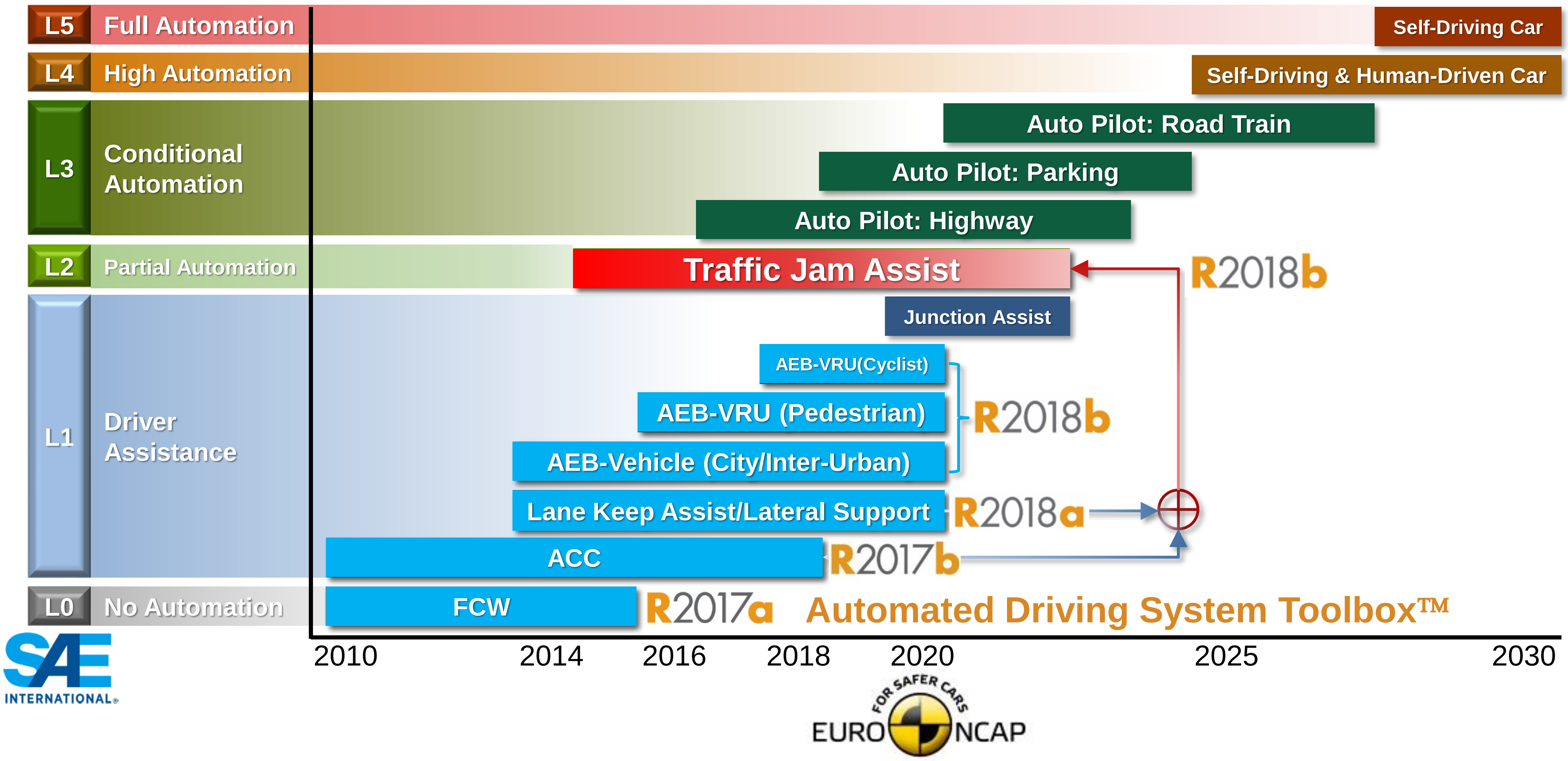
MathWorks
AUTOMOTIVE
CONFERENCE
2018

Design and Test
Traffic Jam Assist

A Case Study
Using Automated Driving System Toolbox™

Seo-Wook Park
Principal Application Engineer, MathWorks

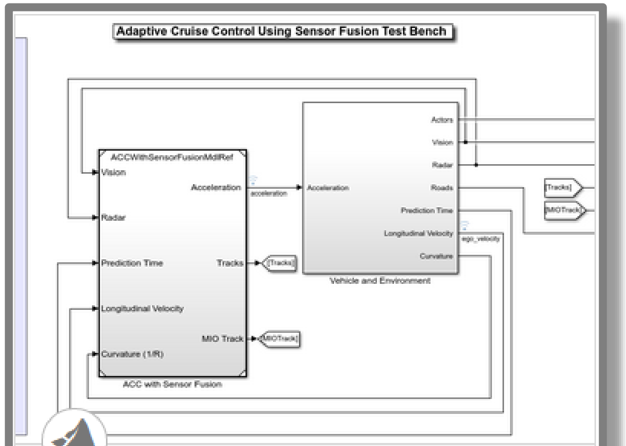
Evolution of ADAS and Autonomous Driving Car Technologies



ACC and Lane Following Control for Traffic Jam Assist

Automated Driving System Toolbox™

R2017b



Adaptive Cruise Control with Sensor Fusion

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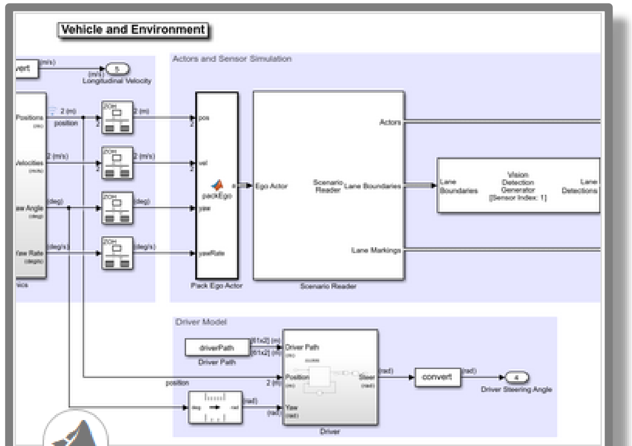
R2018a



Lane Keeping Assist with Lane Detection

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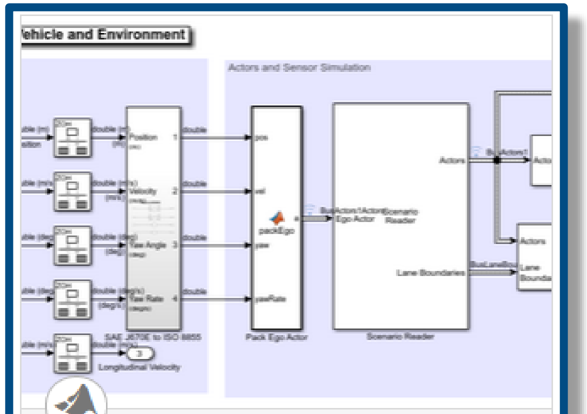
R2018b



Lane Following Control with Sensor Fusion and Lane Detection

ACC
(Longitudinal Control)

Lane Following
(Lateral Control)

Traffic Jam Assist
(Longitudinal + Lateral Control)

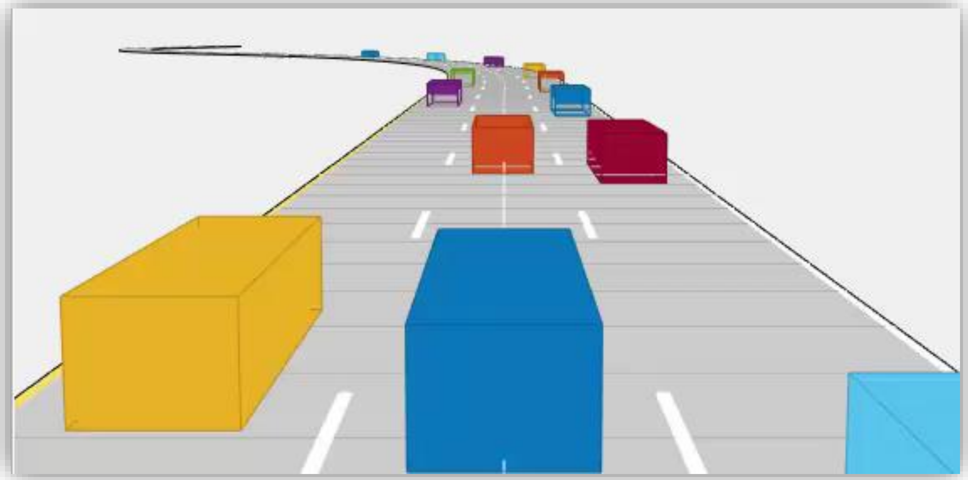
Traffic Jam Assist

- 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

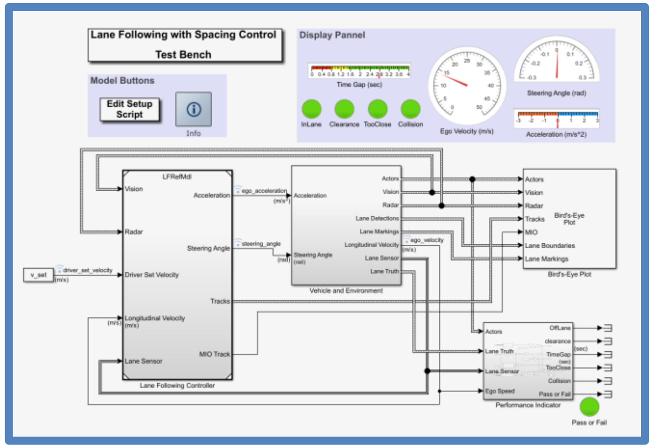
Lateral control with lane following

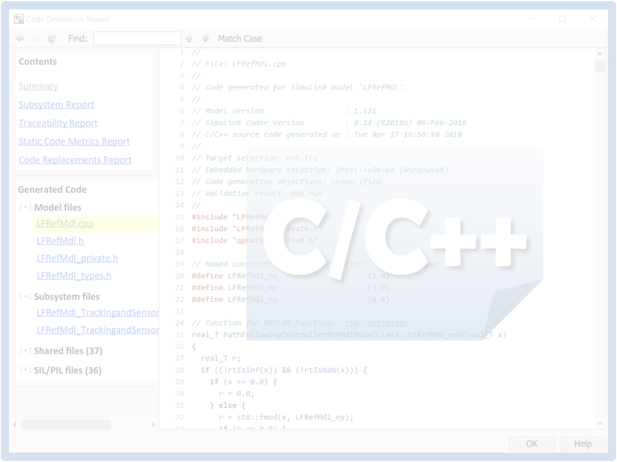


- Partial/conditional automation at level 2/3
  – Speed limit < 60~65 km/h
  – Dense traffic condition in highway

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
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Generate and Verify Code

- SIL test
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- Coverage test

ACC Performance Requirements

ISO 15622

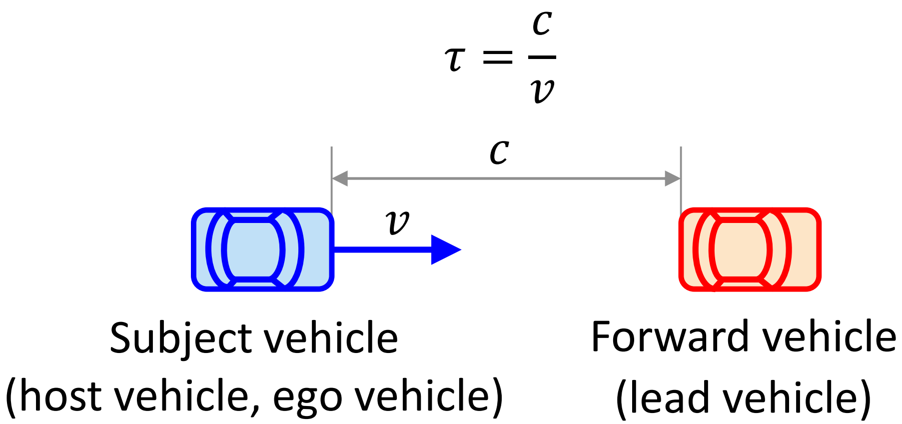
- **Ego velocity control** : $v \le v_{set}$

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

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

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

  τ_{min} : min time gap = 0.8 sec

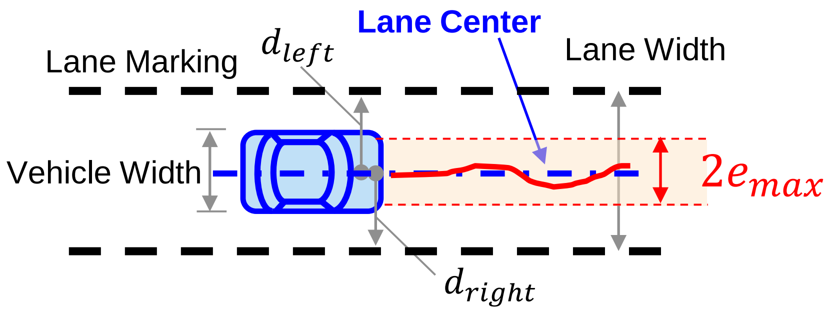


- ACC operation limits
  - Minimum operational speed, v_{min} = 5m/s
  - Average automatic deceleration of ACC ≤ 3.5 m/s^2 (average over 2s)
  - Average automatic acceleration of ACC ≤ 2.0 m/s^2

Lane Following Performance Requirements

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

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



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

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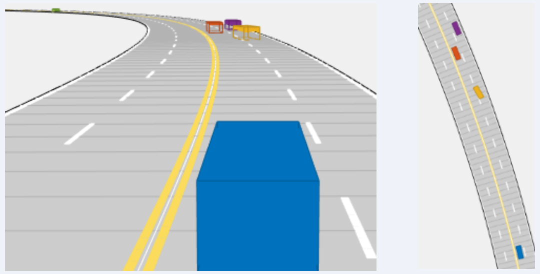
Automated Driving System Toolbox™

