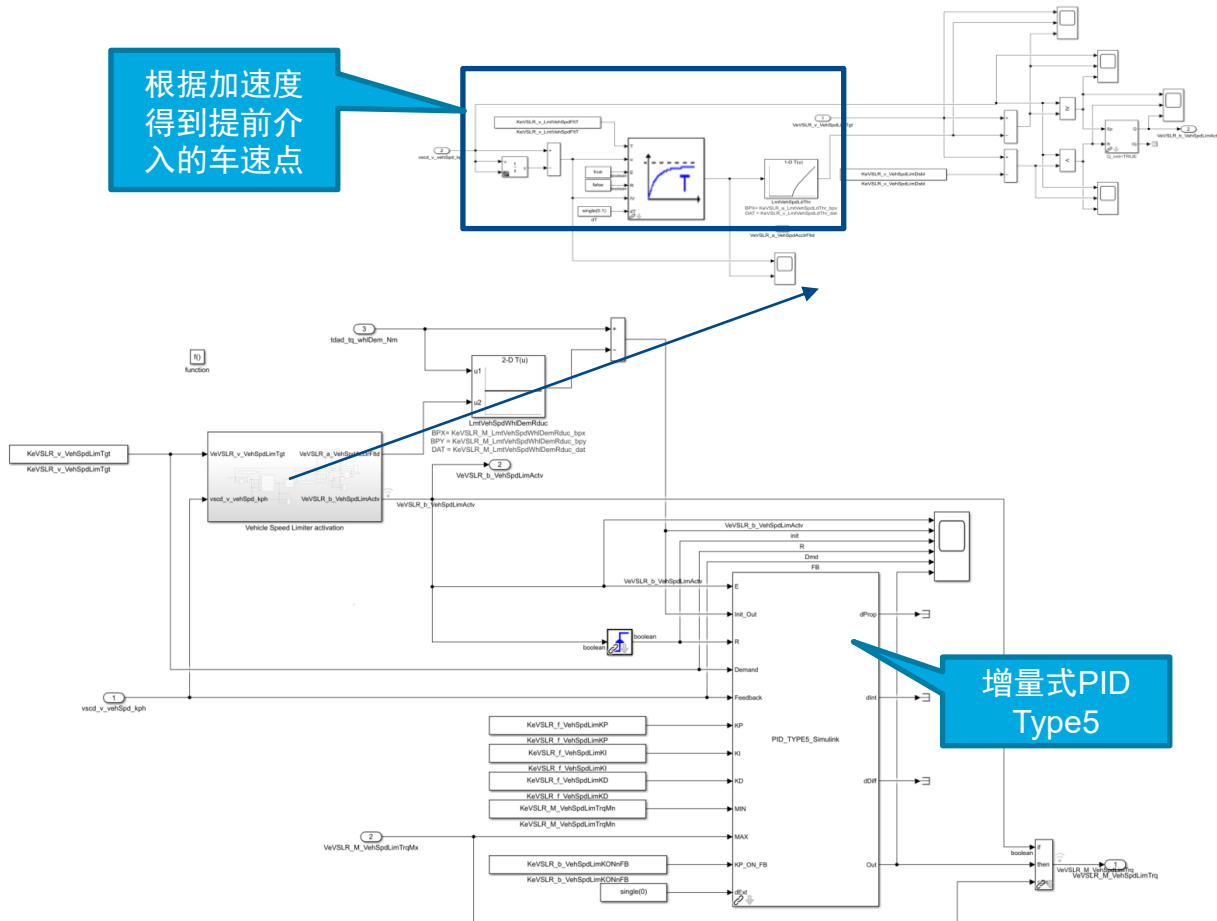
- 原Creep策略：
 - Creep模块根据测速闭环控制输出总扭矩
 - 由分配模块对前后轴进行动力学分配
- 新Creep策略：
 - Creep模块输出前轴根据测速闭环控制输出总扭矩，后轴给定较小的可标定固定扭矩
 - 发送Creep标志到Intervention模块，在非Creep时，平滑过渡到动力学分配
- 新策略考虑到动态分配时，在不断变化的扭矩过程中，电机响应不及时而造成系统震荡。而使用一开环，一闭环的方式，减少了系统的变量，使得系统鲁棒性增加



Front_Rear_Axle_VSC_Torque_Intervention_Distribution中的soft transition

驱动功能更新简介 - 改良的Vehicle Speed Limiter(VSLR)

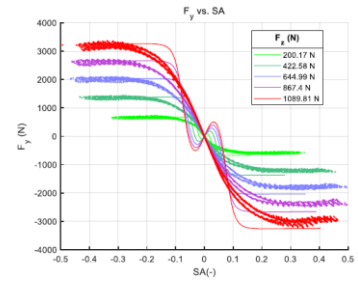
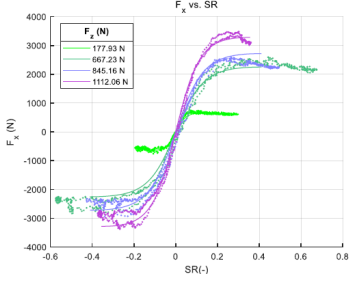
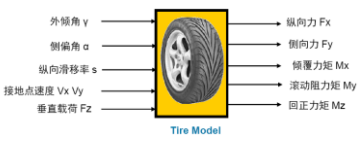
- 增加车辆车速预判算法，在加速度大，但尚未超速时，提前进行最大扭矩包络线限制，效果优于早期设计
- 为车轮滑转设计提供参考



在CLTC工况末端的超速限扭工况

驱动功能更新简介 - 基于动力学分配 (纵向3DOF)

- 纵向动力学分配的核心，是充分利用地面的附着力，将总驱动力限制在轮胎的最大驱动能力之内，并将能力不足的车轮上的驱动力，转移到有能力的车轮上。
- 根据Vehicle Dynamic Core的设计，首先先要估计每个车轮的Fx, Fy, Fz, 才能够将输出的扭矩限制在车轮的极限能力之内，所以在第一阶段涉及Fx和Fz的计算 (第二阶段将在控制算法中使用2DOF车轮和3DOF车身离散模型作为车辆动力学的状态估计依据)
- 由车身模型可以得到每个车轮实时的Fz, 再由Fz, 轮胎特性参数, 滑转率 (轮速), 得到每个车轮实际的Fx, Fx_max。在离散模型中, 使用的是基于Fiala轮胎框架修改的改良Dug-off轮胎模型



