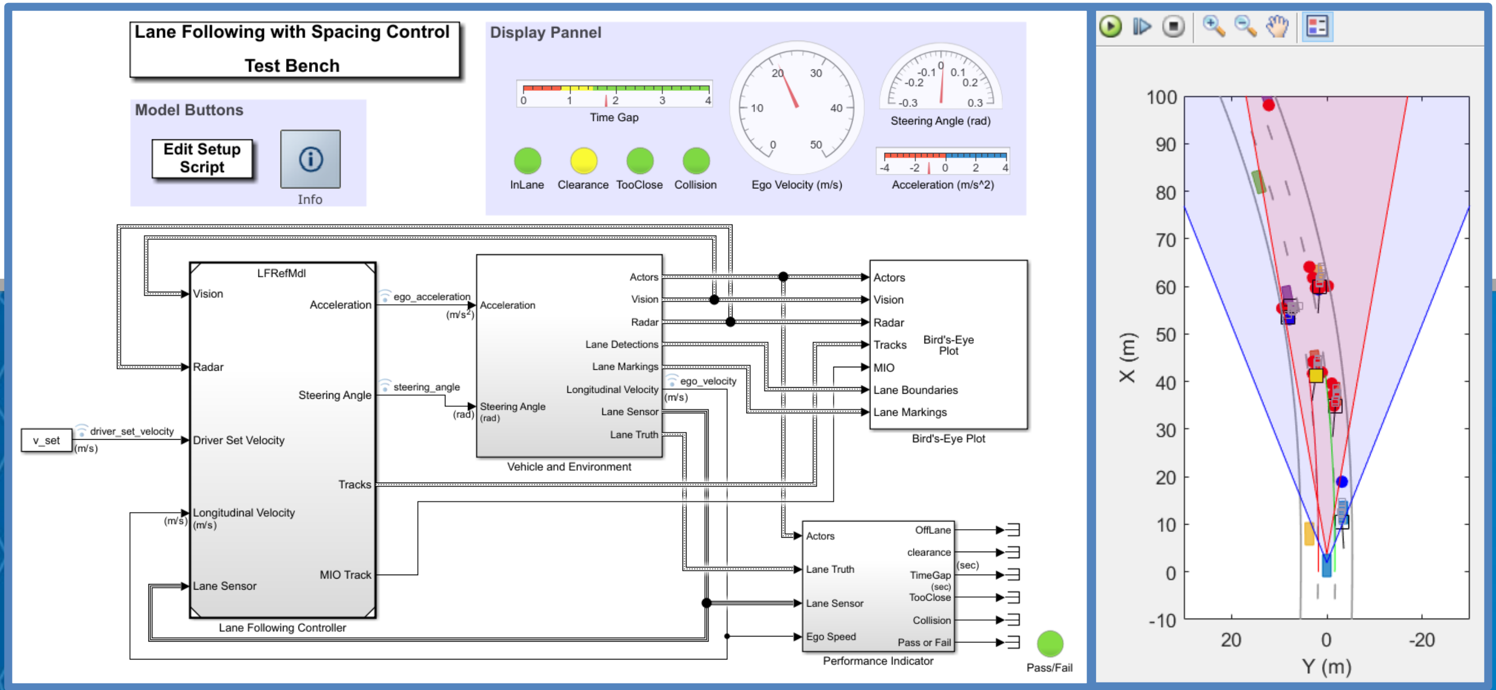
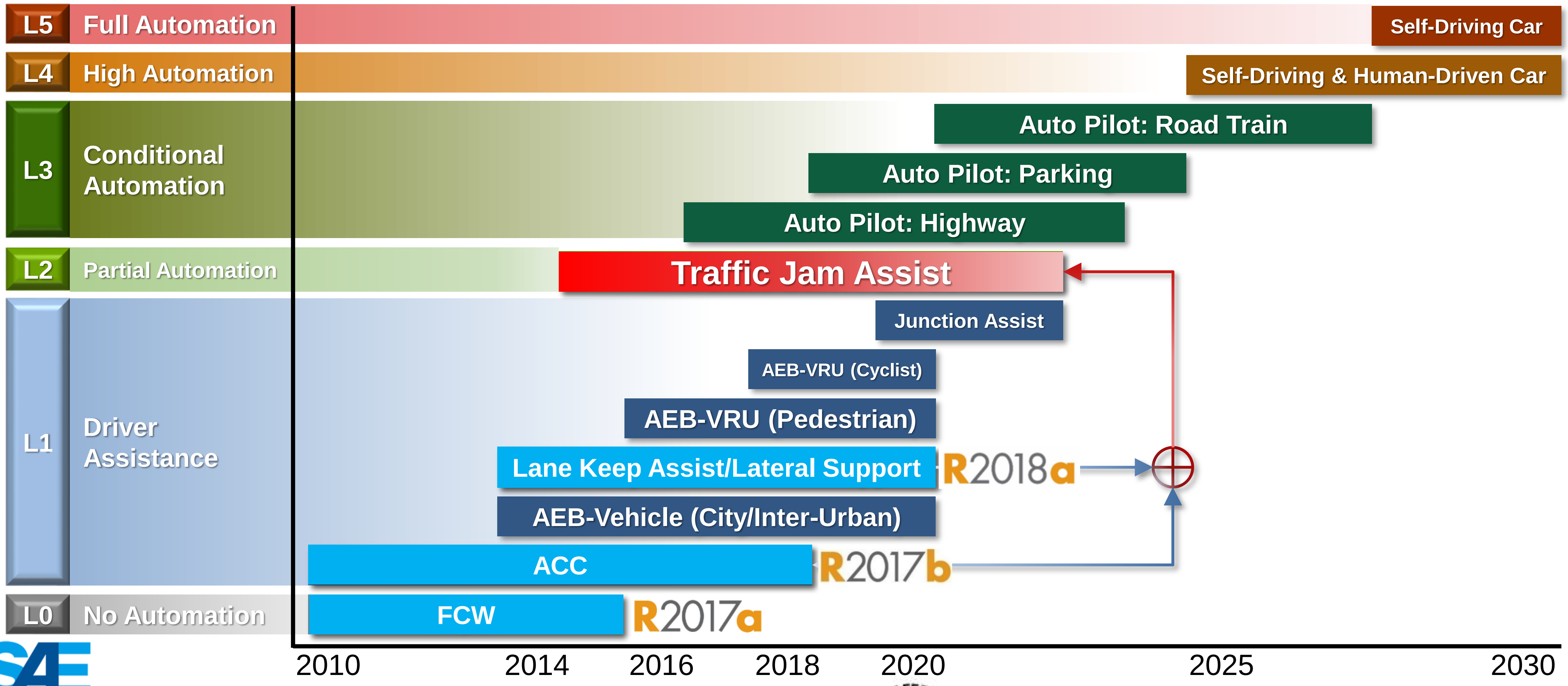
Automated Driving System Toolbox

Design and Test **Traffic Jam Assist**, *A Case Study*



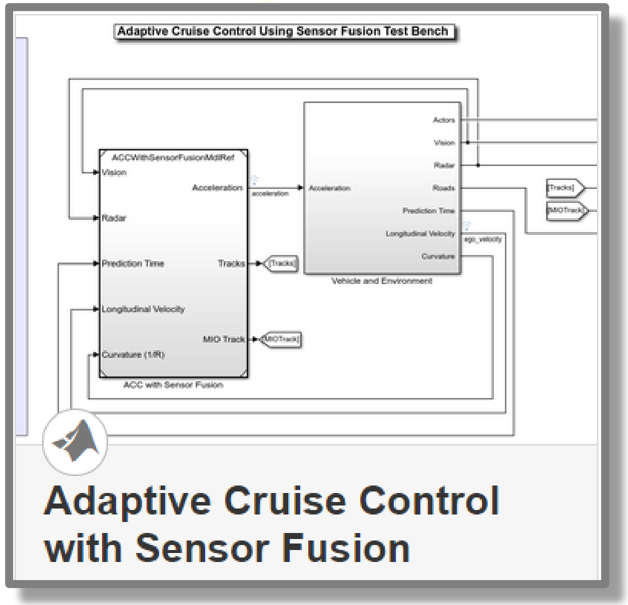
Seo-Wook Park
Principal Application Engineer

Evolution of ADAS/Autonomous Driving Car



ACC and Lane Following Control for Traffic Jam Assist

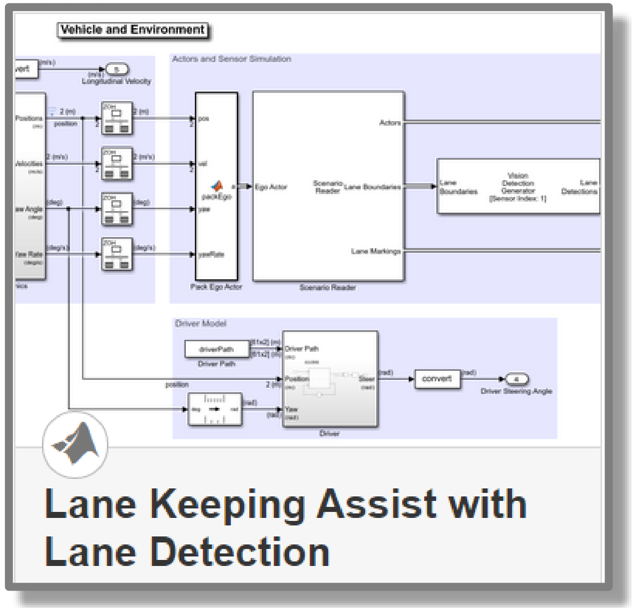
R2017b



ACC

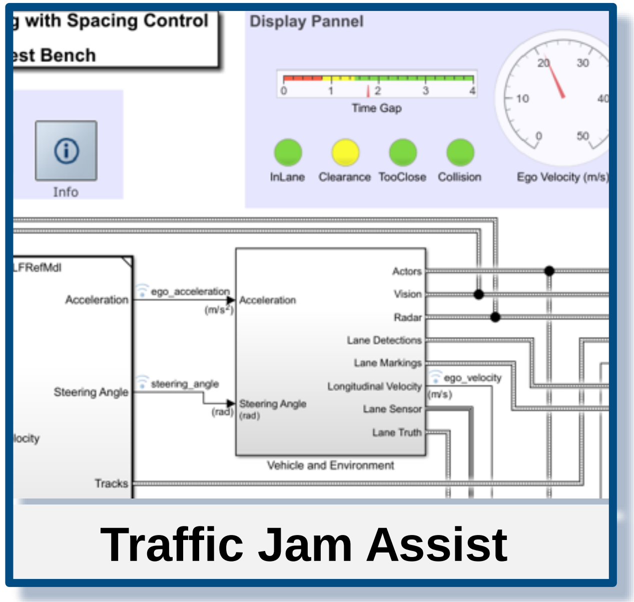
+

R2018a



Lane Following Control

=



Traffic Jam Assist

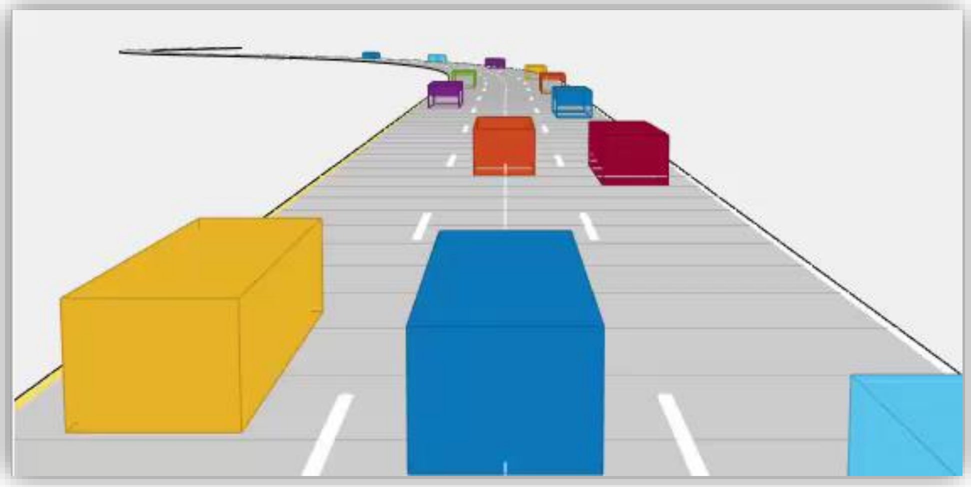
Traffic Jam Assist

- It helps drivers to follow the preceding vehicle automatically with a predefined time interval in a dense traffic condition

… while controlling steering for keeping current lane.

Longitudinal control with ACC with stop & go

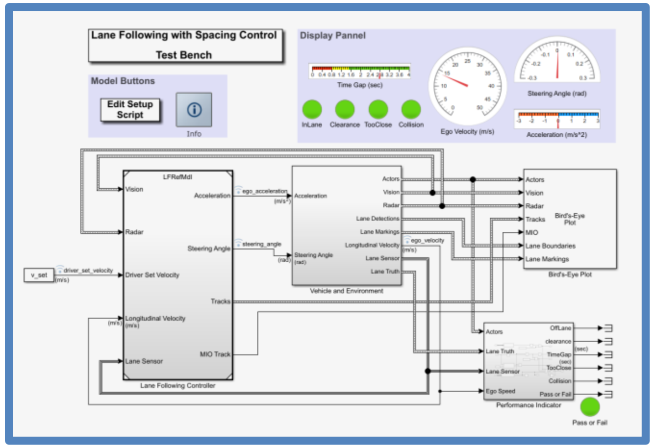
Lateral control with lane following



- Partial/conditional automation at level 2/3
  - Speed limit < 60~65 km/h
  - Dense traffic condition in highway

Automated Driving System Toolbox

Design and Test **Traffic Jam Assist,** *A Case study*

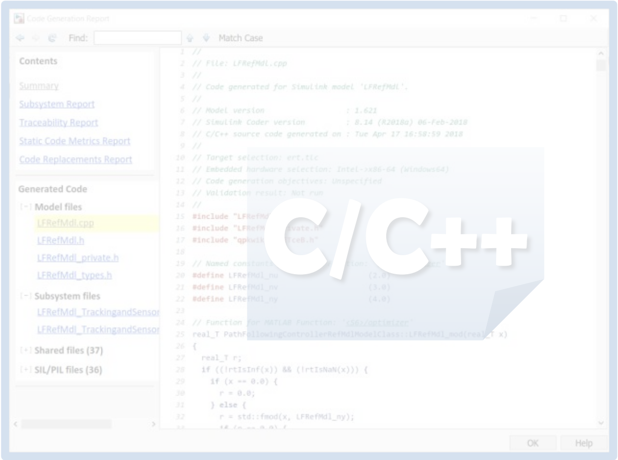


Design ACC and Lane Following Controller

- Create driving scenario
- Synthesize sensor detection
- Include Vehicle Dynamics
- Design sensor fusion algorithm
- Design controller using MPC

Automate Regression Test

- Define performance evaluation metrics
- Develop test cases
- Build test suites
- Verification and validation



