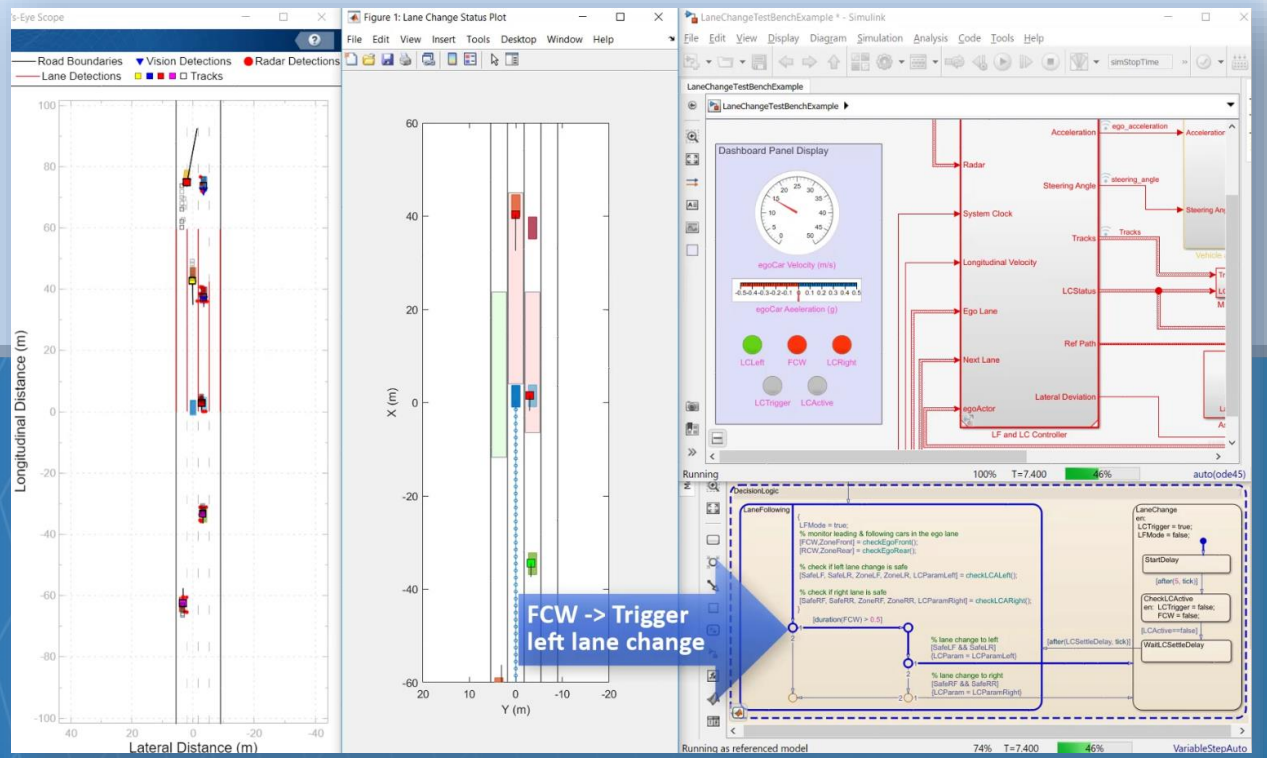
Case Study: Highway Lane Following + Lane Change

Design and test decision making, path planning, and control modules in traffic scenarios



Mark Corless
Industry Marketing, MathWorks

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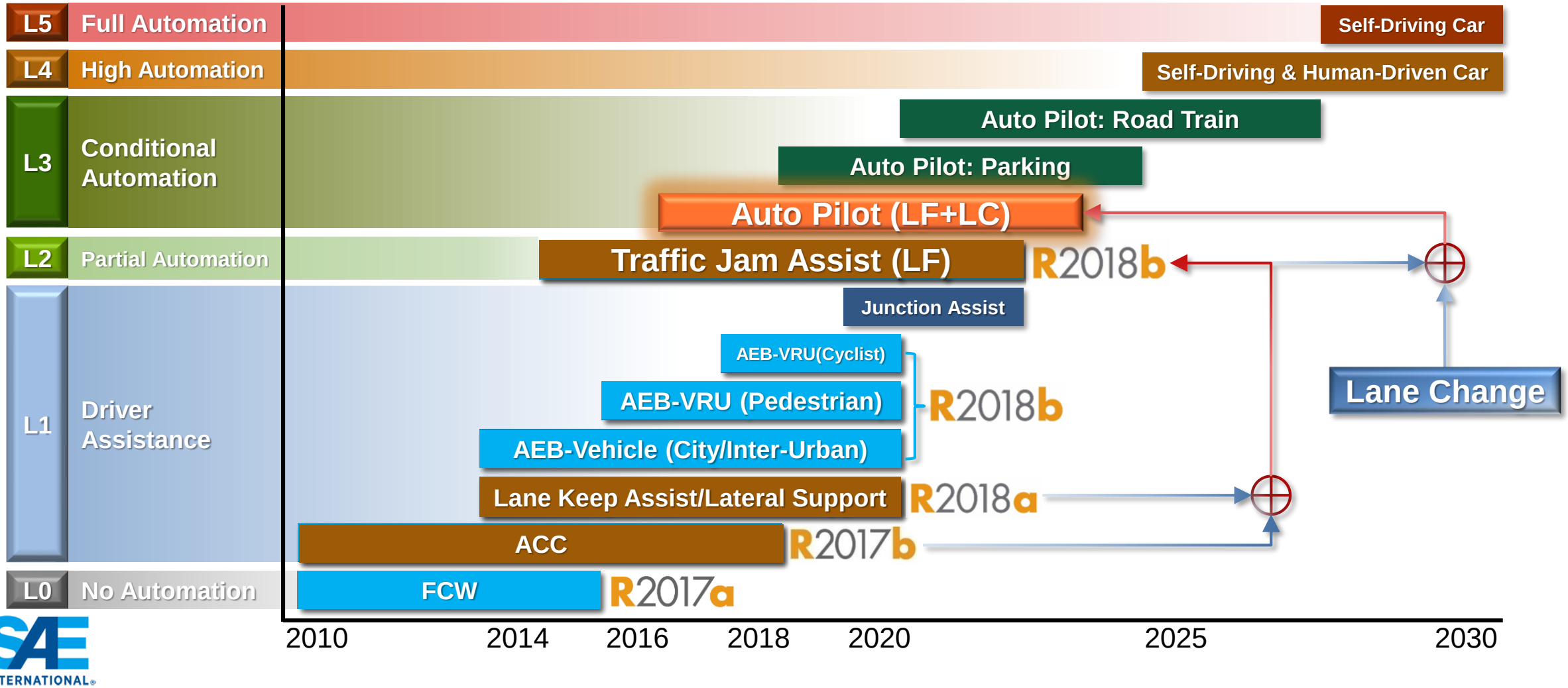
Application Engineering, MathWorks

Marco Roggero
Application Engineering, MathWorks

Evolution of ADAS and Autonomous Driving Car Technologies

Application examples in **Automated Driving Toolbox™**

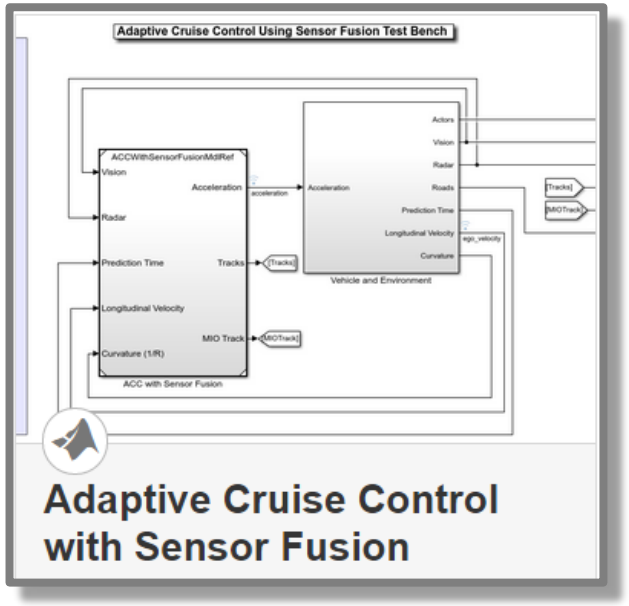


Traffic Jam Assist with ACC and Lane Following Control

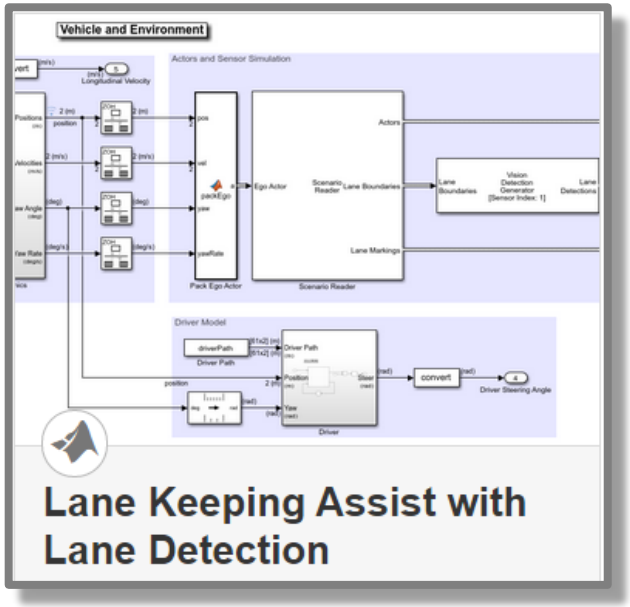
MAC 2018

Automated Driving Toolbox™

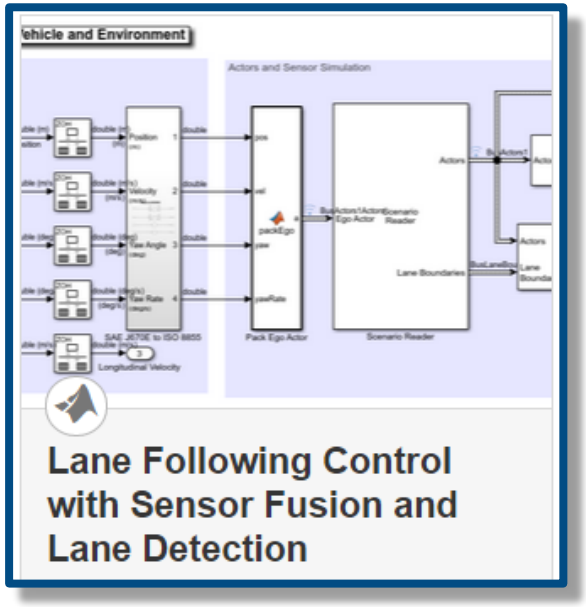
R2017b



R2018a



R2018b



ACC
(Longitudinal Control)

Lane Following
(Lateral Control)

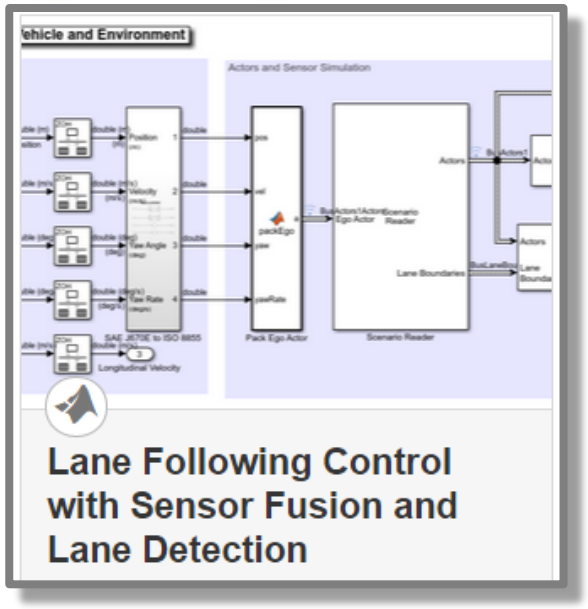
Traffic Jam Assist
(Longitudinal + Lateral Control)

Auto Pilot: Lane Following plus Lane Change

MAC 2019

Automated Driving Toolbox™

R2018b



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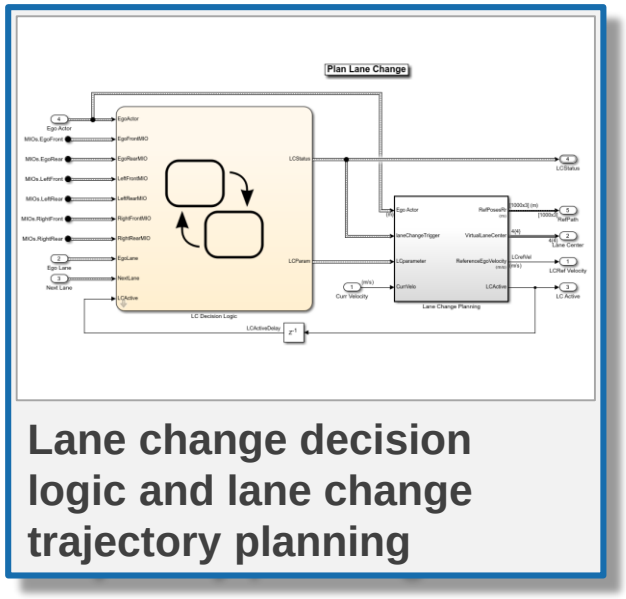

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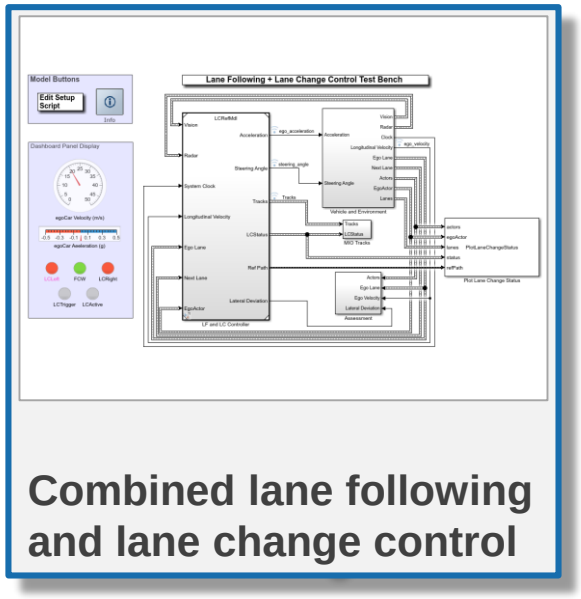


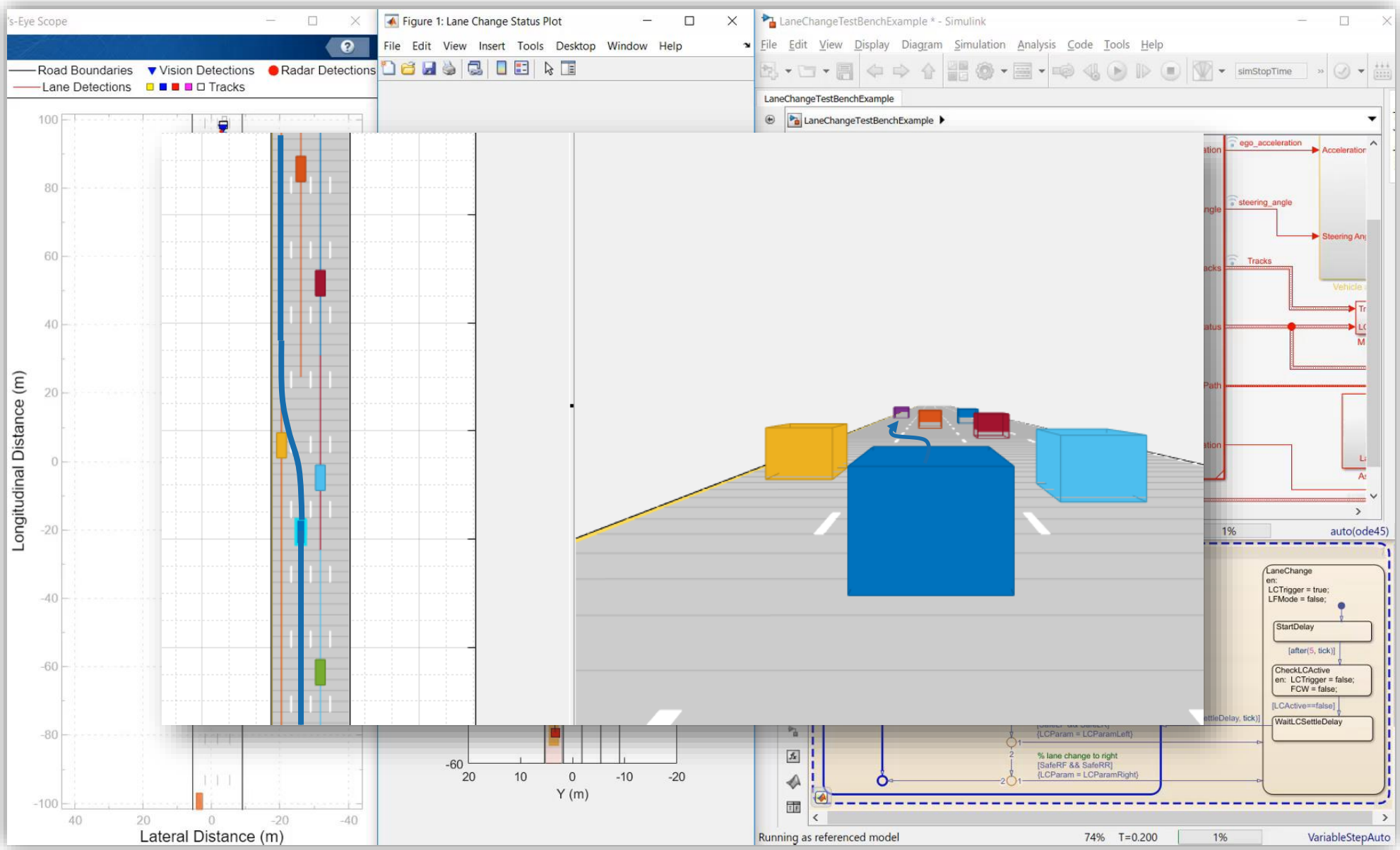
Traffic Jam Assist
(Longitudinal + Lateral Control)

Baseline example

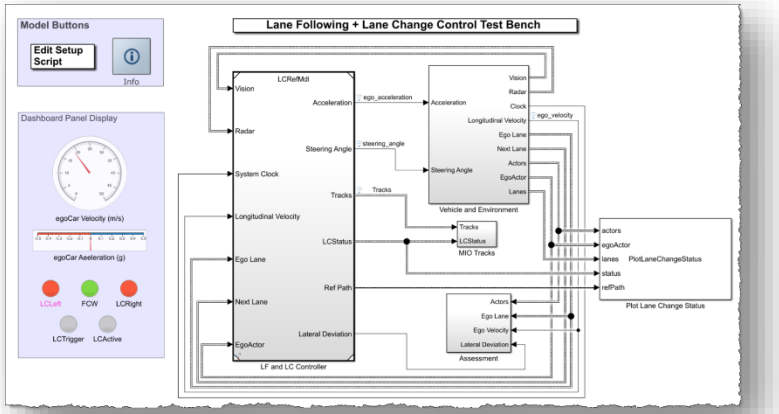
Auto Lane Change
(LC Decision Logic + Planning)

Auto Pilot
(Lane Following + Lane Change)

Single Lane Change Example

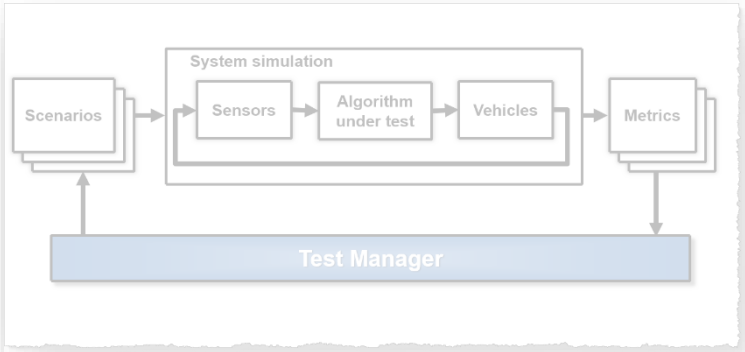


Case Study for Lane Following plus Lane Change



Design lane following + lane change controller

- Review baseline LF example
- Design sensor configuration
- Design additional MIO detectors
- Design safety zone calculation
- Design lane change logic
- Design trajectory planner



Automate regression testing

- Define assessment metrics
- Add predefined scenarios
- Run Simulink test

Test robustness with traffic agents

- Specify driver logic for traffic agents
- Randomize scenarios using traffic agents
- Identify and assess unexpected behavior

Learn about developing a lane following controller

[Lane Following Control with Sensor Fusion]

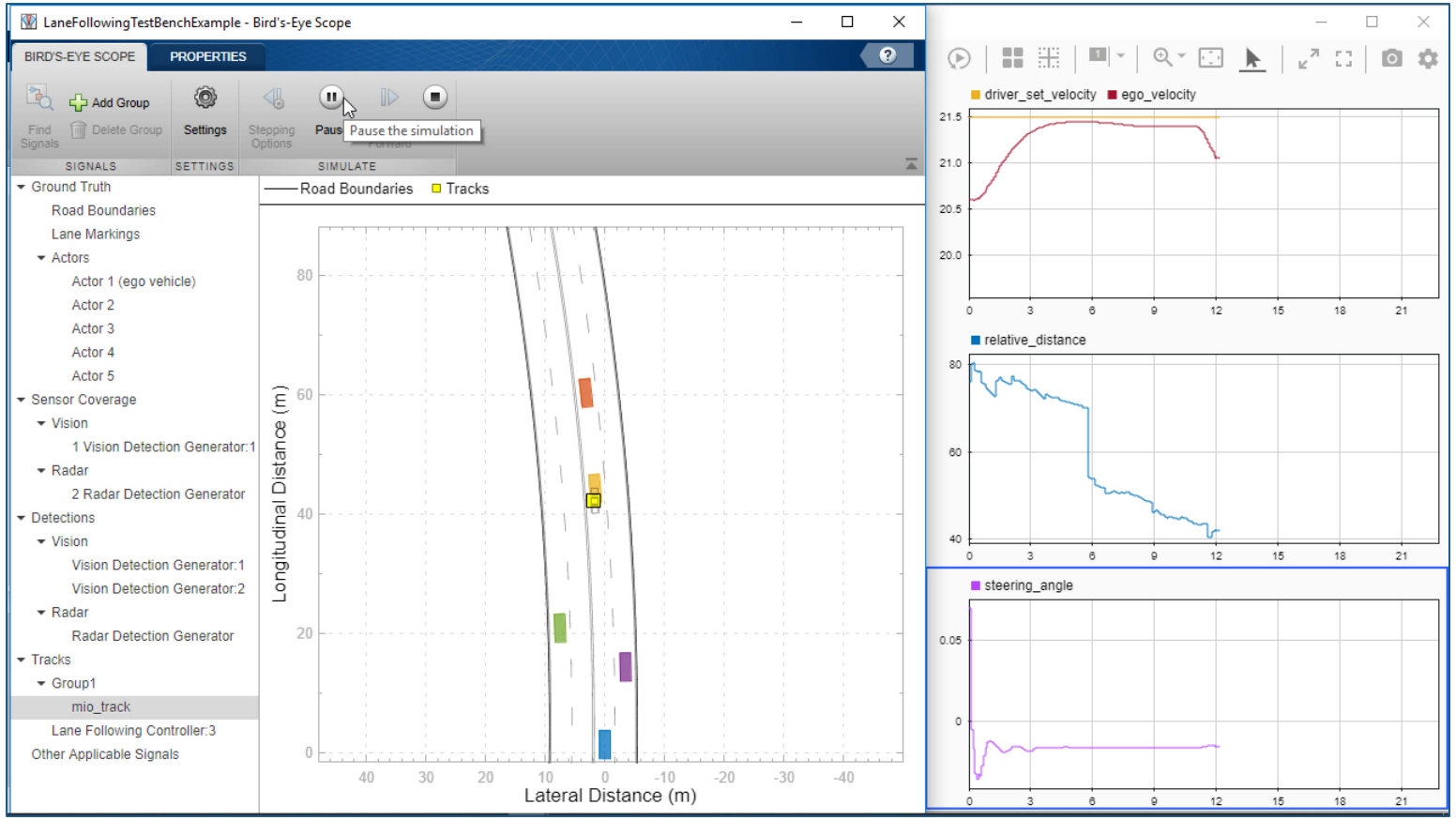
- Specify scenario and sensors
- Design lateral (lane keeping) and longitudinal (lane spacing) model predictive controllers
- Integrate sensor fusion
- Generate C/C++ code
- Test with software in the loop (SIL) simulation