R2018a

Create Test Scenario using Driving Scenario Designer

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

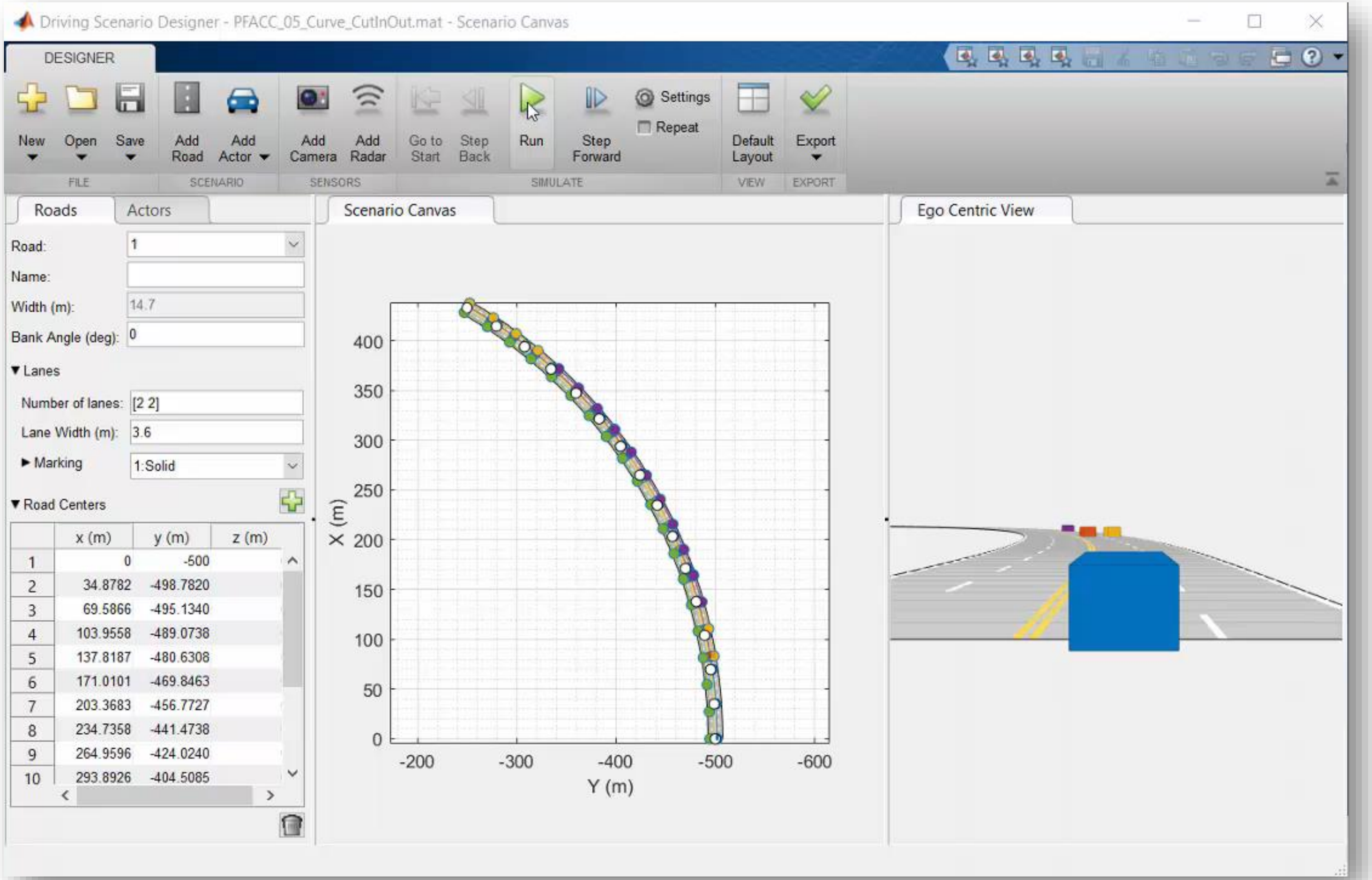
Lead Car

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

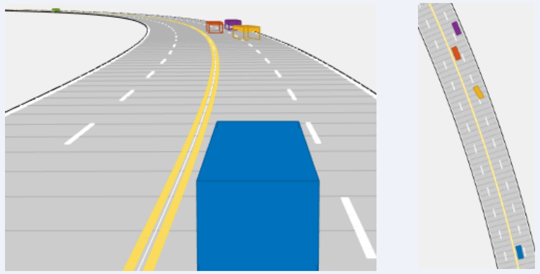
Slow moving car (purple) at 11.1m/s in the 2nd lane



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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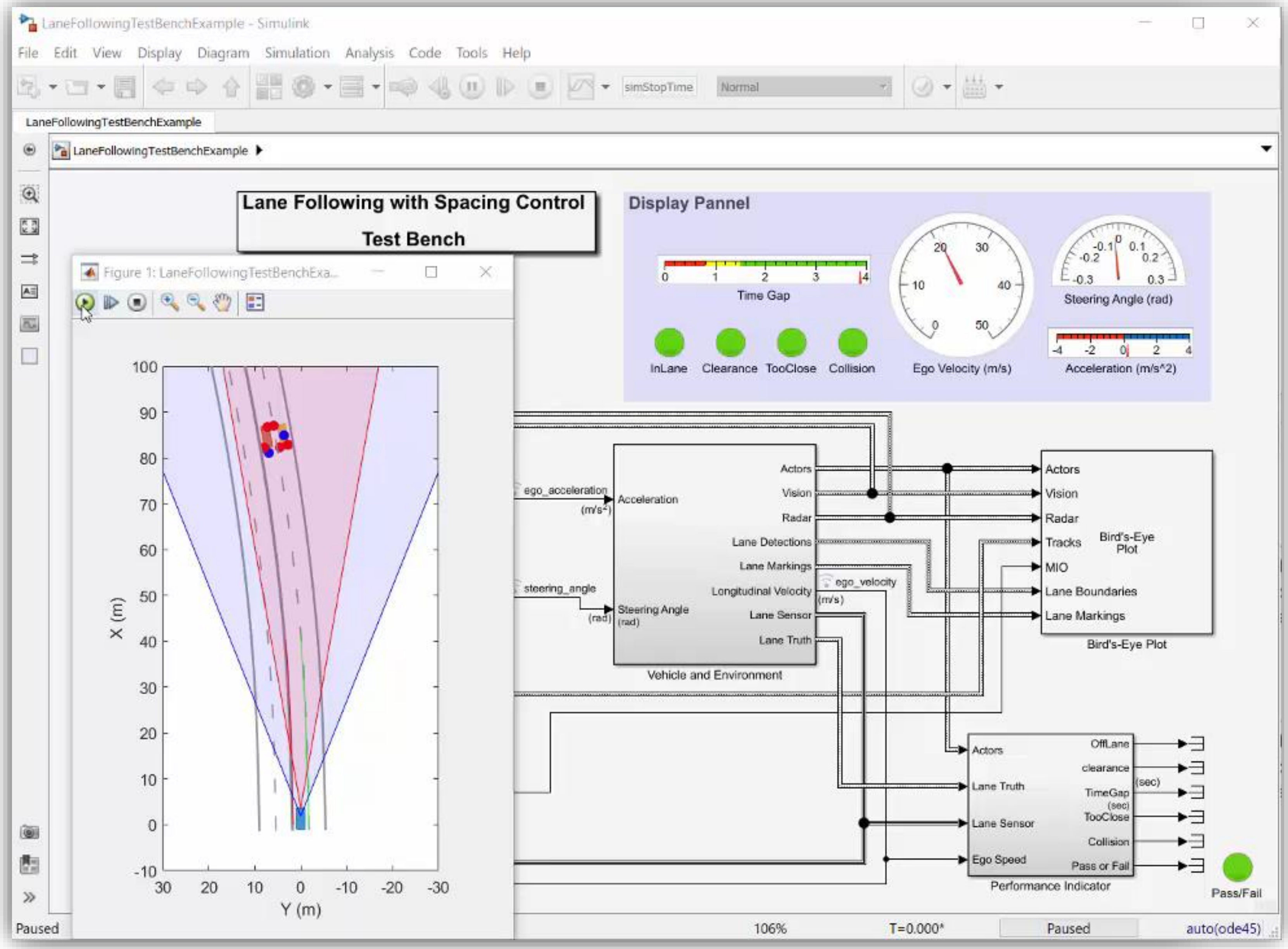

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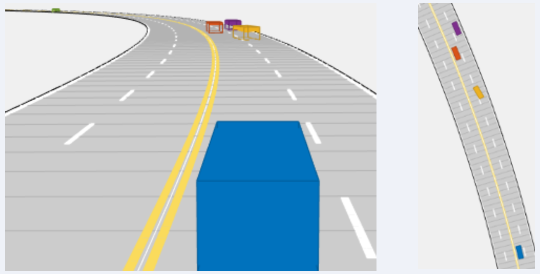

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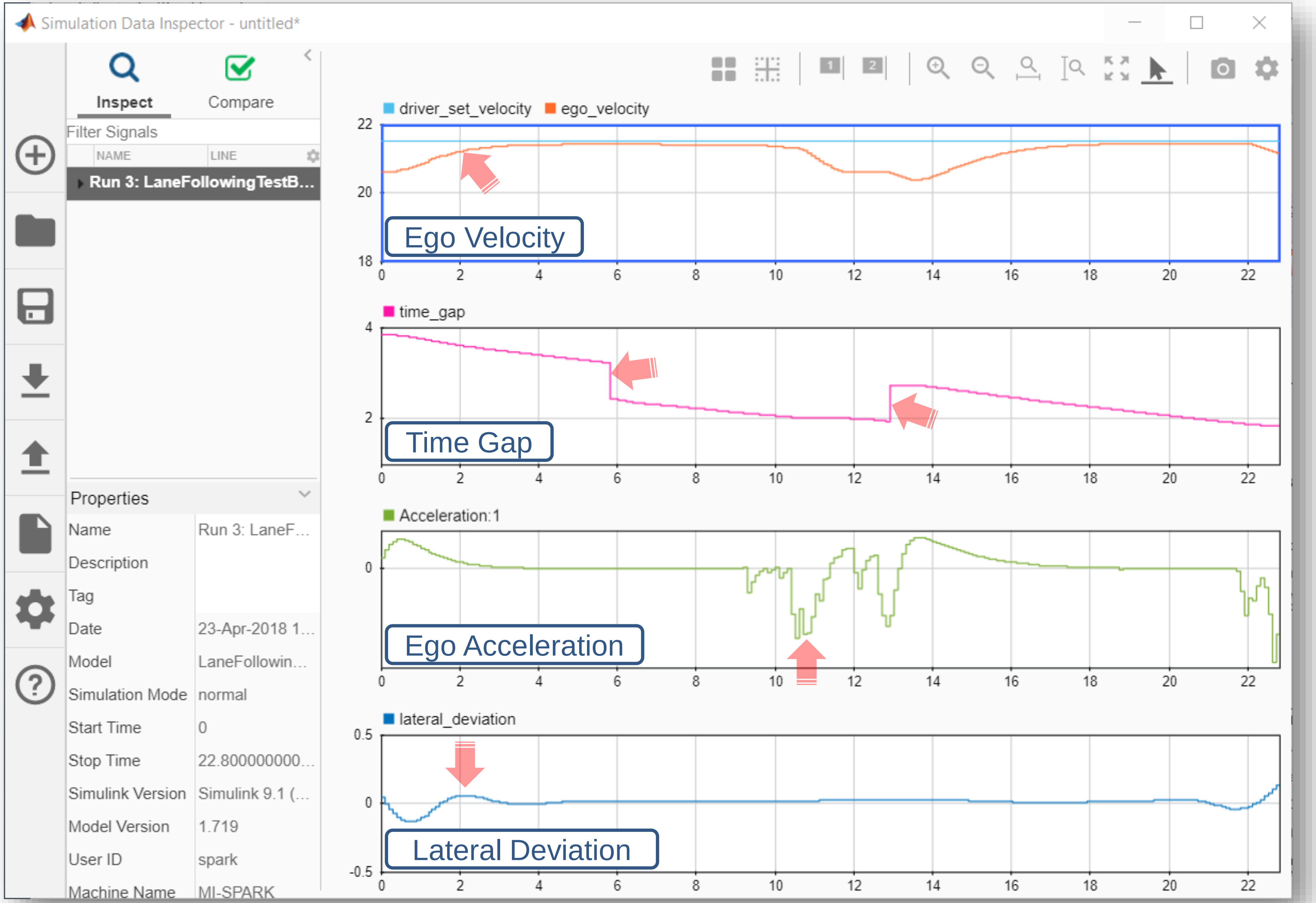
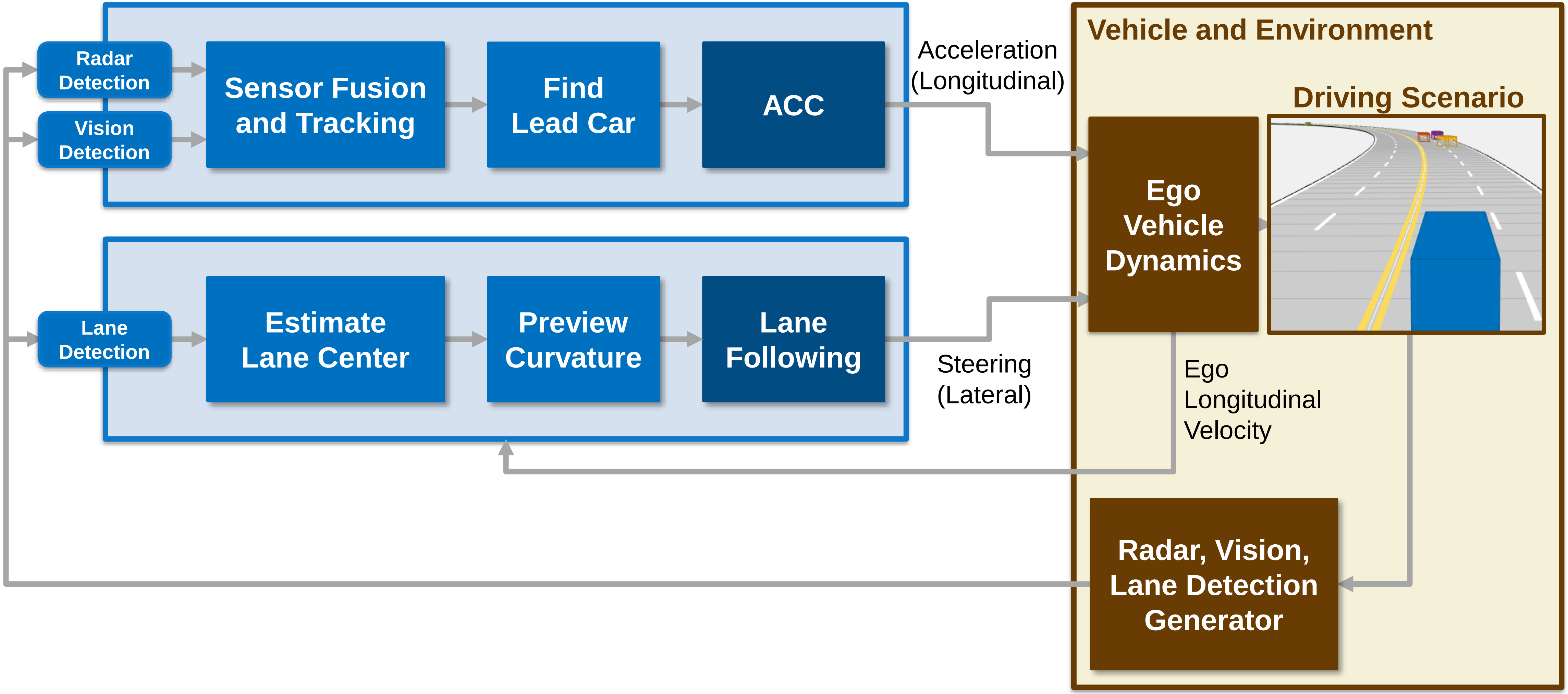