Generate and Verify Code

- SIL test
- Code generation
- Coverage test

ACC Performance Requirements

ISO 15622

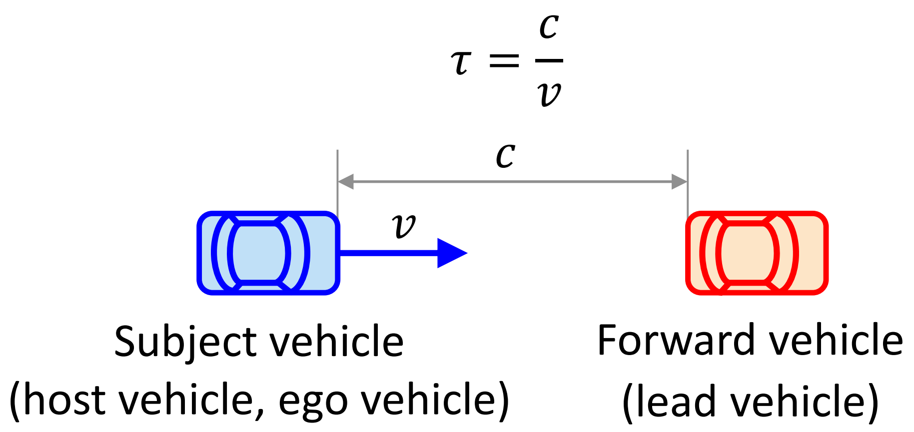
- **Ego velocity control** : $\boxed{v \le v_{set}}$

  where, v : ego velocity, v_{set} : set velocity

- **Time gap control**: $\boxed{\tau \ge \tau_{min}}$

  where, $\tau = \frac{c}{v}$: time gap = 1.5 .. 2.2 sec

  τ_{min} : min time gap = 0.8 sec

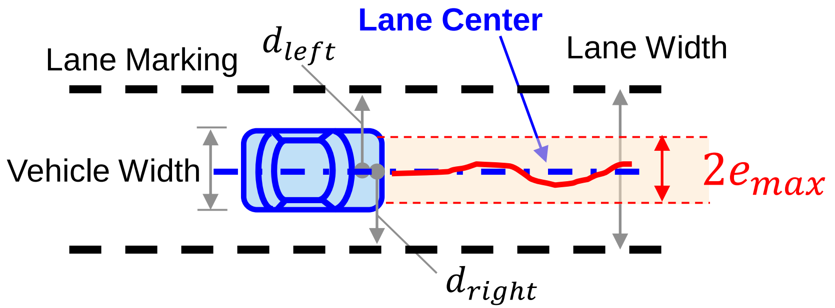


- ACC operation limits
  - Minimum operational speed, v_{min} = 5m/s
  - Average automatic deceleration of ACC ≤ 3.5 m/s^2 (average over 2s)
  - Average automatic acceleration of ACC ≤ 2.0 m/s^2

Lane Following Performance Requirements

- Vehicle should follow the lane center with allowable lateral deviation.

$$\boxed{\left|(d_{left} + d_{right})/2\right| \leq e_{max}}$$



where,

d_{left} : lateral offset of left lane w.r.t. ego car

d_{right} : lateral offset of right lane w.r.t. ego car

e_{max} : allowable lateral deviation

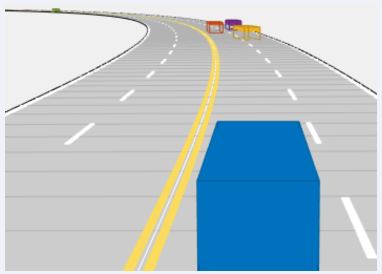
For example, $e_{max} = (LaneWidth - VehicleWidth)/2$ = (3.6-1.8)/2 = 0.9 m

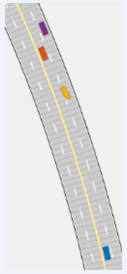
Create Test Scenario using Driving Scenario Designer

R2018a

Test Description

Lead car cut in and out in curved highway (curvature of road = 1/500 m)





Host car

initial velocity = 20.6m/s
HWT(Headway Time) to lead car = 4sec
HW(Headway) to lead car = ~80m
v_set(set velocity for ego car) = 21.5m/s

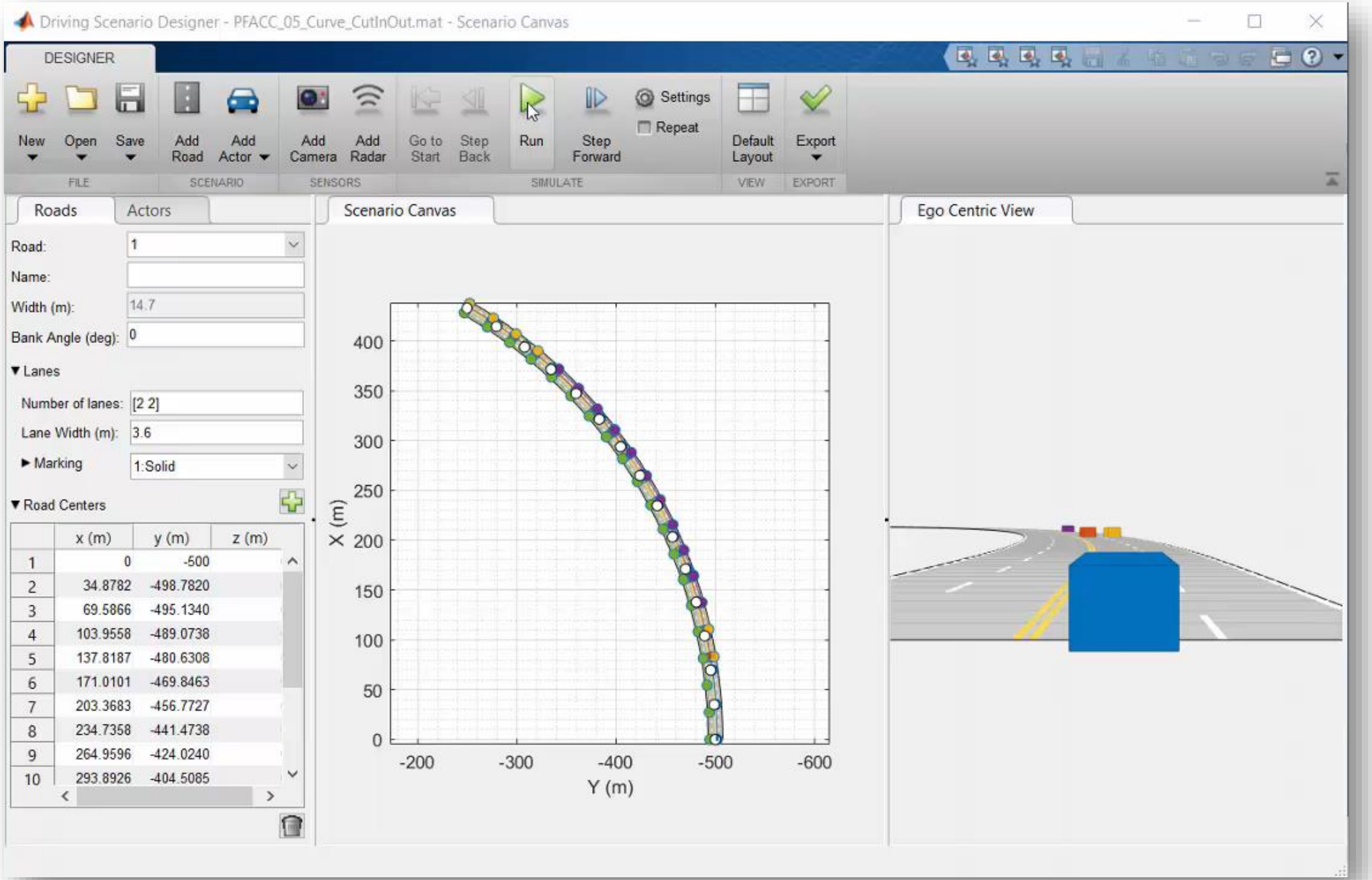
Lead Car

Initially, fast moving car (orange) at 19.4m/s

Passing car (yellow) at 19.6m/s cut in the ego path with HWT=2.3s, then cut out

Third Car

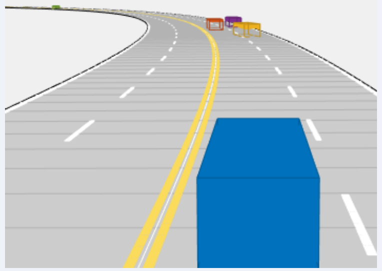
Slow moving car (purple) at 11.1m/s in the 2nd lane

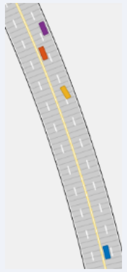


Simulation with Simulink Model for Traffic Jam Assist

Test Description

Lead car cut in and out in curved highway (curvature of road = 1/500 m)





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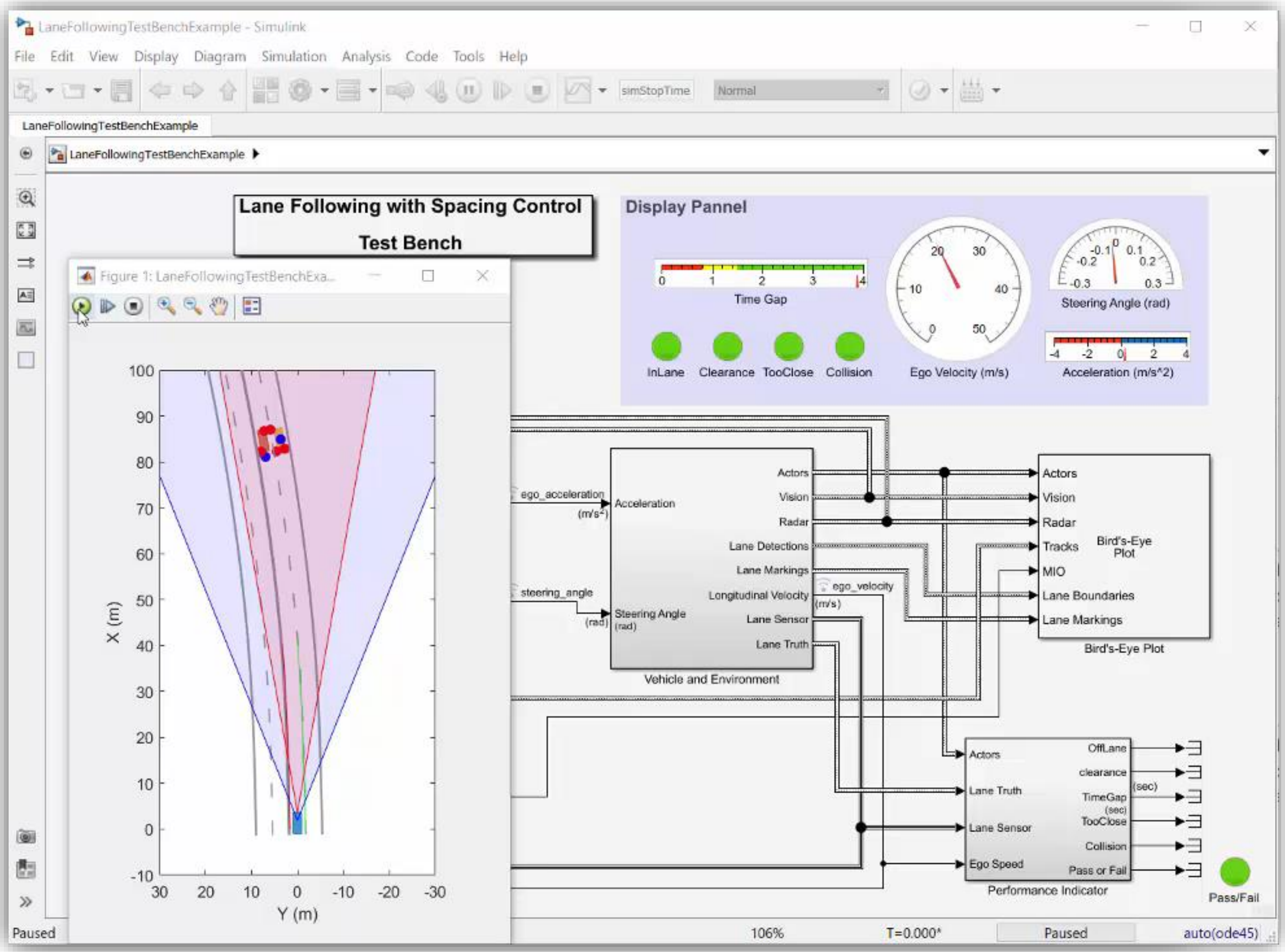

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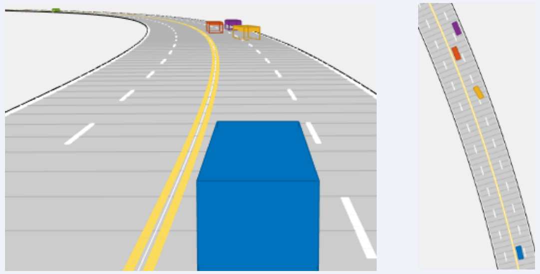

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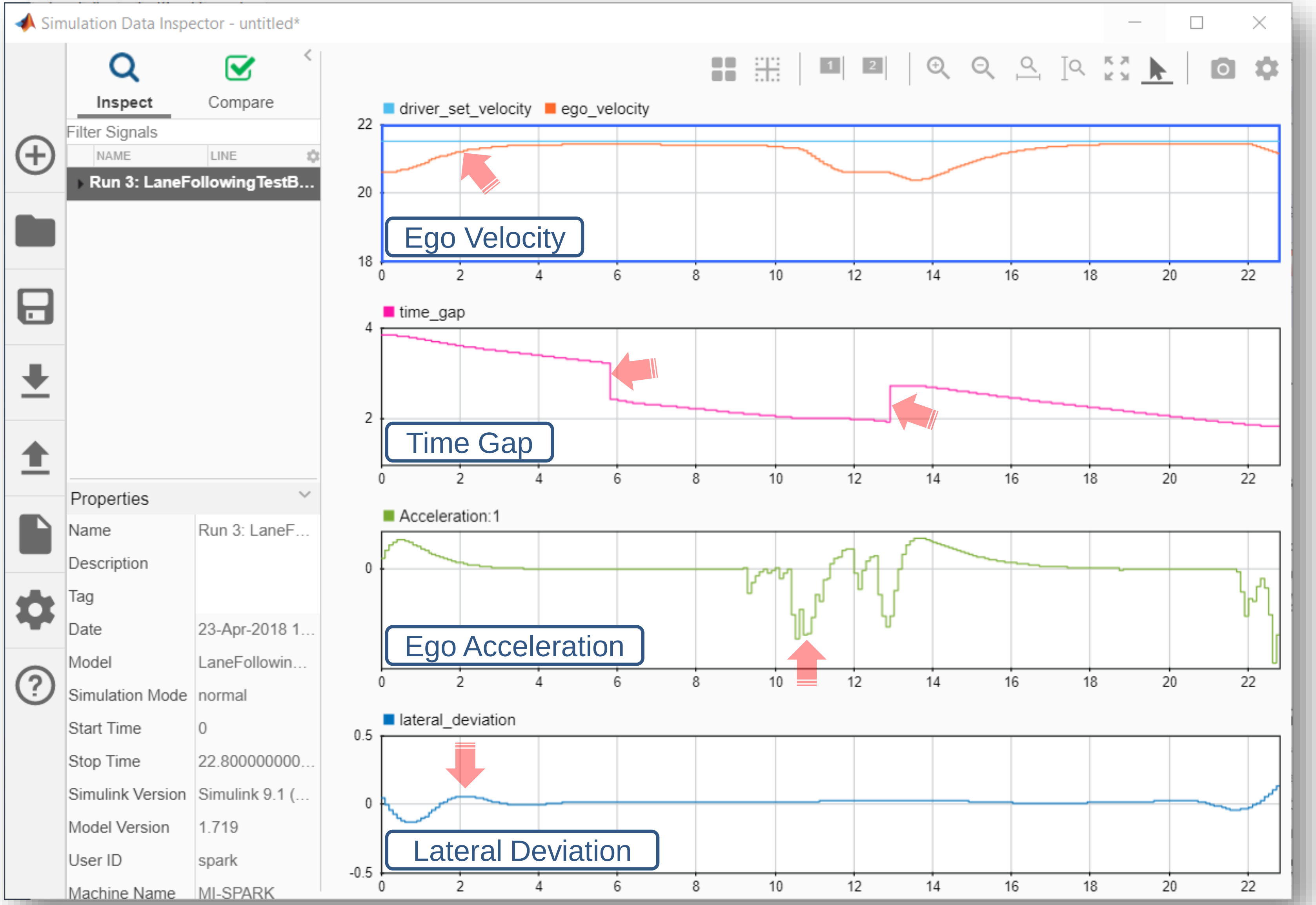
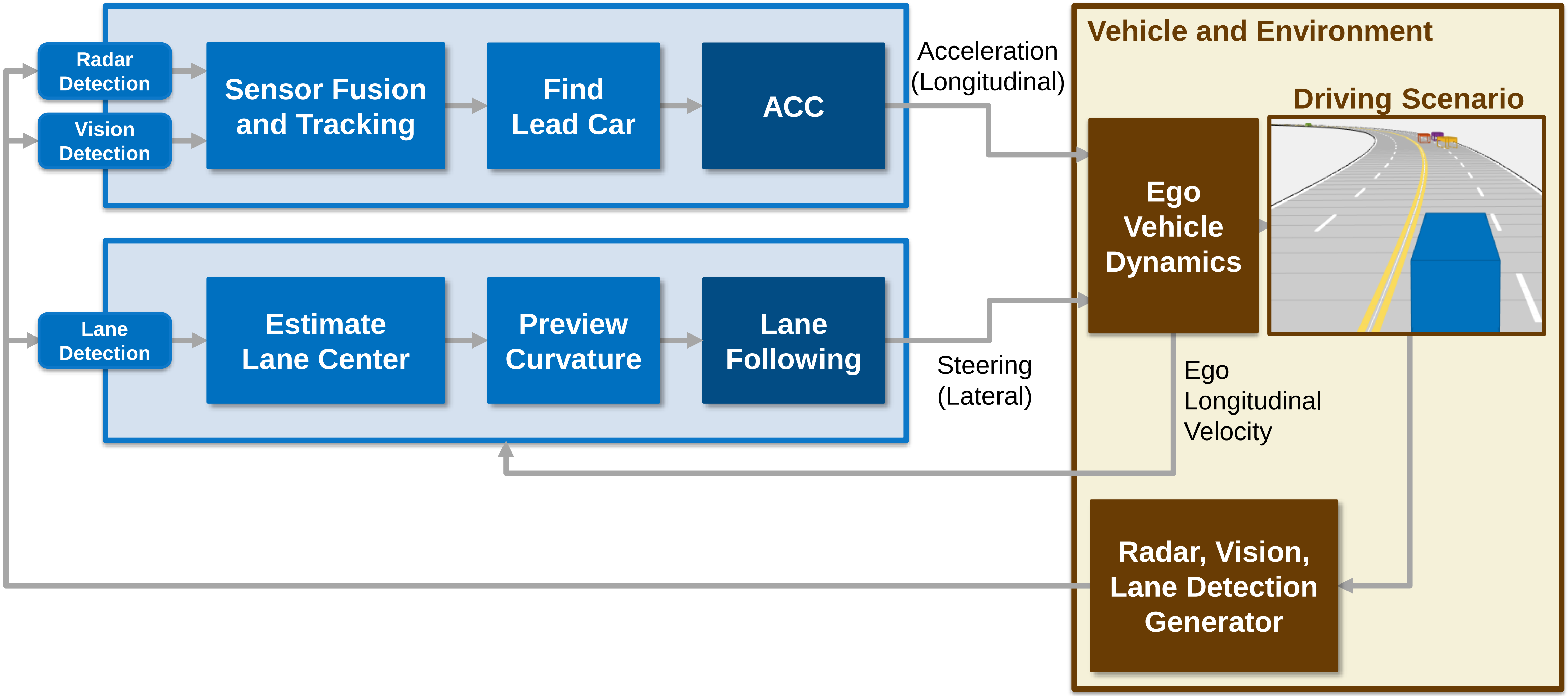