Model Predictive Control Toolbox™

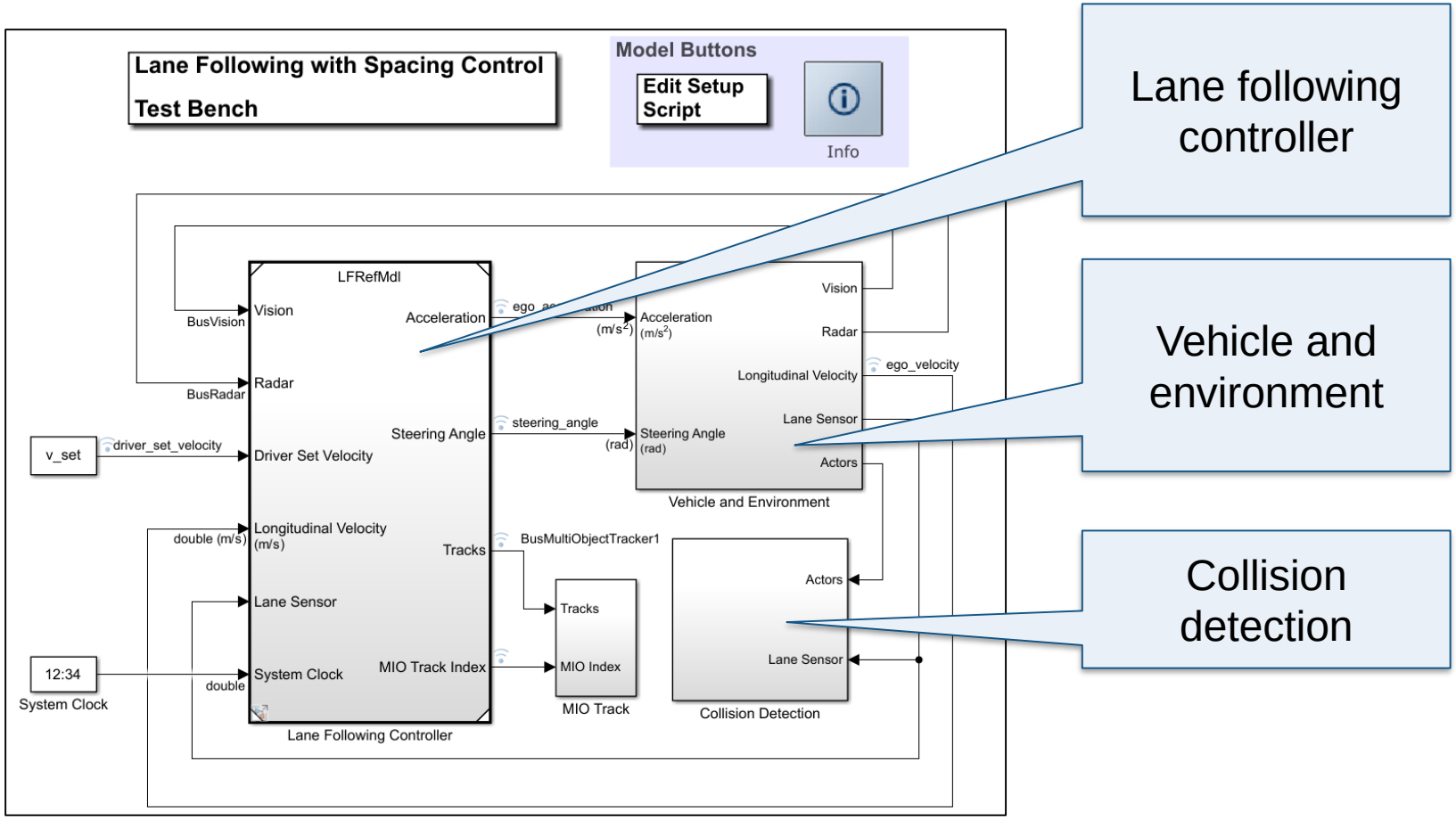
Automated Driving Toolbox™

Embedded Coder®

R2018b



Review lane following test bench model architecture

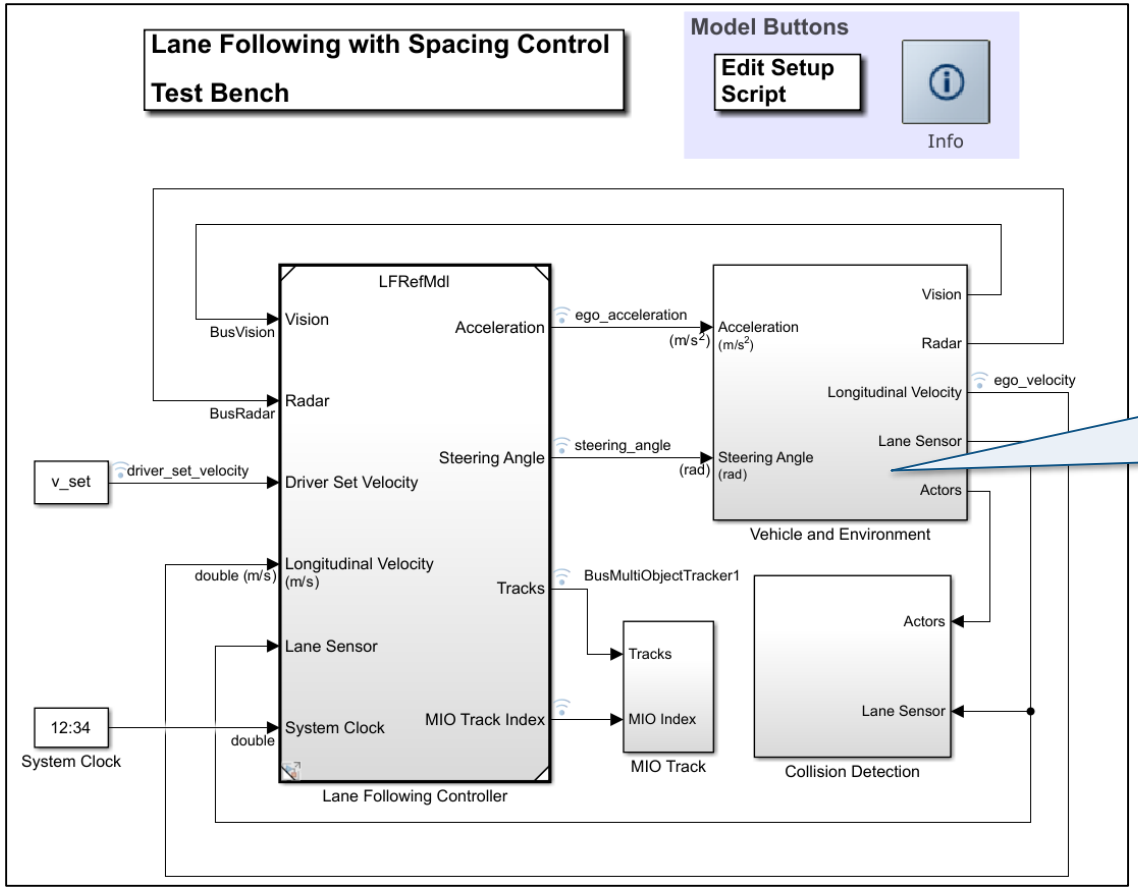


Lane following controller

Vehicle and environment

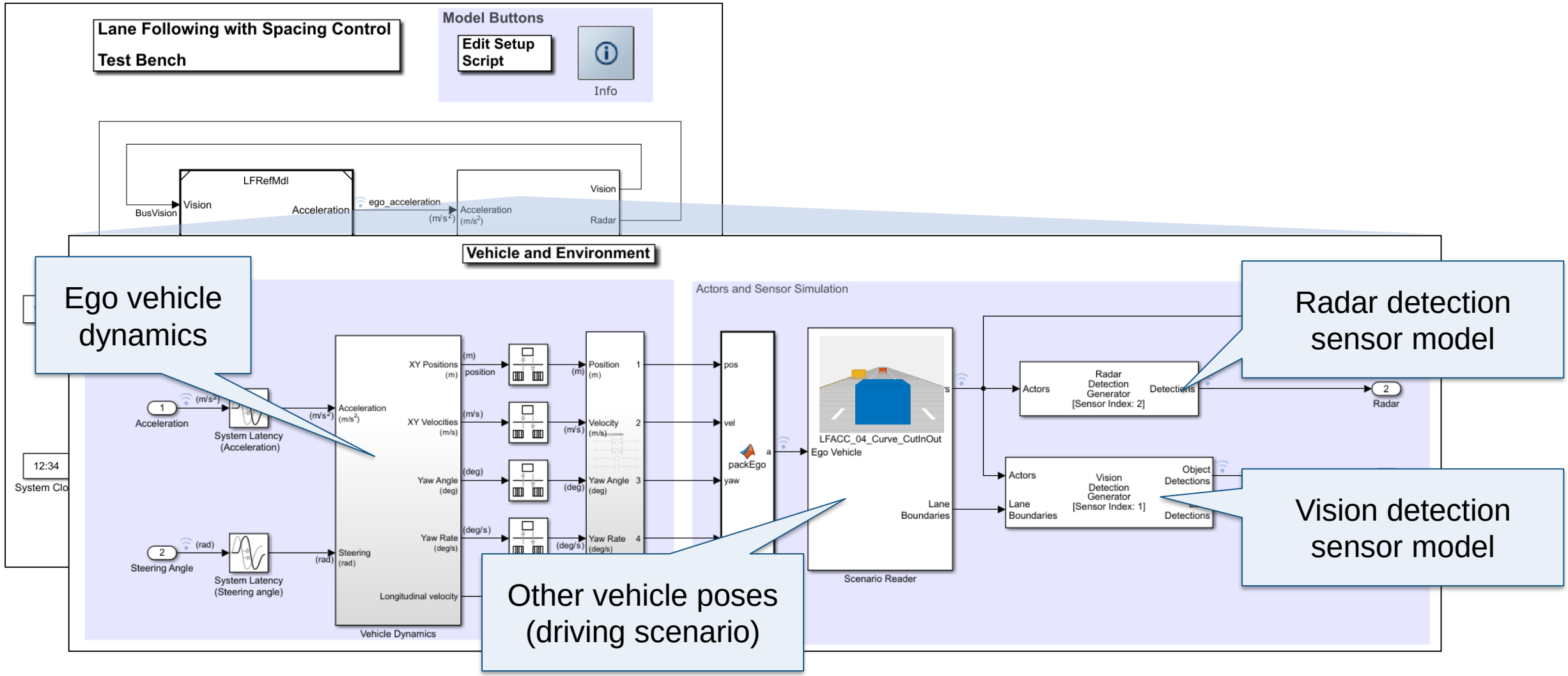
Collision detection

Review lane following test bench model architecture

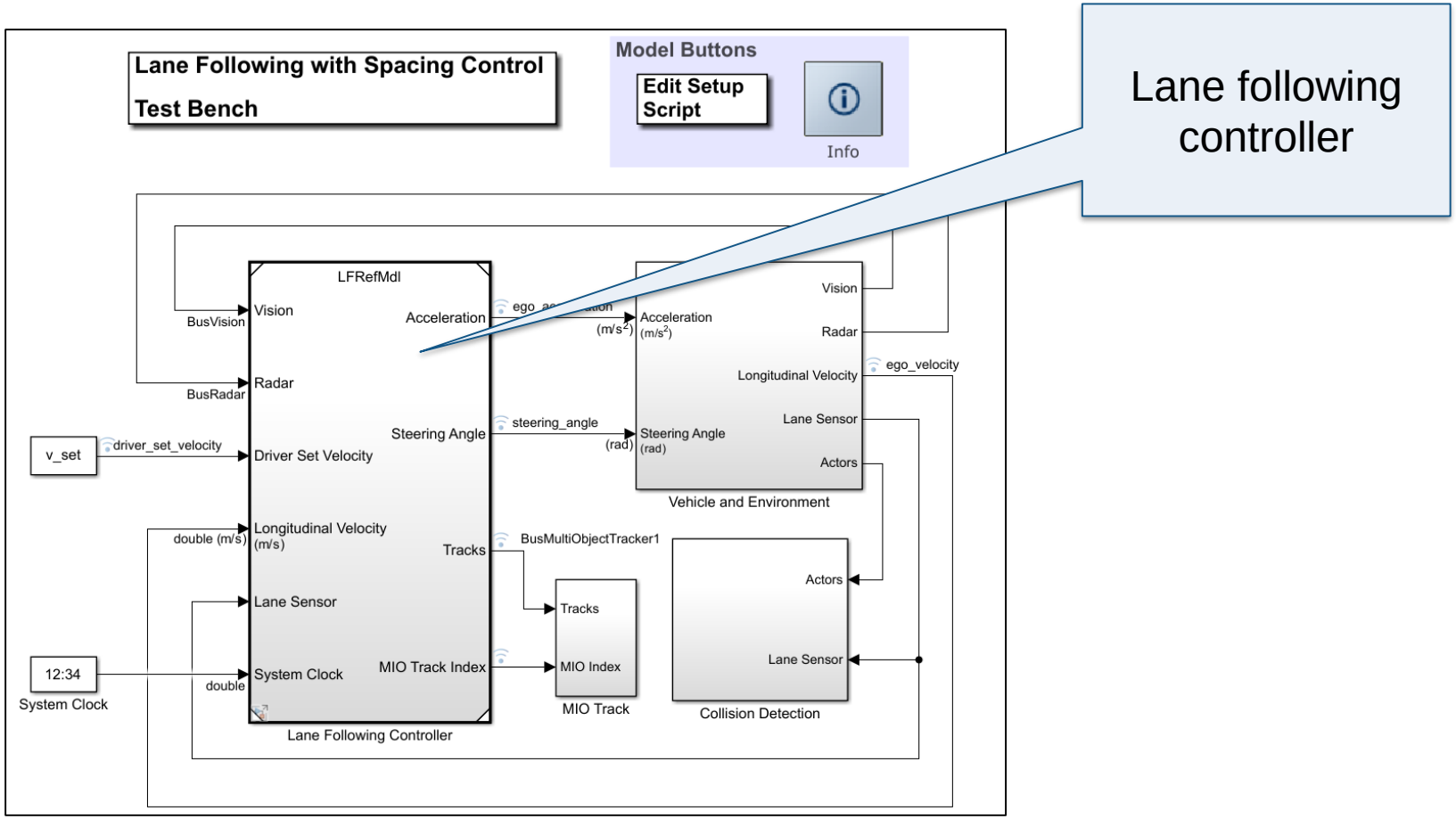


Vehicle and environment

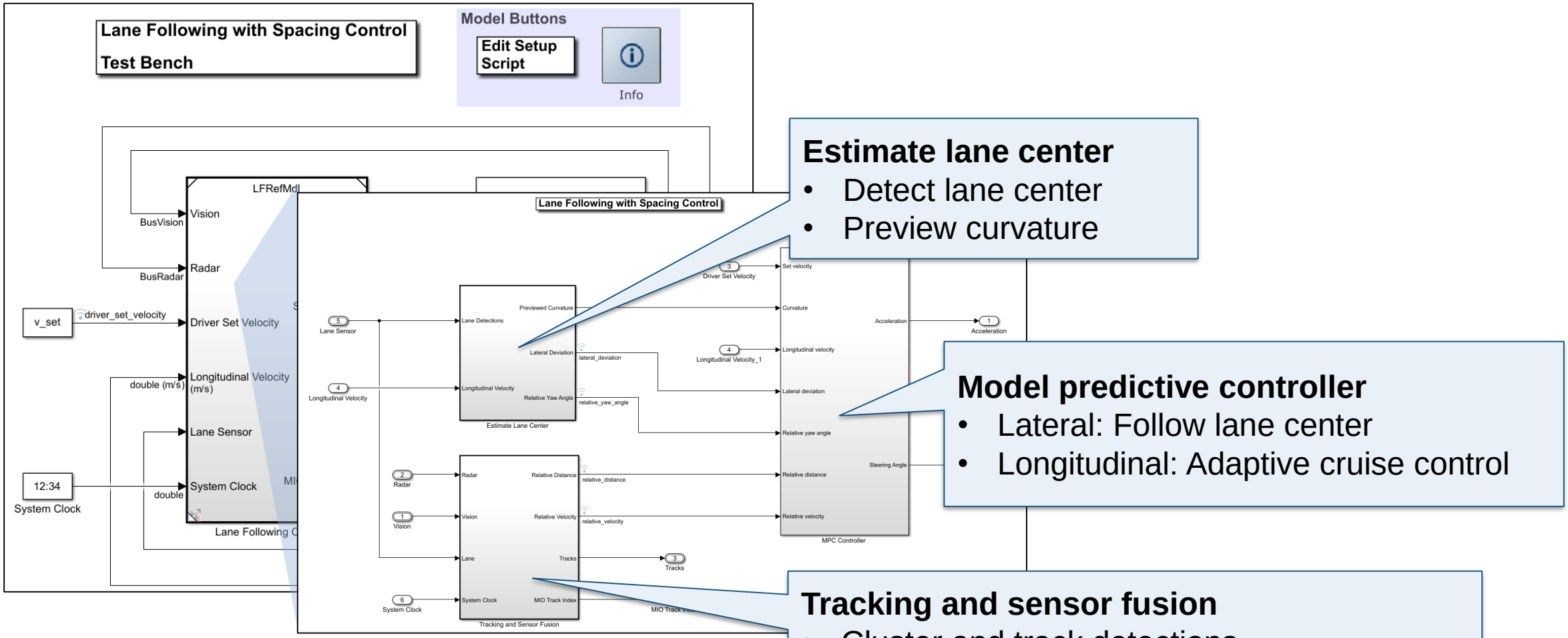
Review vehicle and environment components



Review lane following test bench model architecture



Review lane following controller components

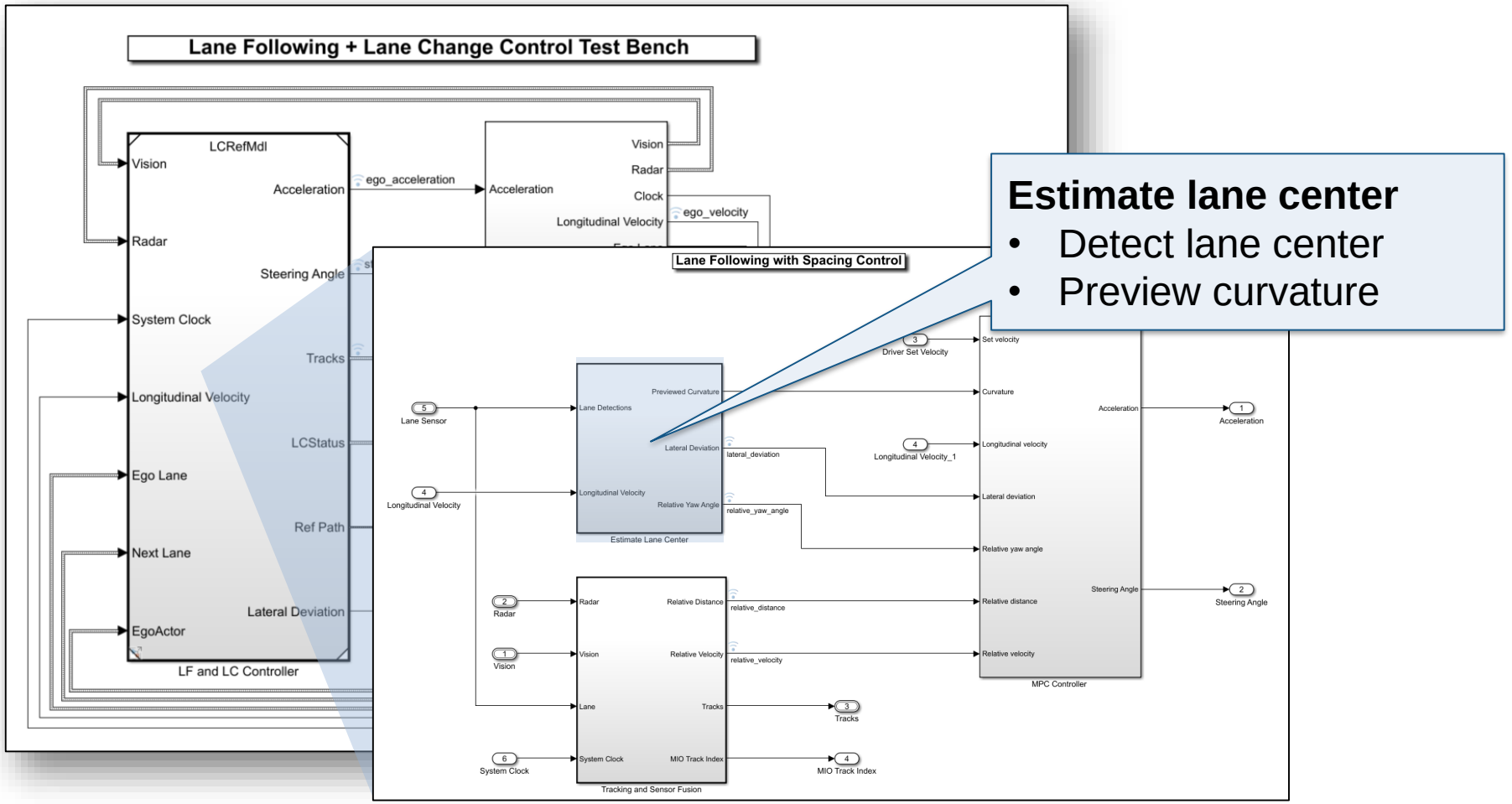


Estimate lane center
- Detect lane center
- Preview curvature

Model predictive controller
- Lateral: Follow lane center
- Longitudinal: Adaptive cruise control

Tracking and sensor fusion
- Cluster and track detections
- Identify most important object (MIO) ahead

Partition design to enable inserting lane change functionality



Estimate lane center

- Detect lane center
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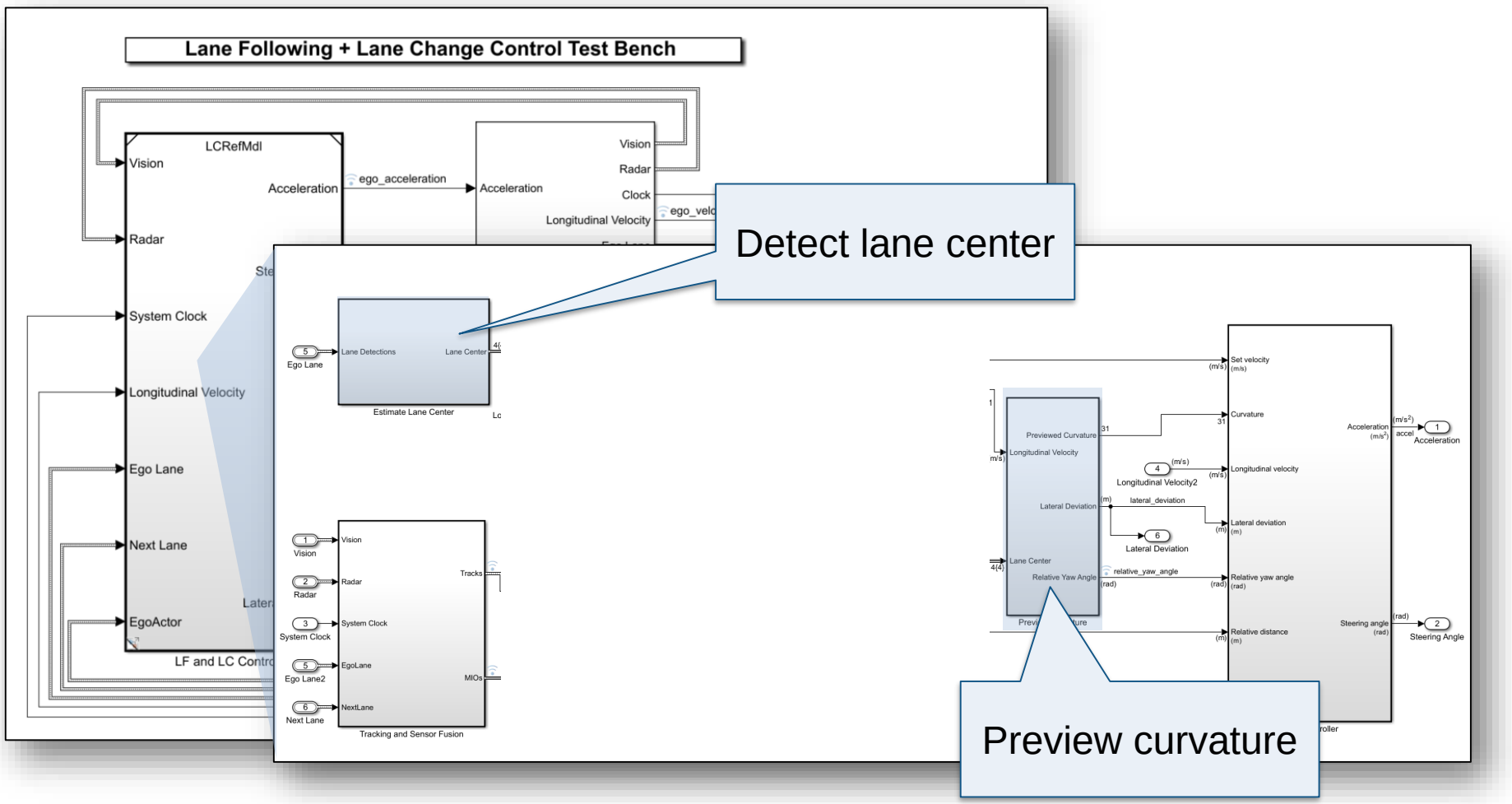
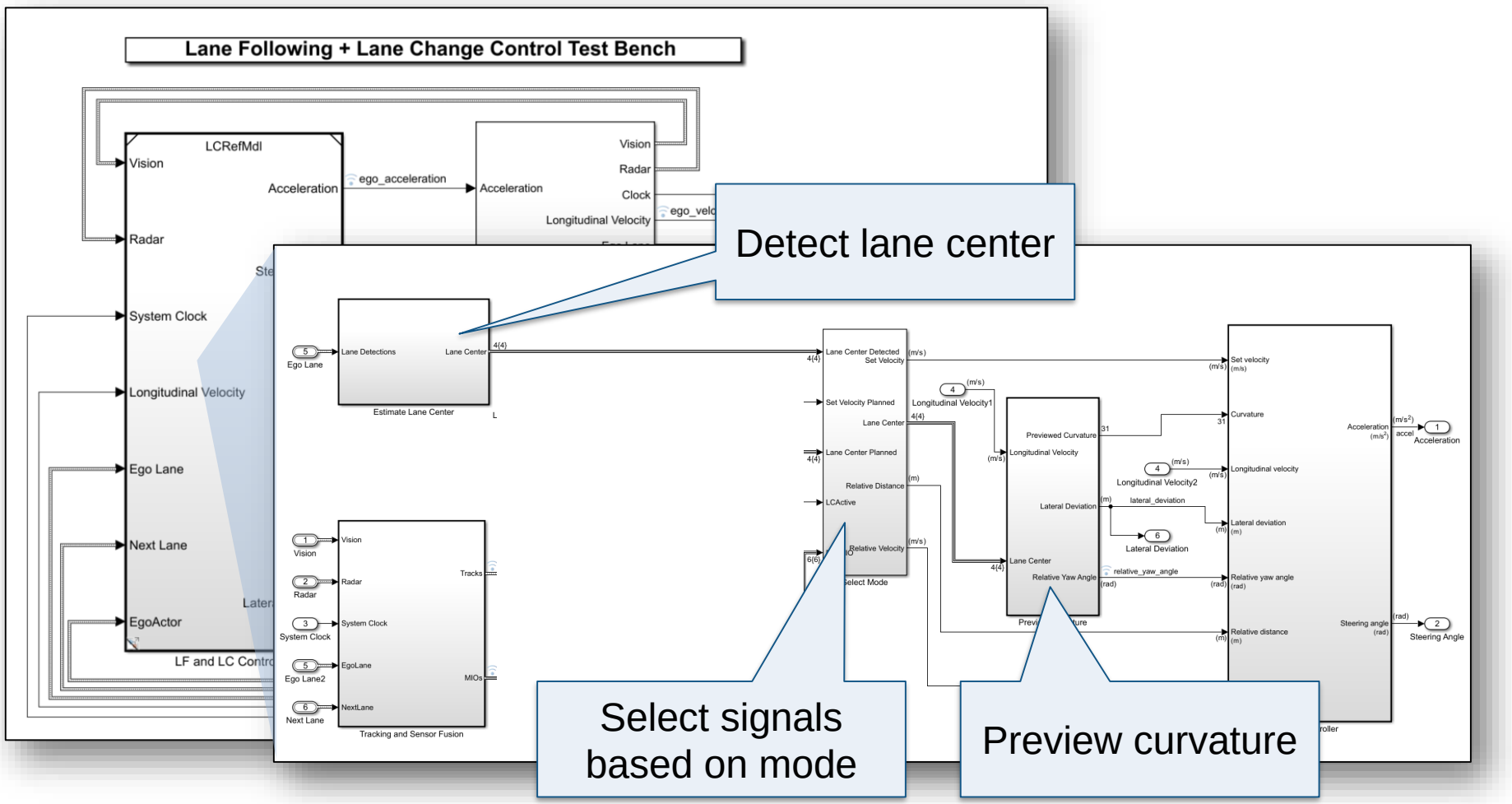
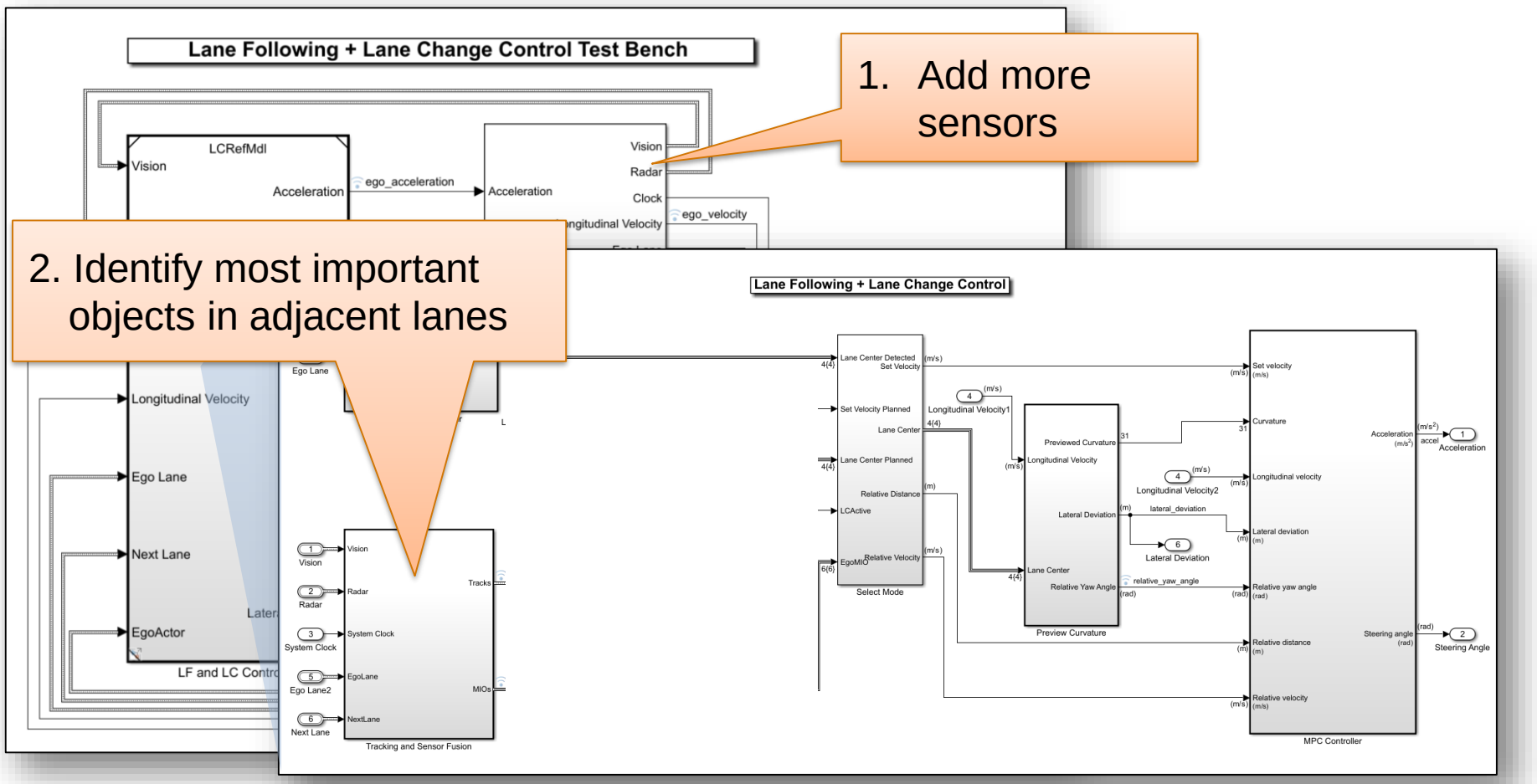
Partition design to enable inserting lane change functionality



