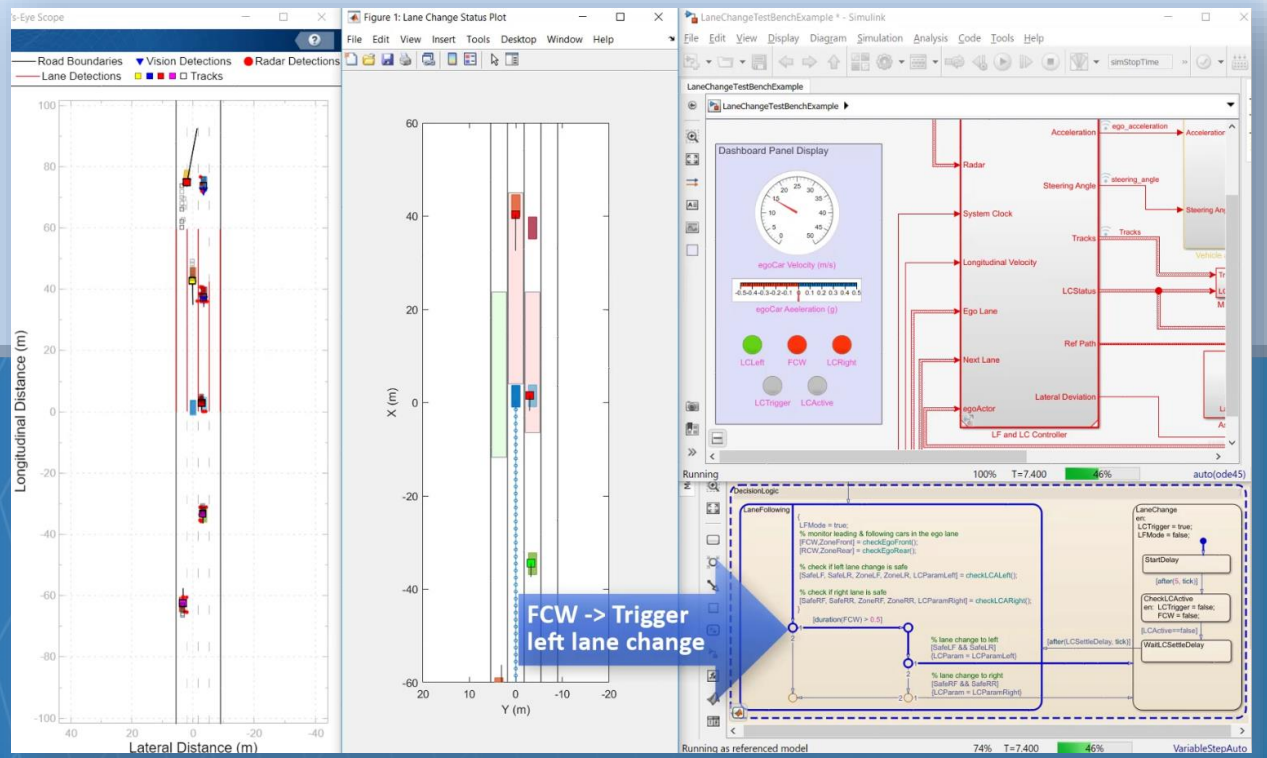
案例研究：高速公路车道跟随与车道变换

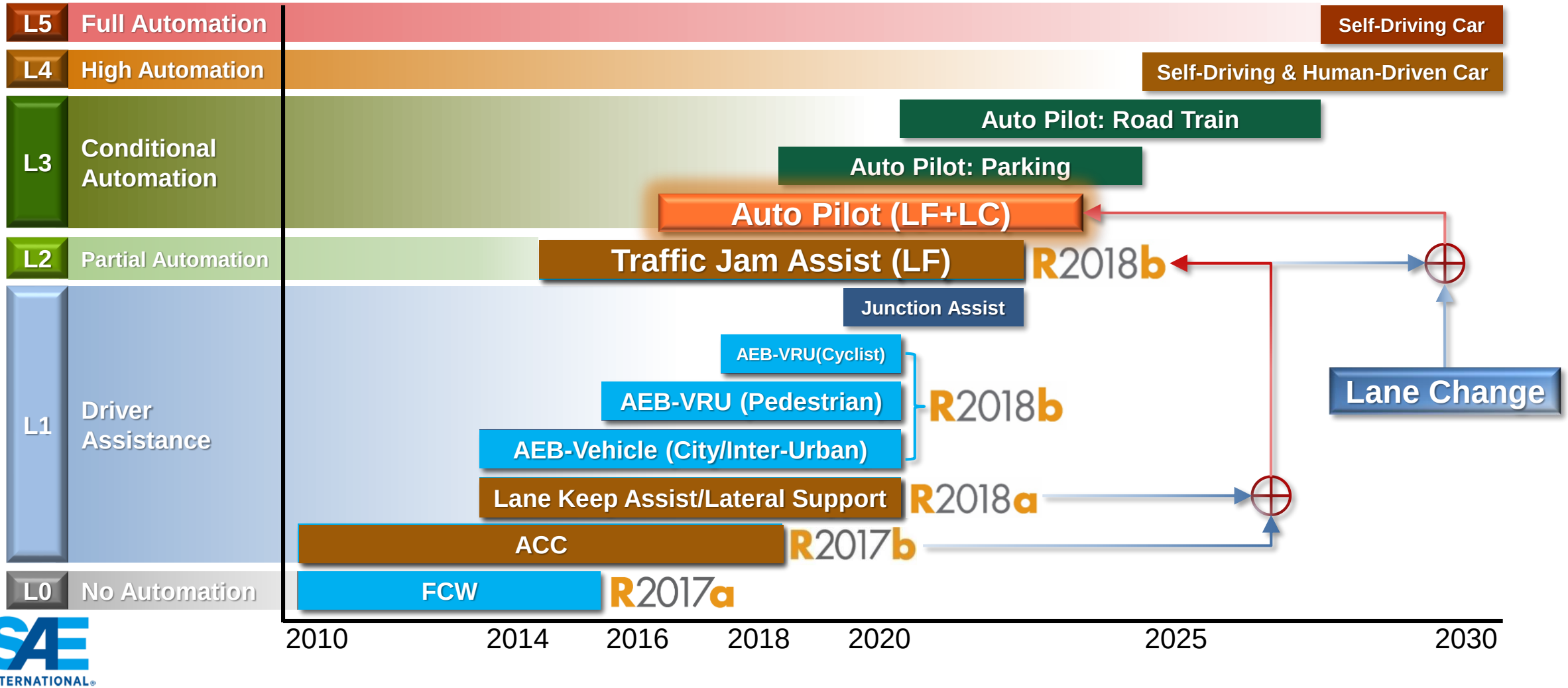
设计与测试高速公路自动驾驶的决策、规划与控制算法



曾超 Senior Consultant
MathWorks 中国

MathWorks参与到ADAS和自动驾驶技术的发展

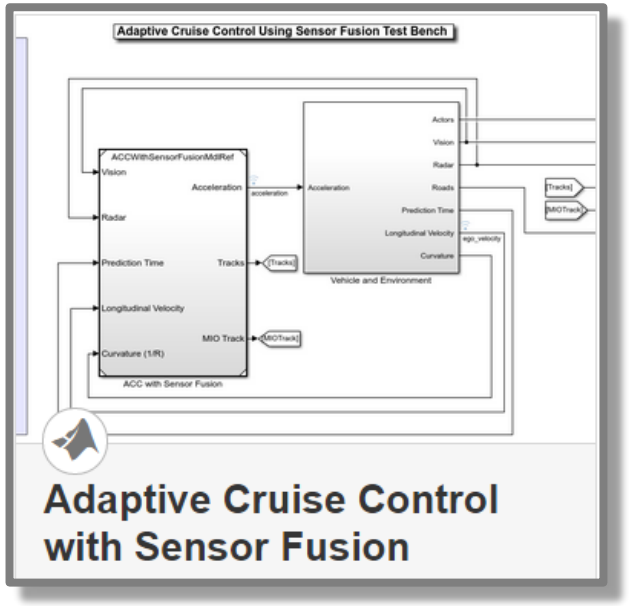
来自 Automated Driving Toolbox™ 的参考示例



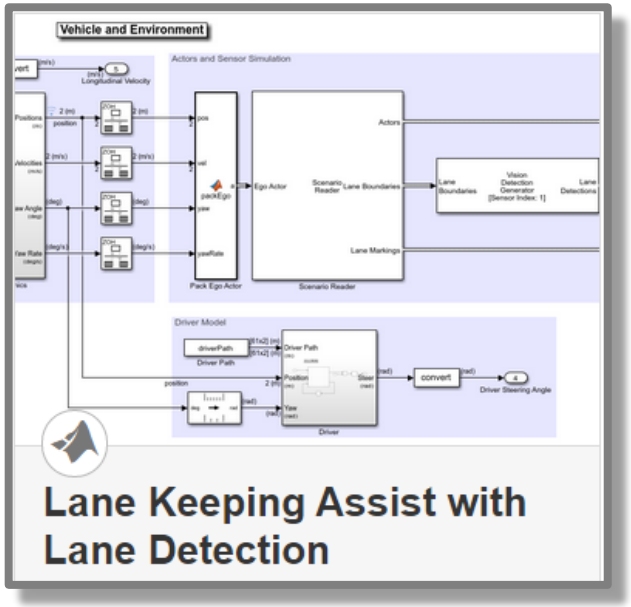
塞车辅助系统

Automated Driving Toolbox™

R2017b



R2018a



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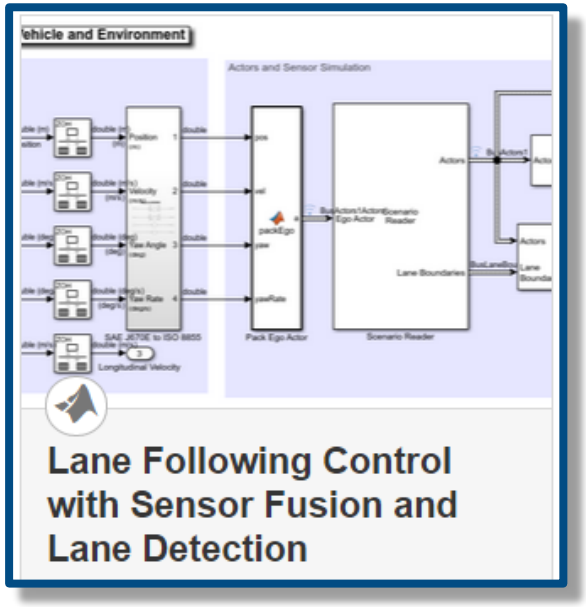


ACC
(Longitudinal Control)

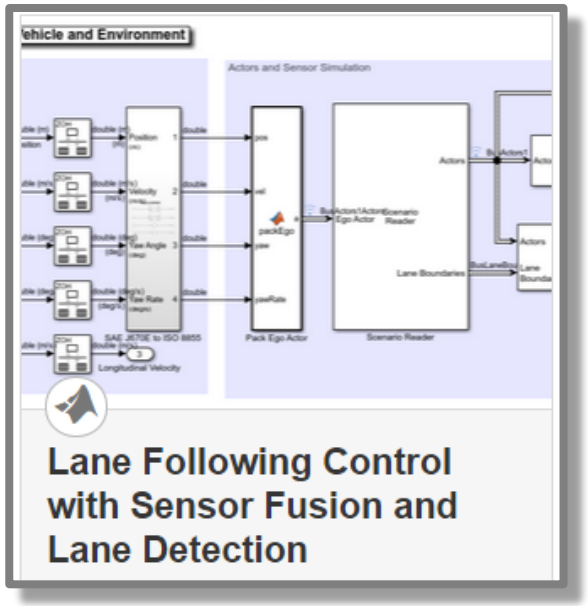
Lane Centering
(Lateral Control)

Traffic Jam Assist
(Longitudinal + Lateral Control)

自动驾驶: 车道跟随 + 车道变换

Automated Driving Toolbox™

R2018b



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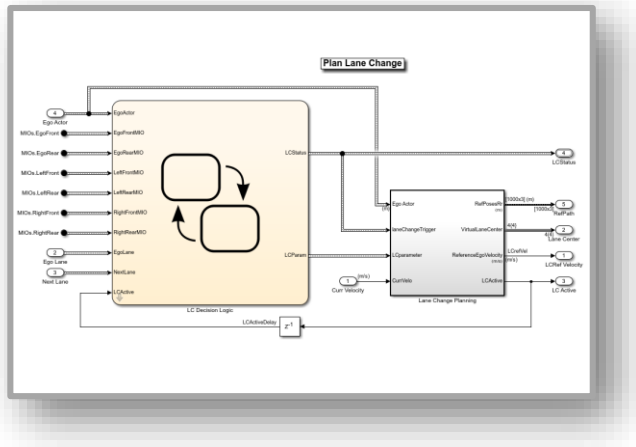

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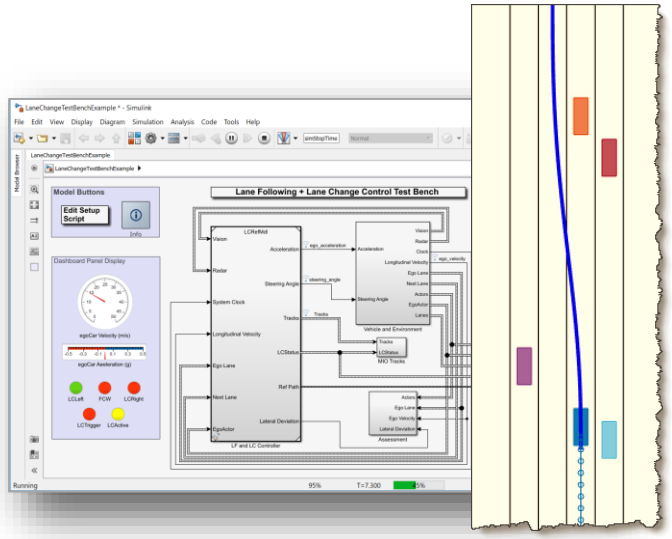


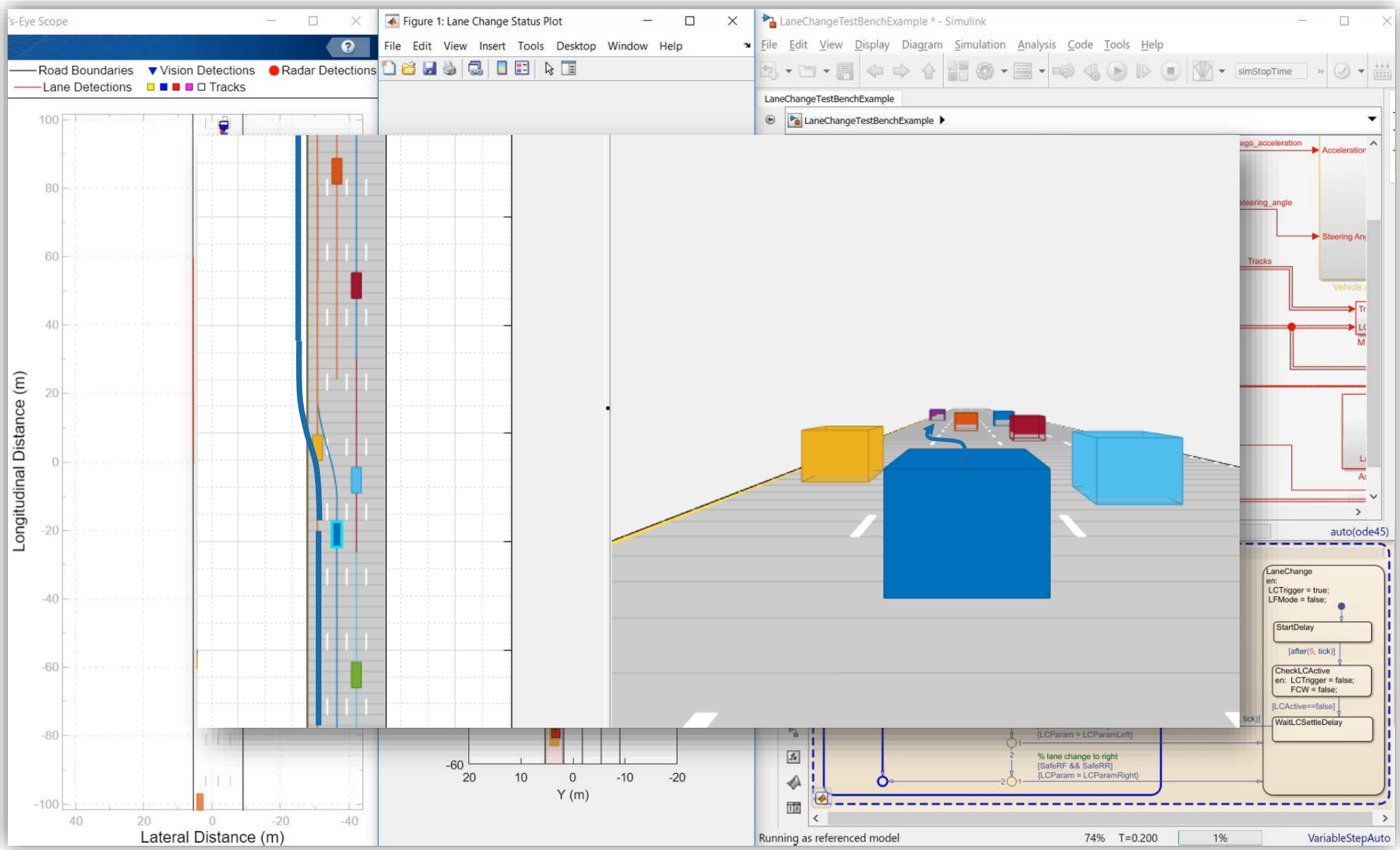
Traffic Jam Assist
(Longitudinal
+ Lateral Control)

Baseline example

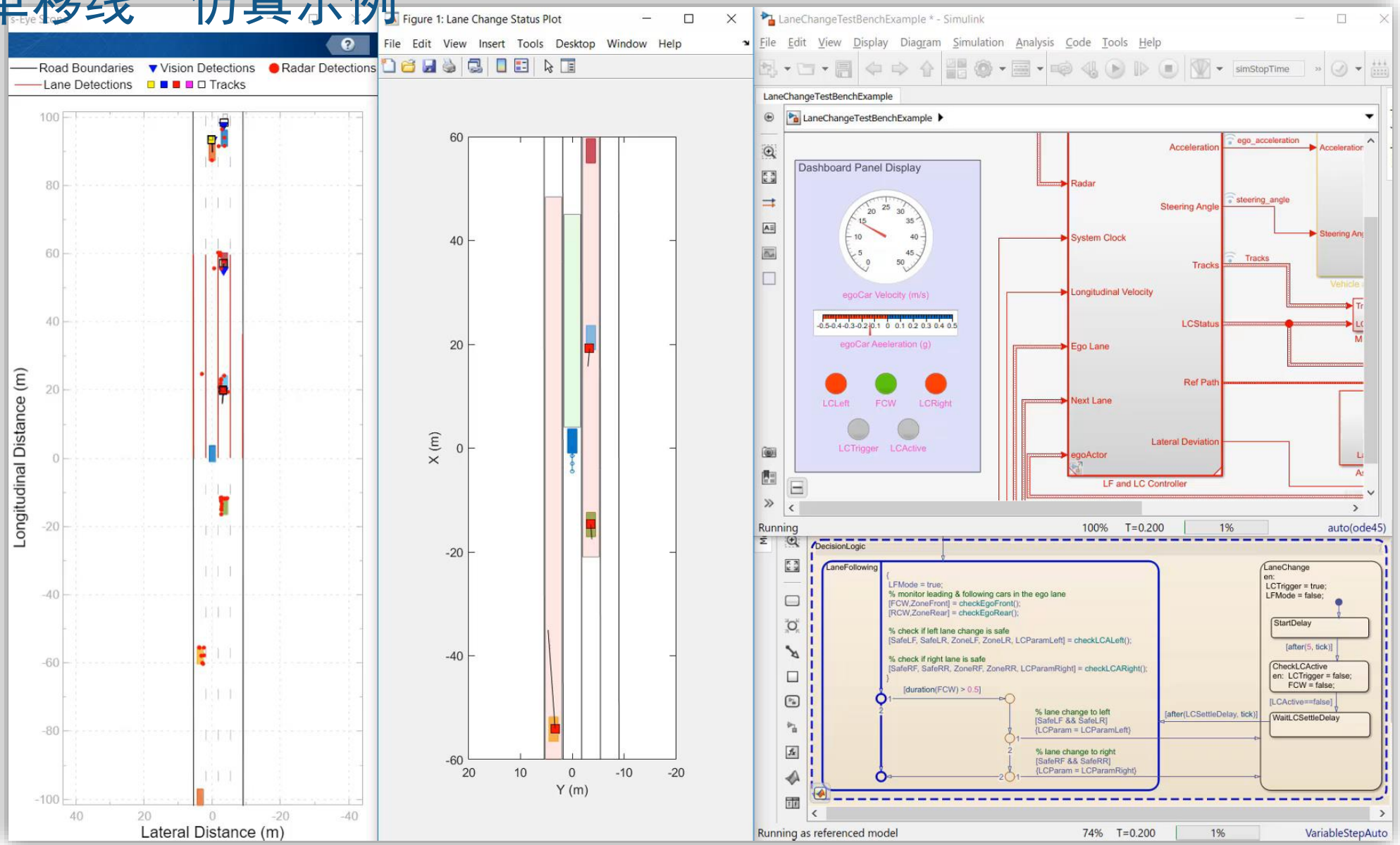
Auto Lane Change
(LC Decision Logic
+ Planning)

Auto Pilot
(Lane Following
+ Lane Change)

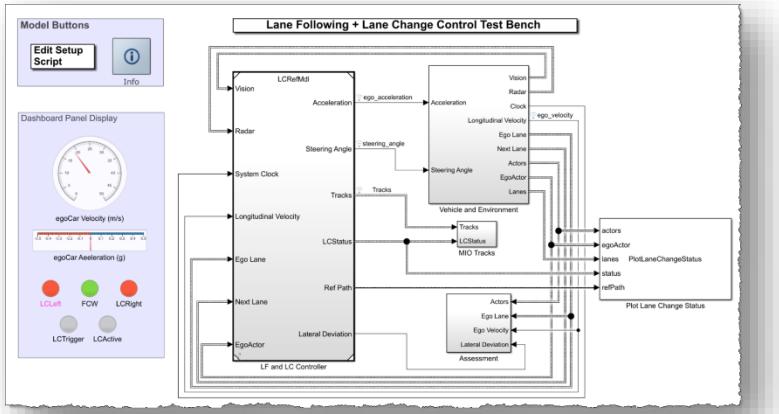
“单移线”仿真示例


Road Boundaries
Vision Detections
Radar Detections
Lane Detections
Tracks
Longitudinal Distance (m)
Lateral Distance (m)
Figure 1: Lane Change Status Plot
File Edit View Insert Tools Desktop Window Help
Y (m)
LaneChangeTestBenchExample * - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
simStopTime
LaneChangeTestBenchExample
ego_acceleration
Acceleration
steering_angle
Tracks
auto(ode45)
LaneChange
en:
LCTrigger = true;
LFMode = false;
StartDelay
[after(5, tick)]
CheckLCActive
en: LCTrigger = false;
FCW = false;
[LCActive==false]
WaitLCSettleDelay
{LCParam = LCParamLeft}
% lane change to right
[SafeRF && SafeRR]
{LCParam = LCParamRight}
Running as referenced model
74%
T=0.200
1%
VariableStepAuto

“单移线”仿真示例

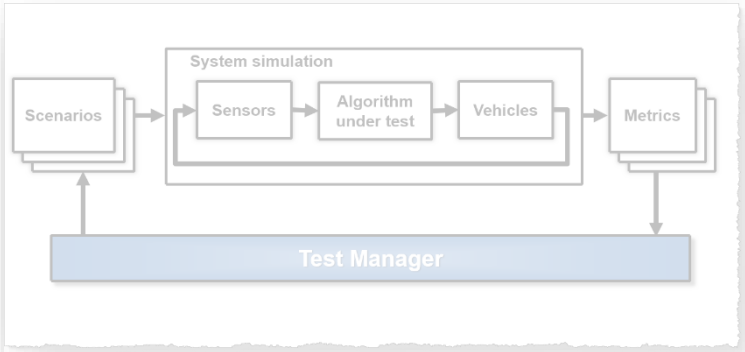

Road Boundaries
Vision Detections
Radar Detections
Lane Detections
Tracks
Longitudinal Distance (m)
Lateral Distance (m)
Figure 1: Lane Change Status Plot
File Edit View Insert Tools Desktop Window Help
X (m)
Y (m)
LaneChangeTestBenchExample * - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
LaneChangeTestBenchExample
Dashboard Panel Display
egoCar Velocity (m/s)
egoCar Aeeleration (g)
LCLeft
FCW
LCRight
LCTrigger
LCActive
Radar
System Clock
Longitudinal Velocity
Ego Lane
Next Lane
egoActor
Acceleration
Steering Angle
Tracks
LCStatus
Ref Path
Lateral Deviation
LF and LC Controller
Running
100%
T=0.200
1%
auto(ode45)
DecisionLogic
LaneFollowing
LaneChange
StartDelay
CheckLCActive
WaitLCSettleDelay
Running as referenced model
74%
T=0.200
1%
VariableStepAuto