Architecture for ACC and Lane Following Controller



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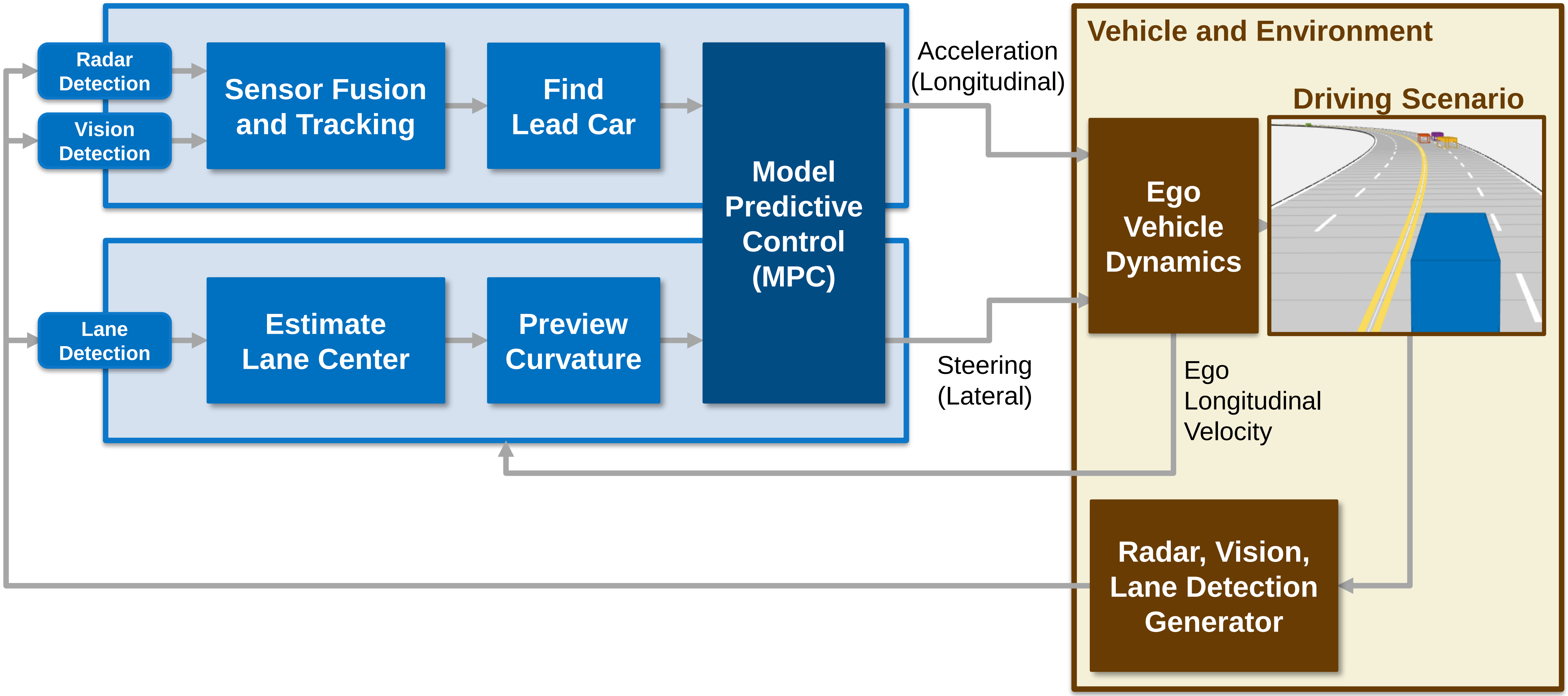
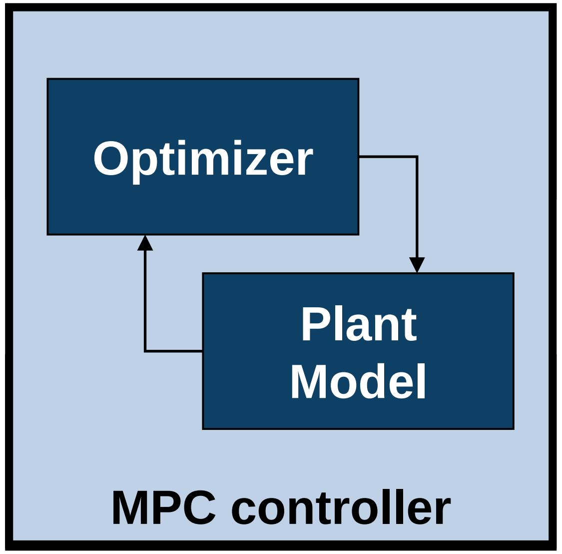


What is model predictive control (MPC)?

- **Multi-variable control** strategy leveraging an internal model to predict plant behavior in the near future

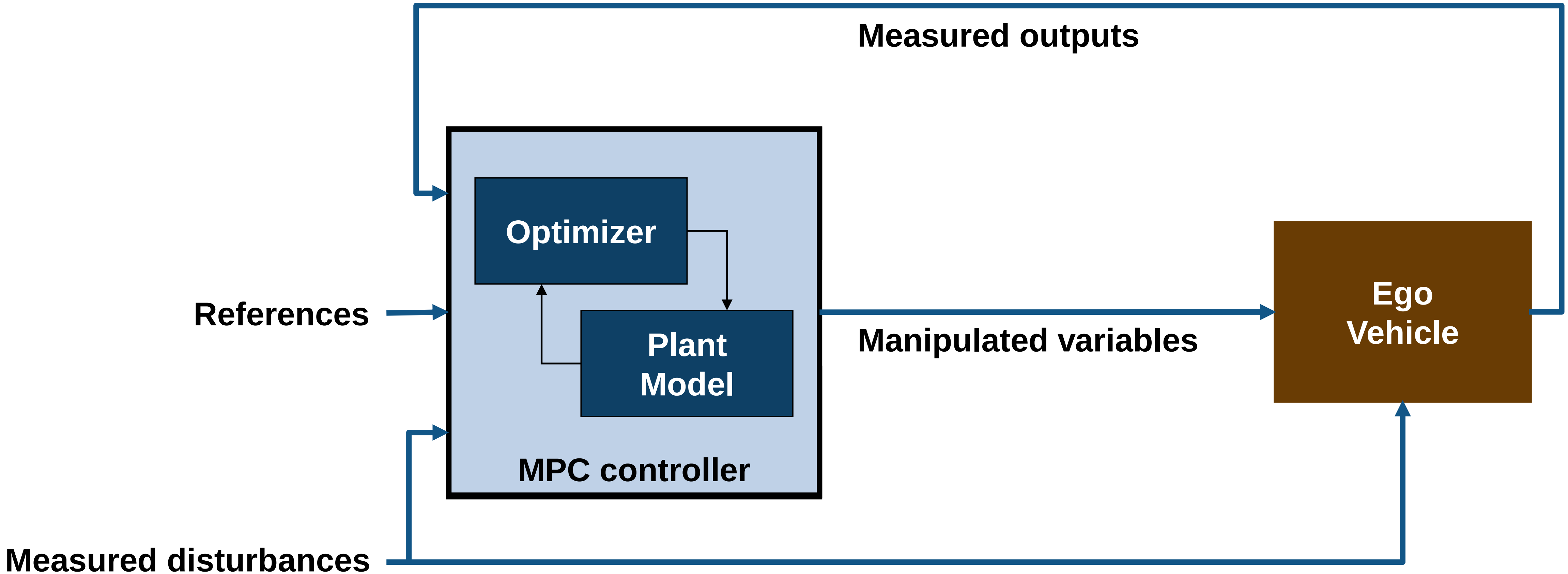
- **Optimizes** for the current timeslot while keeping future timeslots in account



- **Mature** control solution used in industrial applications

- **Gaining popularity in automated driving** applications to improve vehicle responsiveness while maintaining passenger comfort

What is model predictive control (MPC)?



How can MPC be applied to ACC and lane following control?

minimize:

$$w_1|V_{ego} - V_{set}|^2 + w_2|E_{lateral}|^2$$

References
- Ego velocity set point (V_{set})
- Target lateral deviation (=0)

Measured disturbances
- MIO velocity (V_{mio})
- Previewed road curvature (ρ)

subject to:

$$D_{relative} \geq D_{safe}$$
$$a_{min} \leq a \leq a_{max}$$
$$\delta_{min} \leq \delta \leq \delta_{max}$$

MPC controller

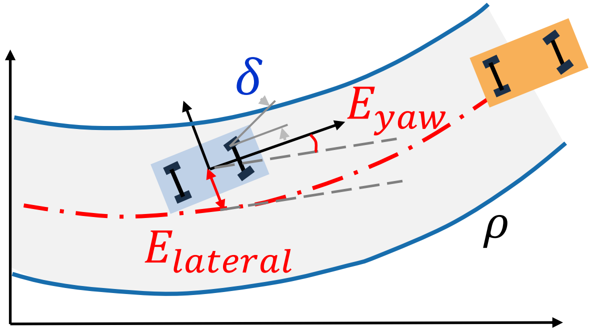
Optimizer

Ego Vehicle Model

Measured outputs
- Relative distance ($D_{relative}$)
- Ego velocity (V_{ego})
- Lateral deviation ($E_{lateral}$)
- Relative yaw angle (E_{yaw})

Manipulated variables
- Acceleration (a)
- Steering angle (δ)

Ego Vehicle



Internal MPC model for ACC and Lane Following Controller

Longitudinal model for ACC

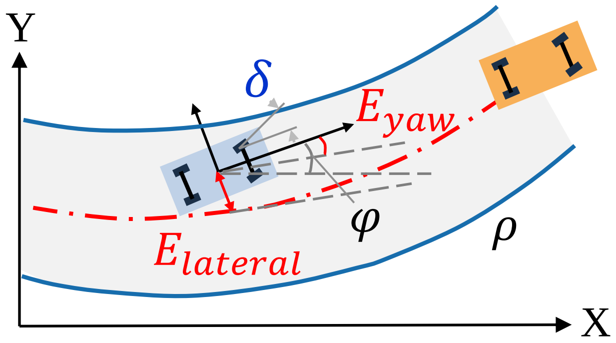
$$\begin{pmatrix} D_{relative} \\ V_{ego} \\ E_{lateral} \\ E_{yaw} \end{pmatrix} = sys \begin{pmatrix} a \\ V_{mio} \\ \delta \\ \rho \end{pmatrix}$$

Lateral model for Lane Following

Measured outputs (OV)
- Relative distance ($D_{relative}$)
- Ego velocity (V_{ego})
- Lateral deviation ($E_{lateral}$)
- Relative yaw angle (E_{yaw})

Manipulated variables (MV)
- Acceleration (a)
- Steering angle (δ)

Measured disturbance (MD)
- MIO velocity (V_{mio})
- Previewed road curvature (ρ)

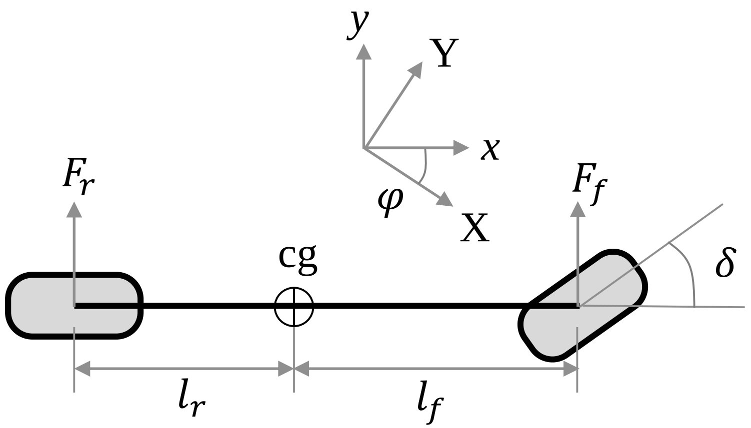


Longitudinal and Lateral Model for MPC

- Longitudinal Model for ACC

$$\frac{d}{dt}\begin{bmatrix} \dot{V}_x \\ V_x \\ D_{relative} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \dot{V}_x \\ V_x \\ D_{relative} \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau} & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ V_{mio} \end{bmatrix}$$

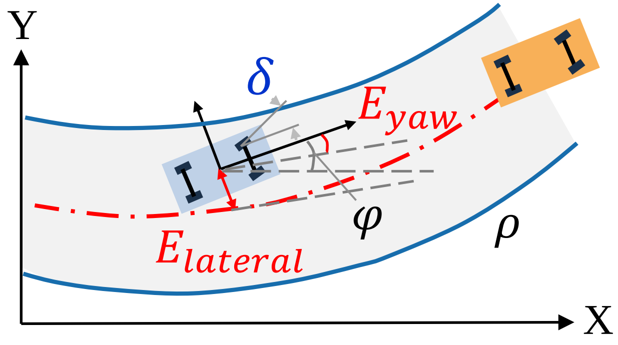
$$\begin{bmatrix} D_{relative} \\ V_x \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{V}_x \\ V_x \\ D_{relative} \end{bmatrix}$$