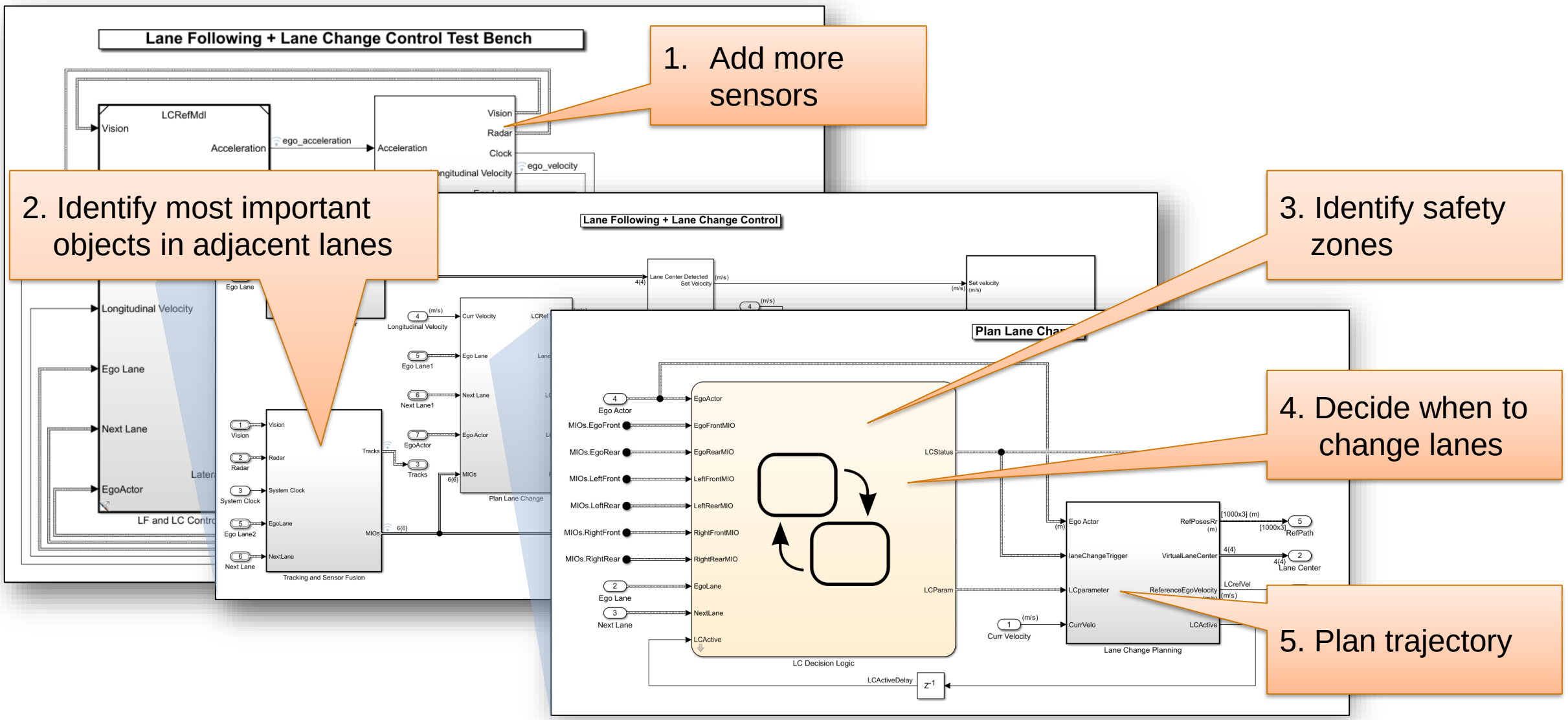
Partition design to enable inserting lane change functionality



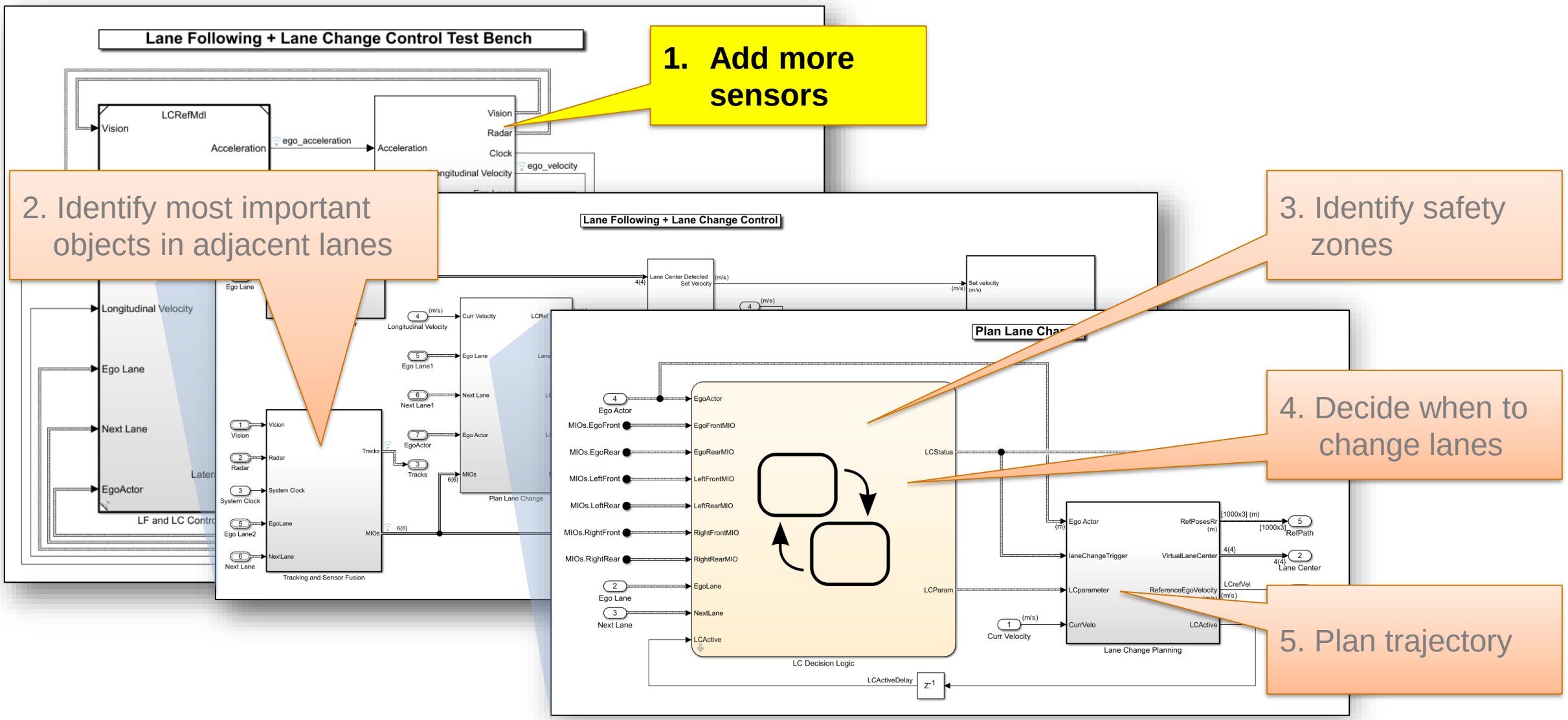
Add lane change functionality to lane following controller



Add lane change functionality to lane following controller



Add lane change functionality to lane following controller

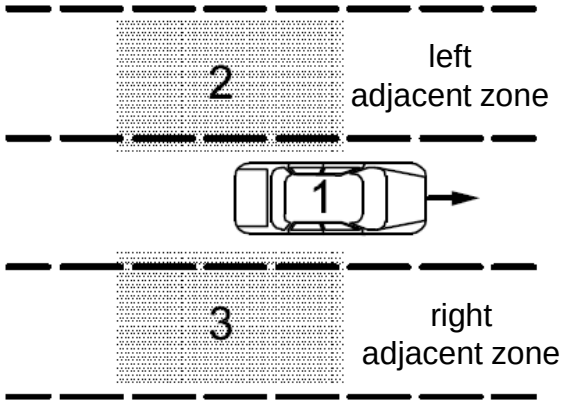


System requirements for lane change

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

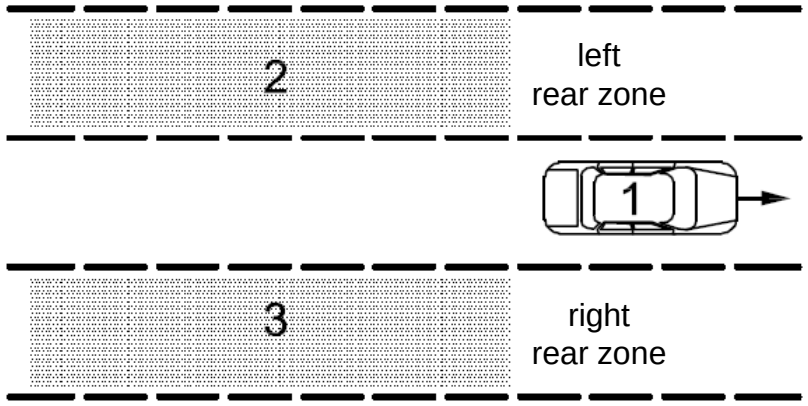
ISO 17387

Adjacent zones
for Blind Spot Detection



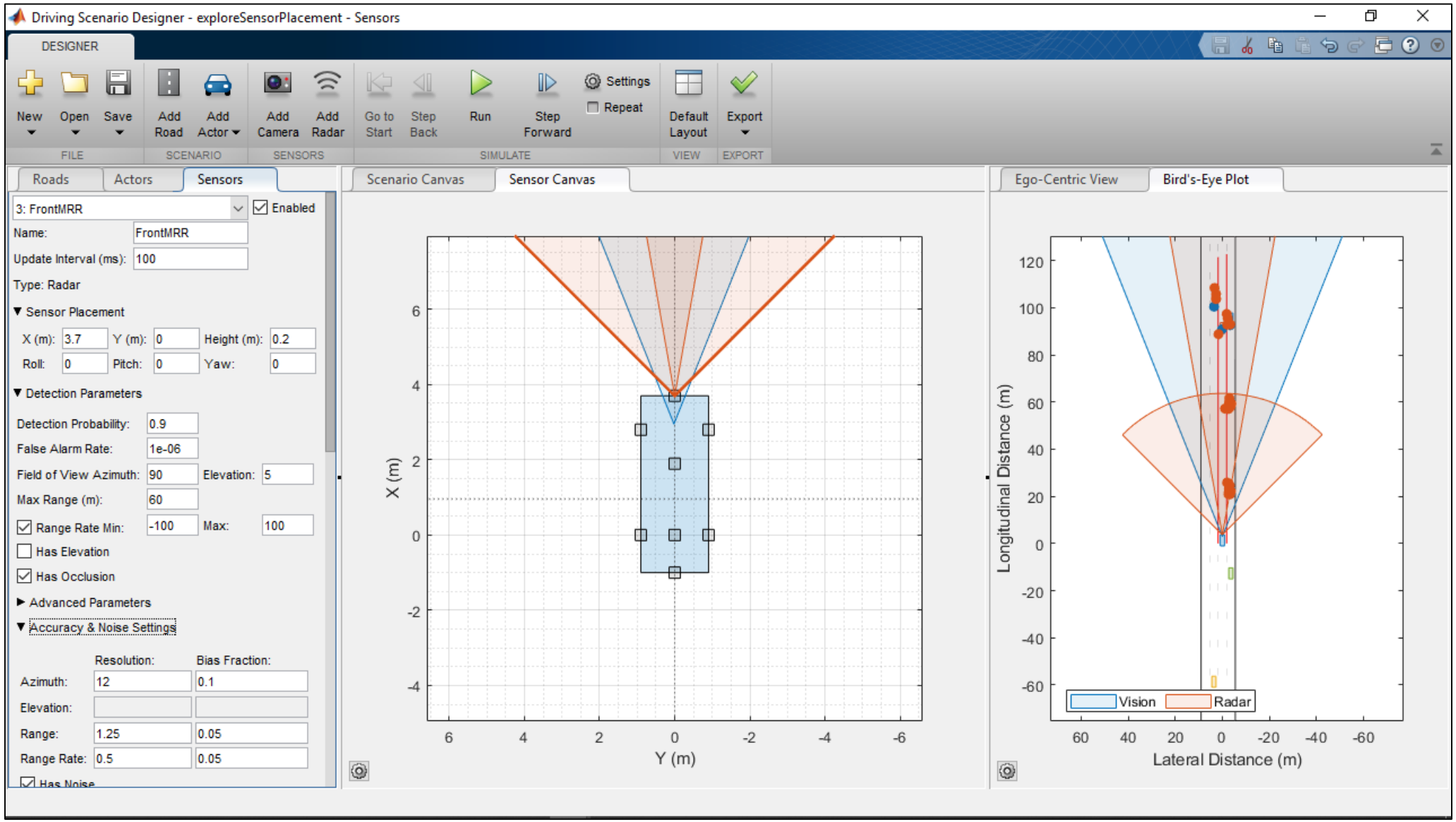
Typically implemented with
Short Range Radar

Rear zones
for closing vehicle warning



Typically implemented with
Mid Range Radar

Explore sensor placement with Driving Scenario Designer

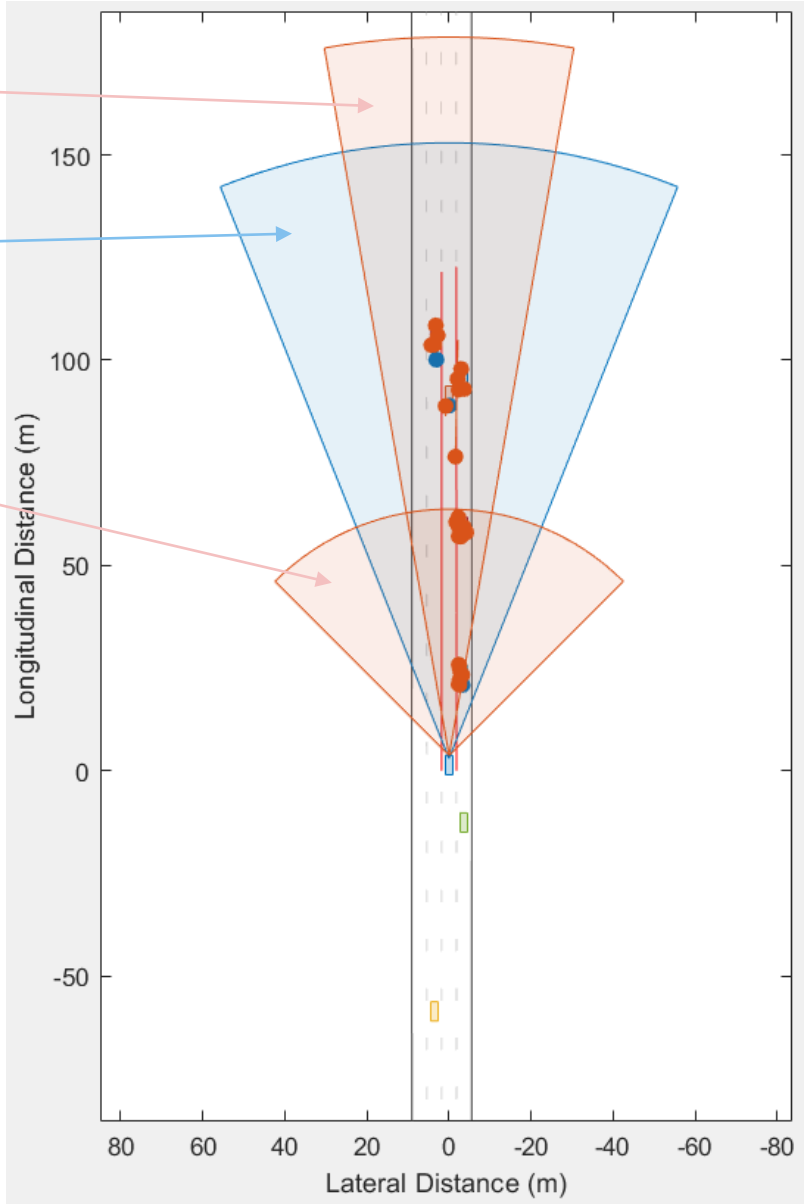


Review sensor configuration for **lane following** example

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

Add rear looking sensors to support **left lane change**

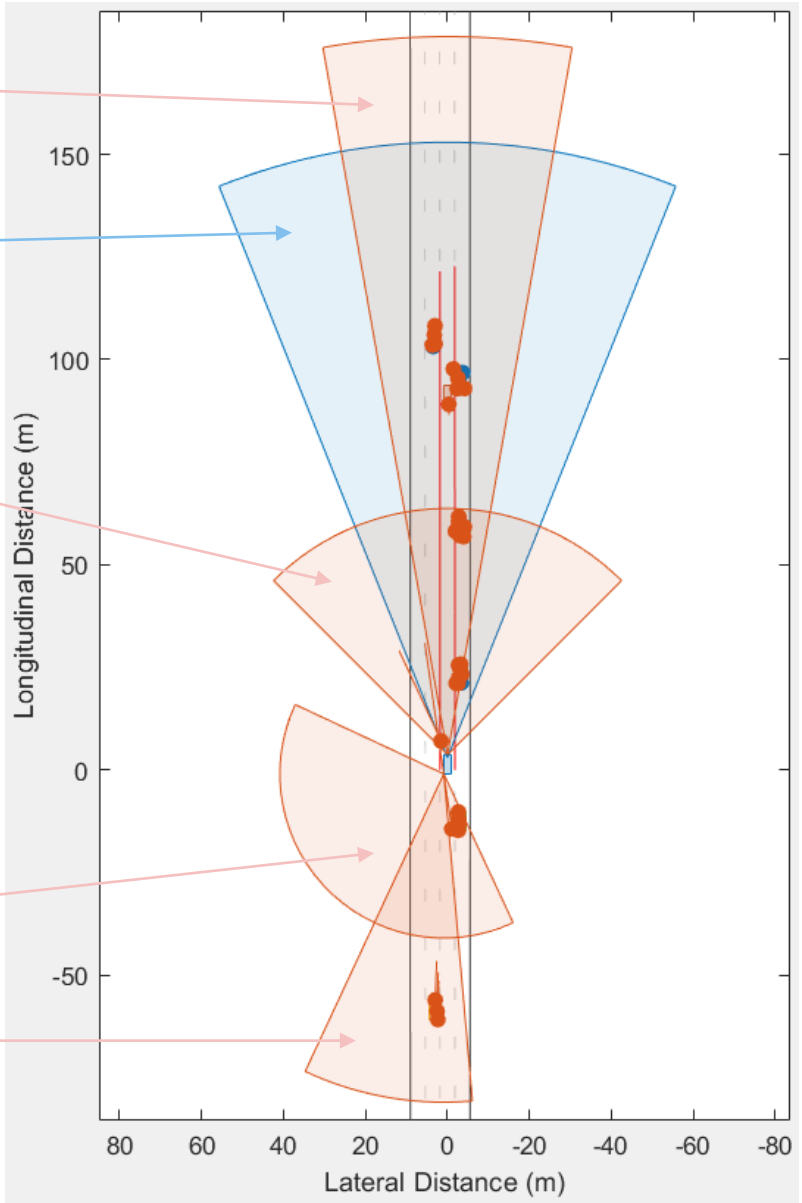
FrontLRR
FoV = 20° x 175m

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

Overall sensor configuration for lane following plus lane change

FrontLRR
FoV = 20° x 175m

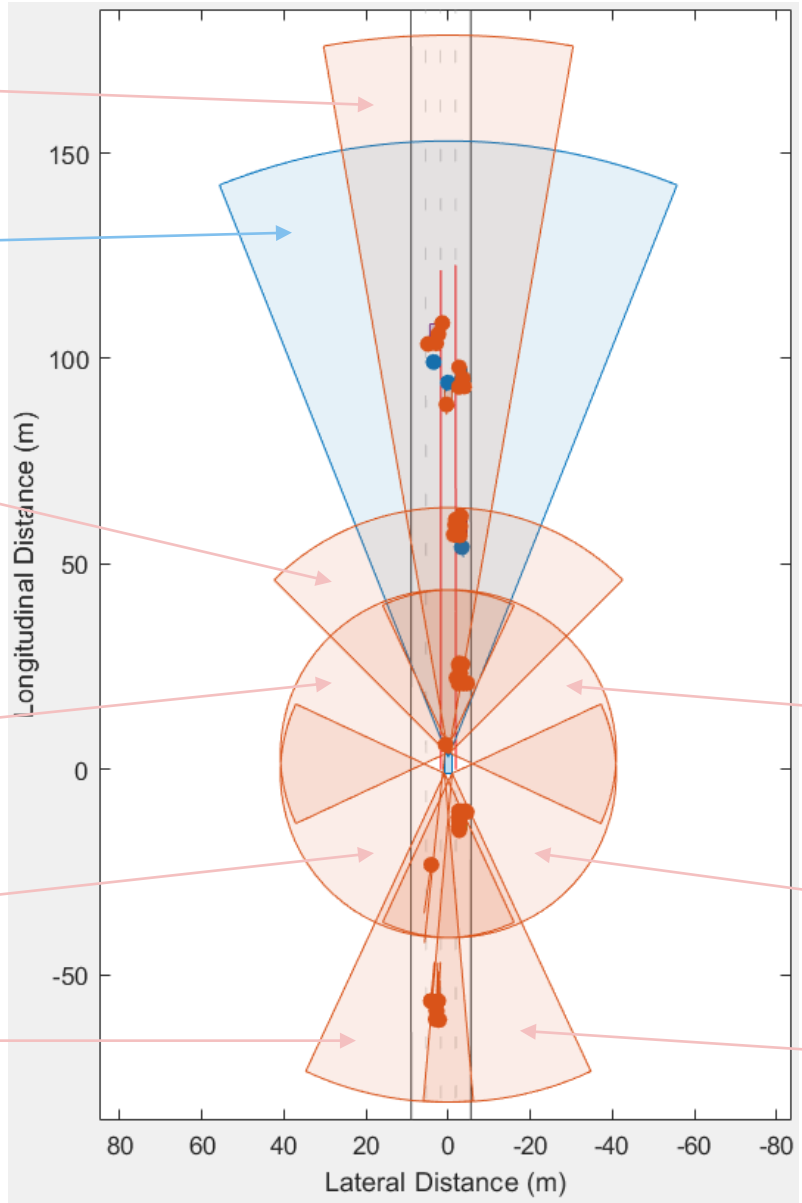
Camera
FoV = 43.6° x 150m

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

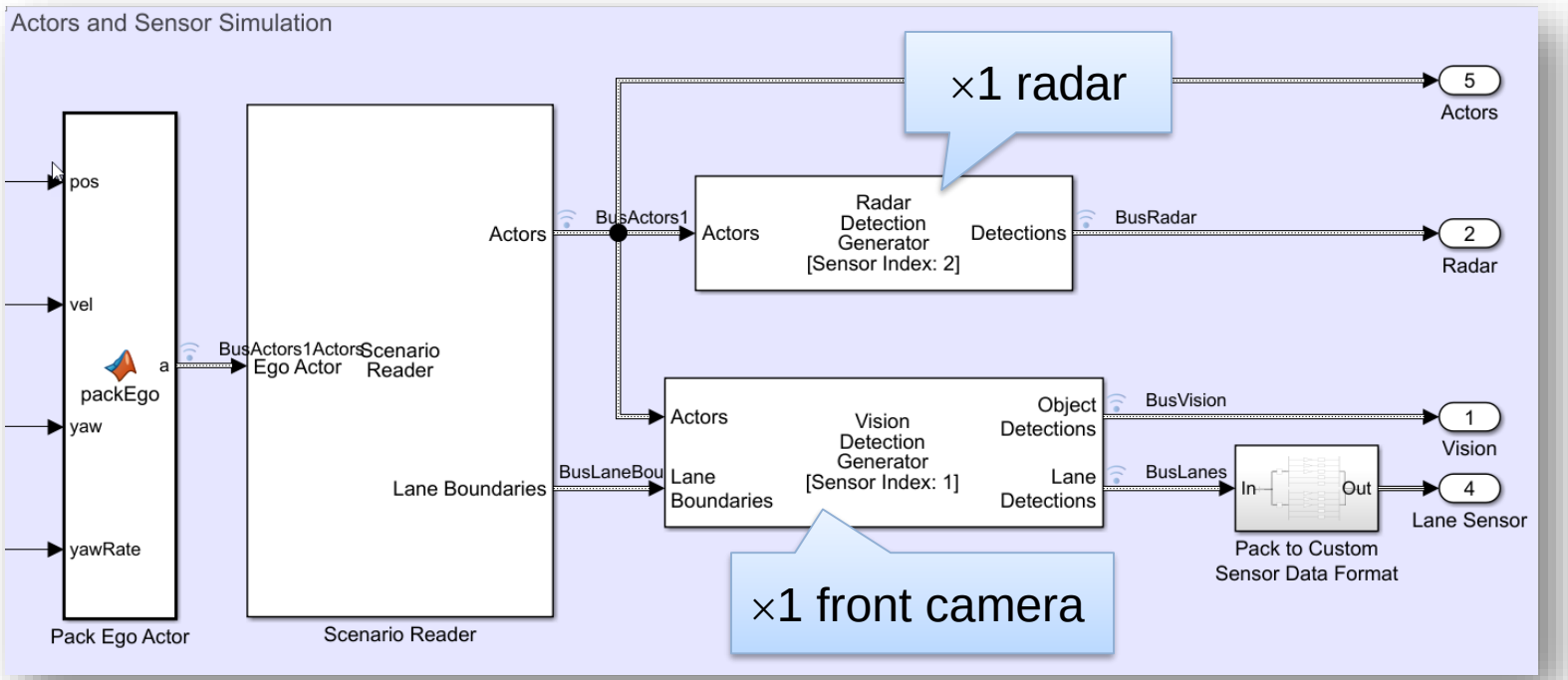
- SRR: Short-Range Radar
- MRR: Mid-Range Radar
- LRR: Long-Range Radar

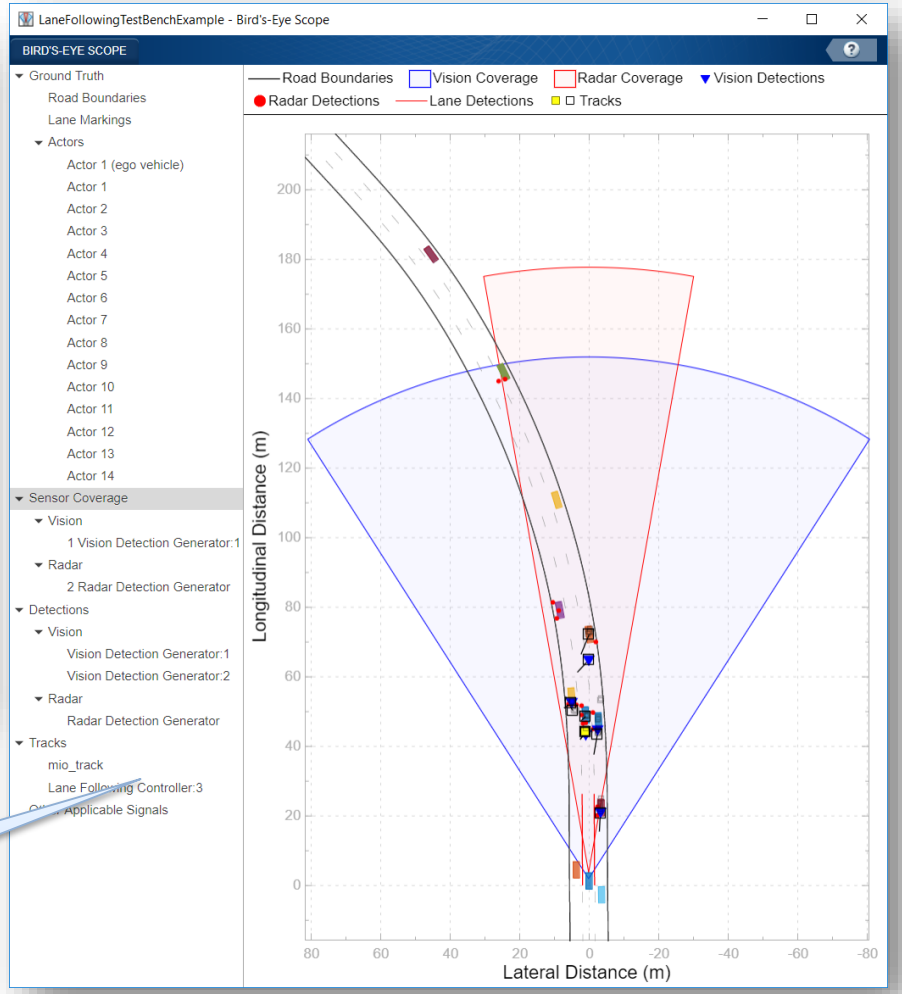
RightFrontSRR
FoV = 140° x 40m

RightRearSRR
FoV = 140° x 40m

RightRearMRR
FoV = 30° x 80m

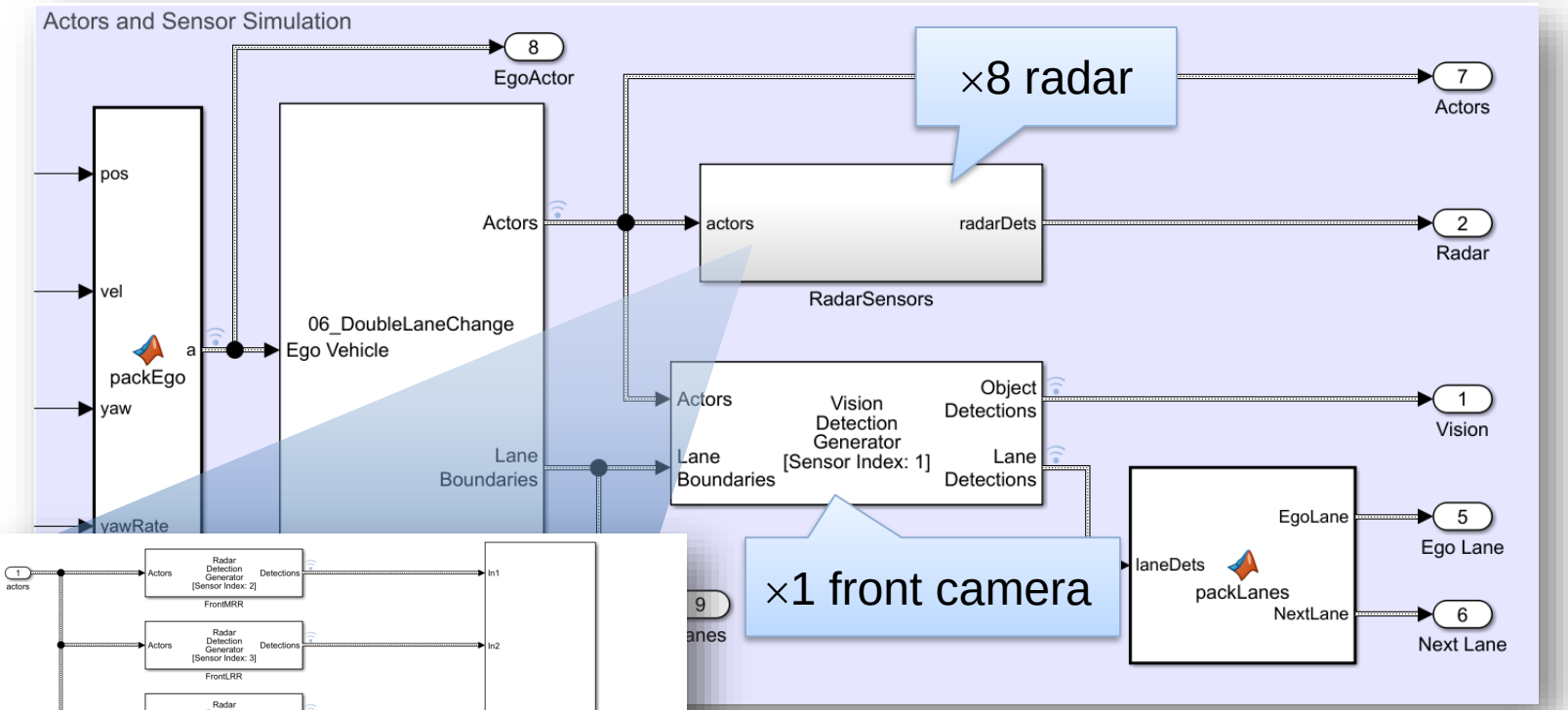
Review sensor models for traffic jam assist