案例研究：设计与测试高速公路自动驾驶（决策、规划与控制）



设计车道跟随 + 车道变换控制器

- 回顾车道跟随控制器
- 添加传感器配置
- 添加关键目标检测器
- 设计安全区域算法
- 设计车道变换逻辑
- 设计路径规划器



自动回归测试

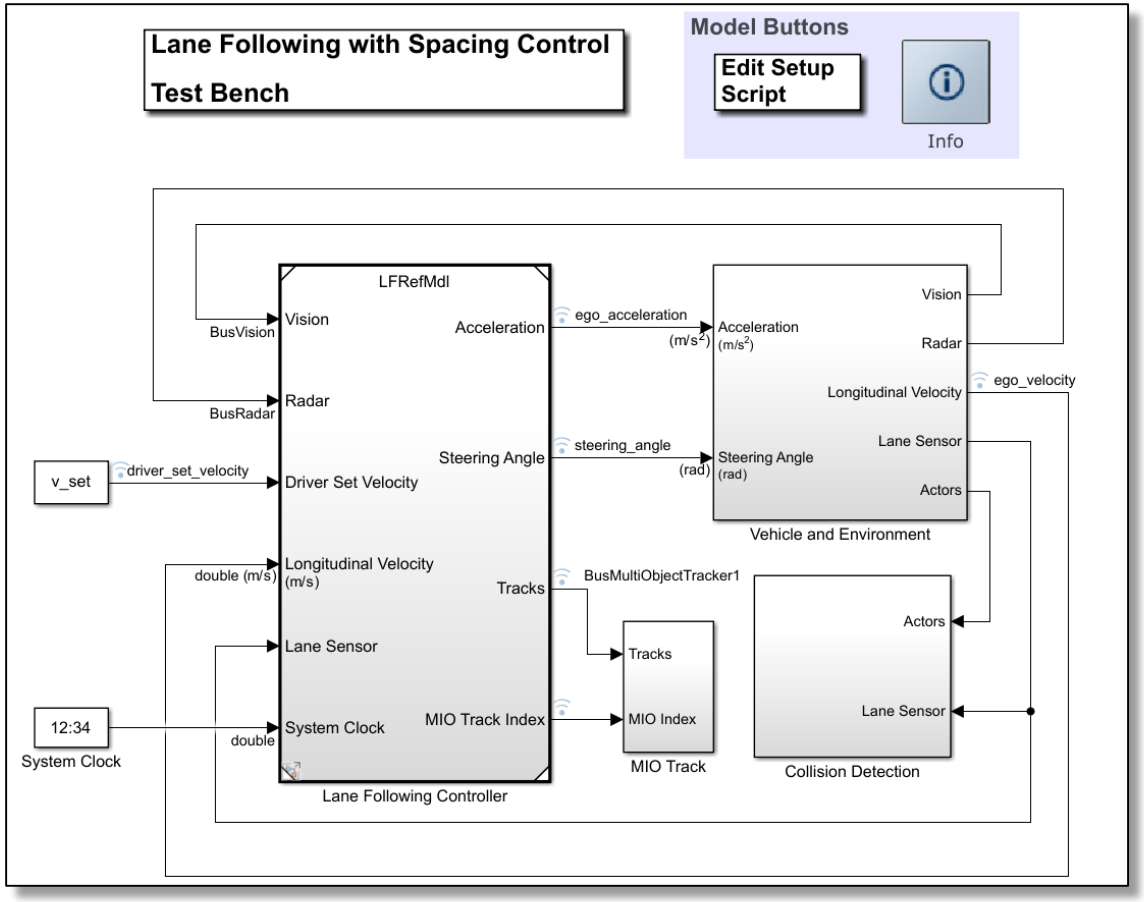
- 创建预定义的场景
- 定义评价指标
- 运行Simulink Test

采用Agent的鲁棒性测试

- 定义Agent的驾驶逻辑
- 采用Agent随机化交通场景
- 识别与评定非预期行为

如何开发一个车道跟随控制器

R2018b
Automated Driving Toolbox™



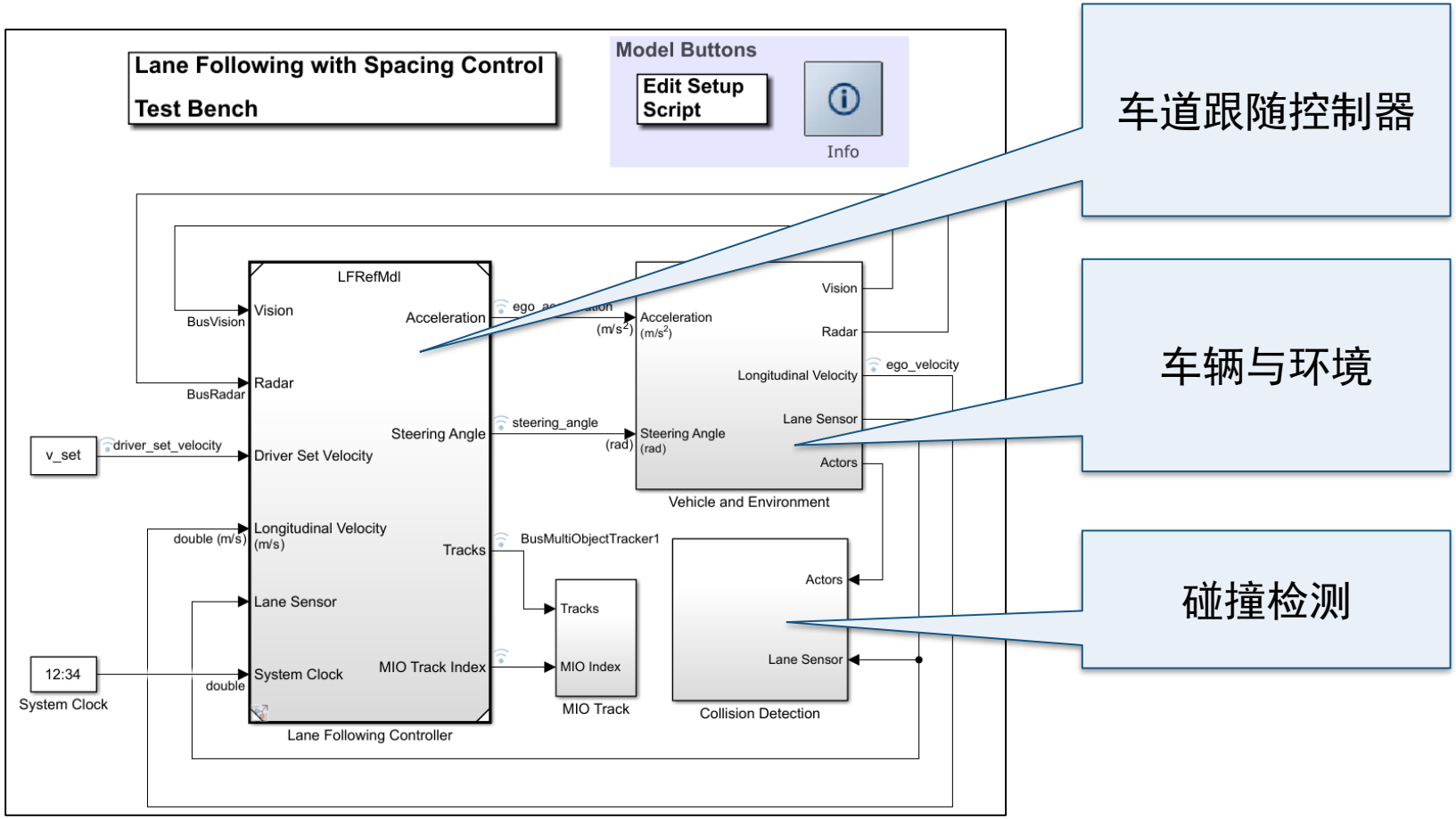
[Lane Following Control with Sensor Fusion]

- 定义场景和传感器
- 设计车辆的横向（车道保持）和纵向（间距管理）模型预测控制算法
- 传感器融合
- 生成C/C++代码
- 软件在环 (SIL) 仿真

Model Predictive Control Toolbox™
Automated Driving Toolbox™
Embedded Coder®

Baseline example

车道跟随控制器的测试框架



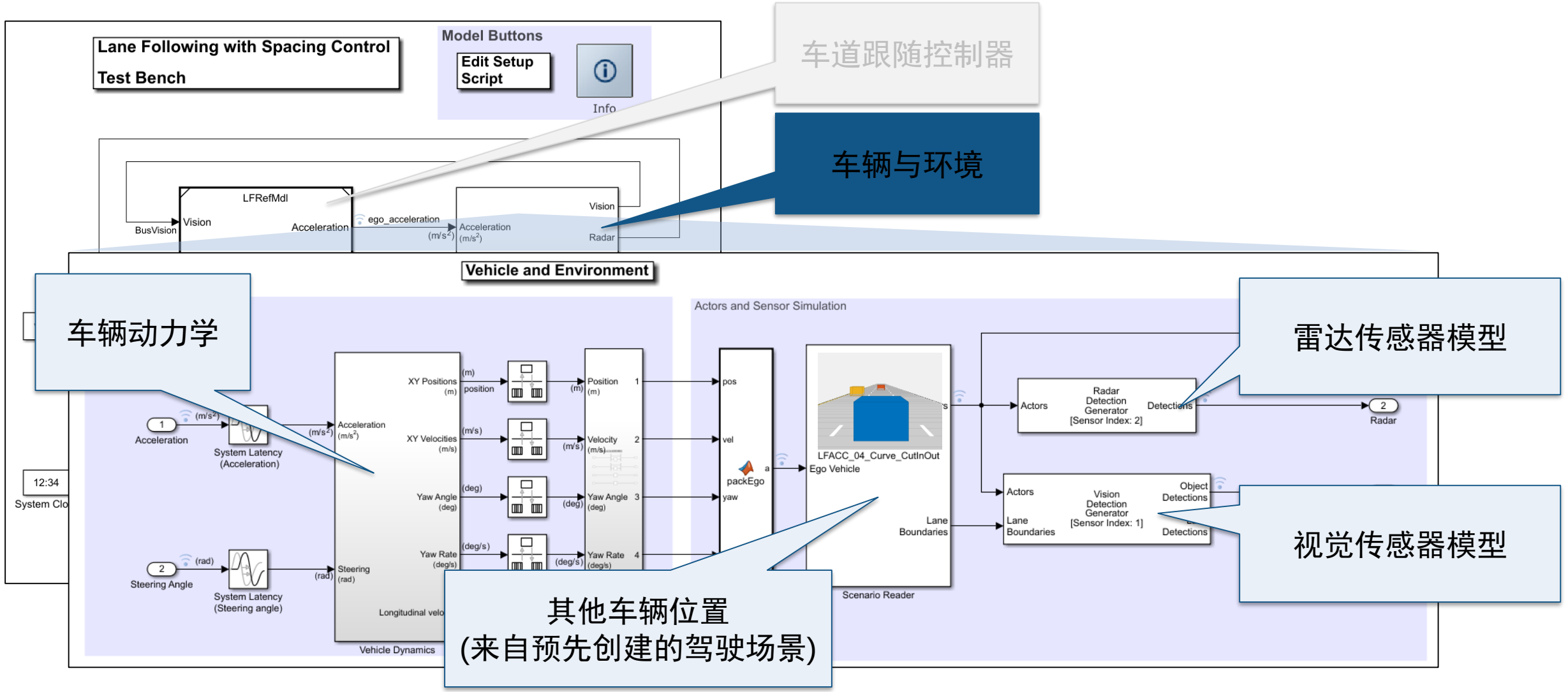
车道跟随控制器

车辆与环境

碰撞检测

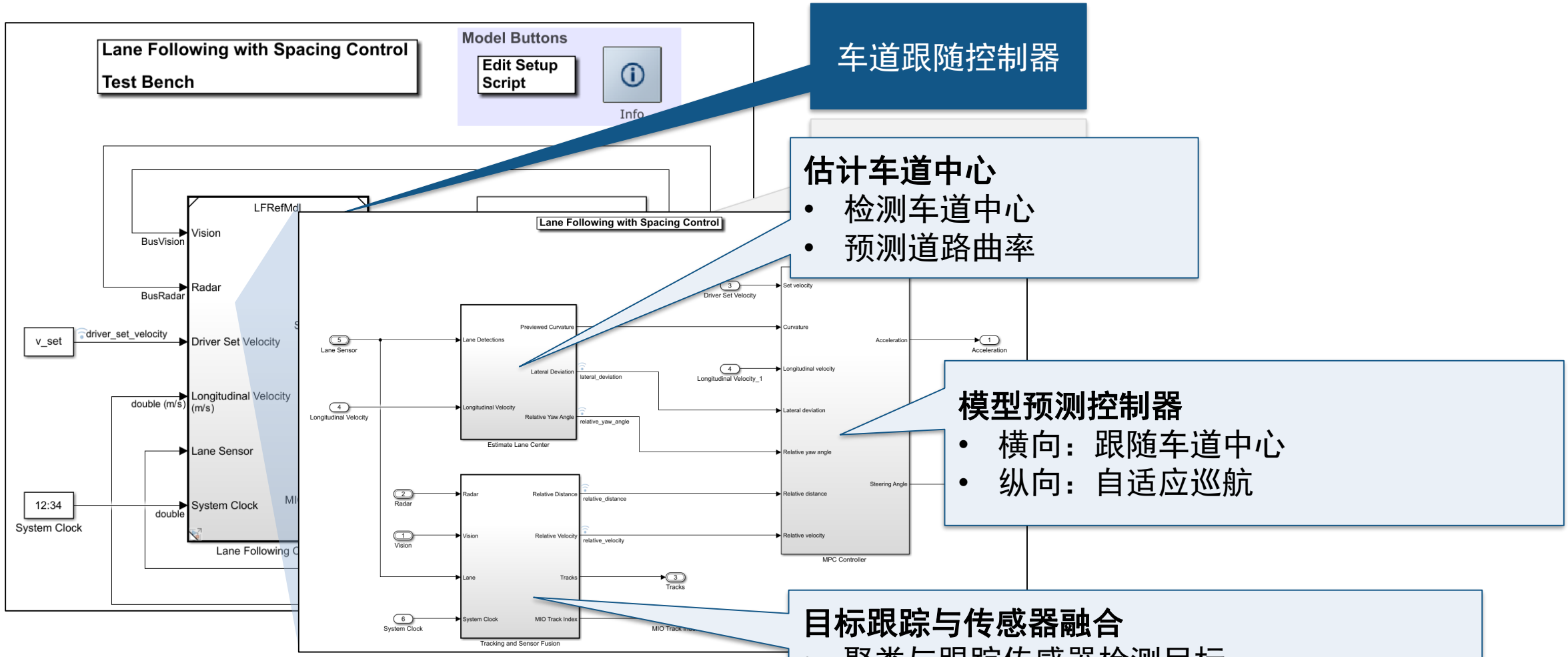
Baseline example

车辆与环境组件



Baseline example

车道跟随控制器组件



车道跟随控制器

估计车道中心

- 检测车道中心
- 预测道路曲率

模型预测控制器

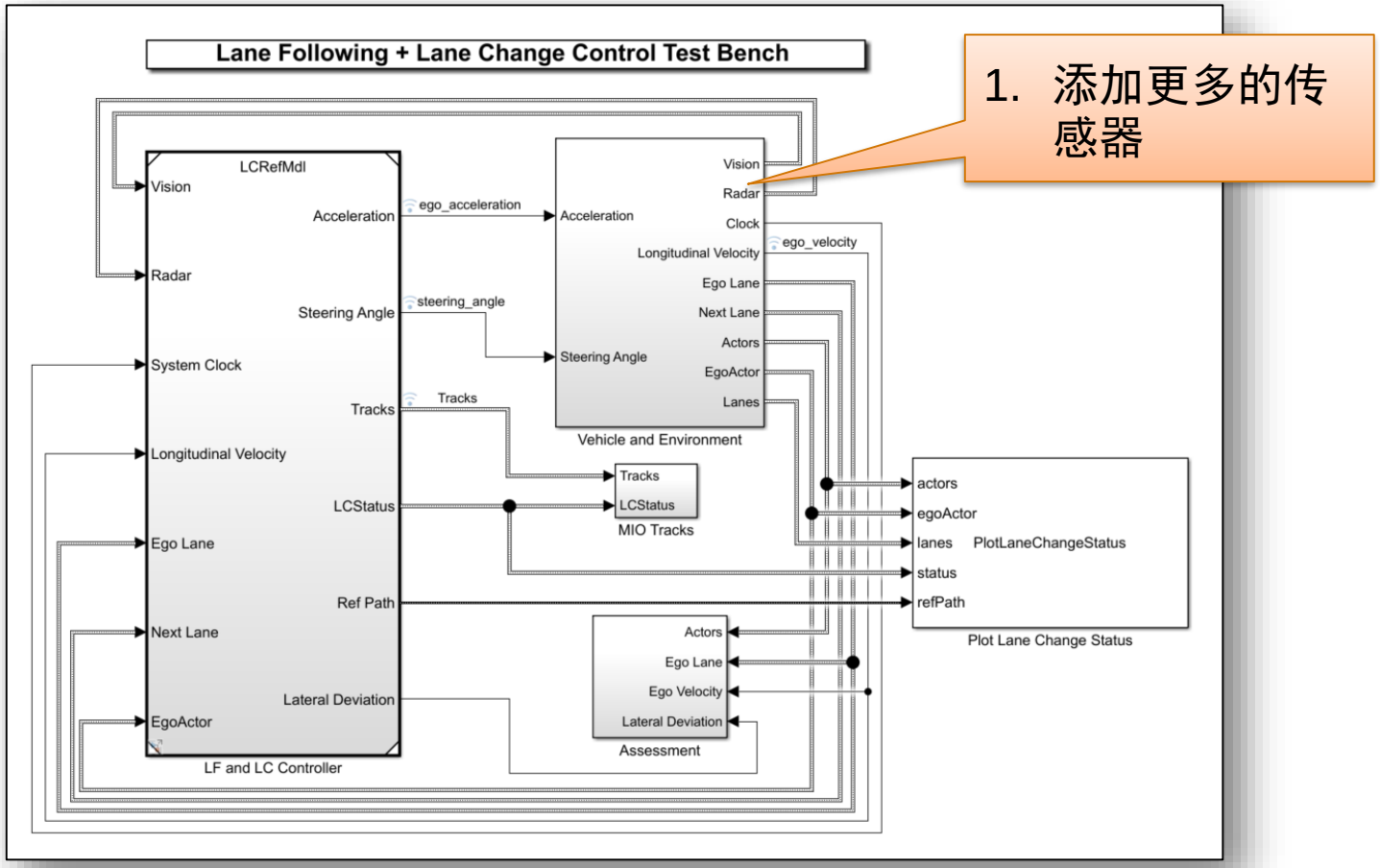
- 横向：跟随车道中心
- 纵向：自适应巡航

目标跟踪与传感器融合

- 聚类与跟踪传感器检测目标
- 识别前方的最重要目标 (MIO)

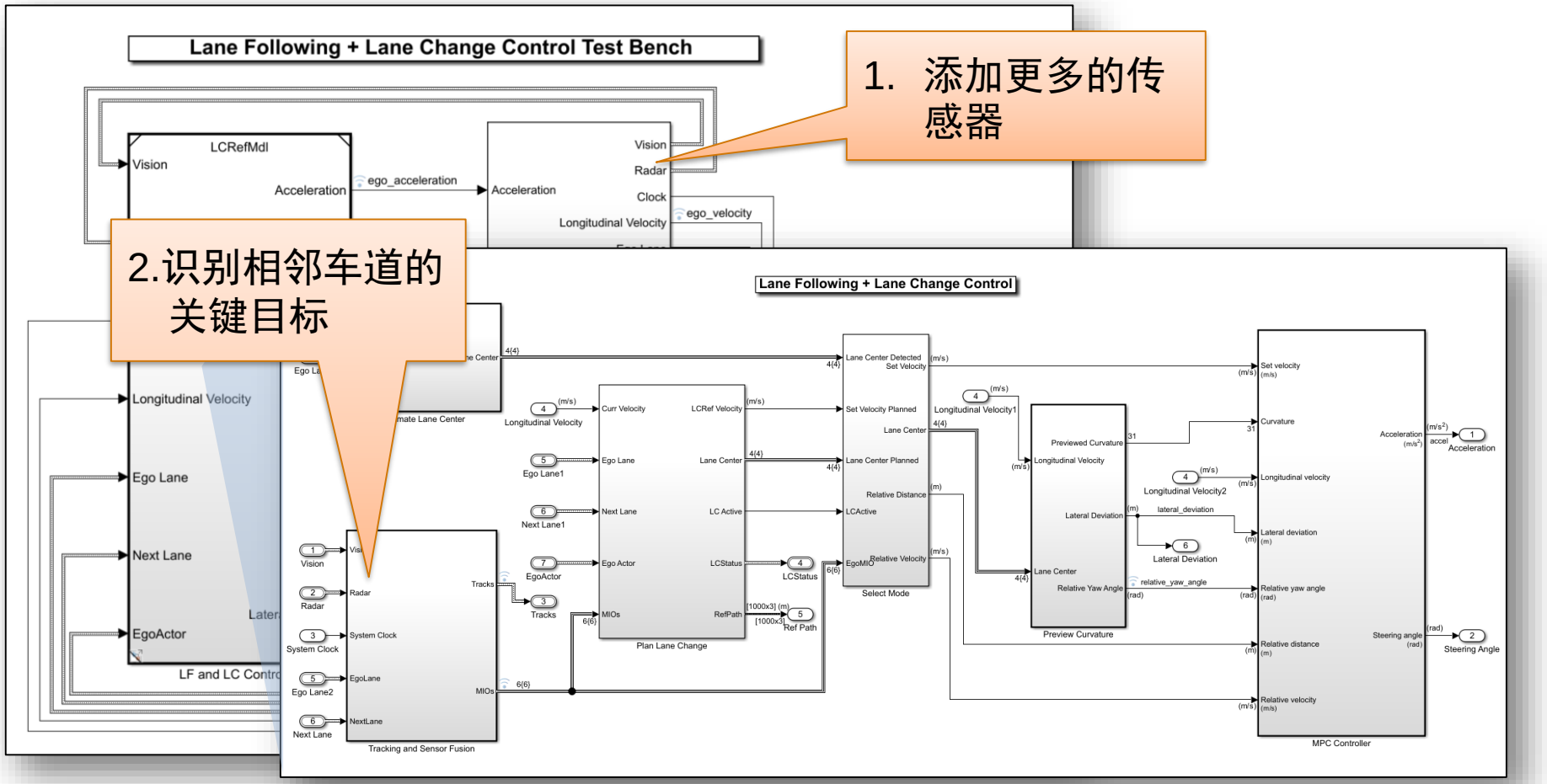
Baseline example

开发车道变换功能



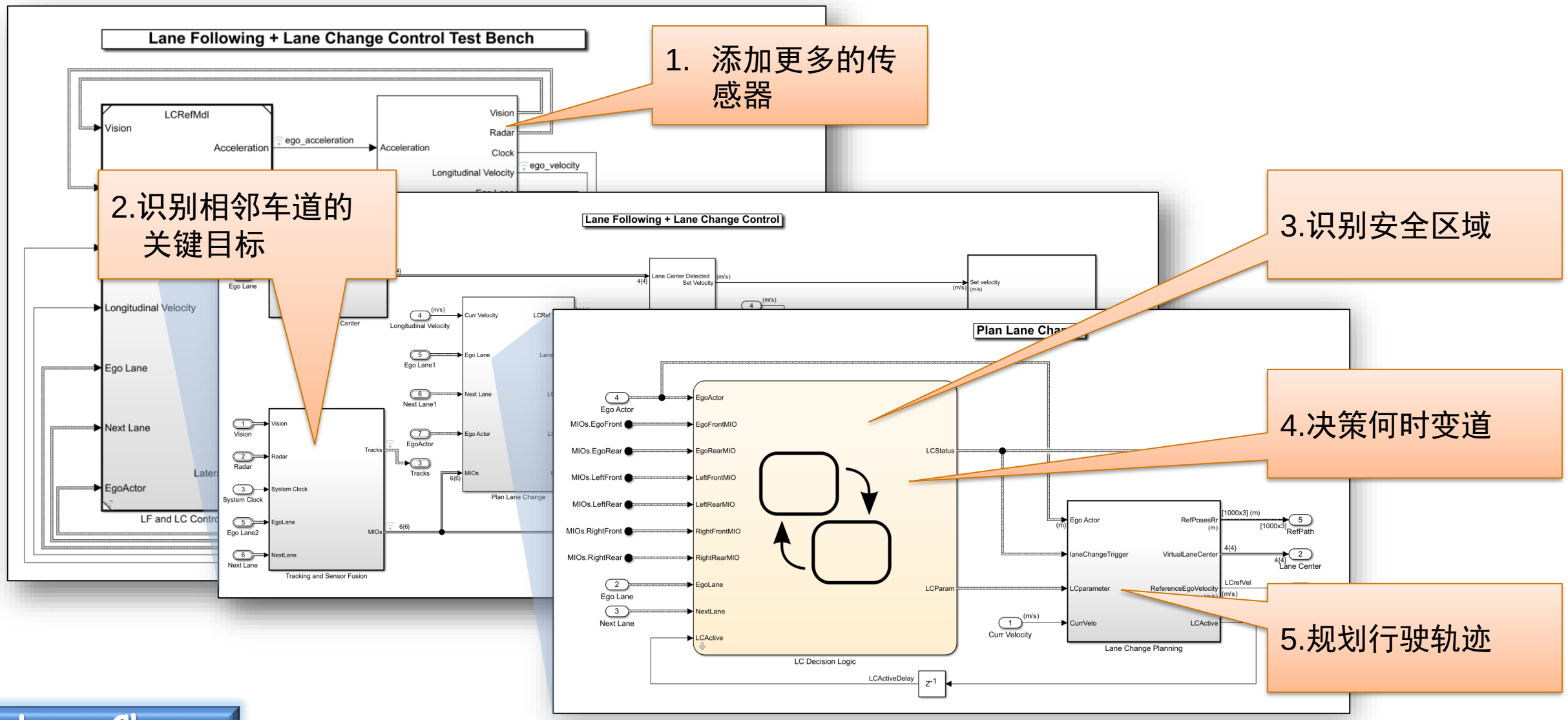
+ Lane Change

开发车道变换功能



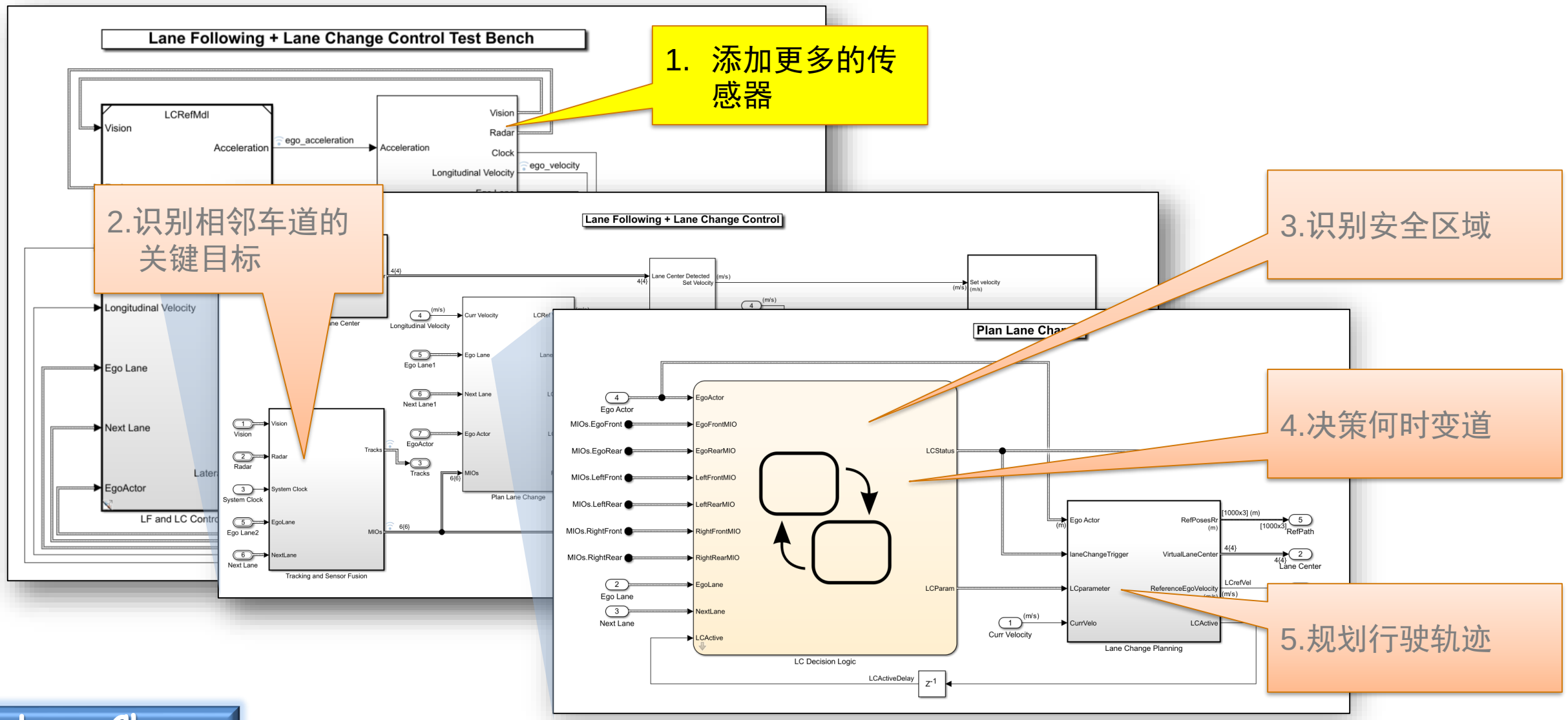
+ Lane Change

开发车道变换功能



+ Lane Change

开发车道变换功能



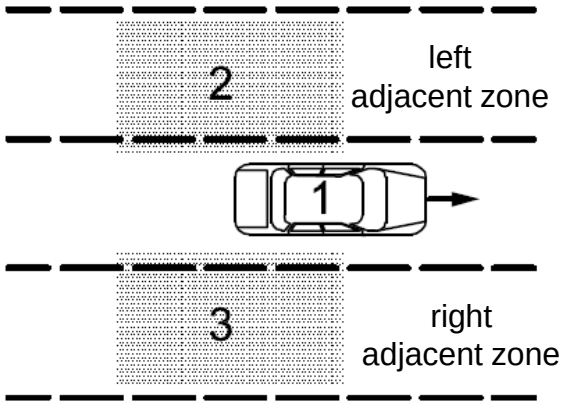
+ Lane Change

车道变换功能的系统需求（来自ISO 17387）

Intelligent transport systems - Lane change decision aid systems (LCDAS)

