

# 用Simulink开发分布式汽车控制器

李智慧

MathWorks高级技术咨询顾问

zhihui.li@mathworks.com

# 特别感谢： 美国福特汽车



## Nate Rolfes

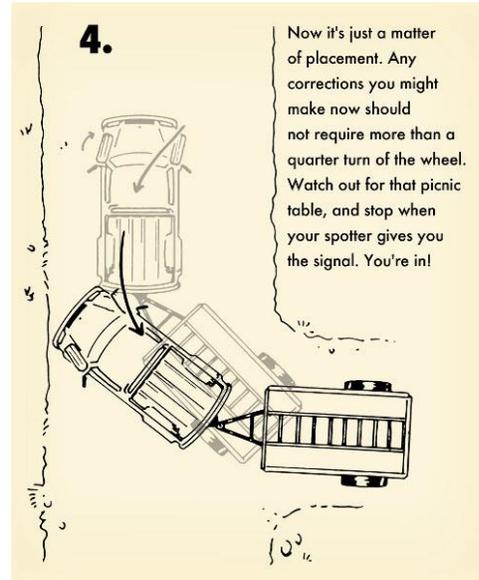
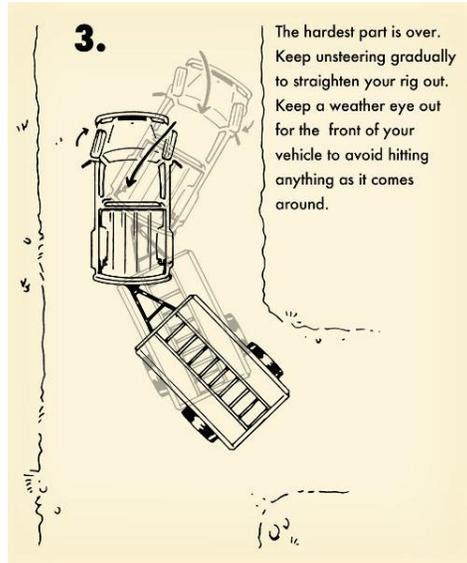
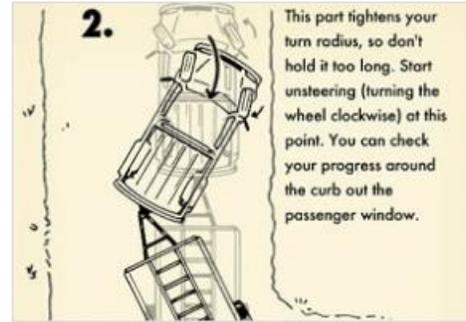
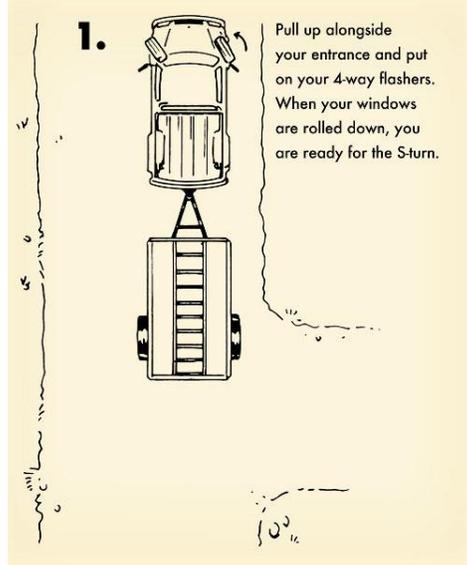


- 内容来自Rolfes先生在今年美国MAC上的演讲
- 产品及架构设计由美国福特公司原创
- MathWorks从工具以及MBD层面支持了开发过程
- 在MathWorks技术咨询帮助下，优化了验证流程并开发了自动化验证工具

# Pro Trailer Backup Assist (TBA)



# 拖车倒车控制难点



## 相关联控制器

### 动力系统

- 通过节气门开度控制车速
- 换挡逻辑状态

### 转向系统

- 转向力矩传感器
- 转向控制输出

### 刹车系统

- 车速传感器获取里程信息
- 加速传感器获取车辆动态信息
- 刹车执行器控制速度

Pro Trailer Backup Assist™ setup

## 相关联控制器

倒车影像系统

- 摄像头探测拖车角度

车身控制器

- 夜间使用时提供照明

## 相关联控制器

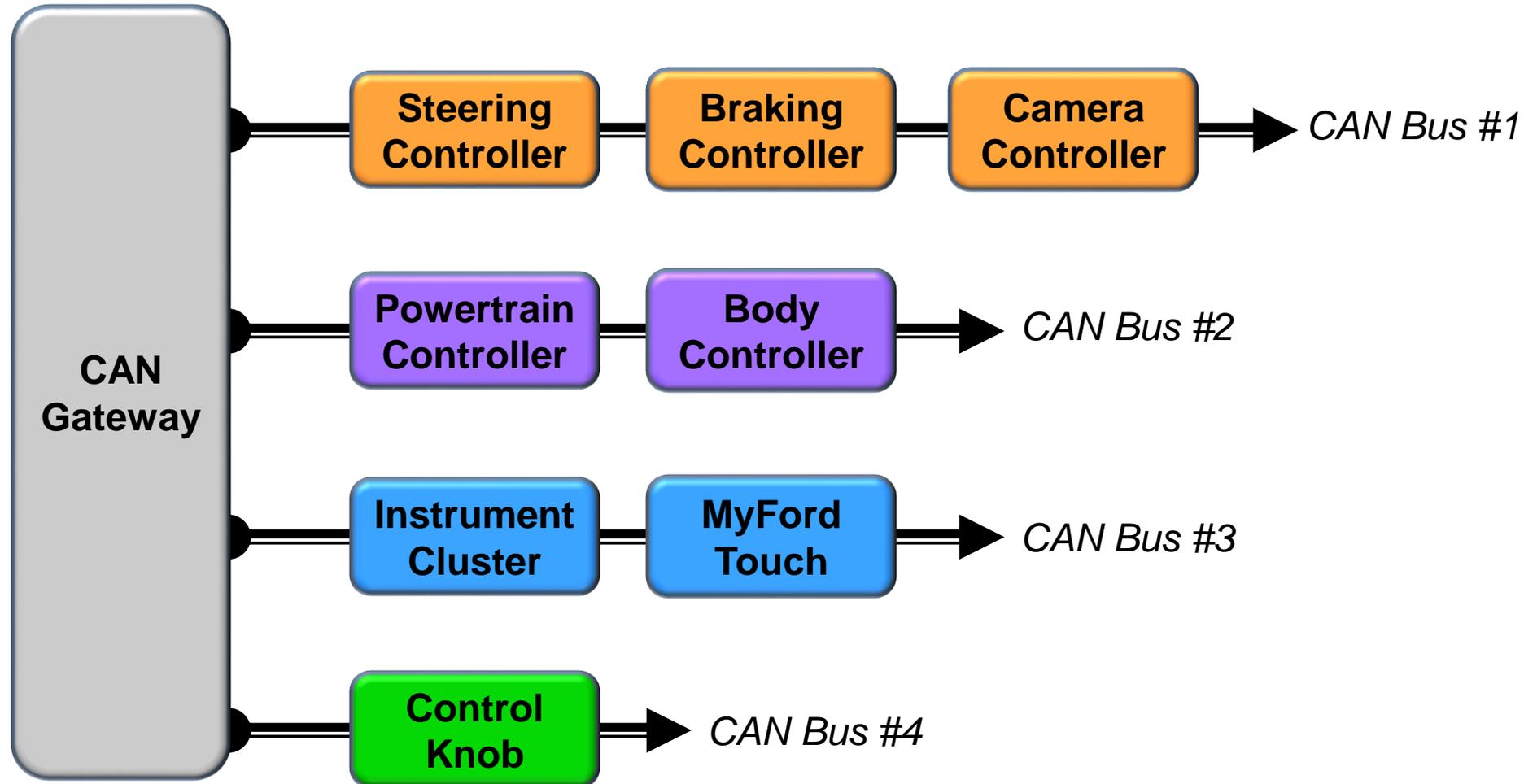
人机接口:

- 警告信息
- 功能激活及控制旋钮
- 司机多向控制按钮
- 后视影像显示



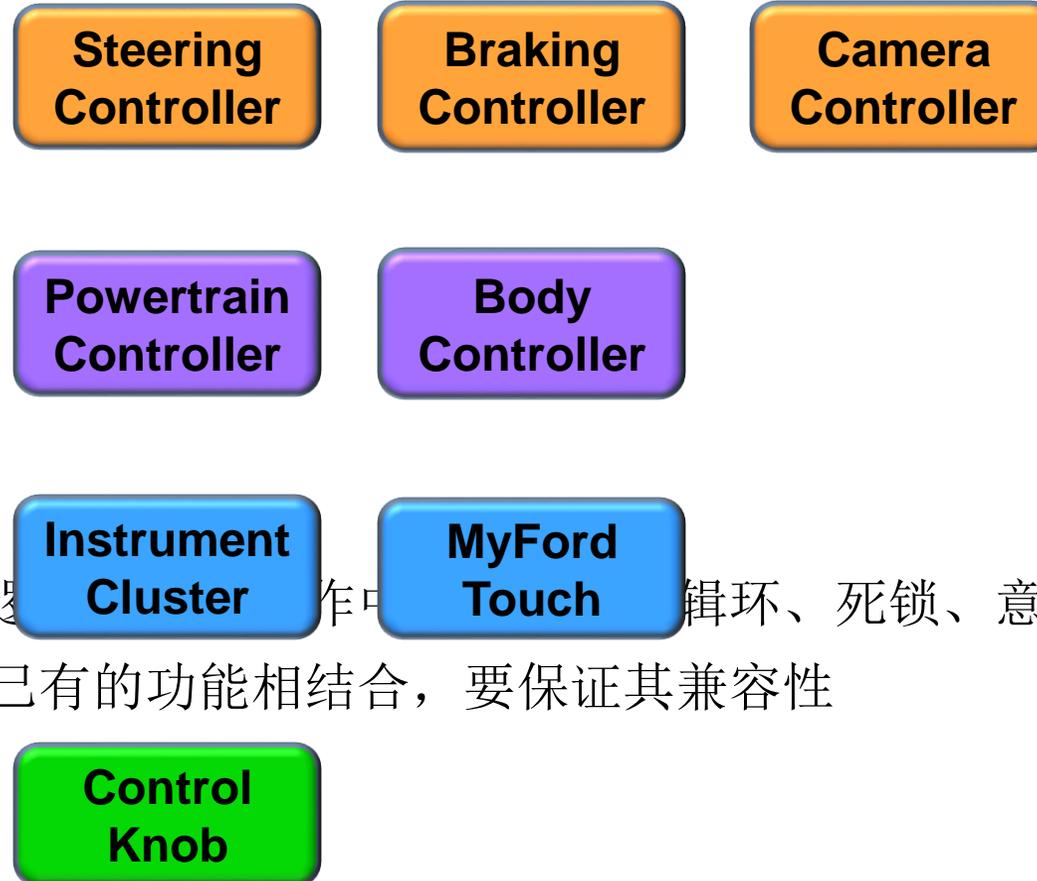
# TBA 系统开发面临的挑战

- 没有一个独立的TBA控制模块
- 所需的功能分散在由4路CAN总线连接的8个控制器当中



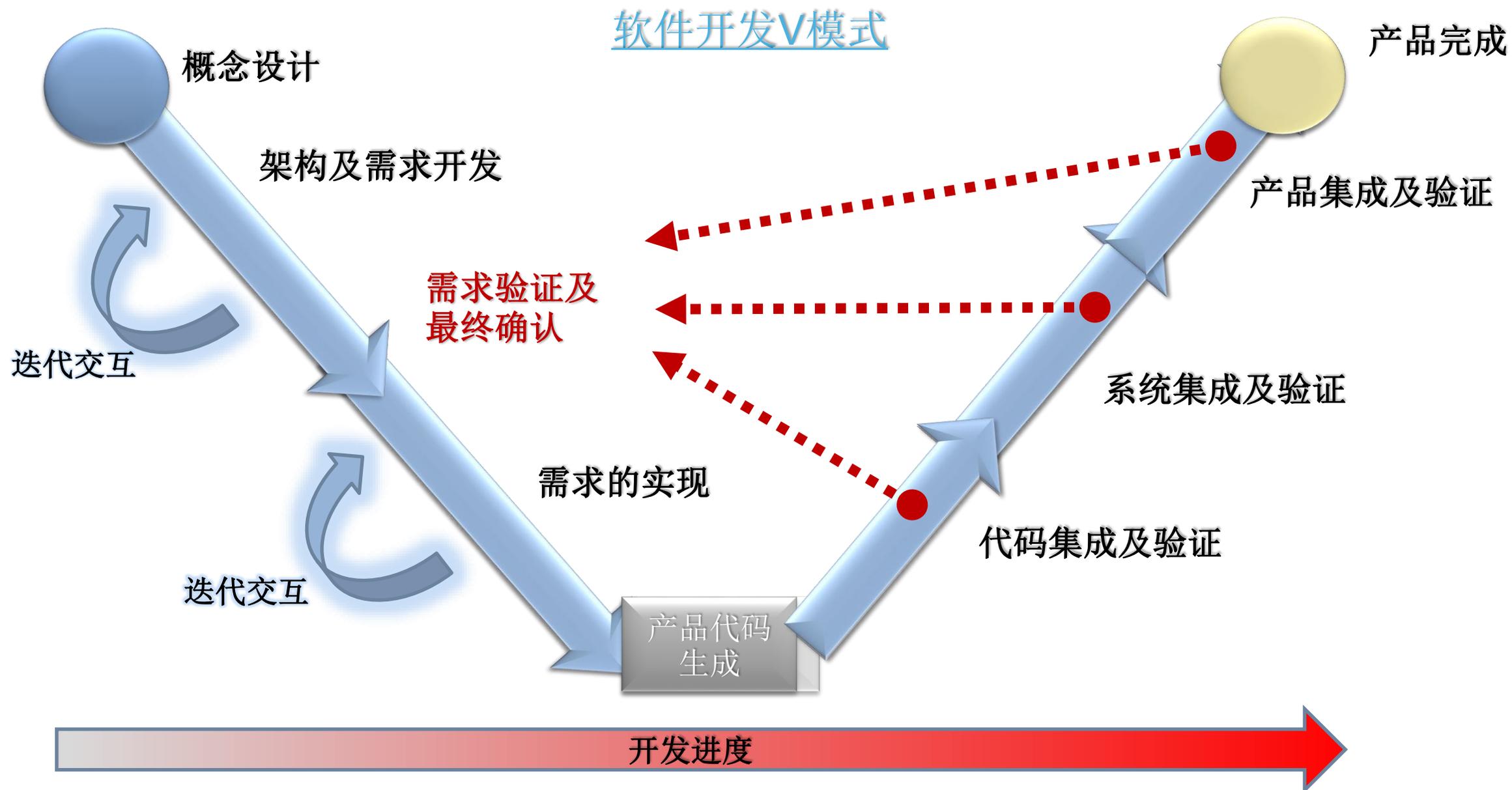
# TBA 系统开发面临的挑战

- 控制逻辑的设计要充分考虑到
  - ✓ 新功能的优化分配及共享
  - ✓ 对已有功能的充分利用
  - ✓ 尽量减少各模块间的通讯
  - ✓ 工程进度

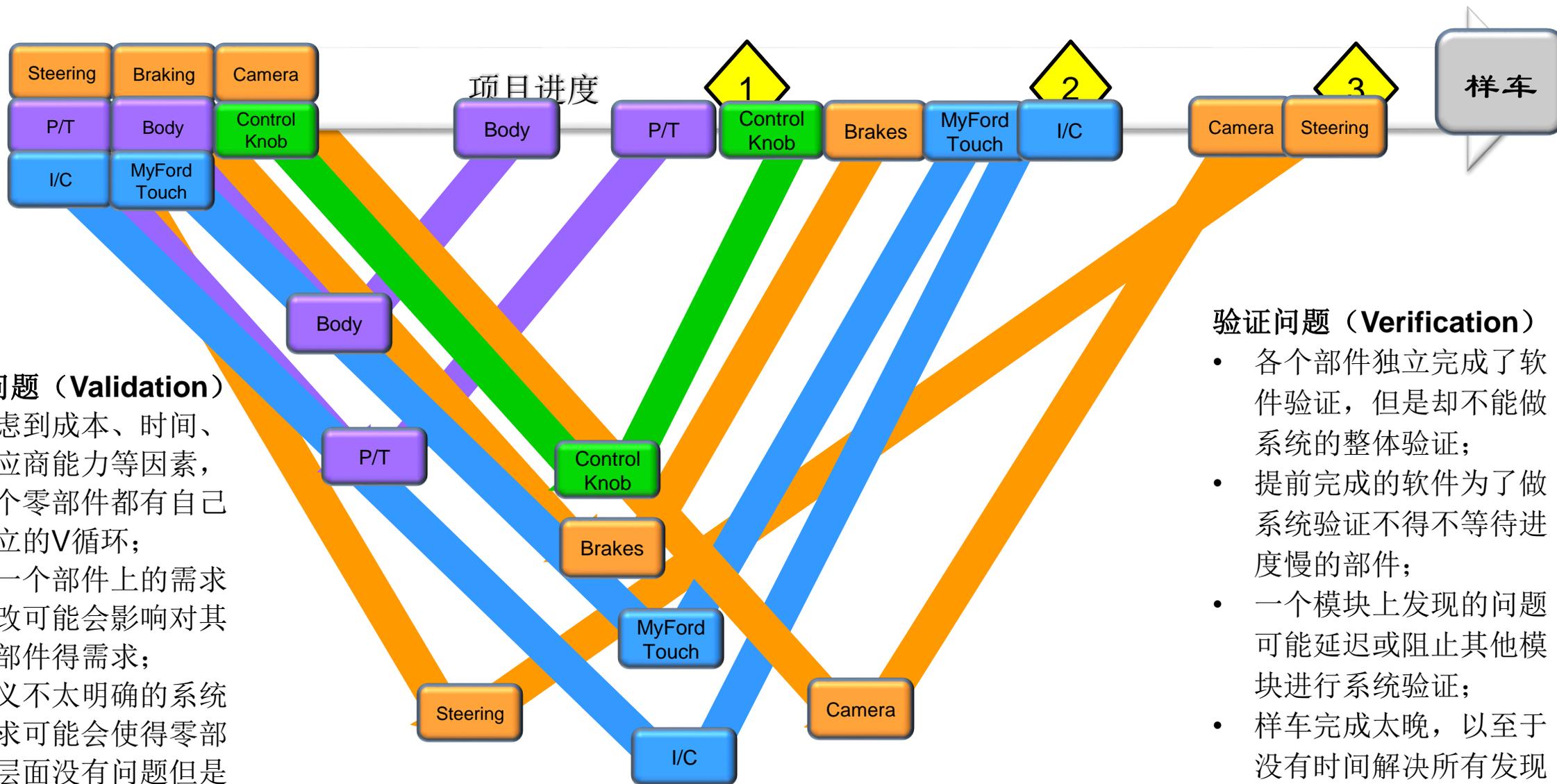


- 系统的每个模块必须满足逻辑环、死锁、意外退出等
- 新功能及其优先级必须与已有的功能相结合，要保证其兼容性

# TBA 系统开发面临的挑战



# TBA 系统开发面临的挑战



## 确认问题 (Validation)

- 考虑到成本、时间、供应商能力等因素，每个零部件都有自己独立的V循环；
- 在一个部件上的需求更改可能会影响对其他部件的需求；
- 定义不太明确的系统需求可能会使得零部件层面没有问题但是最终系统却无法工作

## 验证问题 (Verification)

- 各个部件独立完成了软件验证，但是却不能做系统的整体验证；
- 提前完成的软件为了做系统验证不得不等待进度慢的部件；
- 一个模块上发现的问题可能延迟或阻止其他模块进行系统验证；
- 样车完成太晚，以至于没有时间解决所有发现的问题

# 解决方案

## 1. 需求建模:

- 在交给下游进行软件实现之前，对需求进行建模、仿真从而保证分布式控制逻辑满足系统功能需求

## 2. 分布式网络仿真:

- 创建的仿真环境，连接各个控制器、CAN网络、司机控制输入、车辆交互信息等；
- 该仿真环境既可以运行MIL（虚拟）也可以运行实时的HIL（硬件），而且每个控制器都可以在MIL与HIL间方便切换；
- 根据系统工程师的需要，该仿真环境既可以测试整个系统，也可以单独测试在某个控制器上的功能。

## 3. 确认及验证工具:

- 创建的验证工具可以有效地应用于软件开发V流程:
  - ✓ 测试及确认需求模型 (V的左半边，由上而下)
  - ✓ 验证软件功能模块输出满足需求模型要求 (V的右半边，由下而上)

# 解决方案

## 1. 需求建模:

- 在交给下游进行软件实现之前，对需求进行建模、仿真从而保证分布式控制逻辑满足系统功能需求

## 2. 分布式网络仿真:

- 创建的仿真环境，连接各个控制器、CAN网络、司机控制输入、车辆交互信息等；
- 该仿真环境既可以运行MIL（虚拟）也可以运行实时的HIL（硬件），而且每个控制器都可以在MIL与HIL间方便切换；
- 根据系统工程师的需要，该仿真环境既可以测试整个系统，也可以单独测试在某个控制器上的功能。

## 3. 确认及验证工具:

- 创建的验证工具可以有效地应用于软件开发V流程:
  - ✓ 测试及确认需求模型 (V的左半边，由上而下)
  - ✓ 验证软件功能模块输出满足需求模型要求 (V的又半边，由下而上)

