Automated Driving

with MATLAB® and Simulink®

Mark Corless
Automated Driving Segment Manager
Industry Marketing
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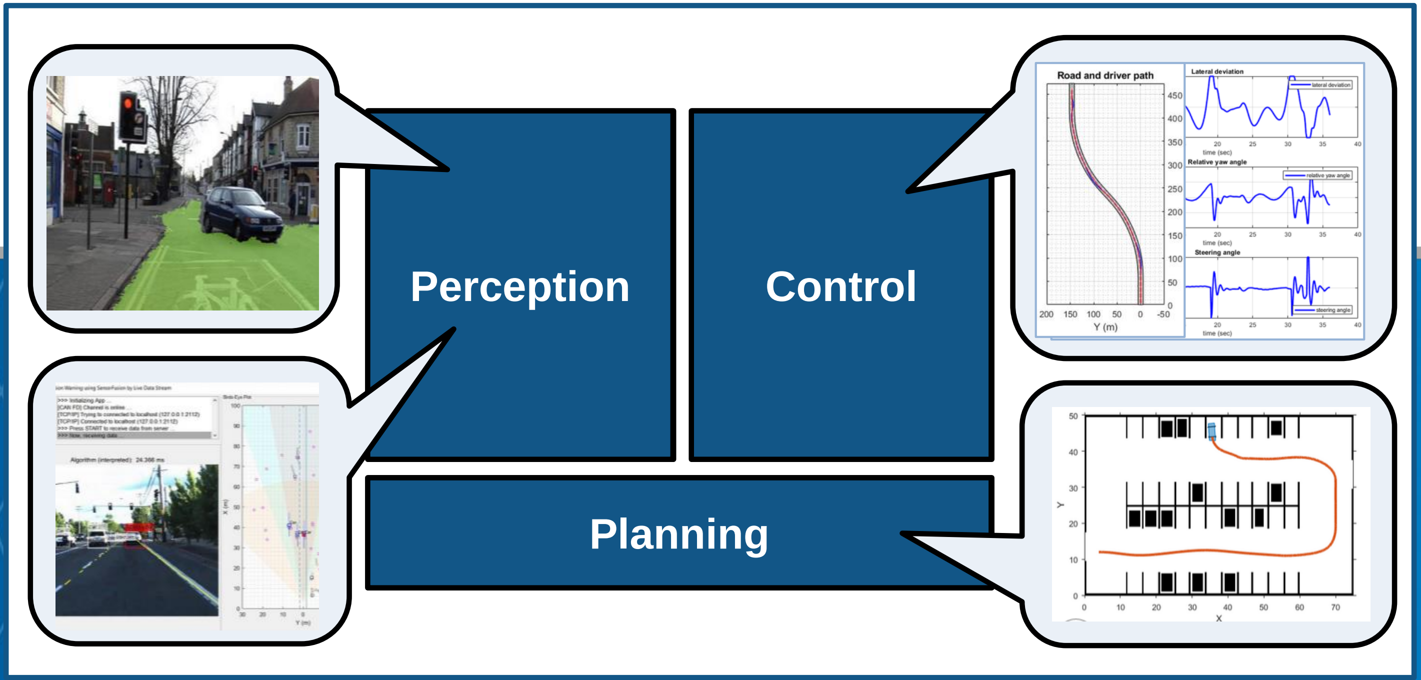
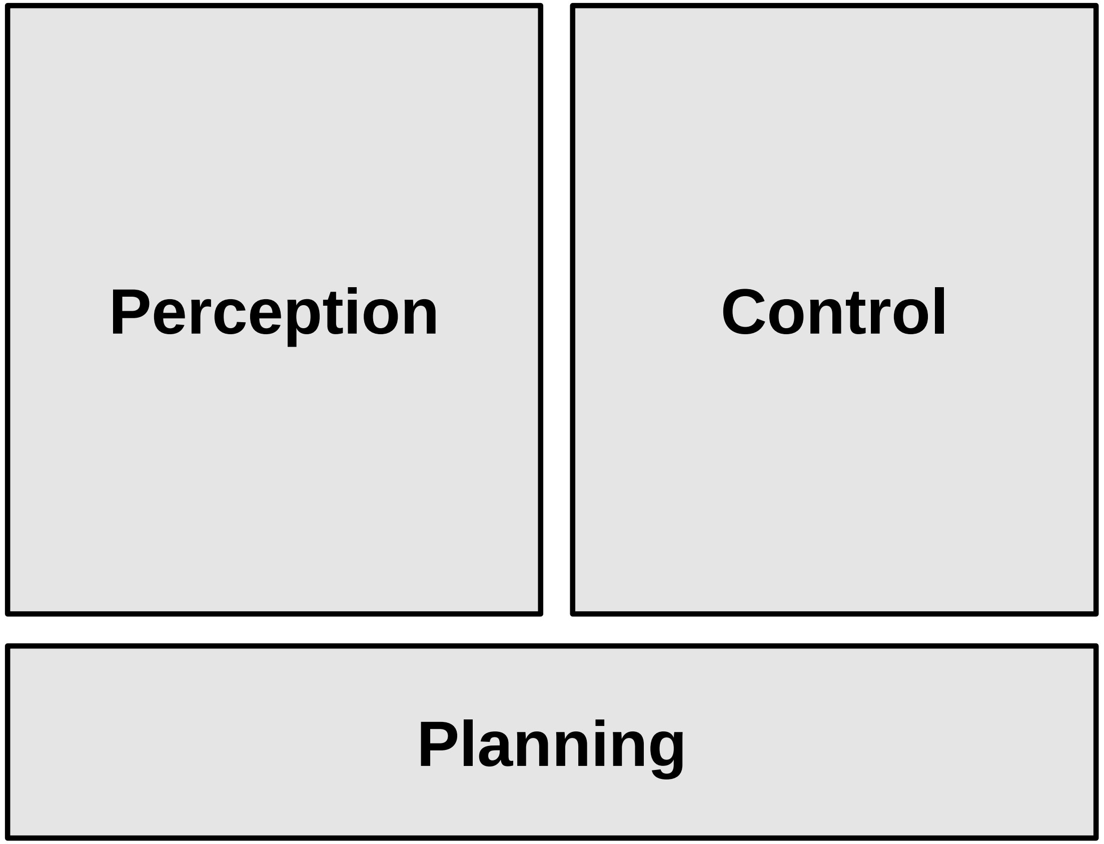