Architecture for ACC and Lane Following Controller



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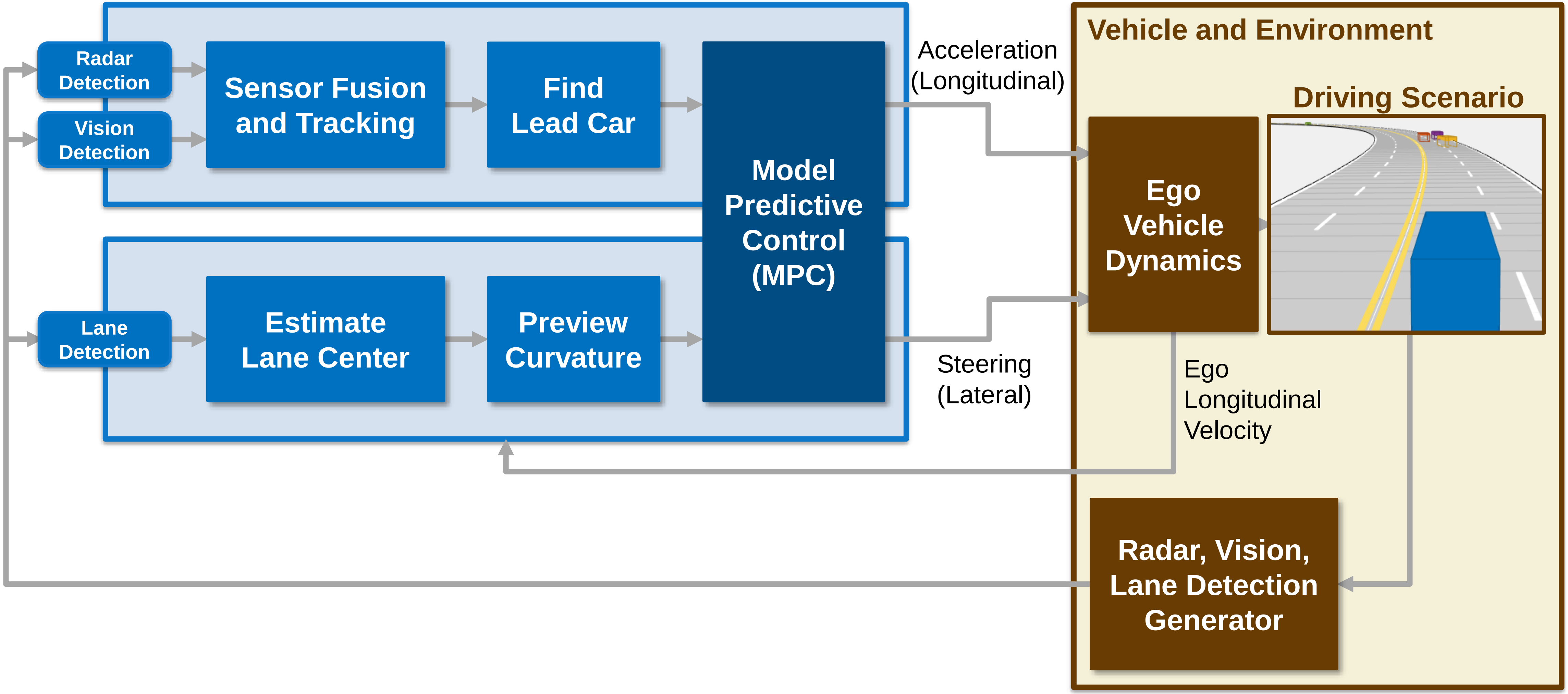
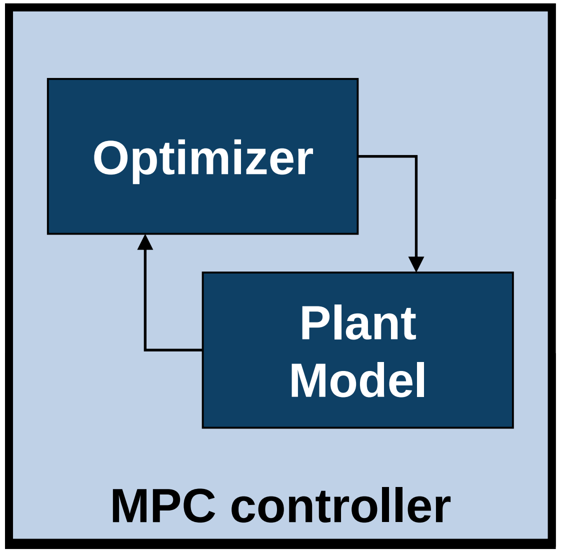


What is model predictive control (MPC)?

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

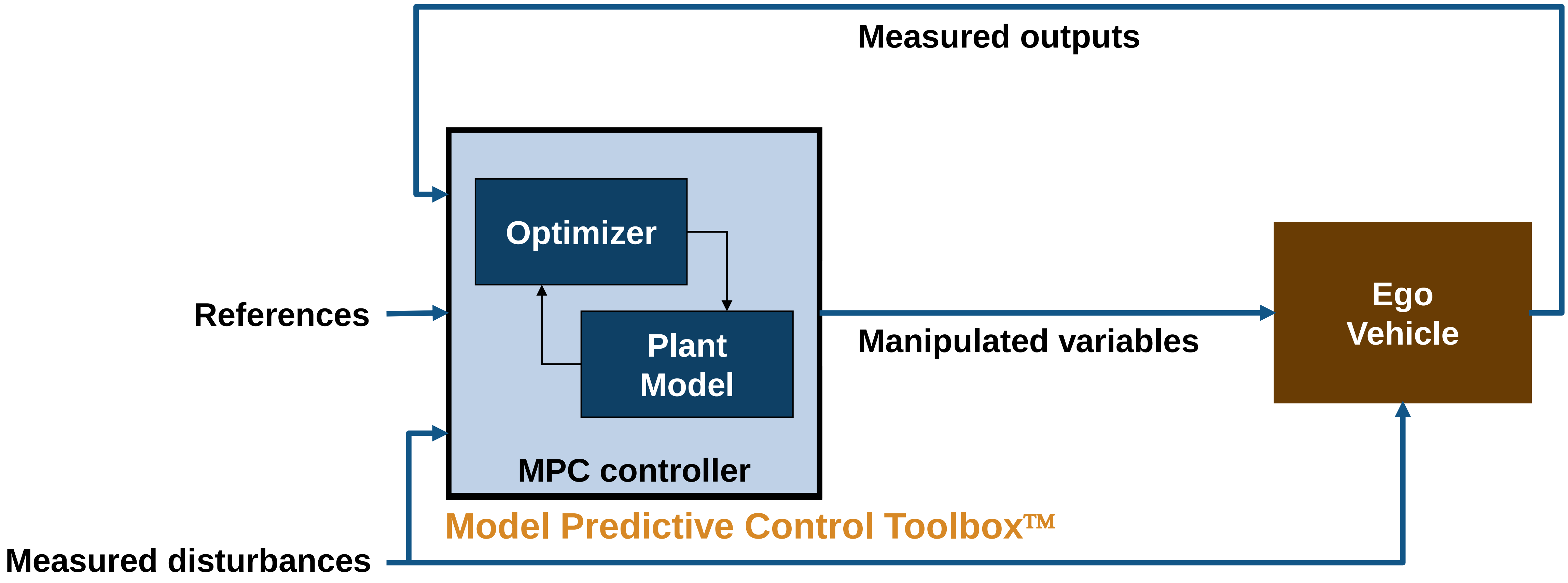
- **Optimizes** for the current timeslot while keeping future timeslots in account



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

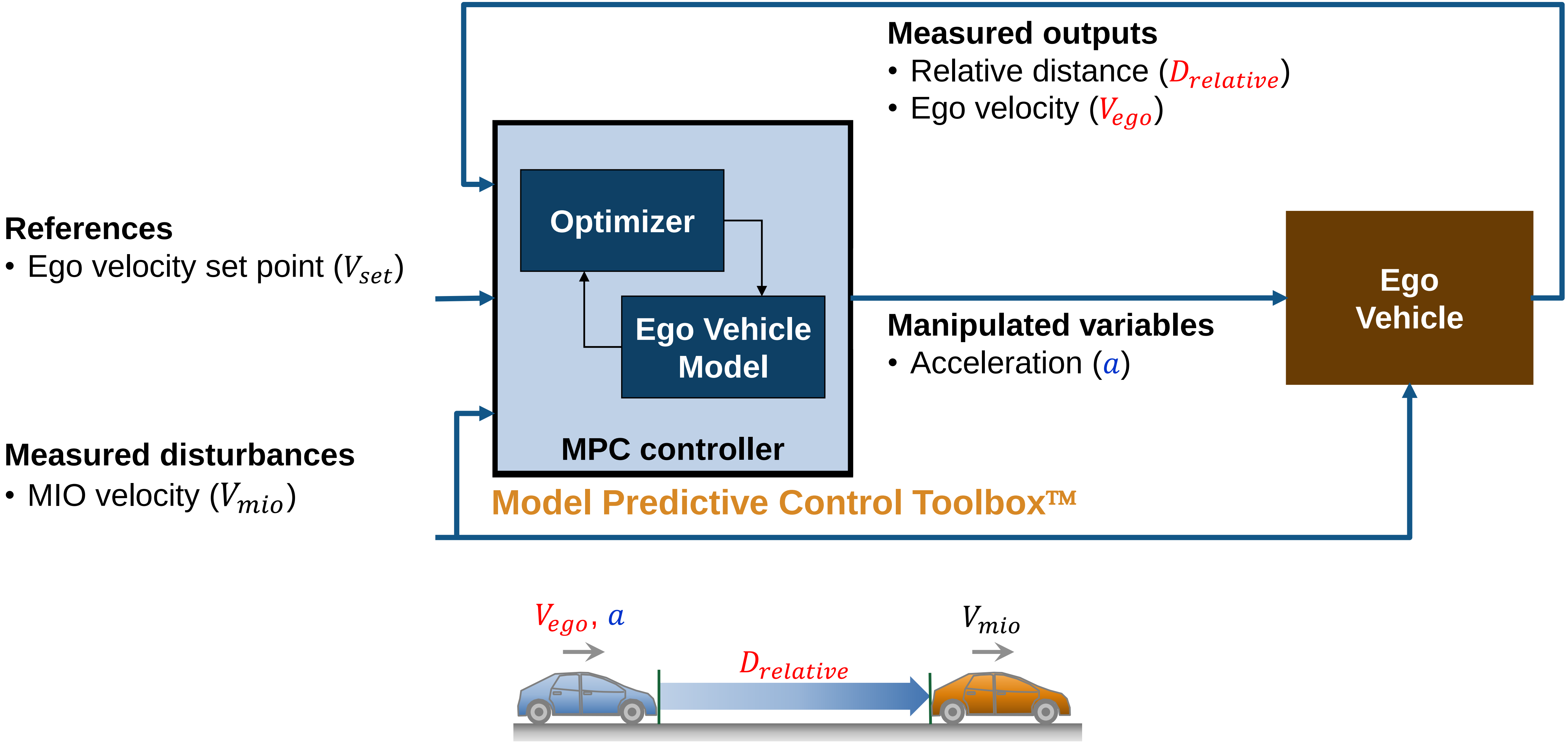
- **Gaining popularity in automated driving** applications to improve vehicle responsiveness while maintaining passenger comfort

What is model predictive control (MPC)?



Model Predictive Control Toolbox™

How can MPC be applied to ACC?



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:

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

Optimizer

Ego Vehicle Model

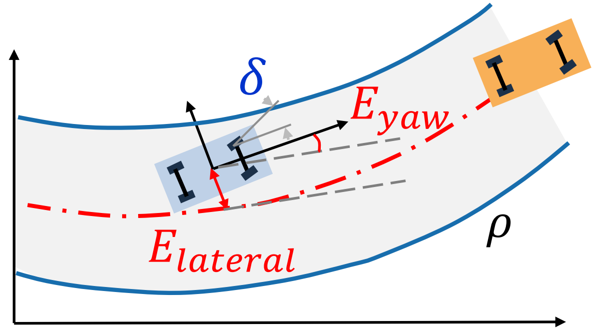
MPC controller

Model Predictive Control Toolbox™

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

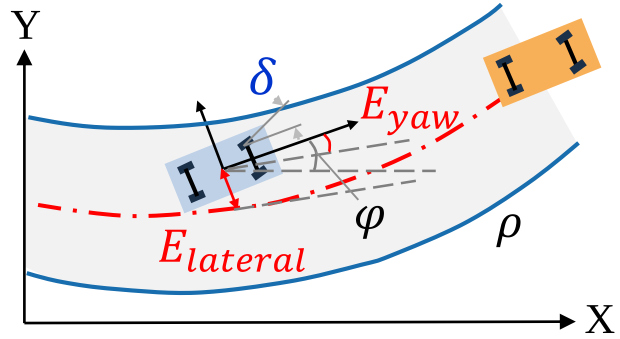


Internal MPC model for ACC and Lane Following Controller

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

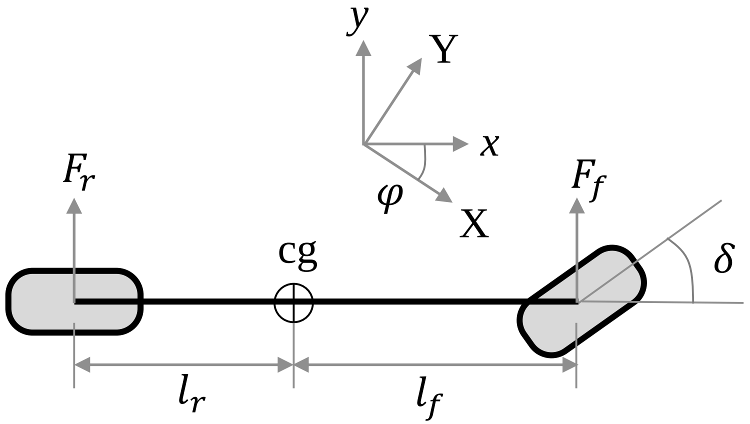
$$\frac{d}{dt}\begin{bmatrix}\dot{V}_x\\ V_x\\ D_{relative}\end{bmatrix}=\begin{bmatrix}-\frac{1}{\tau}&0&0\\ 1&0&0\\ 0&-1&0\end{bmatrix}\begin{bmatrix}\dot{V}_x\\ V_x\\ D_{relative}\end{bmatrix}+\begin{bmatrix}\frac{1}{\tau}&0\\ 0&0\\ 0&1\end{bmatrix}\begin{bmatrix}a\\ V_{mio}\end{bmatrix}$$

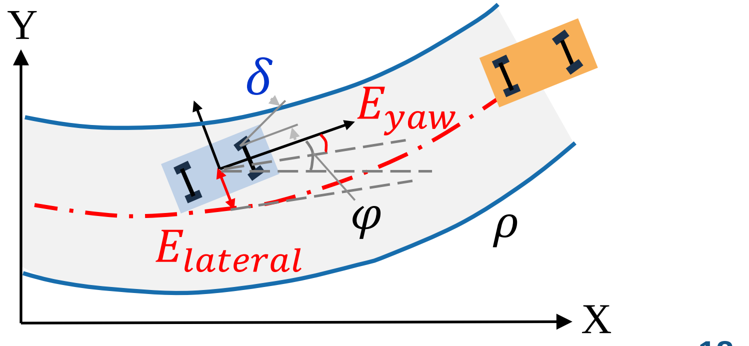
$$\begin{bmatrix}D_{relative}\\ V_x\end{bmatrix}=\begin{bmatrix}0&0&1\\ 0&1&0\end{bmatrix}\begin{bmatrix}\dot{V}_x\\ V_x\\ D_{relative}\end{bmatrix}$$