$$F_x = \frac{C_a S}{1-S} f(z)$$

$$F_y = \frac{C_b \tan(\alpha)}{1-S} f(z)$$

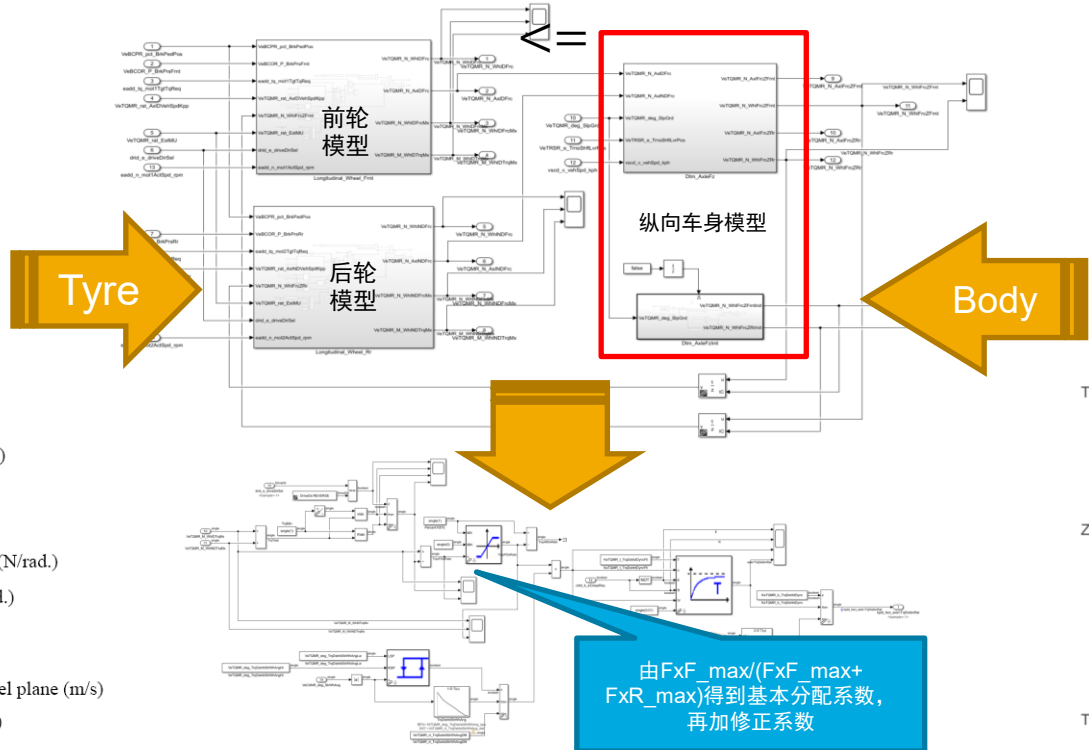
$$z = \frac{\mu F_z (1-S)}{2\sqrt{(C_a S)^2 + (C_b \tan(\alpha))^2}}$$

$$f(z) = \begin{cases} z(2-z), & z < 1 \\ 1, & z \geq 1 \end{cases}$$

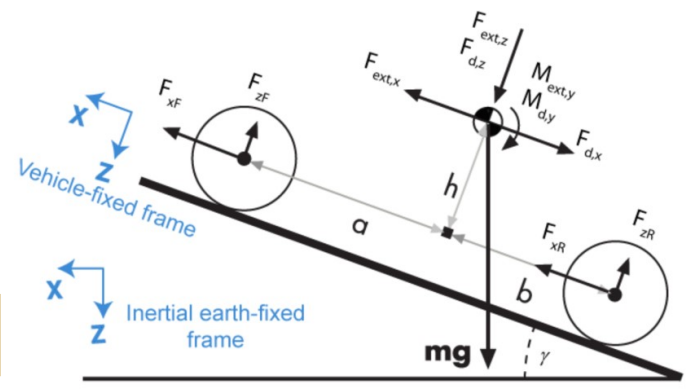
$$V_s = u\sqrt{S^2 + \tan^2 \alpha}$$

$$\mu = \mu_0(1 - A_s V_s)$$

F_x = longitudinal forces of tires (N)
 F_y = lateral forces of tires (N)
 F_z = vertical force of tires (N)
 C_a = longitudinal stiffness of tires (N/rad.)
 C_b = lateral stiffness of tires (N/rad.)
 α = side slip angle of tires (rad.)
 S = longitudinal slip ratio of tires
 μ = maximum friction coefficient
 u = velocity component in the wheel plane (m/s)
 A_s = friction reduction factor (m/s)



Front_Rear_Axle_Torque_Distribution_Priority中的分配系数



The Vehicle Body 1DOF Longitudinal block implements these equations.

$$F_b = m\ddot{x}$$

$$F_b = F_{xF} + F_{xR} - F_{d,x} + F_{ext,x} - mg \sin \gamma$$

Zero normal acceleration and zero pitch torque determine the normal force on each front and rear axles.

$$F_{zF} = \frac{-M_{ext,y} - M_{d,y} + b(F_{d,z} + F_{ext,z} + mg \cos \gamma) - h(-F_{ext,x} + F_{d,x} + mg \sin \gamma + m\ddot{x})}{N_F(a+b)}$$

$$F_{zR} = \frac{M_{ext,y} + M_{d,y} + a(F_{d,z} + F_{ext,z} + mg \cos \gamma) + h(-F_{ext,x} + F_{d,x} + mg \sin \gamma + m\ddot{x})}{N_R(a+b)}$$

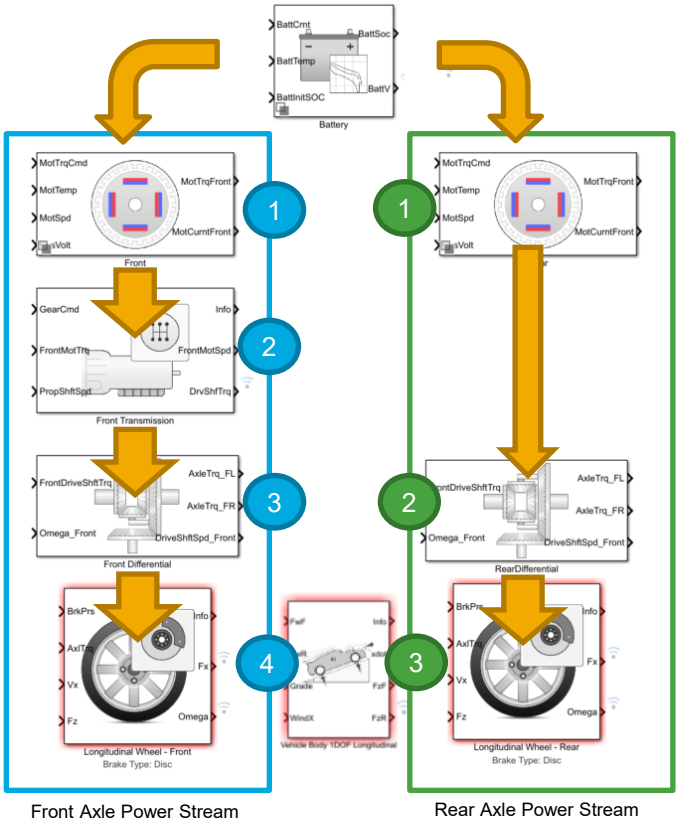
The wheel normal forces satisfy this equation.