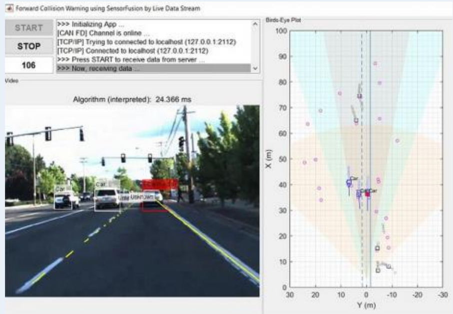
How can you use MATLAB and Simulink to develop automated driving algorithms?



Examples of how you can use MATLAB and Simulink to develop automated driving algorithms

Deep learning

Sensor fusion
with live data

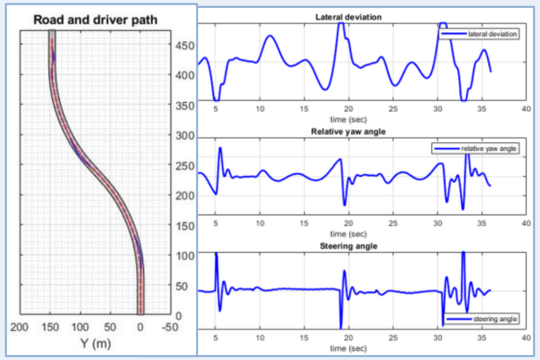


Perception

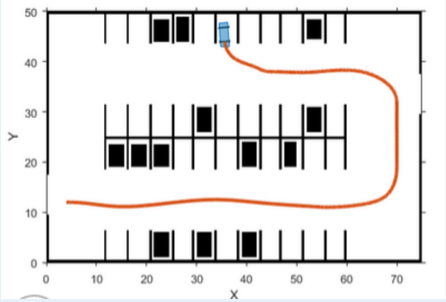
Control

Planning

Sensor models &
model predictive control



Path planning



How can you use MATLAB and Simulink to develop perception algorithms?