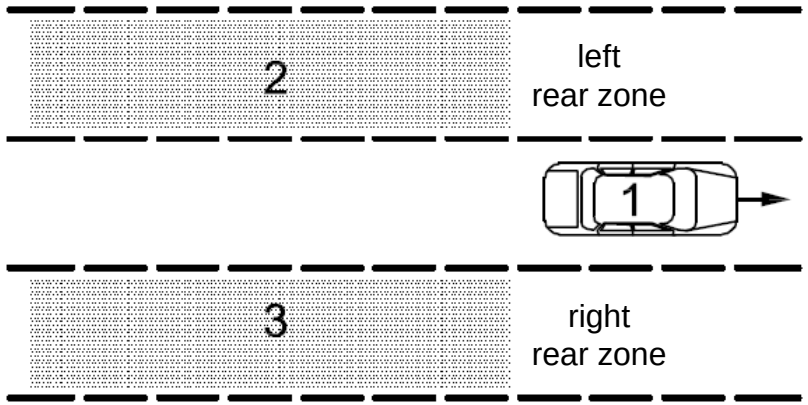
17387

探测相邻区域
（如用于盲点检测）



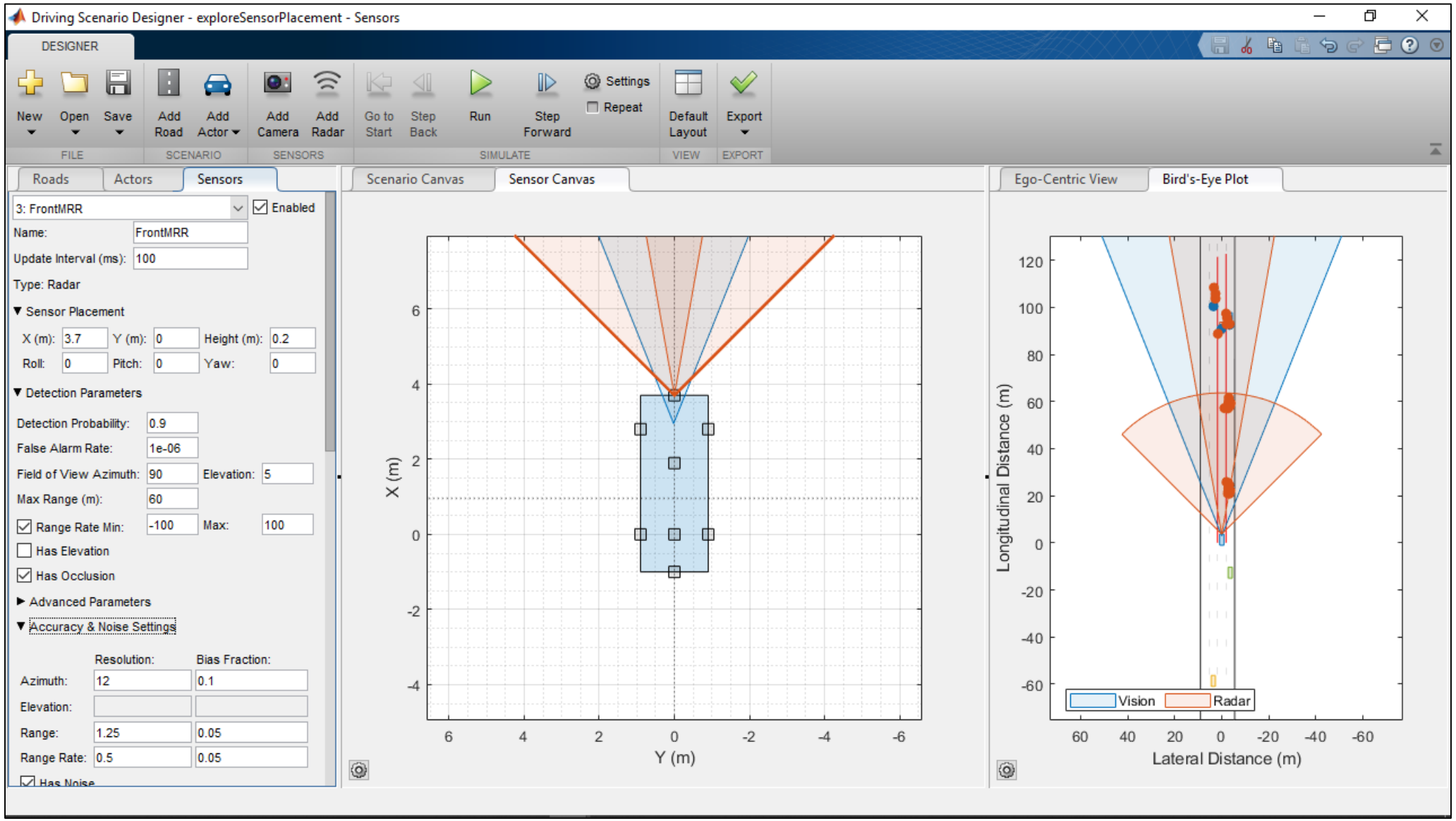
通常采用 **短距雷达**

探测后方区域
（如用于车辆接近预警）



通常采用 **中距雷达**

使用驾驶场景设计器研究传感器配置

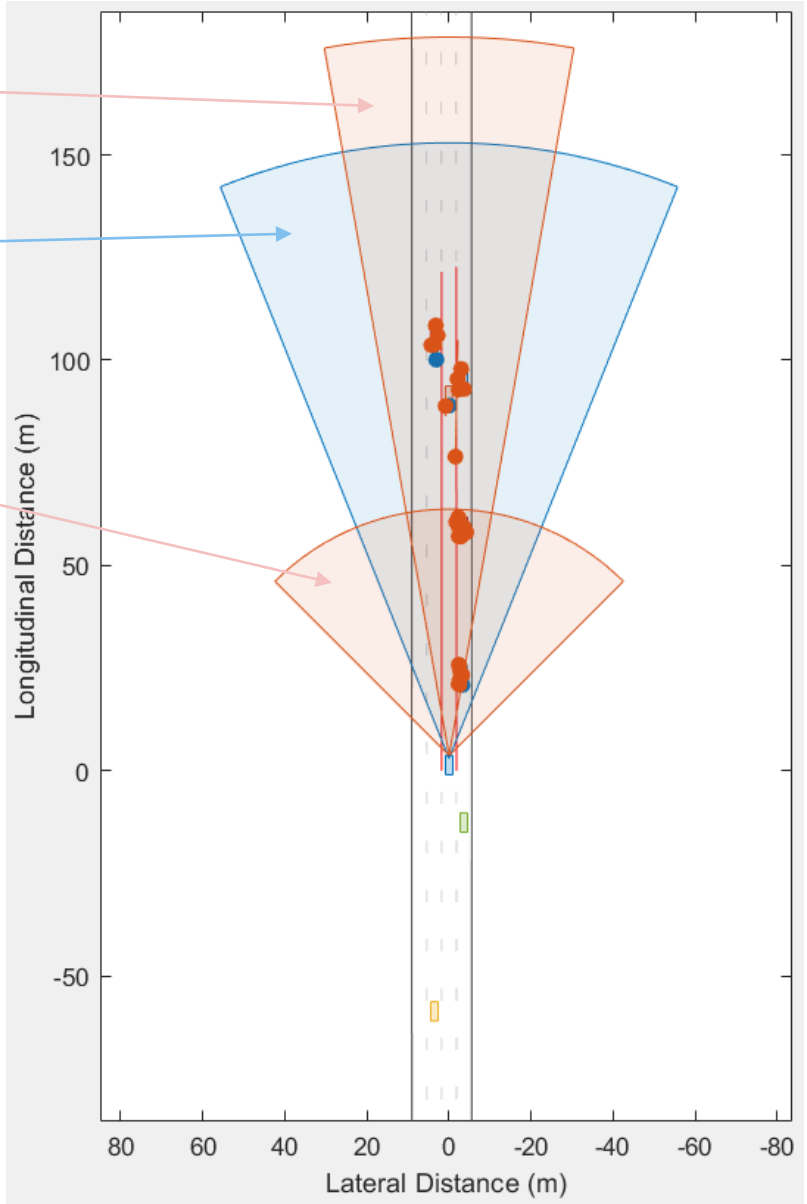


车道跟随的传感器配置

FrontLRR
FoV = 20° x 175m

Camera
FoV = 43.6° x 150m

FrontMRR
FoV = 90° x 60m



- SRR: Short-Range Radar
- MRR: Mid-Range Radar
- LRR: Long-Range Radar

增加后视雷达检车相邻车道后方区域

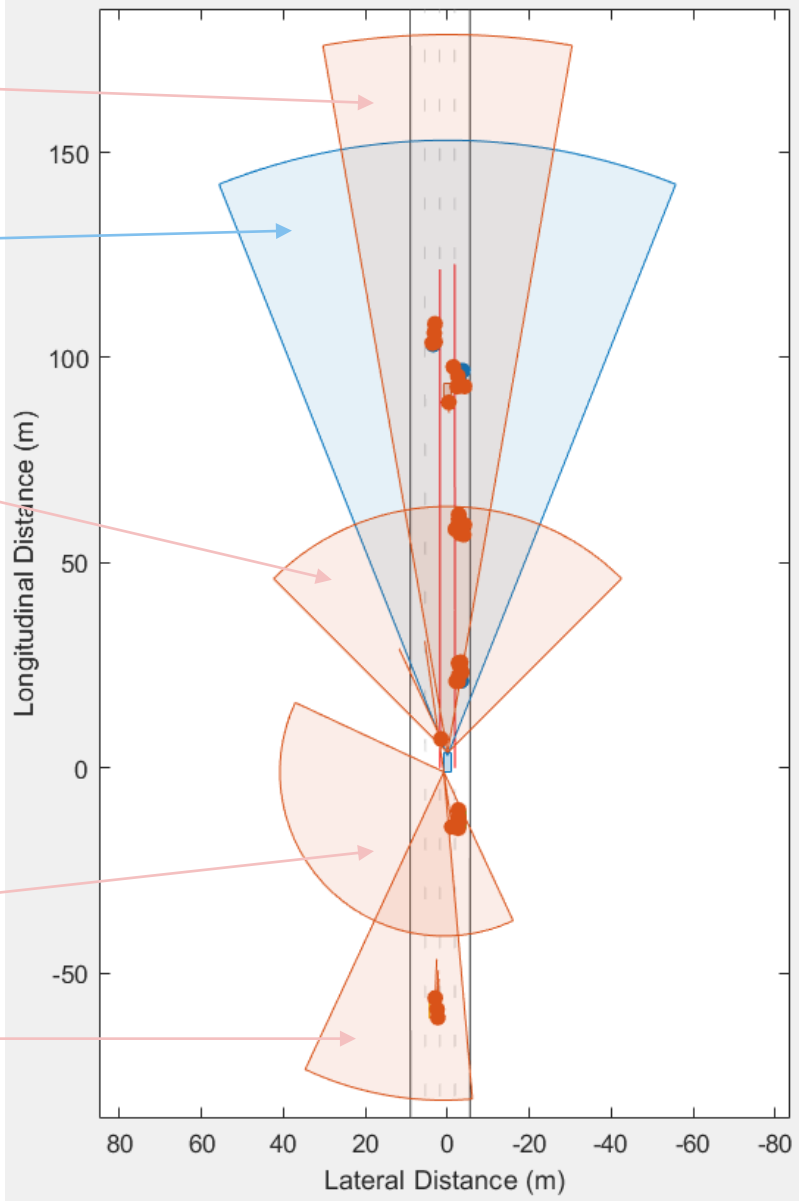
FrontLRR
FoV = 20° x 175m

Camera
FoV = 43.6° x 150m

FrontMRR
FoV = 90° x 60m

LeftRearSRR
FoV = 140° x 40m

LeftRearMRR
FoV = 30° x 80m



- SRR: Short-Range Radar
- MRR: Mid-Range Radar
- LRR: Long-Range Radar

传感器总体配置

FrontLRR
FoV = 20° x 175m

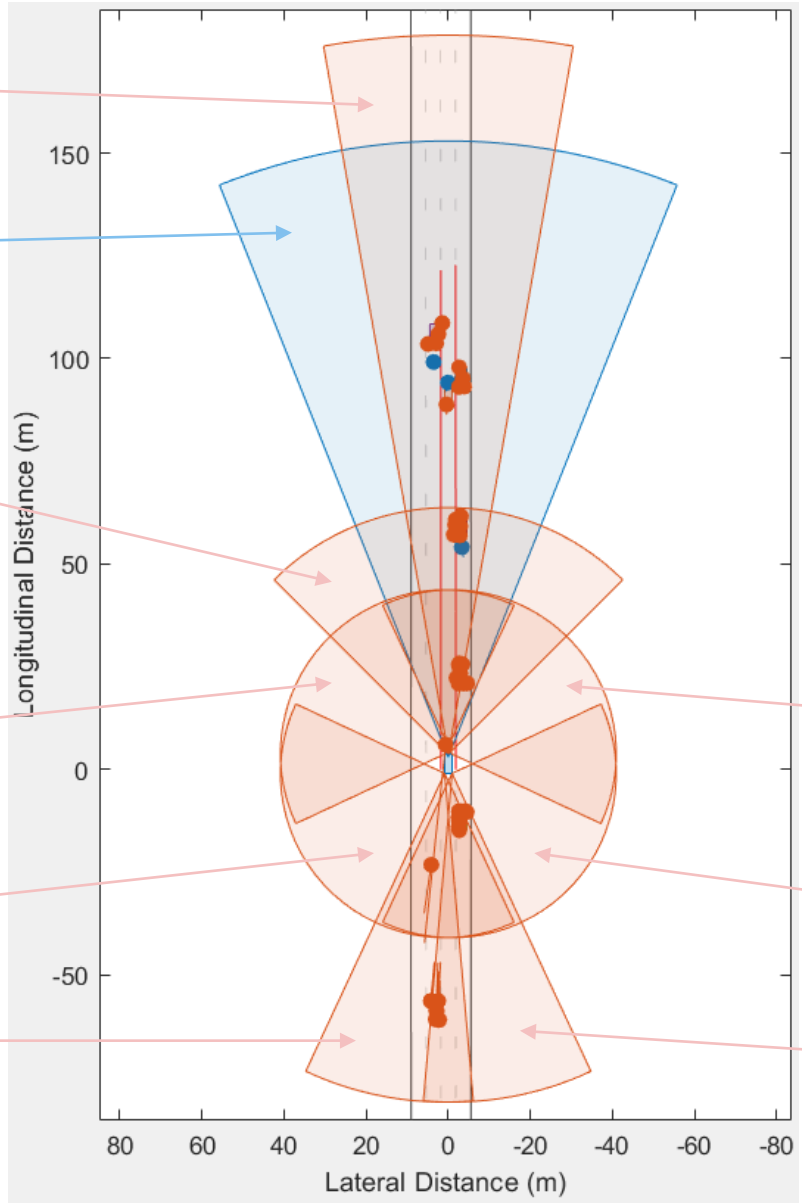
Camera
FoV = 43.6° x 150m

FrontMRR
FoV = 90° x 60m

LeftFrontSRR
FoV = 140° x 40m

LeftRearSRR
FoV = 140° x 40m

LeftRearMRR
FoV = 30° x 80m



×1 front camera
×8 radars

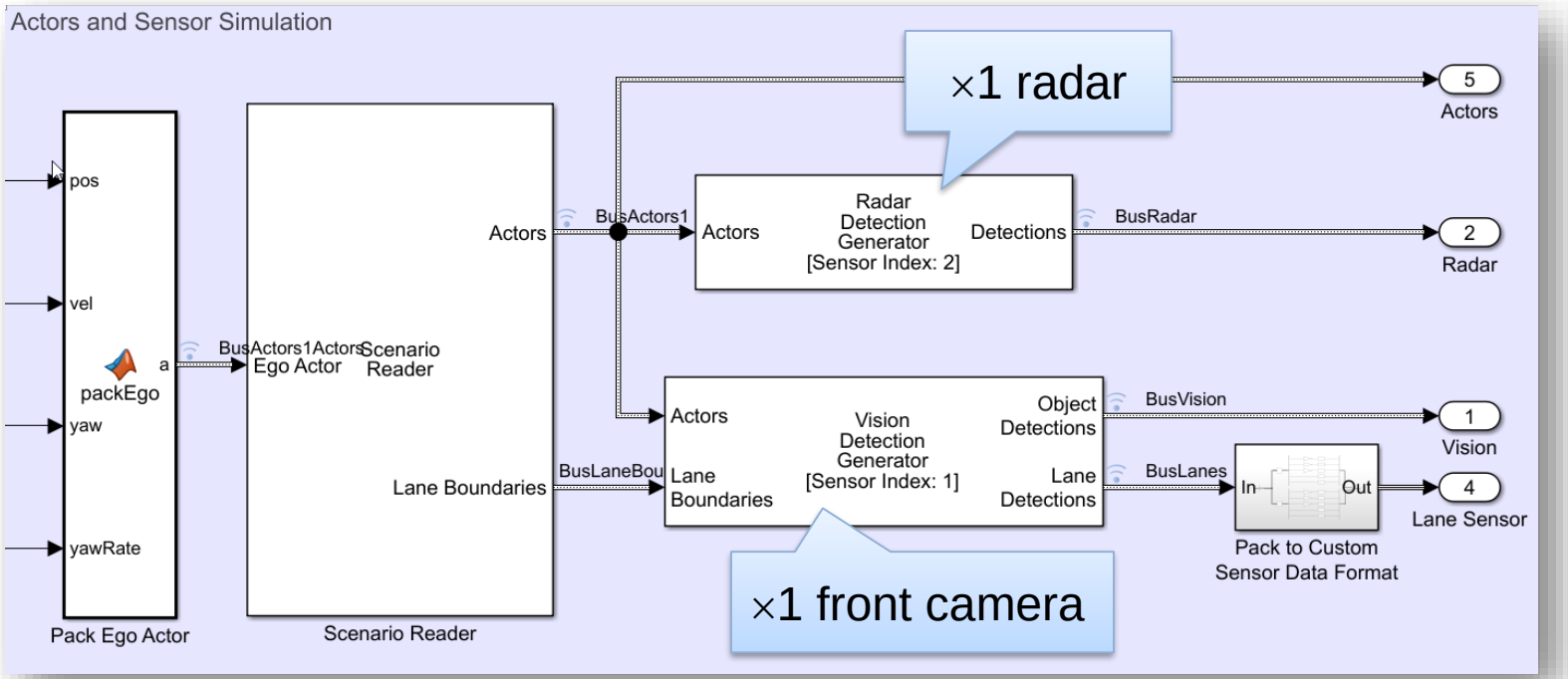
- SRR: Short-Range Radar
- MRR: Mid-Range Radar
- LRR: Long-Range Radar