# 什么是需求建模？

2013-01-2237

## Requirements Modeling and Automated Requirements-Based Test Generation

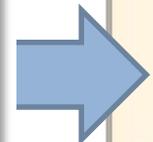
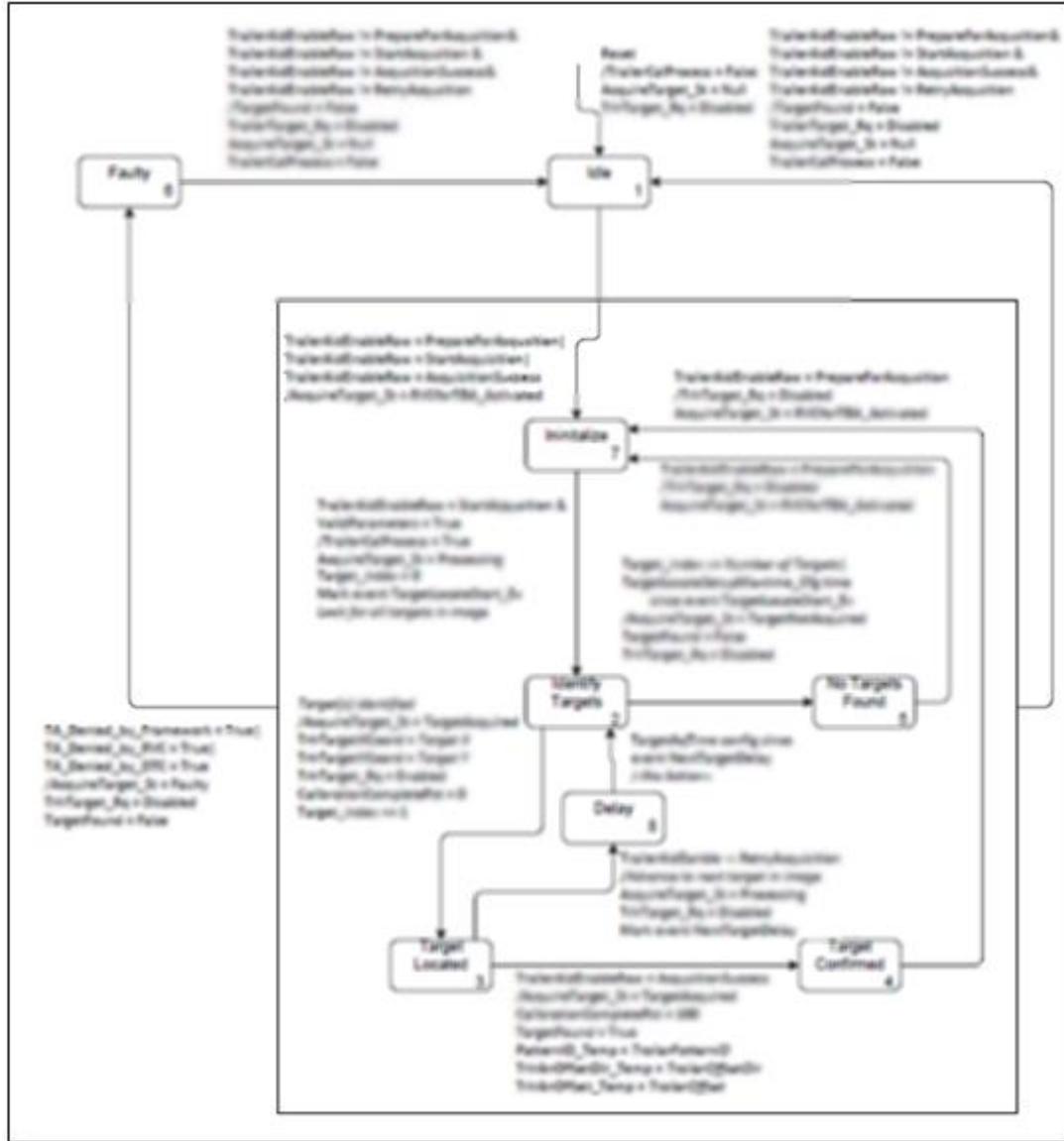
John Lee and Jon Friedman  
MathWorks

Copyright © 2014 SAE International

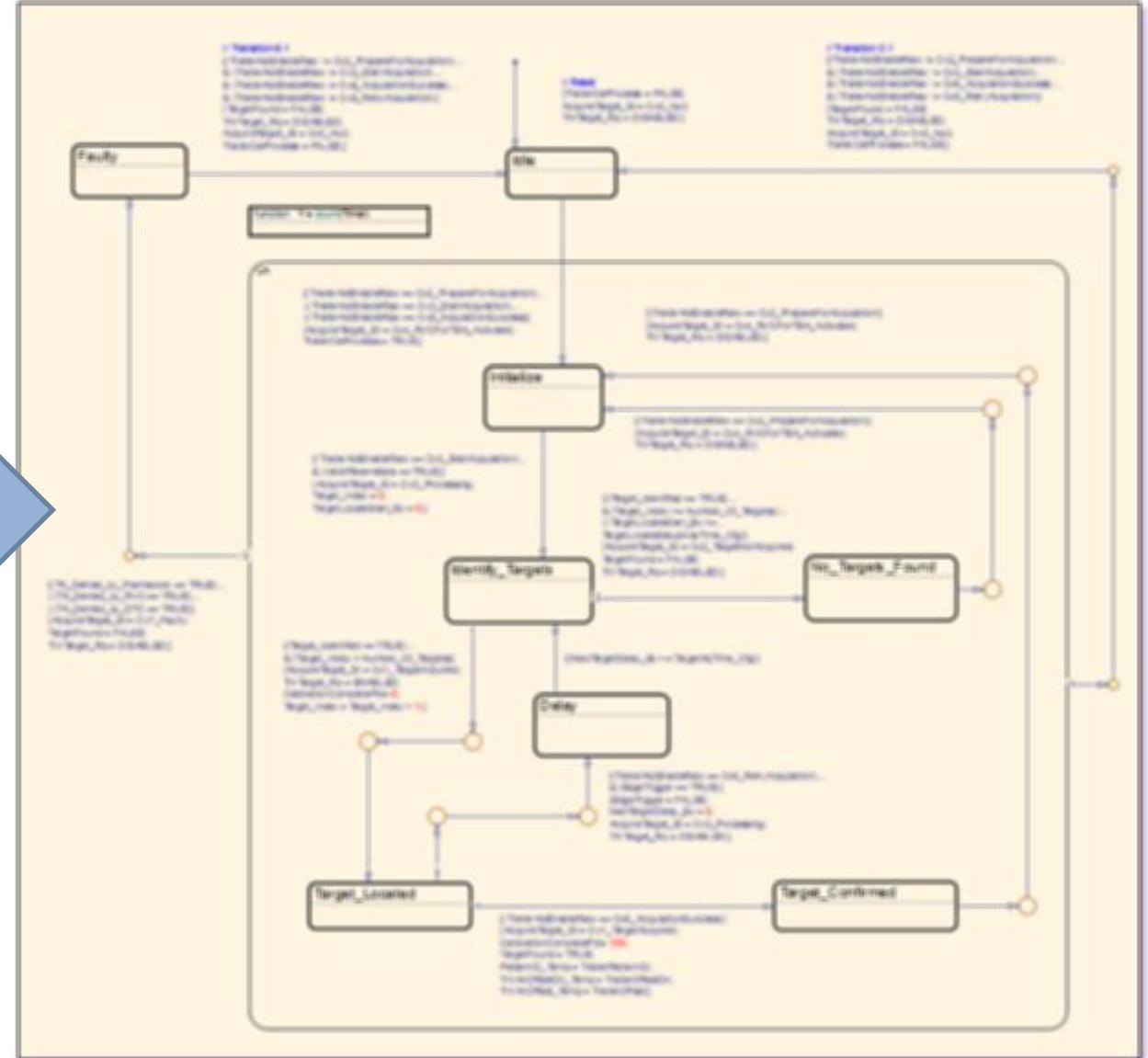
“...需求建模的目的是通过**清晰、精确、可分析并可执行**的方式获得功能性需求，而这个目的往往无法用**自然语言**来实现。  
需求模型可以用来评估多种来源获取的需求的交互性和兼容性，以及开发**测试用例及验收判据（或期望输出）**。  
用需求模型建立测试用例可以让工程师根据需求模型的各种覆盖度概念评估测试是否完善...”

# 需求建模

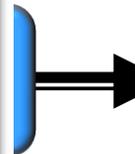
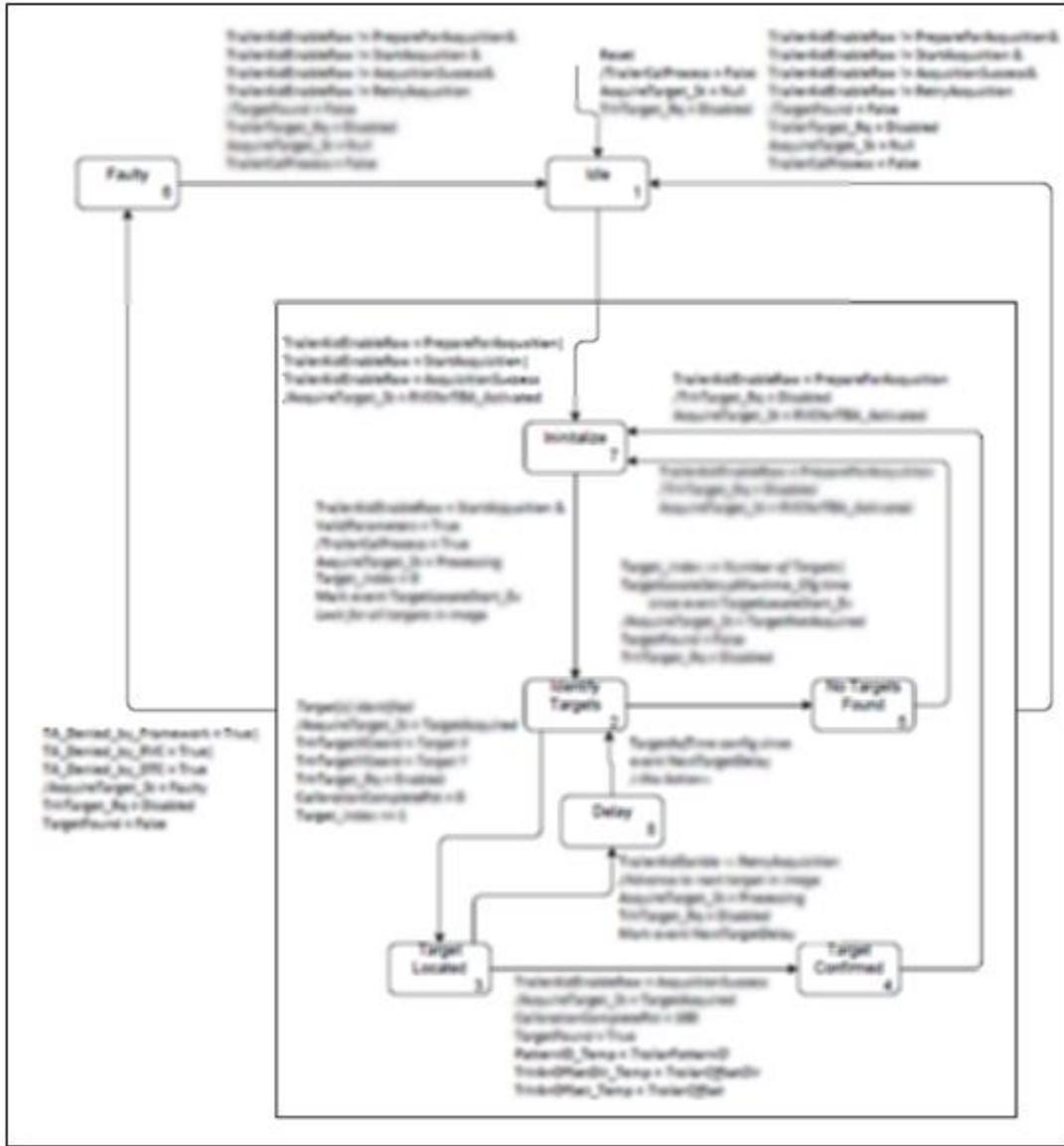
状态机需求文档:



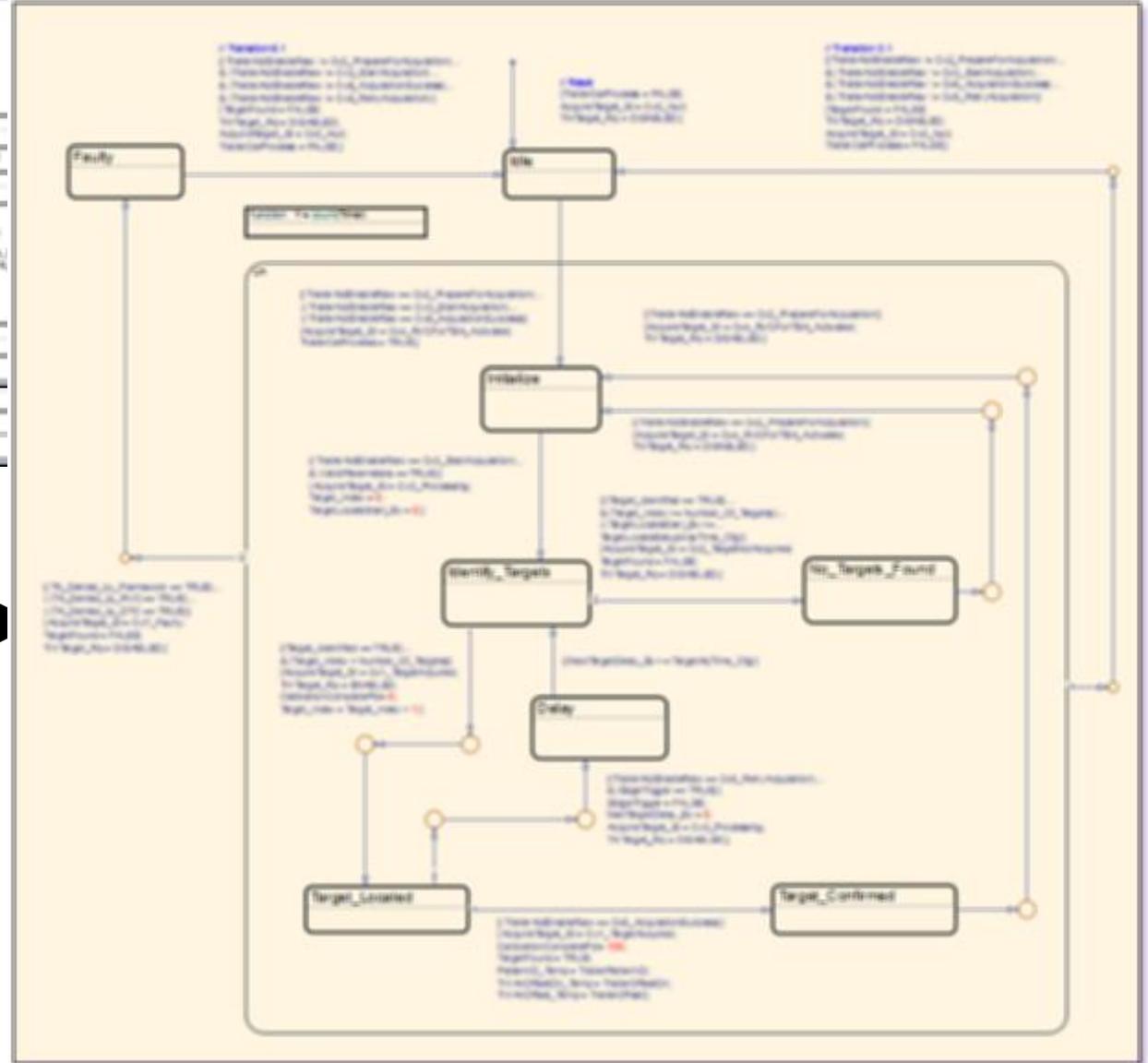
Stateflow 需求模型:



# 需求建模



#4



# 解决方案

## 1. 需求建模:

- 在交给下游进行软件实现之前，对需求进行建模、仿真从而保证分布式控制逻辑满足系统功能需求

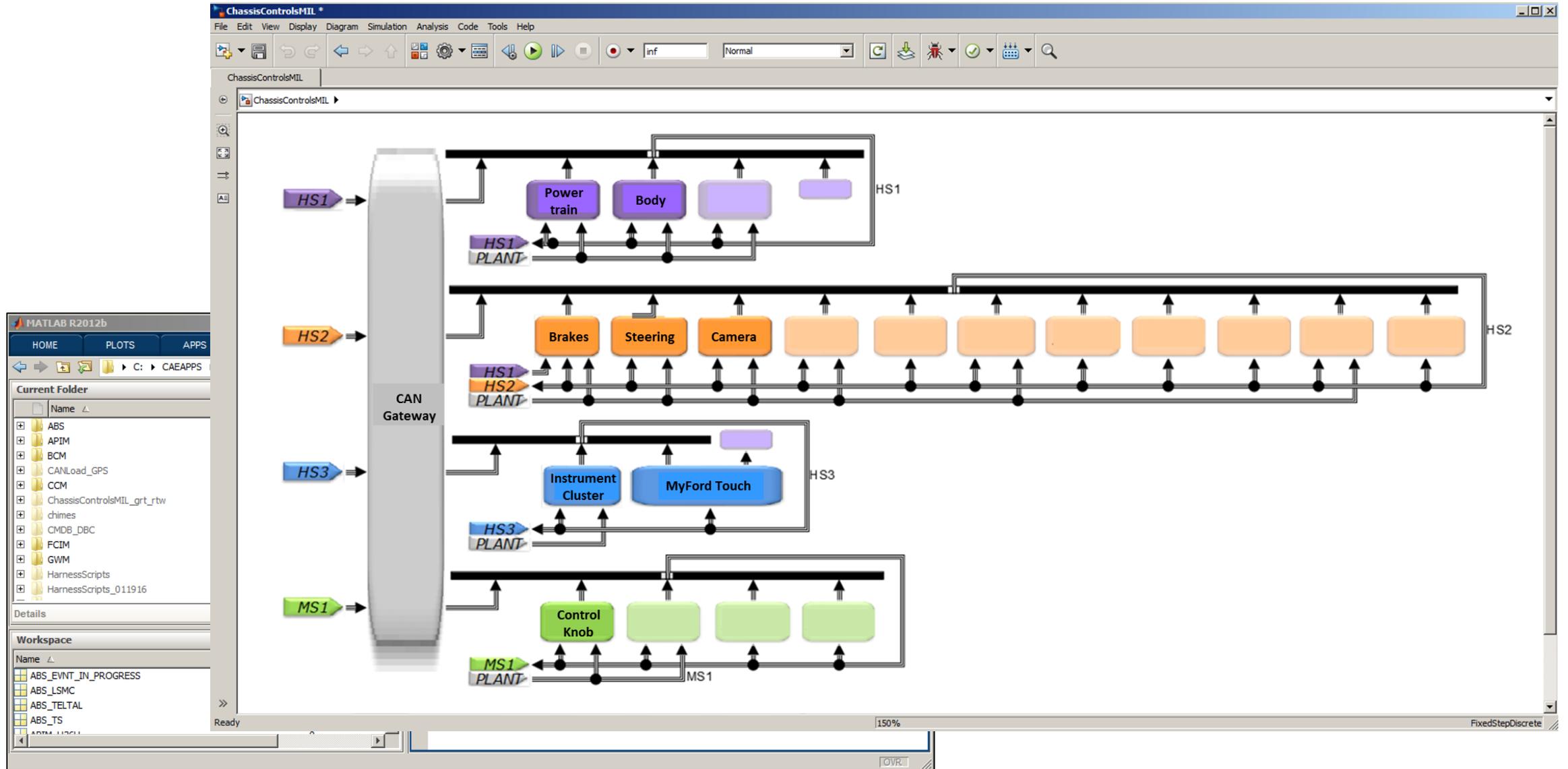
## 2. 分布式网络仿真:

- 创建的仿真环境，连接各个控制器、CAN网络、司机控制输入、车辆交互信息等；
- 该仿真环境既可以运行MIL（虚拟）也可以运行实时的HIL（硬件），而且每个控制器都可以在MIL与HIL间方便切换；
- 根据系统工程师的需要，该仿真环境既可以测试整个系统，也可以单独测试在某个控制器上的功能。

## 3. 确认及验证工具:

- 创建的验证工具可以有效地应用于软件开发V流程:
  - ✓ 测试及确认需求模型 (V的左半边，由上而下)
  - ✓ 验证软件功能模块输出满足需求模型要求 (V的右半边，由下而上)

# 分布式网络仿真



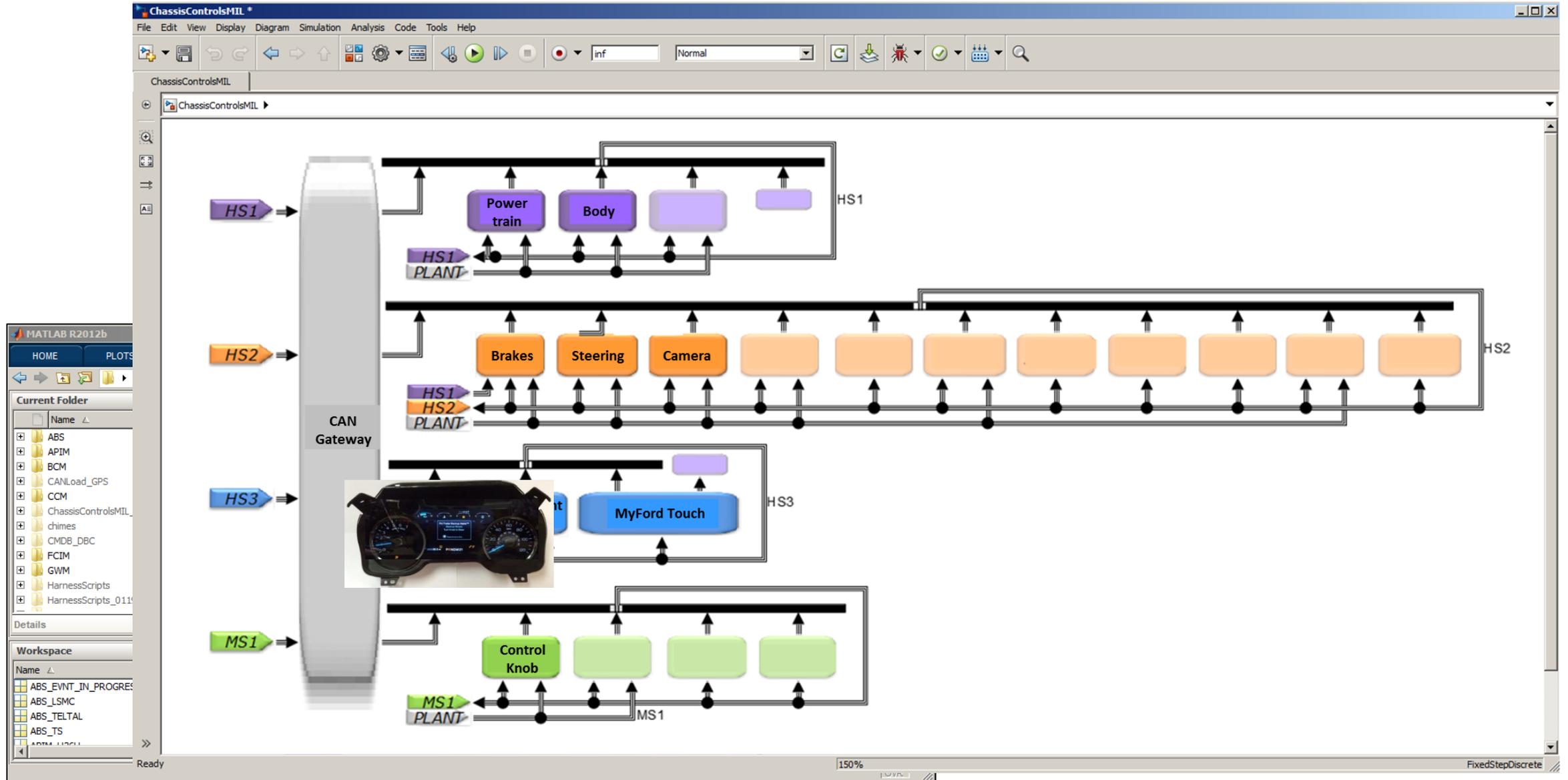
# 分布式网络仿真

The screenshot displays the ChassisControlsMIL GUI in MATLAB R2012b. The main window shows a vehicle model with a CAN bus network and various control systems. The GUI is divided into several sections:

- Simulation Controls:** Includes buttons for START, PAUSE, STOP, CAN BUS, and GPS. It also shows a speedometer reading of 705.2 and buttons for MEM CHECK, RESET MODEL, and Edit GUI.
- Vehicle State:** Displays gear selection (P, N, -0, 0, CLOSED) and other parameters like VehSpd, GearAt, GearMt, SvaComp, SvaOS, Swt, Esc, YawAng, YawRt, HitchAng, WhlDir, and RqSwa.
- Driver Controls:** Features a steering wheel input, brake and accelerator pedals, and buttons for Ignition Status, AT Gear, Turn Signal, and Door/Factory Reset.
- 5-Way Control:** A directional pad with an OK button.
- Trailer Backup Assist (TBA):** A button labeled TBA OFF.
- Trailer Type Connected:** A dropdown menu currently set to None.
- Vehicle Metrics:** Displays Vehicle Speed (0 kph), Vehicle Yaw Rate (0 deg/sec), Wheel Direction (Front: Unk, Rear: Unk), Vehicle Position (X: 1 m, Y: 0 m, Angle: 0 deg), and Steering Wheel Angle (0 deg, 0 Nm).