- Lateral Model for Lane Following

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

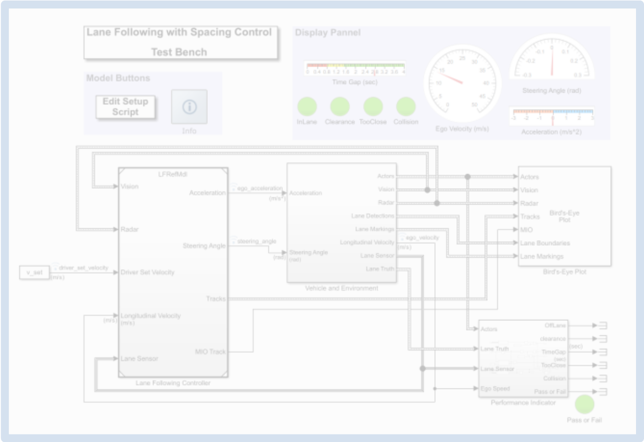
$$\begin{bmatrix}E_{lateral}\\ E_{yaw}\end{bmatrix}=\begin{bmatrix}0&0&1&0\\ 0&0&0&1\end{bmatrix}\begin{bmatrix}V_y\\ \dot{\varphi}\\ E_{lateral}\\ E_{yaw}\end{bmatrix}$$

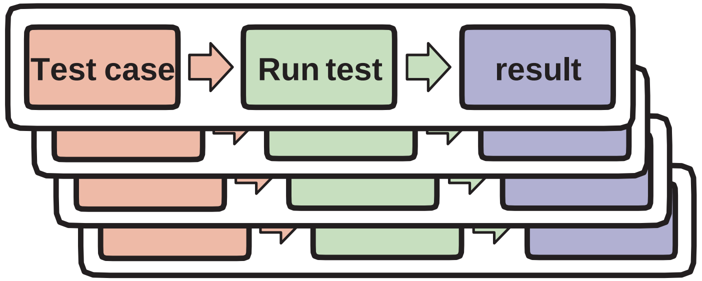


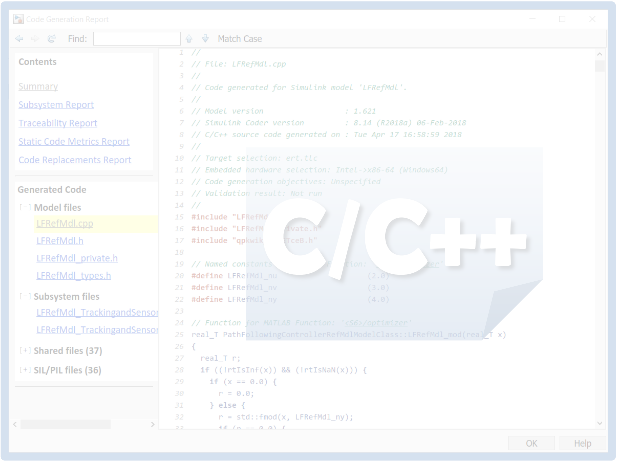


Automated Driving System Toolbox™

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







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Simulation result assessment

Test Description

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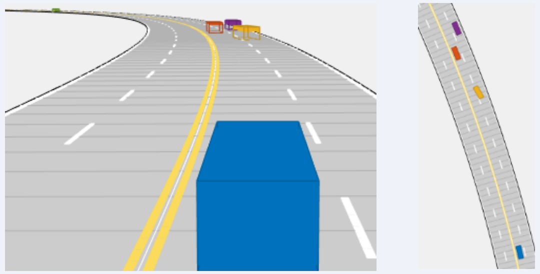

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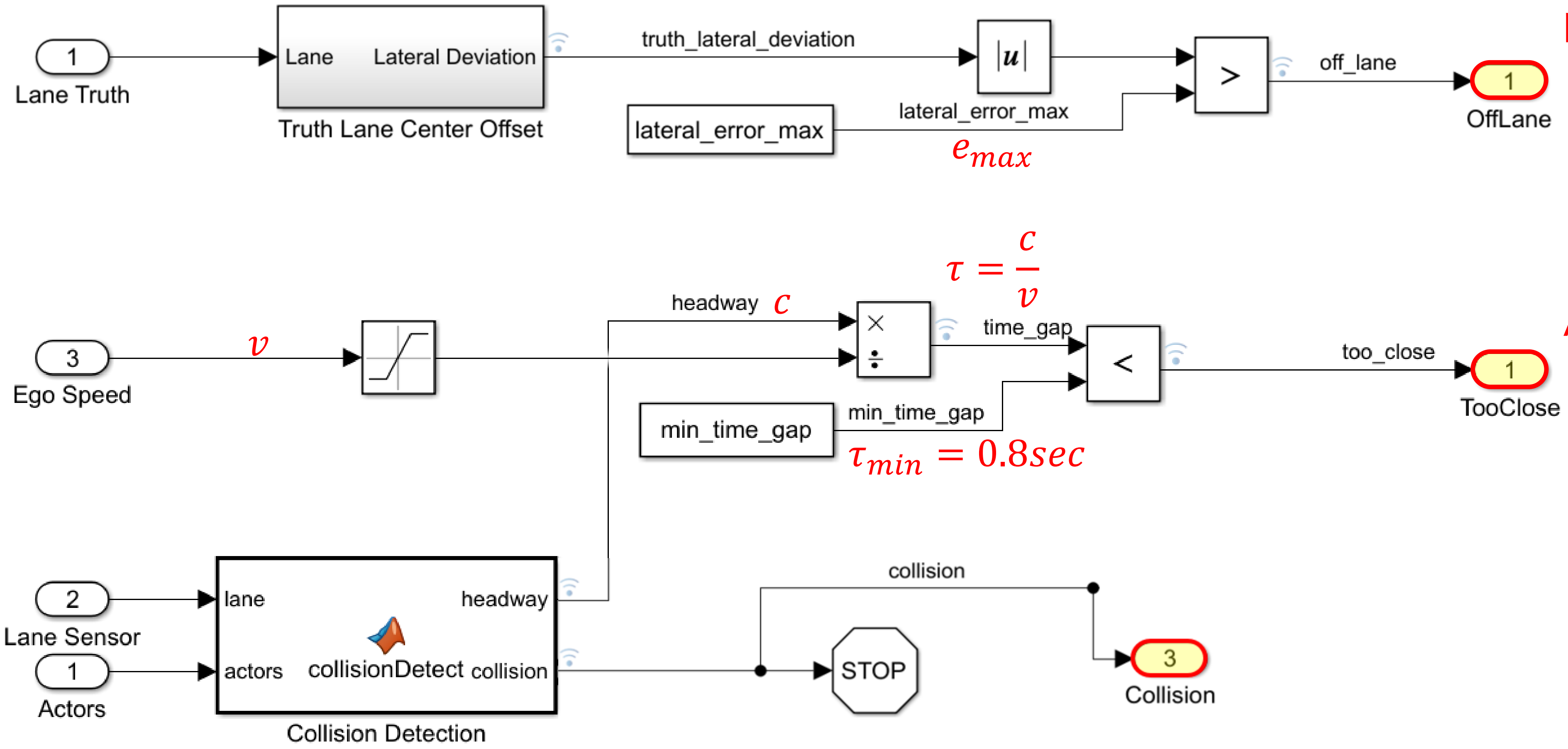
Third Car

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

Performance Indicator



e_{max}

v headway c

$\tau = \frac{c}{v}$

$\tau_{min} = 0.8sec$

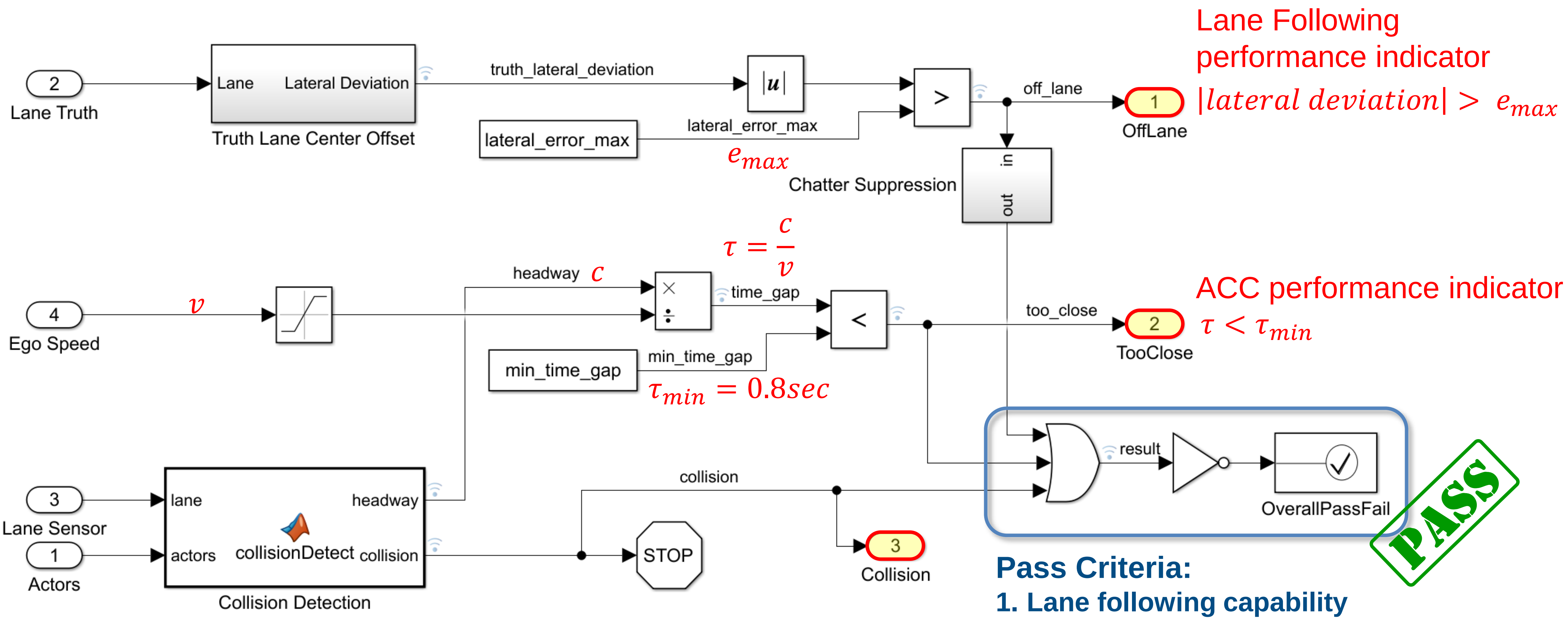
Lane Following performance indicator

$|lateral\ deviation| > e_{max}$

ACC performance indicator

$\tau < \tau_{min}$

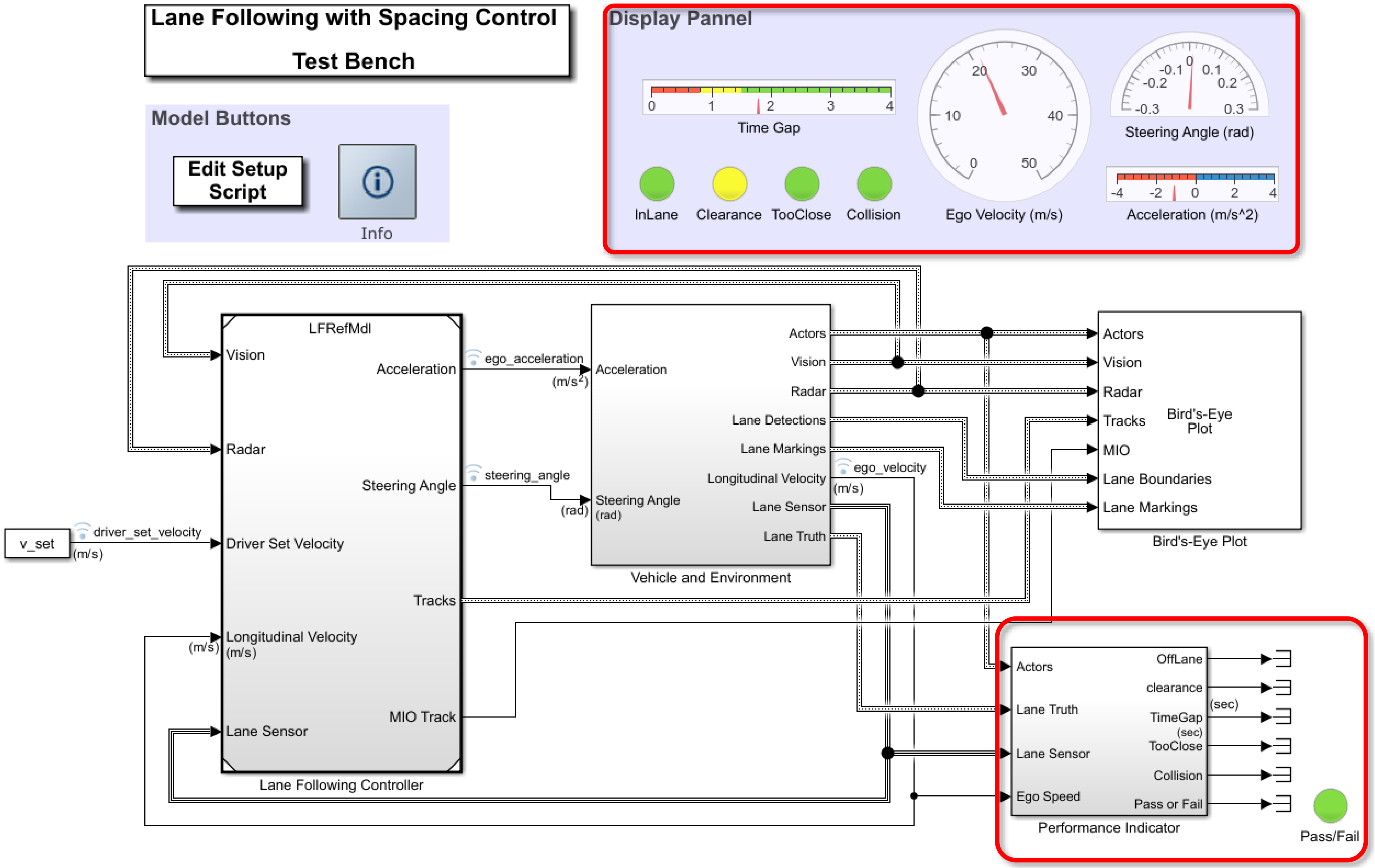
Performance Indicator



Pass Criteria:

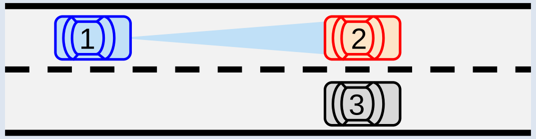
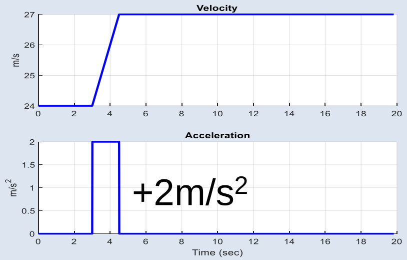
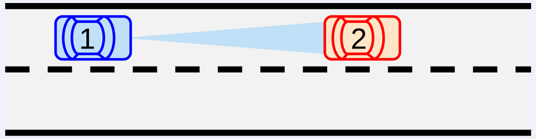
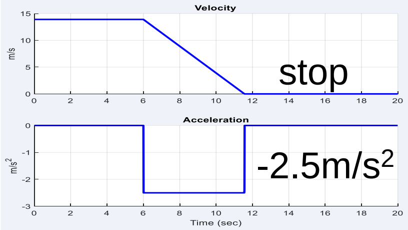
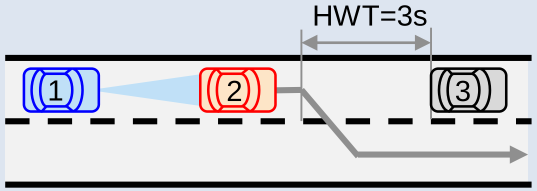
1. **Lane following capability**
2. **ACC space control capability**
3. **No collision detected**