Deep learning

Perception

Control

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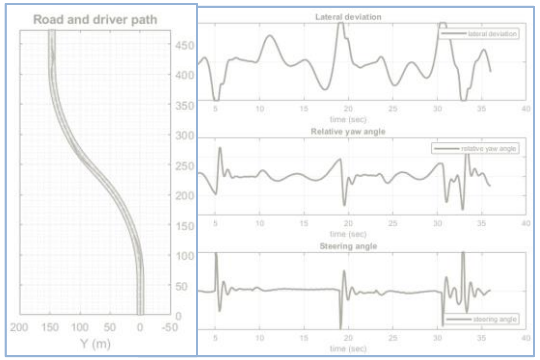
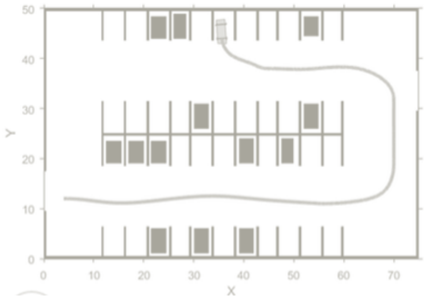
Sensor models & model predictive control



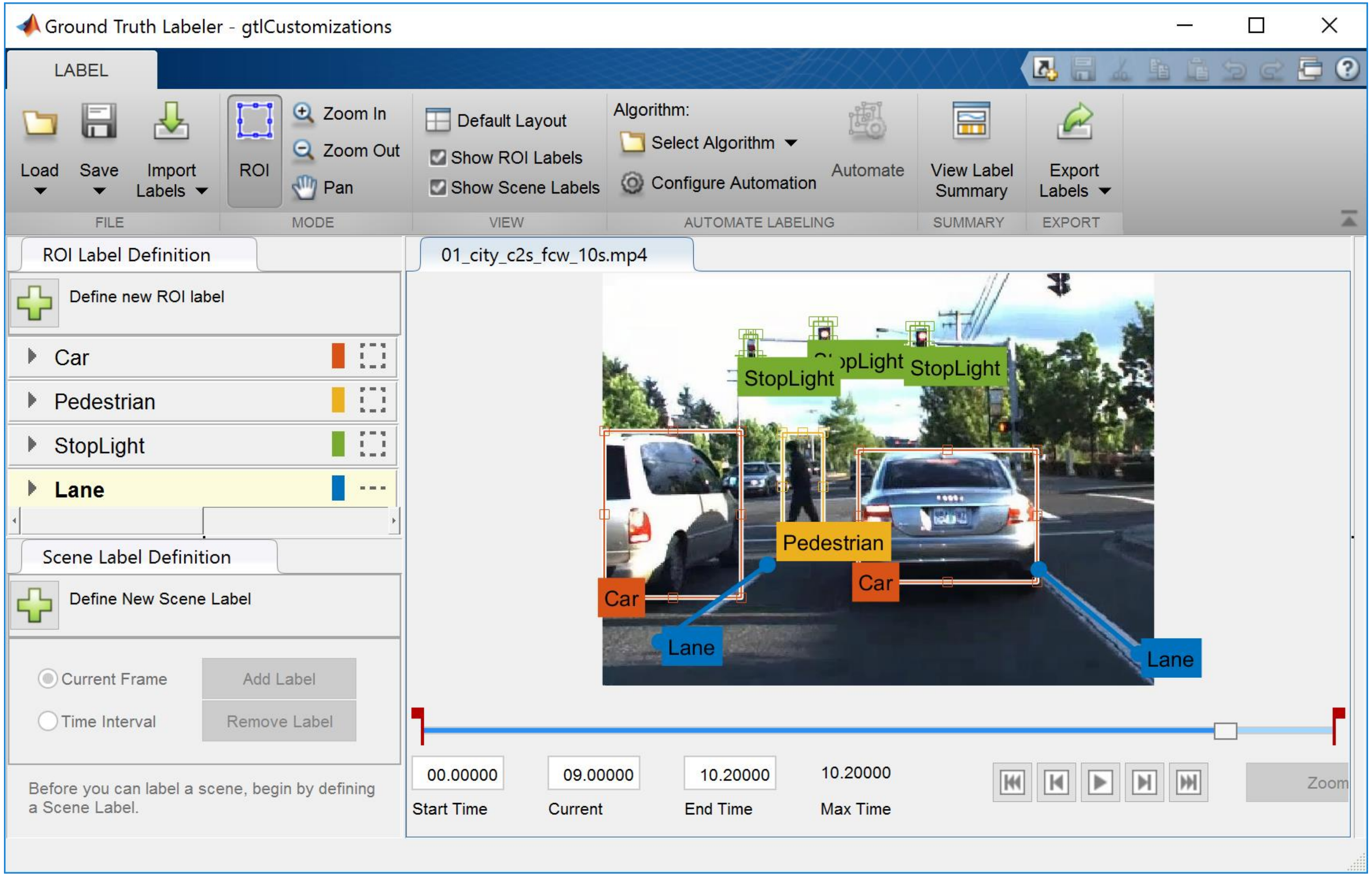
Sensor fusion with live data

Path planning



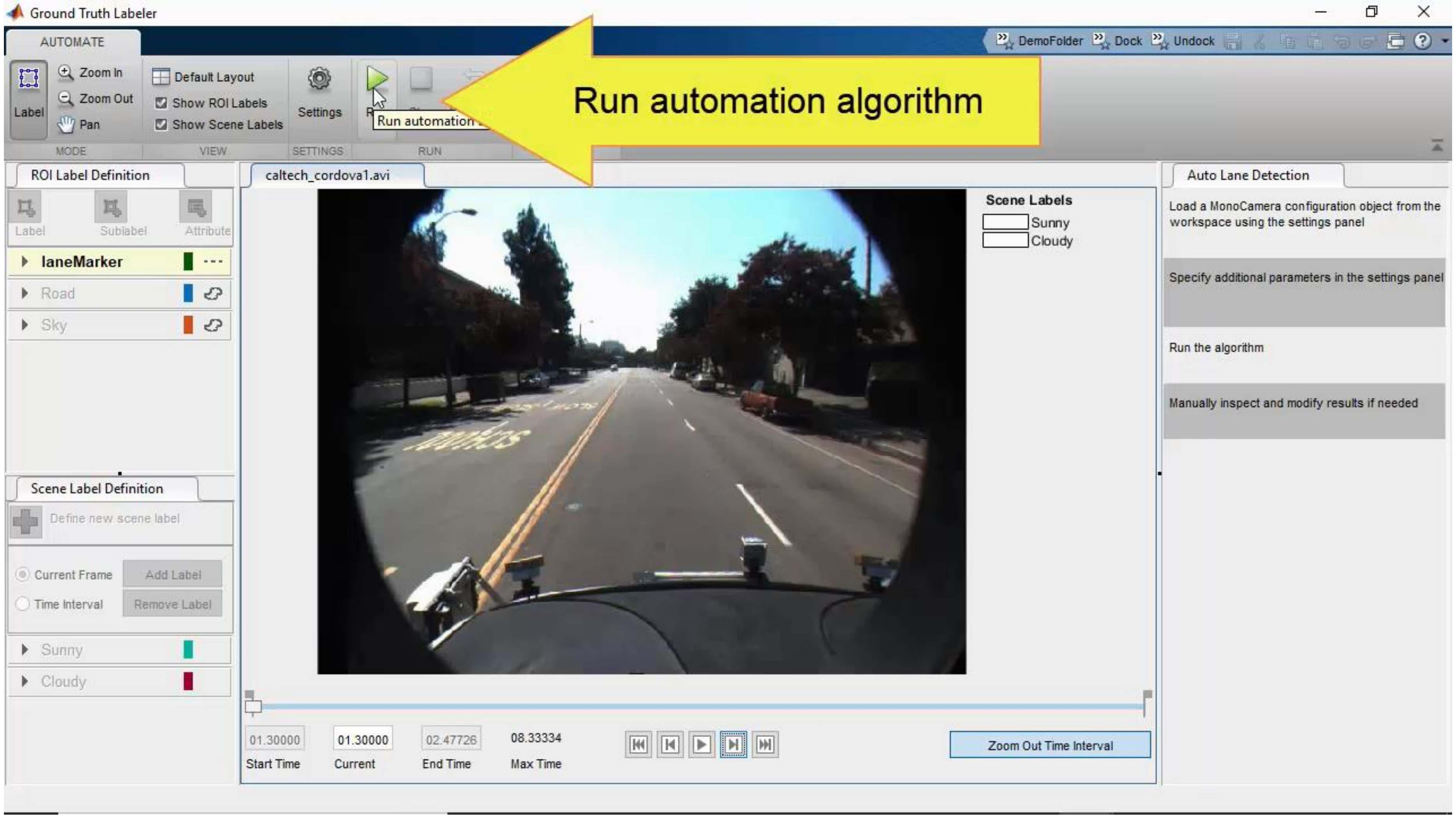
Automated Driving System Toolbox introduced:

Ground Truth Labeling App to label video data

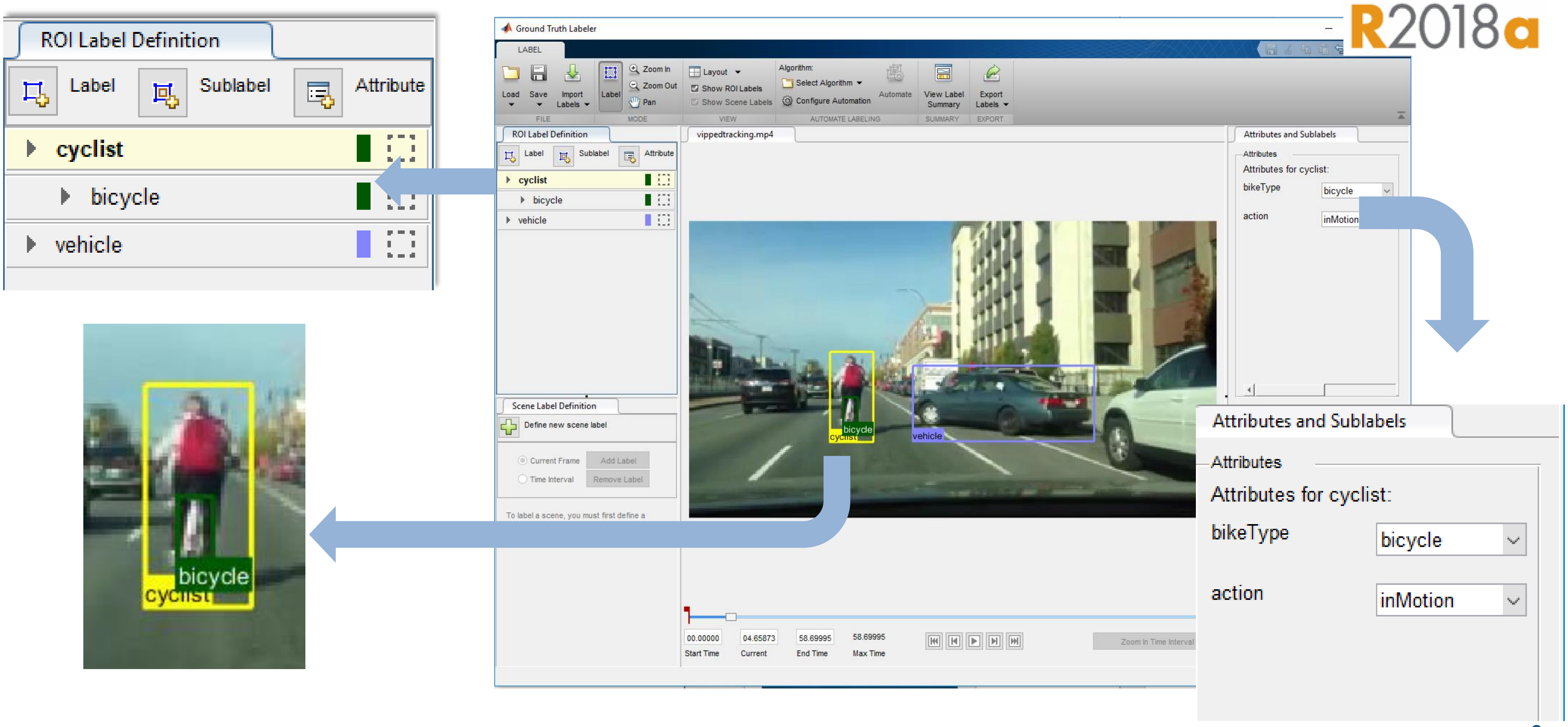


R2017a