- Lateral Model for Lane Following

$$\frac{d}{dt}\begin{bmatrix} V_y \\ \dot{\varphi} \\ E_{lateral} \\ E_{yaw} \end{bmatrix} = \begin{bmatrix} -\frac{2C_f + 2C_r}{mV_x} & -V_x - \frac{2C_f l_f - 2C_r l_r}{mV_x} & 0 & 0 \\ -\frac{2C_f l_f - 2C_r l_r}{I_z V_x} & -\frac{2C_f l_f^2 + 2C_r l_r^2}{I_z V_x} & 0 & 0 \\ 1 & 0 & 0 & V_x \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_y \\ \dot{\varphi} \\ E_{lateral} \\ E_{yaw} \end{bmatrix} + \begin{bmatrix} \frac{2C_f}{m} & 0 \\ \frac{2C_f l_f}{I_z} & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \delta \\ V_x \rho \end{bmatrix}$$

$$\begin{bmatrix} E_{lateral} \\ E_{yaw} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_y \\ \dot{\varphi} \\ E_{lateral} \\ E_{yaw} \end{bmatrix}$$



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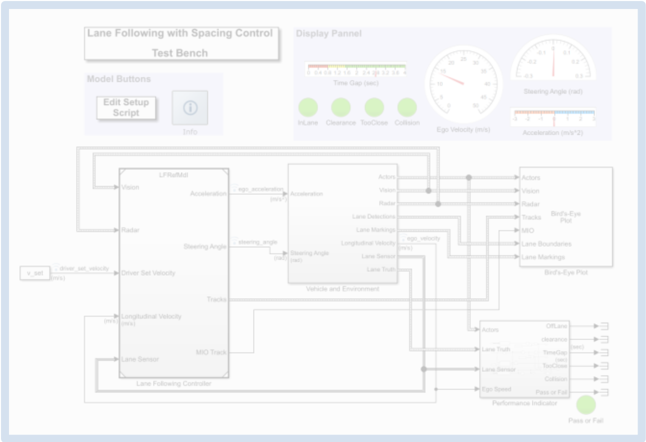

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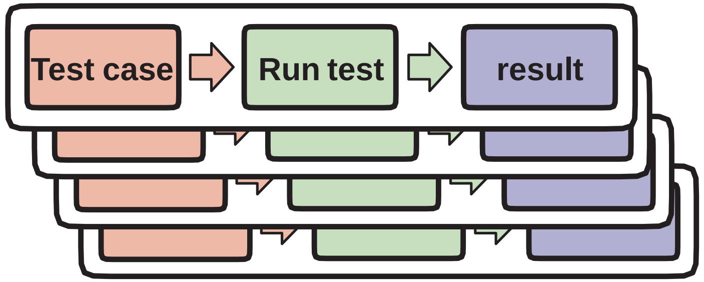

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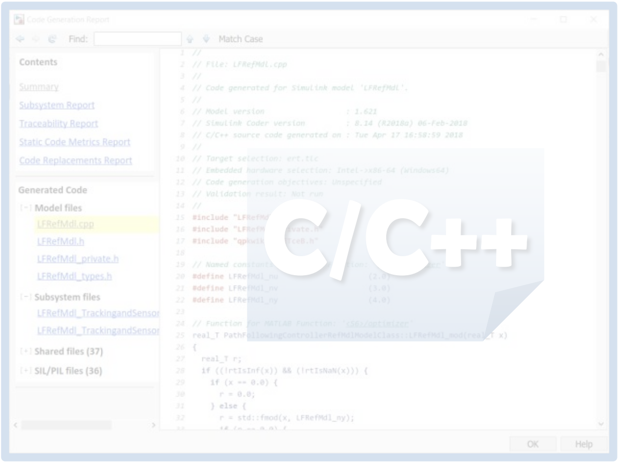

Generate and Verify Code

- SIL test
- Code generation
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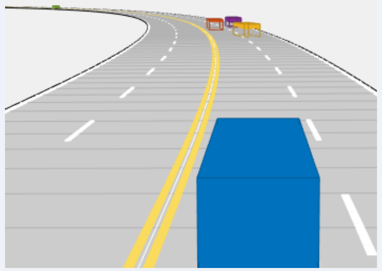
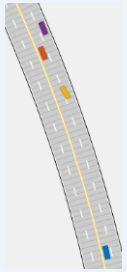
Simulation result assessment

Test Description

Lead car cut in and out in curved highway (curvature of road = 1/500 m)





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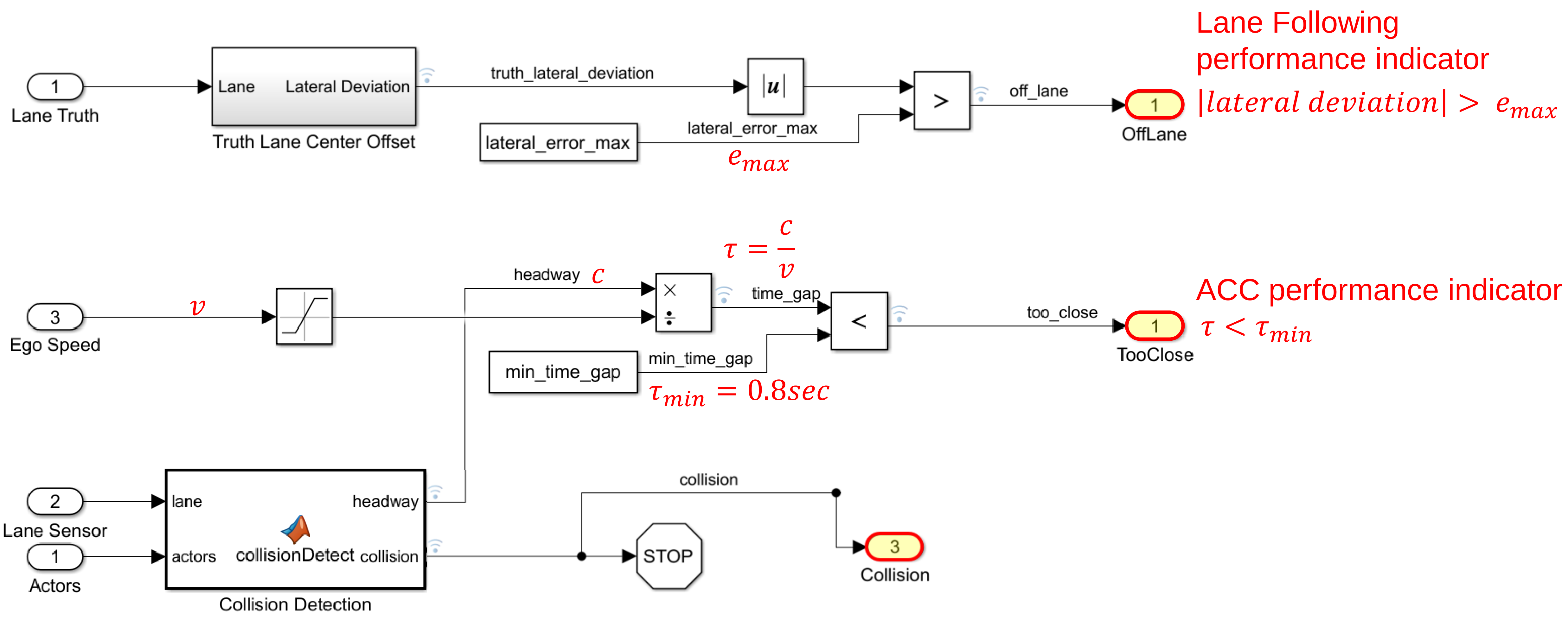
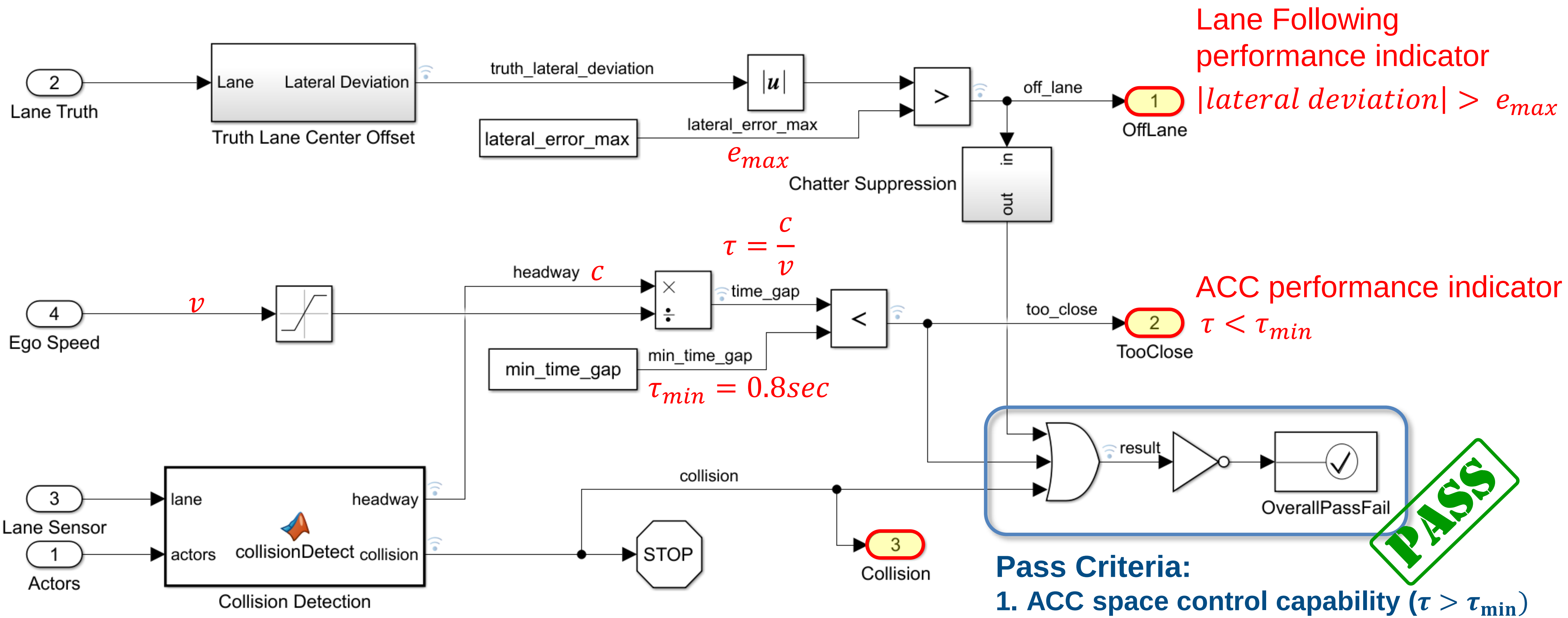
Slow moving car (purple) at 11.1m/s in the 2nd lane

Performance Indicator



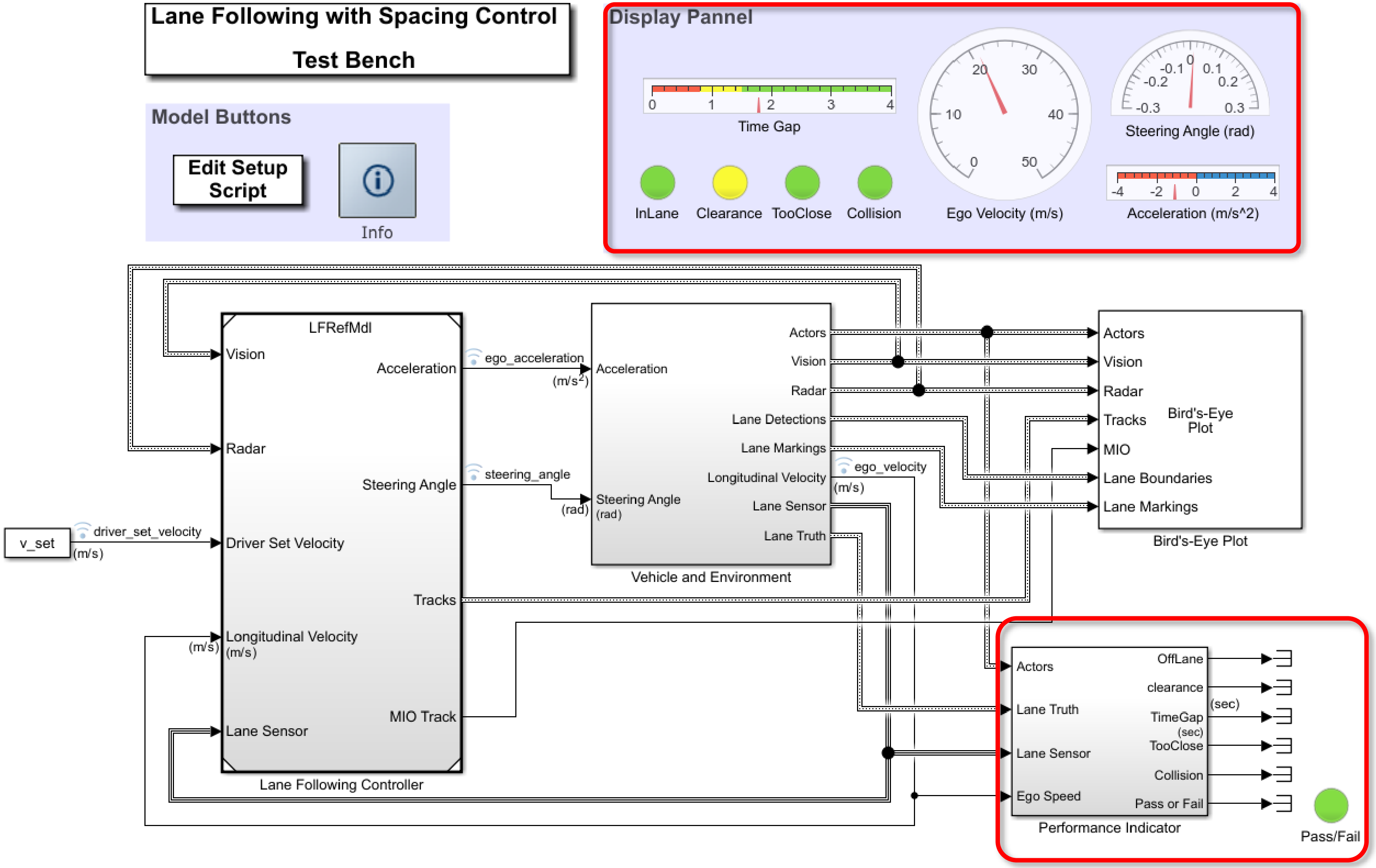
Performance Indicator



Pass Criteria:

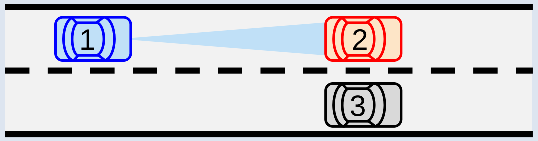
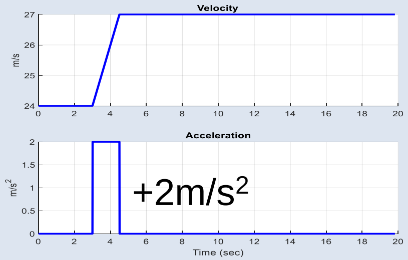
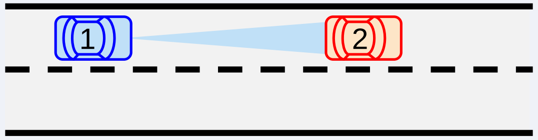
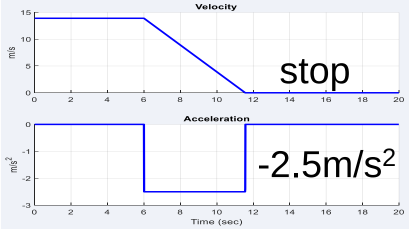
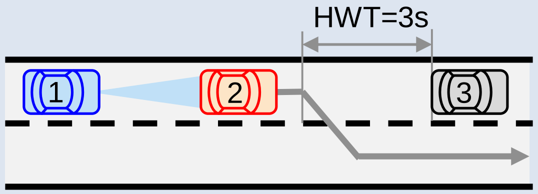
1. **ACC space control capability ($\tau > \tau_{\min}$)**
2. **Lane following capability**
3. **No collision detected**