Performance indicator and dashboard in Simulink model



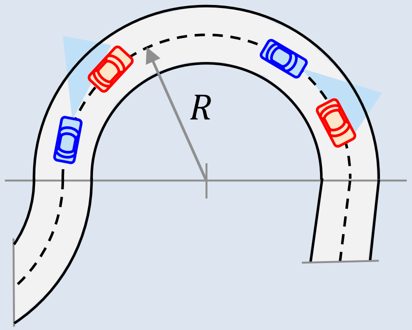
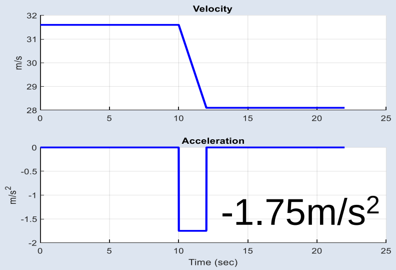
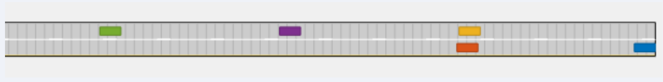
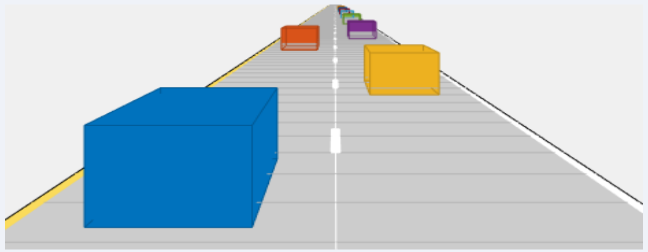
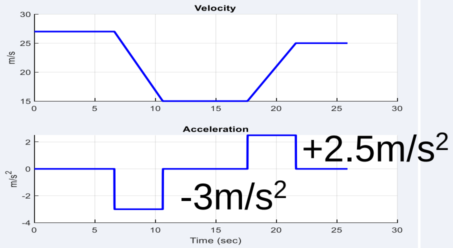
Test scenarios (1/4)

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

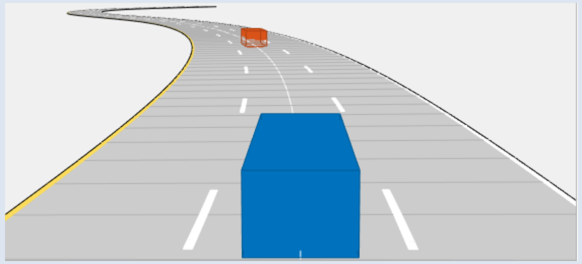
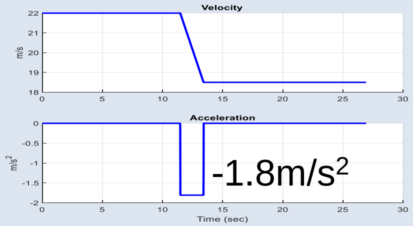
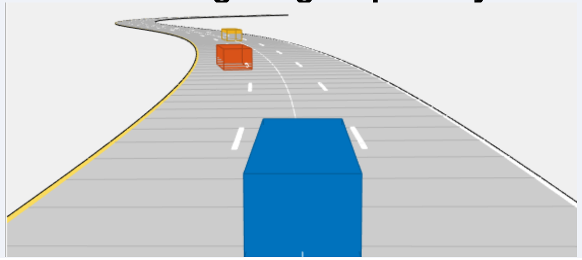
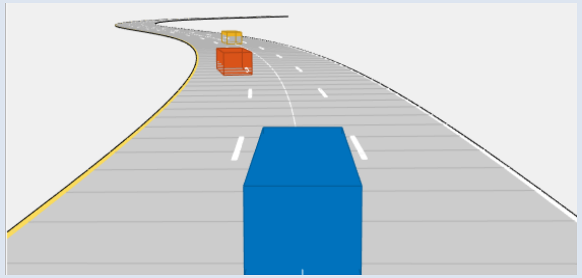
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

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

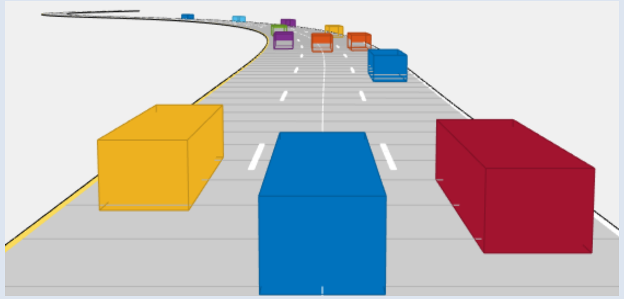
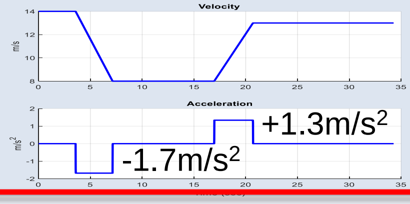
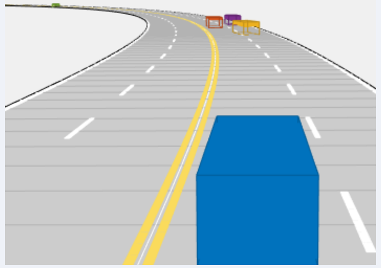
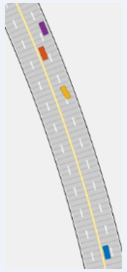
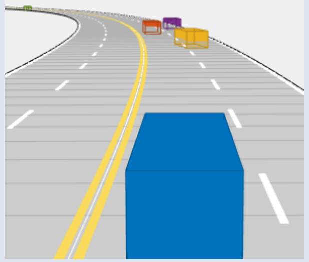
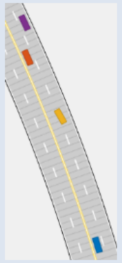
Test scenarios (3/4)

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

No	Test Name	Test Description	Host car	Lead car	Third car	Spec
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

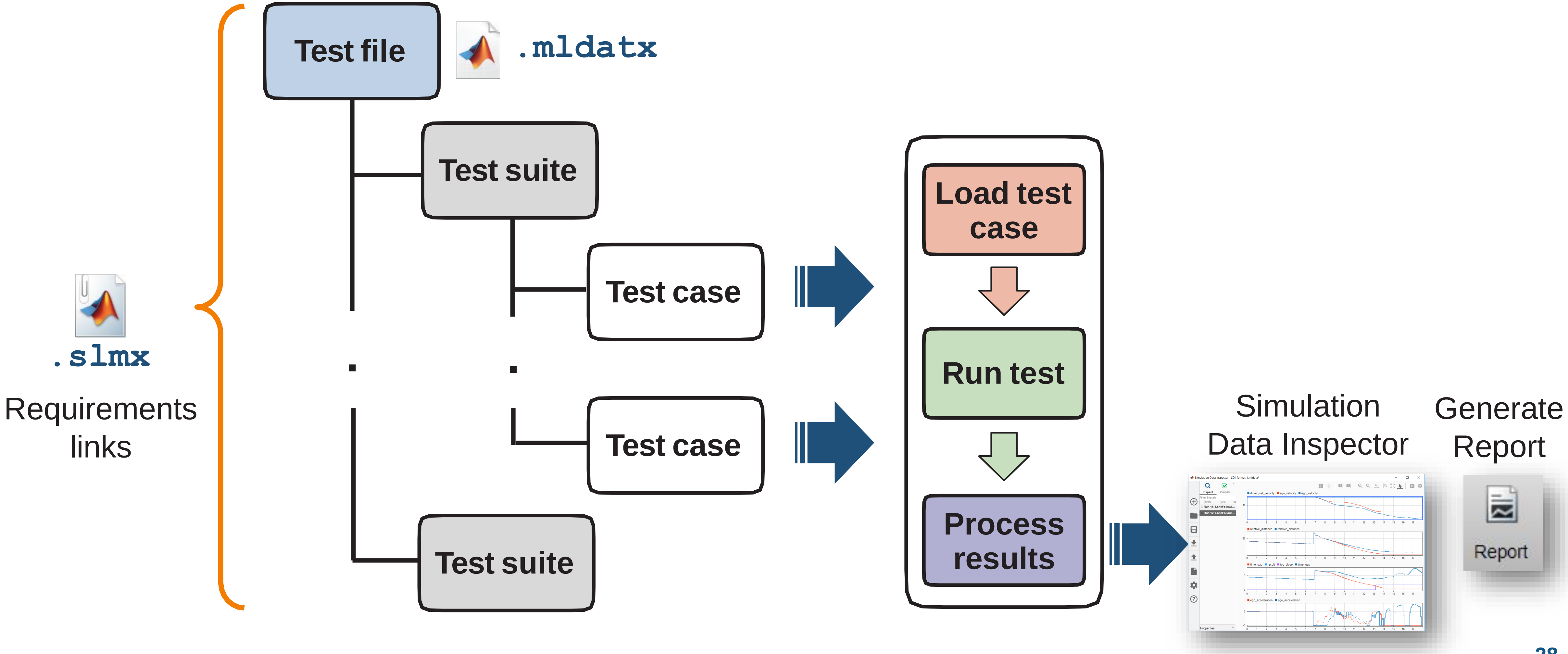
HW : Headway
HWT : Headway time
v_set : set velocity for ego car

Test scenarios (4/4)

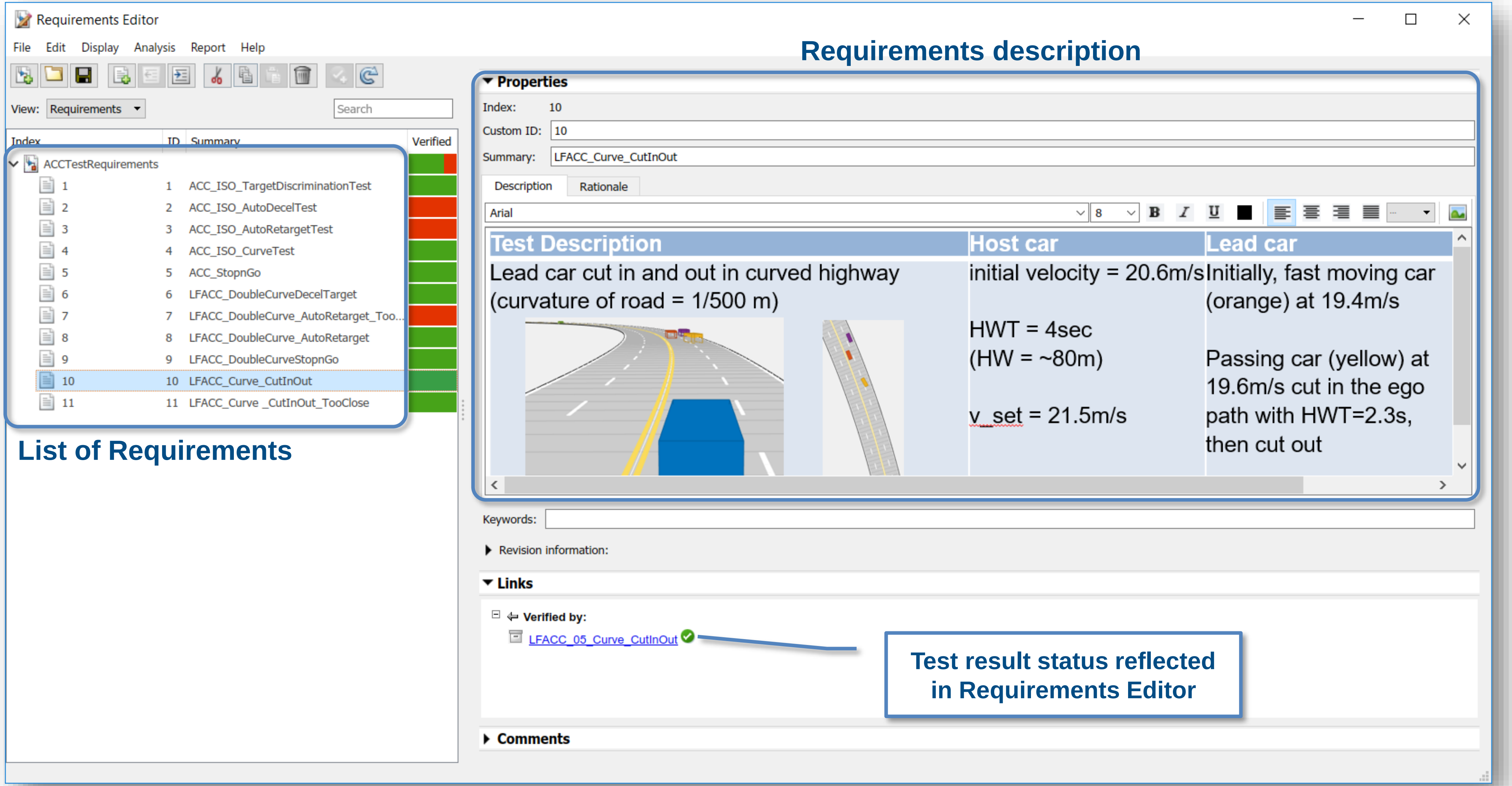
No	Test Name	Test Description	Host car	Lead car	Third car	Spec
9	LFACC_04_DoubleCurve _StopnGo (Similar with ACC_05_StopnGo)	**Stop and Go in curved highway** 	initial velocity = 14m/s HWT = 3.6sec (HW = 50m) v_set = 14m/s	initial velocity = 14m/s Lead car slows down to 8m/s at -1.7m/s^2 and stay constant for 10s, then speed up to 13m/s at 1.3m/s^2 	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 Representative test scenario	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

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

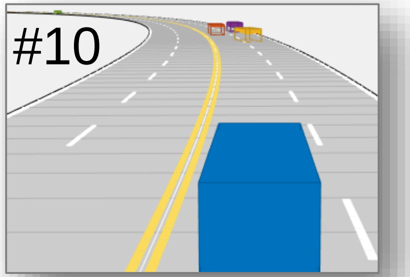
Report Generated by Test Manager

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.