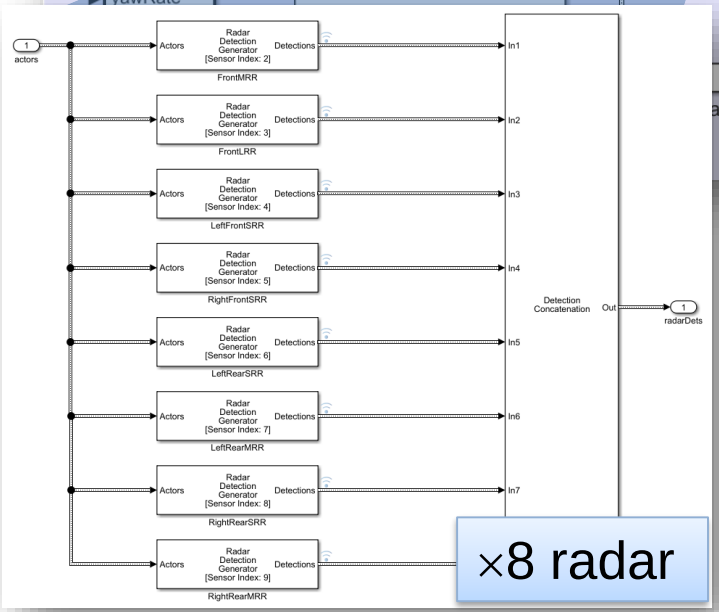




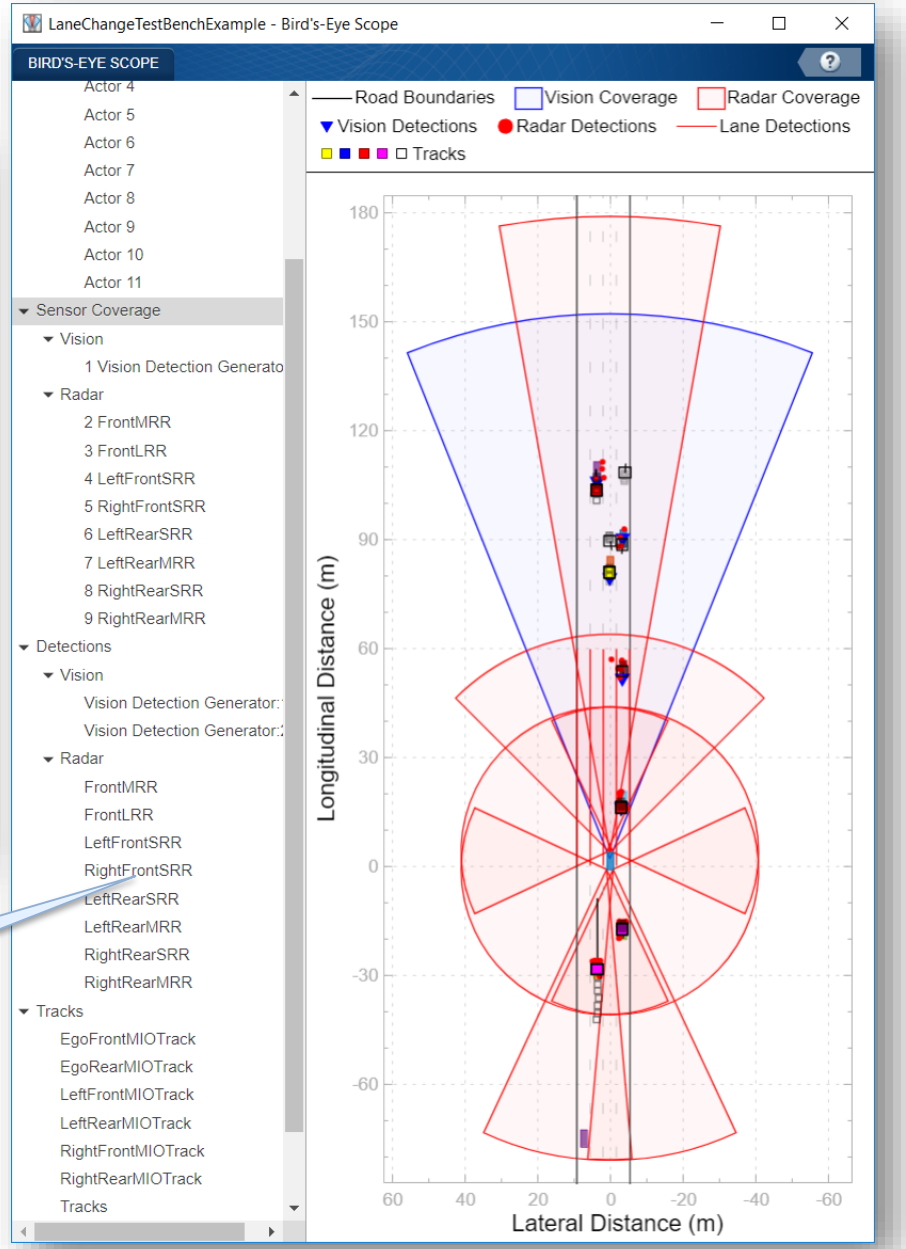
Visualize with
Birds Eye Scope

Add sensor models for lane change

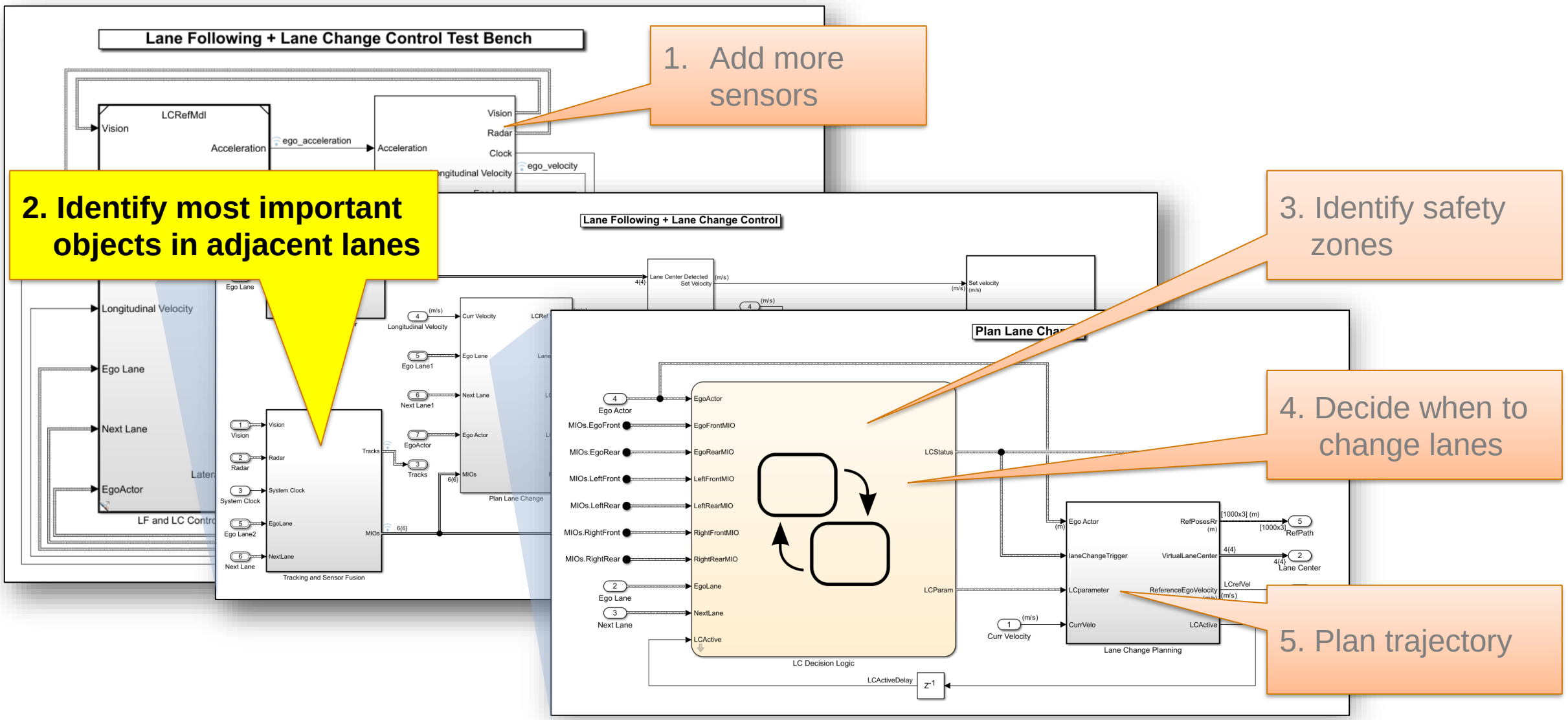




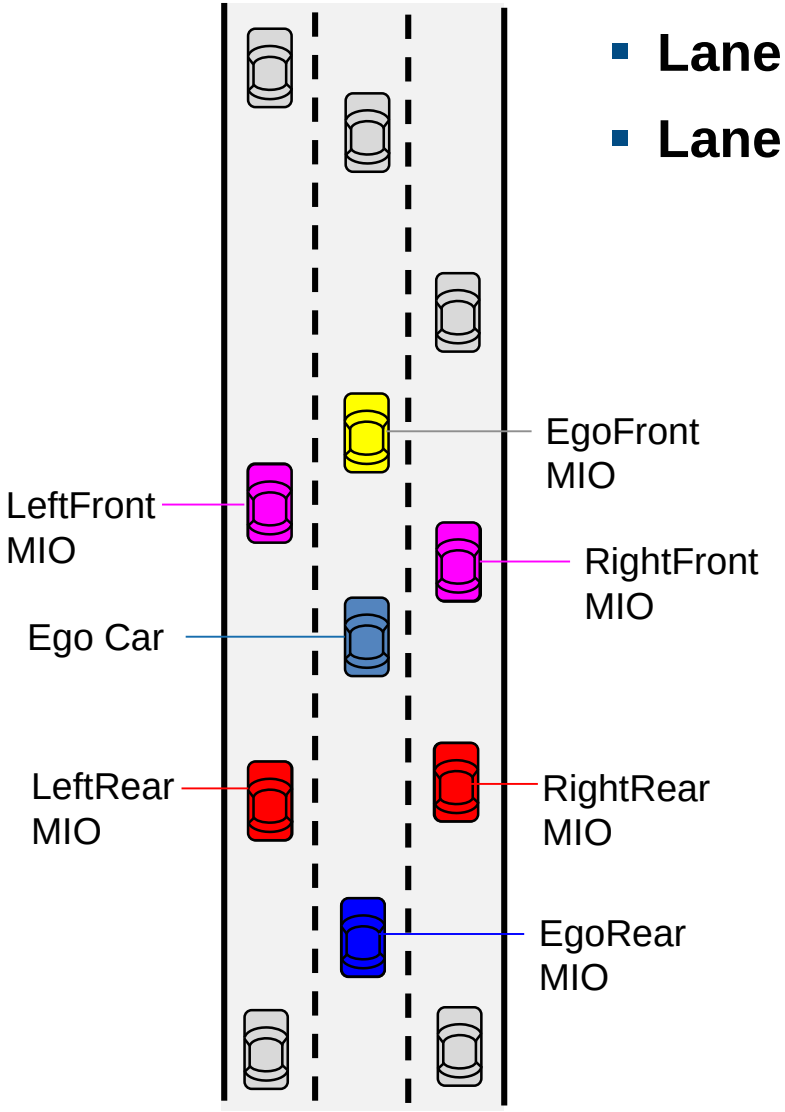
Visualize with
Birds Eye Scope



Add lane change functionality to lane following controller

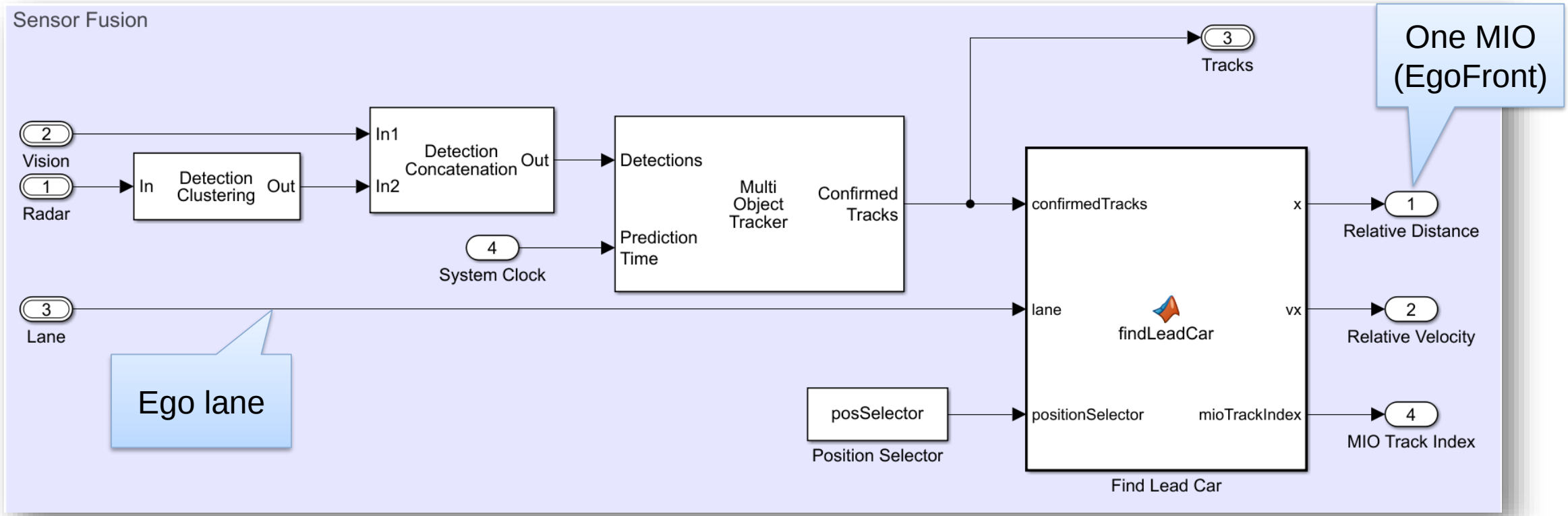


Identify Most Important Objects (MIO) to detect

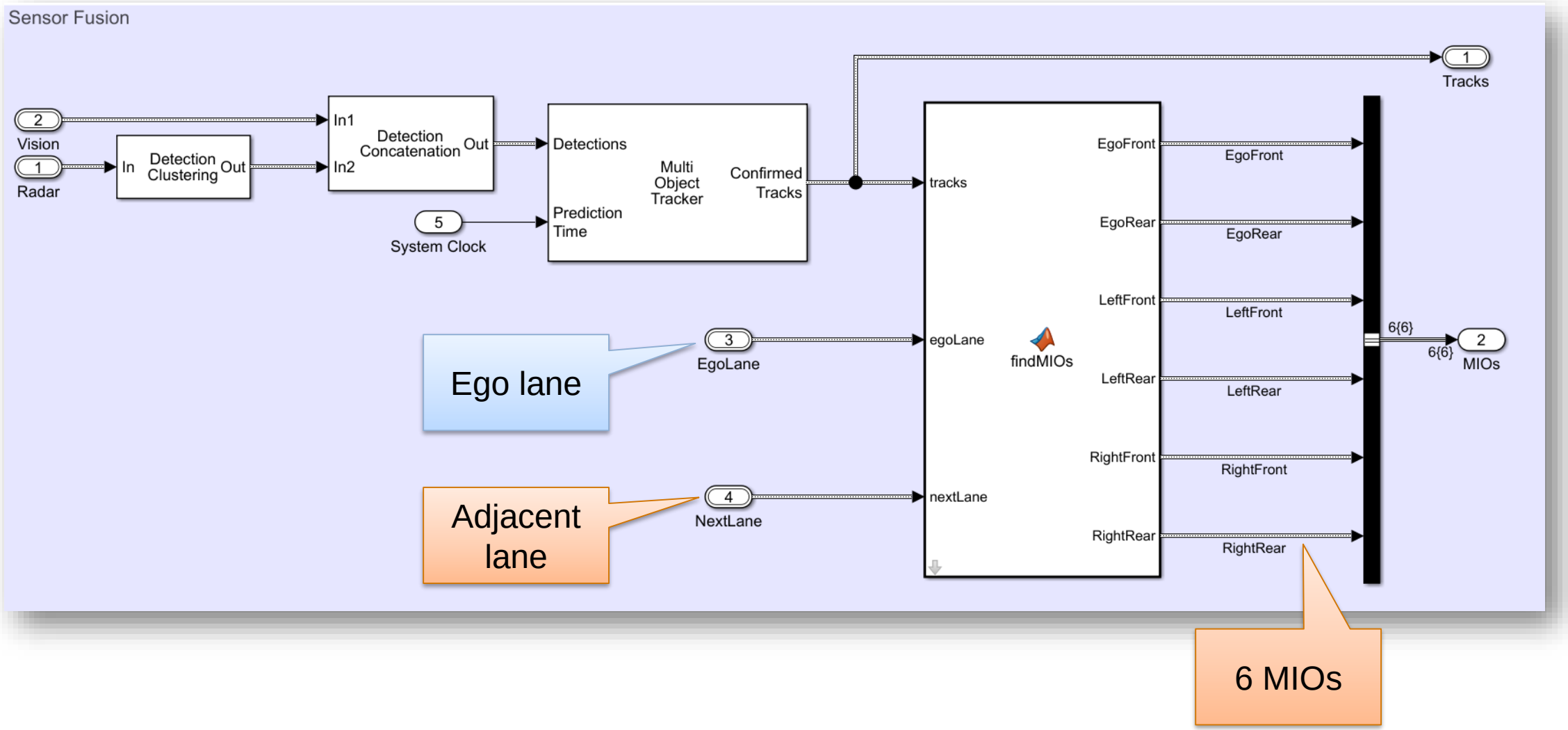


- **Lane following** – one EgoFront MIO is enough
- **Lane change** – needs more MIOs surrounding ego car

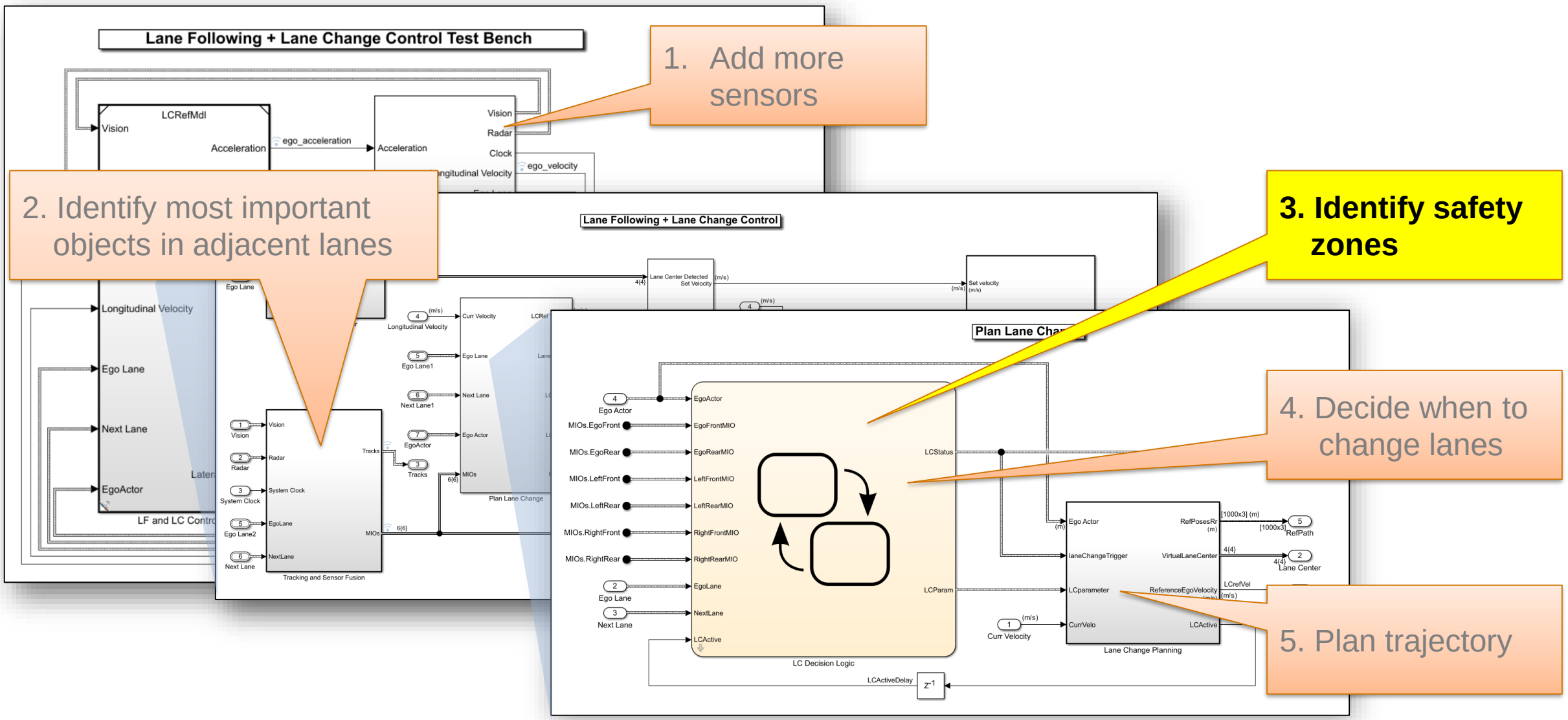
Review baseline MIO detector architecture for traffic jam assist



Add MIO detectors for lane change

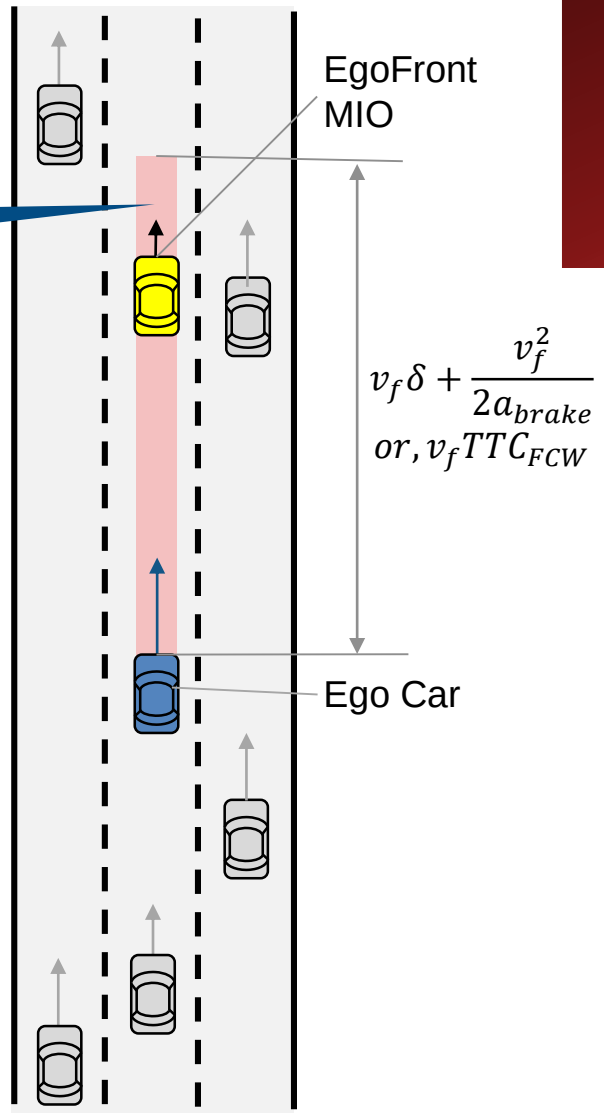


Add lane change functionality to lane following controller



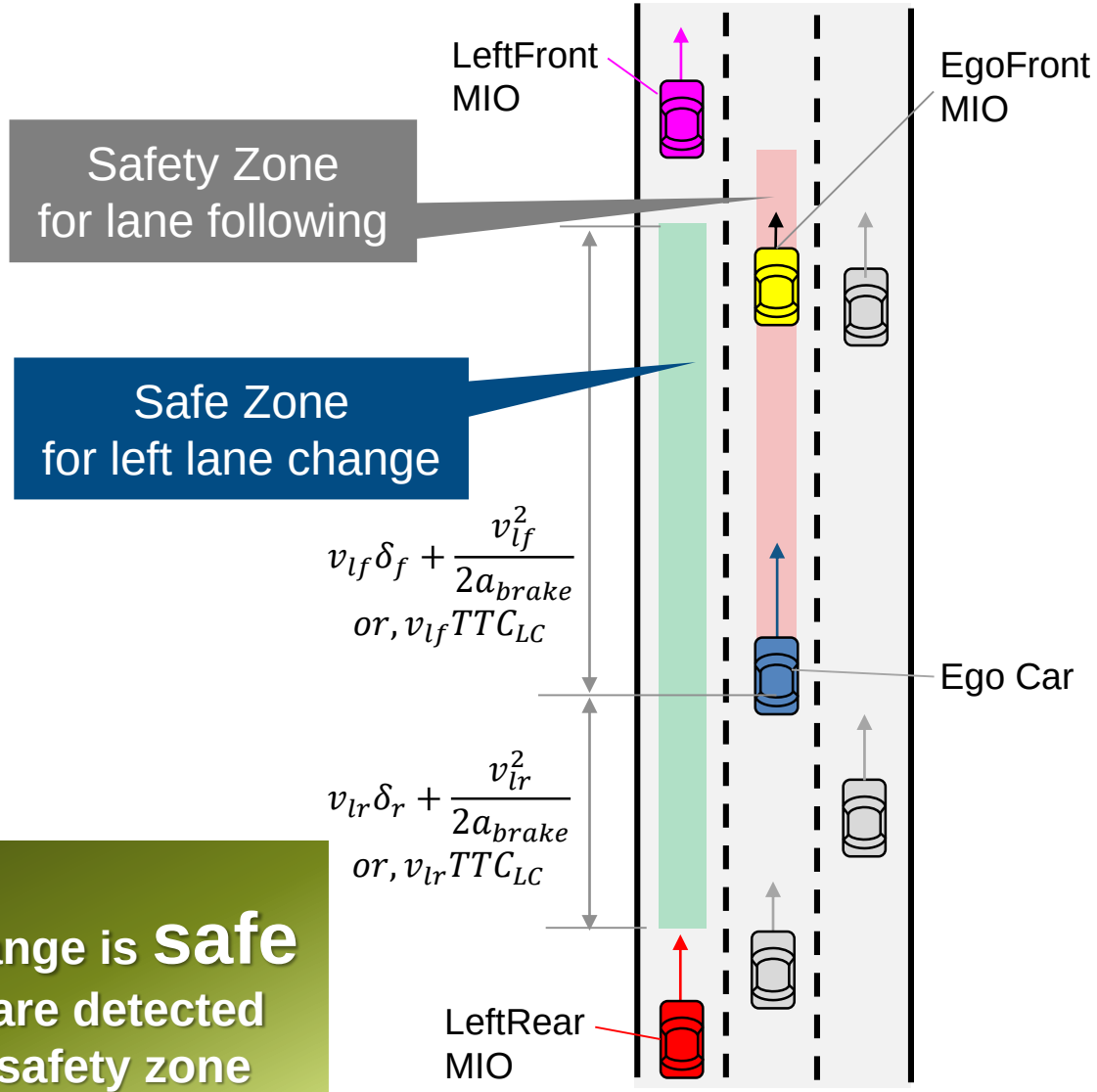
Identify safety zones to calculate

Safety Zone
for lane following



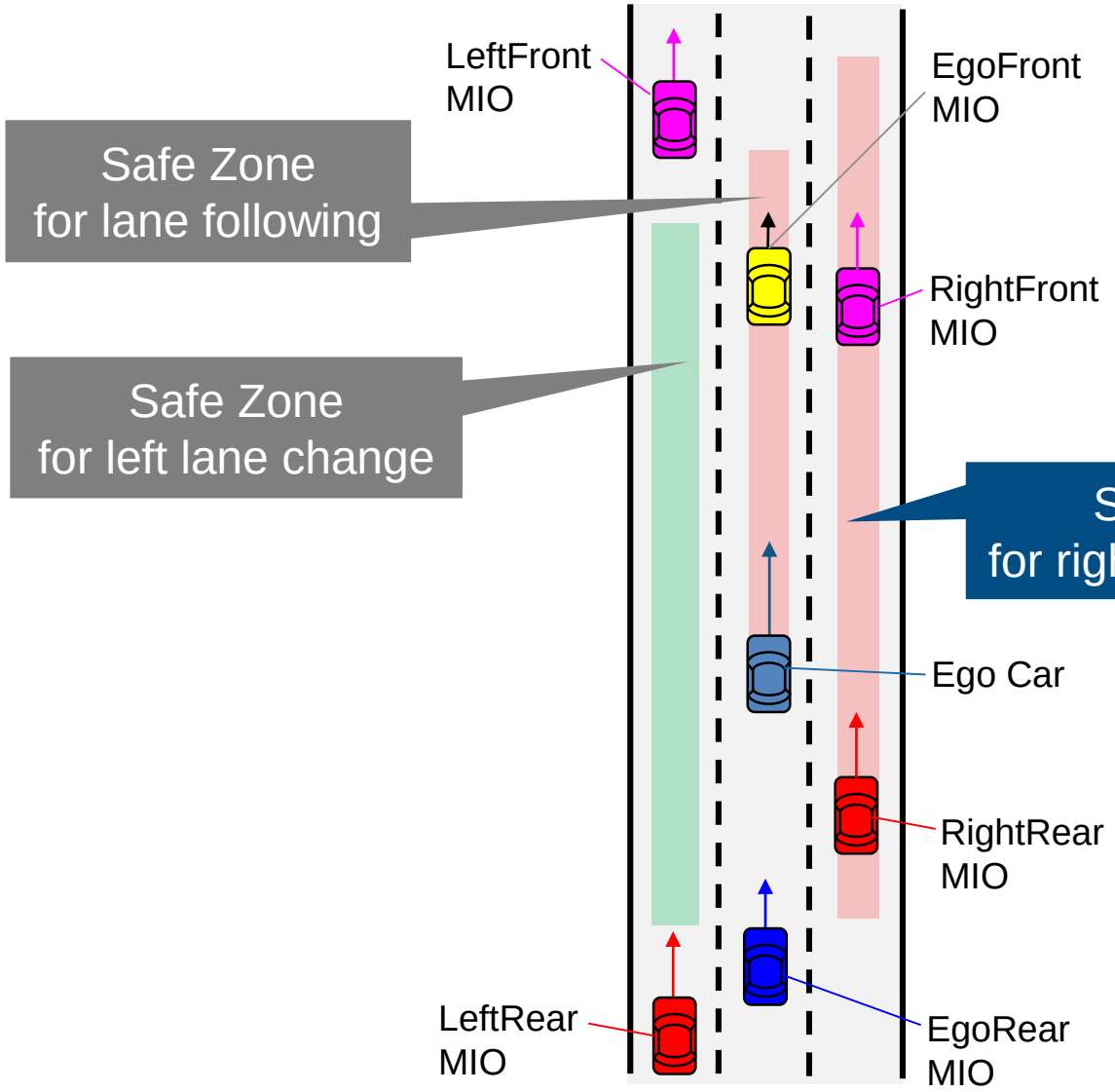
Lane following is unsafe
if ego front MIO is detected within the safety zone