$$N_F F_{zF} + N_R F_{zR} - F_{ext,z} = mg \cos \gamma$$

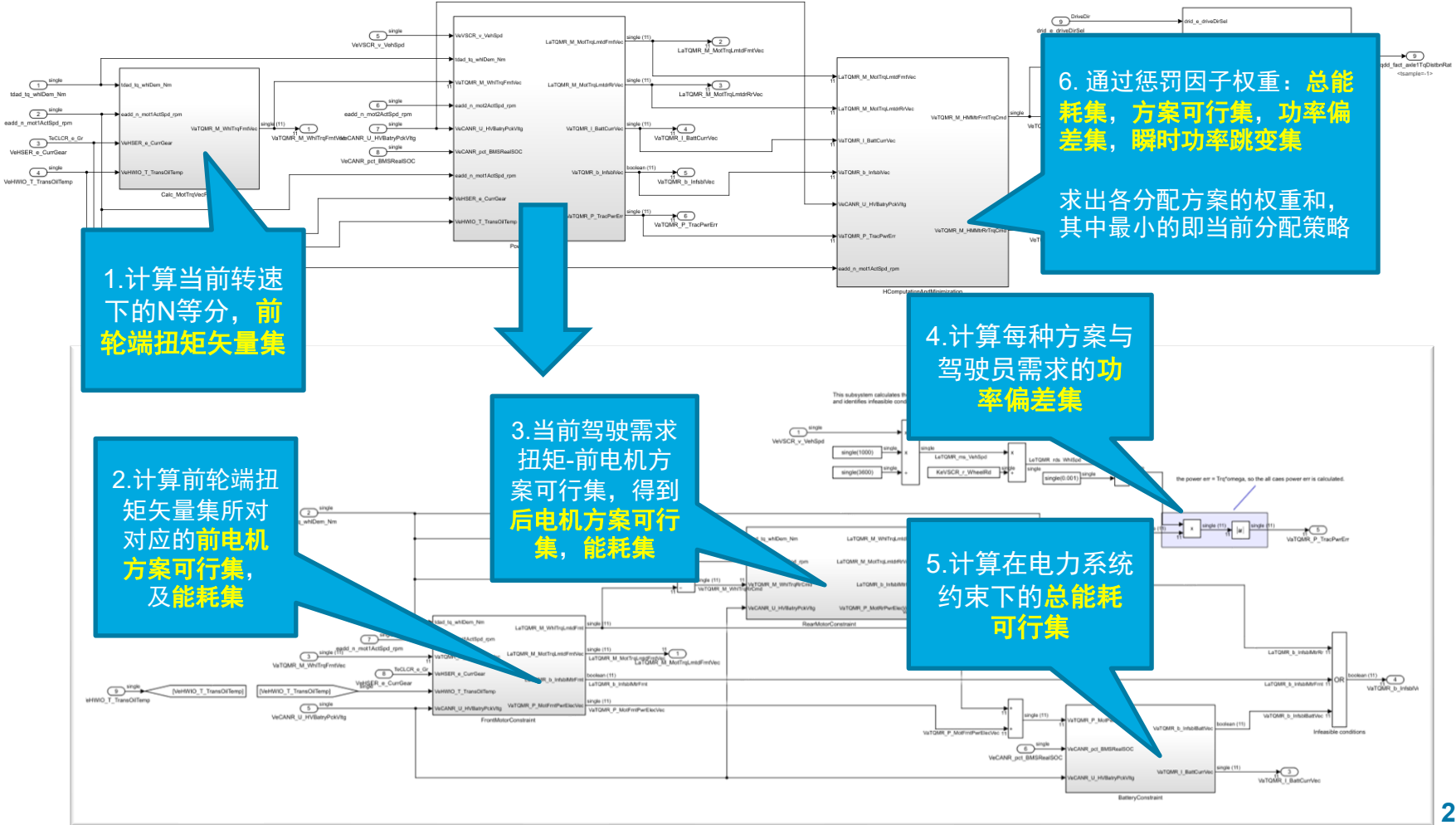
驱动功能更新简介 - 基于经济性分配(纵向)

双轴四驱电动车的经济性驱动分配策略，采用寻优（效率最高）的方法获得，寻优原则如下：

- 1. 在能量传递路径中，则动力源通过传递路径越短，节点损失越小，则效率越高
- 2. 先确定驾驶员的输入，然后枚举每一种分配方法，求出每一种分配方法的能量损失，根据系统约束去除不可能的分配方法后，能耗最小的分配方法最优。



- 由原则1可知，Rear Axle Power Stream的路径更短，应优先使用后桥
- 当后桥电机工作区域不再经济时，原则2将求出能耗最小的分配方法，使前桥电机介入

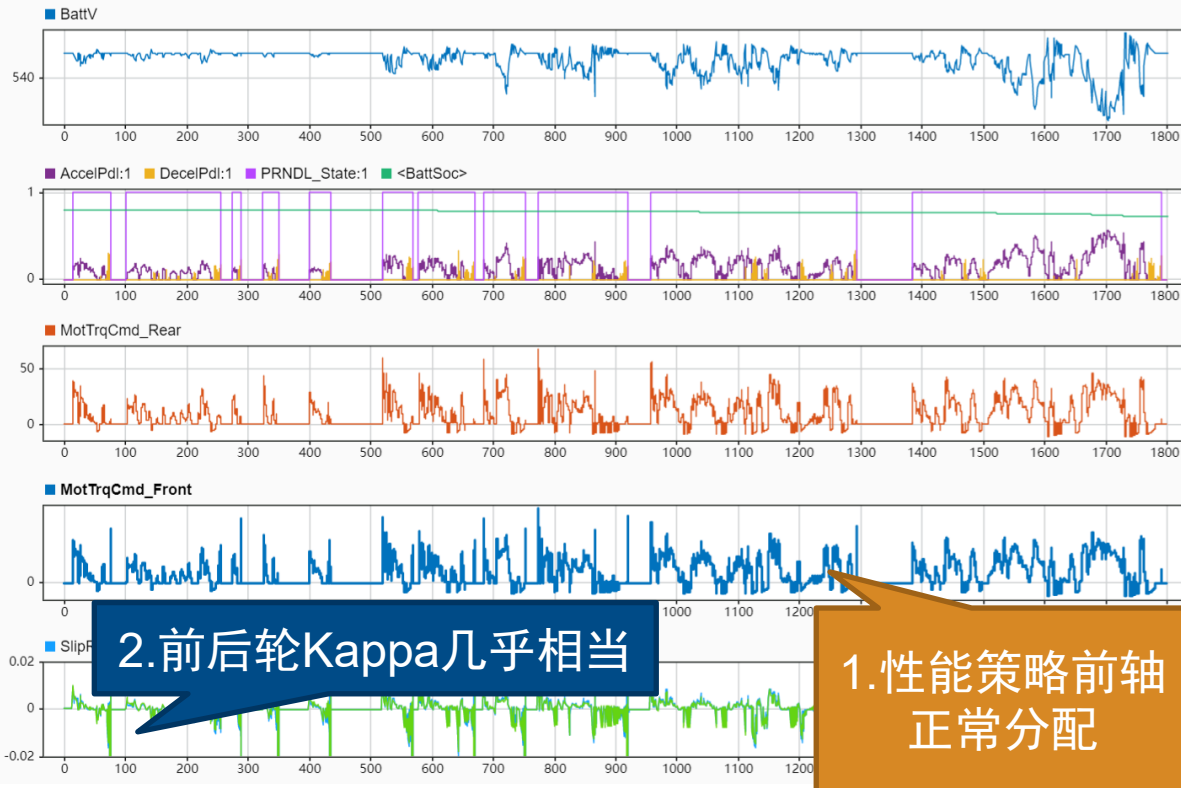


6. 通过惩罚因子权重：总能耗集，方案可行集，功率偏差集，瞬时功率跳变集

求出各分配方案的权重和，其中最小的即当前分配策略

仿真结果分析 - ATEV 四驱策略电耗评估 (Init SOC = 0.8)