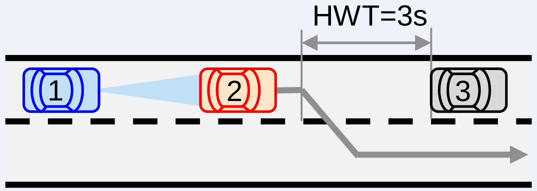
Summary

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

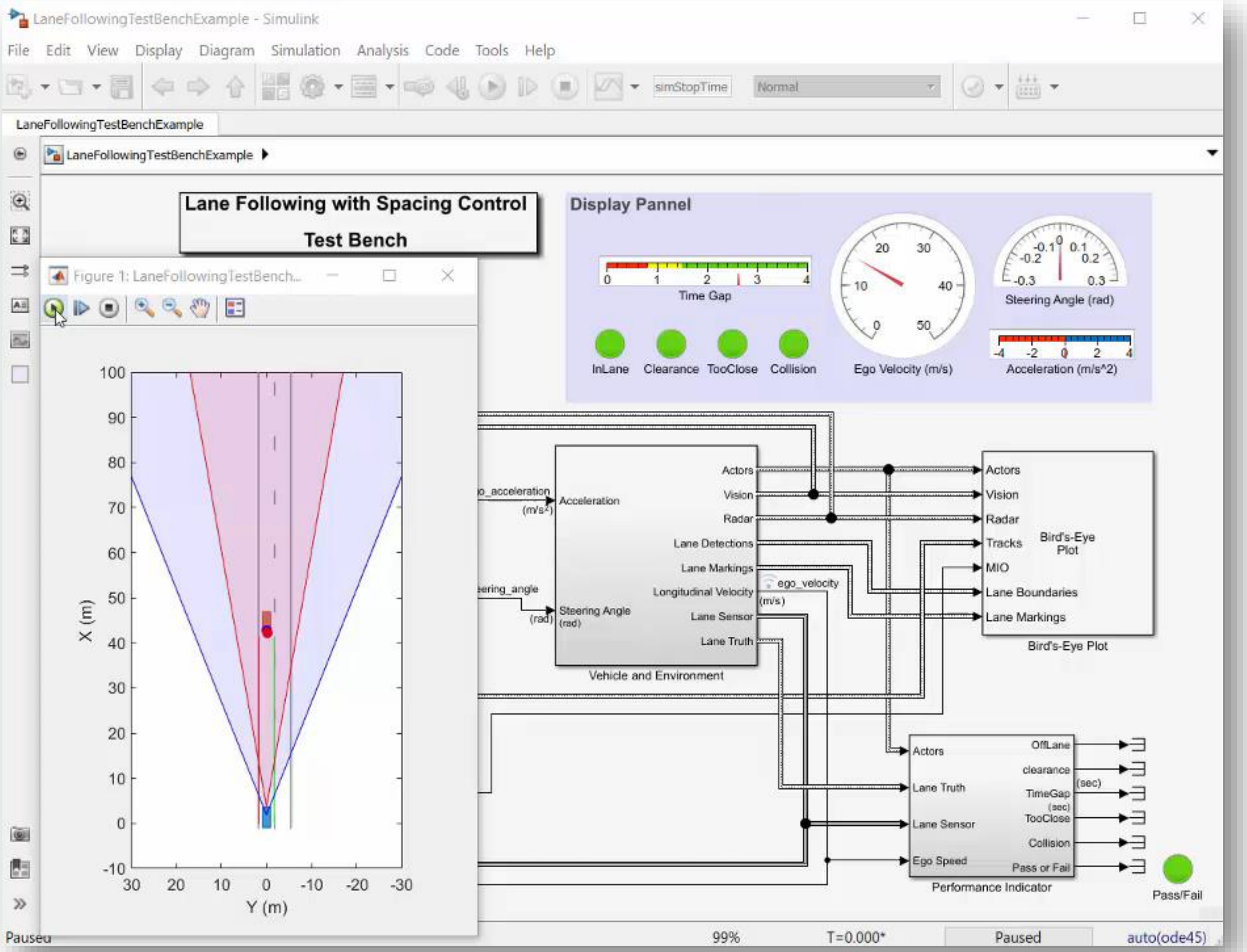
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

constant speed = 2.1m/s

Spec

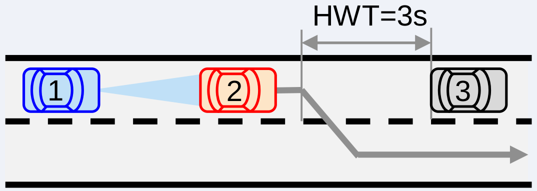
ISO 22178



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

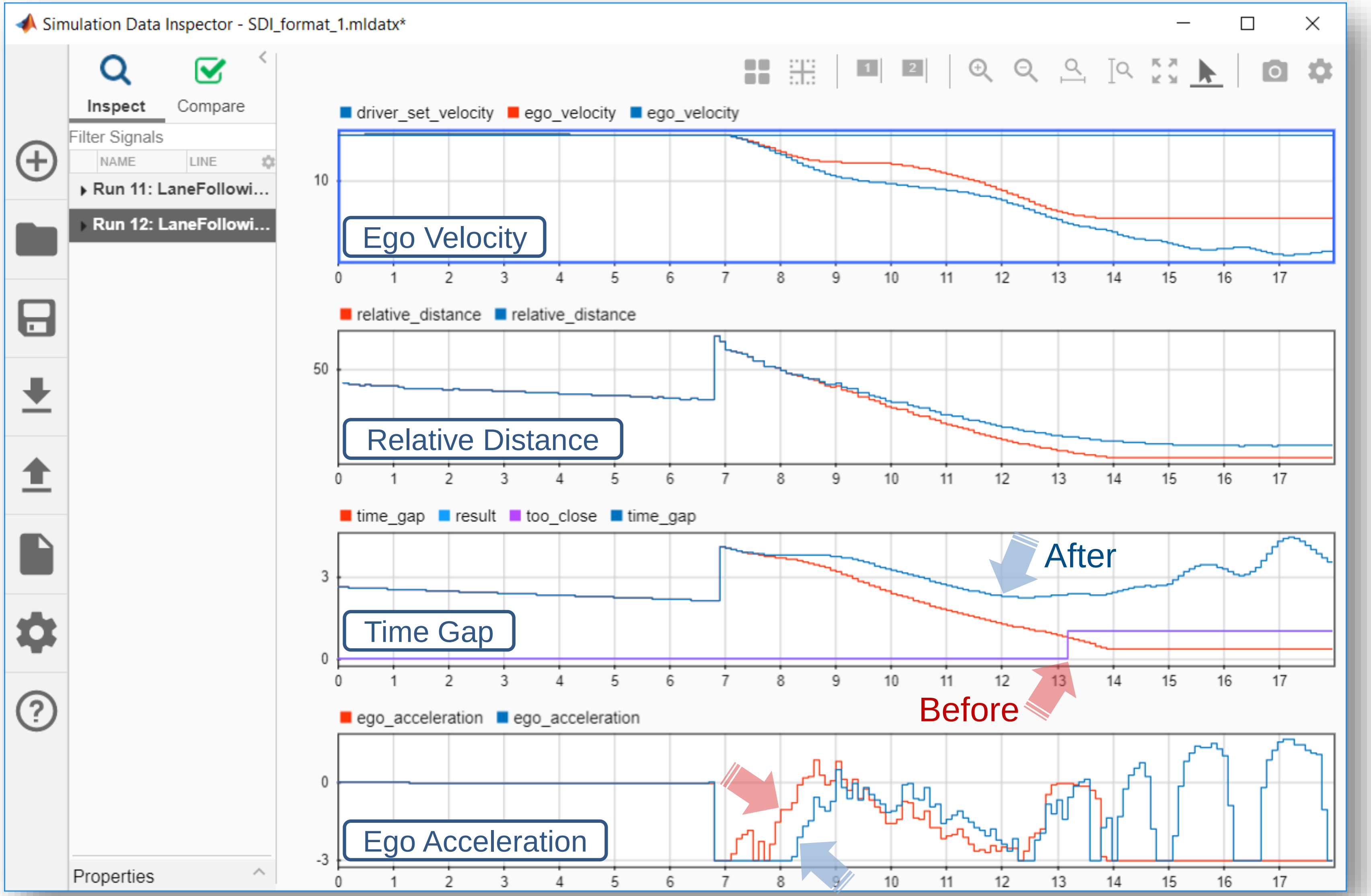
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

constant speed = 2.1m/s

Spec

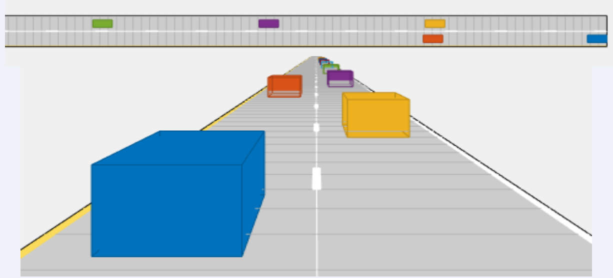
ISO 22178



Fine-tune control parameters (2/3)

Test Description

Stop and Go in highway



Host car

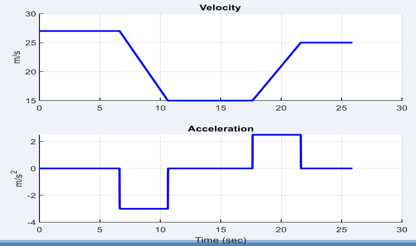
initial velocity = 27m/s

HWT = 1.5sec (HW = 40.5m)

v_set = 27m/s

Lead Car

initial velocity = 27m/s



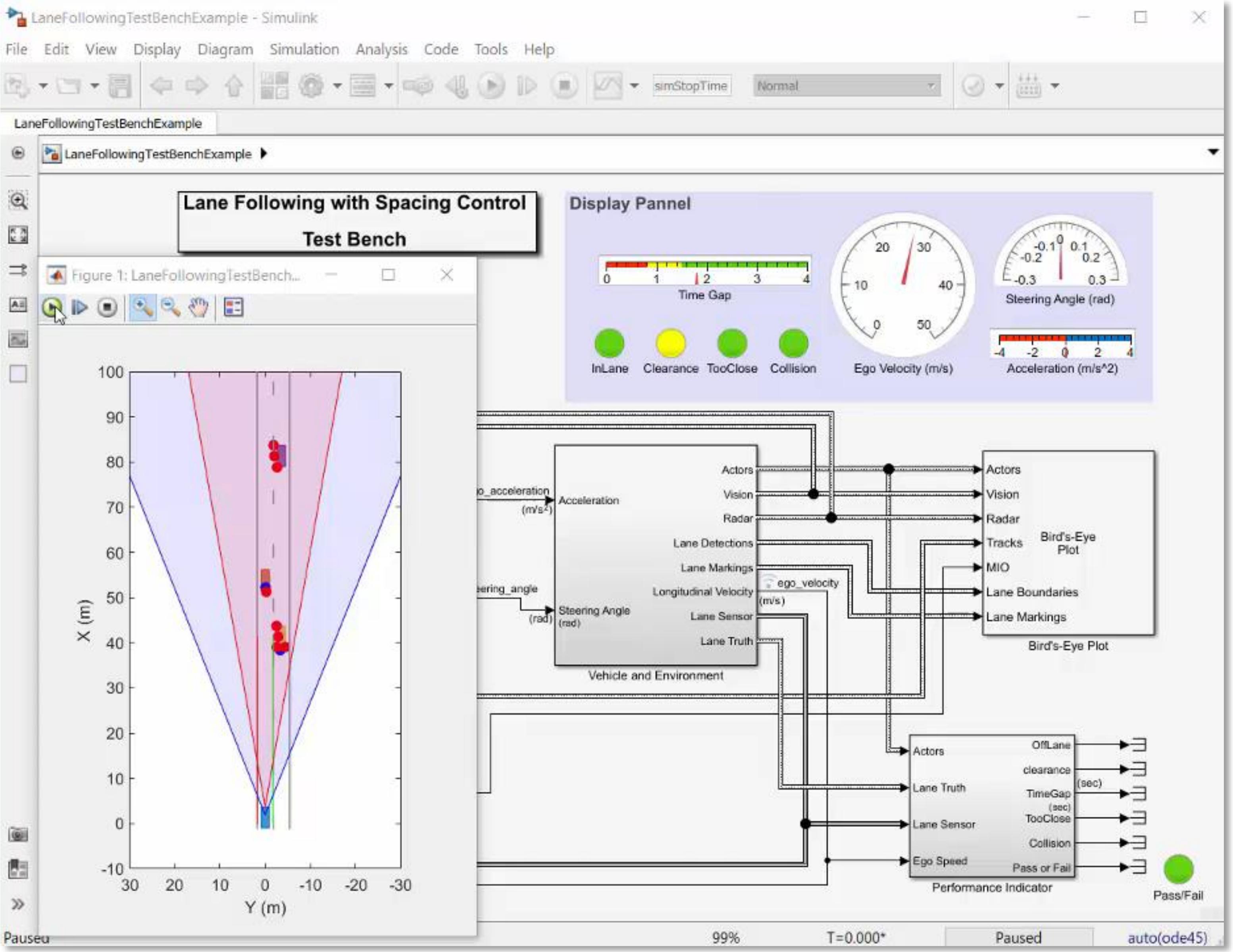
Third Car

8 slow moving cars at 12m/s

in the second lane

Spec

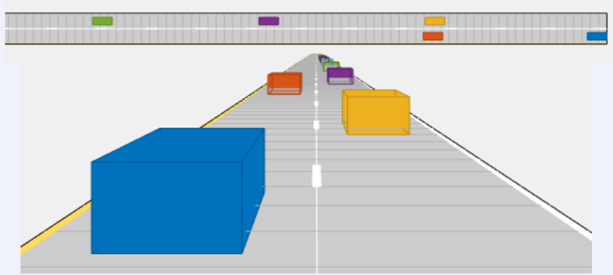
Real-world scenario



Fine-tune control parameters (2/3)

Test Description

Stop and Go in highway



Host car

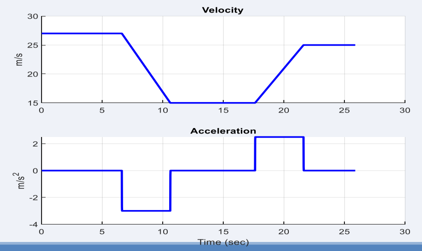
initial velocity = 27m/s

HWT = 1.5sec (HW = 40.5m)