Performance indicator and dashboard in Simulink model



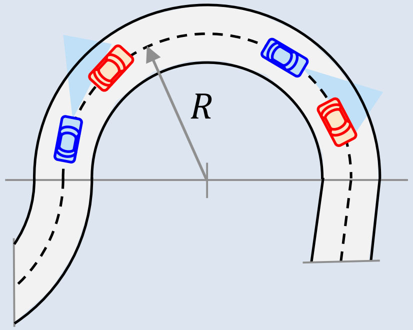
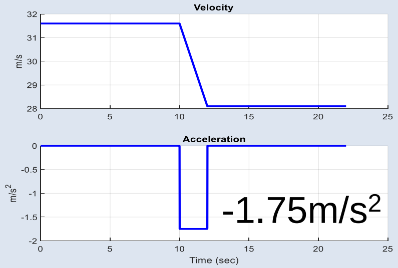
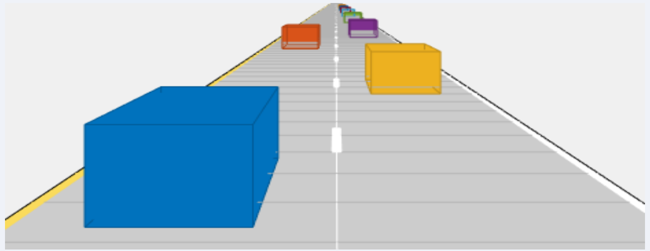
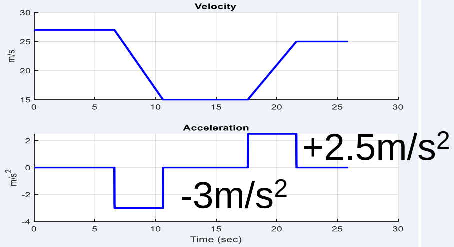
Test scenarios (1/4)

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	ACC_01_ISO _TargetDiscriminationTest	**Target Discrimination Test** 	initial velocity = 30m/s HWT = 2.2sec (HW = 66m) v_set = 30m/s	constant accel 24m/s → 27m/s @ 2m/s^2 V_{end} = 27m/s (97.2kph) 	24m/s	ISO 15622 ISO 22178
2	ACC_02_ISO _ AutoDecelTest	**Automatic Deceleration Test** 	initial velocity = 15m/s HWT = 2.2sec (HW = 33m) v_set = 15m/s	initial velocity = 13.9m/s decelerates to full stop with 2.5m/s^2 	none	ISO 22178
3	ACC_03_ISO _AutoRetargetTest	**Automatic Retargeting Capability Test** 	initial velocity = 15m/s HWT = 2.2sec (HW = 33m) v_set = 15m/s	initial velocity = 13.9m/s Lead car changes lane @ HWT=3s to overtake slow moving car	constant speed = 2.1m/s	ISO 22178

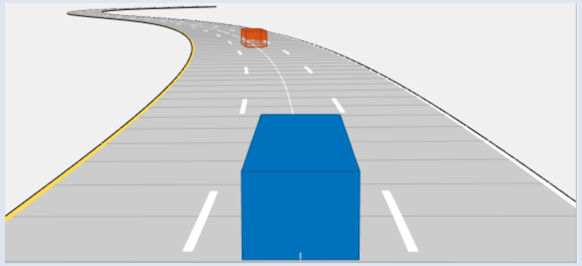
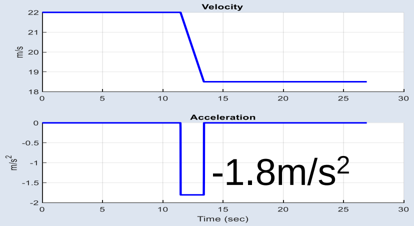
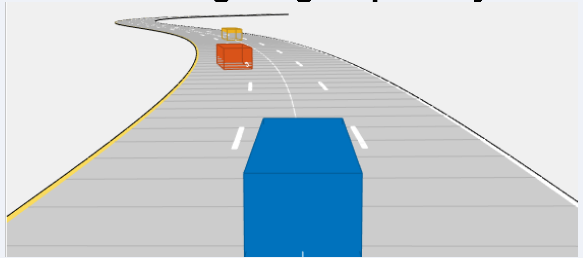
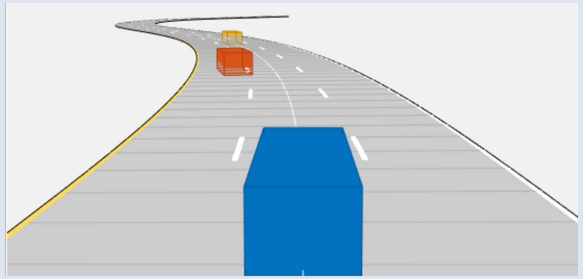
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

Test scenarios (2/4)

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
4	ACC_04_ISO _CurveTest	**Curve Capability Test** (curvature of test track = 1/500 m)  	initial velocity = 31.6m/s HWT = 1.5sec (HW = 47.4m) v_set = 31.6m/s	initial velocity = 31.6m/s Drive at a constant speed for 10s, decrease speed by 3.5m/s in 2s, and keep it constant.  	none	ISO 15622 ISO 22178
5	ACC_05_StopnGo	**Stop and Go in highway**  	initial velocity = 27m/s HWT = 1.5sec (HW = 40.5m) v_set = 27m/s	initial velocity = 27m/s Lead car slows down to 15m/s at $-3m/s^2$ and stay constant for 7s, then speed up to 25m/s at $2.5m/s^2$  	8 slow moving cars at 12m/s in the second lane	Real-world scenario

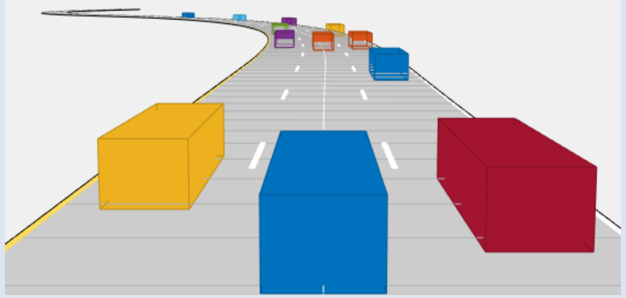
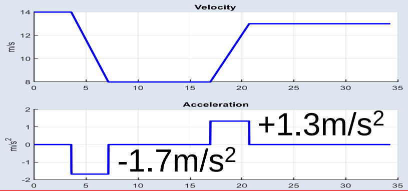
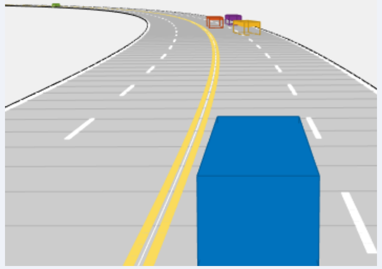
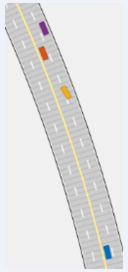
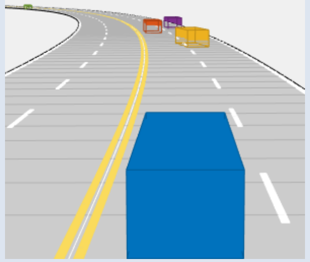
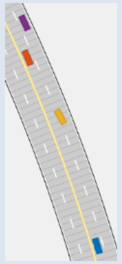
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

Test scenarios (3/4)

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
6	LFACC_01_DoubleCurve _DecelTarget (Similar with ACC_04_ISO _CurveTest)	**Automatic Deceleration Test** 	initial velocity = 22m/s HWT = 2sec (HW = 44m) v_set = 22m/s	initial velocity = 22m/s Drive at a constant speed for about 11s, decrease speed by 3.5m/s in 2s (deceleration: -1.8 m/s^2) and keep it const. 	none	Real-world scenario
7	LFACC_02_DoubleCurve _AutoRetarget_TooSlow (Similar with ACC_03_ISO _AutoRetargetTest)	**Automatic Retargeting Capability Test** 	initial velocity = 15m/s HWT = 2.8sec (HW = 43m) v_set = 15m/s	initial velocity = 13.9m/s Lead car changes lane @ HWT=3s to overtake slow moving car	Slow moving car at constant speed = 2.1m/s	~ISO 22178
8	LFACC_03_DoubleCurve _AutoRetarget (Similar with ACC_03_ISO _AutoRetargetTest)	**Automatic Retargeting Capability Test** 	initial velocity = 15m/s HWT = 2.8sec (HW = 43m) v_set = 15m/s	initial velocity = 13.9m/s Lead car changes lane @ HWT=3s to overtake slow moving car	Slow moving car at constant speed = 10m/s	~ISO 22178

Test scenarios (4/4)

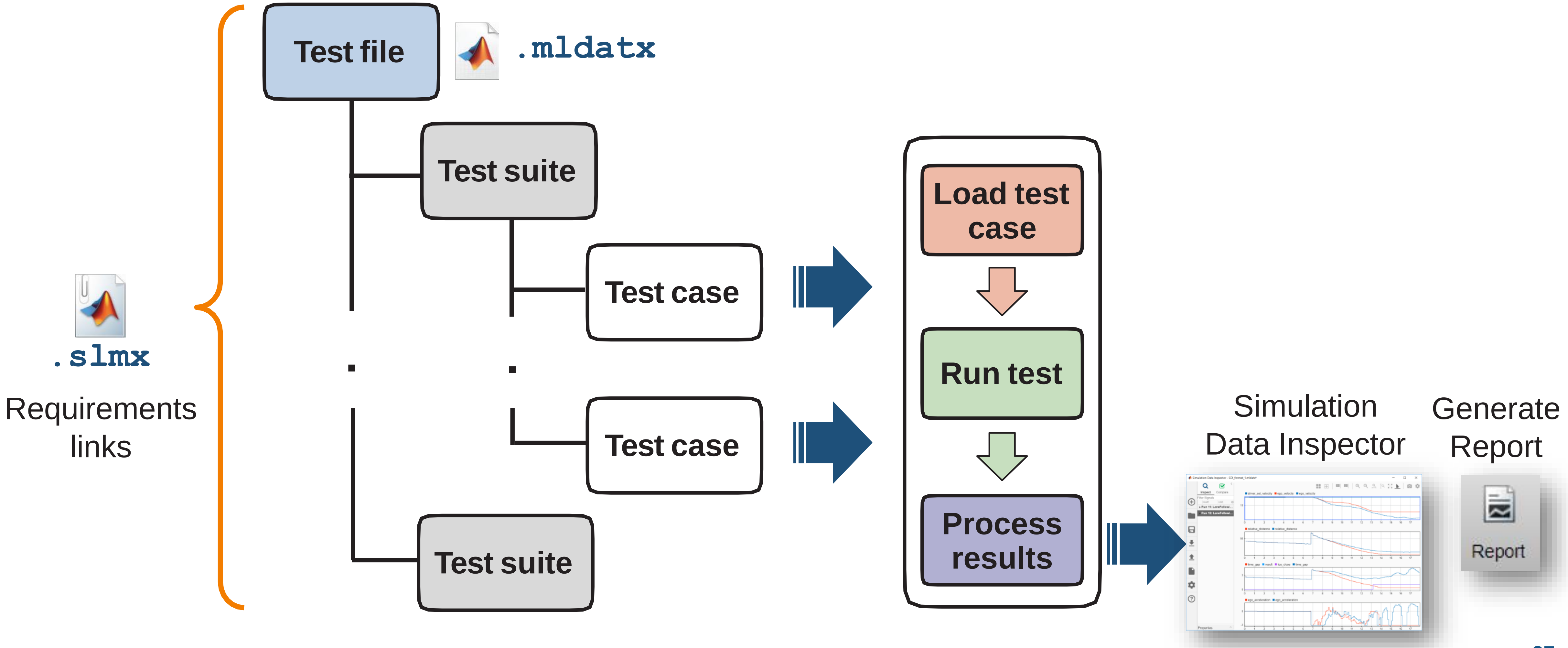
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
9	LFACC_04_DoubleCurve _StopnGo (Similar with ACC_05_StopnGo)	**Stop and Go in curved highway** 	initial velocity = 14m/s HWT = 3.6sec (HW = 50m) v_set = 14m/s	initial velocity = 14m/s Lead car slows down to 8m/s at -1.7m/s² and stay constant for 10s, then speed up to 13m/s at 1.3m/s² 	10 slow moving cars at 8m/s in the 3rd lane 3 fast moving cars at 15m/s in the 1st lane	Real-world scenario
10	LFACC_05_Curve _CutInOut	**Lead car cut in and out in curved highway** (curvature of road = 1/500 m)  	initial velocity = 20.6m/s HWT = 4sec (HW = ~80m) v_set = 21.5m/s	Initially, fast moving car (orange) at 19.4m/s Passing car (yellow) at 19.6m/s cut in the ego path with HWT=2.3s, then cut out	Slow moving car (purple) at 11.1m/s in the 2nd lane	Real-world scenario
11	LFACC_06_Curve _CutInOut_TooClose	**Lead car cut in and out in curved highway** (curvature of road = 1/500 m)  	initial velocity = 20.6m/s HWT = 4sec (HW = ~80m) v_set = 21.5m/s	Initially, fast moving car (orange) at 19.4m/s Passing car (yellow) at 19.6m/s cut in the ego path with HWT=1.5s, then cut out	Slow moving car (purple) at 11.1m/s in the 2nd lane	Real-world scenario