The MATLAB workspace on the left shows the current folder structure, including subfolders like ABS, APIM, BCM, CANLoad\_GPS, CCM, ChassisControlsMIL\_grt\_rtw, chimes, CMD8\_DBC, FCIM, GWM, HarnessScripts, and HarnessScripts\_011916.

# 帶有HIL的分布式网络仿真



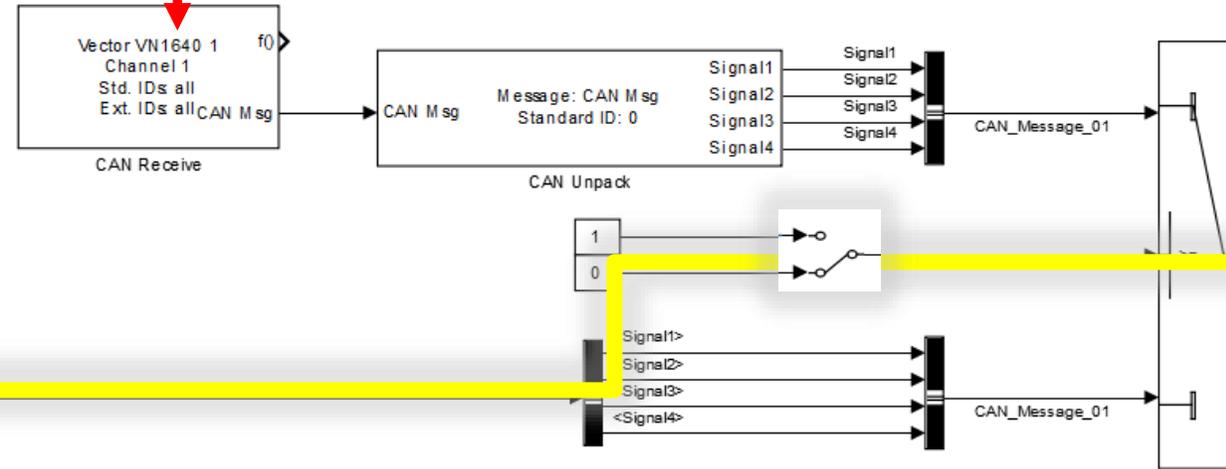
# 利用Vehicle Network Toolbox实现HIL切换

硬件



Vehicle Network Toolbox

**Instrument Cluster Requirement Model (MIL)**



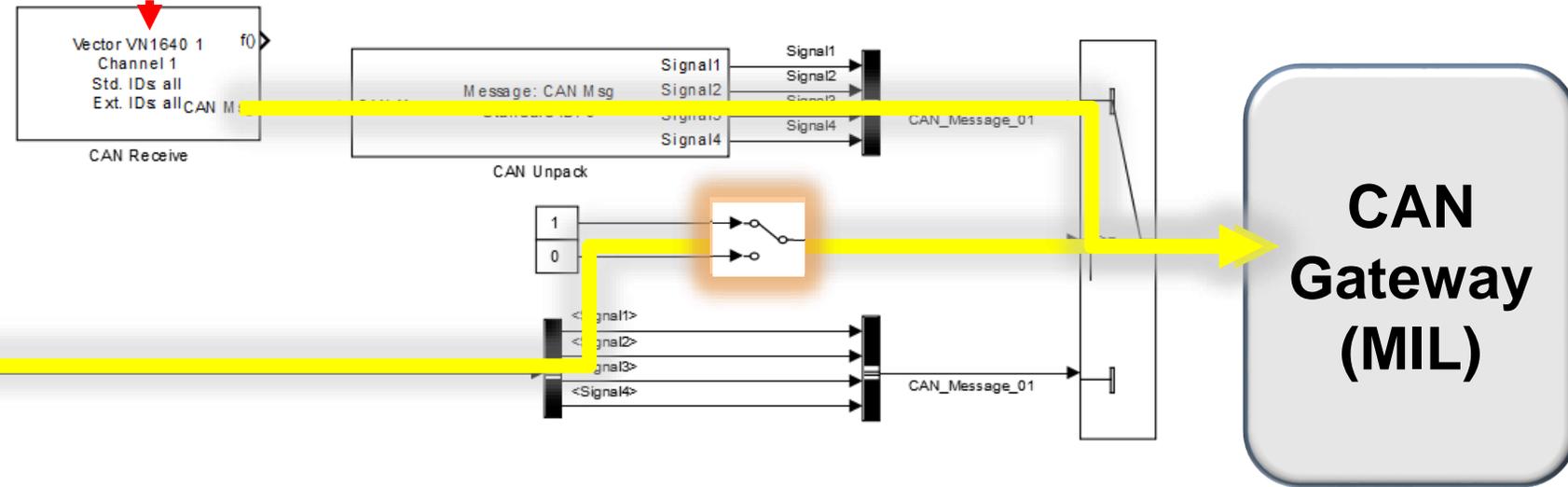
**CAN Gateway (MIL)**

# 利用Vehicle Network Toolbox实现HIL切换

硬件



Vehicle Network Toolbox



# 帶有 HIL 的分布式网络仿真

The screenshot displays the ChassisControlsMIL simulation environment. The main workspace shows a CAN Gateway connected to four hierarchical levels of control and plant models:

- HS1 (High-Speed 1):** Includes Power train, Body, and other vehicle-level components.
- HS2 (High-Speed 2):** Includes Brakes and chassis-level components.
- HS3 (High-Speed 3):** Includes a digital instrument cluster and a camera view.
- MS1 (Medium-Speed 1):** Includes a Control unit and a TRAILER BACK UP button.

On the left, the MATLAB R2012b interface shows the current folder structure and workspace. The bottom right features a simulator GUI with a menu (Display Mode, Trip/Fuel, Towing, Off Road, Settings), a gear selector (P, R, N, D, L, M), and a detailed vehicle status panel showing metrics like speed (0 kph), gear (0), and various control inputs.

# 帶有 HIL 的分布式网络仿真

The screenshot displays the ChassisControlsMIL simulation environment. The main workspace shows a CAN Gateway connected to several HIL (Hardware-in-the-Loop) units:

- HS1 (Power train):** A purple box representing the powertrain, connected to a physical electronic control unit (ECU).
- HS2 (PLANT):** An orange box representing the vehicle chassis/plant, connected to a physical steering rack assembly.
- HS3 (PLANT):** A blue box representing the driver's instrument cluster, connected to a physical dashboard.
- MS1 (PLANT):** A green box representing the trailer backup assist system, connected to a physical steering knob.

On the left, the MATLAB R201x interface shows the current folder structure and workspace variables. The bottom right corner features a detailed GUI for the Pro Trailer Backup Assist, displaying real-time vehicle data and control elements:

- Vehicle State:**

VehSpd	3.9	GearAct	R	GearMf	R	SwaComp	-522	SwaOS	0	Bld	0	CLOSED
YawsAng	53.8	YawRt	10.3	HitchAng	38.6	TC				BldDir	522	
- Driver Controls:** Includes a gear selector (P, R, N, D, L, M), a steering wheel input gauge, and a brake/accelerator pedal indicator.
- Trailer Backup Assist:** Shows a video feed of the trailer, a "Pro Trailer Backup Assist" warning, and a "Press Knob to Exit" instruction.

The bottom right corner also shows simulation controls (START, PAUSE, STOP, CAN BUS, GPS) and a parameter table for the simulation.

# 分布式网络仿真

The screenshot displays the ChassisControlsMIL simulation environment. The main window shows a CAN network diagram with a central CAN Gateway connected to four High-Speed (HS) plants (HS1, HS2, HS3, MS1) and a Micro-Switch (MS1) plant. The HS1 plant includes Power train and Body components. The HS2 plant includes Brakes and a series of six orange blocks. The HS3 plant includes Instrument Cluster and MyFord Touch components. The MS1 plant includes a TRAILER BACKUP button and three green blocks. A 3D model of a vehicle chassis is overlaid on the diagram.

On the left, the MATLAB R2013b workspace shows a file tree for the current folder, including files like ABS, APIM, BCM, CCM, and ChassisCon. The workspace also lists several MATLAB scripts related to ABS and ADAS.

At the bottom right, the ChassisControlsMIL\_GUI window displays a driver interface for a Pro Trailer Backup Assist system. The interface includes a 5-Way Control pad, a Trailer Backup Assist button (TBA ON), and a steering wheel with a knob. The central display shows the vehicle's status: "Pro Trailer Backup Assist", "Backup Slowly", "Turn Knob to Steer", and "Press Knob to Exit". The gear selector shows P, R, N, D, L, M. The speedometer shows 3 kph. The vehicle yaw rate is -5.3 deg/sec. The steering wheel angle is 408 deg. The driver controls section shows the steering wheel input, brake, and accelerator pedals, along with the speed limits and door ajar status.