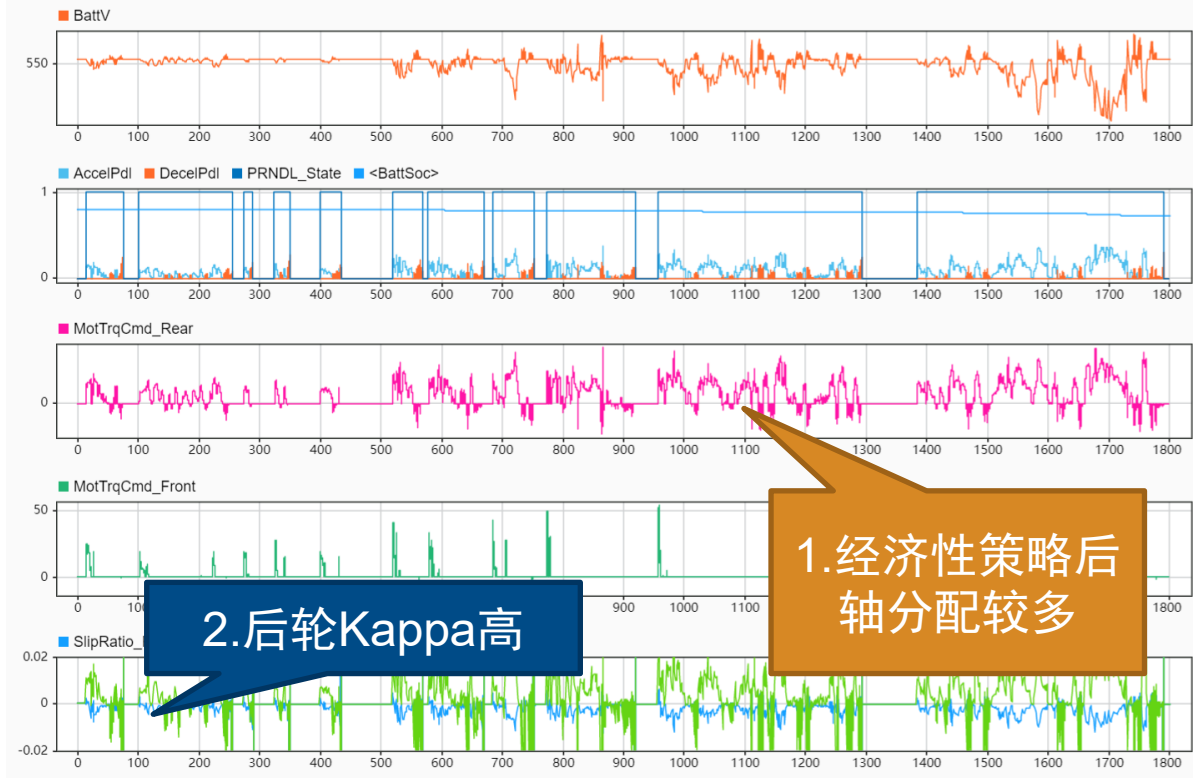
- Run 1: CLTC 性能分配策略 End SOC = 0.73149
- Run 2: CLTC 经济性分配策略 End SOC = 0.73327



Run 1: 性能分配策略

结论

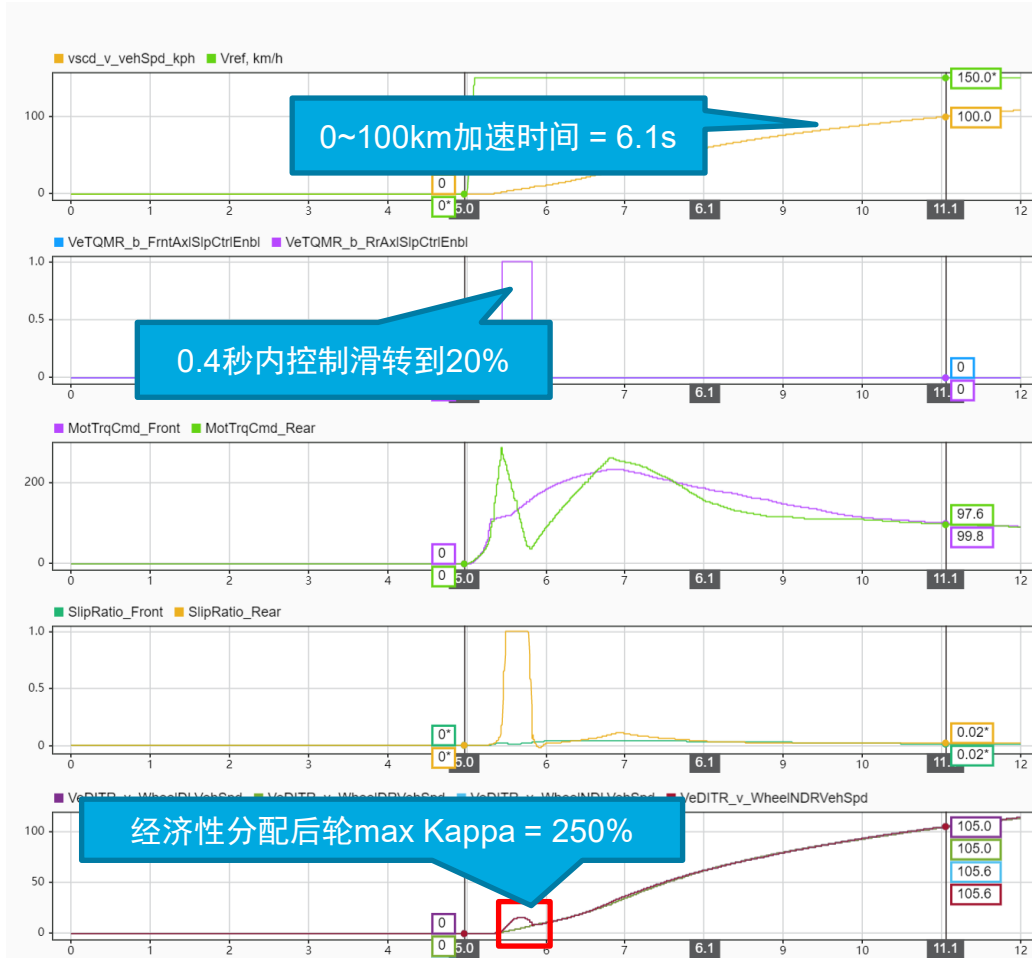
- 集成组提供分配的参考策略 End SOC = 0.73269, 介于两者之间
- 性能策略分配策略前轴扭矩正常分配, 驱动轴效率较低, 导致系统能耗较高。
- 经济性策略则后轴分配较多, 使得系统能耗较低。