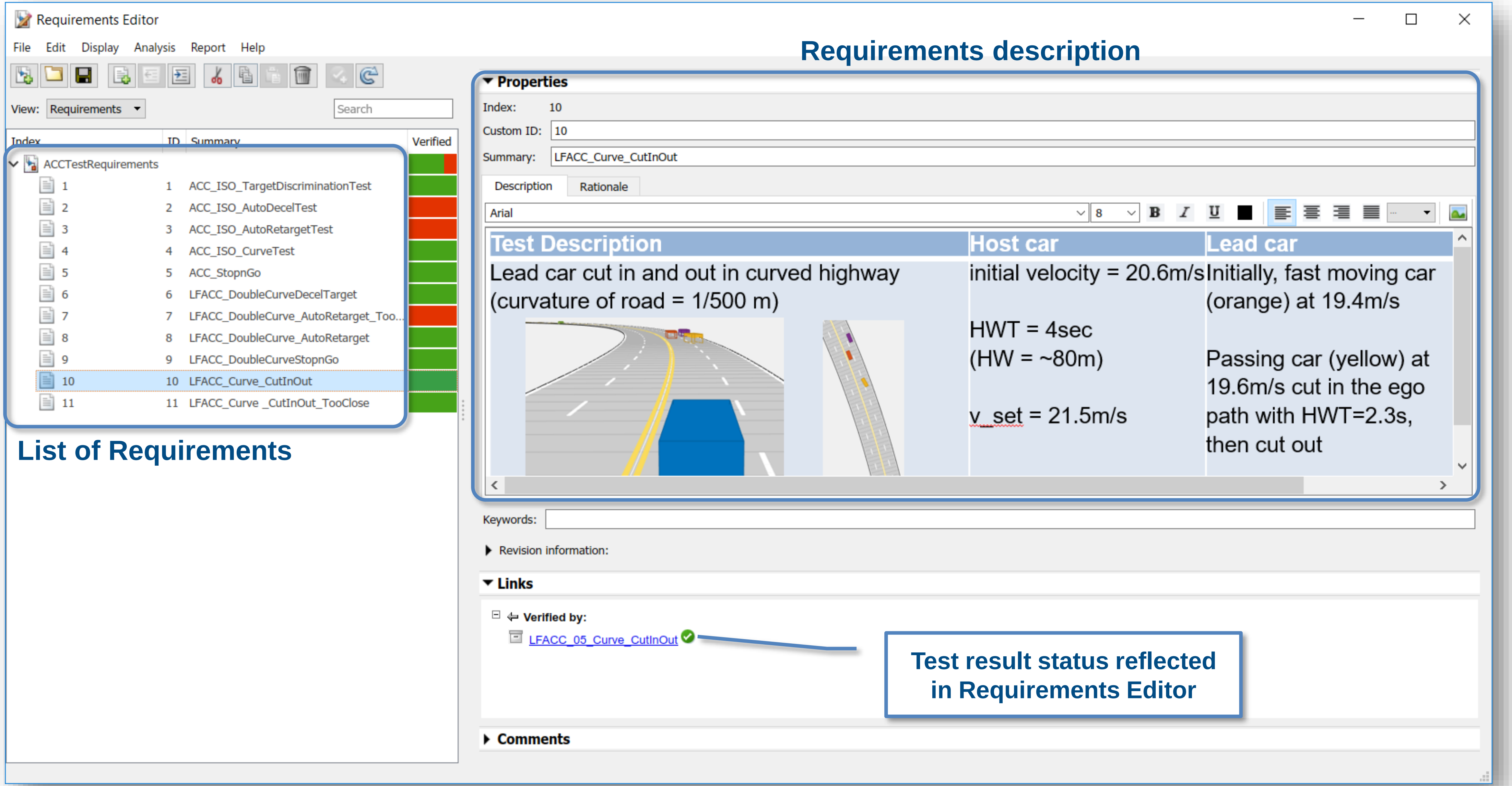
Representative test scenario

Test Manager in Simulink® Test™

- Automate Simulink model testing using test cases with pass-fail criteria



Requirements Editor



Test Report with baseline parameter set for 11 test cases

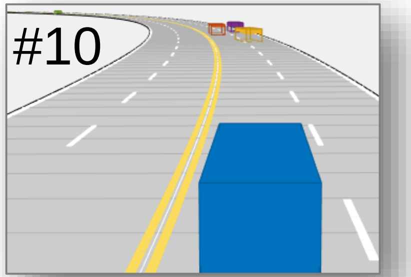
Report Generated by Test Manager

Title: ACCAndLaneFollowing (baseline)
Author: Seo-Wook Park
Date: 21-Apr-2018 16:01:50

Test Environment

Platform: PCWIN64
MATLAB: (R2018a)

Note) Baseline parameter set was tuned based on a single test scenario.



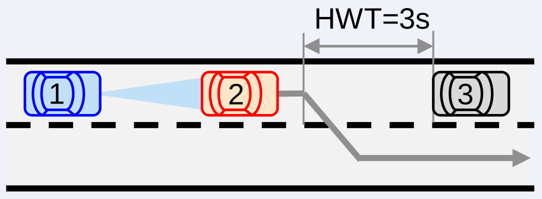
Summary

Name	Outcome	Duration (Seconds)
TestScenarios_Baseline	8 ✓ 3 ✗	565
ACCTest	3 ✓ 2 ✗	210
ACC_01_ISO_TargetDiscriminationTest	✓	35
ACC_02_ISO_AutoDecelTest	✗	22
ACC_03_ISO_AutoRetargetTest	✗	32
ACC_04_ISO_CurveTest	✓	43
ACC_05_StopnGo	✓	73
LFACCTest	5 ✓ 1 ✗	354
LFACC_01_DoubleCurve_DecelTarget	✓	43
LFACC_02_DoubleCurve_AutoRetarget_TooSlow	✗	36
LFACC_03_DoubleCurve_AutoRetarget	✓	65
LFACC_04_DoubleCurve_StopnGo	✓	111
LFACC_05_Curve_CutInOut	✓	48
LFACC_06_Curve_CutInOut_TooClose	✓	49

Fine-tune control parameters (1/3)

Test Description

Automatic Retargeting Capability Test



Host car

initial velocity = 15m/s

HWT = 2.2sec (HW = 33m)

v_set = 15m/s

Lead Car

initial velocity = 13.9m/s

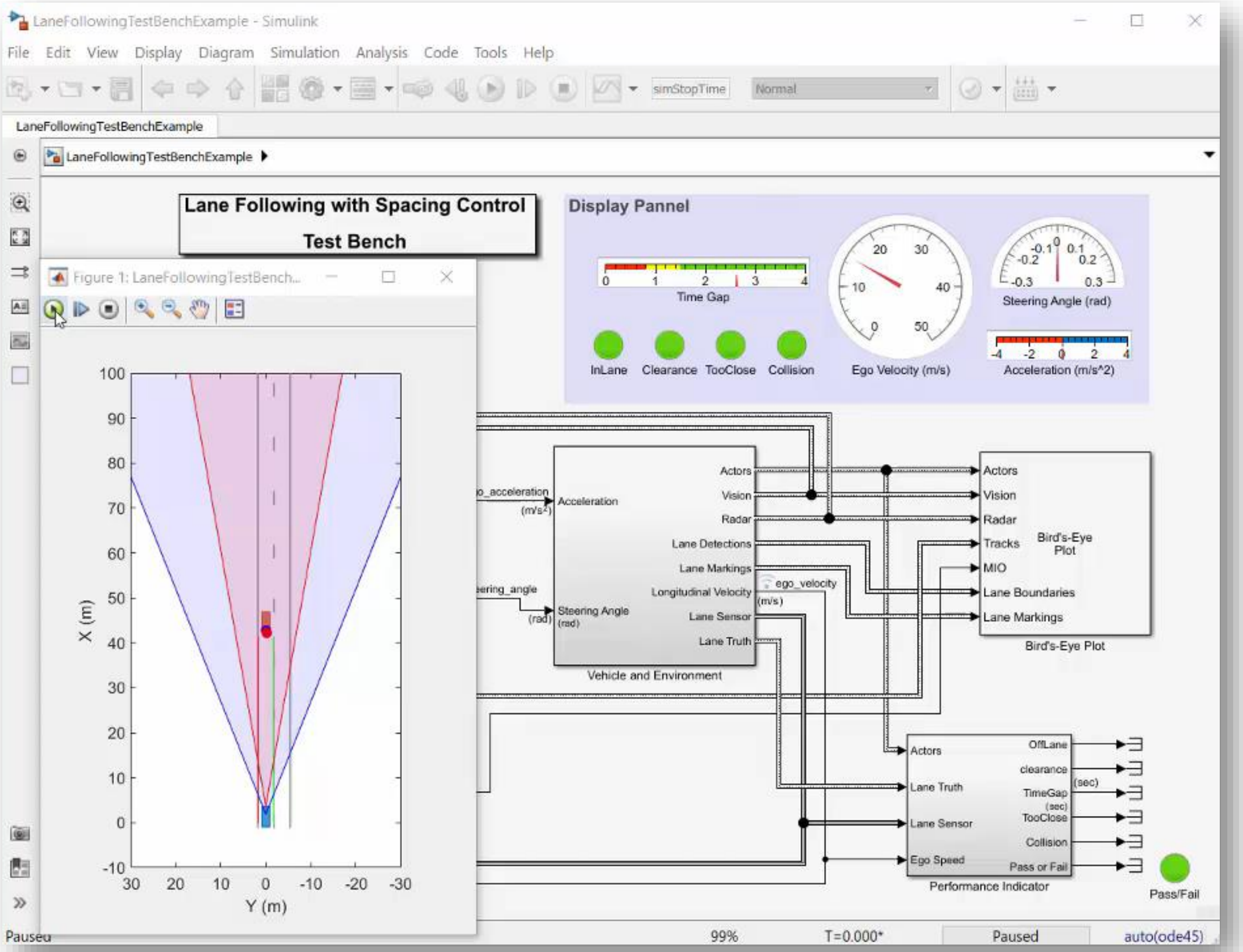
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

constant speed = 2.1m/s

Spec

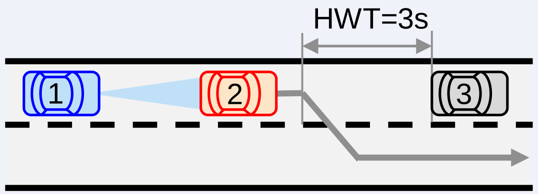
ISO 22178



Fine-tune control parameters (1/3)

Test Description

Automatic Retargeting Capability Test



Host car

initial velocity = 15m/s
HWT = 2.2sec (HW = 33m)
v_set = 15m/s

Lead Car

initial velocity = 13.9m/s

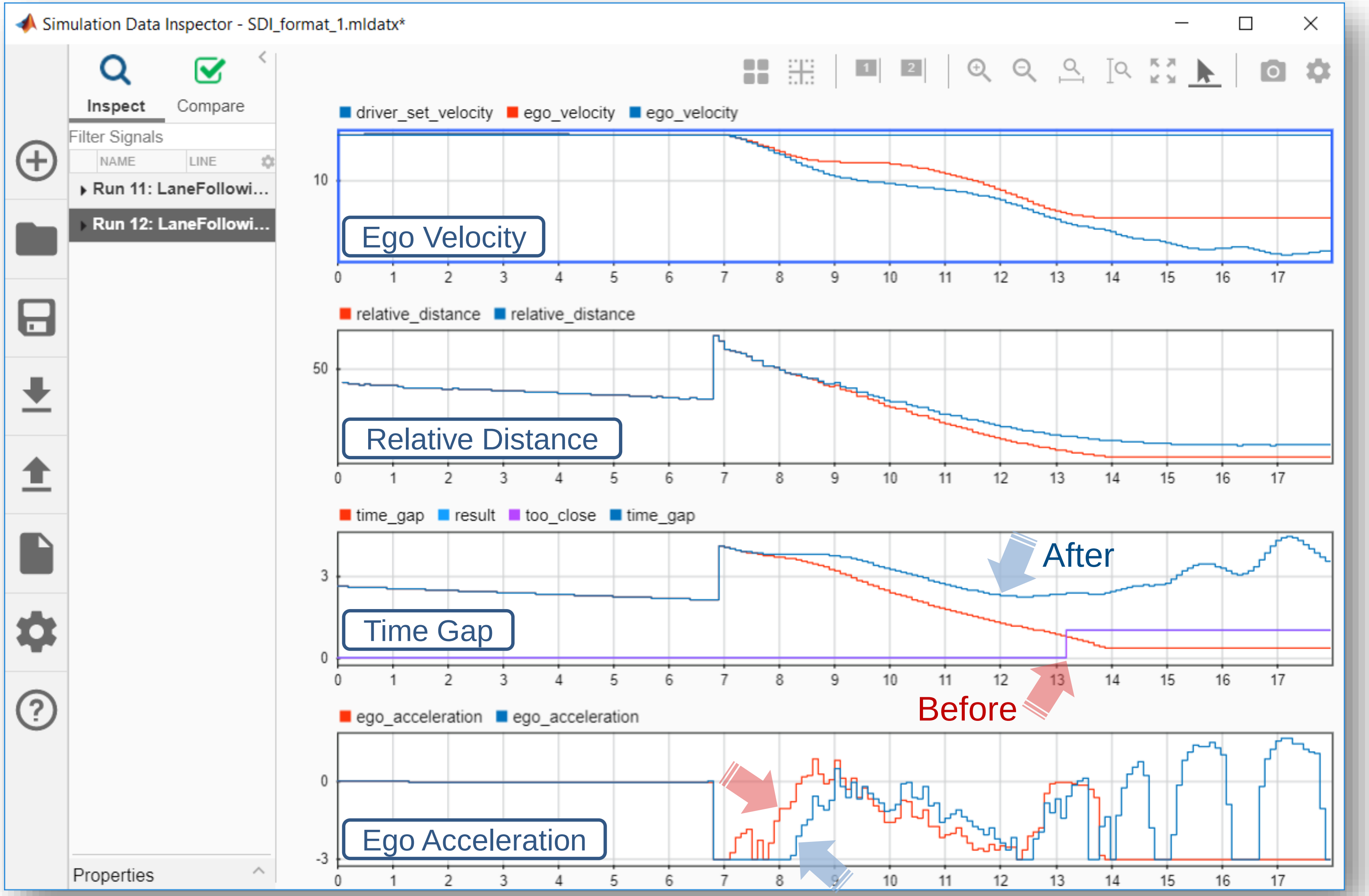
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

constant speed = 2.1m/s

Spec

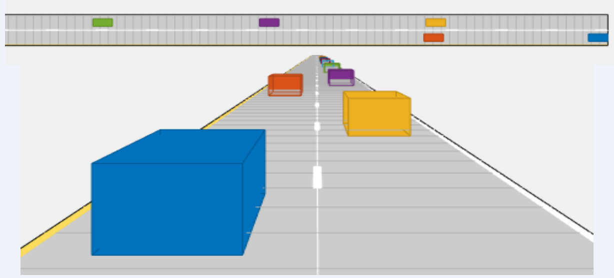
ISO 22178



Fine-tune control parameters (2/3)

Test Description

Stop and Go in highway



Host car

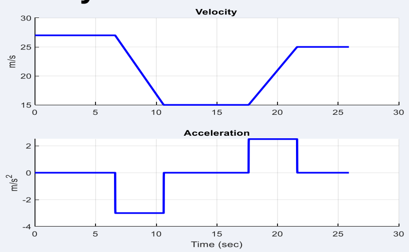
initial velocity = 27m/s

HWT = 1.5sec (HW = 40.5m)

v_set = 27m/s

Lead Car

initial velocity = 27m/s



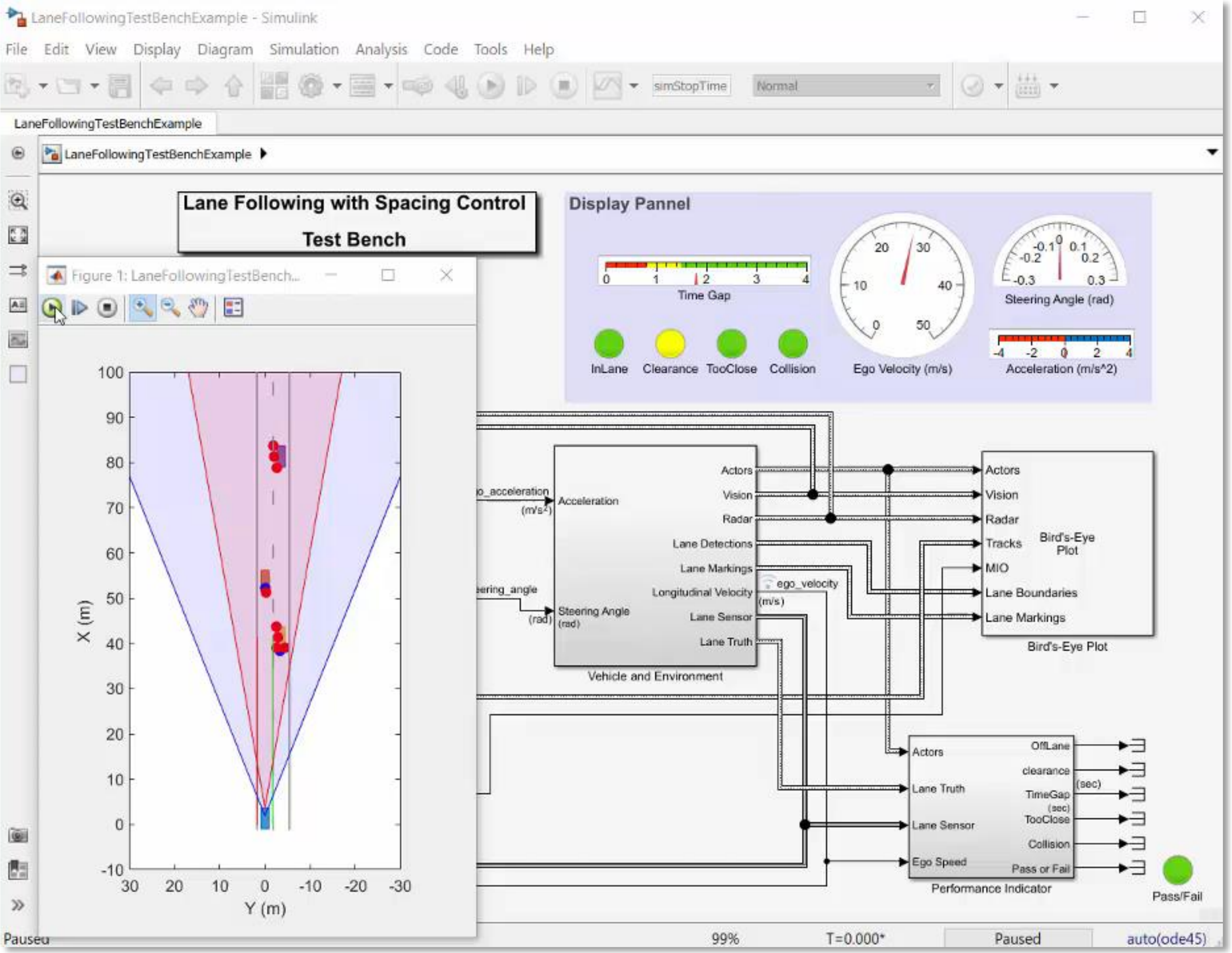
Third Car

8 slow moving cars at 12m/s

in the second lane

Spec

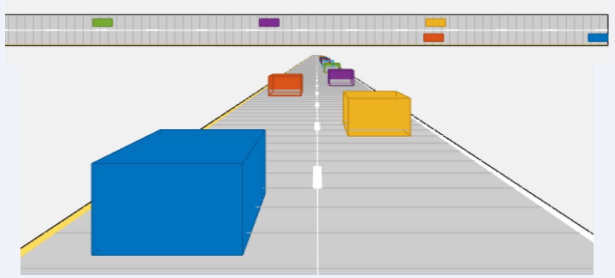
Real-world scenario



Fine-tune control parameters (2/3)