v_set = 27m/s

Lead Car

initial velocity = 27m/s

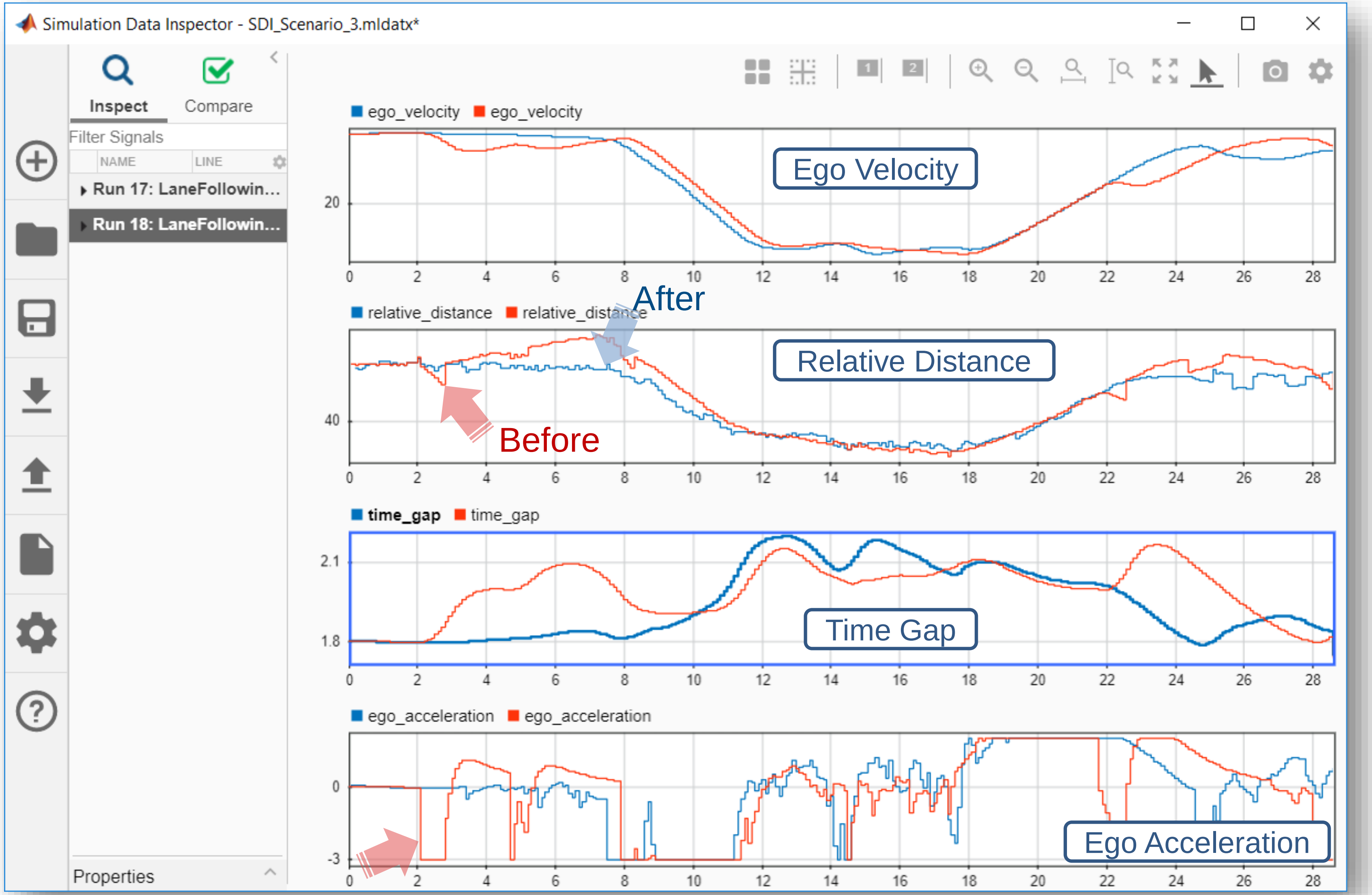


Third Car

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

Spec

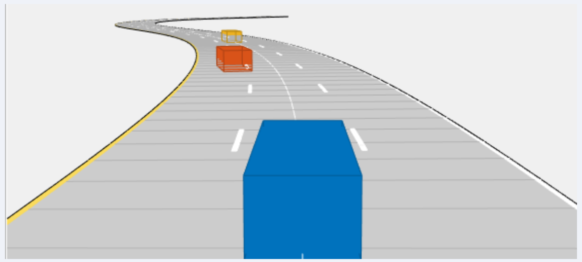
Real-world scenario



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

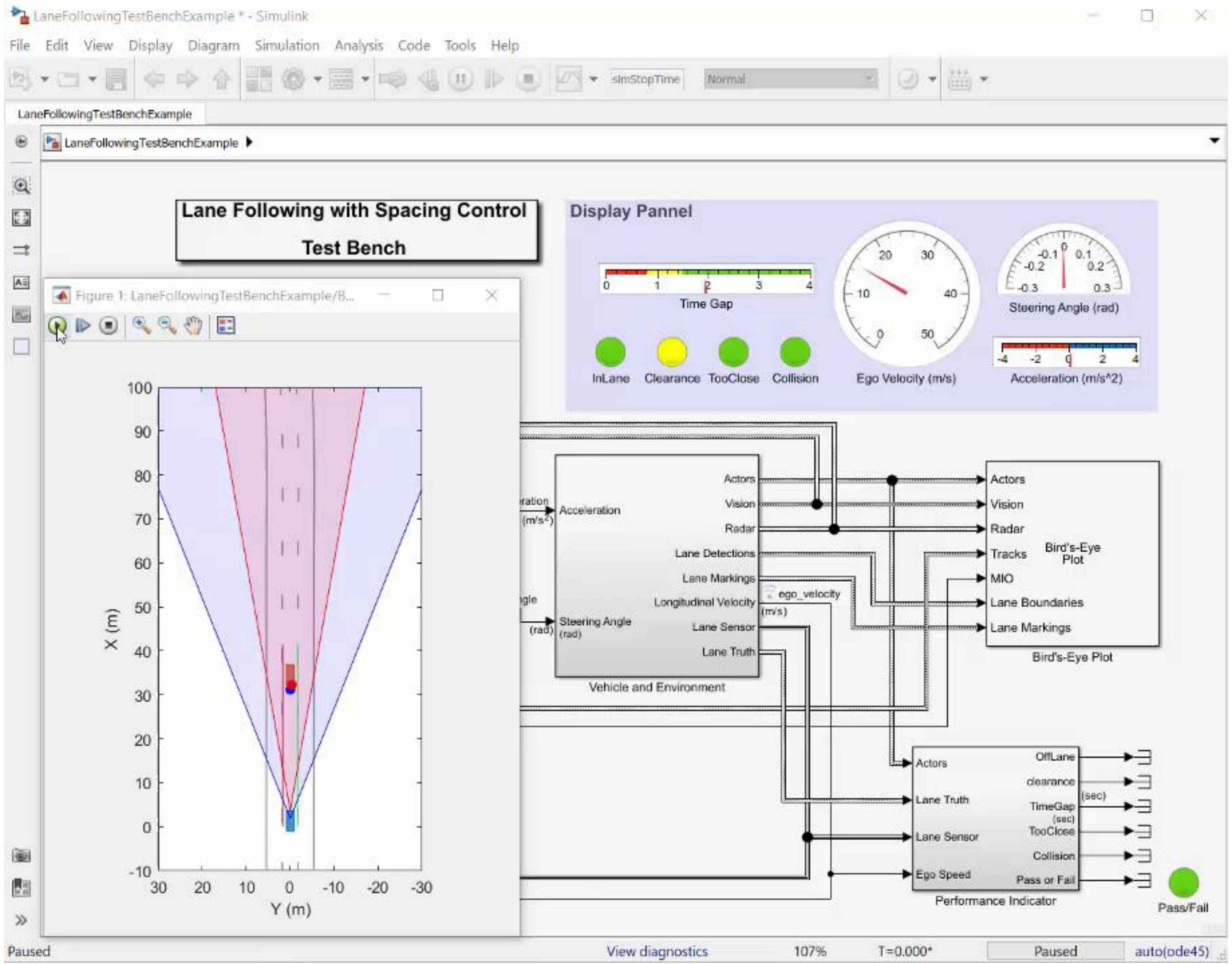
Lead car changes lane @ HWT=3s to overtake slow moving car

Third Car

Slow moving car at constant speed, 2.1m/s

Spec

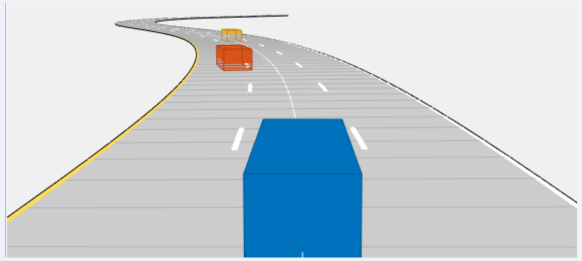
~ISO 22178



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

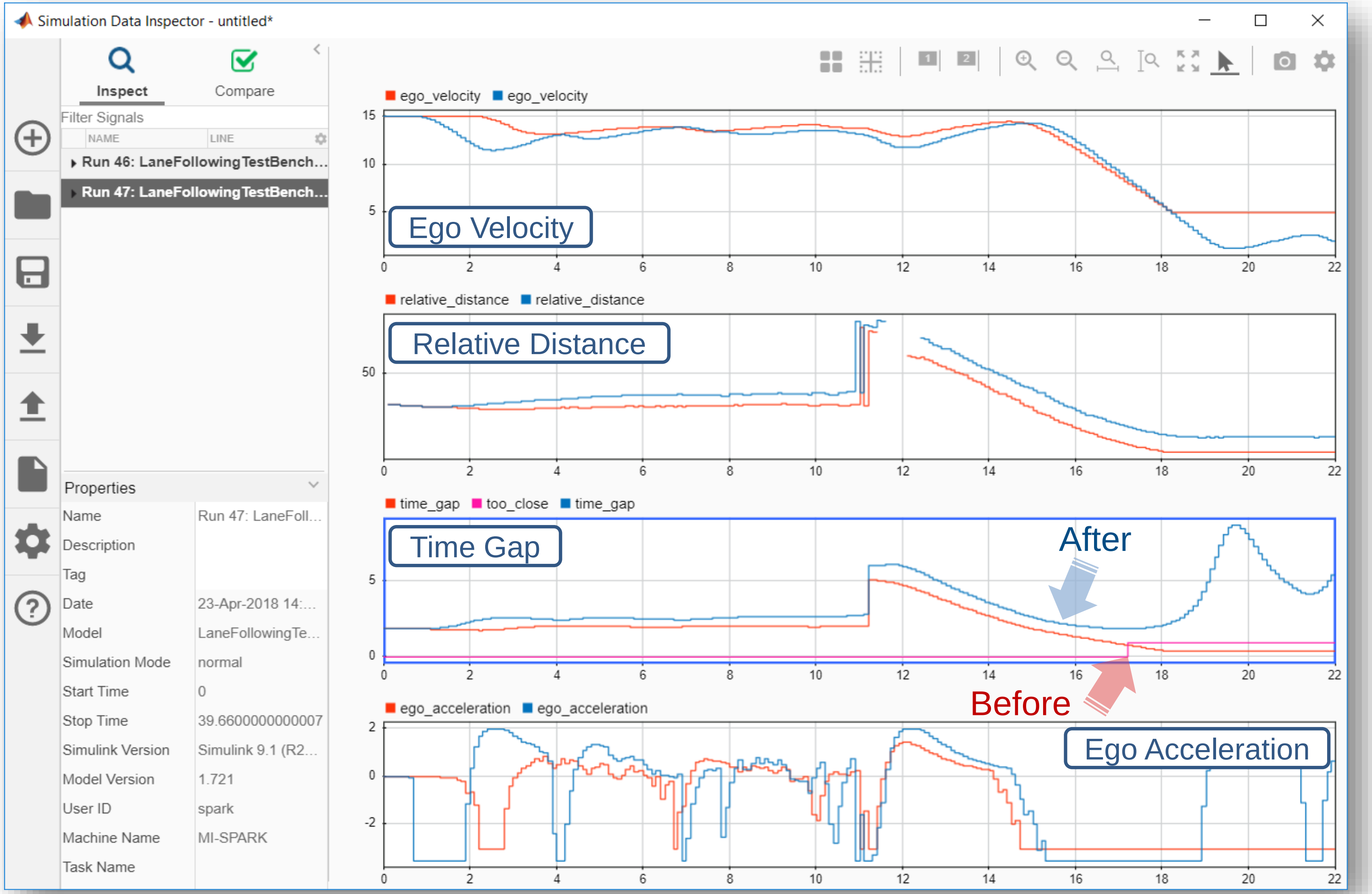
Lead car changes lane @ HWT=3s to overtake slow moving car

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

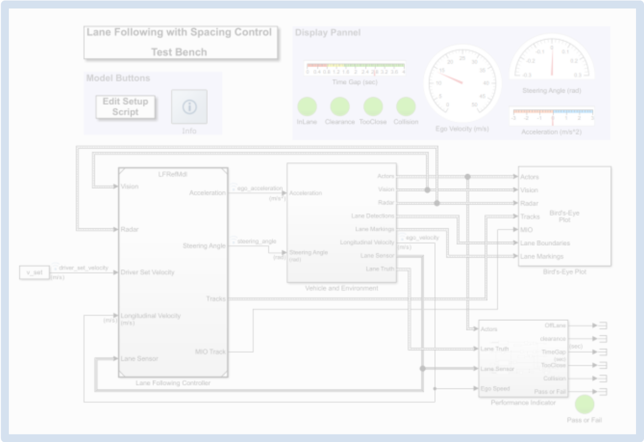
Platform: PCWIN64
MATLAB: (R2018a)