Identify safety zones to calculate



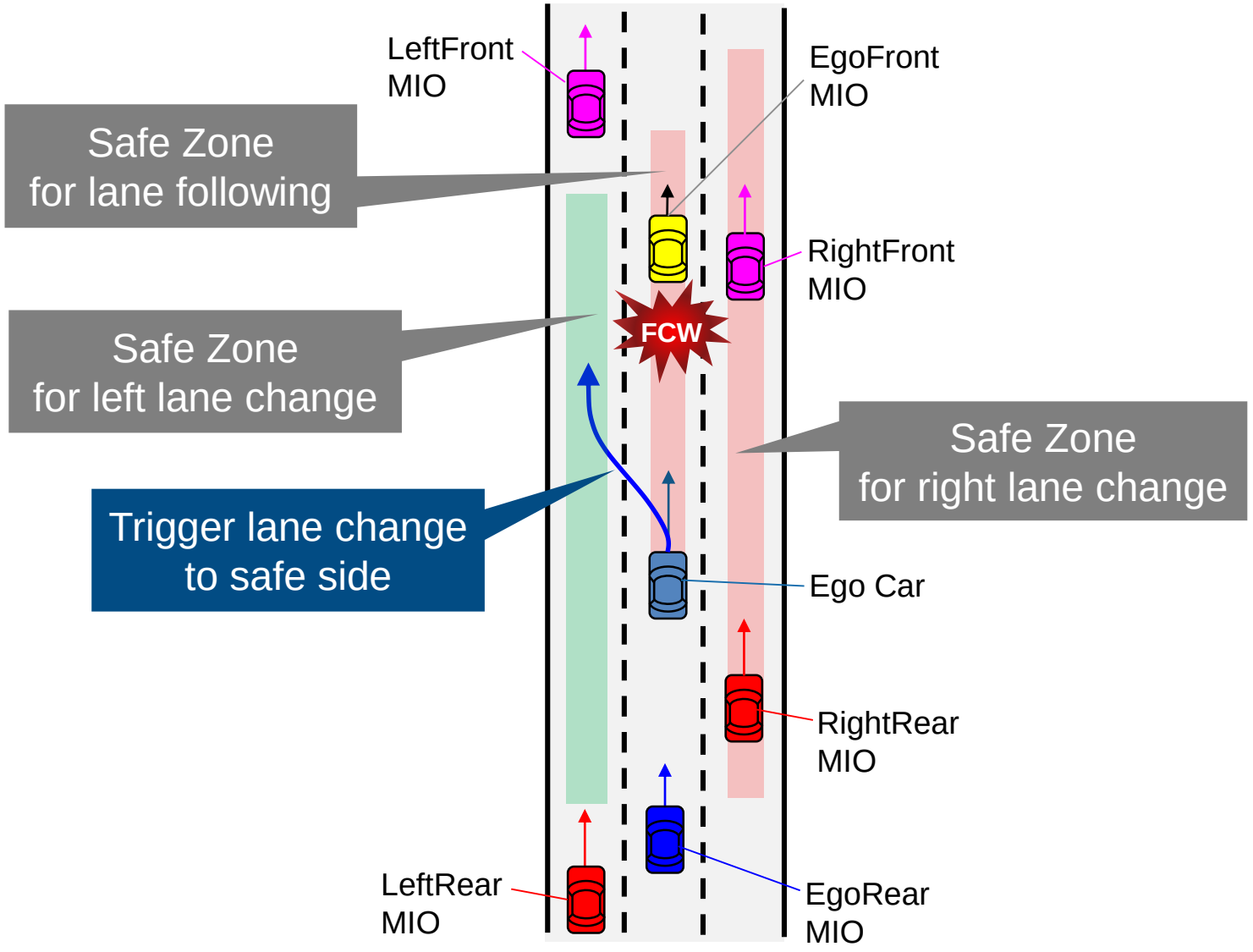
Left lane change is safe if no MIOs are detected within the safety zone

Identify safety zones to calculate

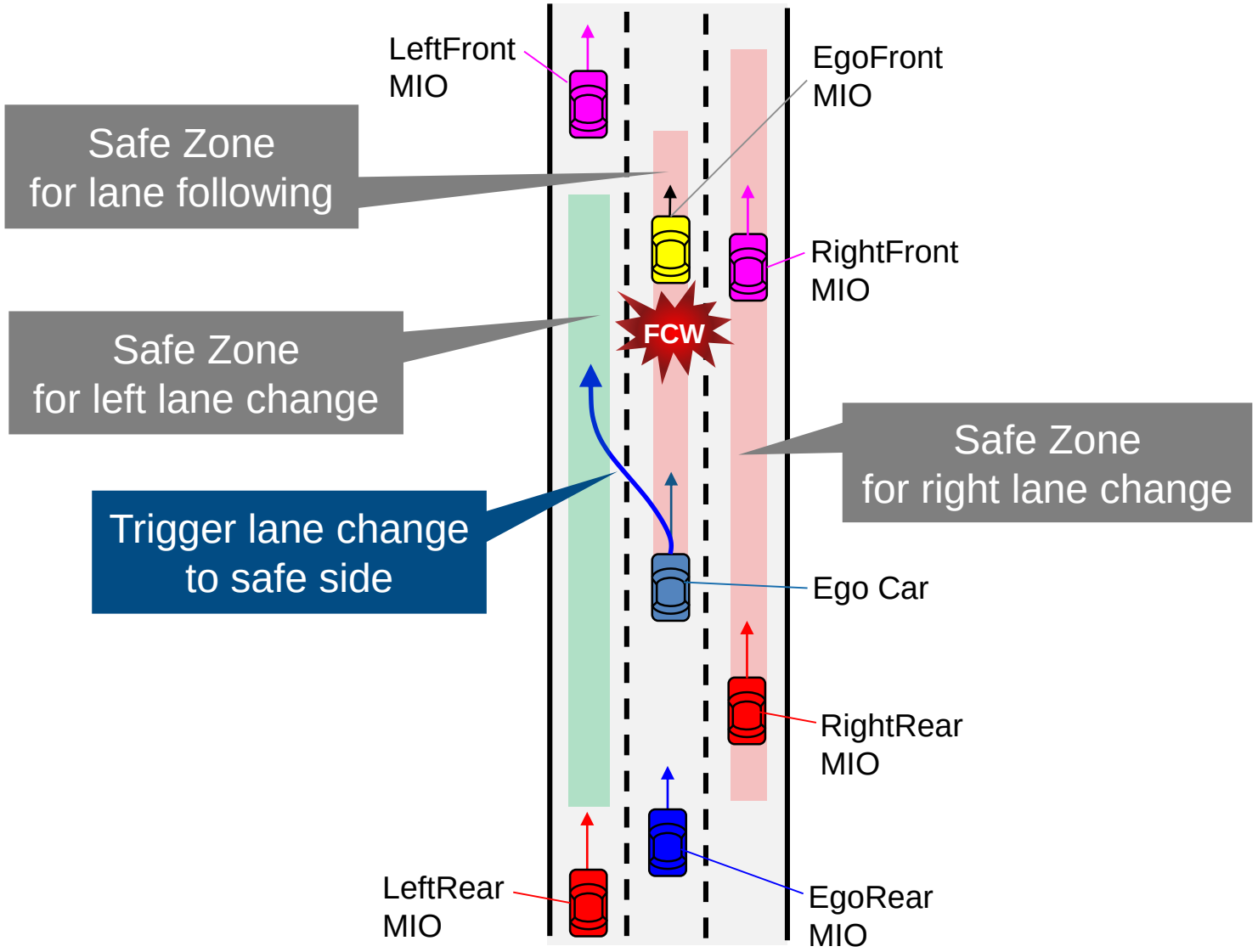


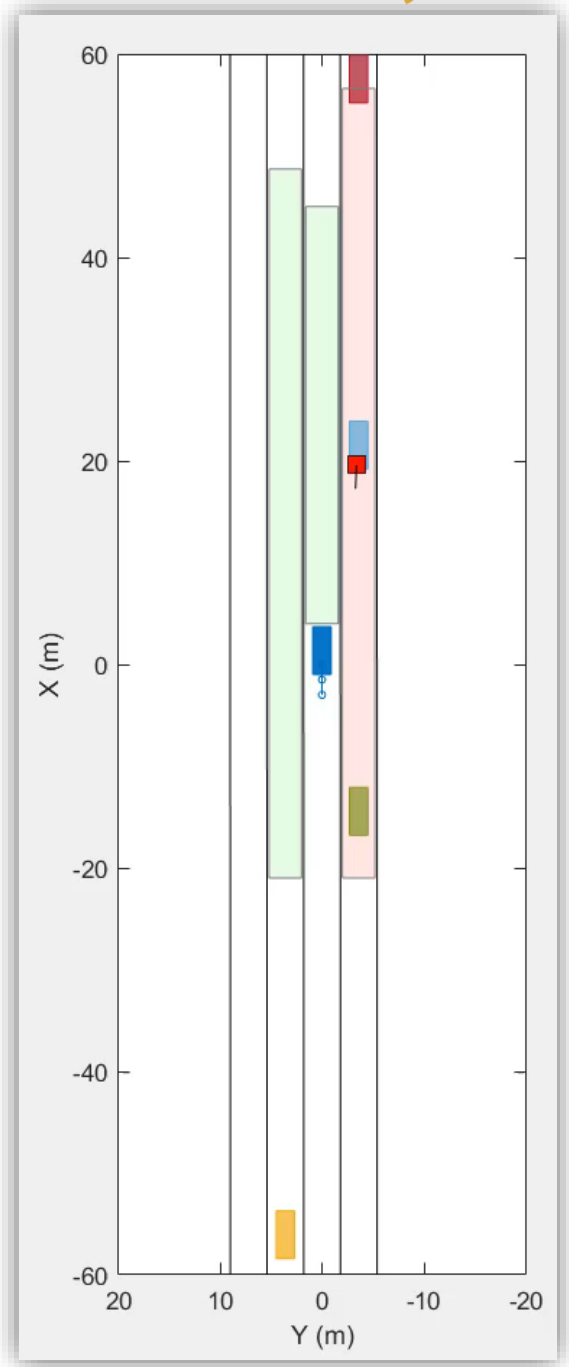
Right lane change is unsafe if MIOs are detected within the safety zone

Identify safety zones to calculate

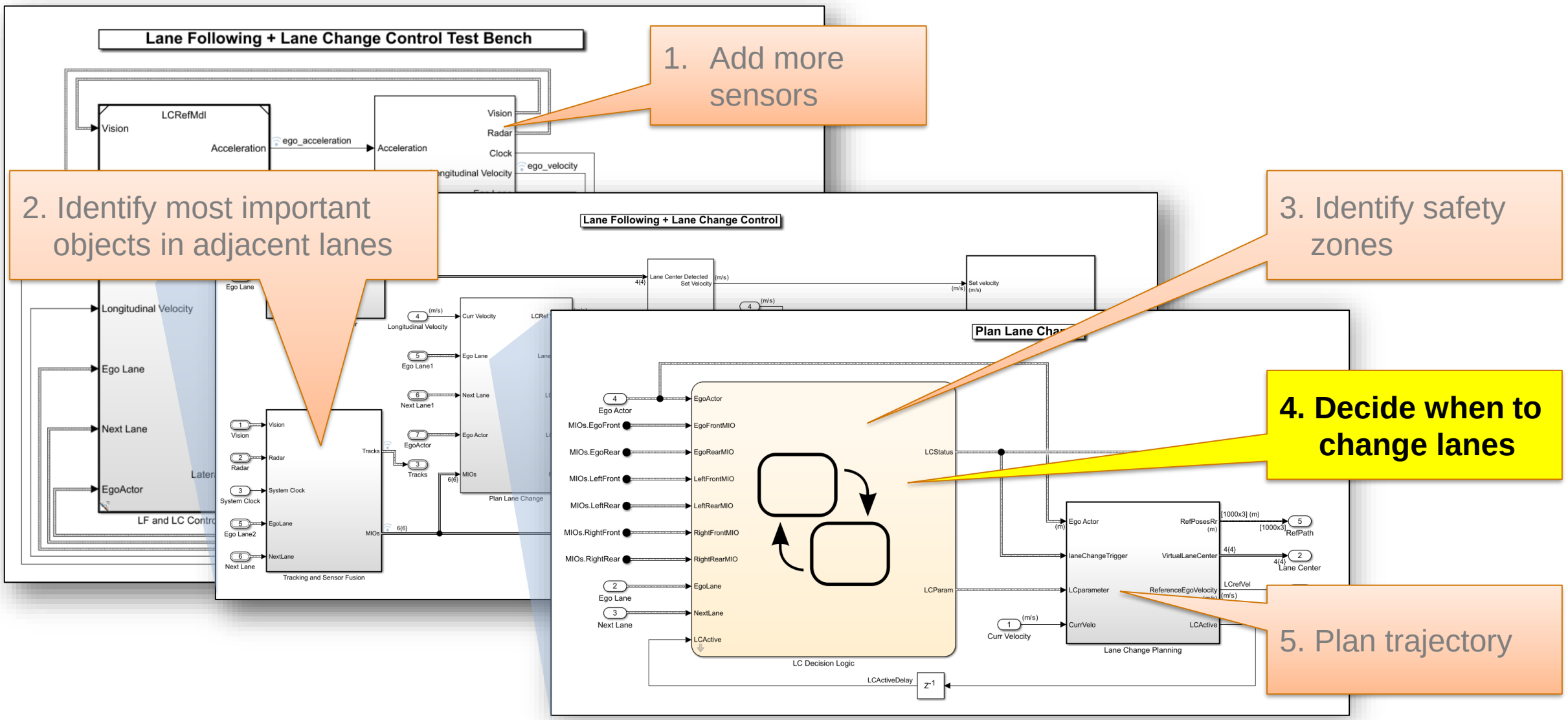


Visualize safety zones

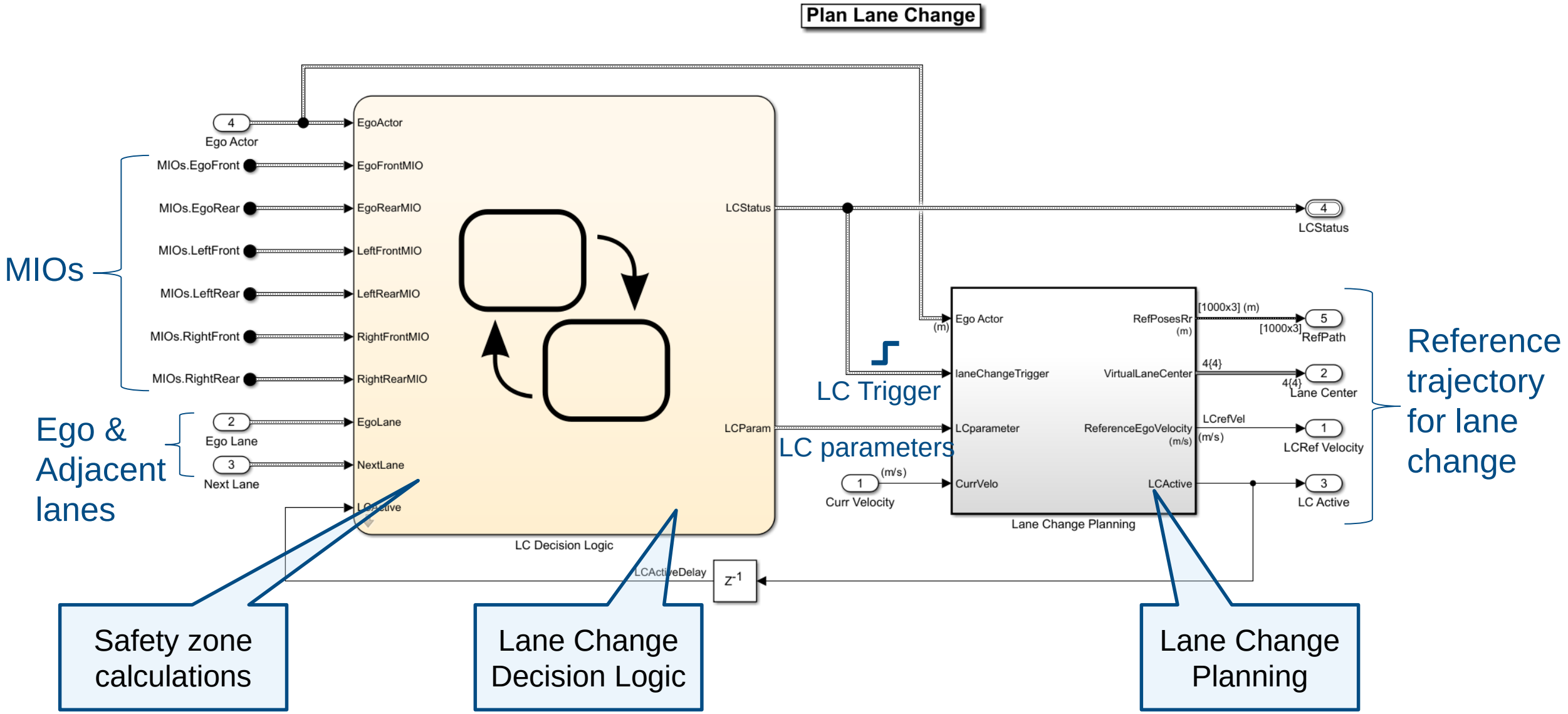




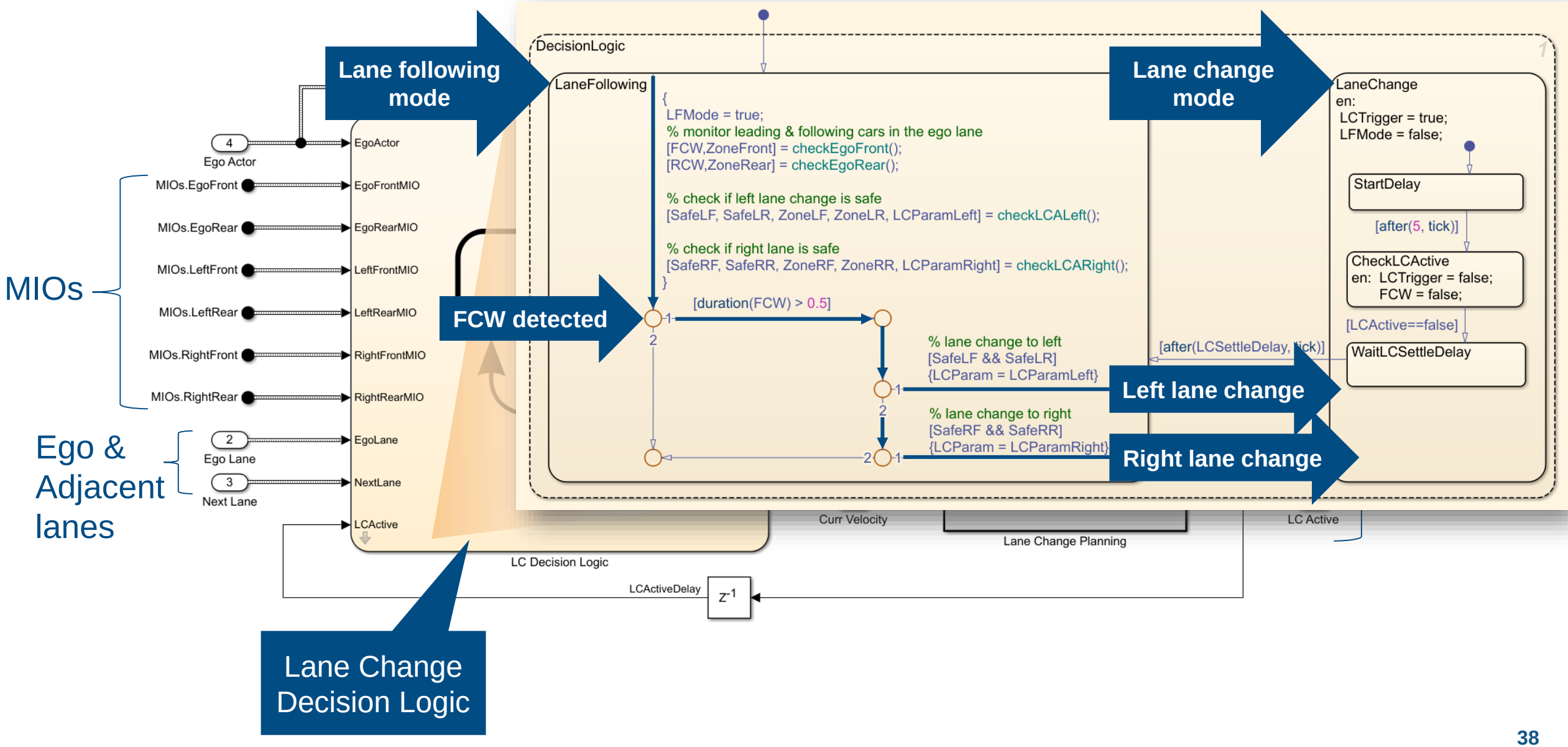
Add lane change functionality to lane following controller