Test Description

Stop and Go in highway



Host car

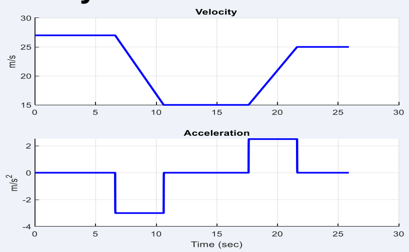
initial velocity = 27m/s

HWT = 1.5sec (HW = 40.5m)

v_set = 27m/s

Lead Car

initial velocity = 27m/s

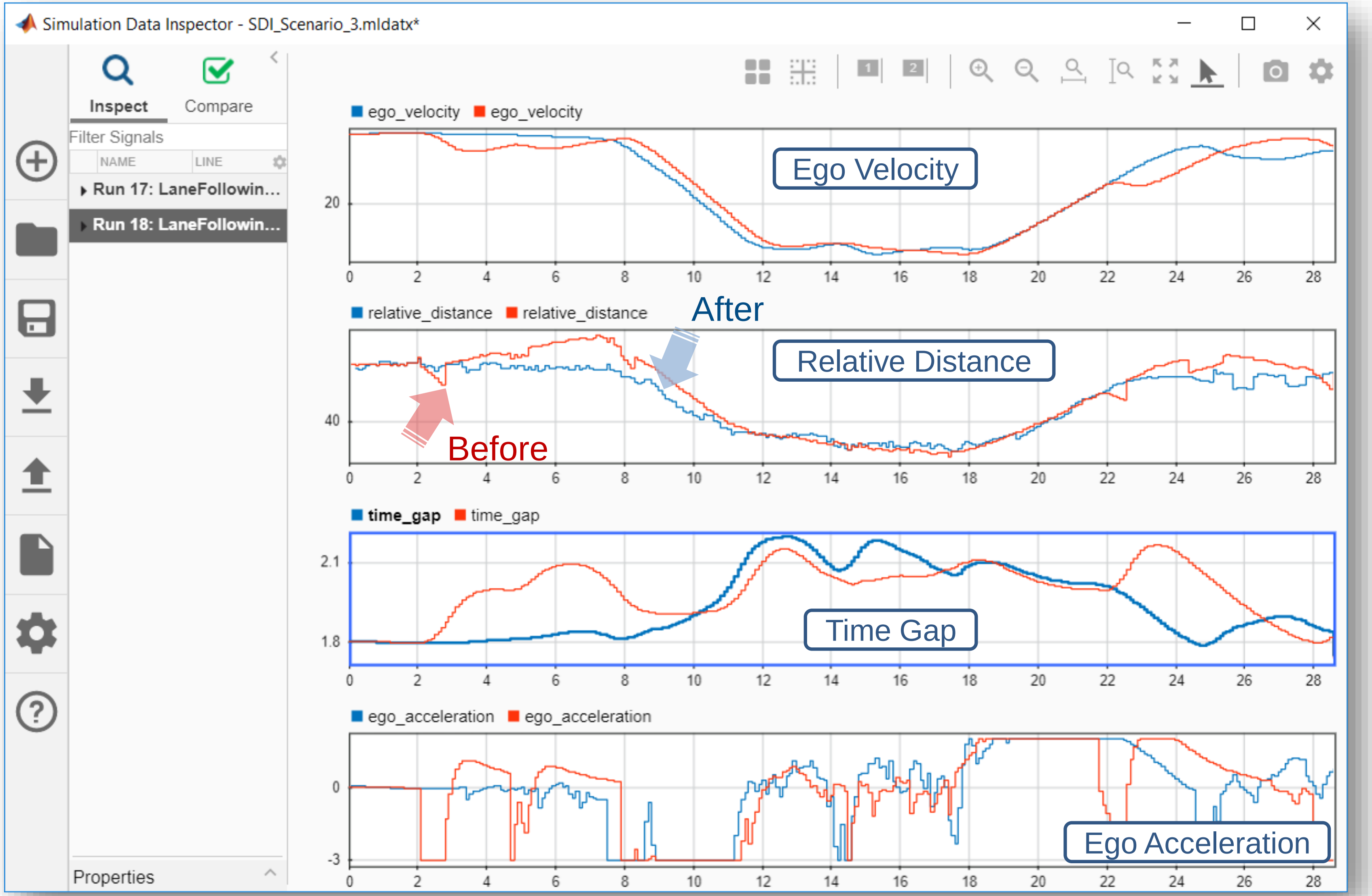


Third Car

8 slow moving cars at 12m/s in the second lane

Spec

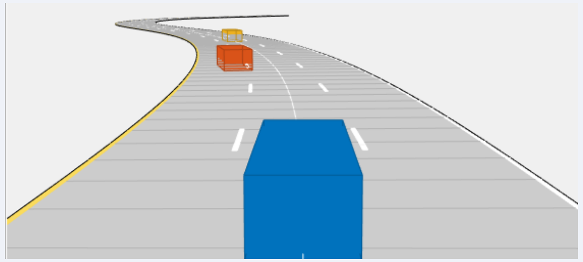
Real-world scenario



Fine-tune control parameters (3/3)

Test Description

Automatic Retargeting Capability Test



Host car

initial velocity = 15m/s
HWT = 2.8sec (HW = 43m)
v_set = 15m/s

Lead Car

initial velocity = 13.9m/s

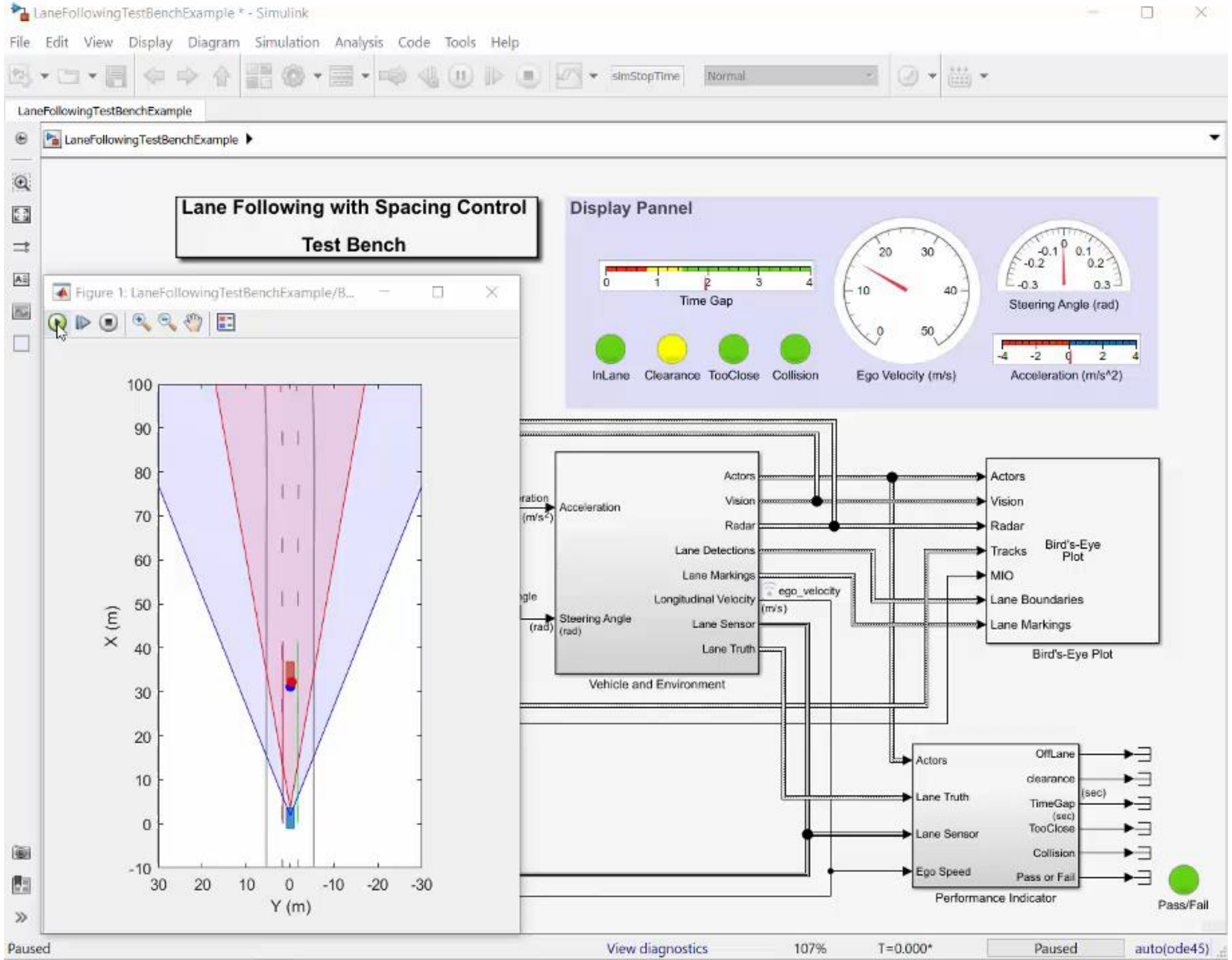
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

Slow moving car at constant speed, 2.1m/s

Spec

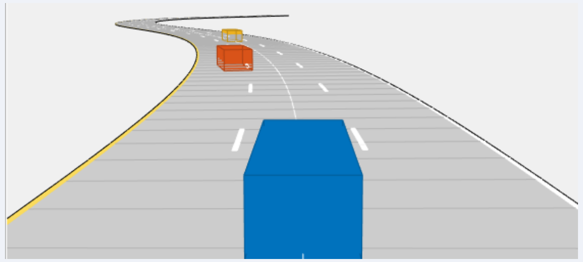
~ISO 22178



Fine-tune control parameters (3/3)

Test Description

Automatic Retargeting Capability Test



Host car

initial velocity = 15m/s
HWT = 2.8sec (HW = 43m)
v_set = 15m/s

Lead Car

initial velocity = 13.9m/s

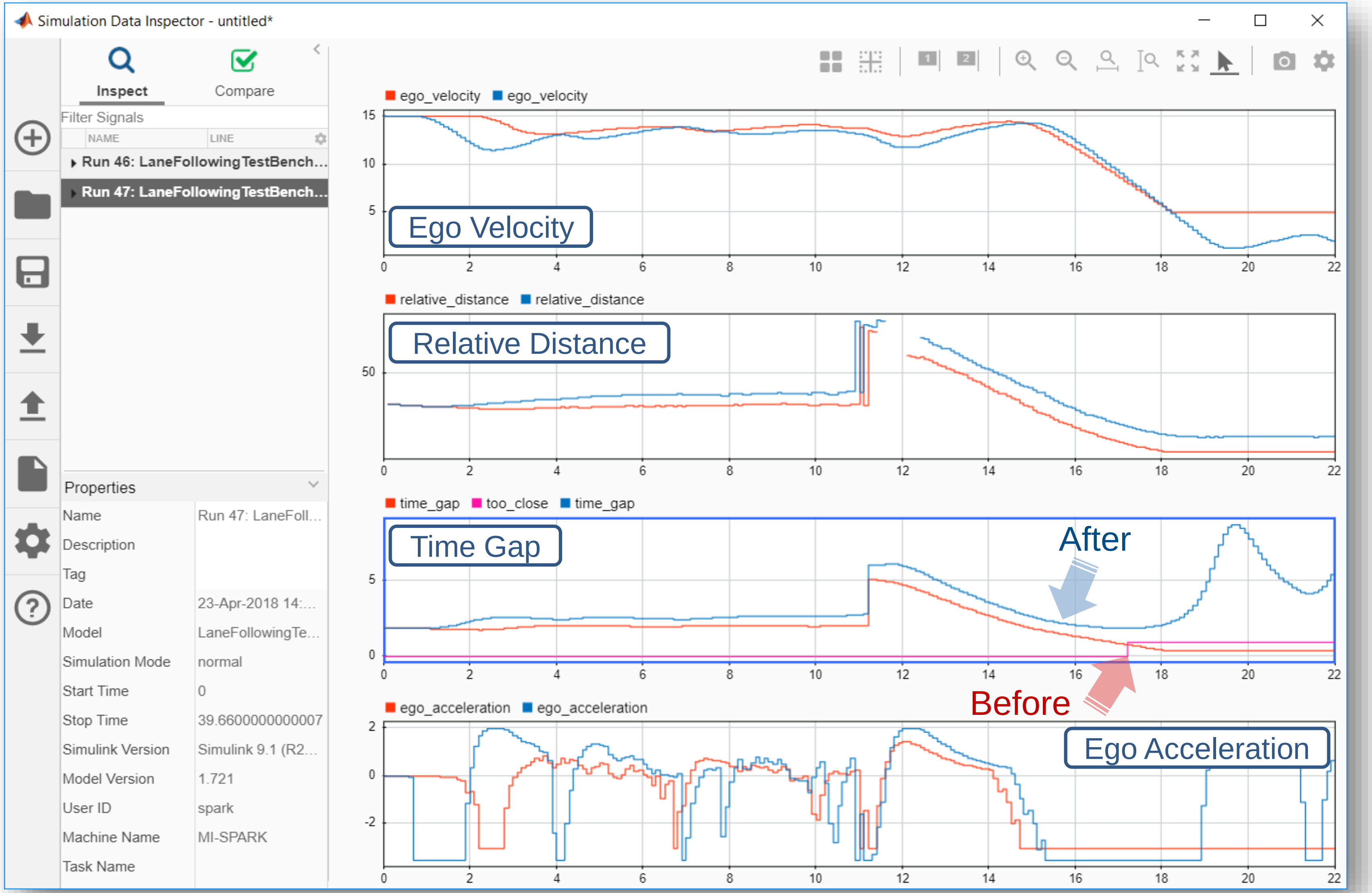
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

Slow moving car at constant speed, 2.1m/s

Spec

~ISO 22178



Baseline vs. Fine-tuned parameters

Parameter Name	Description	Baseline	Fine-tuned
assigThresh	Detection assignment threshold for multiObjectTracker	50	20
time_gap	ACC time gap (sec)	1.5	2.0
default_spacing	ACC safe distance margin (m)	0	10
min_ac	Minimum acceleration (m/s^2)	-3.0	-3.5