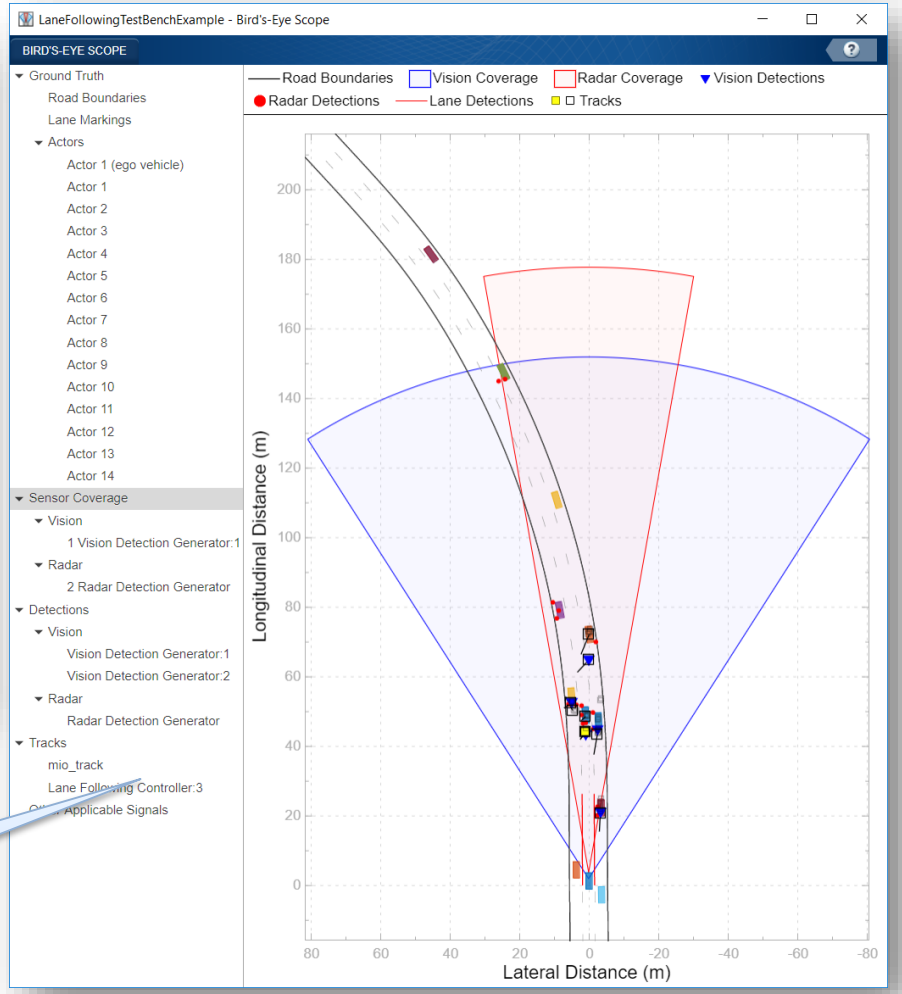
RightFrontSRR
FoV = 140° x 40m

RightRearSRR
FoV = 140° x 40m

RightRearMRR
FoV = 30° x 80m

车道跟随传感器模型

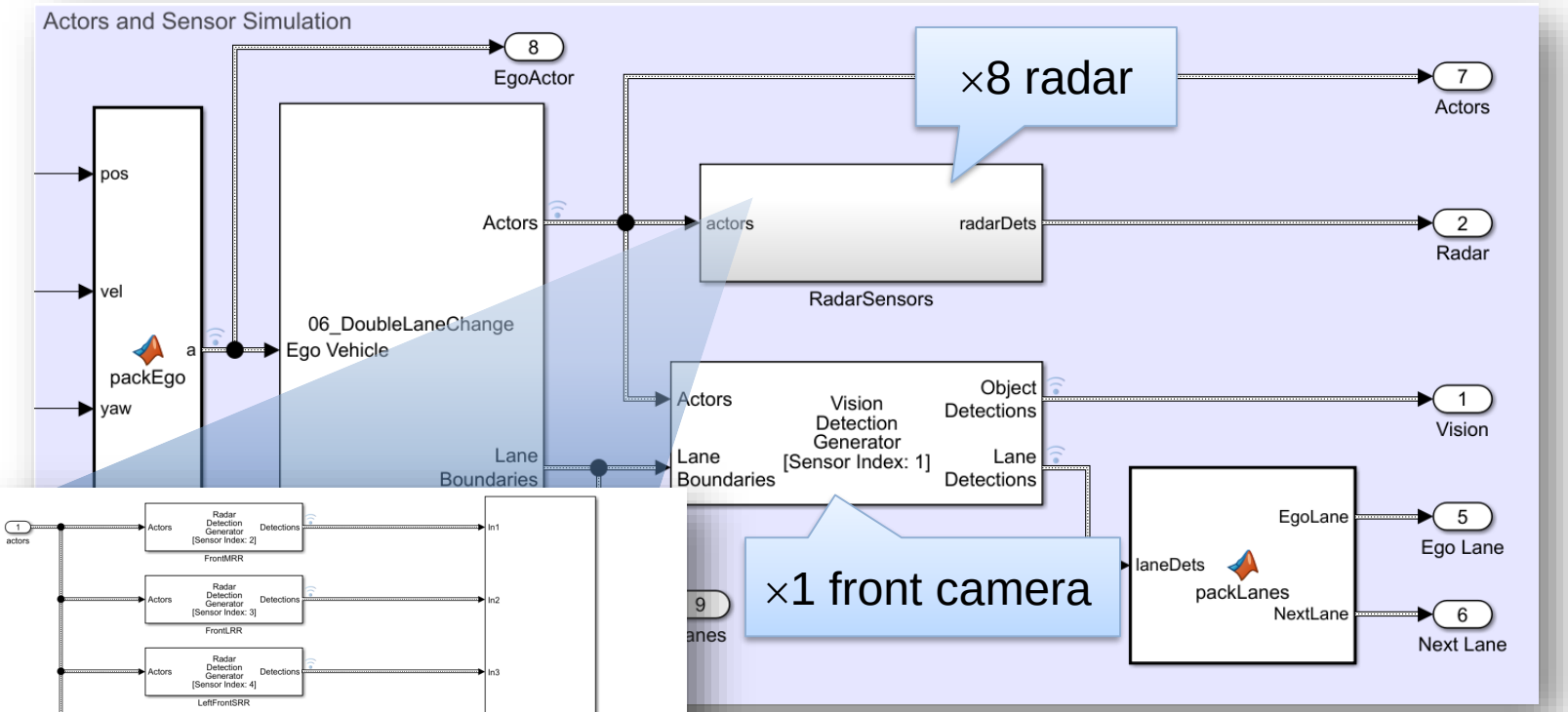


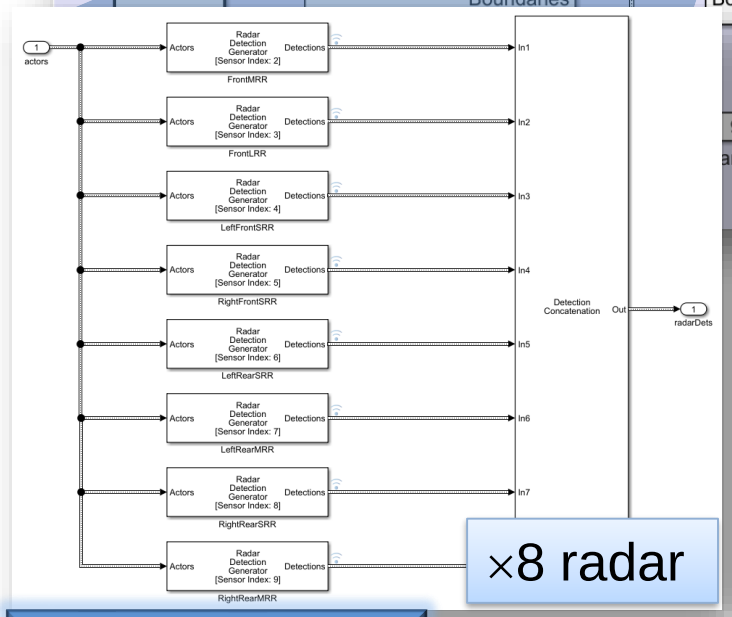


Visualize with
Birds Eye Scope

Baseline example

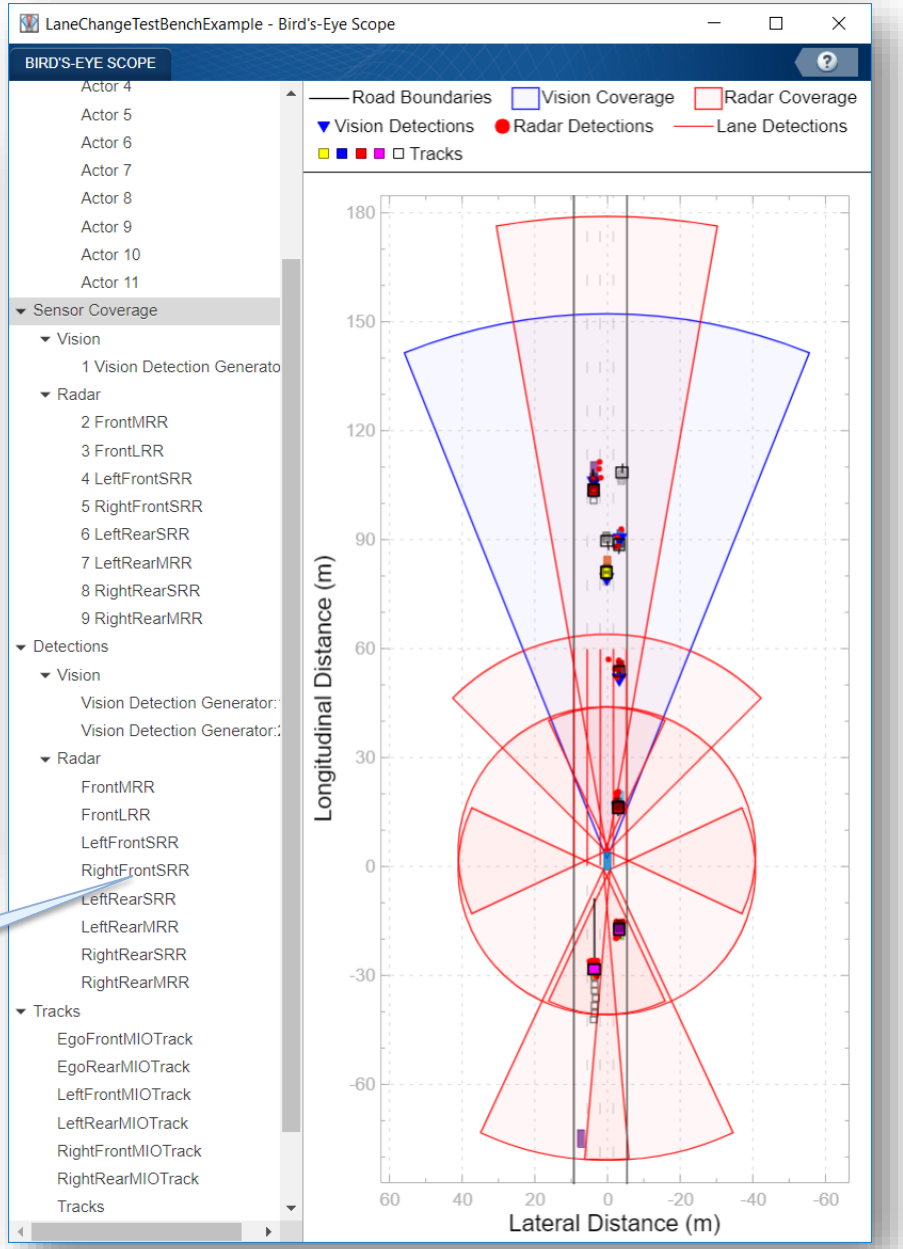
在Simulink中添加传感器模型



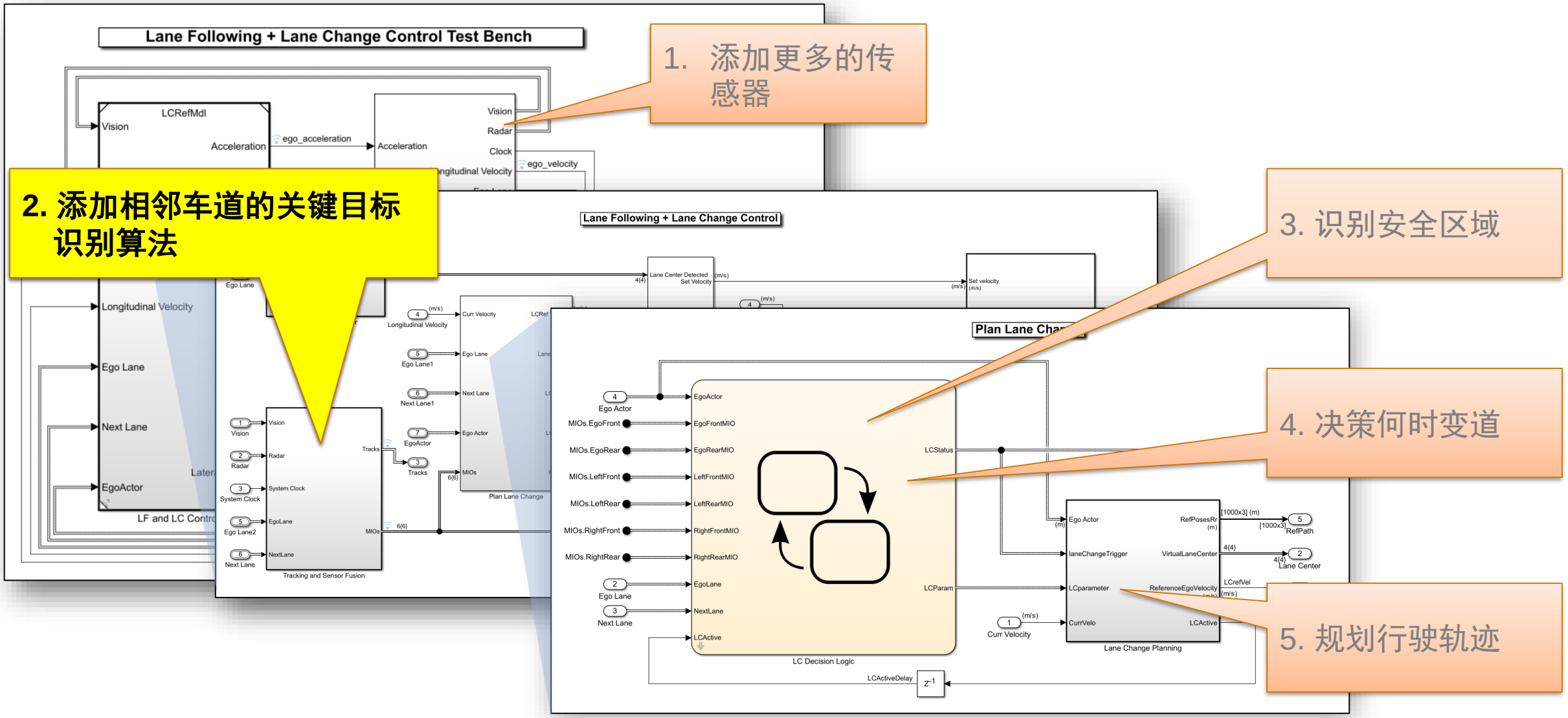


+ Lane Change

利用Bird's Eye Scope
进行可视化

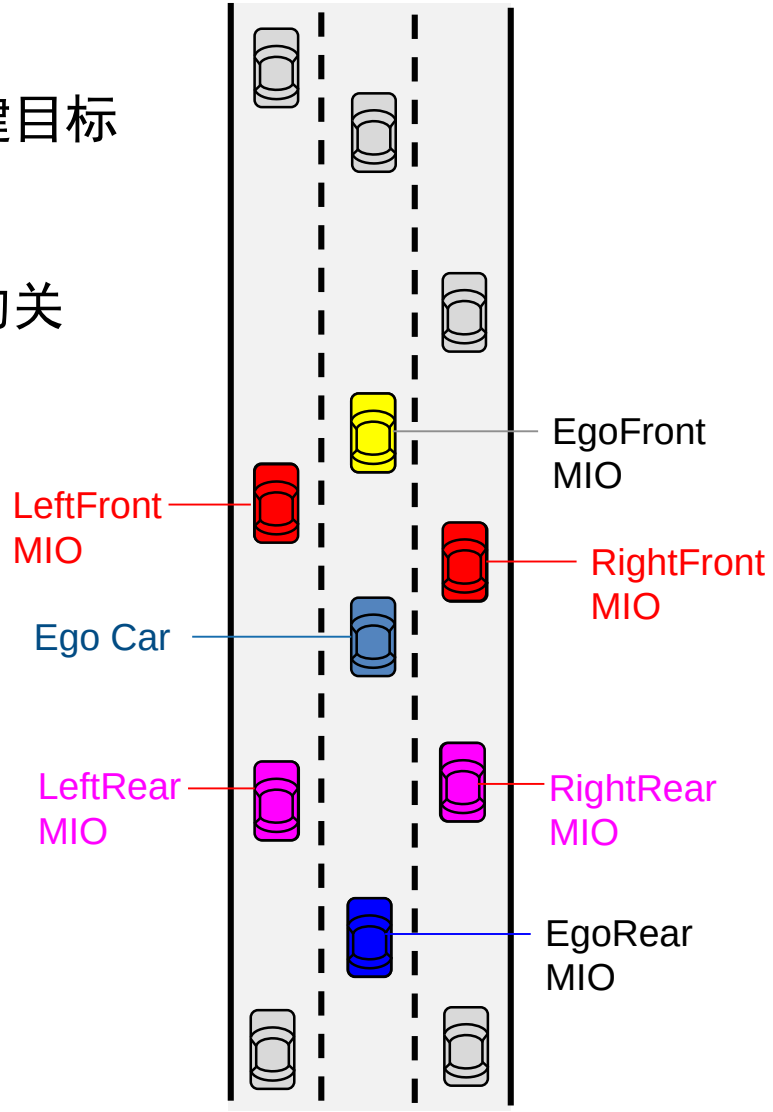


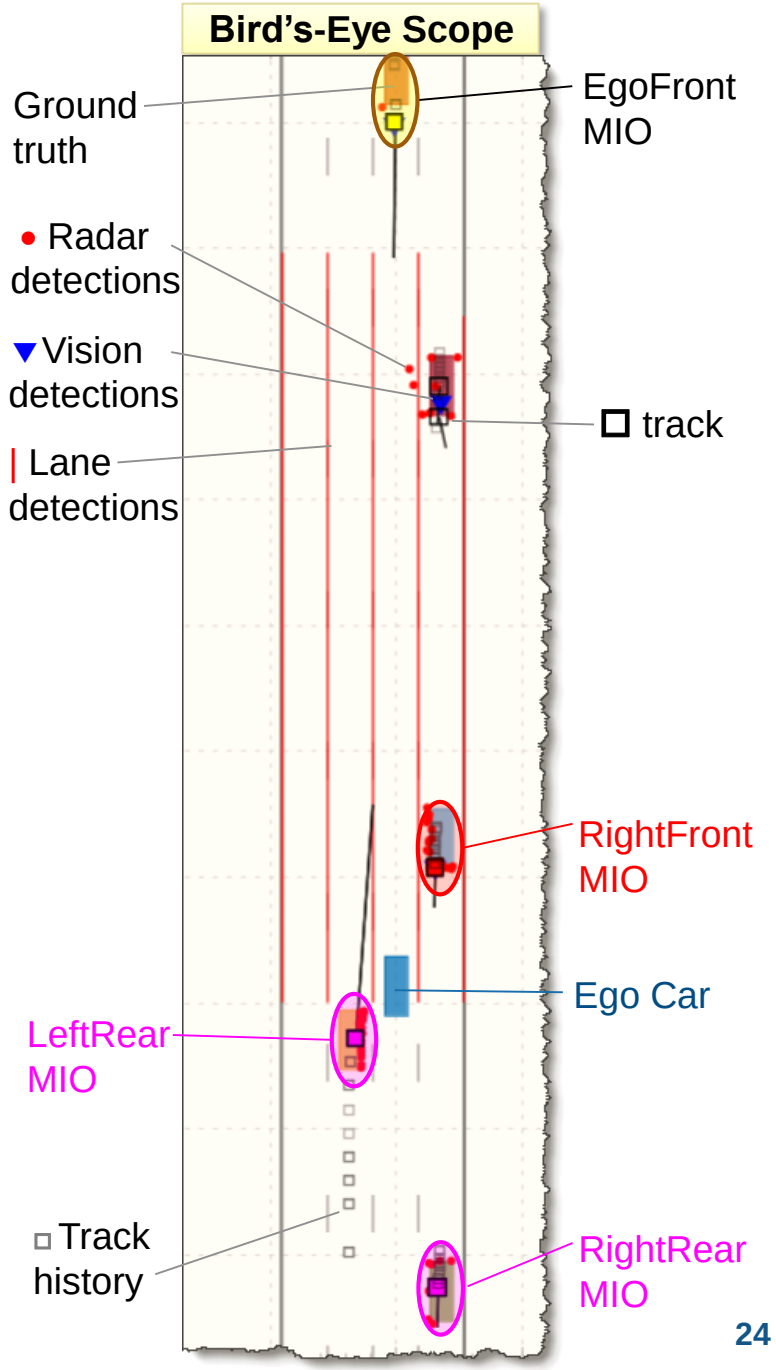
在车道跟随控制器中添加车道变换功能



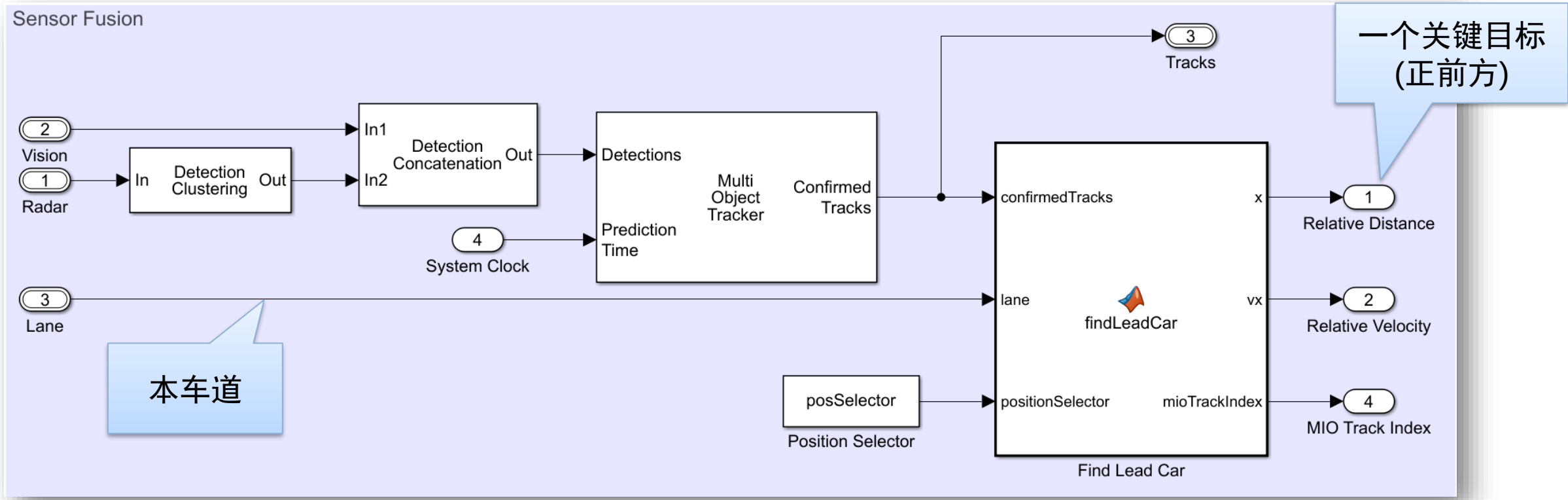
检测关键目标

- 车道跟随
  - 仅需识别一个车前方关键目标
- **车道变换**
  - 需要识别更多环绕本车的关键目标



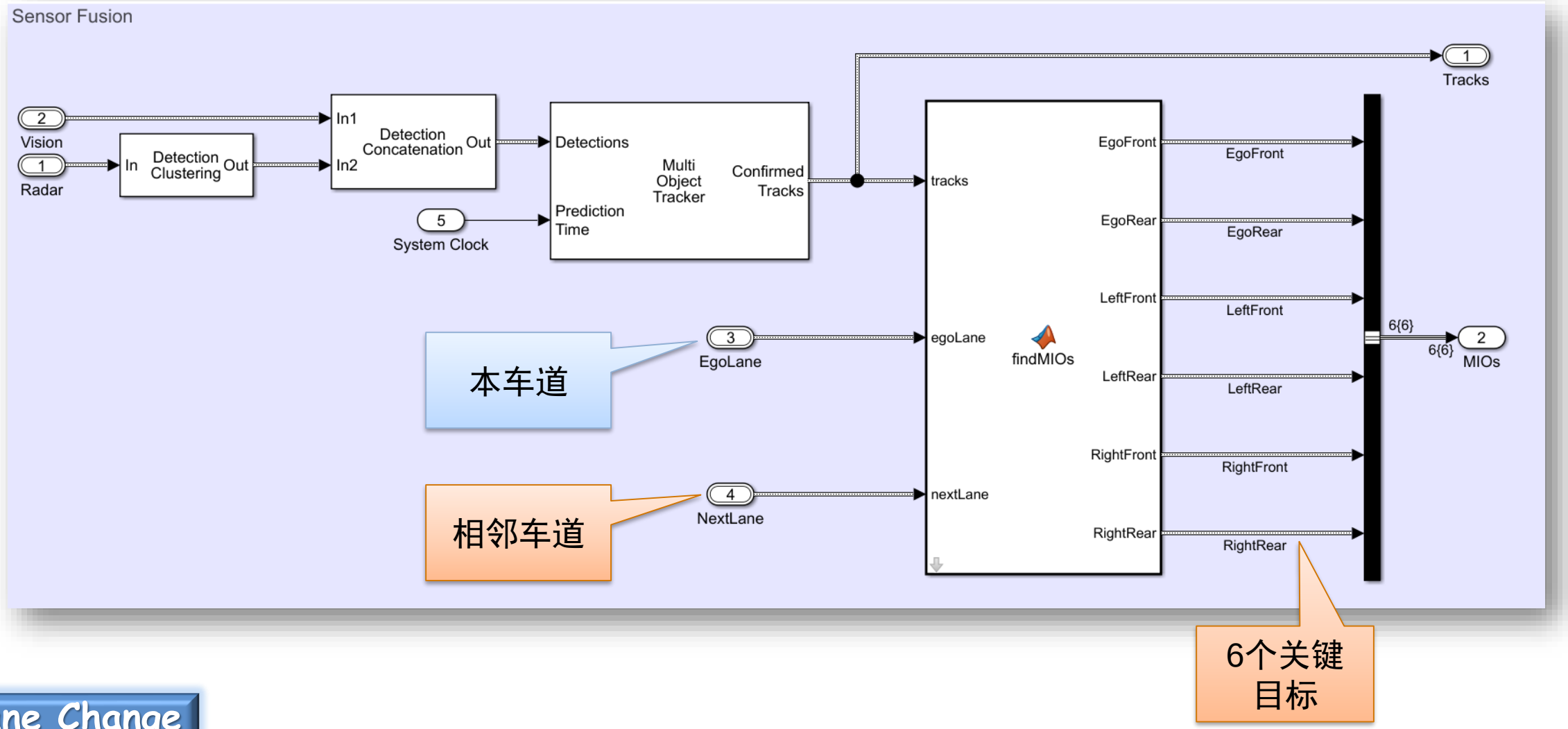


车道保持的关键目标识别



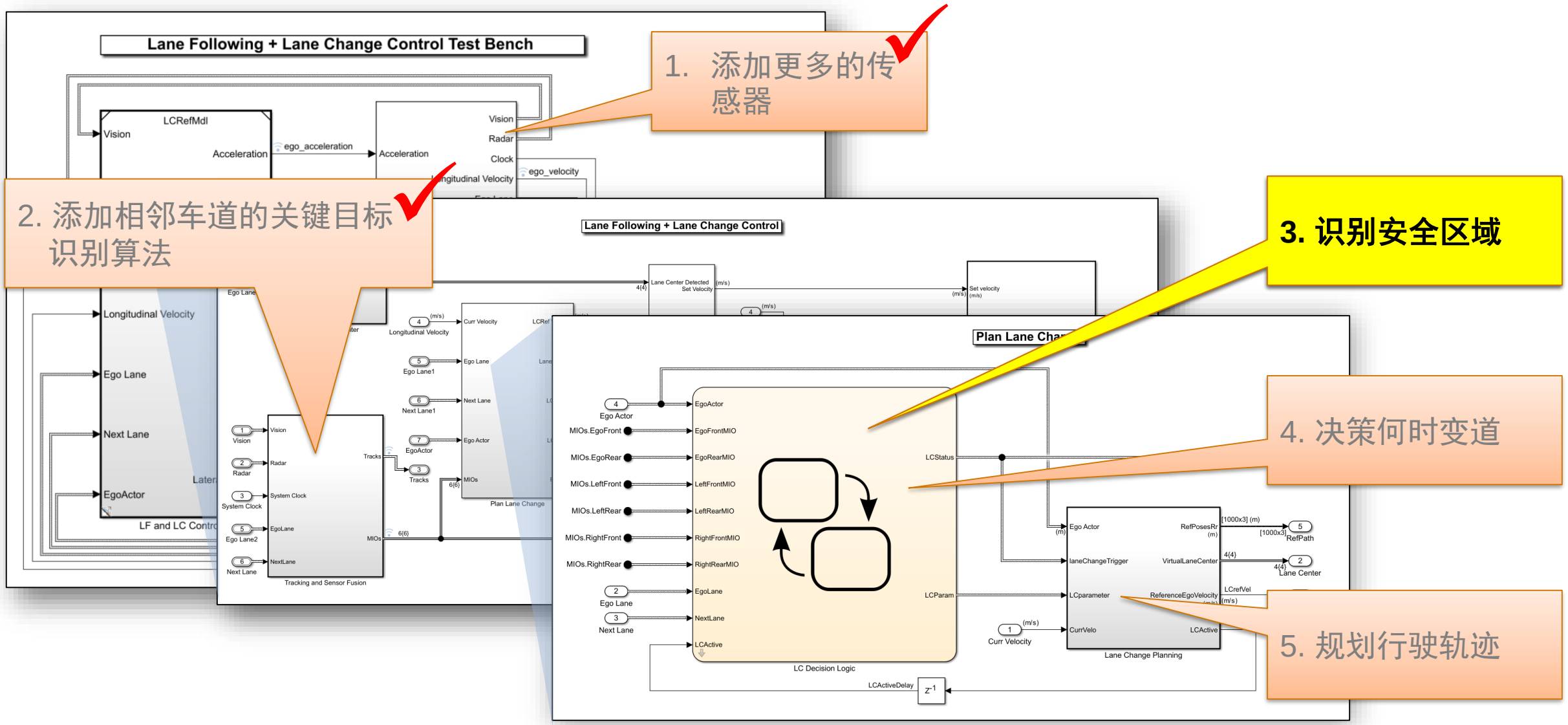
Baseline example

添加用于车道变换的MIO检测器



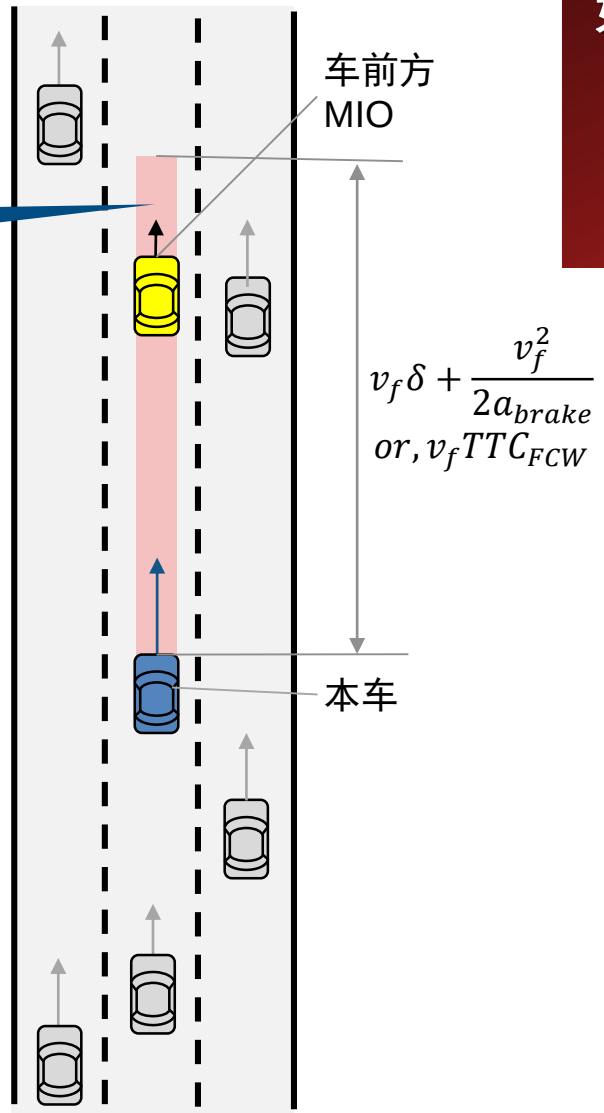
+ Lane Change

在车道跟随控制器中添加车道变换功能



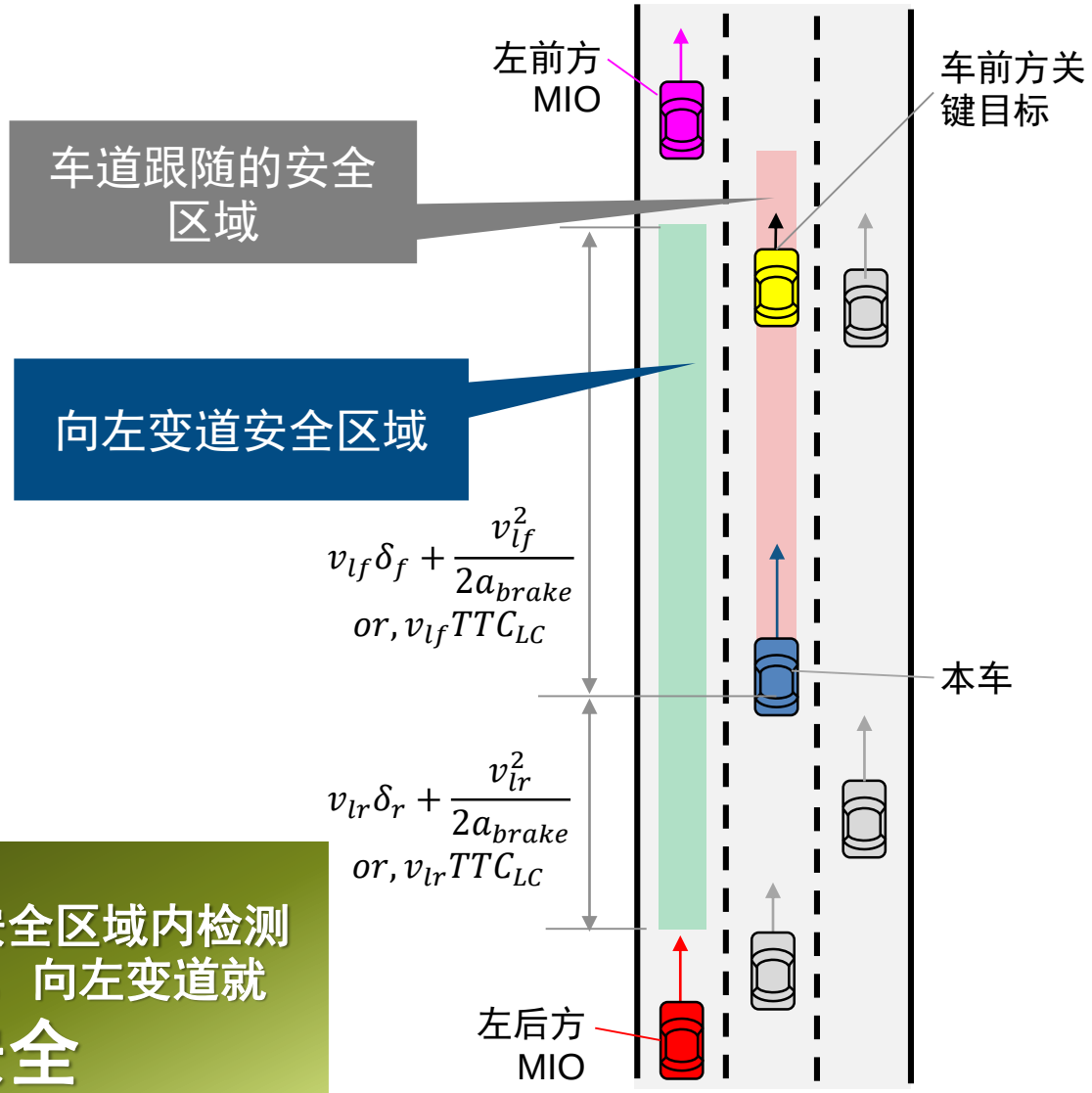
识别安全区域

车道跟随的安全区域



如果在安全区域内检测到车前方关键目标，车道跟随就 **不安全**

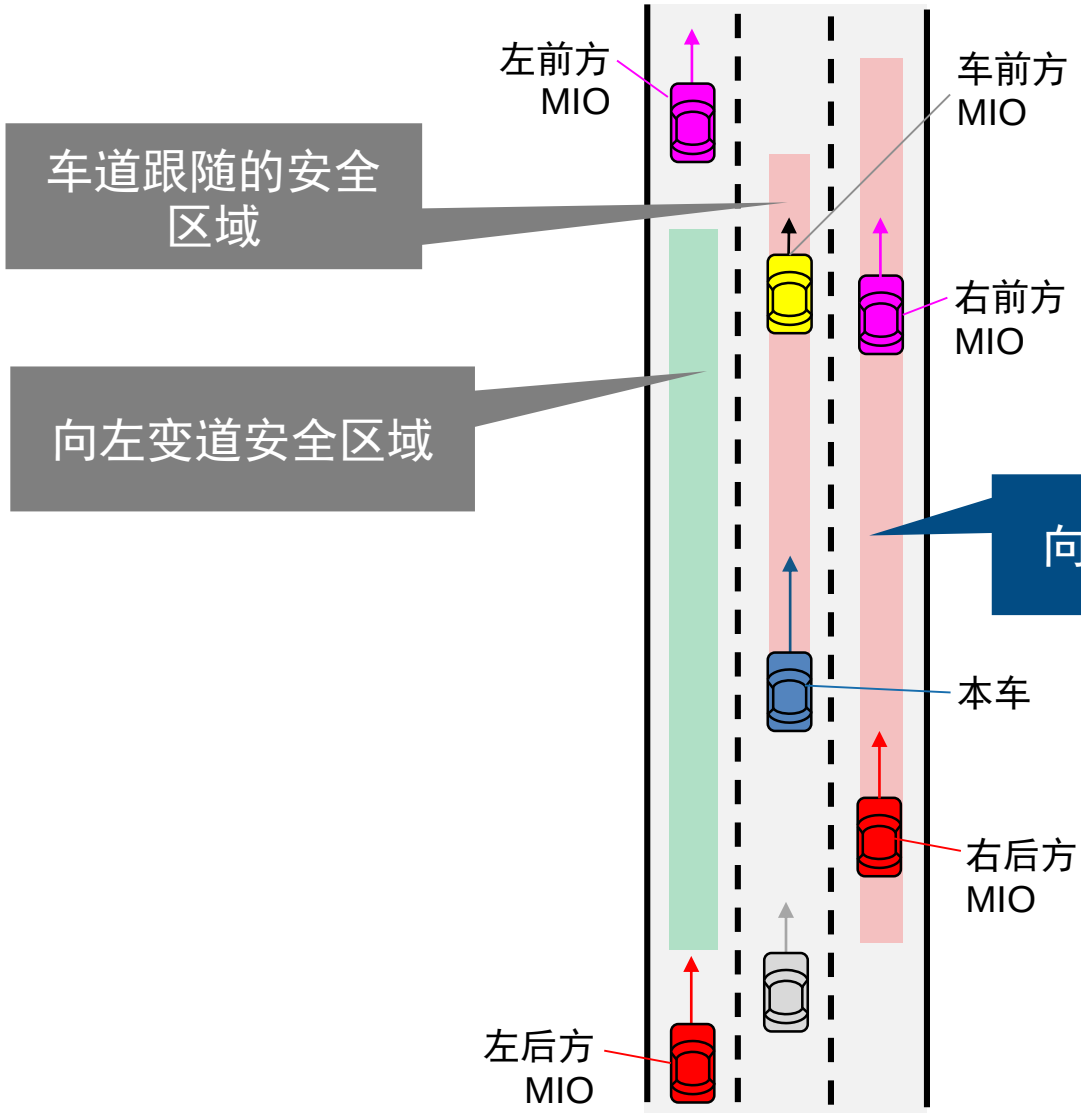
识别安全区域



如果没有在安全区域内检测到关键目标，向左变道就

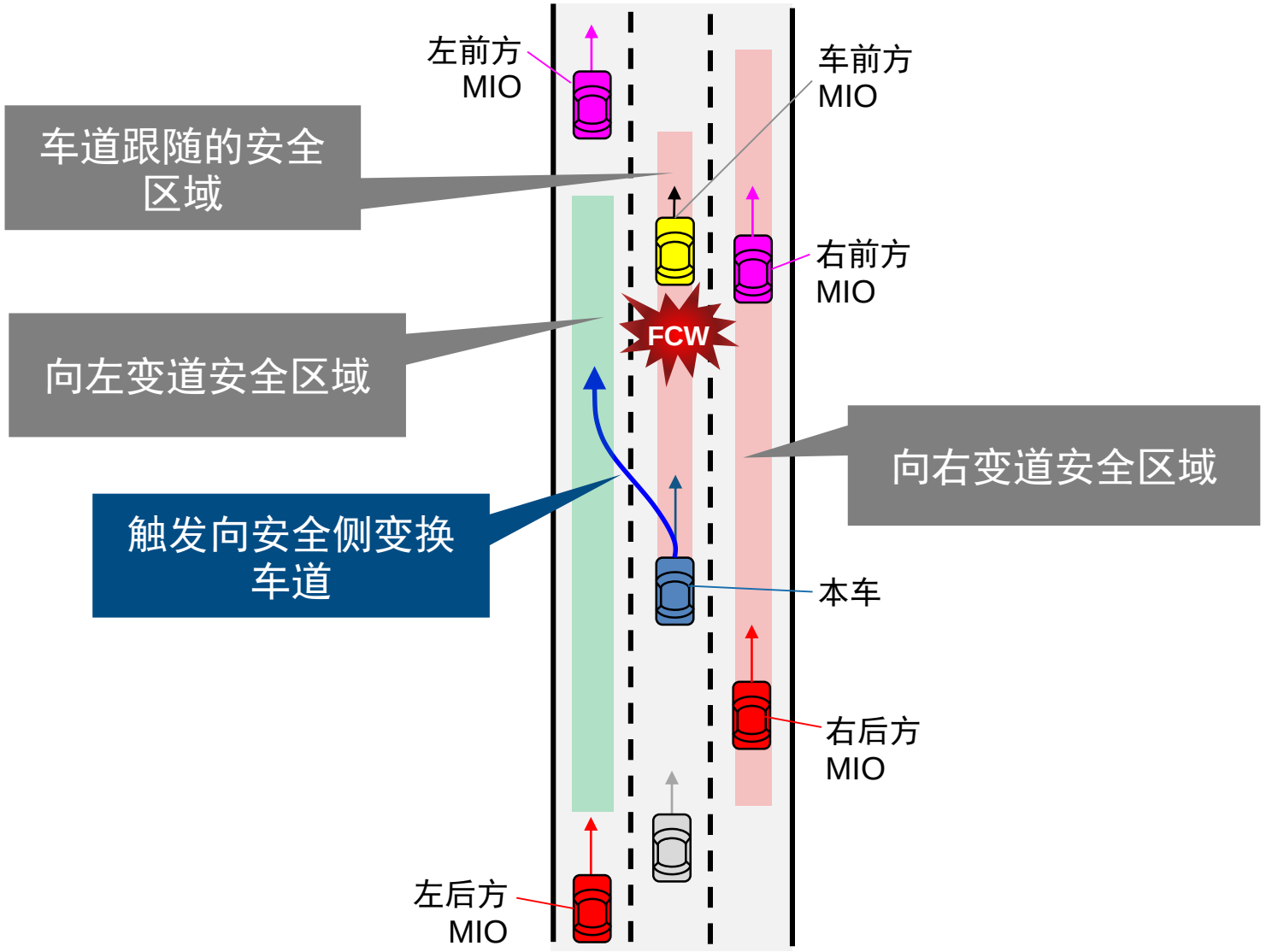
安全

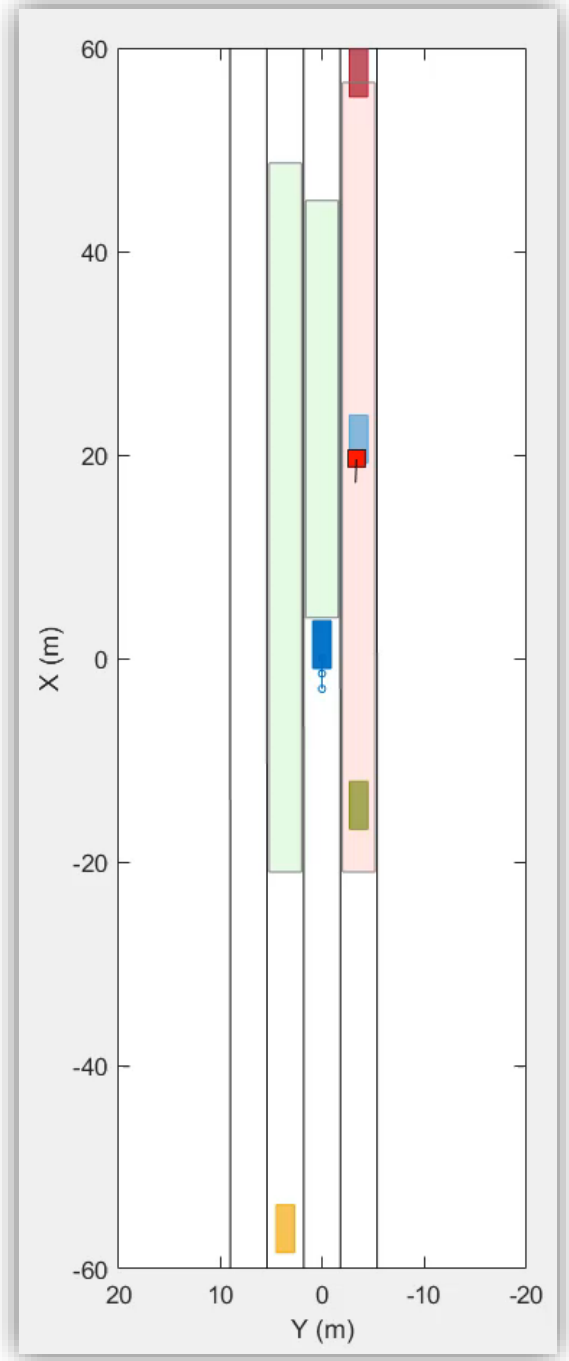
识别安全区域



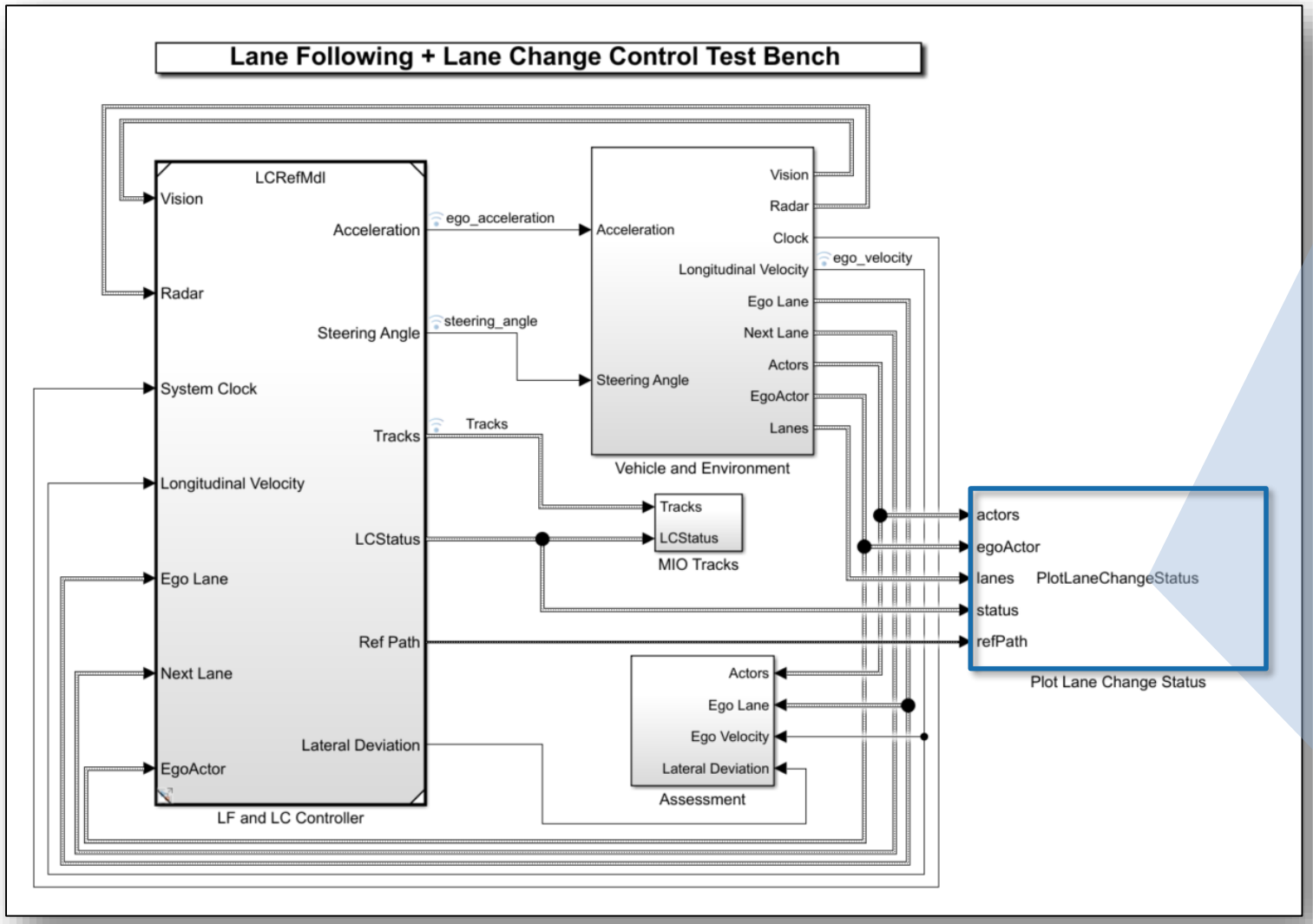
如果在安全区域内检测到关键目标，
向右变道就 **不安全**

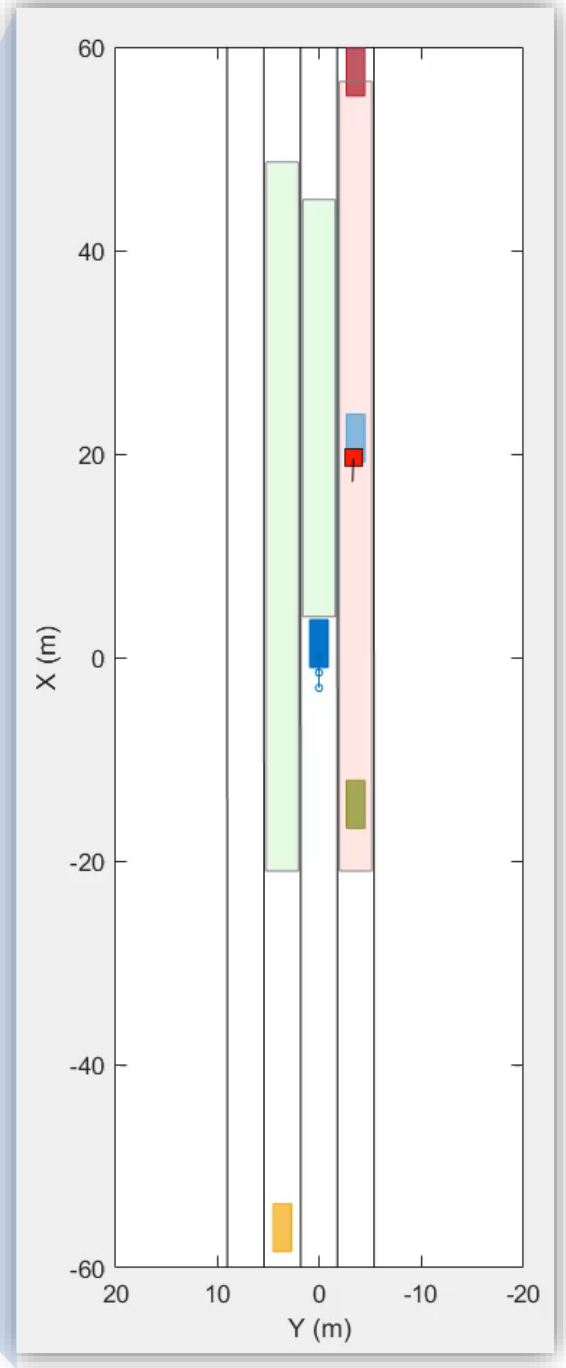
识别安全区域


左前方
MIO
车前方
MIO
车道跟随的安全区域
右前方
MIO
FCW
向左变道安全区域
向右变道安全区域
触发向安全侧变换车道
本车
右后方
MIO
左后方
MIO

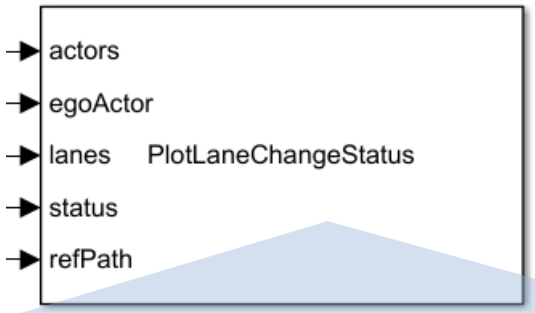

60
40
20
0
-20
-40
-60
X (m)
20
10
0