# 解决方案

## 1. 需求建模:

- 在交给下游进行软件实现之前，对需求进行建模、仿真从而保证分布式控制逻辑满足系统功能需求

## 2. 分布式网络仿真:

- 创建的仿真环境，连接各个控制器、CAN网络、司机控制输入、车辆交互信息等；
- 该仿真环境既可以运行MIL（虚拟）也可以运行实时的HIL（硬件），而且每个控制器都可以在MIL与HIL间方便切换；
- 根据系统工程师的需要，该仿真环境既可以测试整个系统，也可以单独测试在某个控制器上的功能。

## 3. 确认及验证工具:

- 创建的验证工具可以有效地应用于软件开发V流程:
  - ✓ 测试及确认需求模型 (V的左半边，由上而下)
  - ✓ 验证软件功能模块输出满足需求模型要求 (V的又半边，由下而上)

# 确认与验证工具

- 大多数验证工具主要是完成单元级测试验证，很少采用司机在环（driver-in-the-loop）的方式来仿真验证整个系统；
- Simulink 信号生成工具只适合于模型简单、测试用例较少、输入输出数量较少的单元测试；
- 对于有上百个输入输出（而且要测哪一个预先不确定）的分布式逻辑控制模型，修改维护信号生成工具会非常繁杂；
- 测试复杂导致推广困难。



# 确认与验证工具

- 在MathWorks技术咨询帮助下重新设计验证工具
- 测试过程简化、人工干预减少、过程实现自动化，测试人员工作量大  
幅减少：
  - 选择被测信号、定义测试模式
  - 模拟实际工作环境，自动记录测试过程，并生成结构化的测试用例语言描述
  - 方便回放测试过程
  - 结果自动对比
- 整个解决方案得以顺利推广，而且正在应用到其他类似项目

# 确认与验证工具

## 步骤 1: 定义测试用例

A	B	C	D	E	F	G	H
InputLog Signal Name	Description	Signal Designation	Value (discrete / continuous)	Unit	Report Output	Quantize	
throttle	Throttle input	1	cont	%	Change throttle to <value>	0	
brake	Brake input	2	cont	%	Change brake <value>	10	
nomatchinput	test	3	cont	%	blah		

Annotations:

- InputLog Signal Name - Input or playback signal names. This name must match that of the signal names in the InputLog block mask.
- Description - This is a user information field, and is not used.
- Signal Designation - Numerical indicator for each signal. IMPORTANT - each signal must have a unique signal designation (numerical value). For discrete signals, the same designation is to be used for different states.
- Value - specify value type to be either discrete or continuous. For discrete, please use numerical value for each state, and for continuous, please use "cont".
- Unit - Signal unit. This is also a user information field.
- Report Output - This is the description that will be placed in the playback Excel file. Use of <value> is for continuous signals only, and the tool will insert the actual recorded value.
- Quantize - This field tells the tool to band to out continuous signals. The value gives threshold or trigger for the playback Excel file. This field should be empty for discrete signals.

## 一个简单的TBA测试用例

1. 司机启动TBA功能 (按控制按钮)
2. 司机几秒钟后开始倒车 (挂倒挡, 踩加速踏板)
3. 司机停车 (踩刹车踏板)
4. 司机关闭TBA功能 (按控制按钮)

Signal Designation	Value (discrete / continuous)	Unit	Report Output	Quantize	Observer
	0		Shift to Park		1
	1		Shift to First Gear		1
	2		Shift to Second Gear		1
	3		Shift to Third Gear		1
	4		Shift to Fourth Gear		1
	cont		test <value>	20	0
	cont		speed is <value> mph	10	0

Annotations:

- Value - specify value type to be either discrete or continuous. For discrete, please use numerical value for each state, and for continuous, please use "cont".
- Unit - Signal unit. This is also a user information field.
- Report Output - This is the description that will be placed in the playback Excel file. Use of <value> is for continuous signals only, and the tool will insert the actual recorded value.
- Quantize - This field tells the tool to band to out continuous signals. The value gives threshold or trigger for the playback Excel file.

# 确认与验证工具

## 步骤2: 自动生成测试框架

The screenshot displays the **harnessGUI** interface for configuring a test harness. The **harnessGUI** window includes sections for:

- Harness Configuration:** Selecting a configuration file (e.g., `configurationFile.xlsx`).
- Harness and Logging:** A red box highlights the **Create harness** button. Other options include LogFile, Logging On/Off, and the current log file (`LogFile1`).
- Logging File Conversion:** Options for selecting, loading, generating playback, and output files, with a checkbox for **Convert first**.
- Replay:** Controls for selecting, loading, resetting, and starting/stopping a replay, along with a status display.

The main workspace shows a **ChassisControlsMIL** diagram with four hardware simulation (HS) and model simulation (MS) plants:

- HS1 PLANT:** Connected to **Power train** and **Body** components.
- HS2 PLANT:** Connected to **Brakes**, **Steering**, and **Camera** components.
- HS3 PLANT:** Connected to **Instrument Cluster** and **MyFord Touch** components.
- MS1 PLANT:** Connected to **Control Knob** components.

A **Test Harness** dialog box is overlaid, showing **Step 3: Generating playback subsystem** with a progress bar. The Ford logo and **Global Chassis Engineering Test Case Tool** are visible in the bottom right corner.

# 确认与验证工具

## 步骤3: 仿真并记录测试用例

The screenshot displays the MATLAB/Simulink environment for the ChassisControlsMIL simulation. The main workspace shows a vehicle model with a powertrain and body, connected to a network labeled HS1. Several windows are open:

- harnessGUI:** Shows configuration options for the harness, including file selection and logging settings.
- simulator\_gui:** A driver interface with a menu (Trip/Fuel, Towing, Off Road, Settings), a gear selector (P, R, N, D, L, M), and various vehicle status indicators.
- ChassisControlsMIL\_GUI:** Contains simulation controls (START, PAUSE, STOP, CAN BUS, GPS), vehicle state (0 P N 0 0 0 CLOSED), and driver controls (Steering Wheel Input, Brake, Accel, etc.).

The MATLAB R2012b interface on the left shows the current folder and workspace with files related to the simulation.

# 确认与验证工具

## 步骤4: 生成测试用例回放文件 (Excel)

**自动生成测试用例回放文件**

Time	Driver Input
0	
2.82	TBA Button Pressed
3.14	TBA Button Not Pressed
4.26	Down Pressed
4.5	Down Not Pressed
5.54	Up Pressed
5.78	Up Not Pressed
6.86	Ok Pressed
7.06	Ok Not Pressed
16.94	Shift gear to Reverse
19.78	Accel pedal 25 %
22.34	Brake Pedal 25 %
22.76	Brake Pedal 50 %
23.16	Brake Pedal 75 %
24.12	Brake Pedal 50 %
24.46	Brake Pedal 25 %
24.82	Brake Pedal 0 %
26.64	TBA Button Pressed
26.9	TBA Button Not Pressed
30.1	Ok Pressed
30.42	Ok Not Pressed
38.86	Shift gear to Park

**测试用例报告**

Time	Driver Input	HMI Request	HMI Status	Camera Status	Setup Status	Steering Angle	Vehicle Speed
0		1 HMI	Inactive	Null	Inactive	0 deg	0 kph
2.82	TBA Button Pressed	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
3.14	TBA Button Not Pressed	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
3.26		2 HMI	Inactive	Null	Inactive	0 deg	0 kph
4.26	Down Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
4.5	Down Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
5.54	Up Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
5.78	Up Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
6.86	Ok Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
7.06	Ok Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
7.24		2 HMI	ActivateTba	Null	Inactive	0 deg	0 kph
7.32		2 HMI	ActivateTba	TbaActive	Inactive	0 deg	0 kph
7.46		2 HMI	DeactivateTba	TbaActive	Inactive	0 deg	0 kph
7.58		4 HMI	DeactivateTba	TbaActive	Inactive	0 deg	0 kph
7.84		4 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
15.46		14 HMI	Inactive	Inactive	Inactive	0 deg	0 kph
16.94	Shift gear to Reverse	14 HMI	Inactive	Inactive	Inactive	0 deg	0 kph
17.5		5 HMI	Inactive	Inactive	Inactive	0 deg	0 kph
18.78	Accel pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
19.14	Accel pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.004036 kph
19.66	Accel pedal 75 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	1.1564 kph
20.98	Accel pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	6.101 kph
21.3	Accel pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.9395 kph
21.72	Accel pedal 0 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.7276 kph
22.34	Brake Pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.4148 kph
22.76	Brake Pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	3.9163 kph
23.16	Brake Pedal 75 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.98992 kph
24.12	Brake Pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
24.46	Brake Pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
24.82	Brake Pedal 0 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
26.64	TBA Button Pressed	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
26.9	TBA Button Not Pressed	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
27.02		13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
30.1	Ok Pressed	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
30.42	Ok Not Pressed	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
32.04		1 HMI	Inactive	Null	Inactive	0 deg	0 kph
38.86	Shift gear to Park	1 HMI	Inactive	Null	Inactive	0 deg	0 kph

# 确认与验证工具

## 步骤5: 测试用例的回放及记录

The screenshot displays the ChassisControlsMIL software interface, which is used for simulation and testing of vehicle control systems. The interface is divided into several main sections:

- Simulation Controls:** Located on the right, it includes buttons for START, PAUSE, STOP, CAN BUS, and GPS. It also shows a speedometer reading of 587.6 and various simulation parameters like SIM Parameters, Helper, Edit Variants, Set Variants, and Edit GPS.
- Vehicle State:** This section displays the current gear (P), engine status (Run), and other vehicle metrics such as Vehicle Speed (0 kph), Vehicle Yaw Rate, Wheel Direction, and Vehicle Position (X: 173 m, Y: 0 m).
- Driver Controls:** This section provides a virtual driver's perspective, including Steering Wheel Input (HWT Nm), Brake, Accel, Speed Limits, AT Gear, Ignition Status, and Turn Signal.
- Harness Configuration:** Located in the center-left, it allows users to select configuration files (mappingFile.xlsx), create harnesses, and manage logging (TestCase8, Logging On/Off).
- Replay:** This section is used for replaying test cases, showing replay info (file/sample time) and replay status.
- 5-Way Control:** A central control panel with directional buttons and a central OK button, used for manual control during simulation.
- Trailer Backup Assist (TBA):** A section for managing trailer backup assist, showing TBA OFF and Trailer Type Connected (None).

At the bottom of the interface, there is a diagram showing a control signal path from a 'Knob' to 'MS1 PLANT' and back to 'MS1'. The status bar at the bottom indicates 'Ready', '150%', and 'FixedStepDiscrete'.

# 确认与验证工具

## 步骤6: 测试结果自动比较 (最初测试结果与回放结果)

The image displays two side-by-side Excel spreadsheets comparing test results. The left spreadsheet is titled 'TestCaseOutput7.xls [Compatibility Mode] - Excel' and the right is 'TestCase7\_new.xls [Compatibility Mode] - Excel'. Both spreadsheets show a table with columns: Time, Driver Input, HMI Request, HMI Status, Camera Status, Setup Status, Steering Angle, and Vehicle Speed. The data rows are identical, showing a sequence of events like button presses and gear shifts with corresponding HMI and vehicle status changes.

Time	Driver Input	HMI Request	HMI Status	Camera Status	Setup Status	Steering Angle	Vehicle Speed
0		1 HMI	Inactive	Null	Inactive	0 deg	0 kph
2.82	TBA Button Pressed	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
3.14	TBA Button Not Pressed	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
3.26		2 HMI	Inactive	Null	Inactive	0 deg	0 kph
4.26	Down Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
4.5	Down Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
5.54	Up Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
5.78	Up Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
6.86	Ok Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
7.06	Ok Not Pressed	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
7.24		2 HMI	ActivateTba	Null	Inactive	0 deg	0 kph
7.32		2 HMI	ActivateTba	TbaActive	Inactive	0 deg	0 kph
7.46		2 HMI	DeactivateTba	TbaActive	Inactive	0 deg	0 kph
7.58		4 HMI	DeactivateTba	TbaActive	Inactive	0 deg	0 kph
7.84		4 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
15.46		14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
16.94	Shift gear to Reverse	14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
17.5		5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
18.78	Accel pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
19.14	Accel pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.004036 kph
19.66	Accel pedal 75 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	1.1564 kph
20.98	Accel pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	6.101 kph
25	Accel pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.9395 kph
21.72	Accel pedal 0 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.7276 kph
22.34	Brake Pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.4148 kph
22.76	Brake Pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	3.9163 kph
23.16	Brake Pedal 75 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.98992 kph
24.12	Brake Pedal 50 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
24.46	Brake Pedal 25 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
24.82	Brake Pedal 0 %	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
26.64	TBA Button Pressed	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
26.9	TBA Button Not Pressed	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
27.02		13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
30.1	Ok Pressed	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
30.42	Ok Not Pressed	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
32.04		1 HMI	Inactive	Null	Inactive	0 deg	0 kph
38.86	Shift gear to Park	1 HMI	Inactive	Null	Inactive	0 deg	0 kph