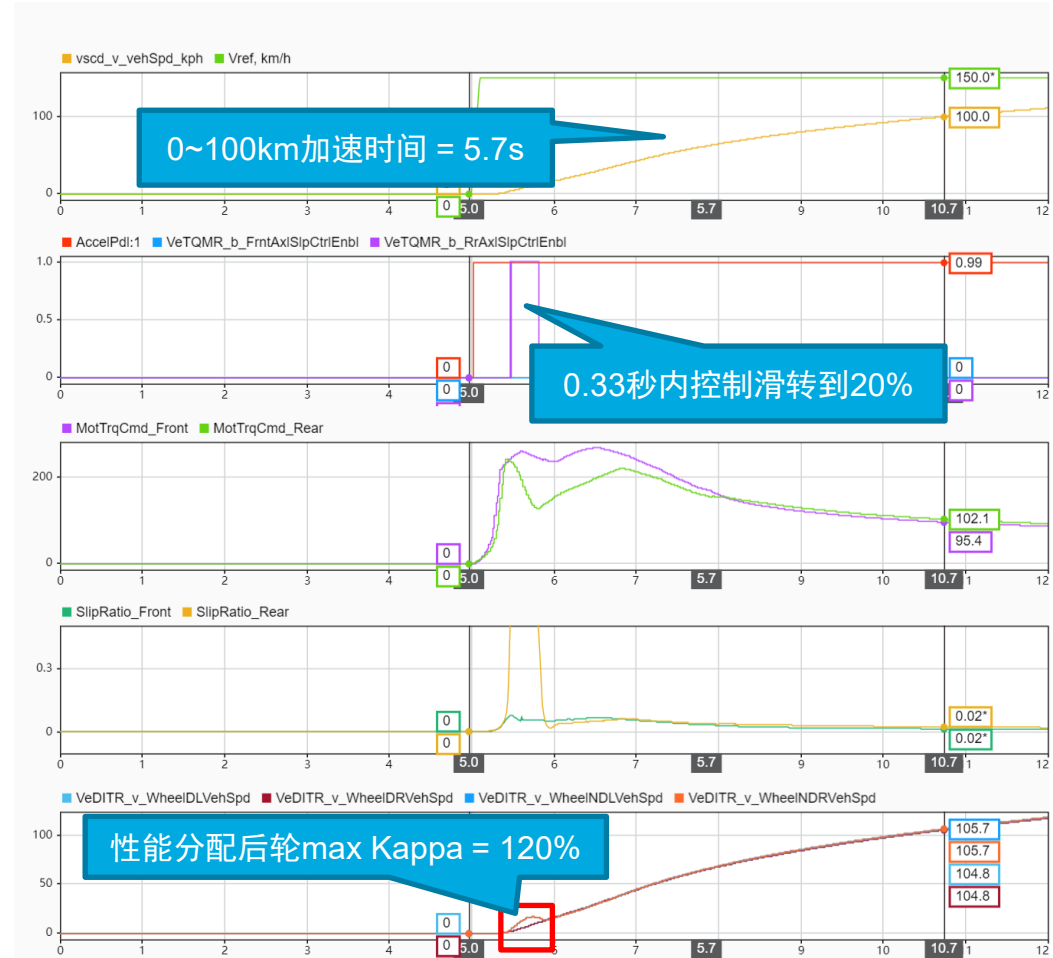
Run 2: 经济性分配策略

仿真结果分析 - 仿真及结果分析 (WOT: 经济性分配 VS 性能分配)

- 性能分配充分利用车轮的附着力，性能分配加速时间更短，后轮滑转时间窗口更小，滑转率更低。



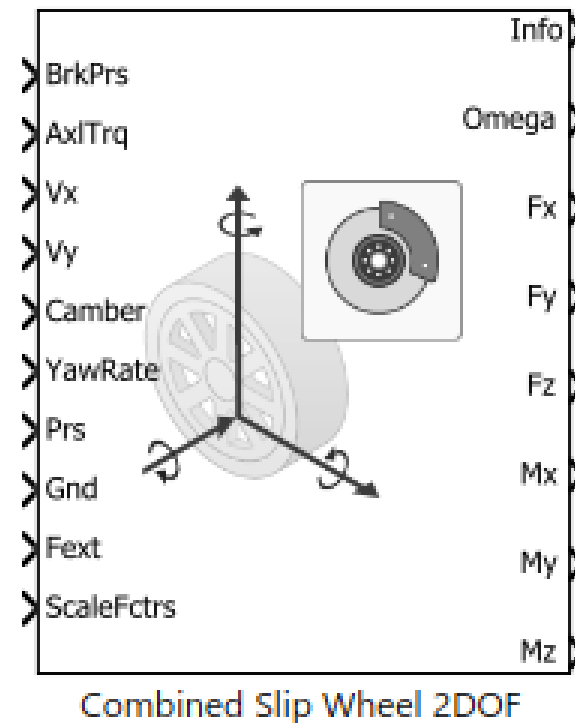
经济性分配



性能分配

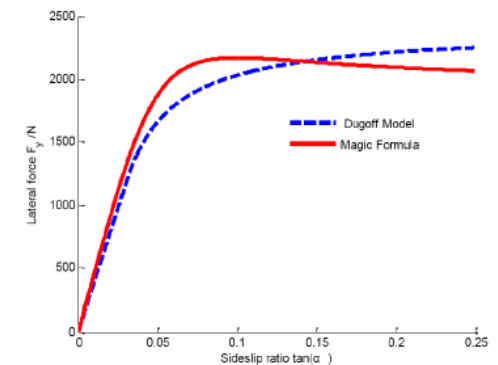
2DOF轮胎离散模型

- 1. 魔术公式(MF)轮胎模型
 - 基于实测数据，计算准确
 - 参数较多，难标定
 - 模型复杂，不适用于控制算法使用
 - 在被控对象段，会继续采用MF模型
- 2. 原Dugoff轮胎模型
 - 模型简单，可用于控制算法。
 - 可反映不同附着系数路面情况
 - 非线性区域计算不准确
 - 高滑移率区域误差大



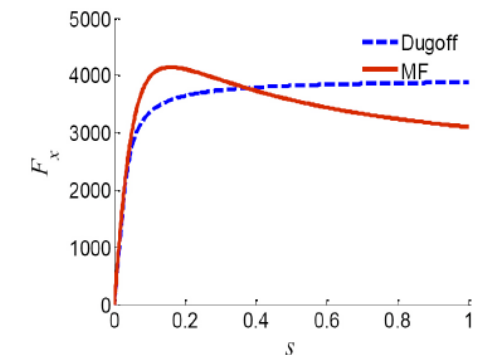
$$F_x = C_s \frac{S}{1+S} \cdot f(\lambda) \quad \lambda = \frac{\mu_{\max} F_z (1+S)}{2\sqrt{(C_s S)^2 + (C_\alpha \tan \alpha)^2}}$$

$$F_y = C_\alpha \frac{\tan(\alpha)}{1+S} \cdot f(\lambda) \quad f(\lambda) = \begin{cases} (2-\lambda)\lambda, & \lambda < 1 \\ 1, & \lambda \geq 1 \end{cases}$$



(b). Lateral tire force calculated by Dugoff and MF model

Figure 1. (cont.) Tire force calculated by Dugoff and MF model



(a). Longitudinal tire force calculated by Dugoff and MF model

Figure 1. Tire force calculated by Dugoff and MF model

Notes:

图片来源: SAE2014-01-0123 Mingyuan Bian, Long Chen, Yugong Luo, and Keqiang Li Tsinghua University
A Dynamic Model for Tire/Road Friction Estimation under Combined Longitudinal/Lateral Slip Situation