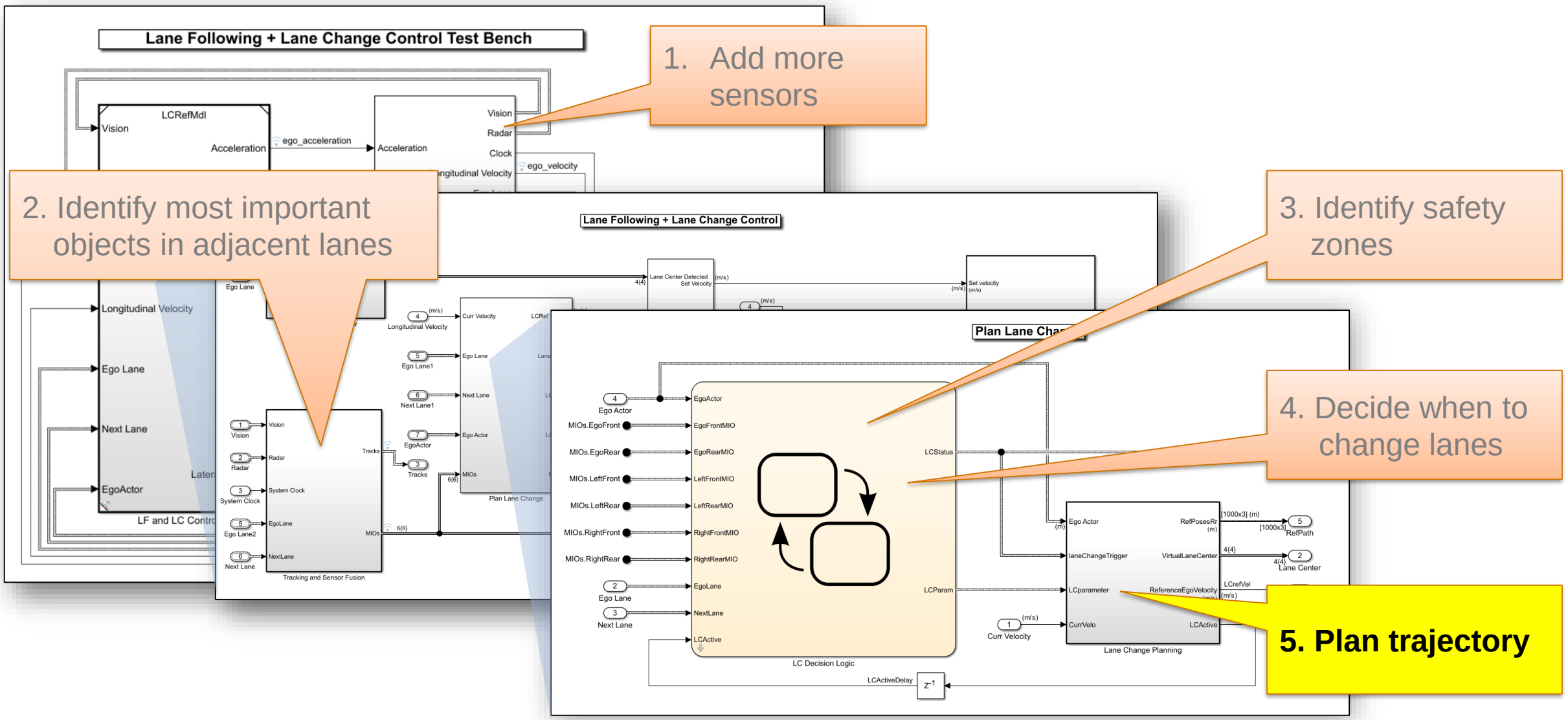
Lane change decision logic and planning



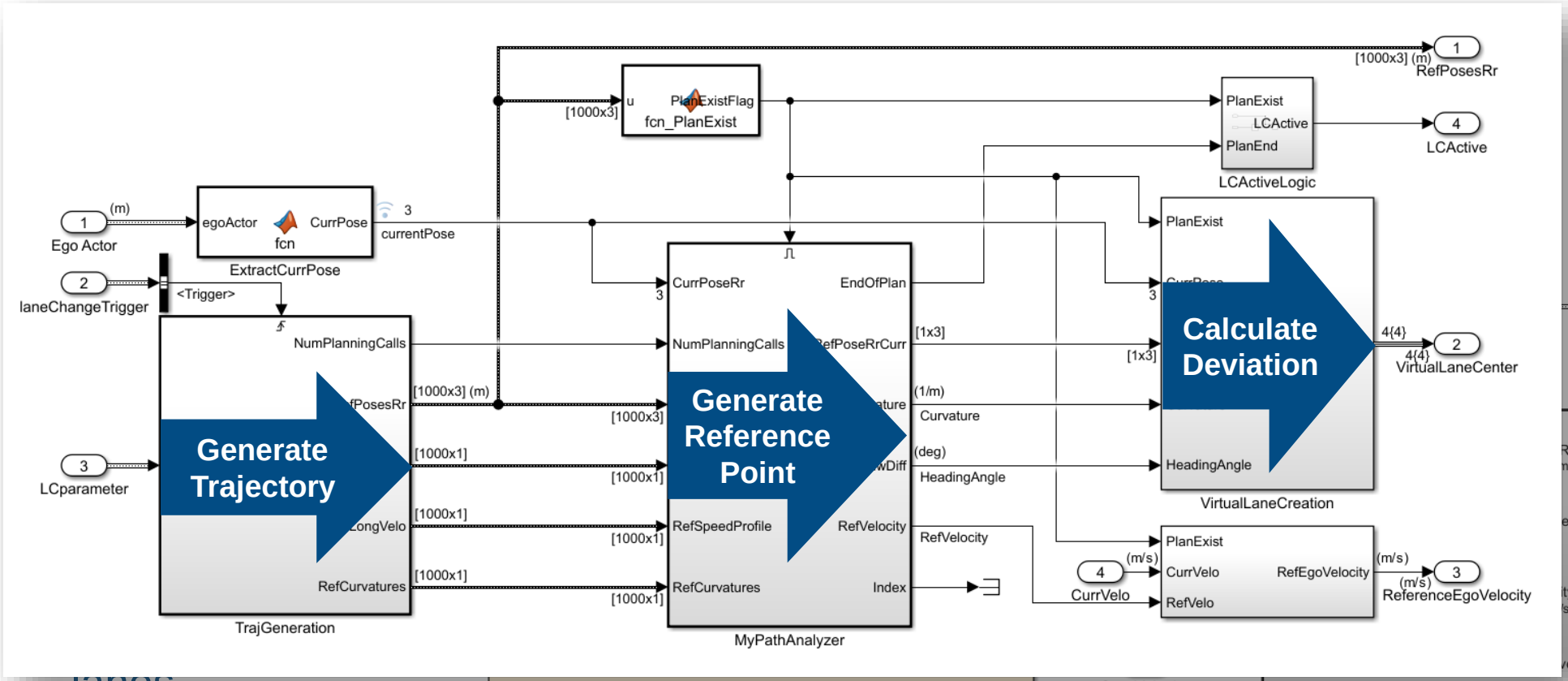
Design lane change decision logic



Add lane change functionality to lane following controller



Design lane change planning



Reference lane change trajectory

Generate trajectory

- Quintic polynomial

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

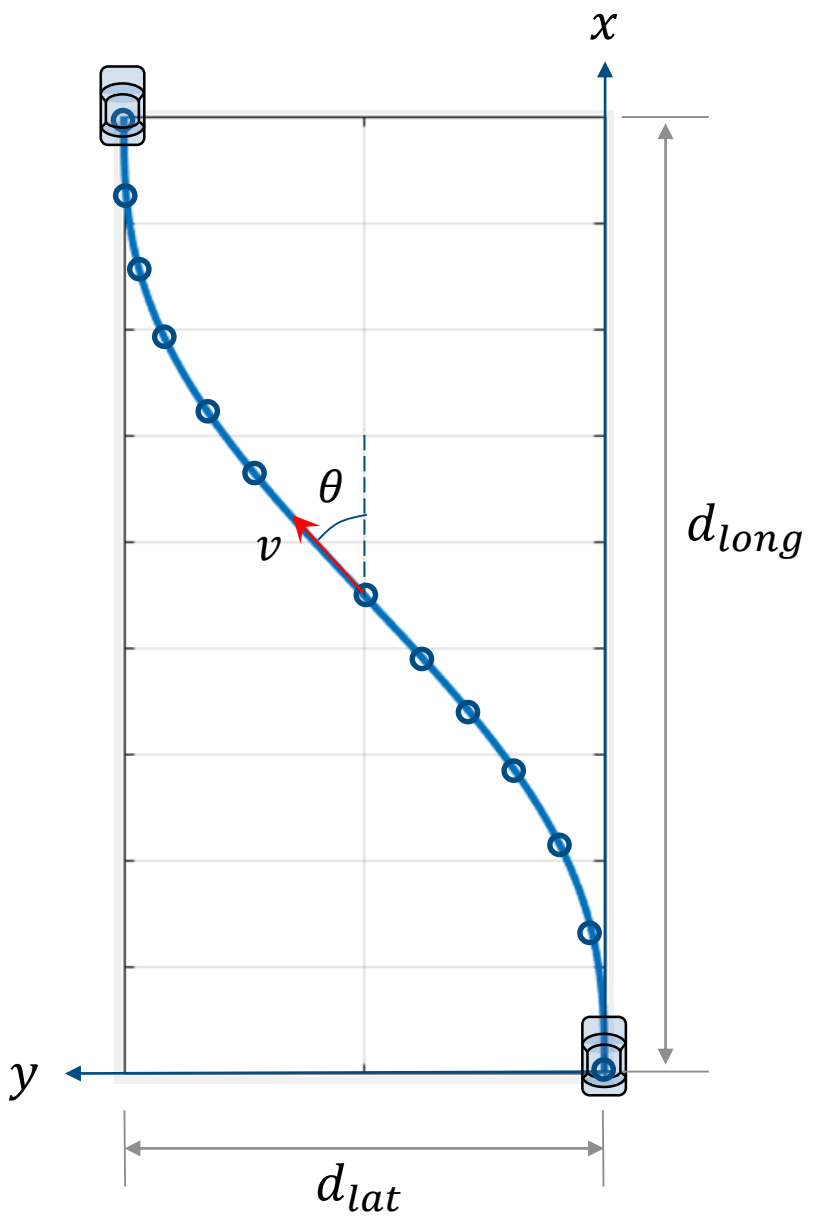
$$where\ s = longitudinal\ or\ lateral\ distance$$

- Start boundary conditions

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

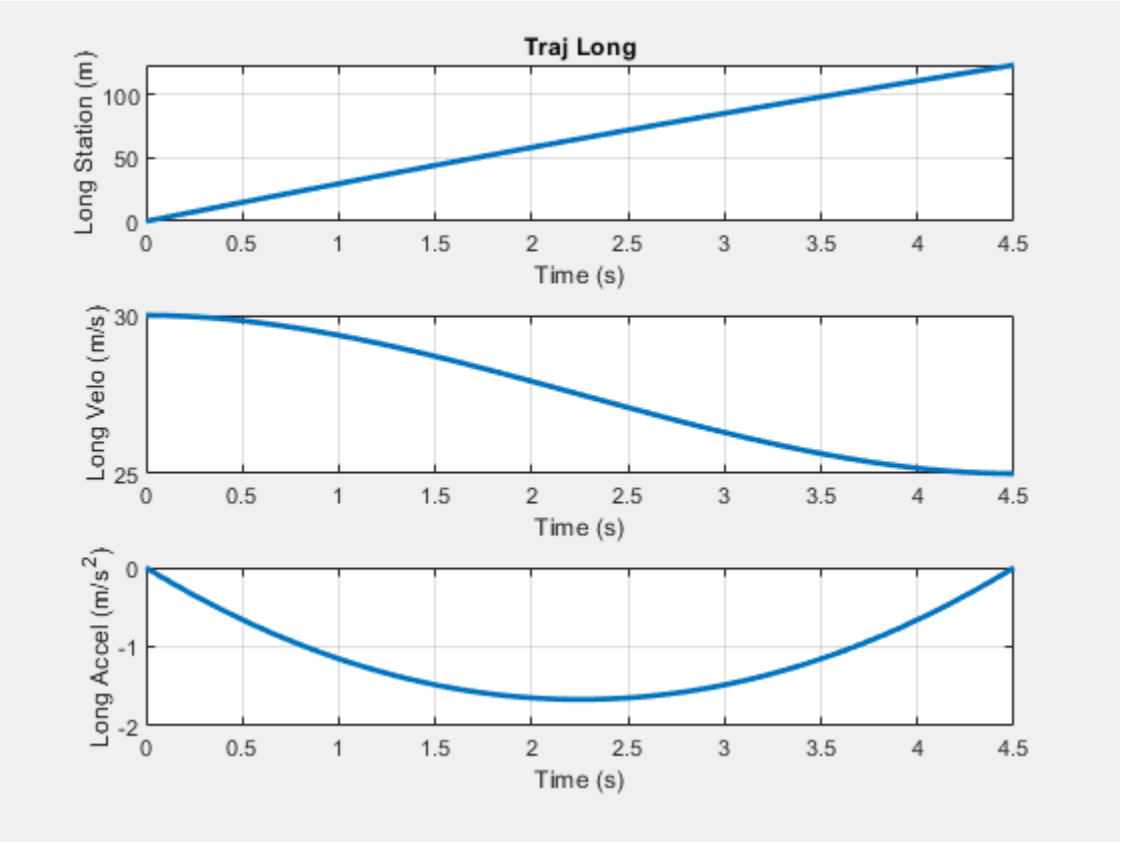
- End boundary conditions

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

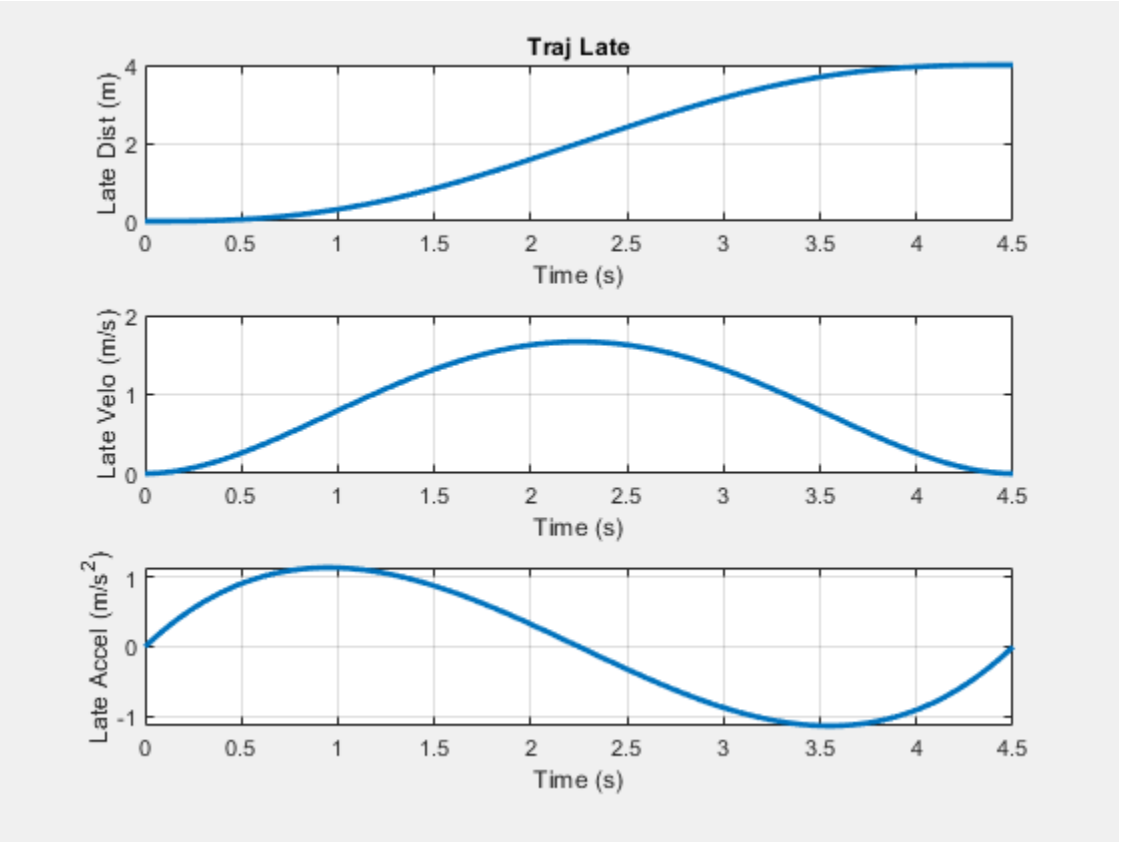


Example of trajectory generation for lane change

Longitudinal trajectory

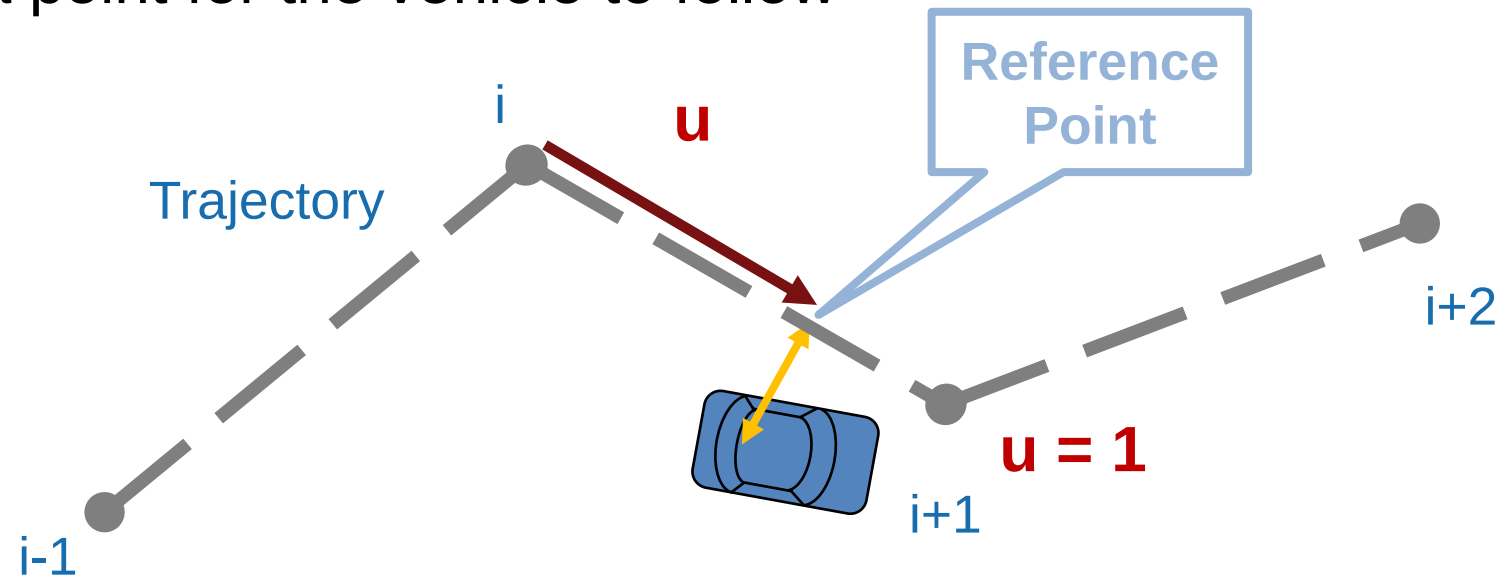


Lateral trajectory



Generate reference point

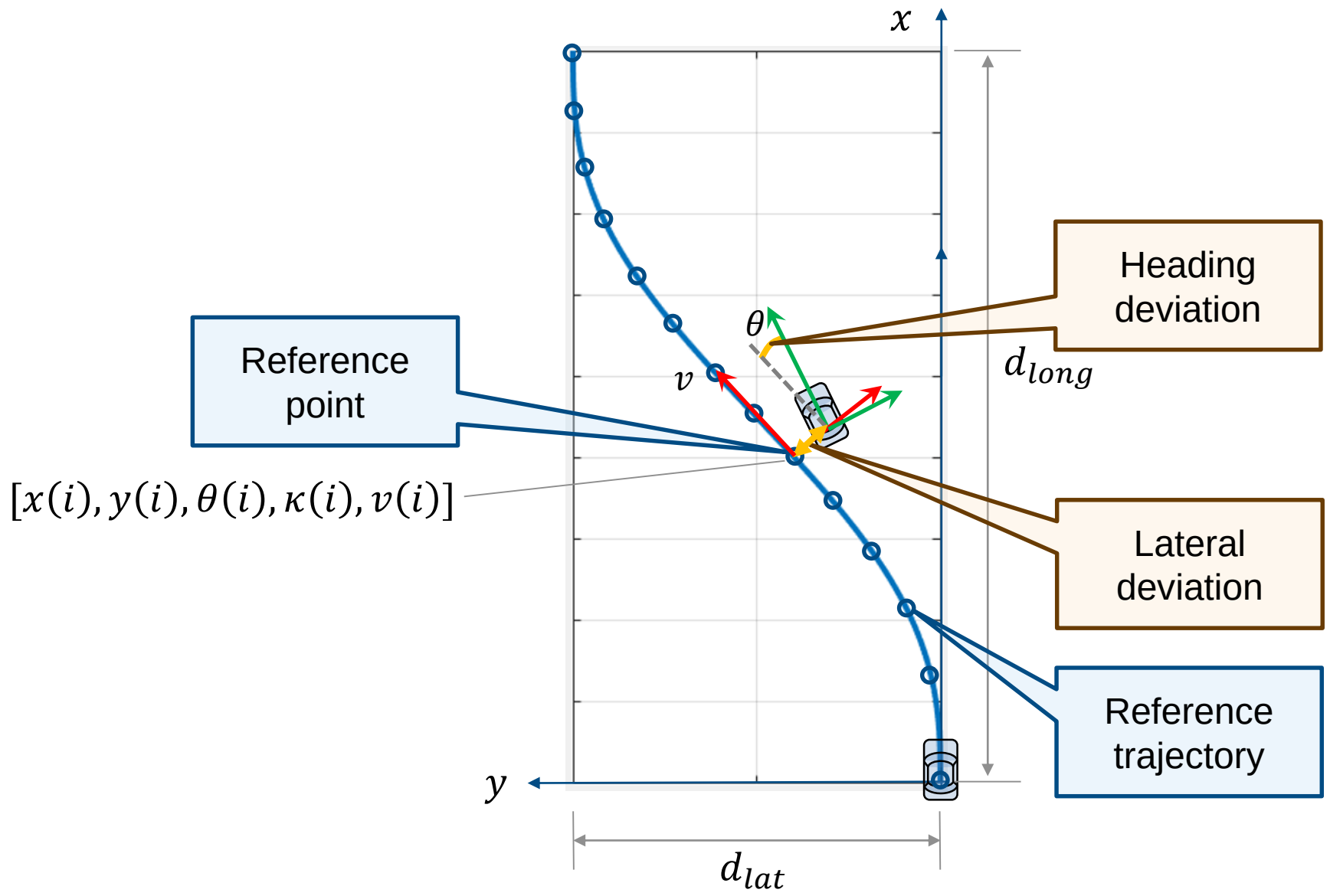
- Find a point for the vehicle to follow



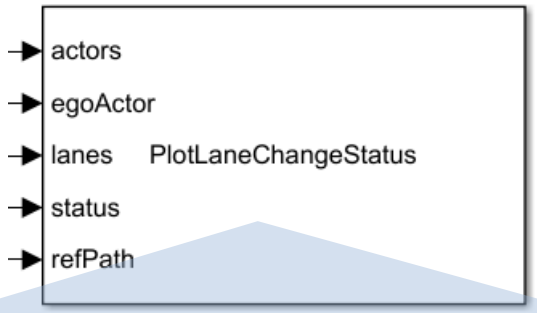

```
% Normalized distance between current position and section starting point
u = (RXY.*DeltaXY)/(DeltaXY.*DeltaXY);

% Find section ending point
indexIncrement = ceil(u-1);
```

Incremental projection

Calculate deviations from reference point



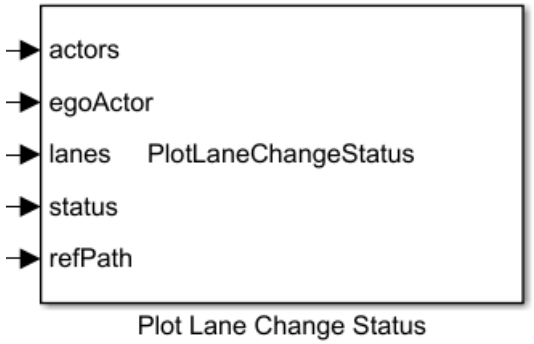
Create custom visualization for safety zones and trajectory



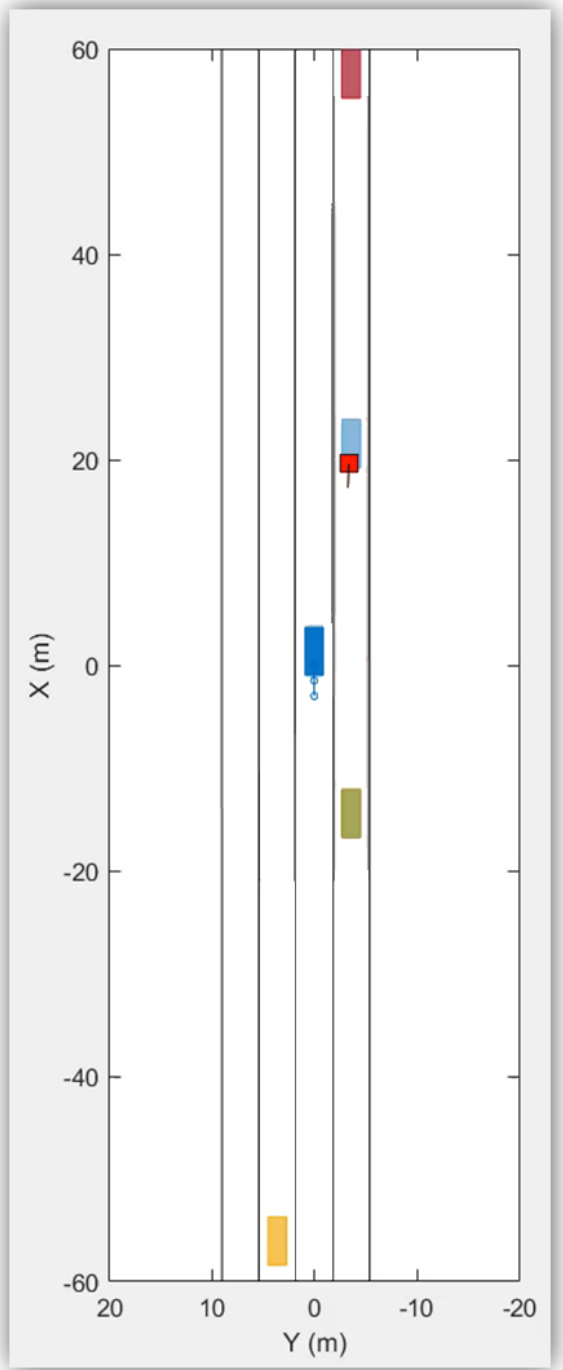
PlotLaneChangeStatus.m

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

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

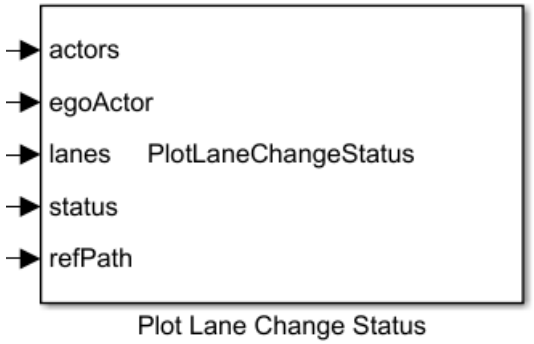
Create birds eye plot with utilities from Automated Driving Toolbox




```
% 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);
```

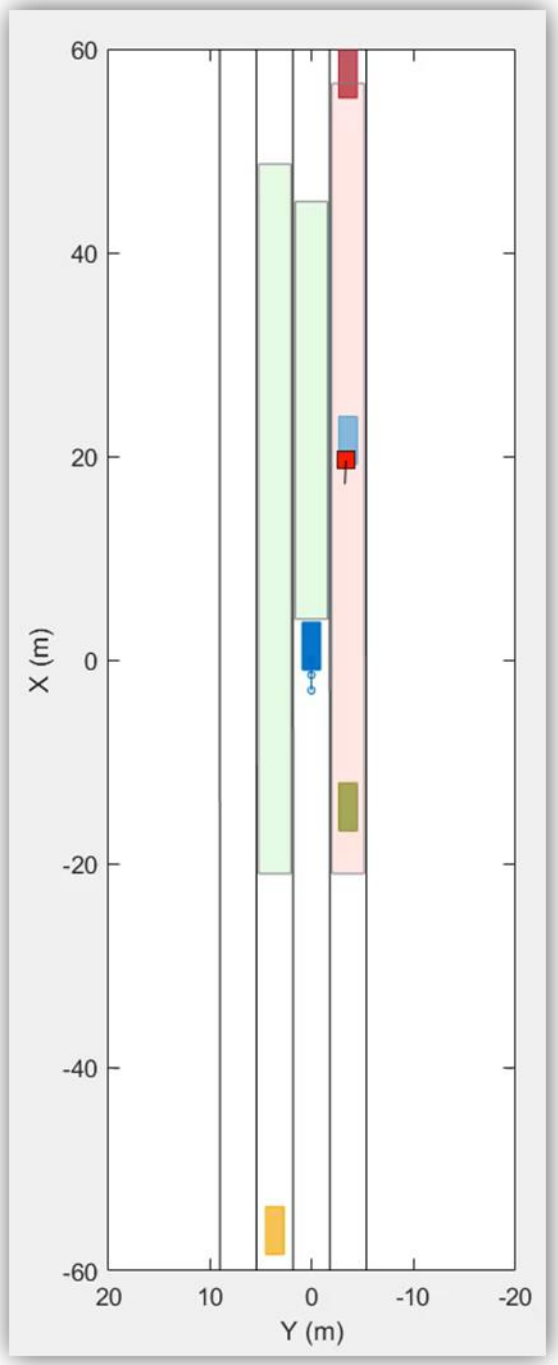


Plot safety zones and trajectory with MATLAB

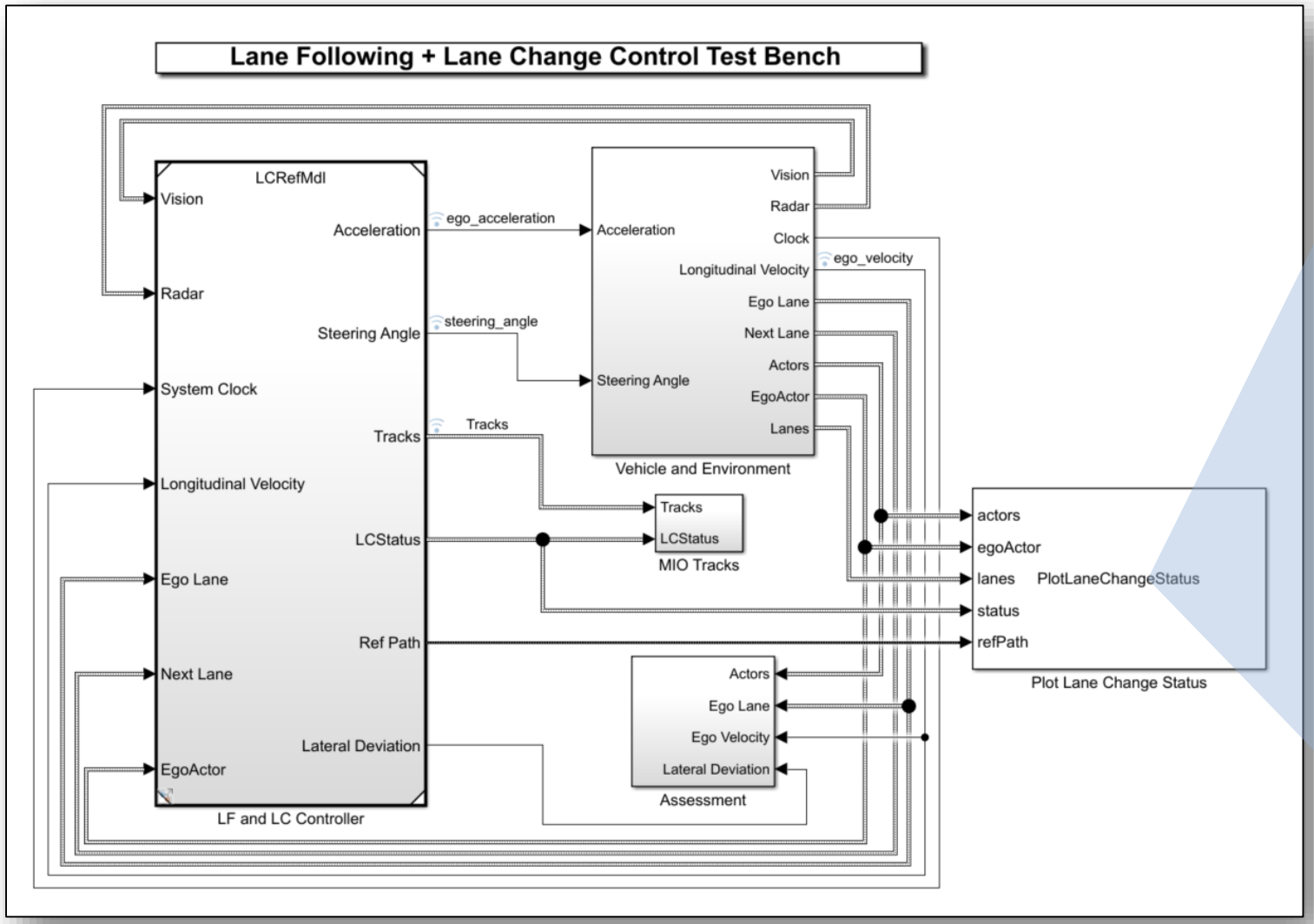


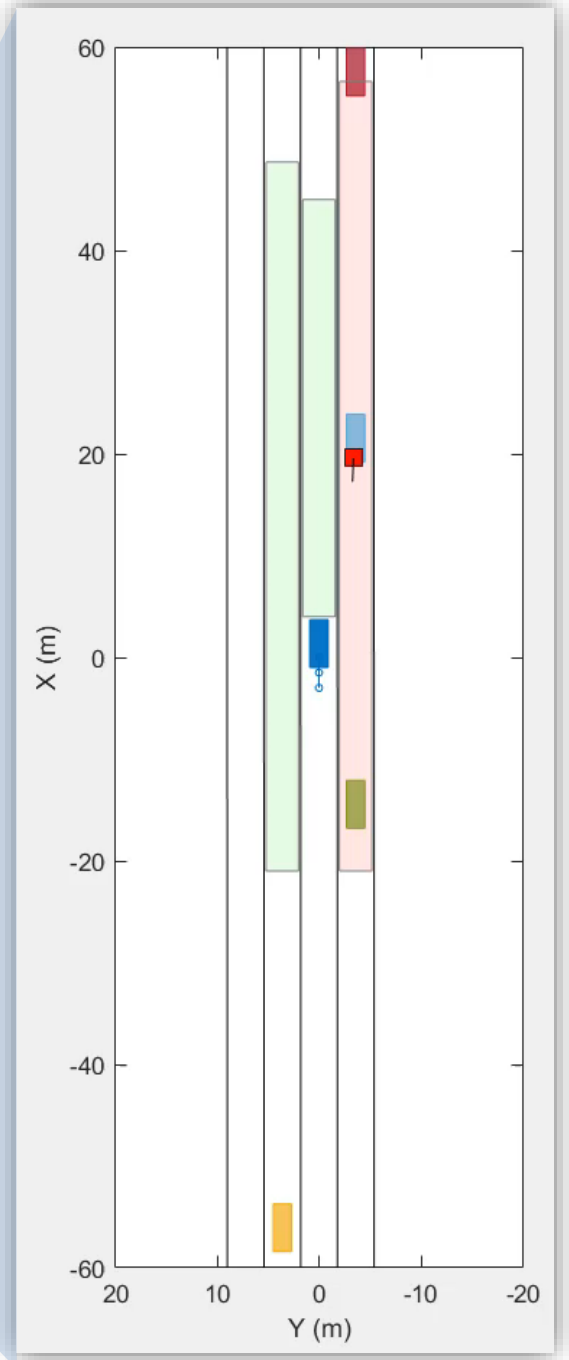

```
% create patches for safety zones
obj.ZoneFront = patch(hax,0,0,[0 0 0]);
set(obj.ZoneFront,'XData',[],'YData',[],...
    'FaceColor','green','FaceAlpha',0.1);
```