# 确认与验证工具

## 步骤6: 测试结果自动比较 (最初测试结果与回放结果)

Time	Value	Component	State	Value	Component	State	Value	Component	State	Value	Component	State	Value	Component	State	Value	Component	State			
4	2.8200000	TBA Button	11	1	1 HMI	Inactive	Null	Inactive	0 deg	0 kph	4	5.1000000	TBA Button	11	1	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
5	3.1400000	TBA Button	11	0	1 HMI	Inactive	Null	Inactive	0 deg	0 kph	5	5.4200000	TBA Button	11	0	1 HMI	Inactive	Null	Inactive	0 deg	0 kph
6	3.2600000				2 HMI	Inactive	Null	Inactive	0 deg	0 kph	6	5.5400000				2 HMI	Inactive	Null	Inactive	0 deg	0 kph
7	4.2600000	Down Pres	7	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	7	6.5400000	Down Pres	7	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
8	4.5	Down Not	7	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	8	6.7800000	Down Not	7	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
9	5.5400000	Up Pressed	6	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	9	7.8200000	Up Pressed	6	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
10	5.7800000	Up Not Pre	6	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	10	8.0600000	Up Not Pre	6	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
11	6.8600000	Ok Pressed	10	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	11	9.1399999	Ok Pressed	10	1	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
12	7.0600000	Ok Not Pre	10	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph	12	9.3400000	Ok Not Pre	10	0	2 HMI	Inactive	Null	Inactive	0 deg	0 kph
13	7.2400000				2 HMI	ActivateTb	Null	Inactive	0 deg	0 kph	13	9.7200000				2 HMI	ActivateTb	Null	Inactive	0 deg	0 kph
14	7.3200000				2 HMI	ActivateTb	TbaActive	Inactive	0 deg	0 kph	14	9.8000000				2 HMI	ActivateTb	TbaActive	Inactive	0 deg	0 kph
15	7.4600000				2 HMI	Deactivate	TbaActive	Inactive	0 deg	0 kph	15	9.9400000				2 HMI	Deactivate	TbaActive	Inactive	0 deg	0 kph
16	7.5800000				4 HMI	Deactivate	TbaActive	Inactive	0 deg	0 kph	16	10.0600000				4 HMI	Deactivate	TbaActive	Inactive	0 deg	0 kph
17	7.8400000				4 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	17	10.3200000				4 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
18	15.4600000				14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	18	17.9400000				14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
19	16.9400000	Shift gear t	4	1	14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	19	19.2200000	Shift gear t	4	1	14 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
20	17.5				5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	20	19.7800000				5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
21	18.7800000	Accel pedal	3	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	21	21.0600000	Accel pedal	3	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
22	19.1400000	Accel pedal	3	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.004036 k	22	21.4200000	Accel pedal	3	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.004036 k
23	19.6600000	Accel pedal	3	75	5 HMI	Inactive	TbaActive	Inactive	0 deg	1.1564 kph	23	21.9400000	Accel pedal	3	75	5 HMI	Inactive	TbaActive	Inactive	0 deg	1.1564 kph
24	20.9800000	Accel pedal	3	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	6.101 kph	24	23.2599999	Accel pedal	3	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	6.101 kph
25	21.3000000	Accel pedal	3	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.9395 kph	25	23.5800000	Accel pedal	3	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.9395 kph
26	21.7200000	Accel pedal	3	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.7276 kph	26	24	Accel pedal	3	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.7276 kph
27	22.3400000	Brake Peda	2	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.4148 kph	27	24.6200000	Brake Peda	2	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	5.4148 kph
28	22.7600000	Brake Peda	2	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	3.9163 kph	28	25.0400000	Brake Peda	2	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	3.9163 kph
29	23.1600000	Brake Peda	2	75	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.98992 kp	29	25.4400000	Brake Peda	2	75	5 HMI	Inactive	TbaActive	Inactive	0 deg	0.98992 kp
30	24.1200000	Brake Peda	2	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	30	26.4000000	Brake Peda	2	50	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
31	24.4600000	Brake Peda	2	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	31	26.7400000	Brake Peda	2	25	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
32	24.8200000	Brake Peda	2	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	32	27.1000000	Brake Peda	2	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
33	26.6400000	TBA Button	11	1	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	33	28.9200000	TBA Button	11	1	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
34	26.9000000	TBA Button	11	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	34	29.1800000	TBA Button	11	0	5 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
35	27.0200000				13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	35	29.3000000				13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
36	30.1000000	Ok Pressed	10	1	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	36	32.3799999	Ok Pressed	10	1	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
37	30.4200000	Ok Not Pre	10	0	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph	37	32.7000000	Ok Not Pre	10	0	13 HMI	Inactive	TbaActive	Inactive	0 deg	0 kph
38	32.0400000				1 HMI	Inactive	Null	Inactive	0 deg	0 kph	38	34.3200000				1 HMI	Inactive	Null	Inactive	0 deg	0 kph
39	38.8600000	Shift gear t	4	0	1 HMI	Inactive	Null	Inactive	0 deg	0 kph	39	41.1399999	Shift gear t	4	0	1 HMI	Inactive	Null	Inactive	0 deg	0 kph

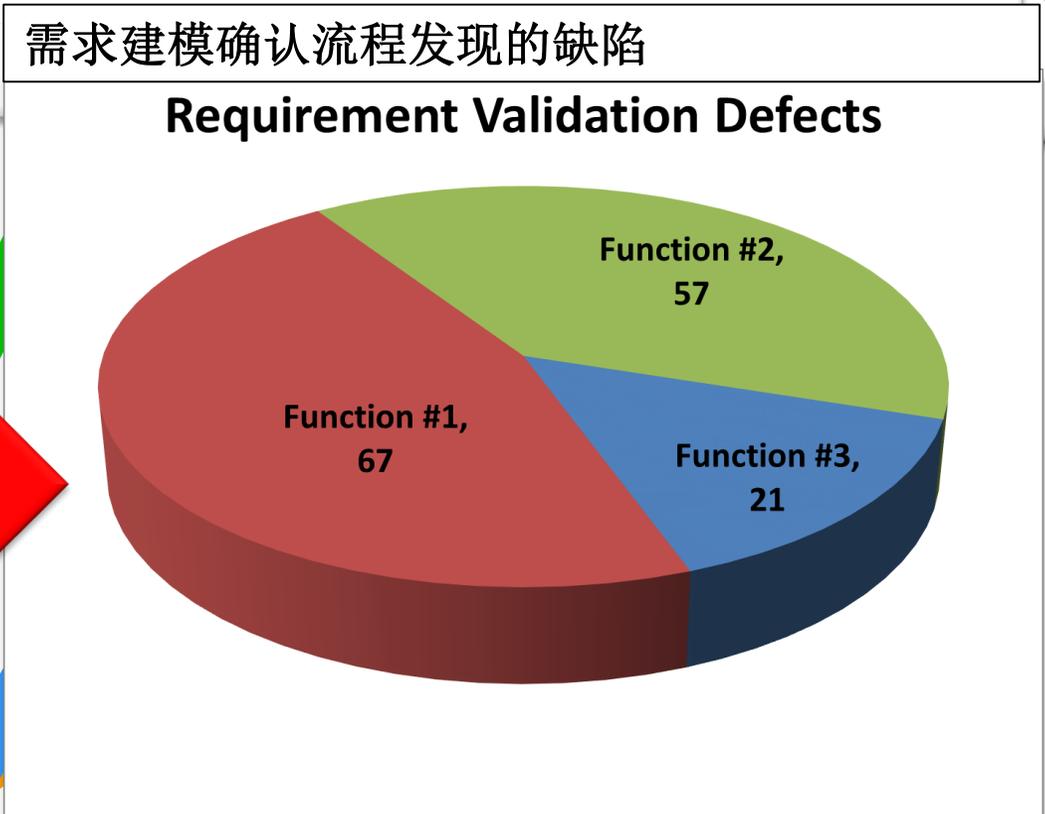
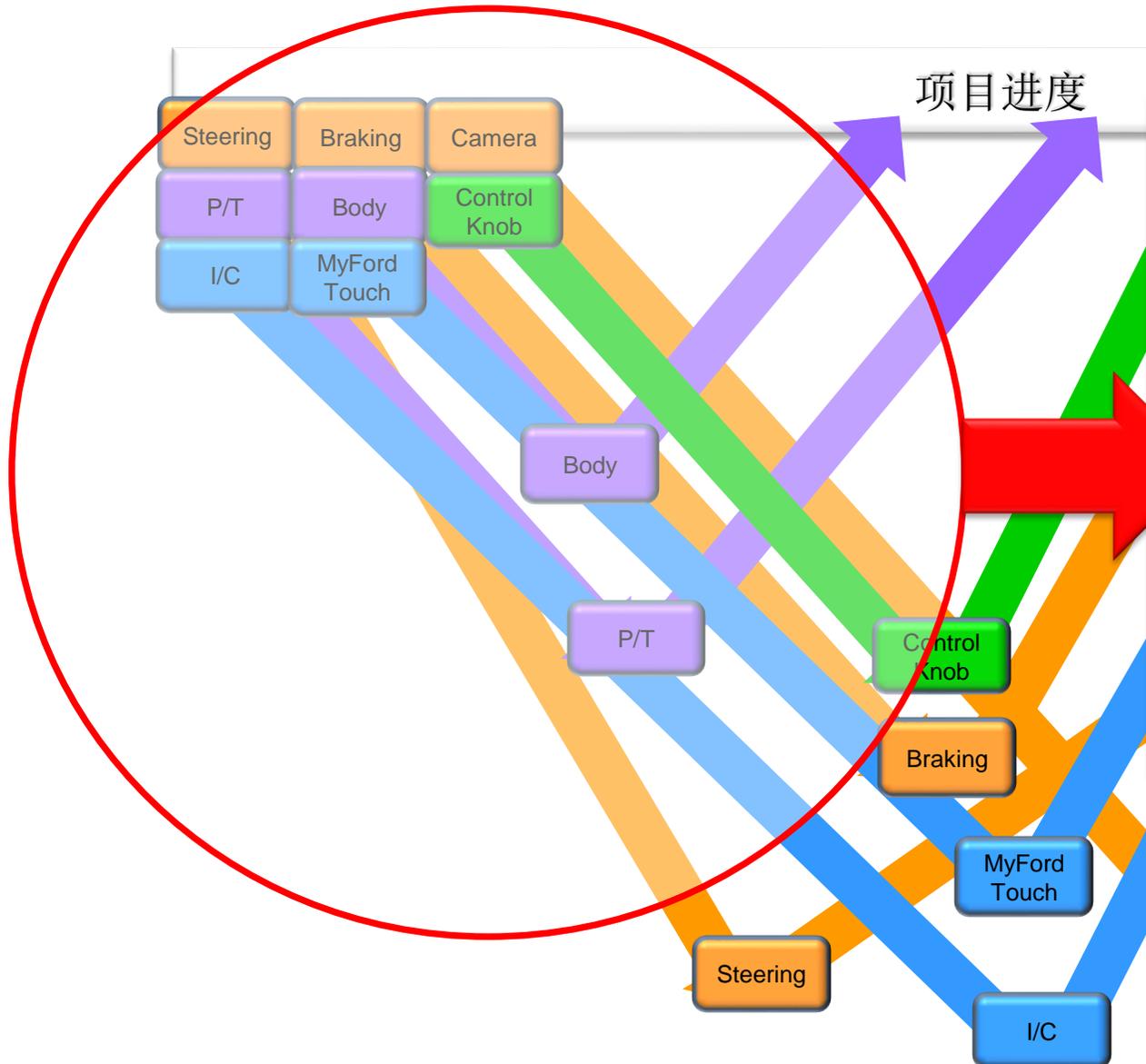
- ABS\_EVT\_IN\_I
- ABS\_LSMC
- ABS\_TELTAL
- ABS\_TS
- ARM\_H2CU