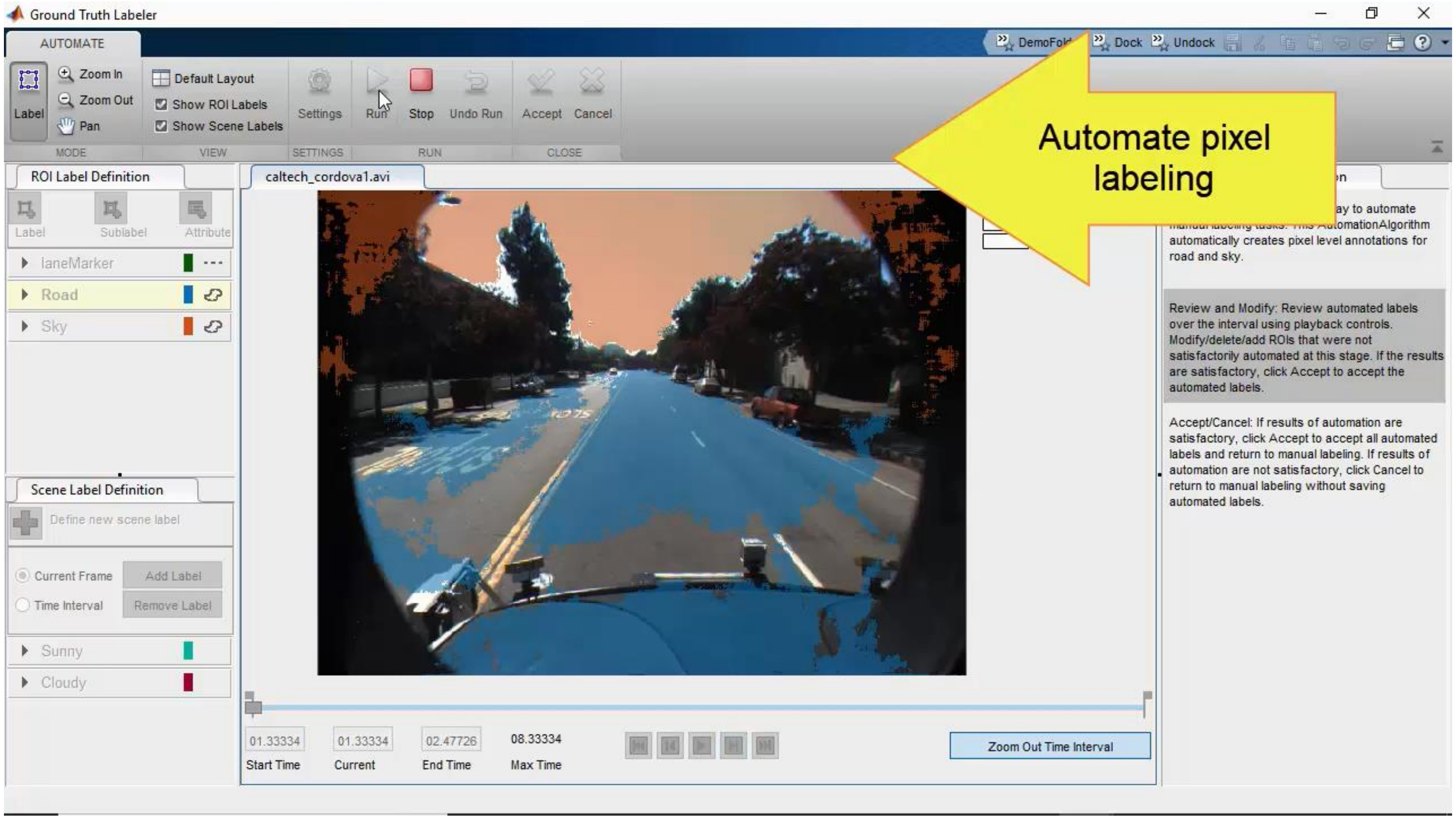
Automate labeling lanes with Ground Truth Labeler