-10
-20
Y (m)

安全区域与轨迹的可视化





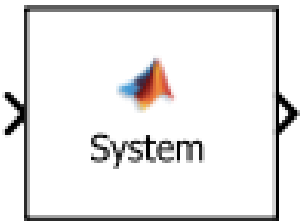
安全区域与轨迹的可视化



Plot Lane Change Status

PlotLaneChangeStatus.m

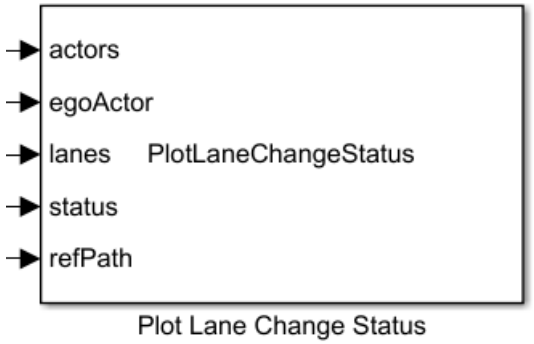
```
classdef PlotLaneChangeStatus < matlab.System
    % Custom helper visualization to show status of MIOs, safety zones, and
    % ego trajectory during lane change

    properties(Access = private)
        Figure
        BEP
        OutlinePlotter
        LaneBoundaryPlotter
        SafeMIOPlotter
        UnSafeMIOPlotter
        ActorPatches
        ZoneFront
        ZoneLeft
        ZoneRight
        EgoTrace
        EgoPath
        LCPath
```



MATLAB System

- 使用MATLAB System block在Simulink中实现可视化算法。

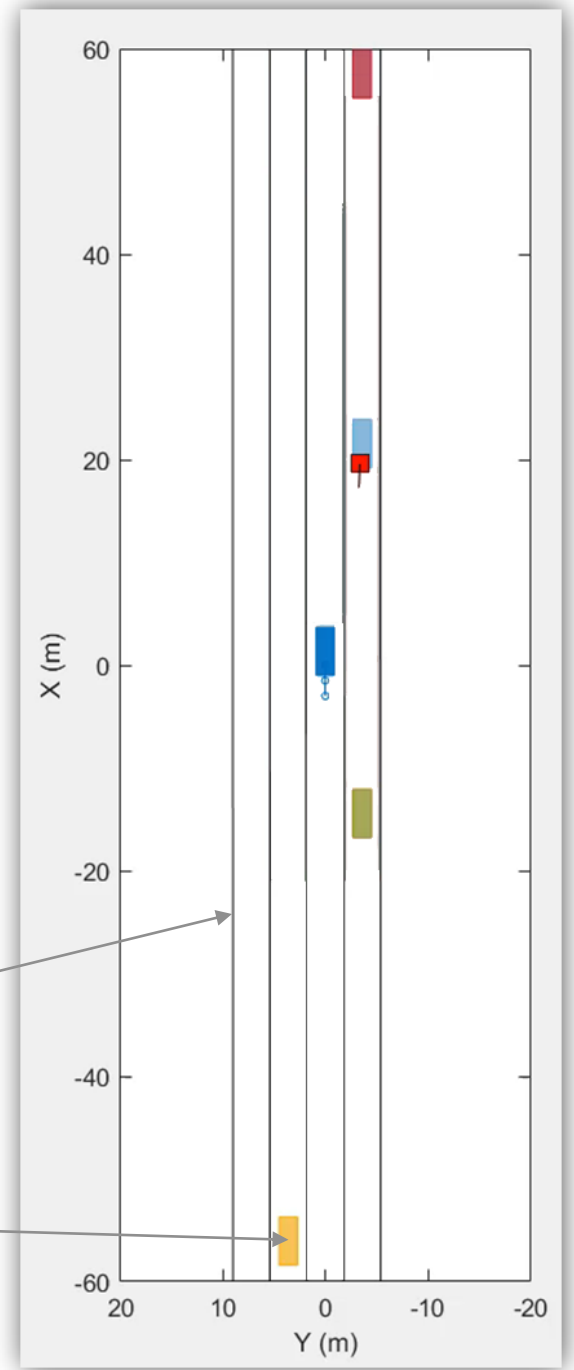
可视化需要使用的命令



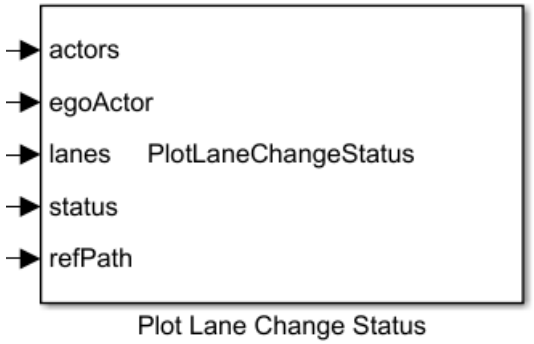

```
% create birds eye plot
obj.BEP = birdsEyePlot('Parent', hax,...
    'XLimits', [-60, 60],...
    'YLimits', [-20, 20]);
```

```
% create lane plotter
obj.LaneBoundaryPlotter = laneBoundaryPlotter(obj.BEP,...
    'DisplayName','Lane boundaries');
```

```
% create outline plotter for target actors
obj.OutlinePlotter = outlinePlotter(obj.BEP);
```

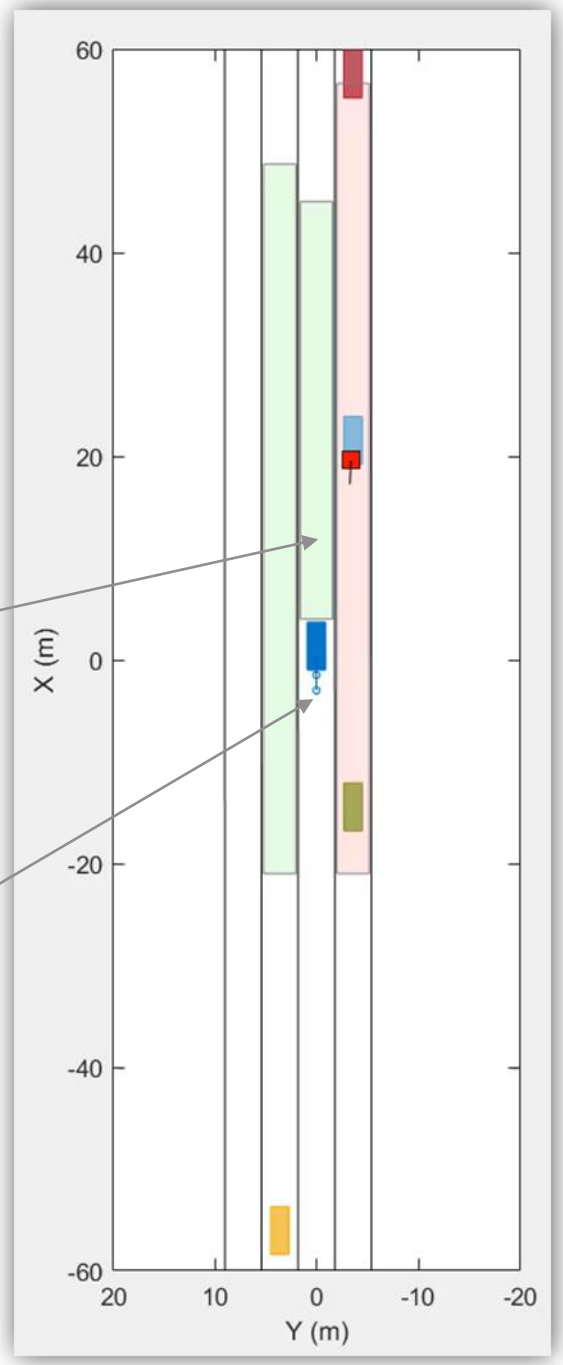


可视化需要使用的命令

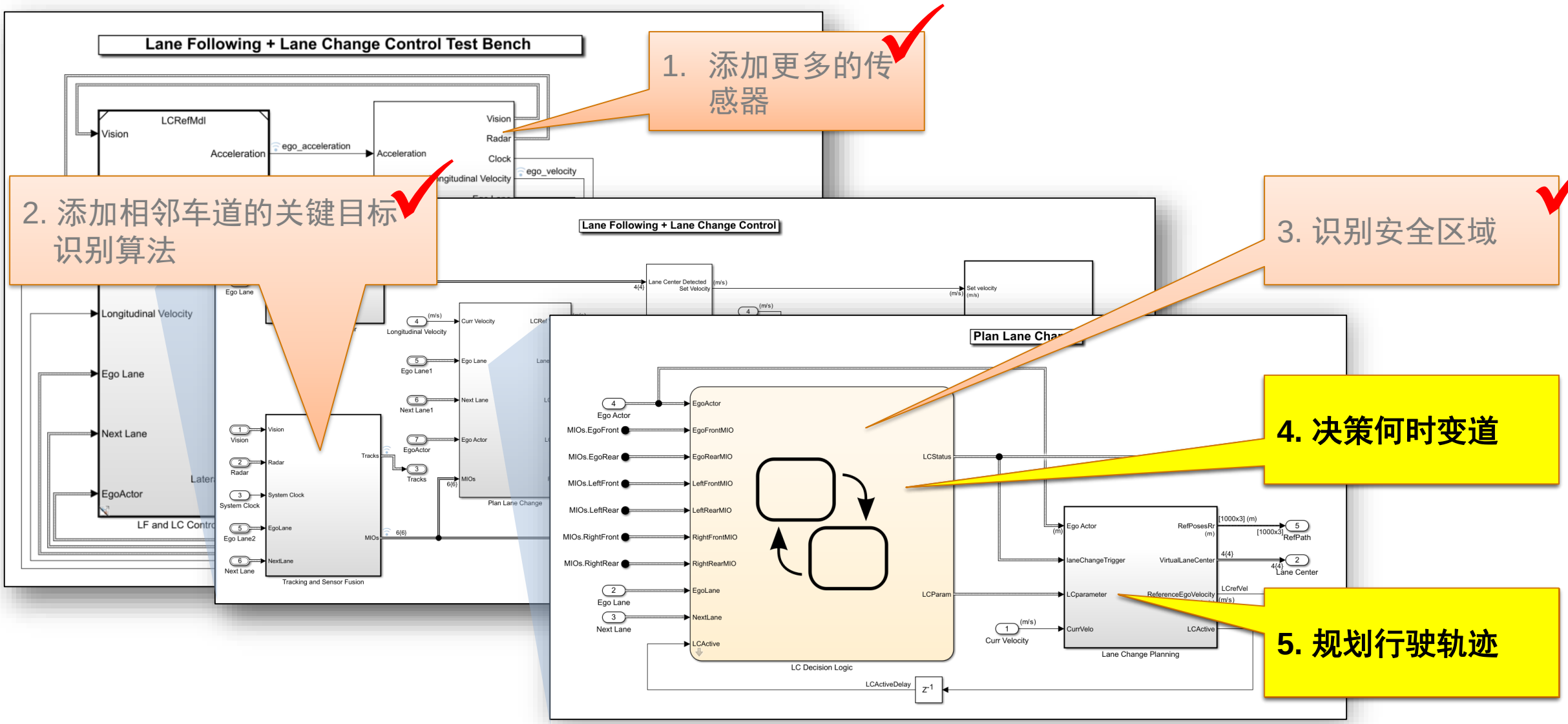



```
% create patches for safety zones
obj.ZoneFront = patch(hax,0,0,[0 0 0]);
set(obj.ZoneFront,'XData',[],'YData',[],...
    'FaceColor','green','FaceAlpha',0.1);
```