2DOF轮胎离散模型

- Modified Dugoff轮胎模型
 - 基于Dugoff轮胎模型，改进非线性区域
 - 引入非线性区域修正因子
 - 考虑修正因子受垂直载荷得影响

$$F_x = C_s \cdot \frac{S}{1+S} \cdot f(\lambda) \cdot G_S$$

$$F_y = C_\alpha \cdot \frac{\tan \alpha}{1+S} \cdot f(\lambda) \cdot G_\alpha$$

$$G_S = (1.15 - 0.75\mu_{\max}) \cdot S^2 - (1.63 - 0.75\mu_{\max}) \cdot S + 1.27$$

$$G_\alpha = (\mu_{\max} - 1.6) \cdot \tan \alpha + 1.155$$

$$\lambda = \frac{\mu_{\max} F_z (1+S)}{2\sqrt{(C_s S)^2 + (C_\alpha \tan \alpha)^2}}$$

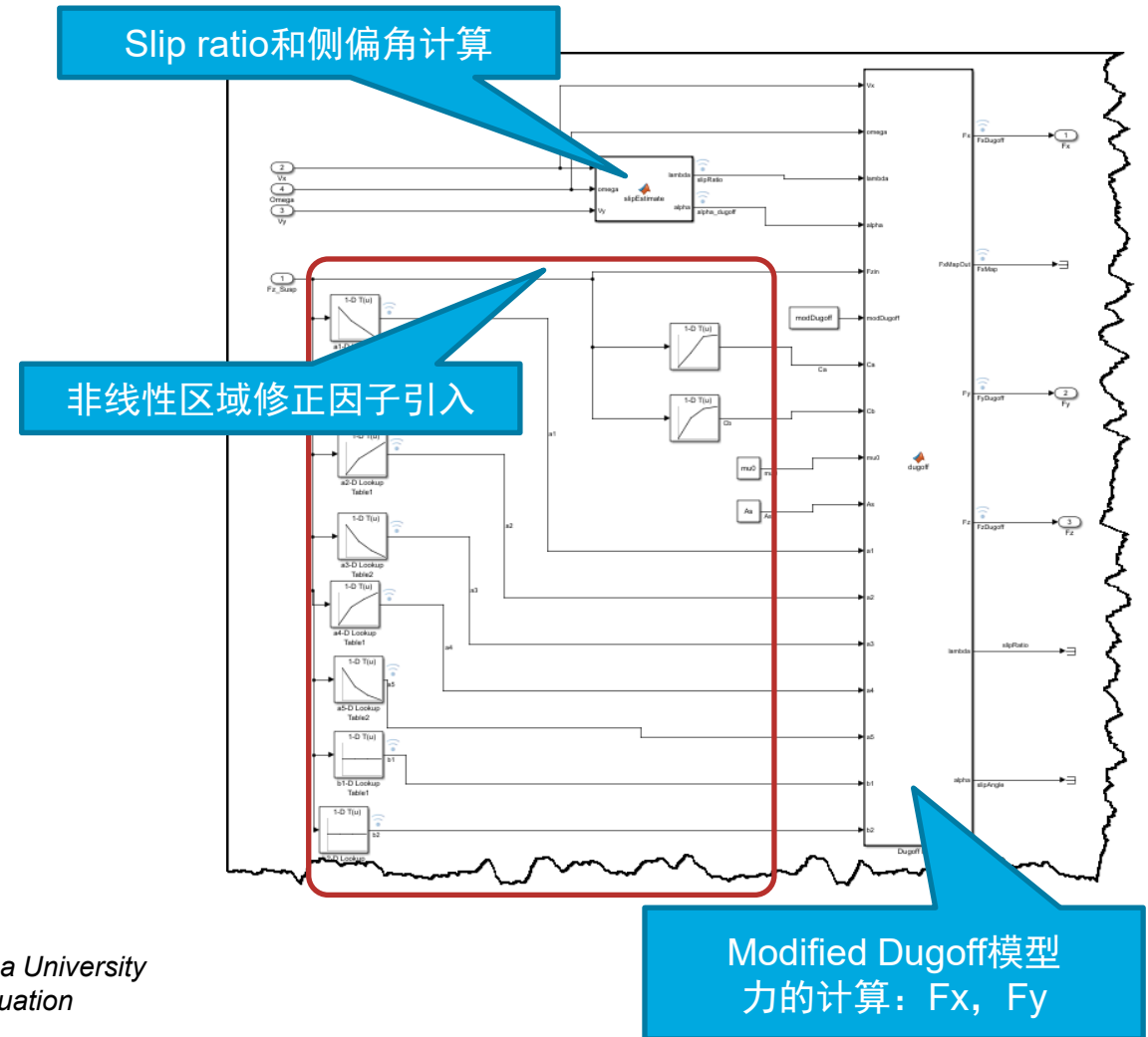
$$\lambda = \frac{\mu_{\max} F_z (1+S)}{2\sqrt{(C_s S)^2 + (C_\alpha \tan \alpha)^2}}$$

$$f(\lambda) = \begin{cases} (2-\lambda)\lambda, & \lambda < 1 \\ 1, & \lambda \geq 1 \end{cases}$$

$$f(\lambda) = \begin{cases} (2-\lambda)\lambda, & \lambda < 1 \\ 1, & \lambda \geq 1 \end{cases}$$

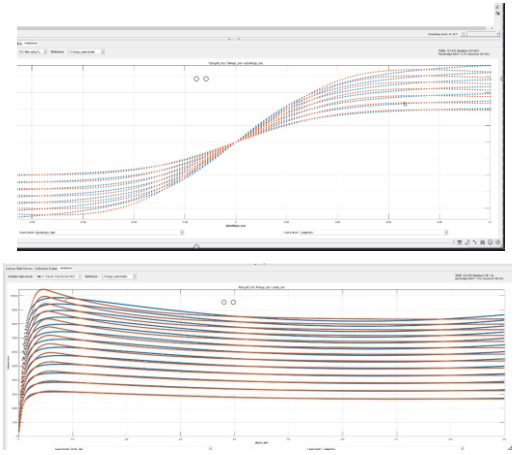
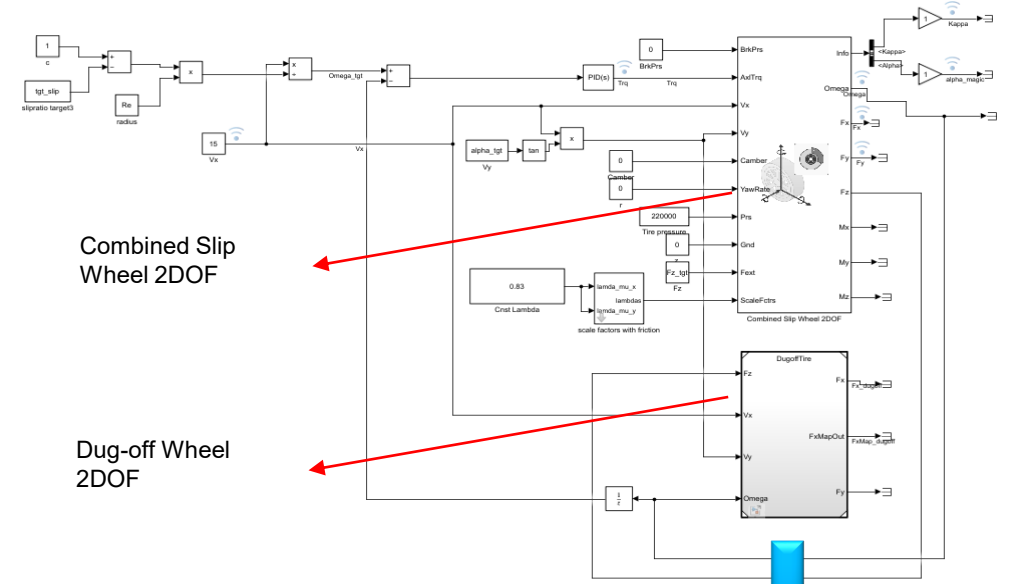
Notes:

图片来源: SAE2014-01-0123 Mingyuan Bian, Long Chen, Yugong Luo, and Keqiang Li Tsinghua University
A Dynamic Model for Tire/Road Friction Estimation under Combined Longitudinal/Lateral Slip Situation



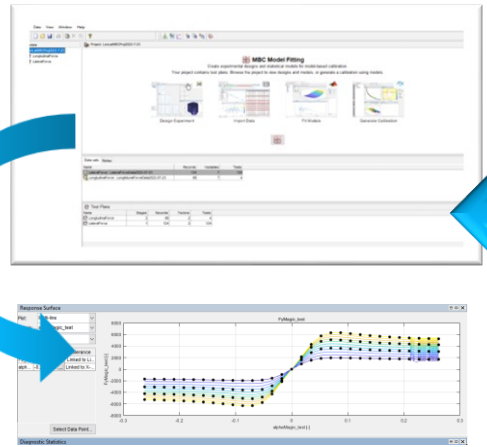
2DOF轮胎离散模型

- Modified Dugoff轮胎模型标定：
 - 数据：以魔术公式模型为测试对象，获取数据。
 - 工况：
 - 纯纵向滑移工况
 - 纯侧滑工况
 - 复合工况（纵滑+侧滑）
 - 标定方法：使用MBC工具（Model-Based Calibration Toolbox）自动标定



Feature: FyDugoff_mod(Fz_test, slp1to_test, alphamagic_test)
 Fitted by: FxMagic_test(slp1to_test, Fz_test) Model

Optimization in CAGE



Model fitting

LongitudinalForceData2022-07-23.csv

Fz_test	Kappa_test	slp1to_test	FxMagic_test	FxDugoff_t	alphaMagi	FyMagic_test
2000	0	0	-0.00035	0.01	539.8551	
2000	0.017385	0.01	2232.376	1145.148	-0.01	509.9786
2000	0.027769	0.02	2687.838	1537.518	-0.01	465.4158
2000	0.038388	0.03	2944.912	1659.499	-0.01	418.0054
2000	0.049229	0.04	3083.757	1710.891	-0.01	373.9412
2000	0.060299	0.05	3156.156	1734.152	-0.01	335.1429
2000	0.071605	0.06	3190.669	1743.521	-0.01	301.6089
2000	0.083155	0.07	3202.942	1745.092	-0.01	272.7174
2000	0.094957	0.08	3201.848	1741.902	-0.01	247.7445
2000	0.10702	0.09	3192.631	1735.635	-0.01	226.0338
2000	0.11924	0.1	3173.498	1726.005	-0.01	207.0348

测试数据集



Projects

New Project

Open Project

Recent projects:

- D:_\onLst\MBCProj2022-7-23.mat
- D:_UseFMBCProj.mat
- D:_MBCOOEprojctV1.mat
- D:_AirChargeMBCproject.mat

Open Recent Project

Case Studies

Examples

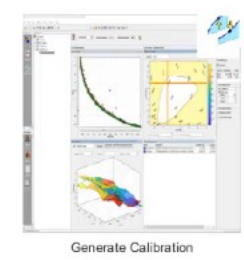
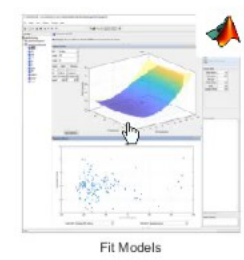
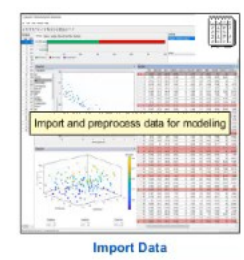
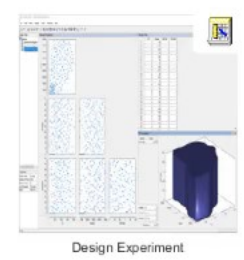
- Dual CAM gasoline engine with spark optimiz...
- Multi-injection diesel tested with pilot injection ...
- CI Mapped Engine - Fuel Input
- CI Mapped Engine - Torque Input
- SI Mapped Engine - Torque Input
- PMSM maximum efficiency calibration

Help Open Example

MBC Model Fitting

Create experimental designs and statistical models for model-based calibration.

Your project is empty. Design an experiment or import data for modeling.