Specify attributes and sublabels in Ground Truth Labeler App



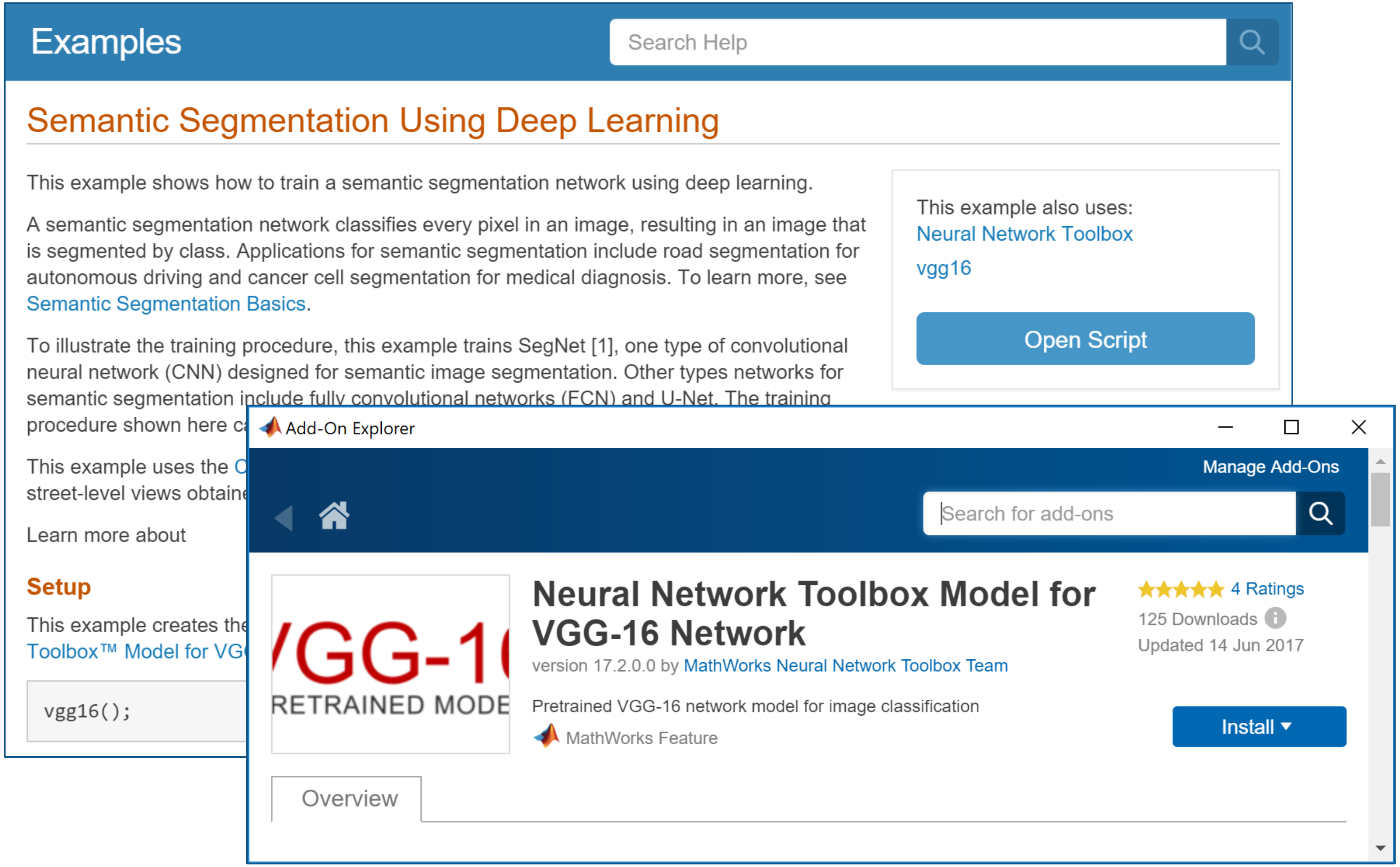
Automate labeling pixels with Ground Truth Labeler



Learn how to train a deep learning network using this example

- **Train free space detection network** using deep learning

Computer Vision System Toolbox™



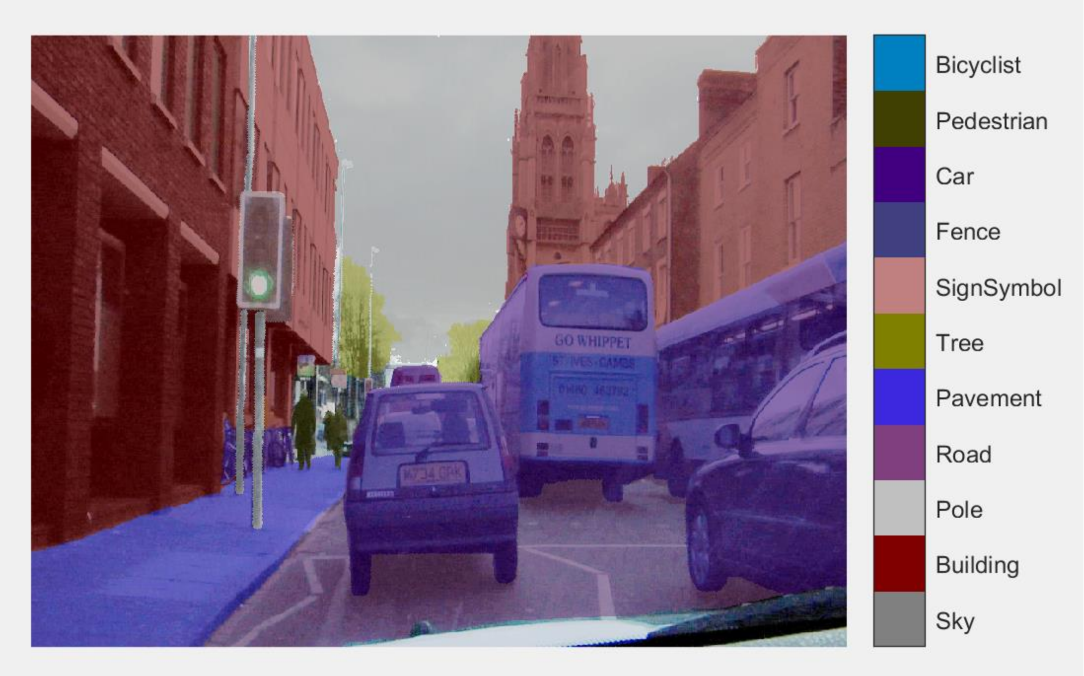
Load and plot training images

```
% Create datastore for images
imds = imageDatastore(imgDir);
I = readimage(imds, 1);
I = histeq(I);
imshow(I)
```