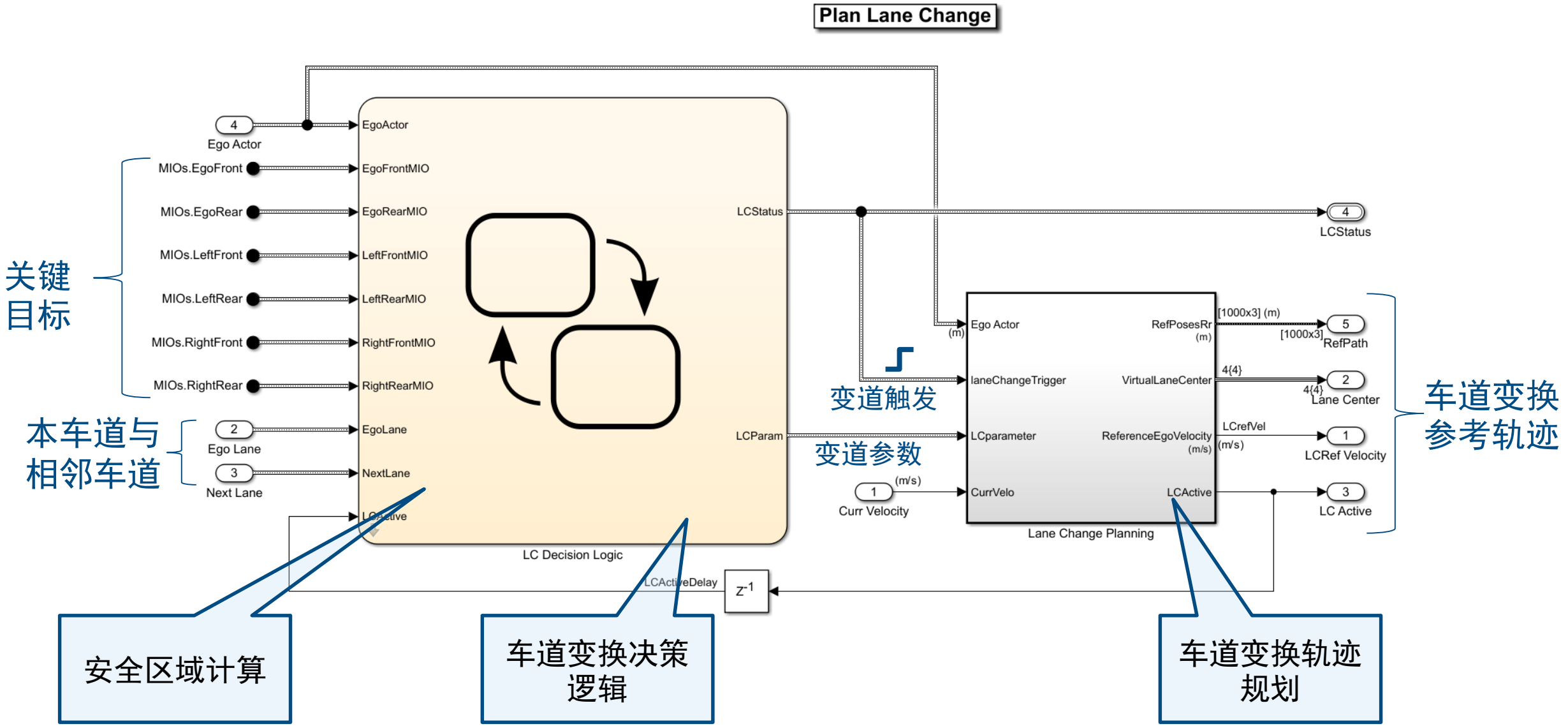
```
% create line for trajectory path
obj.LCPath = line(hax, 0, 0,...
    'Color','blue',...
    'LineWidth',2,...
    'LineStyle','-');
```



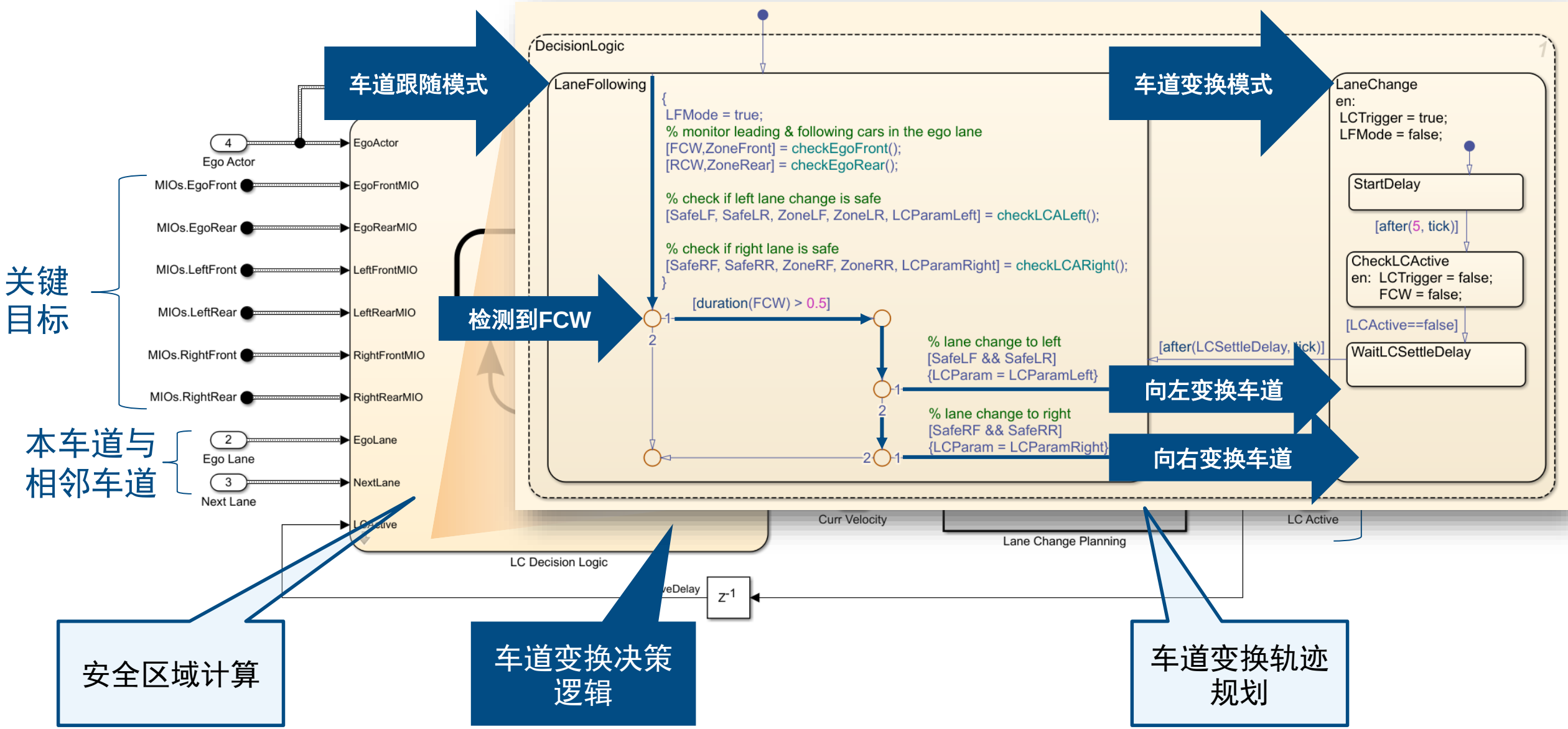
在车道跟随控制器中添加车道变换功能



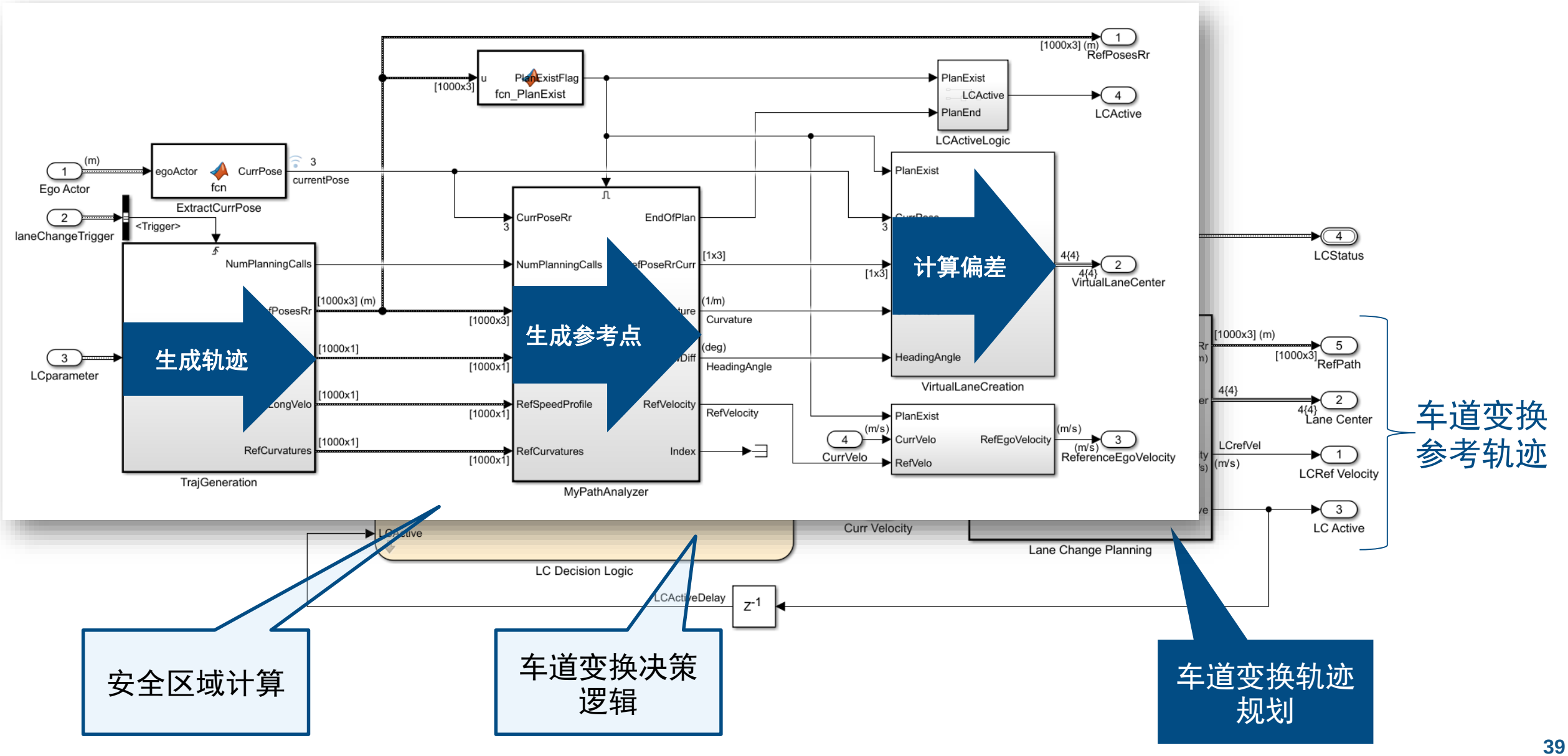
车道变换决策逻辑与轨迹规划



设计车道变换决策逻辑


车道跟随模式
车道变换模式
检测到FCW
向左变换车道
向右变换车道
关键目标
本车道与相邻车道
安全区域计算
车道变换决策逻辑
车道变换轨迹规划
DecisionLogic
LaneFollowing
LaneChange
Ego Actor
Ego Lane
Next Lane
EgoActor
EgoFrontMIO
EgoRearMIO
LeftFrontMIO
LeftRearMIO
RightFrontMIO
RightRearMIO
EgoLane
NextLane
MIOs.EgoFront
MIOs.EgoRear
MIOs.LeftFront
MIOs.LeftRear
MIOs.RightFront
MIOs.RightRear
LFMode = true;
% monitor leading & following cars in the ego lane
[FCW,ZoneFront] = checkEgoFront();
[RCW,ZoneRear] = checkEgoRear();
% check if left lane change is safe
[SafeLF, SafeLR, ZoneLF, ZoneLR, LCParamLeft] = checkLCALeft();
% check if right lane is safe
[SafeRF, SafeRR, ZoneRF, ZoneRR, LCParamRight] = checkLCARight();
[duration(FCW) > 0.5]
% lane change to left
[SafeLF && SafeLR]
{LCParam = LCParamLeft}
% lane change to right
[SafeRF && SafeRR]
{LCParam = LCParamRight}
LCTrigger = true;
LFMode = false;
StartDelay
[after(5, tick)]
CheckLCActive
en: LCTrigger = false;
FCW = false;
[LCActive==false]
WaitLCSettleDelay
[after(LCSettleDelay, tick)]
Curr Velocity
LC Active
LC Decision Logic
Lane Change Planning
z-1

设计车道变换轨迹规划


Ego Actor
egoActor
fcn
CurrPose
ExtractCurrPose
currentPose
laneChangeTrigger
<Trigger>
LCparameter
NumPlanningCalls
RefPosesRr
LongVelo
RefCurvatures
TrajGeneration
生成轨迹
fcn_PlanExist
PlanExistFlag
LCActiveLogic
PlanExist
LCActive
PlanEnd
RefPosesRr
LCActive
CurrPoseRr
EndOfPlan
NumPlanningCalls
RefSpeedProfile
RefVelocity
RefCurvatures
Index
MyPathAnalyzer
生成参考点
VirtualLaneCreation
HeadingAngle
Curvature
RefVelocity
计算偏差
VirtualLaneCenter
LCStatus
CurrVelo
RefEgoVelocity
ReferenceEgoVelocity
RefPath
Lane Center
LCRef Velocity
LC Active
LC Decision Logic
Curr Velocity
Lane Change Planning
LCActiveDelay
z-1
安全区域计算
车道变换决策逻辑
车道变换轨迹规划
车道变换参考轨迹

生成轨迹

- 五次多项式

$$s(t) = a_5t^5 + a_4t^4 + a_3t^3 + a_2t^2 + a_1t + a_0$$
$$\dot{s}(t) = 5a_5t^4 + 4a_4t^3 + 3a_3t^2 + 2a_2t + a_1$$
$$\ddot{s}(t) = 20a_5t^3 + 12a_4t^2 + 6a_3t + 2a_2$$

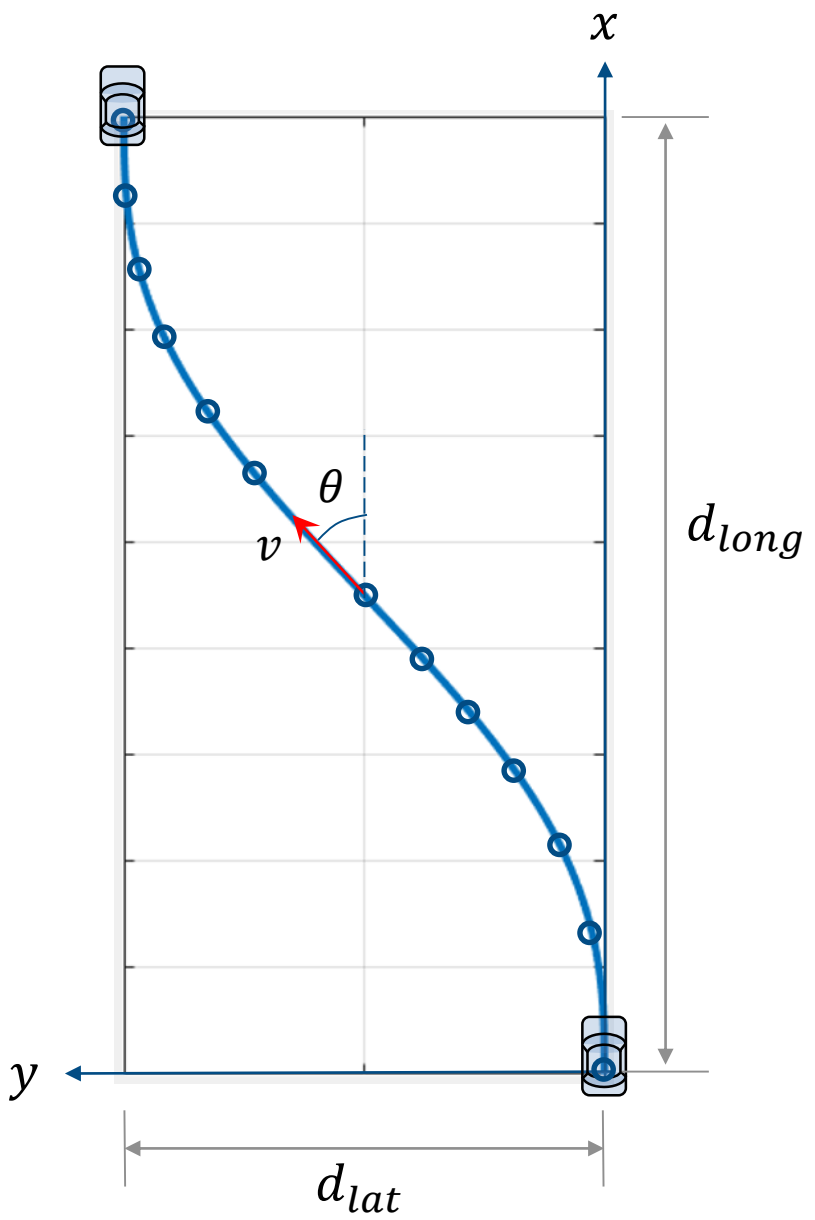
$$where\ s = longitudinal\ or\ lateral\ distance$$

- 起点的边界条件

$$a_0 = s_{start}$$
$$a_1 = \dot{s}_{start}$$
$$2a_2 = \ddot{s}_{start}$$

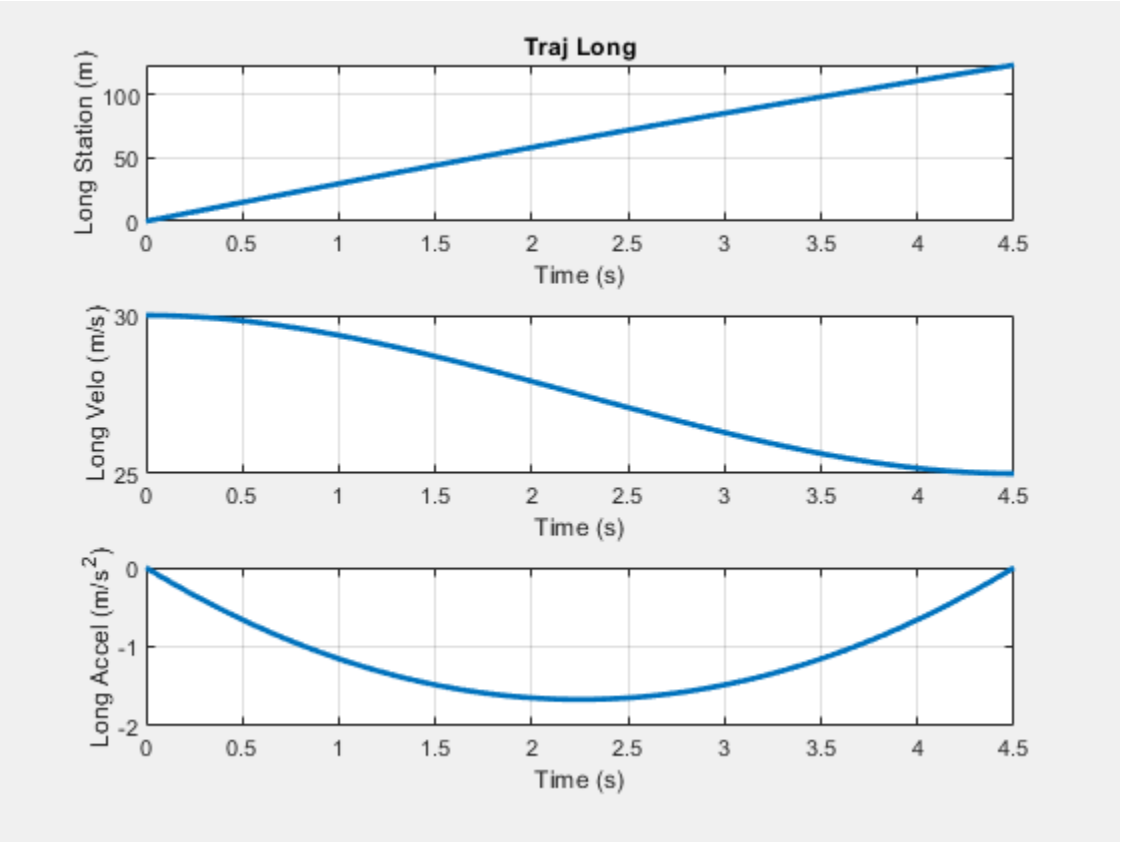
- 终点的边界条件

$$a_5t_f^5 + a_4t_f^4 + a_3t_f^3 + a_2t_f^2 + a_1t_f + a_0 = s_{end}$$
$$5a_5t_f^4 + 4a_4t_f^3 + 3a_3t_f^2 + 2a_2t_f + a_1 = \dot{s}_{end}$$
$$20a_5t_f^3 + 12a_4t_f^2 + 6a_3t_f + 2a_2 = \ddot{s}_{end}$$

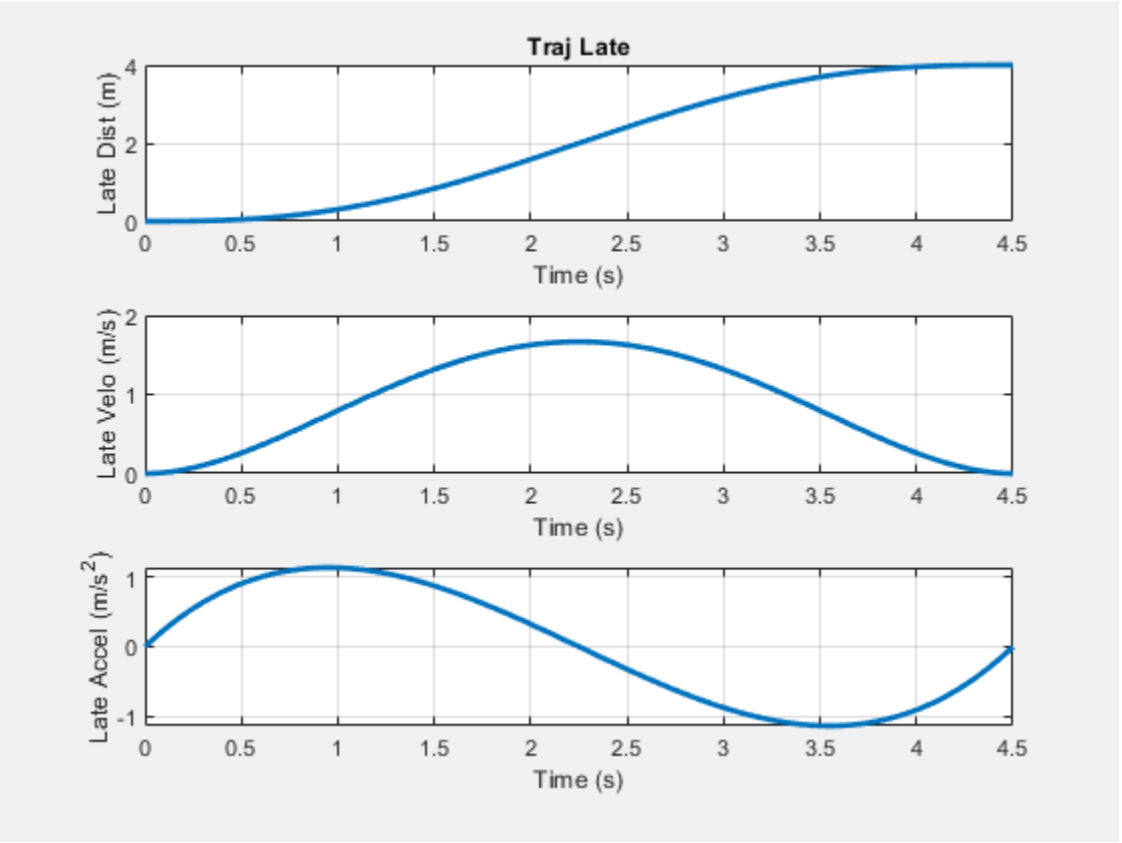


变道轨迹样例

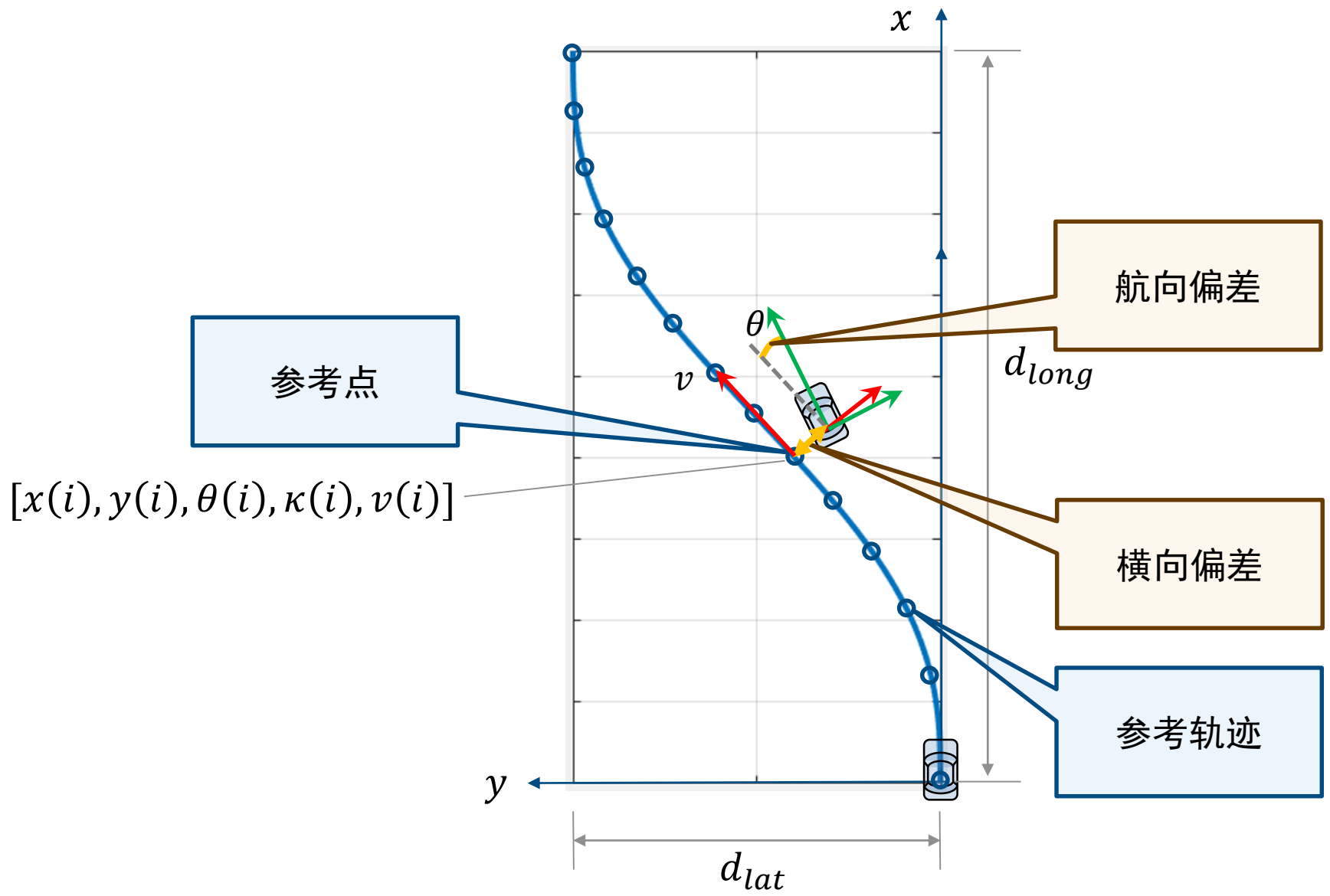
Longitudinal trajectory



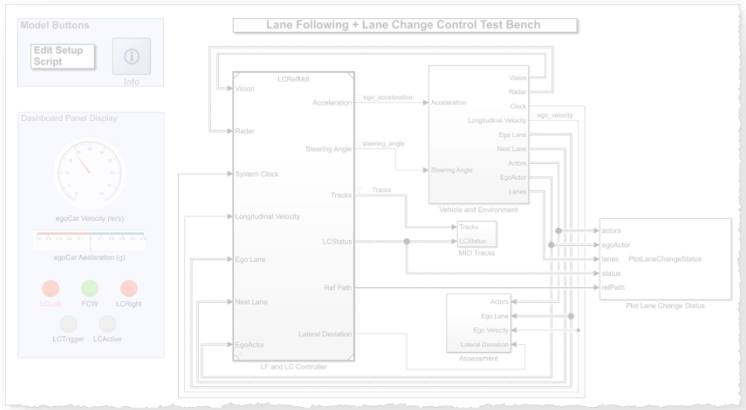
Lateral trajectory



计算车辆到参考点的偏差

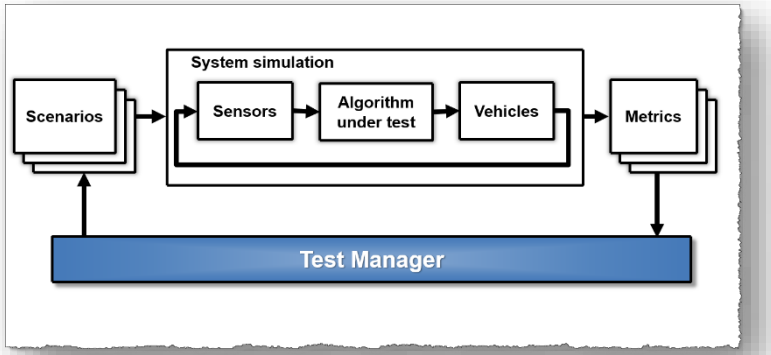


案例研究：设计与测试高速公路自动驾驶（决策、规划与控制）



设计车道跟随 + 车道变换控制器

- 回顾车道跟随控制器
- 添加传感器配置
- 添加关键目标检测器
- 设计安全区域算法
- 设计车道变换逻辑
- 设计路径规划器



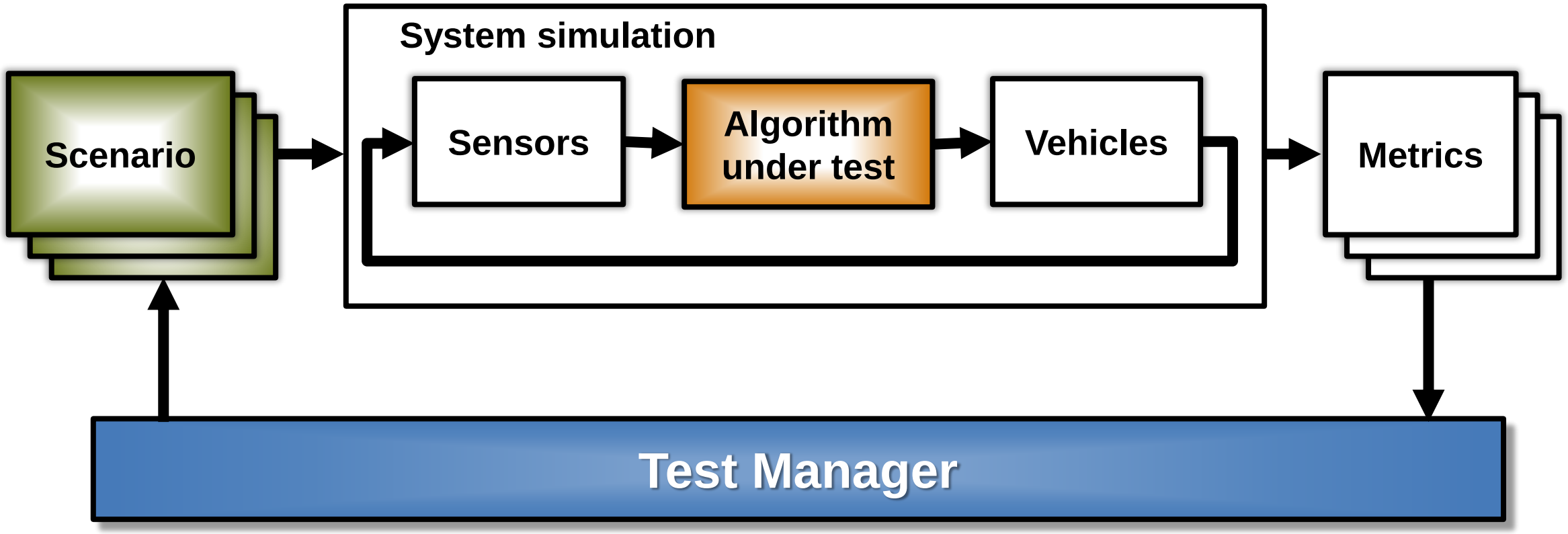
自动回归测试

- 创建预定义的场景
- 定义评价指标
- 运行Simulink Test

采用Agent的鲁棒性测试

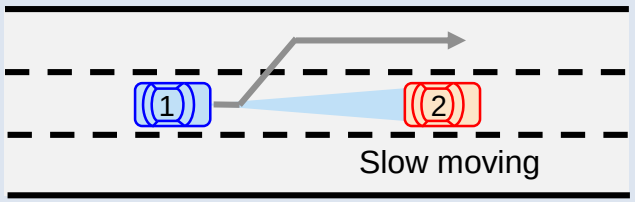
- 定义Agent的驾驶逻辑
- 采用Agent随机化交通场景
- 识别与评定非预期行为