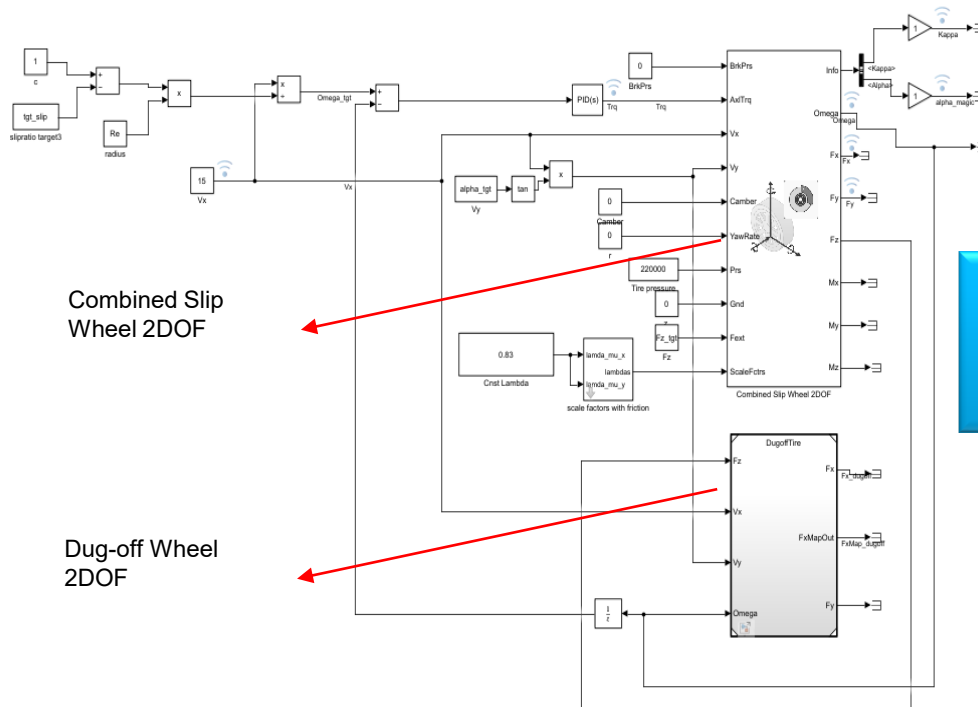
Browse Project

Project Summary

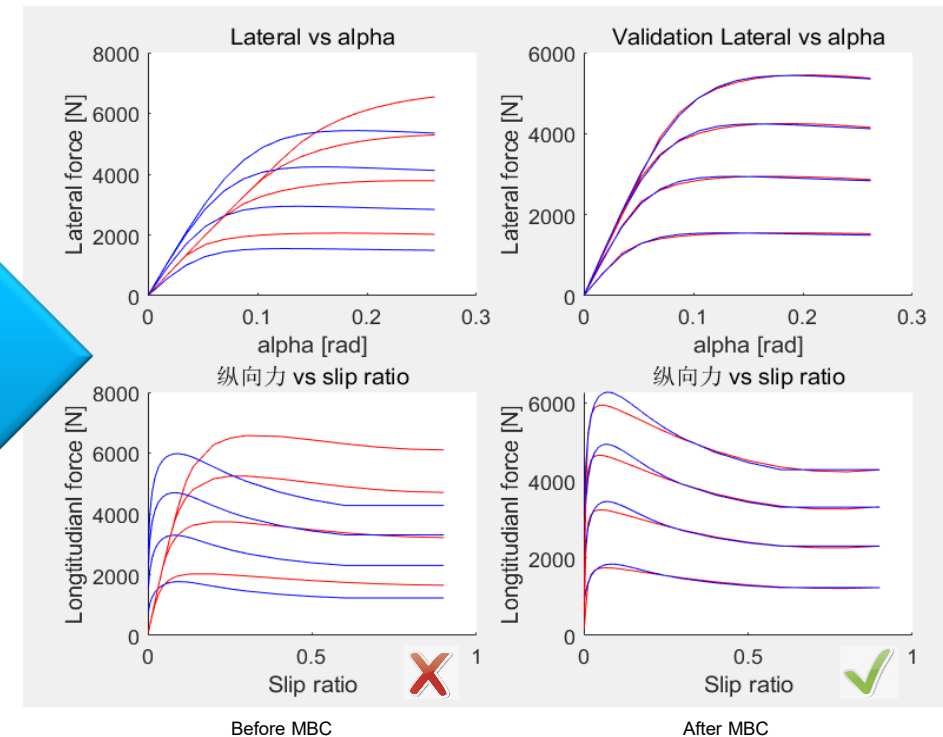
Type	Number
Test Plans	0
Data sets	0
Models	0

Modified Dugoff轮胎模型标定结果

- 在算法中使用2DOF轮胎离散模型代替现有1DOF轮胎模型
 - 测试魔术公式轮胎模型和Dug-off轮胎模型，同时获取两个轮胎模型在相同输入下的轮胎驱动力 F_x/F_y 和slip ratio/侧偏力 α 数据，用于对比两个轮胎模型在相同输入条件下的输出力。
 - 使用MBC工具箱对Dog-off轮胎模型中的参数进行自动标定，完成参数校准，可使用并行处理

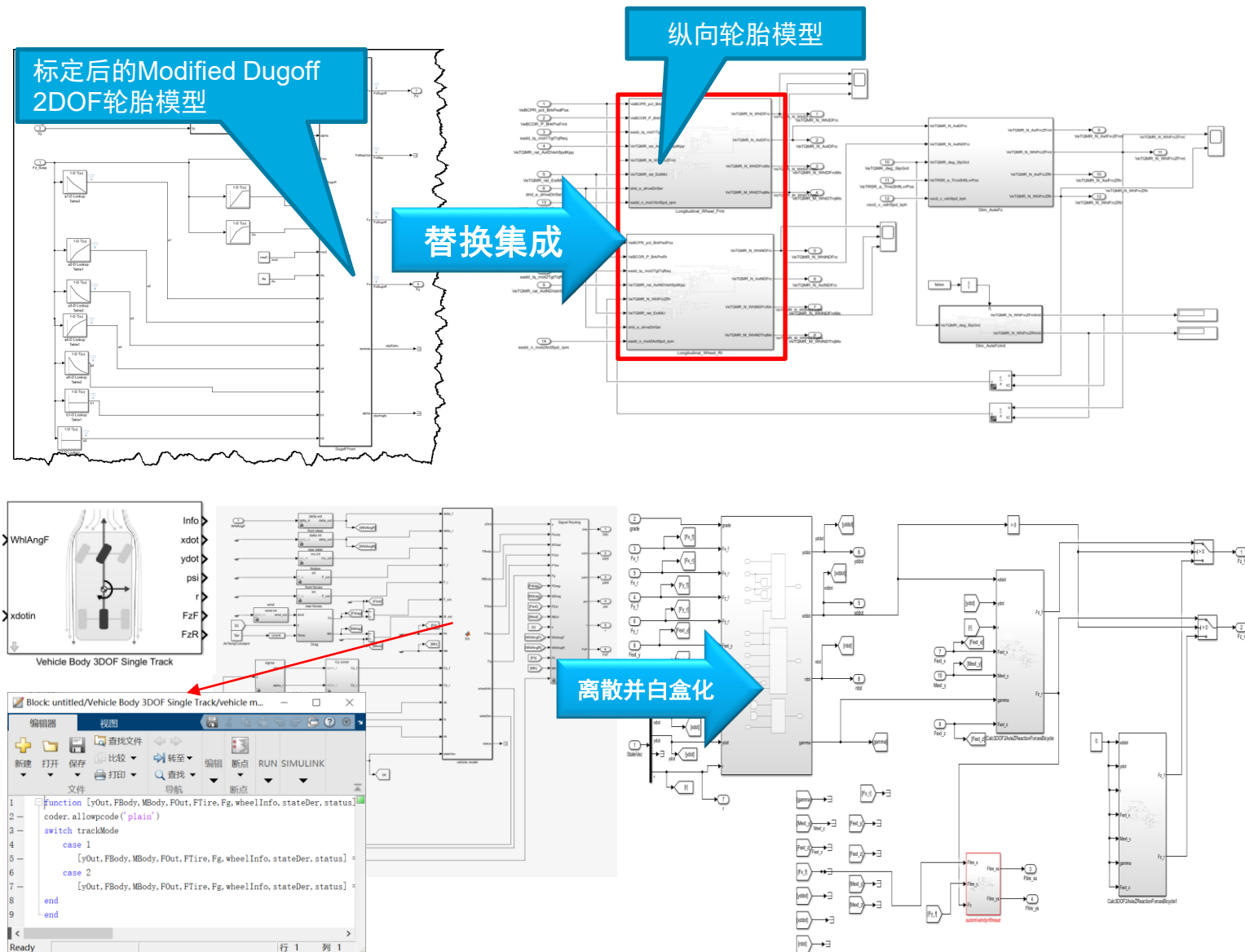


MBC前后
结果对比



下一步的工作（待更新）

- Modified Dugoff轮胎模型集成到控制算法中
 - Modified Dugoff轮胎模型集成
 - 基于Modified Dugoff轮胎模型的摩擦圆驱动力分配控制算法测试
 - 更新后算法闭环测试
- 在算法中使用3DOF车身离散模型代替现有1DOF车身模型
 - 已完成3DOF模型离散模型，待集成
- 完成Yaw控制功能，进行MIL测试，完善策略
- 软硬件集成测试
- 实车调试



2022 MathWorks 中国汽车年会

Thank you