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

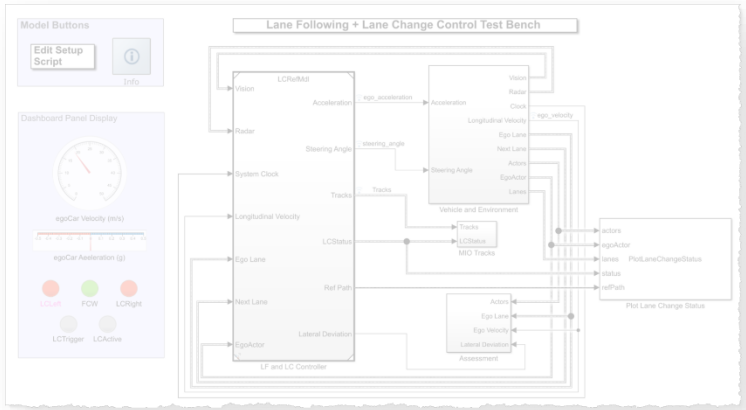


Visualize safety zones and trajectory



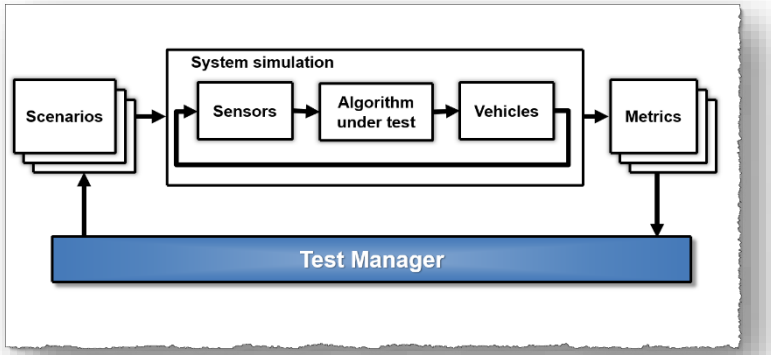


Case Study for Lane Following plus Lane Change



Design lane following + lane change controller

- Review baseline LF example
- Design sensor configuration
- Design additional MIO detectors
- Design safety zone calculation
- Design lane change logic
- Design trajectory planner



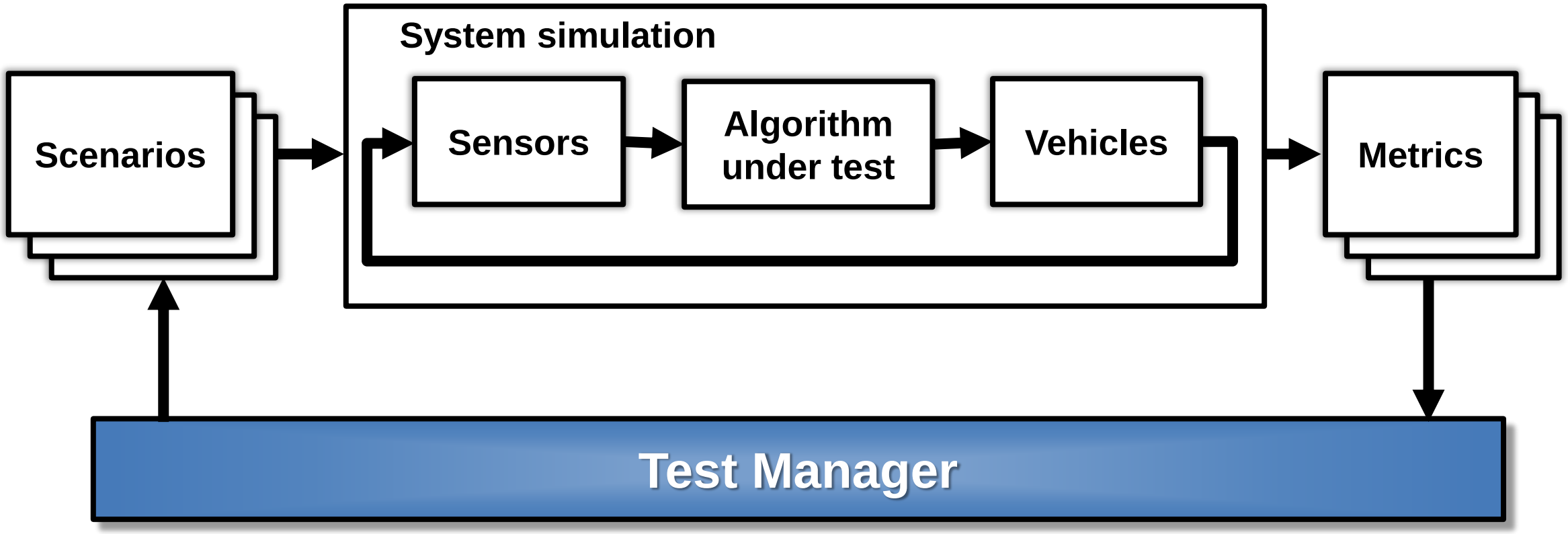
Automate regression testing

- Define assessment metrics
- Add predefined scenarios
- Run Simulink test

Test robustness with traffic agents

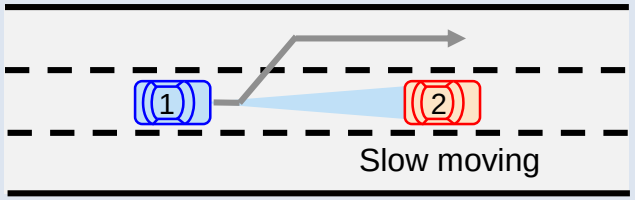
- Specify driver logic for traffic agents
- Randomize scenarios using traffic agents
- Identify and assess unexpected behavior

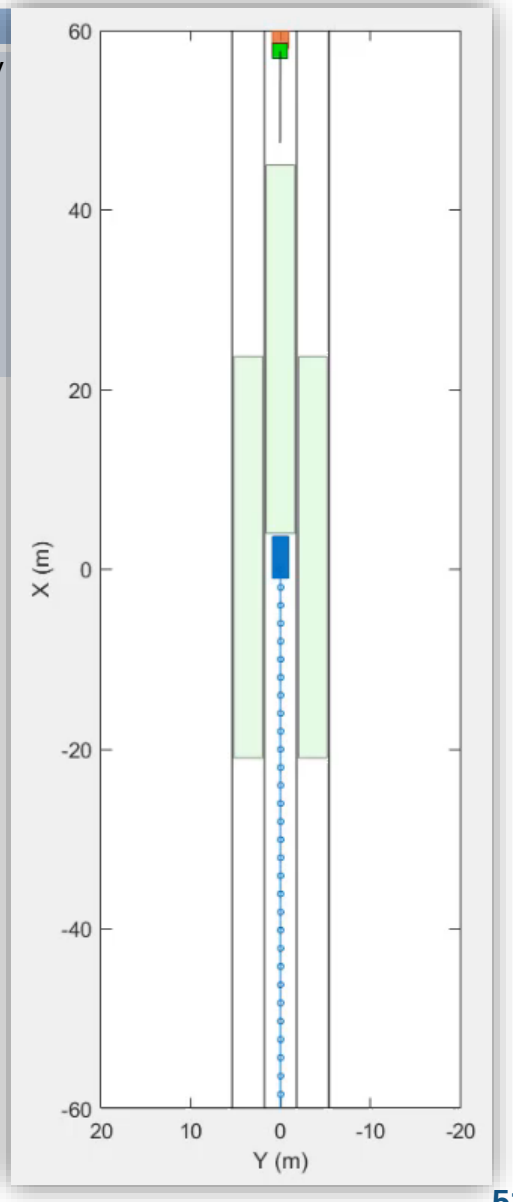
Manage testing against scenarios



Create test scenarios

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



Create test scenarios

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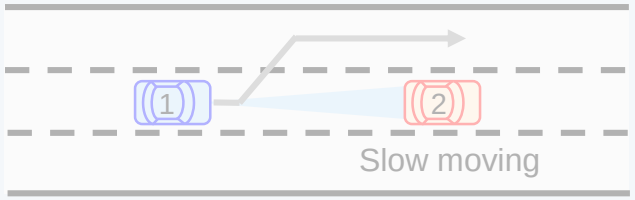
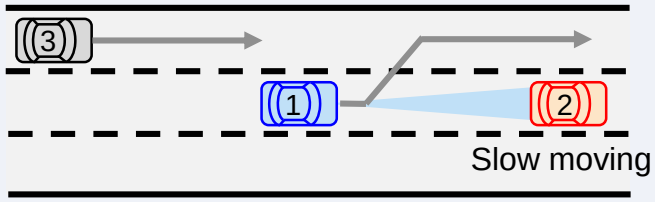
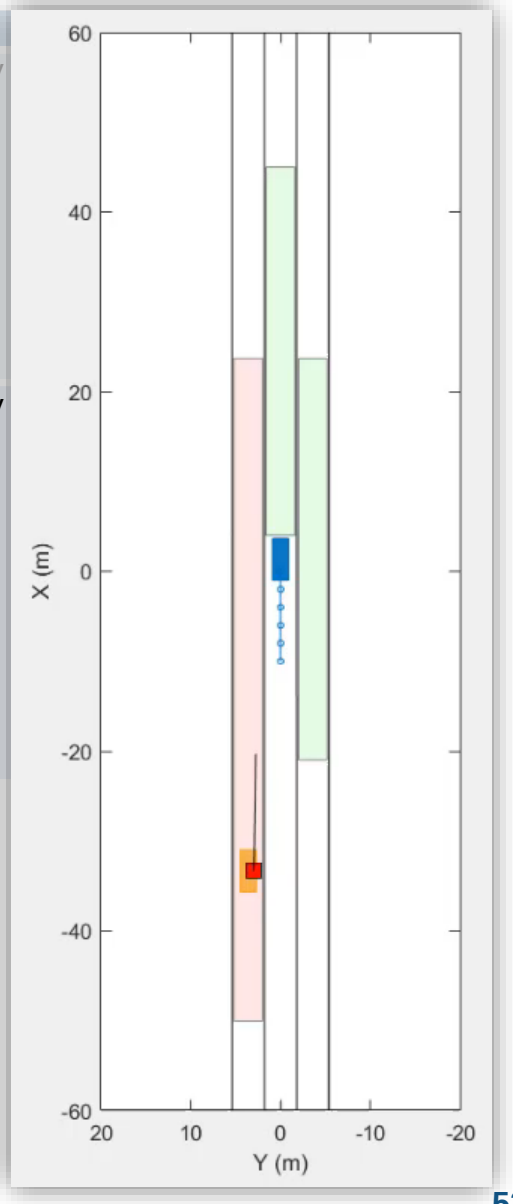
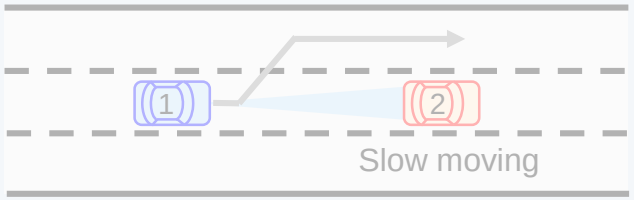
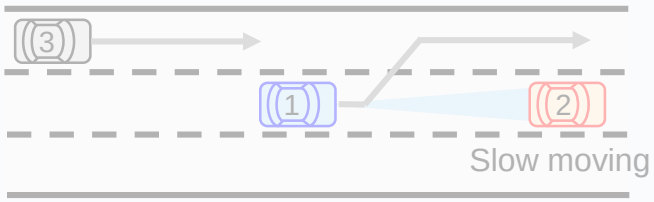
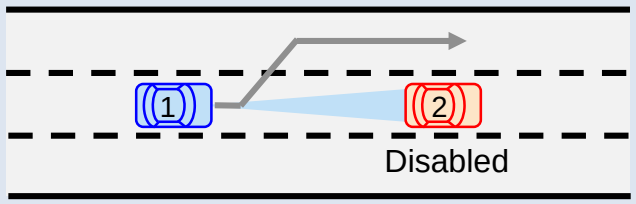
No	Test Name	Test Description	Host car	Lead car
1	01_SlowMoving	Passing for slow moving lead car 	initial velocity = 20m/s HWT = 6.5sec (HW = 130m) v_set = 20m/s	constant velocity 10m/s
2	02_SlowMoving WithPassingCar	Passing for slow moving Lead car With rapidly approaching car in adjacent lane 	initial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



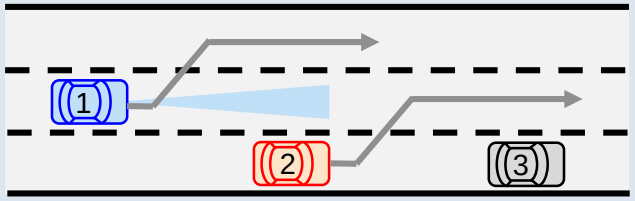
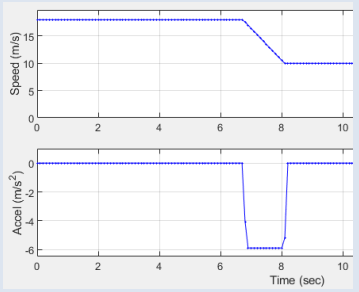
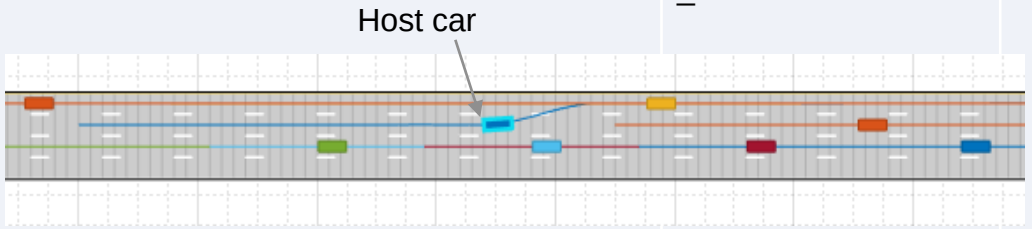
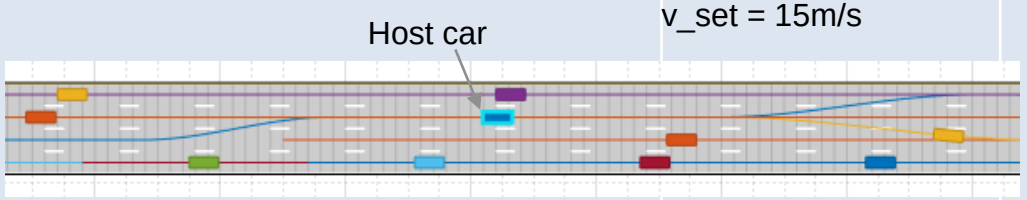
Create test scenarios

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	

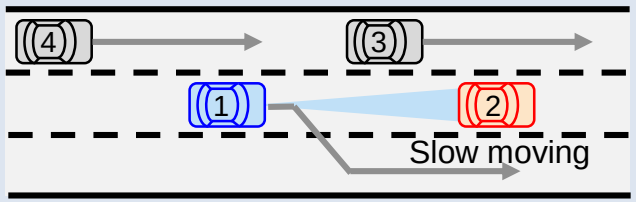
Create test scenarios

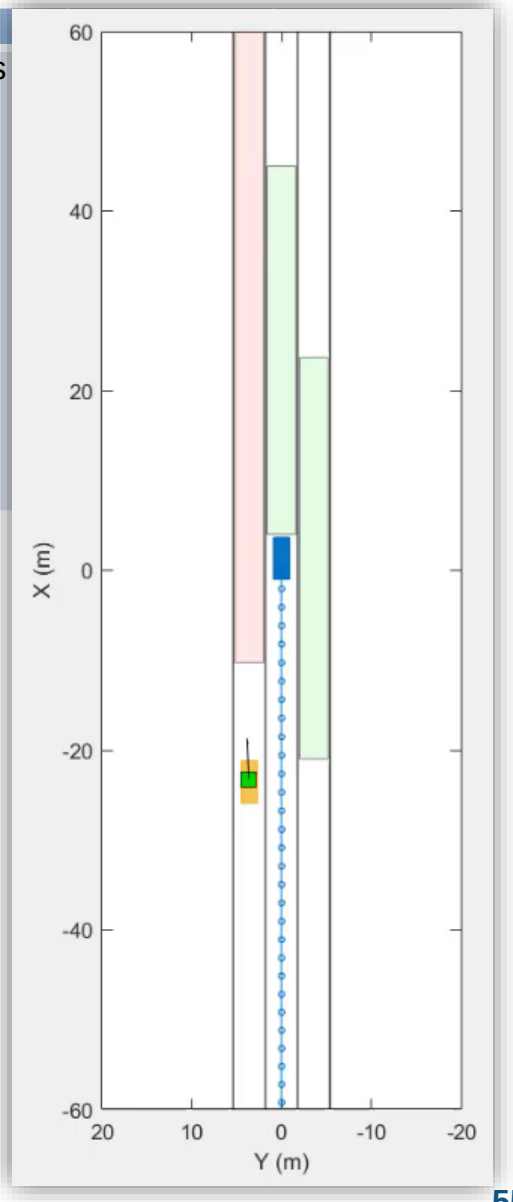
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

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	

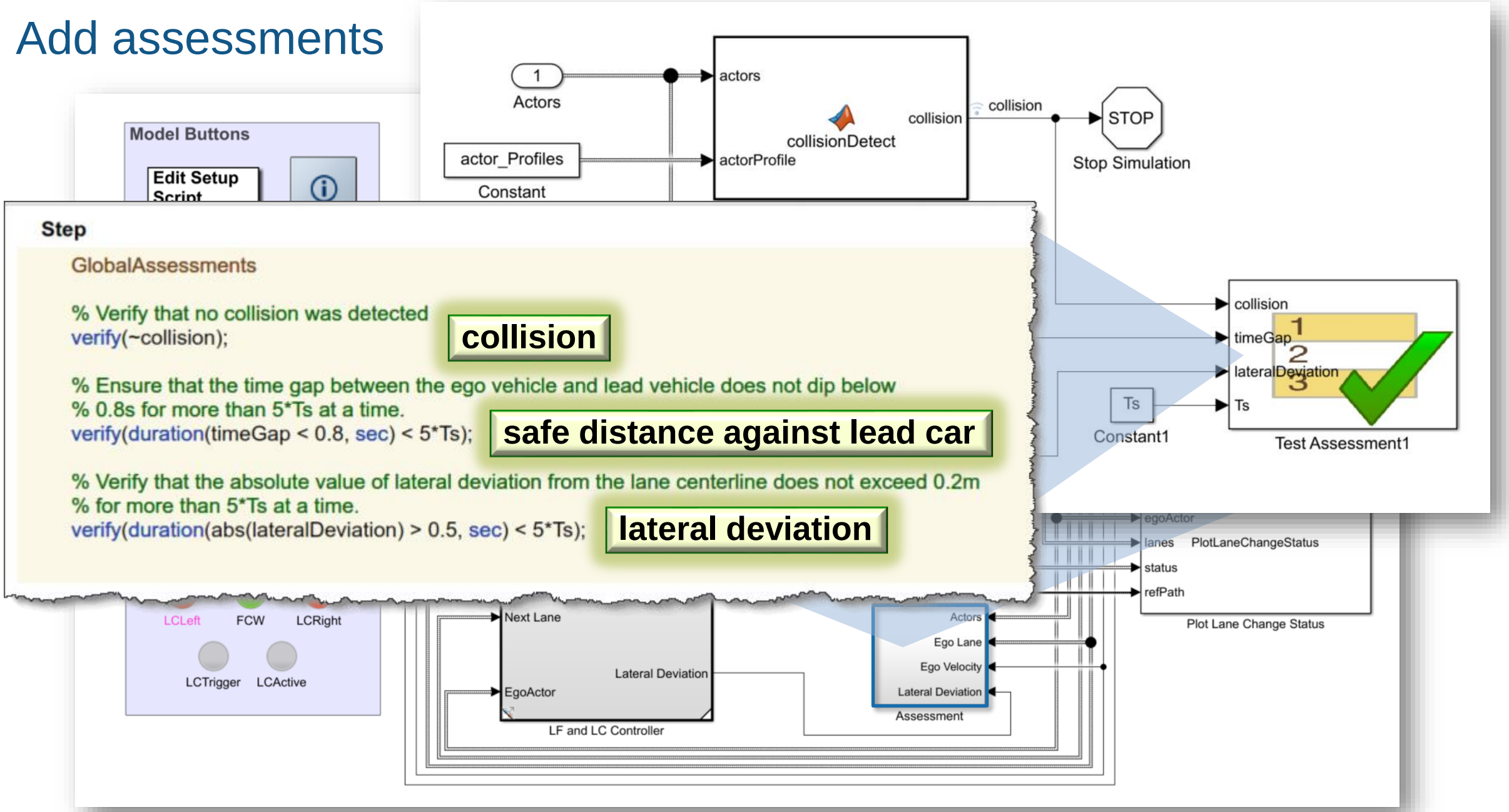
Create test scenarios

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



Add assessments



Review report generated by Test Manager test cases

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

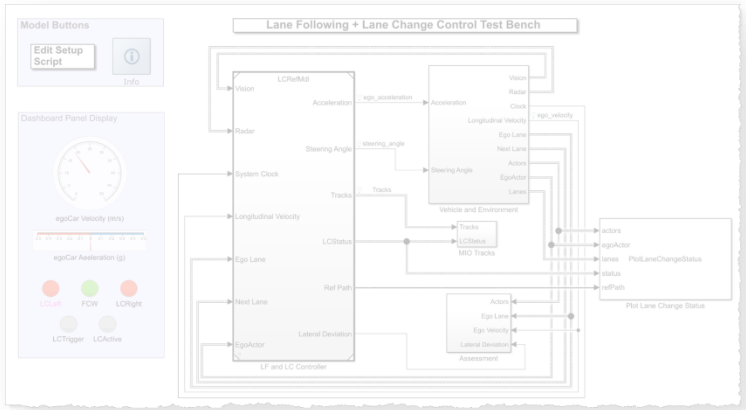
Platform: PCWIN64
MATLAB: (R2019a)

TestReport

Summary

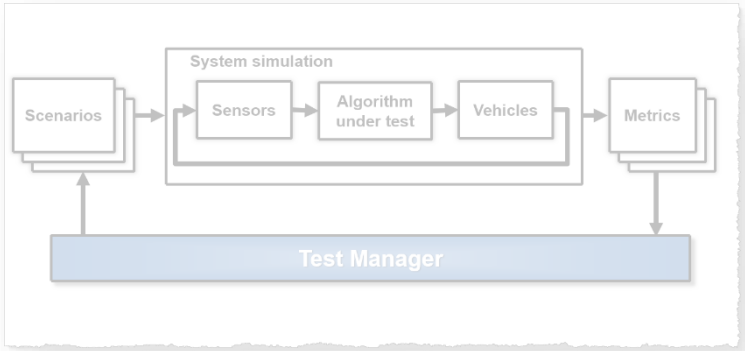
Name	Outcome	Duration (Seconds)
LCTestCases	7	2059
StraightPath	7	2059
01_SlowMoving	✓	304
02_SlowMovingWithPassingCar	✓	224
03_DisabledCar	✓	330
04_CutInWithBrake	✓	235
05_SingleLaneChange	✓	314
06_DoubleLaneChange	✓	420
07_RightLaneChange	✓	228

Case Study for Lane Following plus Lane Change



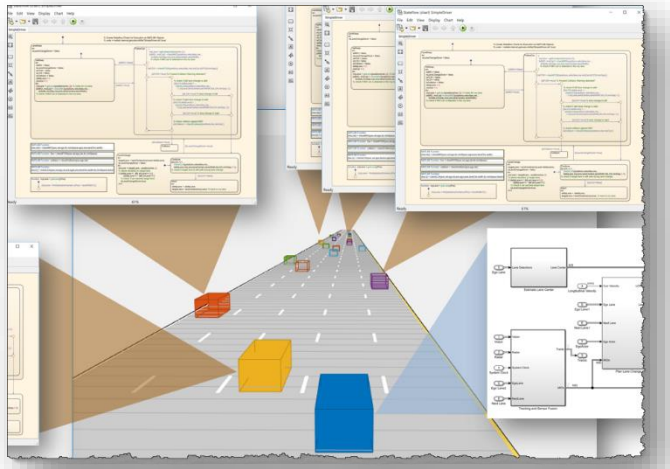
Design lane following + lane change controller

- Review baseline LF example
- Design sensor configuration
- Design additional MIO detectors
- Design safety zone calculation
- Design lane change logic
- Design trajectory planner



Automate regression testing

- Define assessment metrics
- Add predefined scenarios
- Run Simulink test



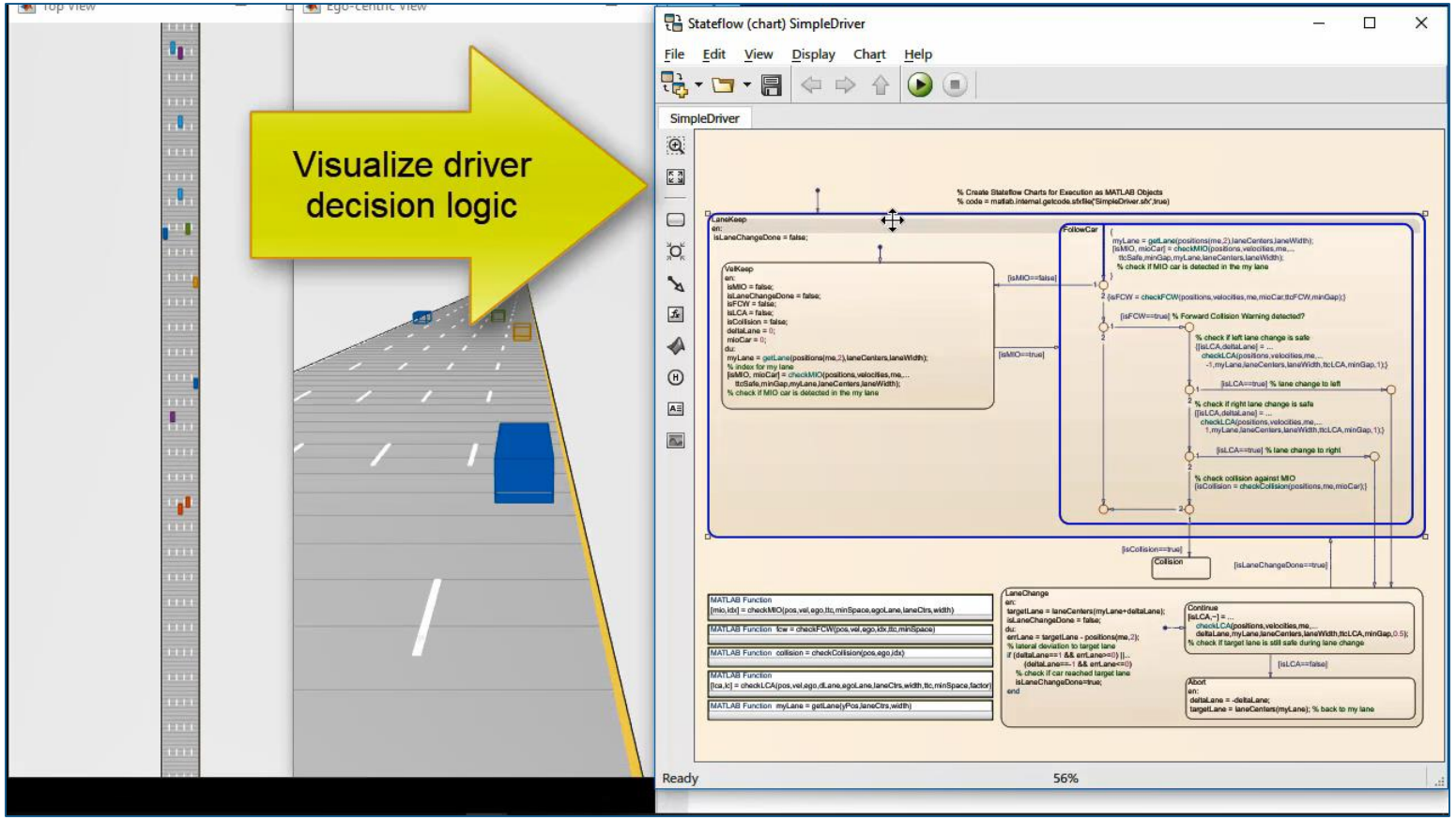
Test robustness with traffic agents

- Specify driver logic for traffic agents
- Randomize scenarios using traffic agents
- Identify and assess unexpected behavior