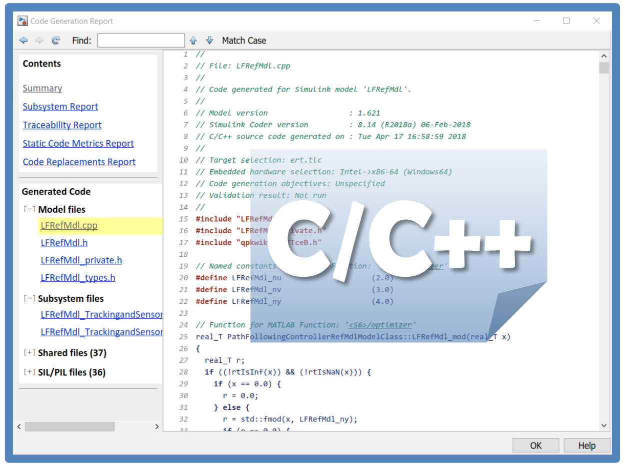
Summary

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

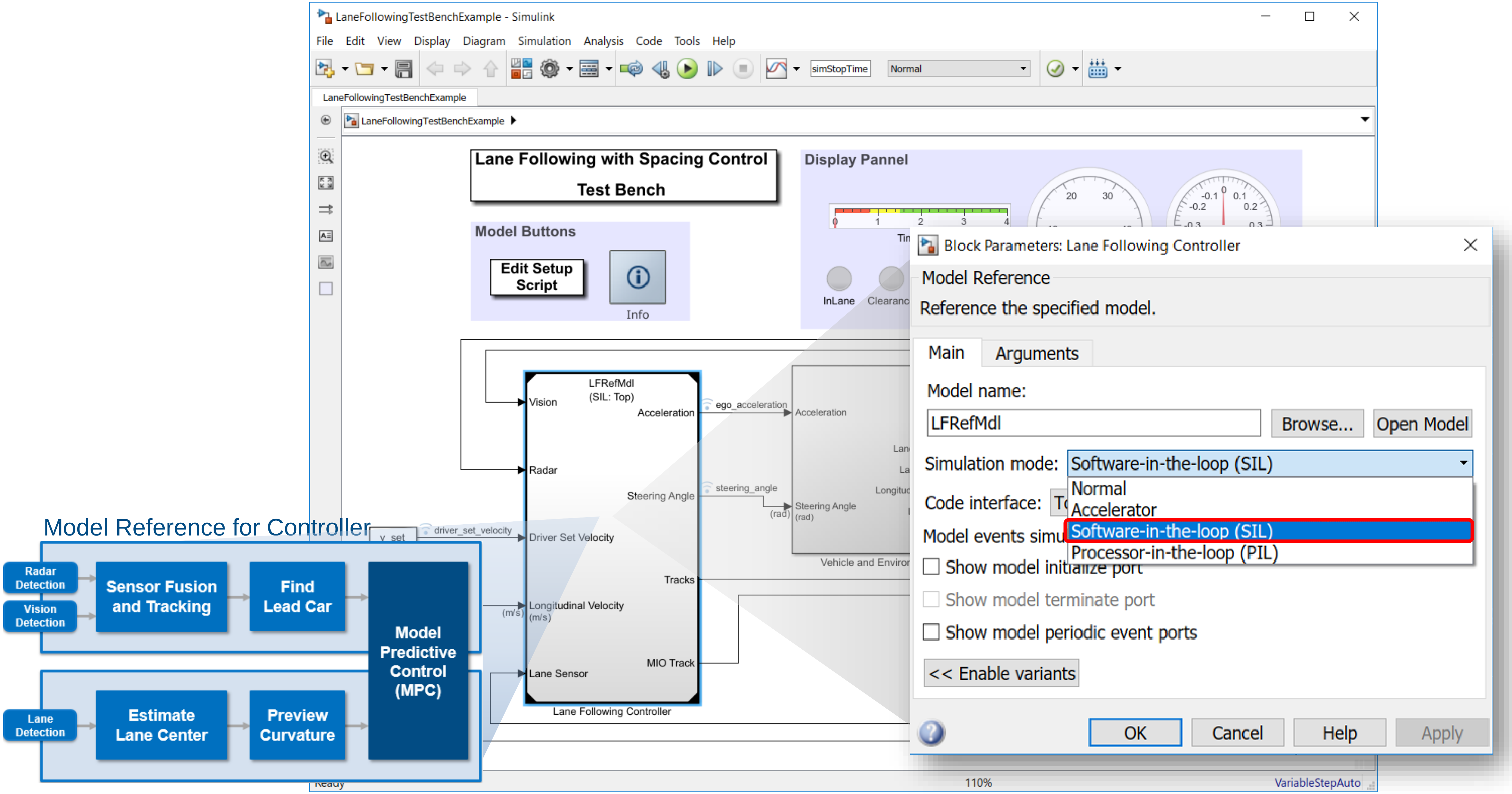
Automate Regression Test

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

Generate and Verify Code

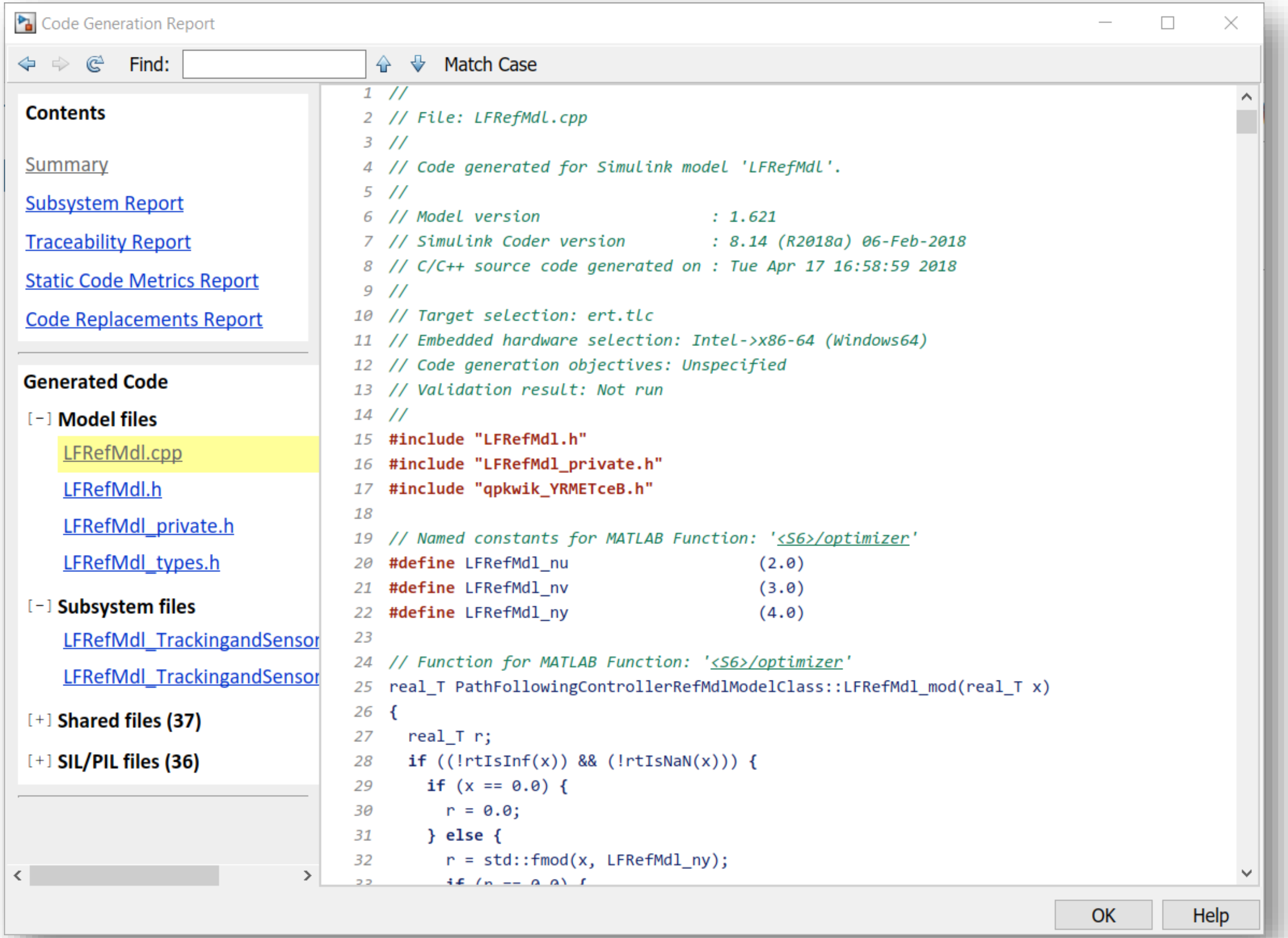
- SIL test
- Code generation
- Coverage test

Simulation with SIL mode



Code Generation Report

Embedded Coder™



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

Summary By Mo

Model Object


```
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:

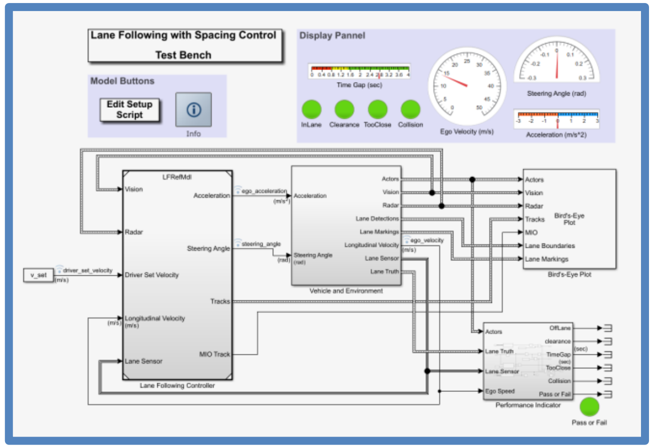
Description:	True	False
track->pUsedHistoryLength < track->ConfirmationParameters[1]	0	13038
rtIsNaN(track->ConfirmationParameters[1])	0	13038

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

Design and Test Traffic Jam Assist

A Case study Using **• Automated Driving System Toolbox™ • MPC Toolbox™ • VDBS™ • Simulink™ • Simulink Test™ • Simulink Control Design™ • Embedded Coder™**



Design ACC and Lane Following Controller

- Create driving scenario
- Synthesize sensor detection
- Include Vehicle Dynamics
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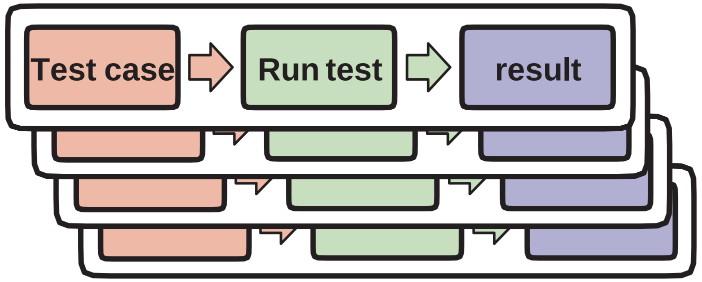
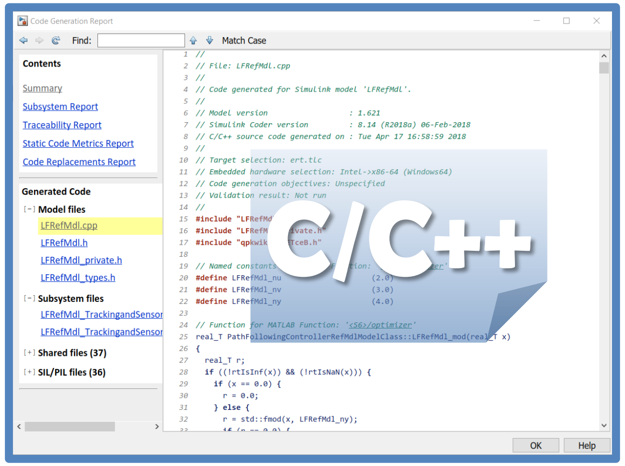


Automate Regression Test

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

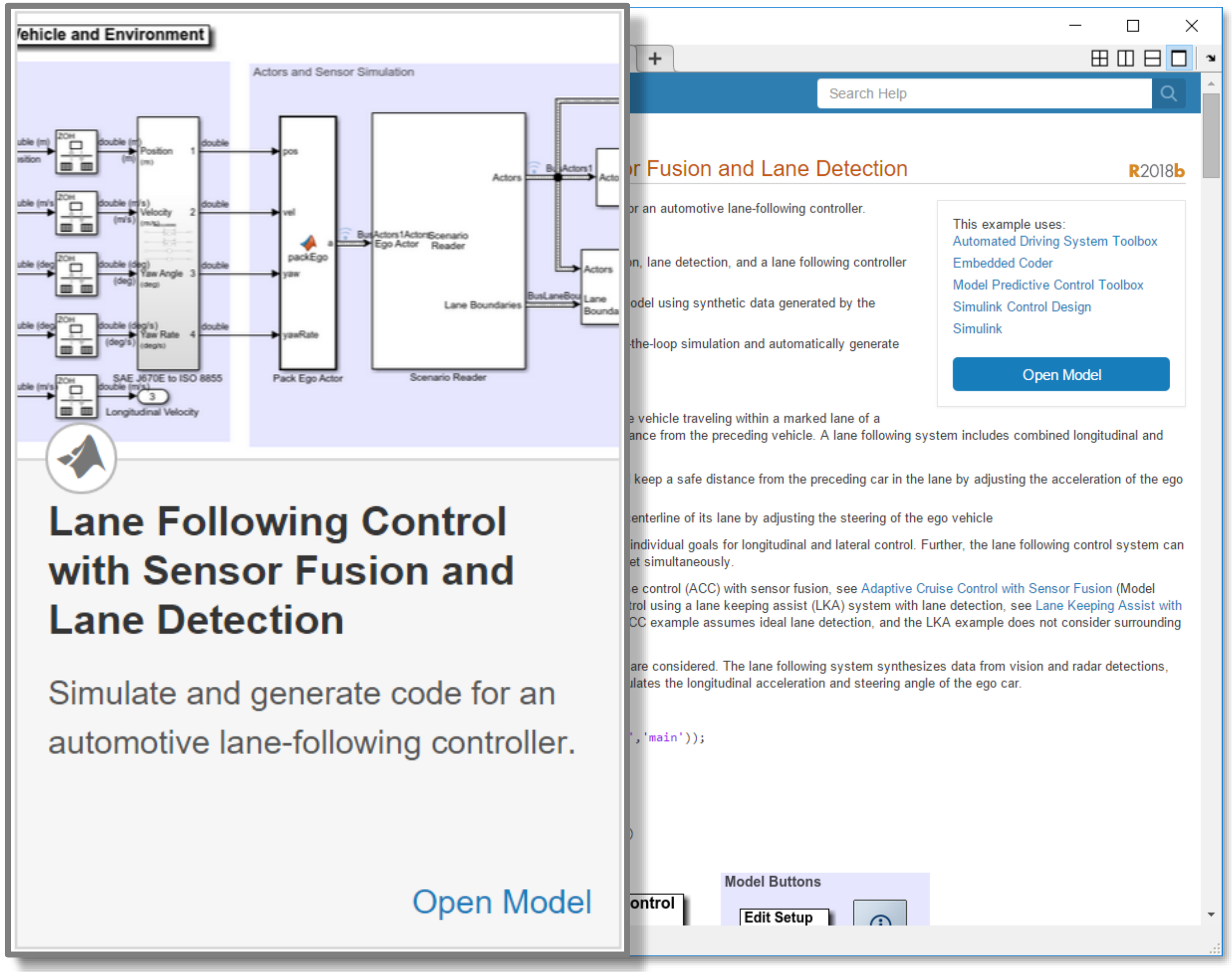


Generate and Verify Code

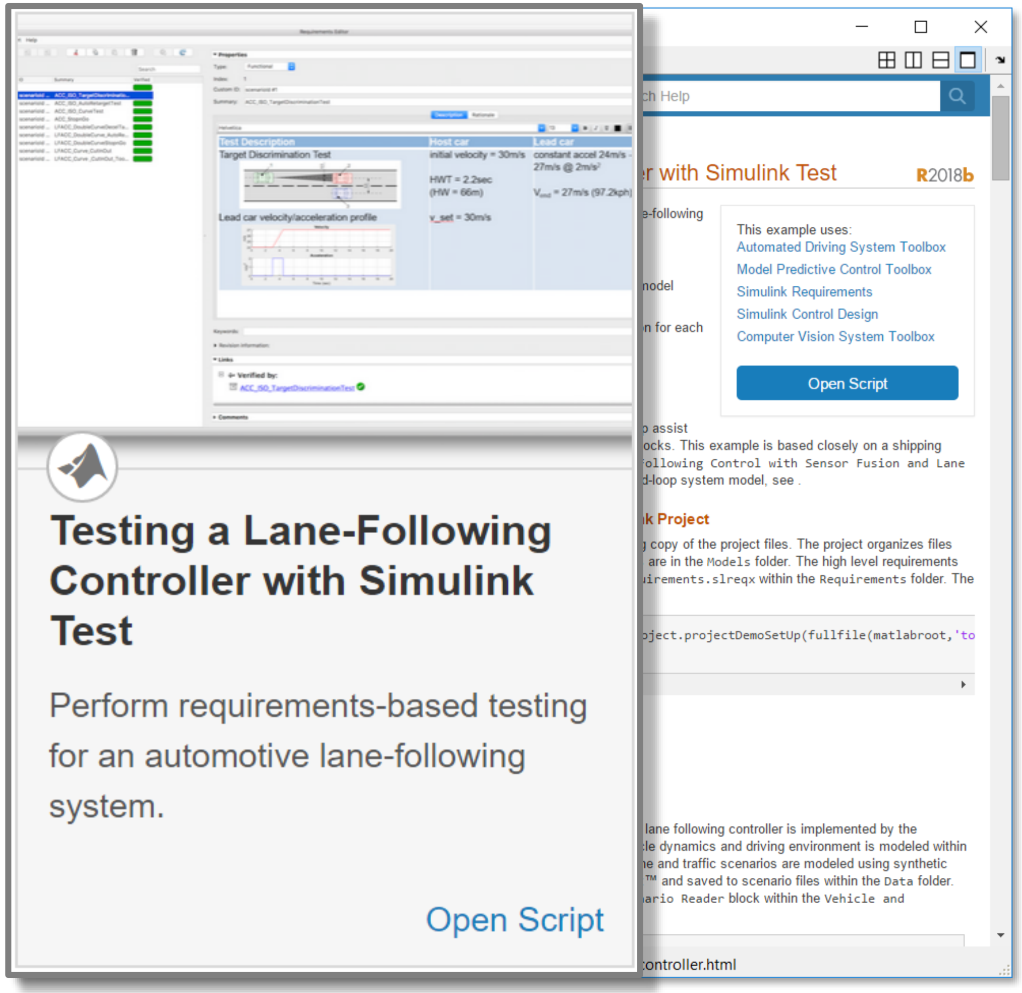
- SIL test
- Code generation
- Coverage test

Learn more about Traffic Jam Assist (Lane Following Control) by exploring examples in R2018b

Automated Driving System Toolbox™



Simulink Test™



Thank you for your attention !!

Email: seo-wook.park@mathworks.com