Test Report with fine-tuned parameter set for 11 test cases

Report Generated by Test Manager

Title: ACCAndLaneFollowing Fine-tuned
Author: Seo-Wook Park
Date: 26-Apr-2018 13:53:39

Test Environment

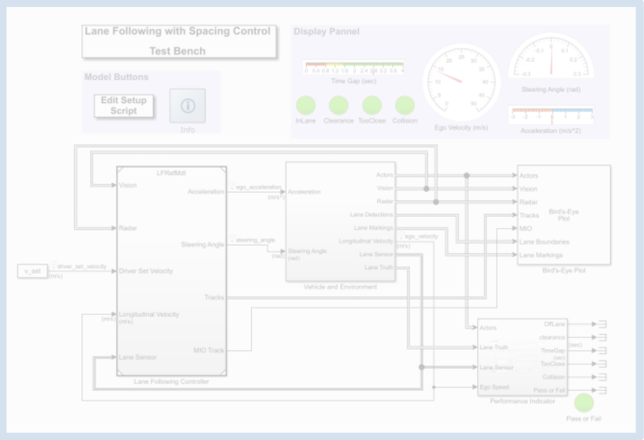
Platform: PCWIN64
MATLAB: (R2018a)

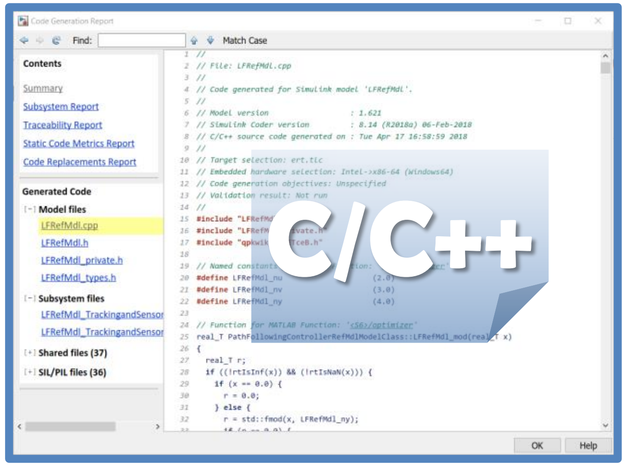
Summary

Name	Outcome	Duration (Seconds)
TestScenarios_FineTuned	11	3541
ACCTest	5	1521
ACC_01_ISO_TargetDiscriminationTest		245
ACC_02_ISO_AutoDecelTest		323
ACC_03_ISO_AutoRetargetTest		262
ACC_04_ISO_CurveTest		331
ACC_05_StopnGo		360
LFACCTest	6	2015
LFACC_01_DoubleCurve_DecelTarget		333
LFACC_02_DoubleCurve_AutoRetarget_TooSlow		380
LFACC_03_DoubleCurve_AutoRetarget		291
LFACC_04_DoubleCurve_StopnGo		398
LFACC_05_Curve_CutInOut		335
LFACC_06_Curve_CutInOut_TooClose		278

Automated Driving System Toolbox

Design and Test **Traffic Jam Assist,** *A Case study*





Design ACC and Lane Following Controller

- Create driving scenario
- Synthesize sensor detection
- Include Vehicle Dynamics
- Design sensor fusion algorithm
- Design controller using MPC

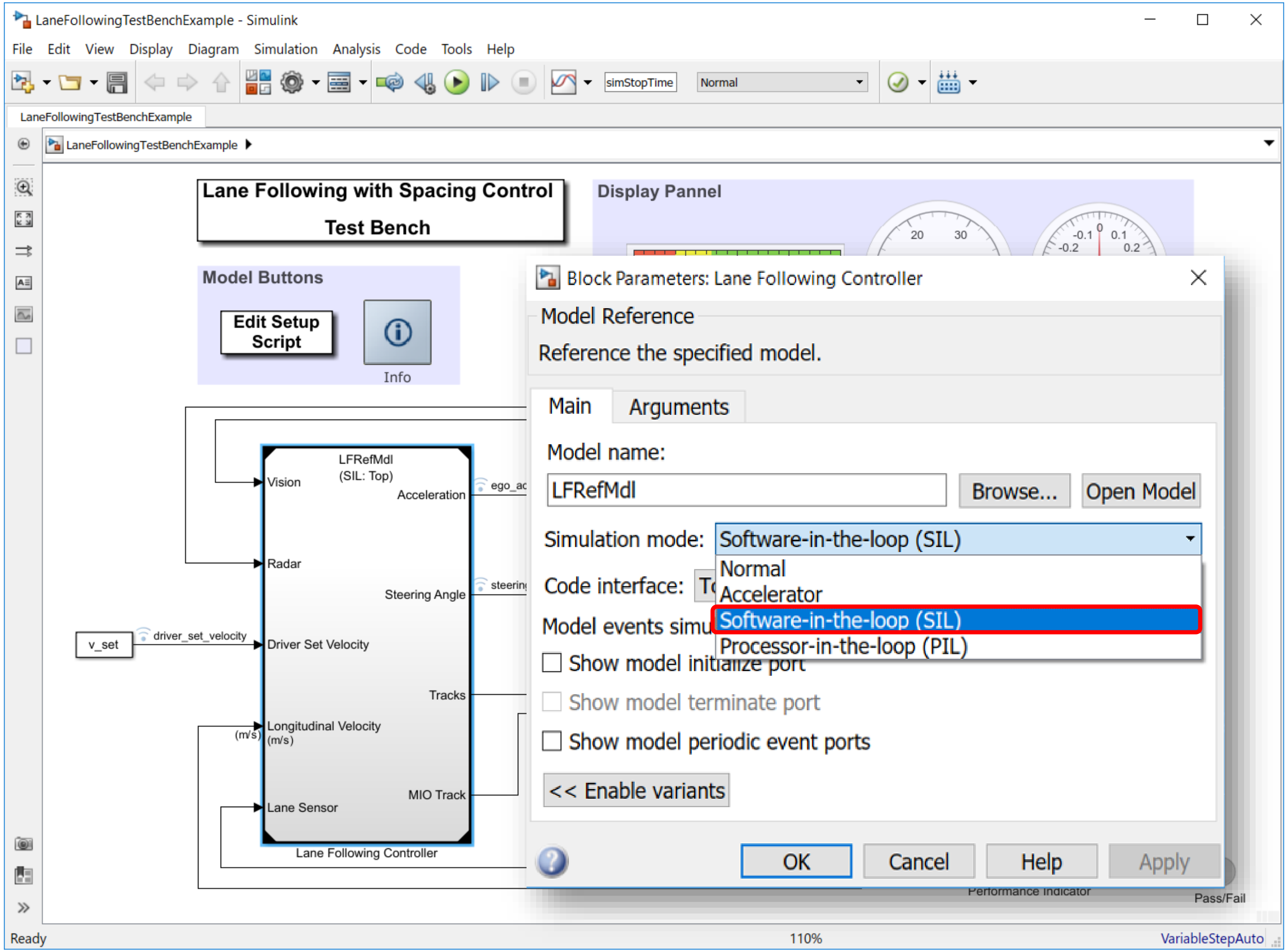
Automate Regression Test

- Define performance evaluation metrics
- Develop test cases
- Build test suites
- Verification and validation

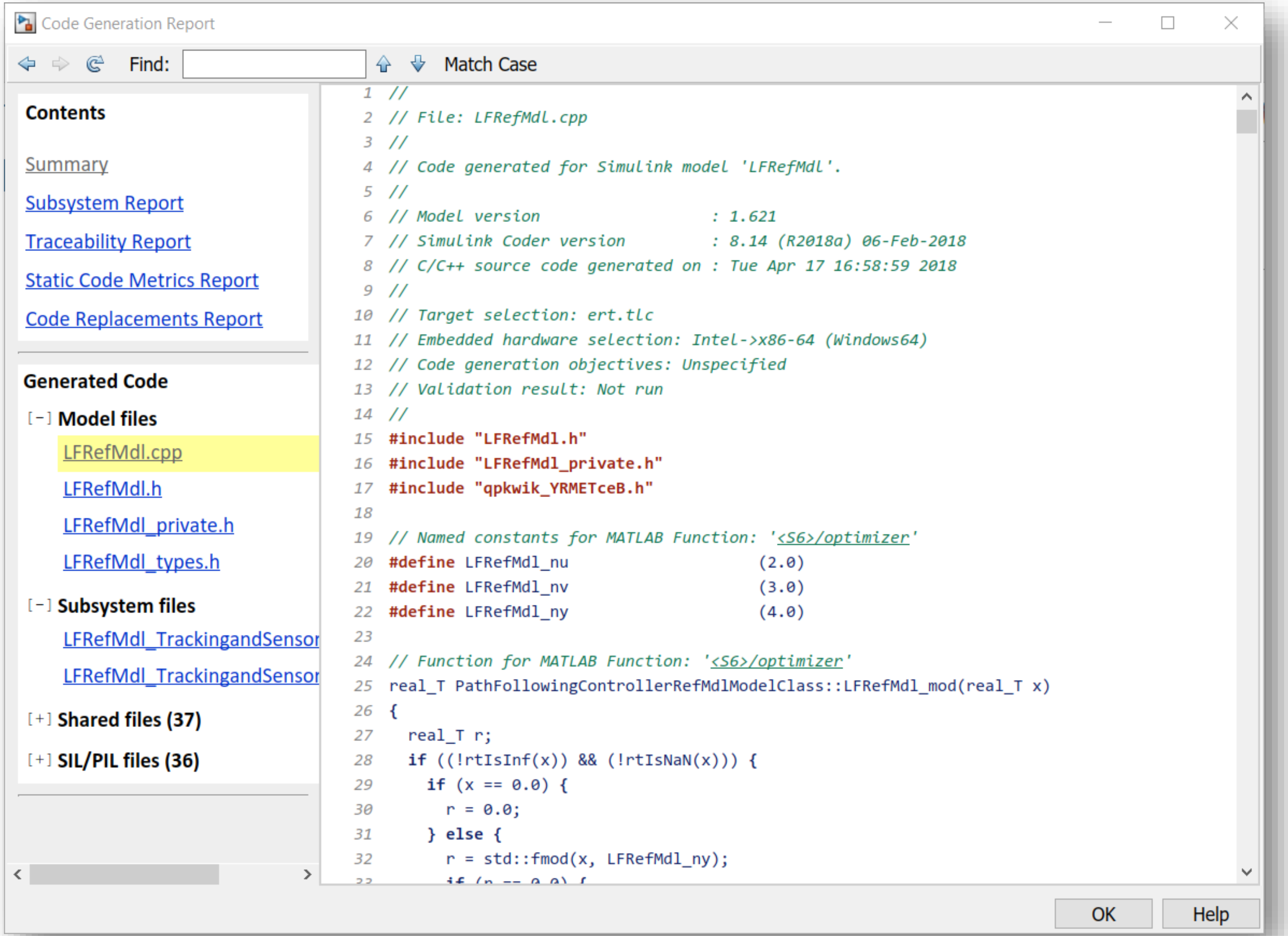
Generate and Verify Code

- SIL test
- Code generation
- Coverage test

Simulation with SIL mode



Code Generation Report



Aggregated Code Coverage Report

Report Generate

Title:	ACCAndLane
Author:	Seo-Wook Pa
Date:	26-Apr-2018 1

Test Environment

Platform:	PCWIN64
MATLAB:	(R2018a)

Summary

File/Complexity

TOTAL COVERAGE

1. . . . LFRefMdl.cpp
2. . . . LFRefMdl_TrackingandS
3. . . . rtGetInf.cpp
4. . . . rtGetNaN.cpp
5. . . . rt_nonfinite.cpp

Summary By Mo

Model Object

1. LFRefMdl
2. . . . Controller
3. . . . . . . MPC Controller
4. . . . . MPC
5. . . . . optimizer
6. . . . . . . Safe distance
7. . . . Estimate Lane Center
8. . . . . . . Center from Left
9. . . . . . . Center from Left and I
10. . . . . . . Center from Right
11. . . . . . . MATLAB Function
12. . . . . . . Preview curvature
13. . . . Tracking and Sensor Fus
14. . . . . . . Clock
15. . . . . Counter Limited
16. . . . . . . Find Lead Car

```
static boolean_T LFRefMdl_objectTrack_checkPromotion(const
  driving_internal_objectTrack_LFRefMdl_T *track)
{
  boolean_T toPromote;
  real_T history;
  int32_T b;
  boolean_T track_data[50];
  int32_T track_size[2];
  if (track->ObjectClassID != 0.0) {
    toPromote = true;
  } else {
    if ((track->pUsedHistoryLength < track->ConfirmationParameters[1]) ||
```

X

Decisions analyzed:

(track->pUsedHistoryLength < track->ConfirmationParameters[1]) || rtIsNaN(track->ConfirmationParameters[1])	50%
false	13038/13038
true	0/13038

Conditions analyzed:

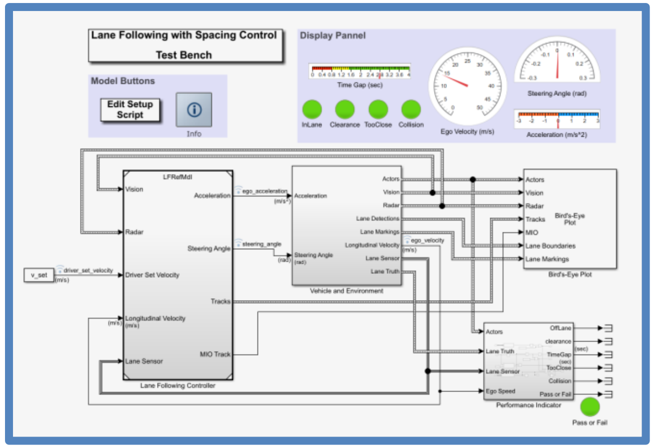
Description:	True	False
track->pUsedHistoryLength < track->ConfirmationParameters[1]	0	13038
rtIsNaN(track->ConfirmationParameters[1])	0	13038

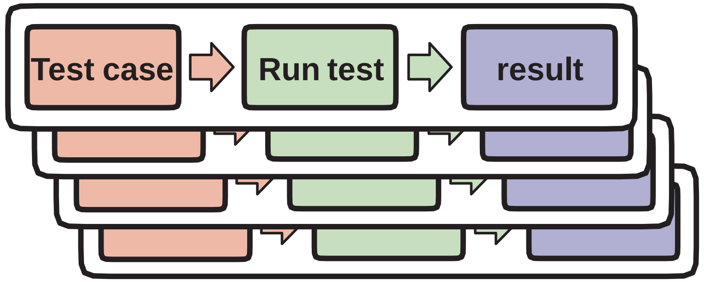
MC/DC analysis (combinations in parentheses did not occur)

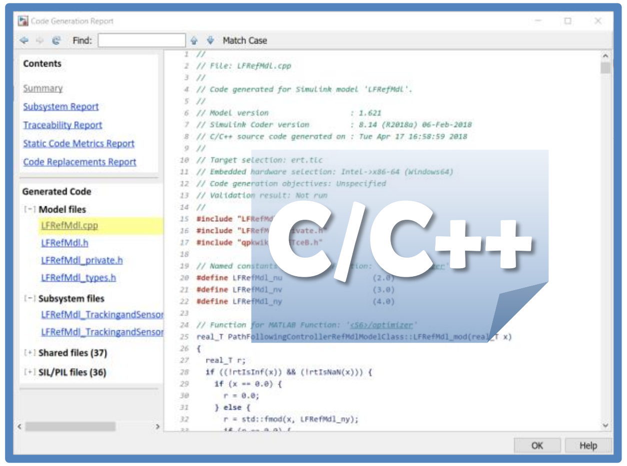
decision outcomes:	True Out	False Out
Conditions:		
track->pUsedHistoryLength < track->ConfirmationParameters[1]	(Tx)	FF
rtIsNaN(track->ConfirmationParameters[1])	(FT)	FF

Automated Driving System Toolbox

Design and Test **Traffic Jam Assist,** *A Case study*







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- SIL test
- Code generation
- Coverage test

Thank you for your attention !!

Email: seo-wook.park@mathworks.com