Simulate interaction between driver agents

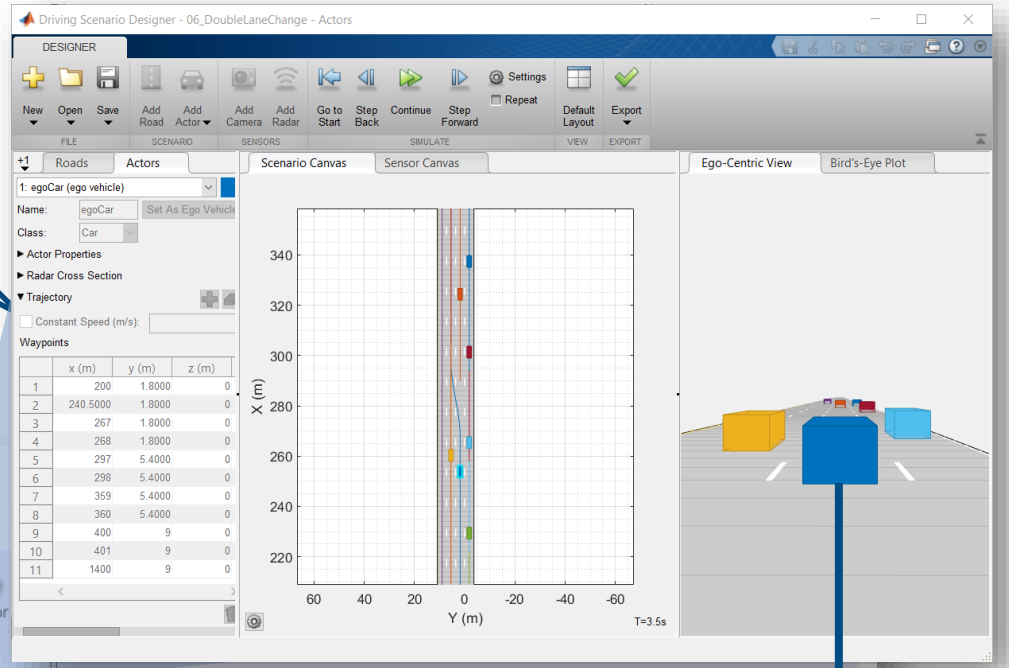
Proof of Concept

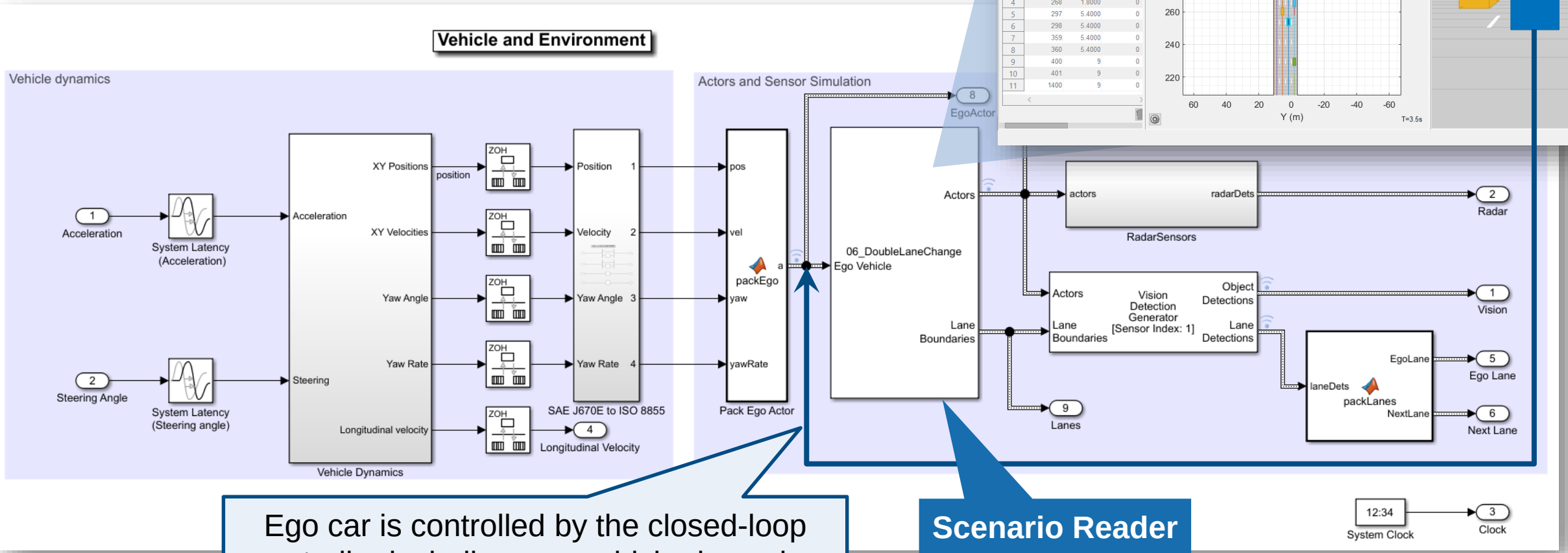
- Graphically define driver decision logic
- Integrate into cuboid driving scenario
- Visualize and debug



Scenario Reader

Driving scenario is pre-defined by DSD



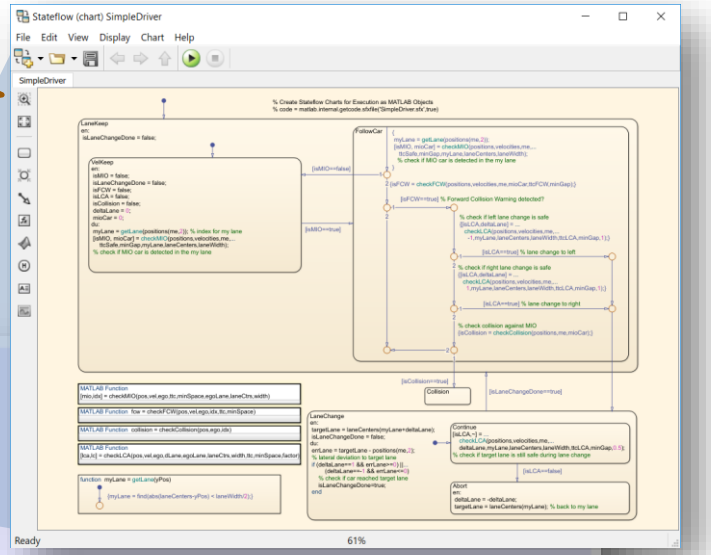


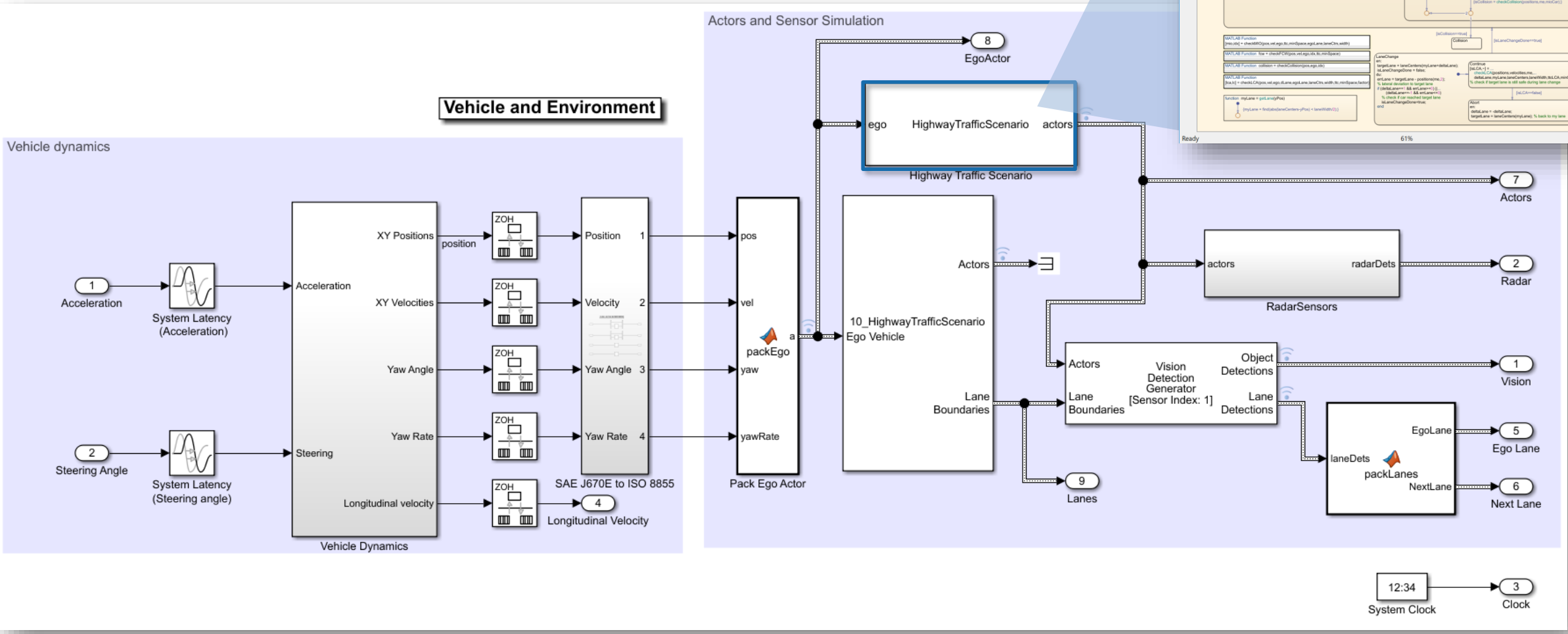
Ego car is controlled by the closed-loop controller including ego vehicle dynamics

Scenario Reader Block

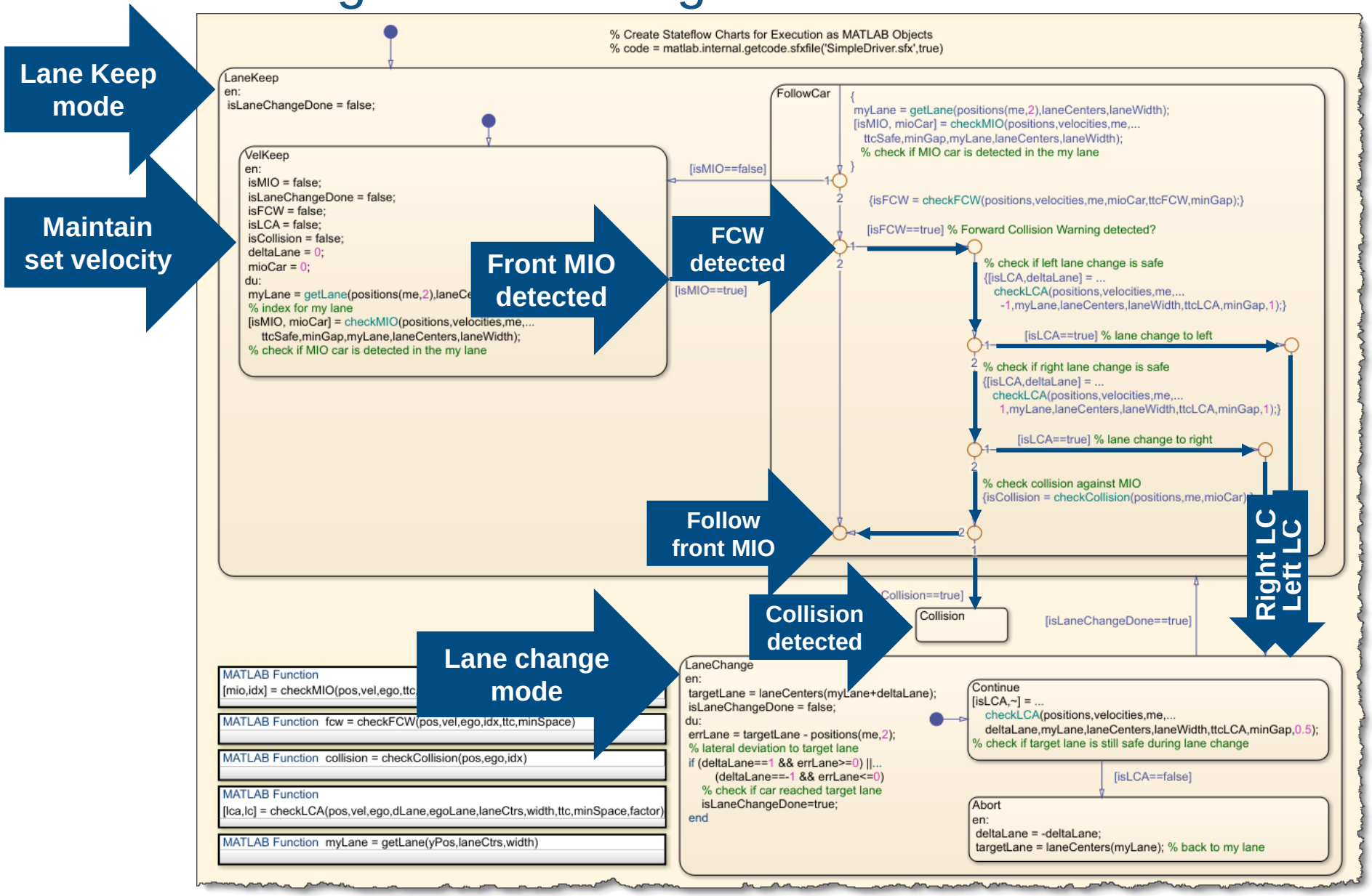
Traffic agent

State machine implementing driver logic

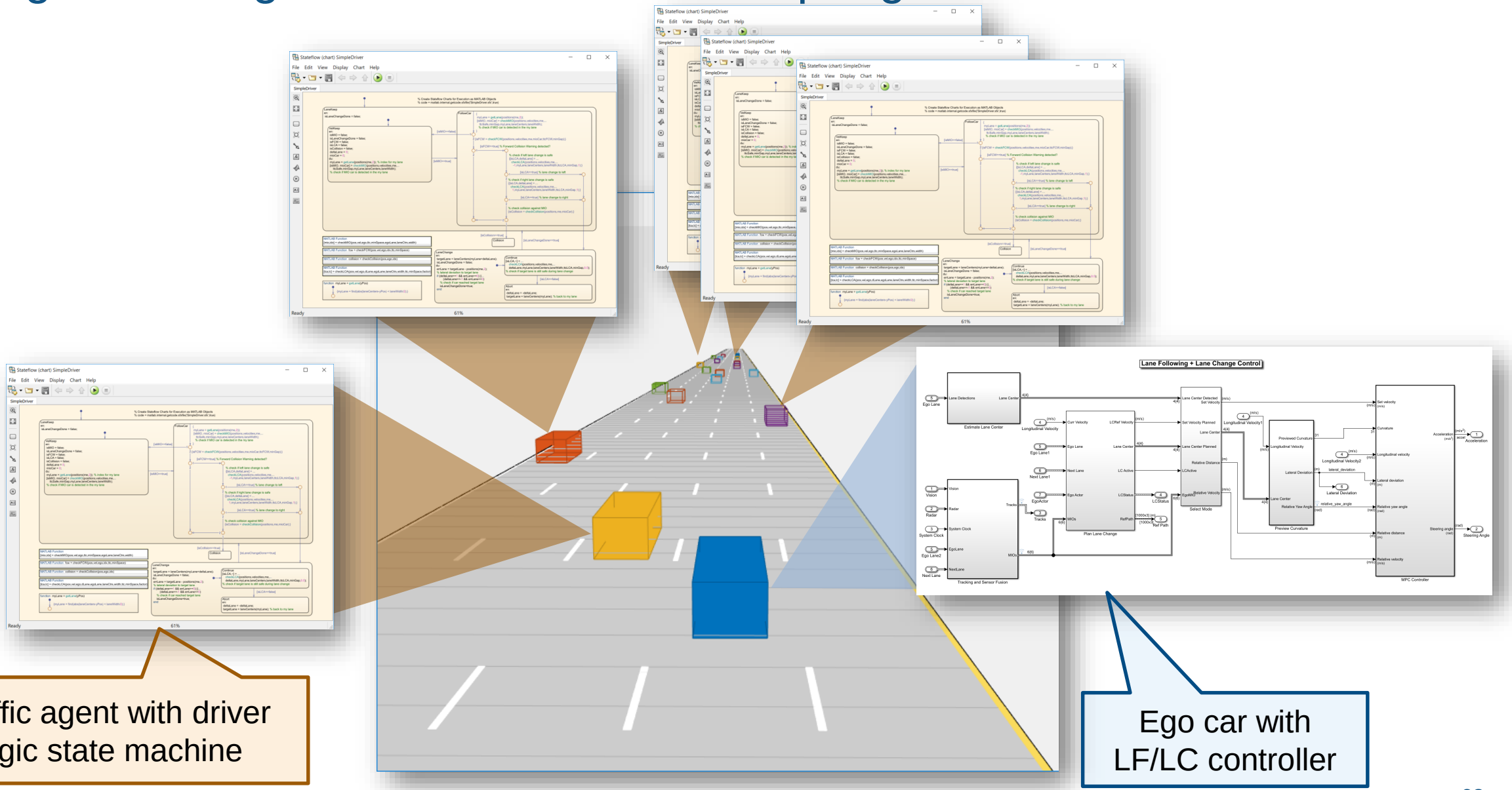




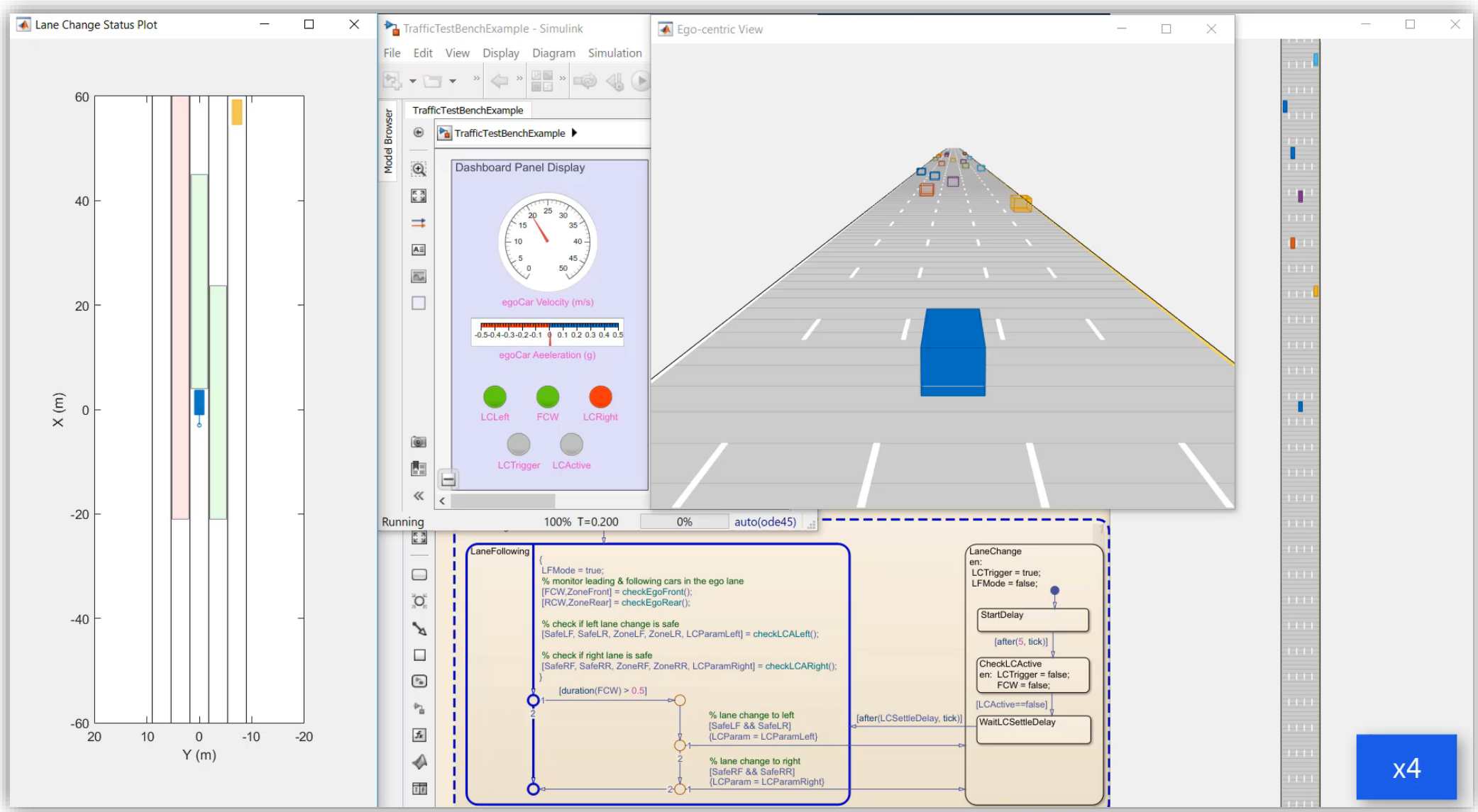
Implement driver logic for traffic agent



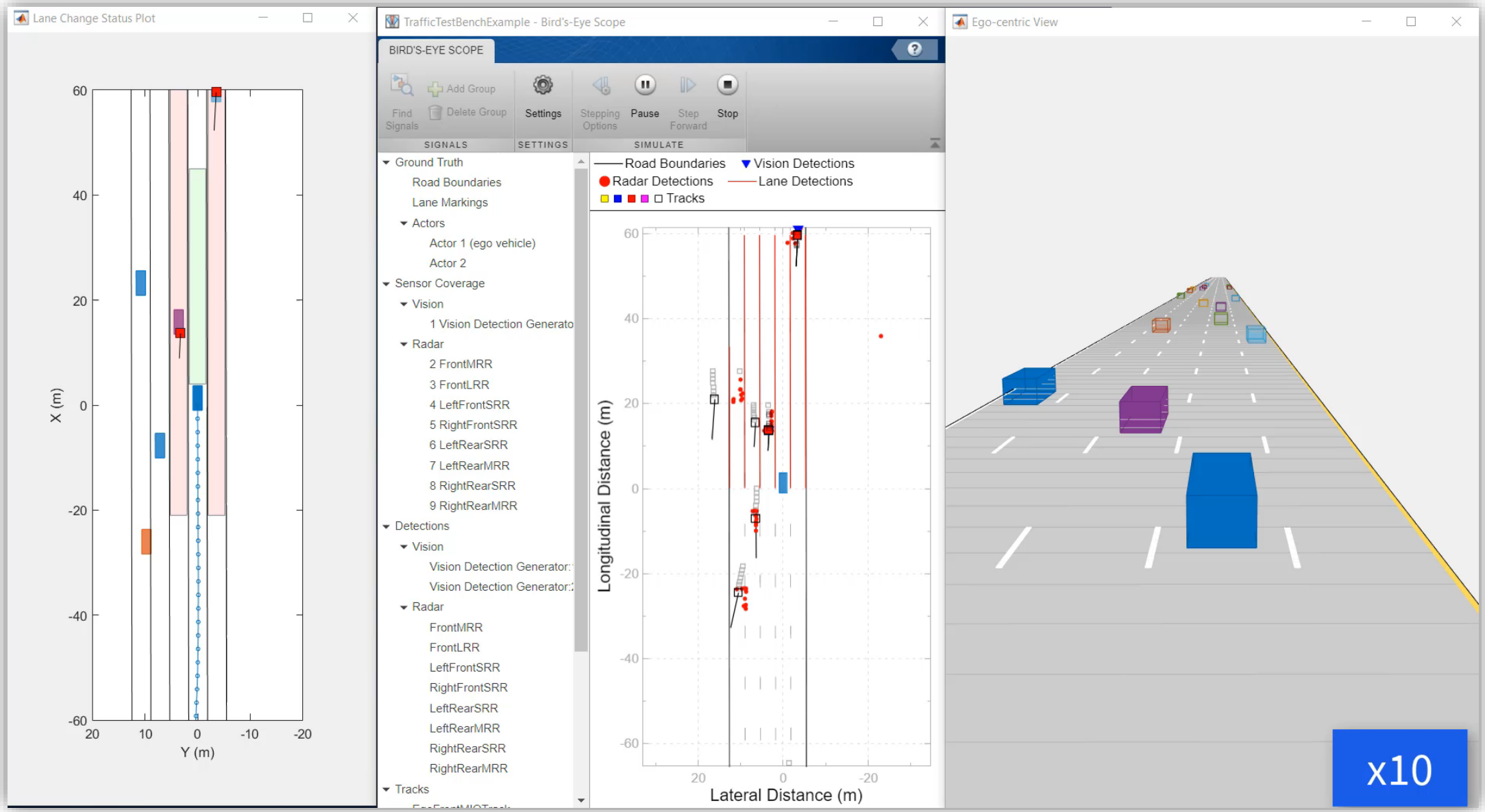
Assign traffic agents to all vehicles except ego car



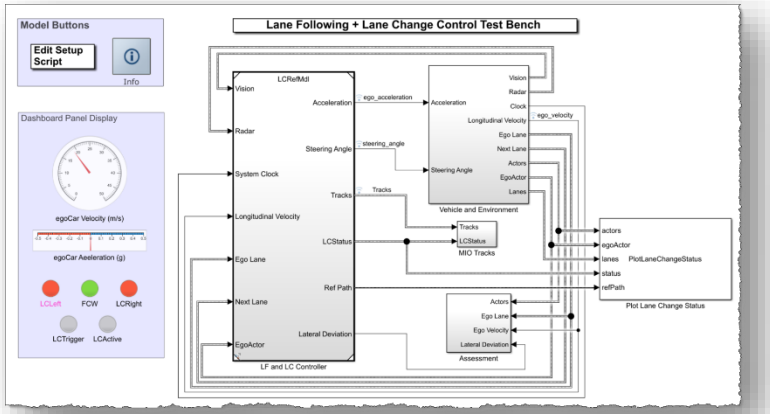
Simulate with traffic agents



Analyze results for near collision scenario



Recap: Case Study for Lane Following plus Lane Change



Design lane following + lane change controller

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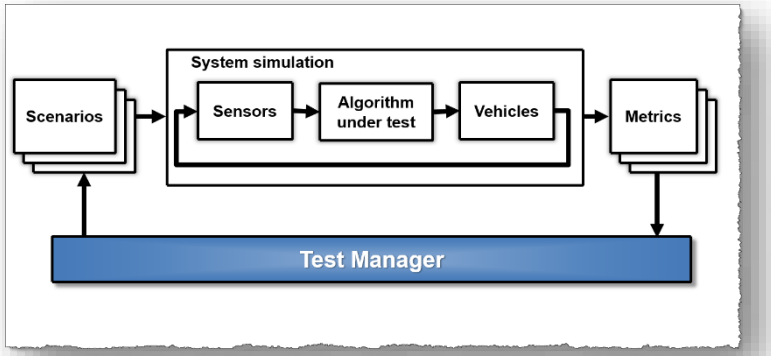

Automate regression testing

- Define assessment metrics
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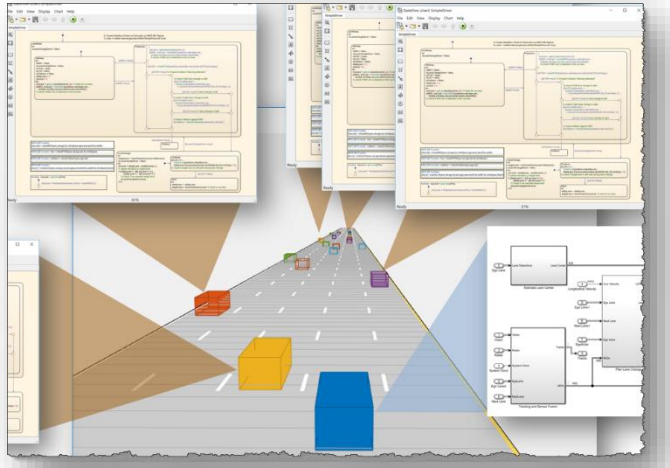

Test robustness with traffic agents

- Specify driver logic for traffic agents
- Randomize scenarios using traffic agents
- Identify and assess unexpected behavior