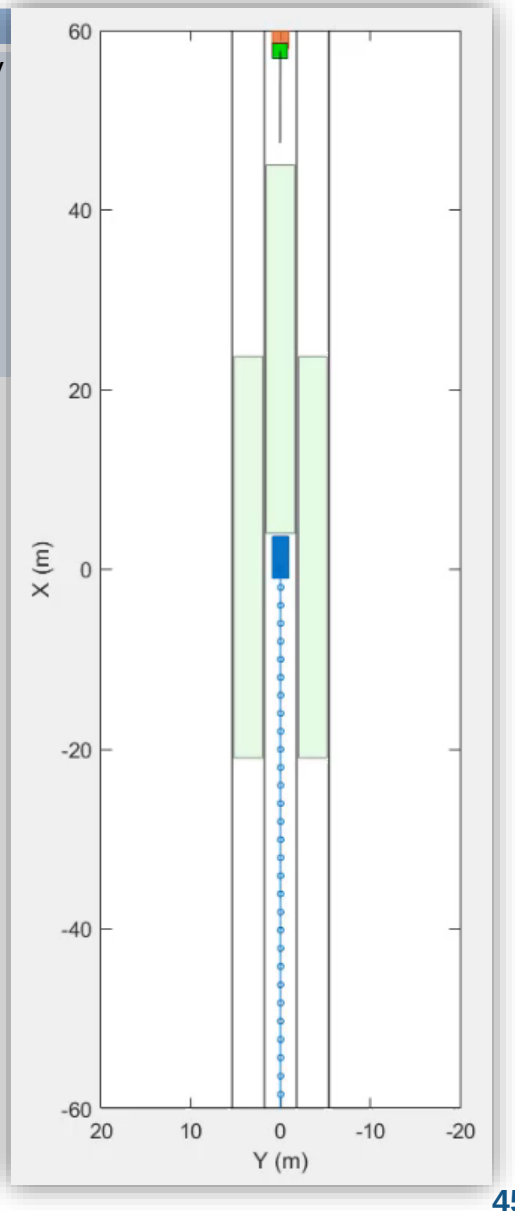
Manage testing against scenarios



创建测试场景

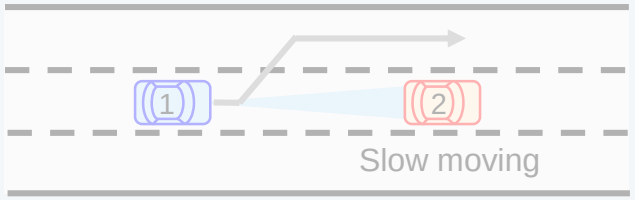
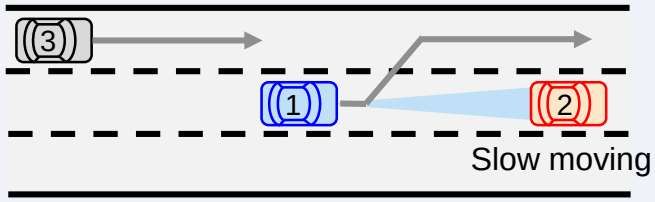
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

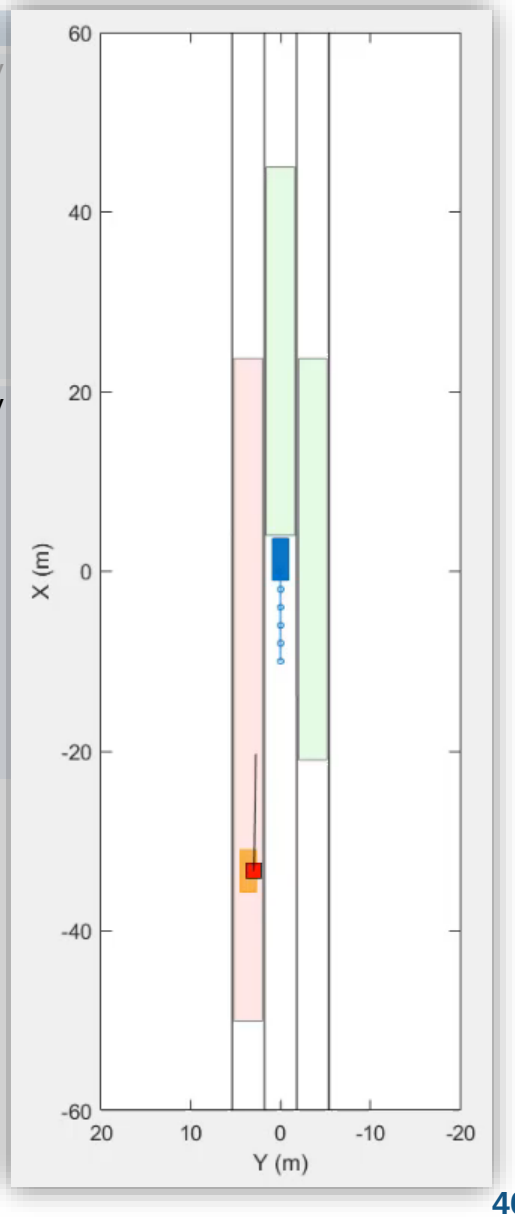
No	Test Name	Test Description	Host car	Lead car
1	01_SlowMoving	Passing for slow moving lead car 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity 10m/s



创建测试场景

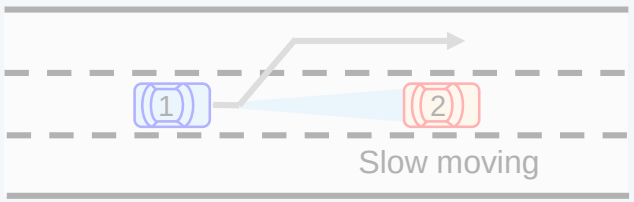
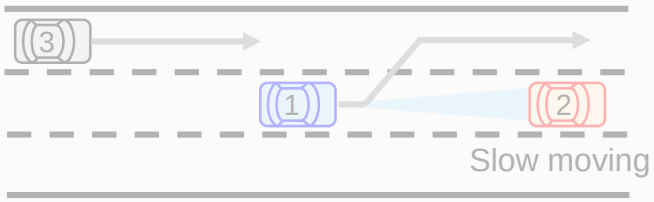
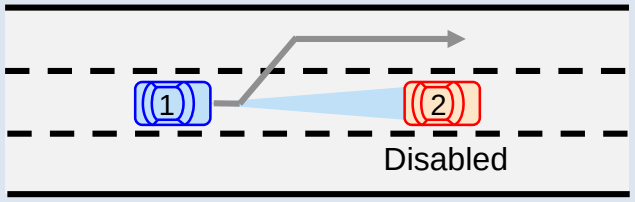
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

No	Test Name	Test Description	Host car	Lead car
1	01_SlowMoving	Passing for slow moving lead car 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity 10m/s
2	02_SlowMoving WithPassingCar	Passing for slow moving Lead car With rapidly approaching car in adjacent lane 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity 10m/s



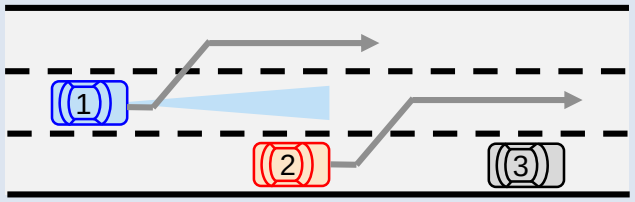
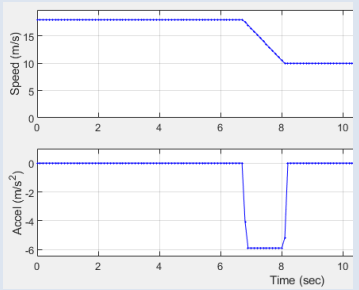
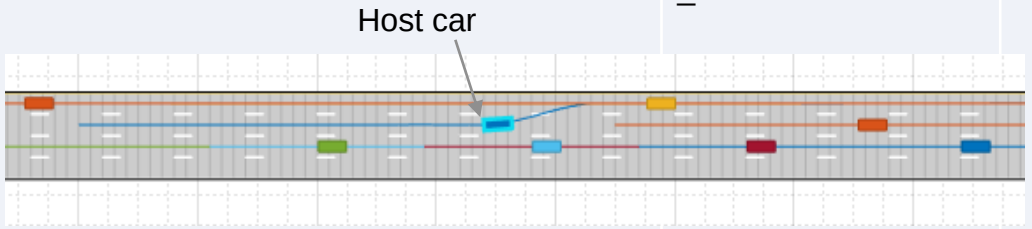
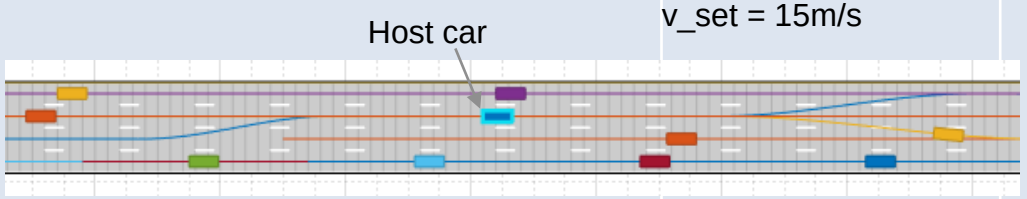
创建测试场景

HW : Headway
HWT : Headway time
v_set : set velocity for ego car

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
1	01_SlowMoving	Passing for slow moving lead car 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity = 10m/s	None	
2	02_SlowMoving WithPassingCar	Passing for slow moving Lead car With rapidly approaching car in adjacent lane 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity = 10m/s	Constant velocity = 33m/s	
3	03_DisabledCar	Passing for disabled lead car 	initial velocity = 20m/s HWT = 12sec (HW = 240m) v_set = 20m/s	Stationary	none	

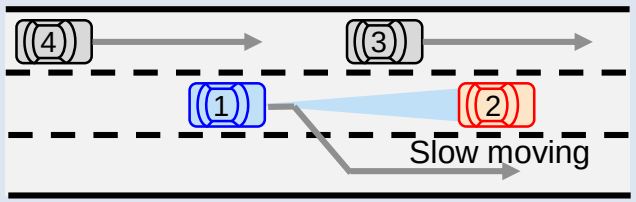
创建测试场景

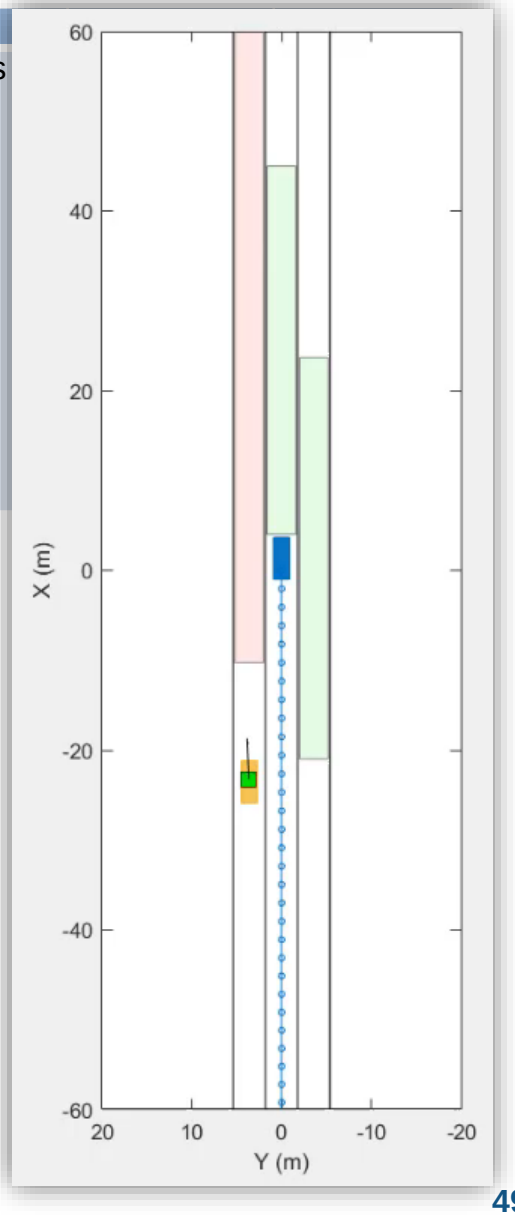
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
4	04_CutInWithBrake	Passing for cut-in car with brake 	initial velocity = 20m/s v_set = 20m/s	initial velocity = 18m/s Cut-in with brake @ 6m/s^2 (18m/s→10m/s) 	constant velocity = 10m/s	
5	05_SingleLaneChange	Single lane change with dense traffic condition 	initial velocity = 15m/s v_set = 15m/s	Slow moving	Dense traffic	
6	06_DoubleLaneChange	Double lane change with dense traffic condition 	initial velocity = 15m/s v_set = 15m/s	Slow moving	Dense traffic	

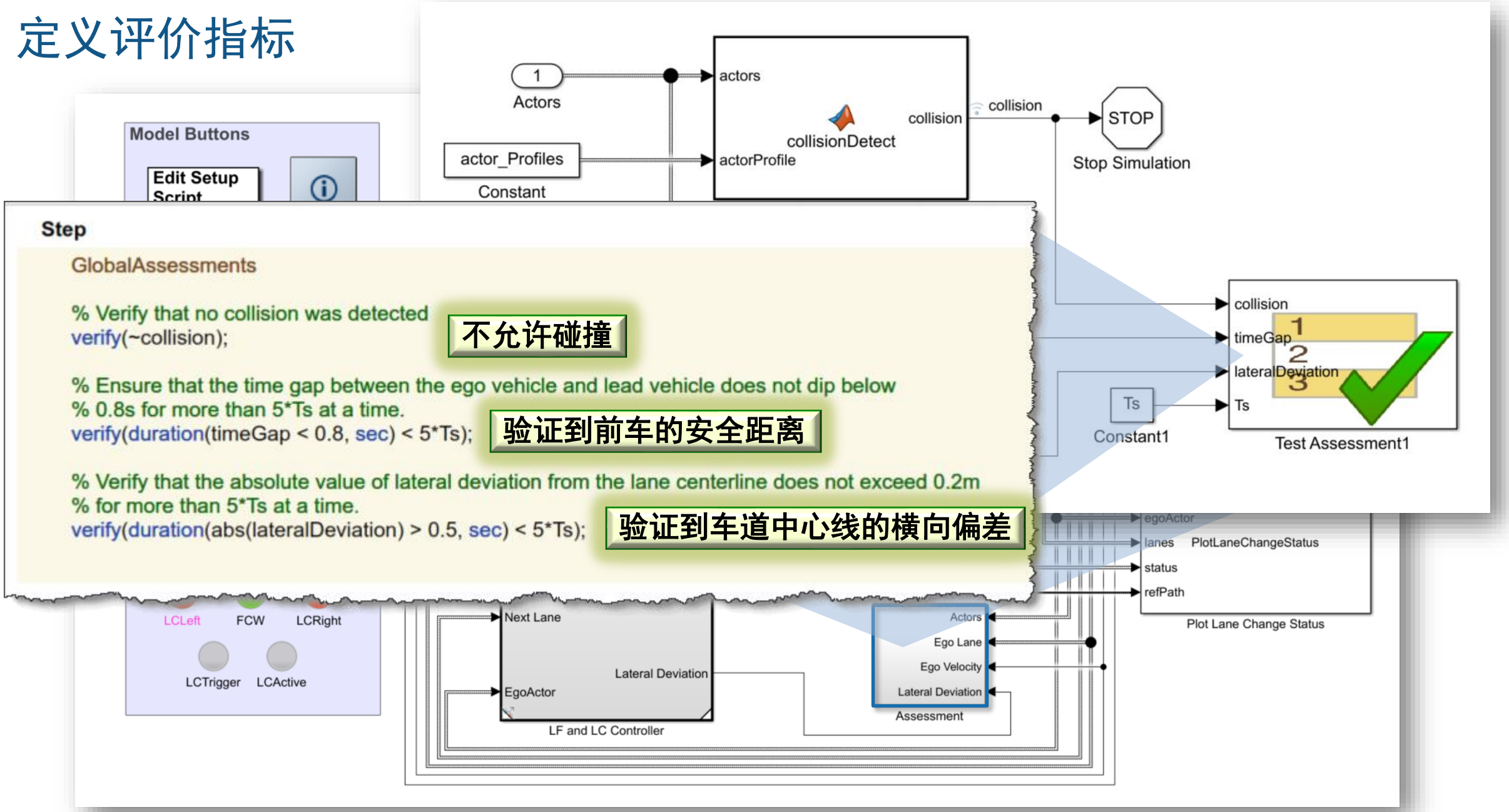
创建测试场景

HW : Headway
HWT : Headway time
v_set : set velocity for ego car

No	Test Name	Test Description	Host car	Lead car
7	07_RightLaneChange	Passing for slow moving lead car to right lane 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity = 10m/s



定义评价指标


Step
GlobalAssessments
% Verify that no collision was detected
verify(~collision);
不允许碰撞
% Ensure that the time gap between the ego vehicle and lead vehicle does not dip below
% 0.8s for more than 5*Ts at a time.
verify(duration(timeGap < 0.8, sec) < 5*Ts);
验证到前车的安全距离
% Verify that the absolute value of lateral deviation from the lane centerline does not exceed 0.2m
% for more than 5*Ts at a time.
verify(duration(abs(lateralDeviation) > 0.5, sec) < 5*Ts);
验证到车道中心线的横向偏差
Model Buttons
Edit Setup Script
LCLeft
FCW
LCRight
LCTrigger
LCActive
1
Actors
actor_Profiles
Constant
actors
collisionDetect
collision
actorProfile
collision
STOP
Stop Simulation
collision
timeGap
lateralDeviation
Ts
Test Assessment1
Ts
Constant1
egoActor
lanes
PlotLaneChangeStatus
status
refPath
Plot Lane Change Status
Next Lane
Lateral Deviation
EgoActor
LF and LC Controller
Actors
Ego Lane
Ego Velocity
Lateral Deviation
Assessment

通过Test Manager自动生成测试报告

Report Generated by Test Manager

Title: Lane Following + Lane Change Control Test
Author: Seo-Wook Park
Date: 04-Apr-2019 12:03:36

Test Environment

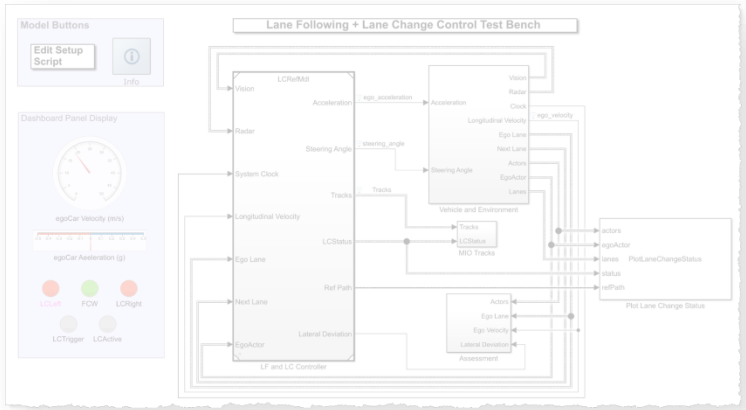
Platform: PCWIN64
MATLAB: (R2019a)

TestReport

Summary

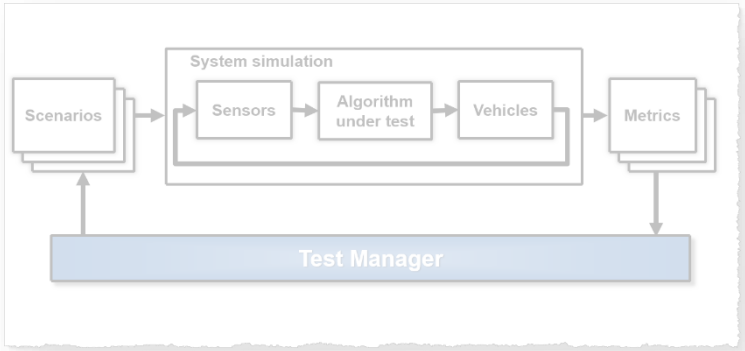
Name	Outcome	Duration (Seconds)
LCTestCases	7	2059
StraightPath	7	2059
01_SlowMoving		304
02_SlowMovingWithPassingCar		224
03_DisabledCar		330
04_CutInWithBrake		235
05_SingleLaneChange		314
06_DoubleLaneChange		420
07_RightLaneChange		228

案例研究：设计与测试高速公路自动驾驶（决策、规划与控制）



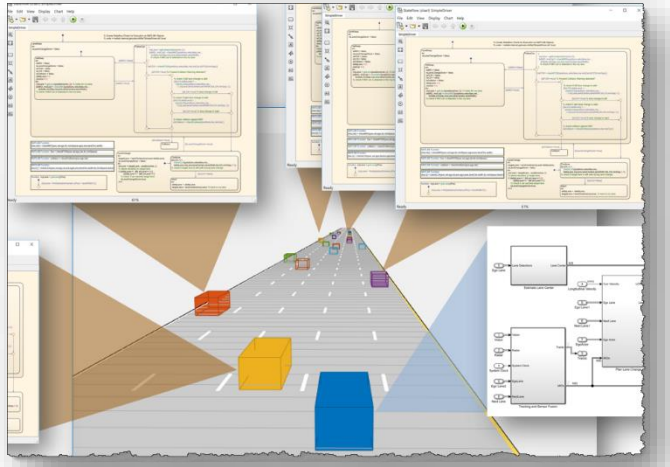
设计车道跟随 + 车道变换控制器

- 回顾车道跟随控制器
- 添加传感器配置
- 添加关键目标检测器
- 设计安全区域算法
- 设计车道变换逻辑
- 设计路径规划器



自动回归测试

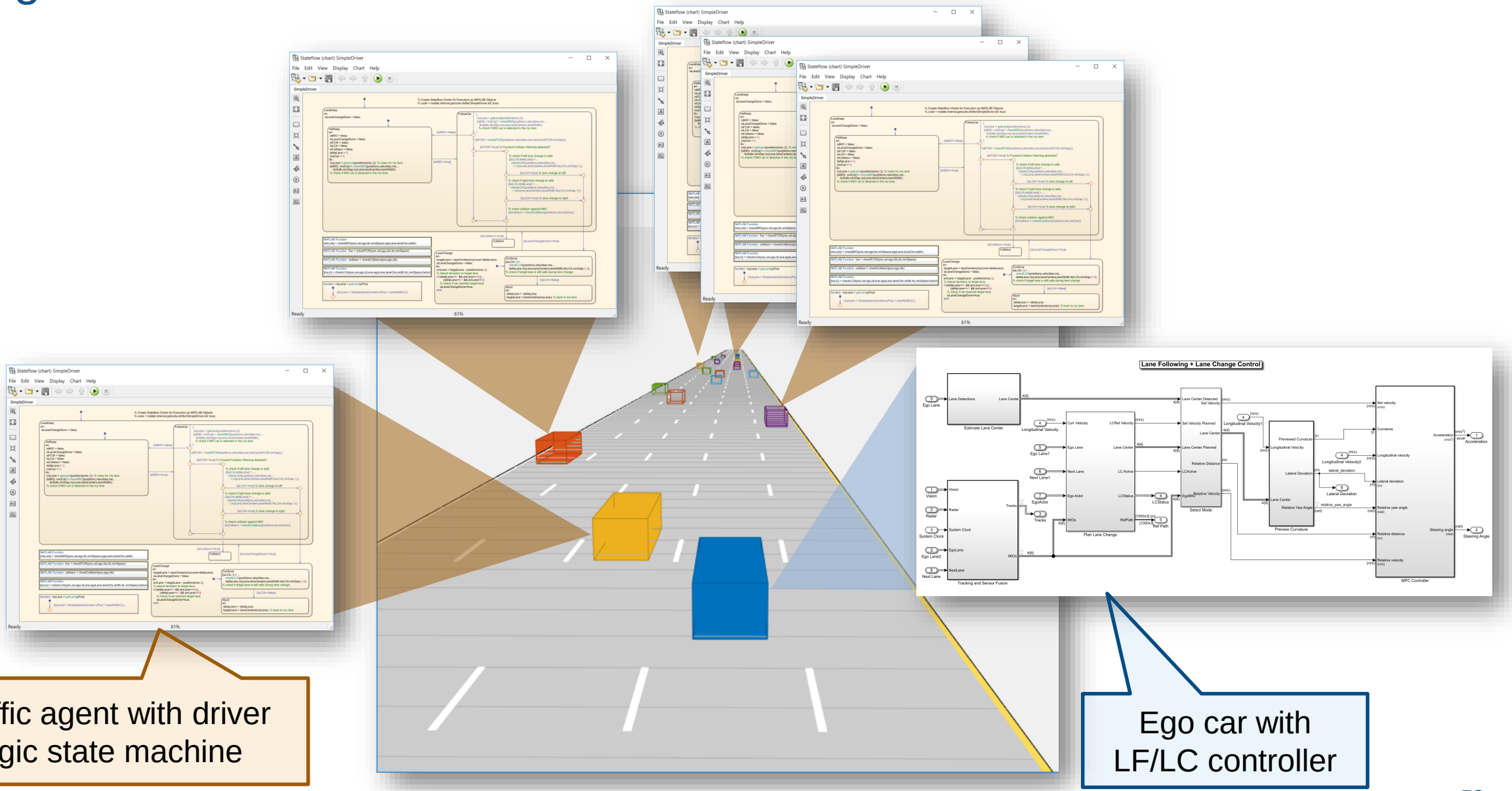
- 创建预定义的场景
- 定义评价指标
- 运行Simulink Test



采用Agent的鲁棒性测试

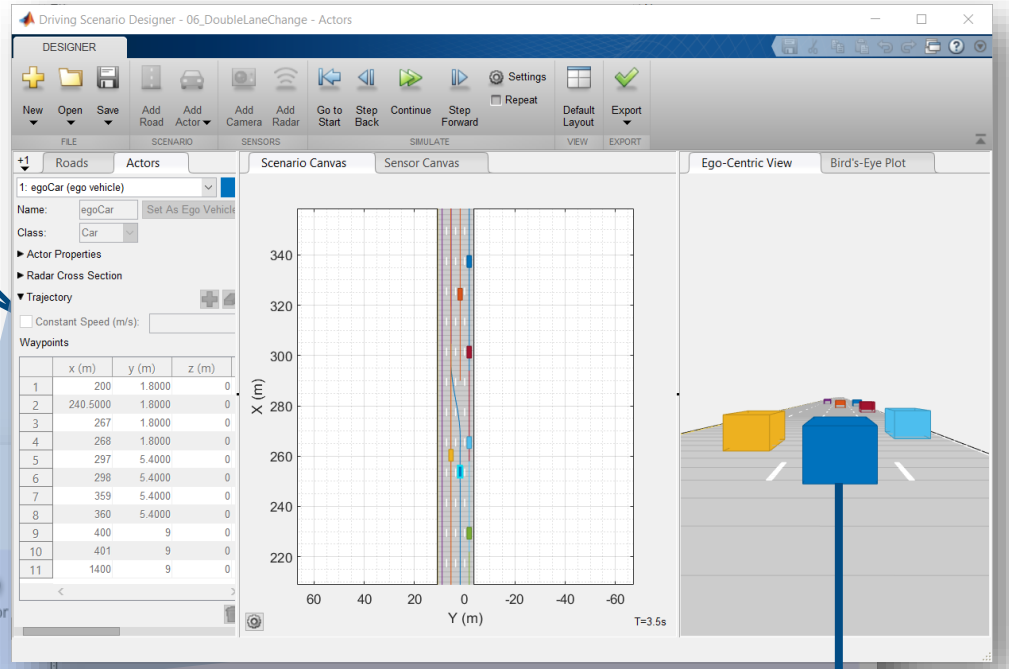
- 定义Agent的驾驶逻辑
- 采用Agent随机化交通场景
- 识别与评定非预期行为