Ready

150%

FixedStepDiscrete

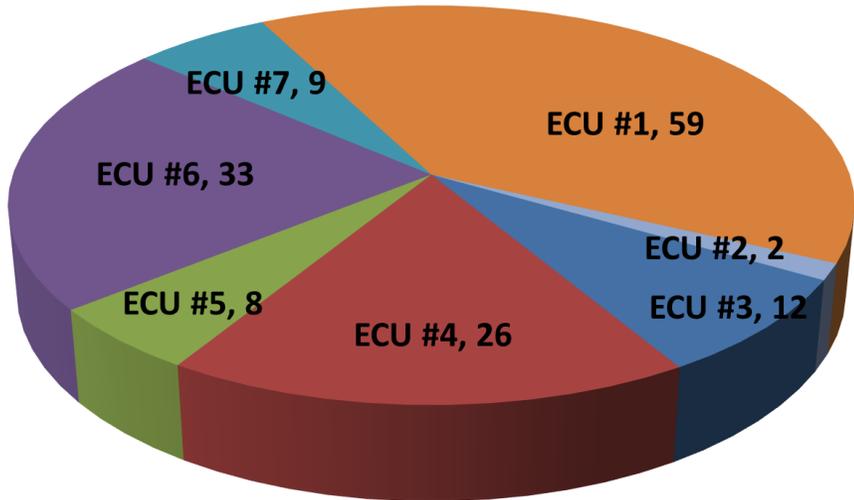
# 确认结果



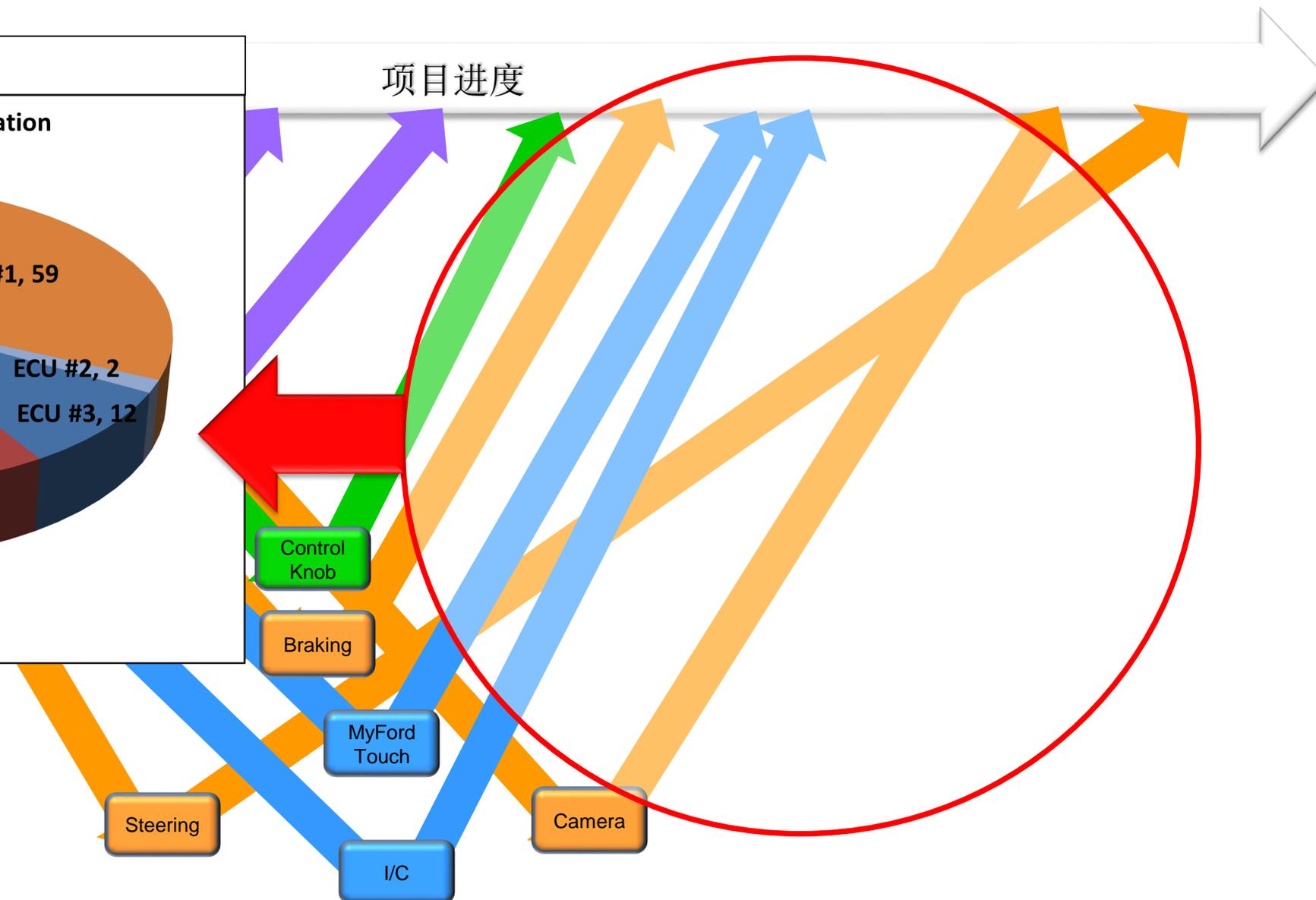
# 验证结果

需求建模验证流程发现的缺陷

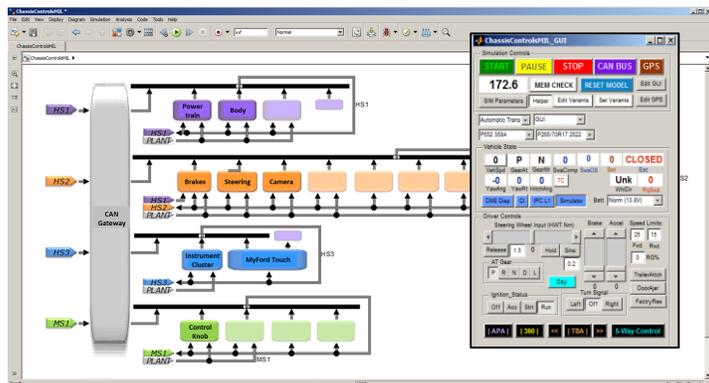
Requirement Modeling Verification



项目进度



# 解决方案

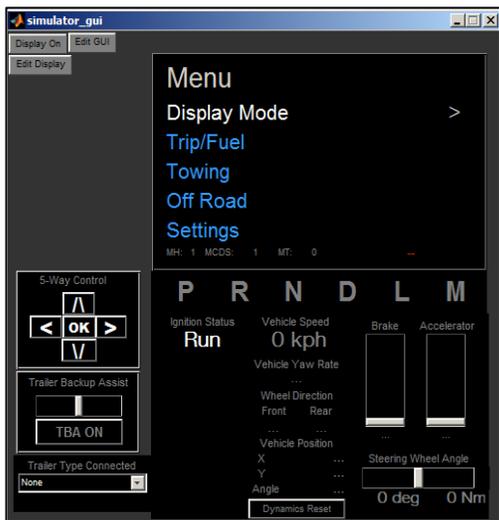


集成仿真环境：  
用需求模型测试所有功能需求

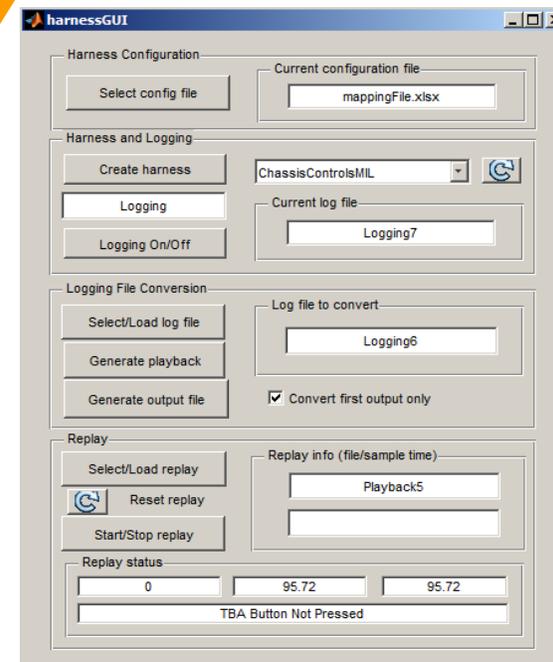
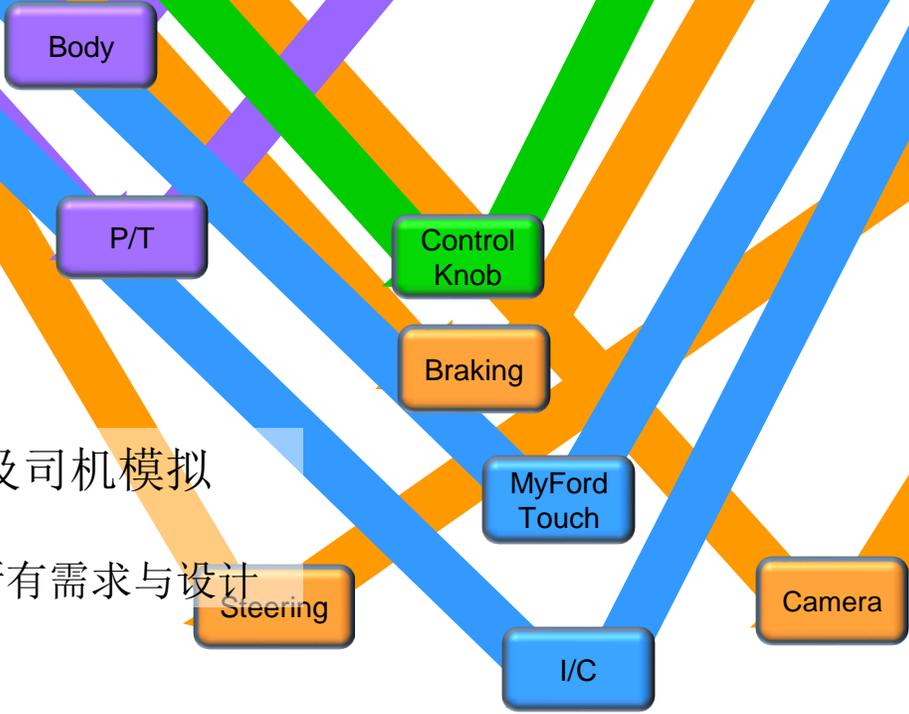
项目进度

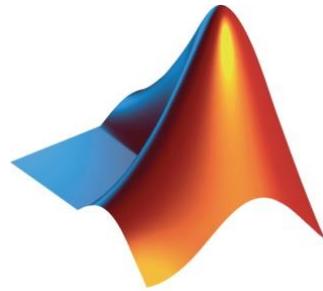
验证工具：  
测试用例记录与回放，  
生成可重复验证脚本，  
自动重复执行  
MIL/HIL 测试

样车完成



车辆及司机模拟器：  
确认所有需求与设计符合





# MathWorks®

*Accelerating the pace of engineering and science*

© 2016 The MathWorks, Inc. MATLAB and Simulink are registered trademarks of The MathWorks, Inc. See [www.mathworks.com/trademarks](http://www.mathworks.com/trademarks) for a list of additional trademarks. Other product or brand names may be trademarks or registered trademarks of their respective holders.