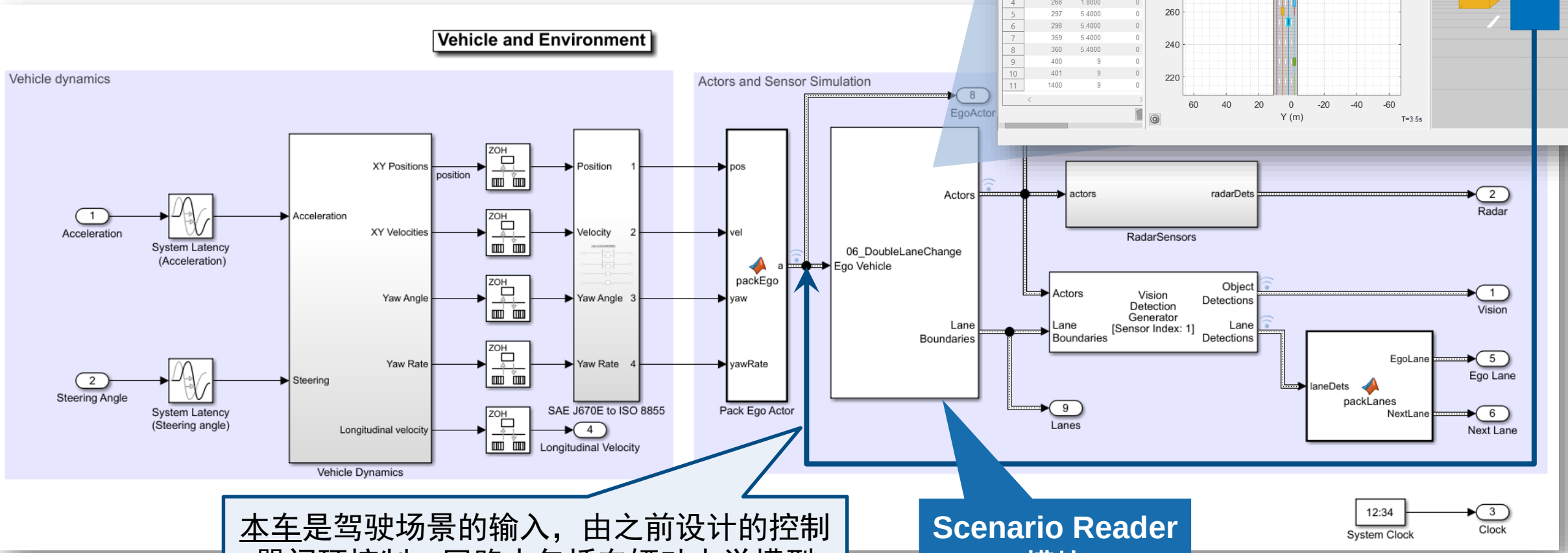
将Agents分配给其他所有参与车辆



读取驾驶场景

在驾驶场景设计器中预先定义驾驶场景



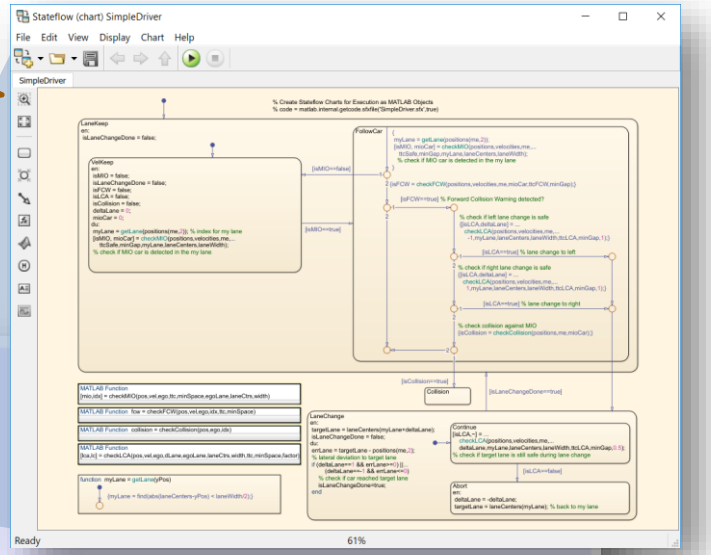


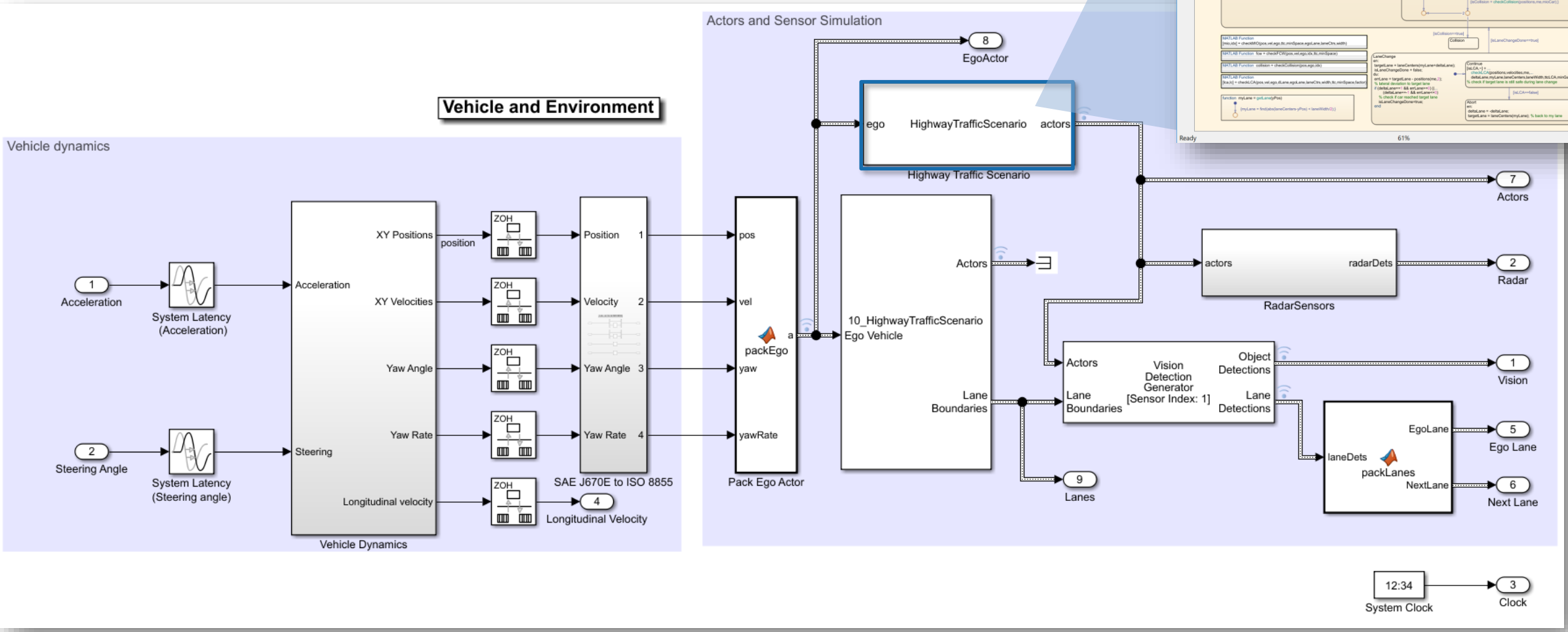
本车是驾驶场景的输入，由之前设计的控制器闭环控制，回路中包括车辆动力学模型

Scenario Reader 模块

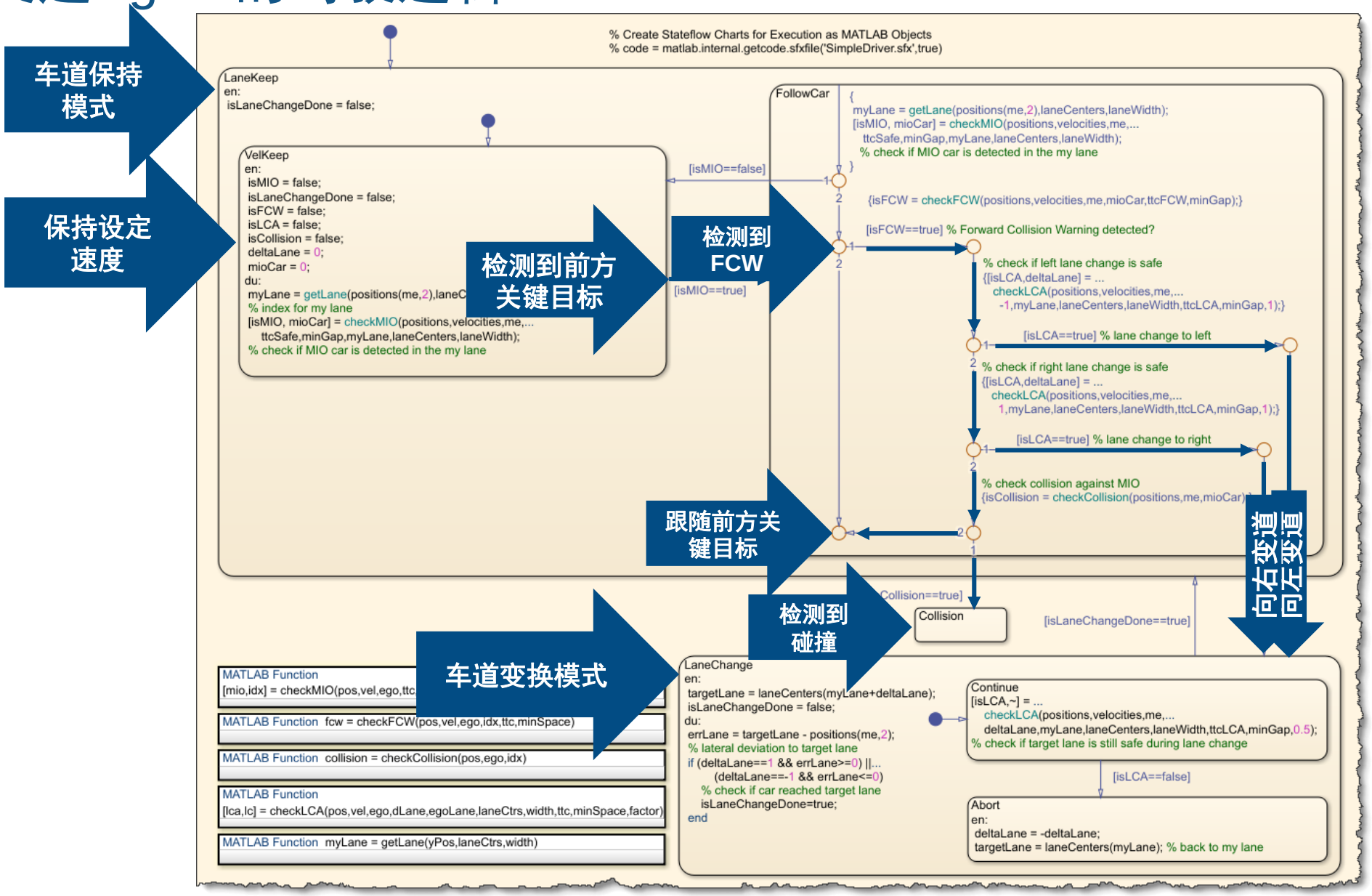
实现交通Agent的驾驶逻辑

驾驶逻辑的状态机实现

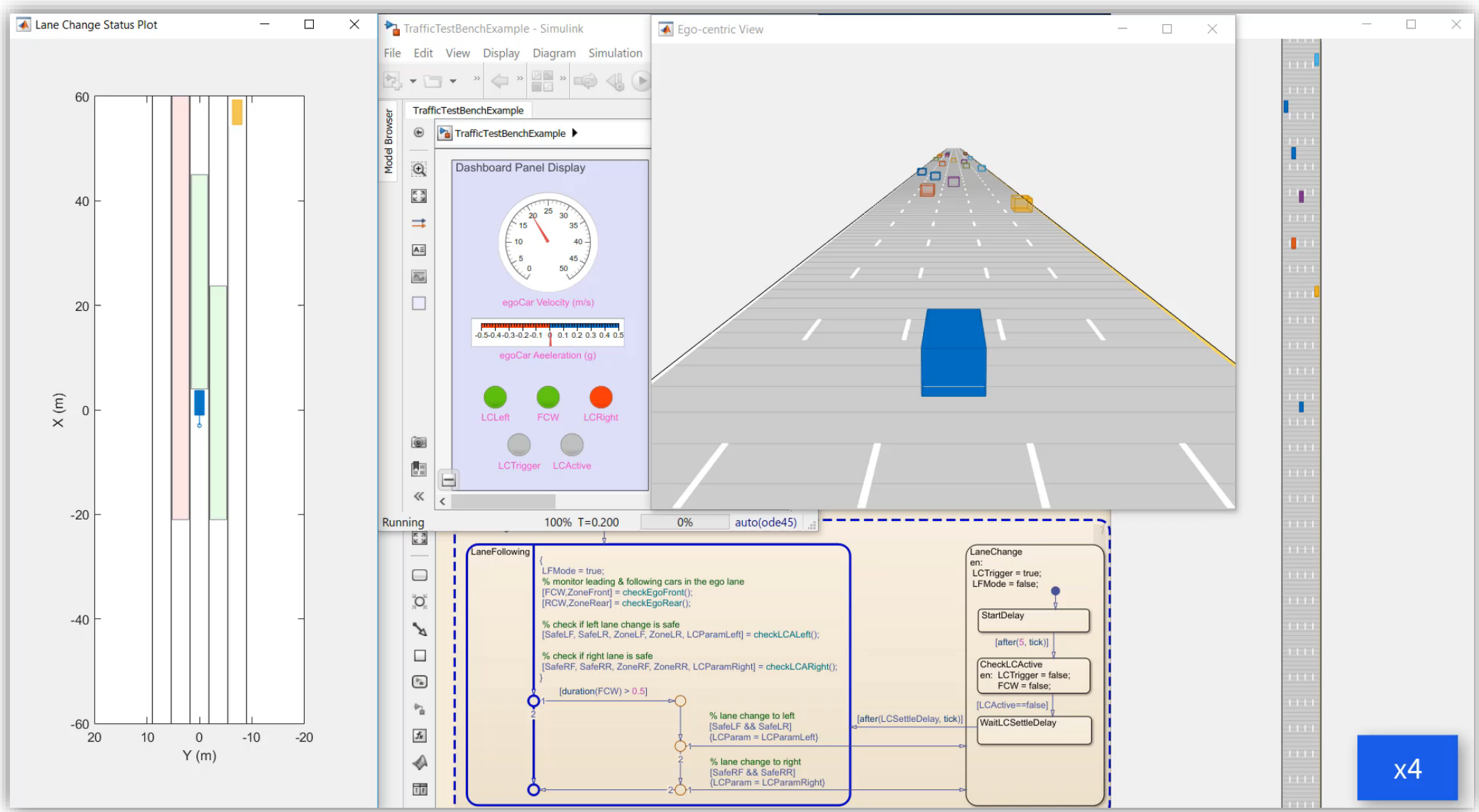




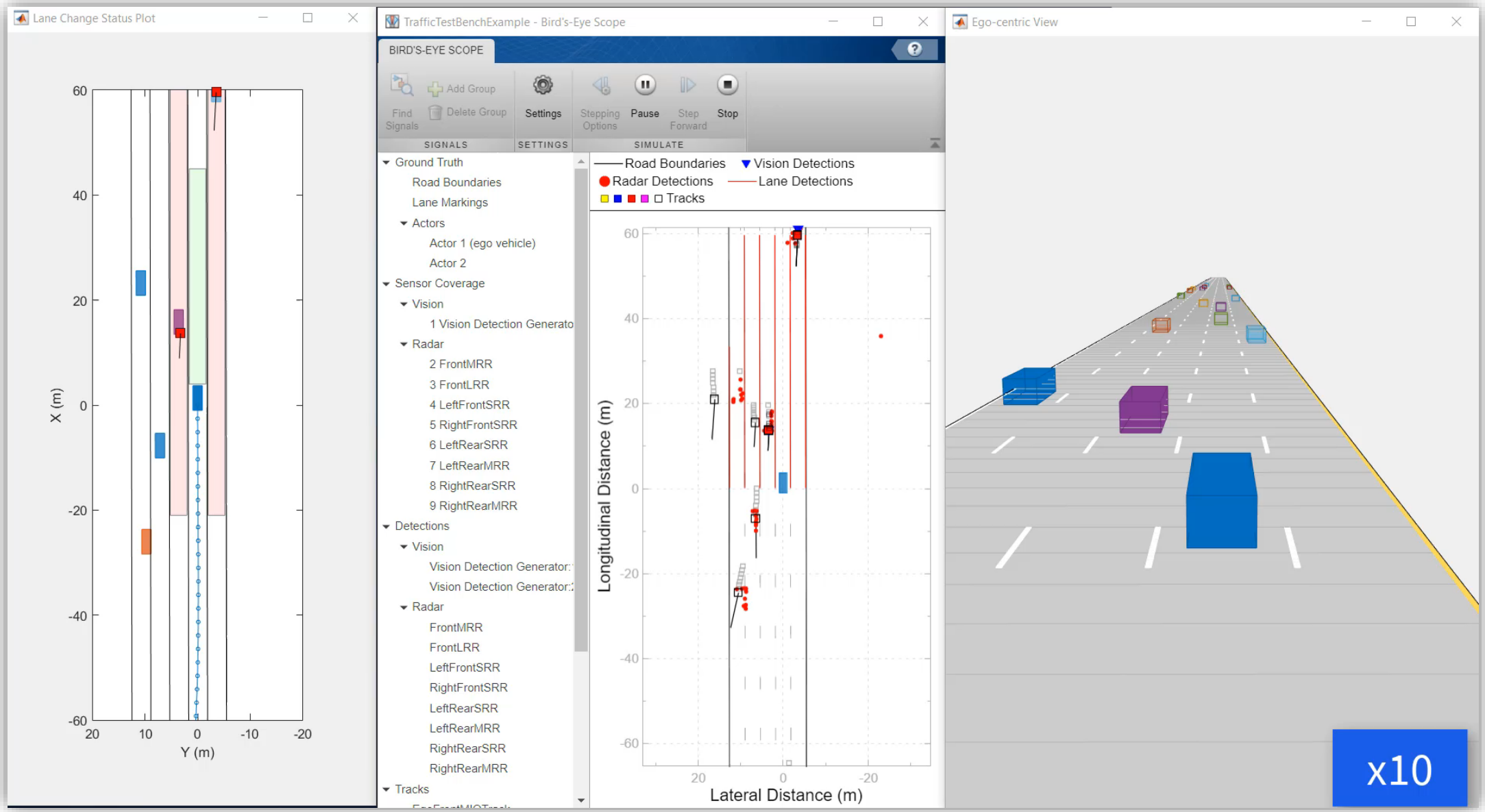
实现交通Agent的驾驶逻辑



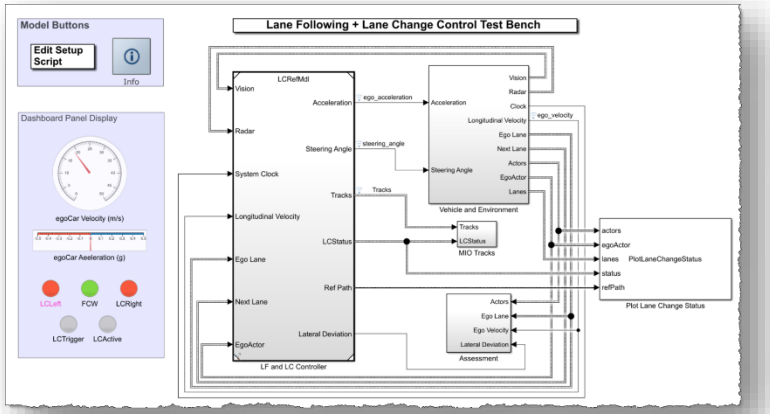
带多个交通Agent仿真



分析濒临碰撞的仿真结果



案例研究：设计与测试高速公路自动驾驶（决策、规划与控制）



设计车道跟随 + 车道变换控制器

- 回顾车道跟随控制器
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- 添加MIO检测器
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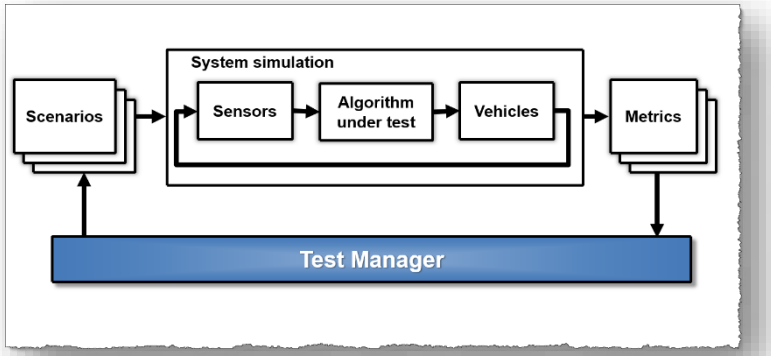

自动回归测试

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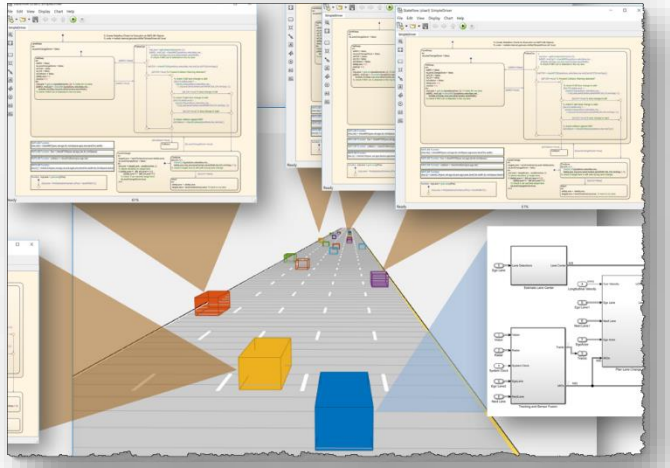
- 添加预定义的场景
- 运行Simulink Test



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- 采用Agent随机化交通场景
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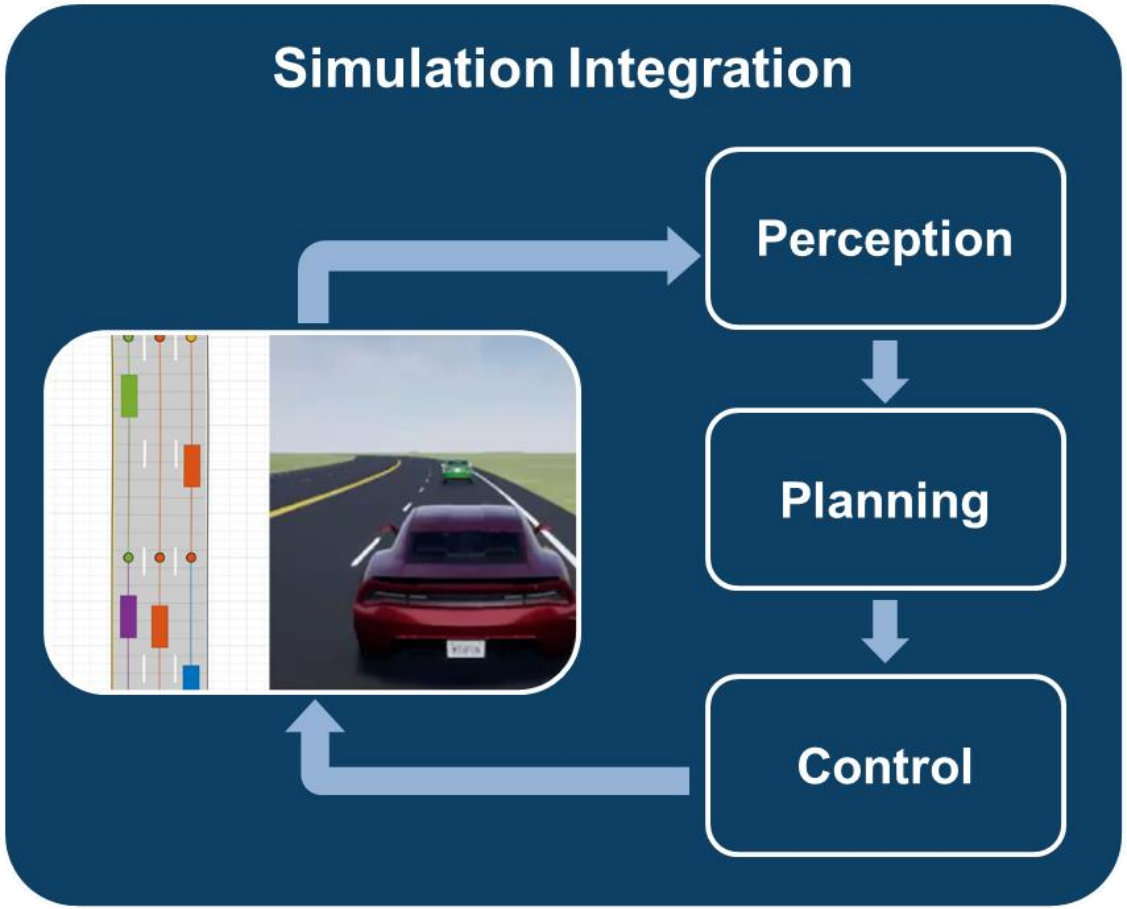
Contact us to learn more



Would you like to discuss any of these topics in more detail?

Contact your local team or reach out to me at hzeng@mathworks.com