`imageDatastore`
manages large collections of images

Load and overlay pixel labels

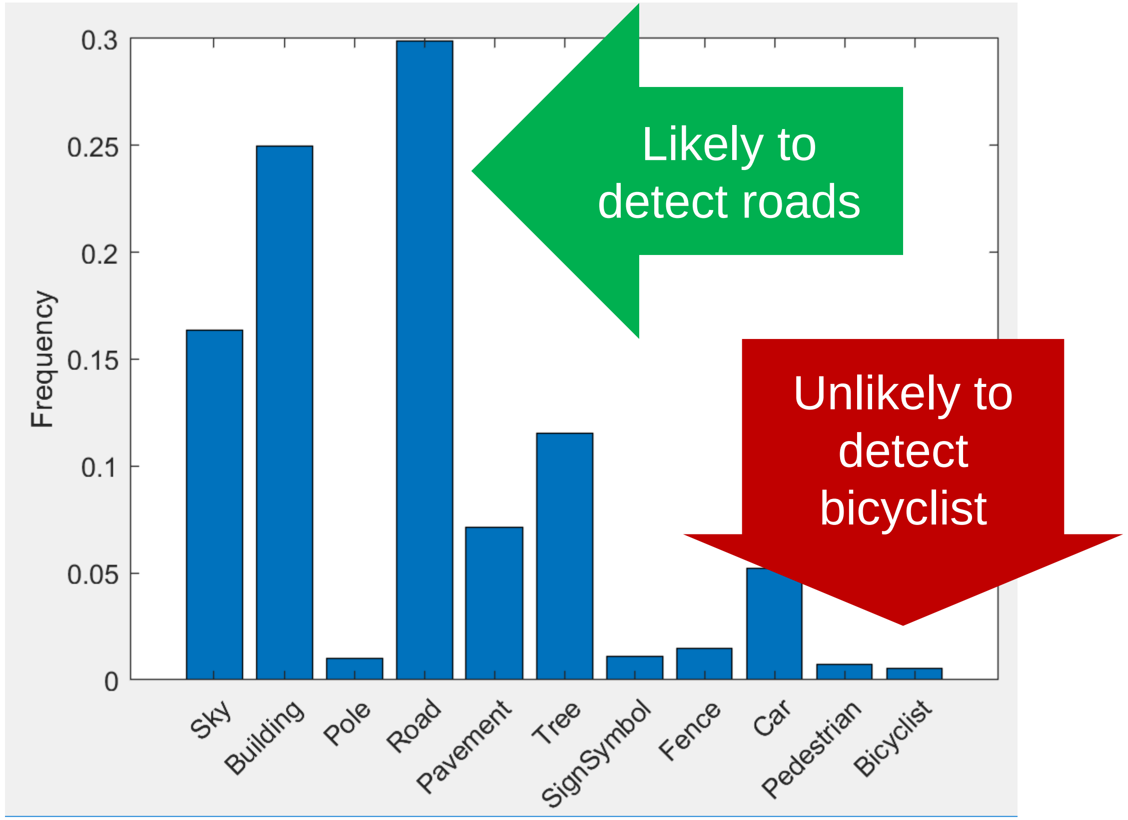
```
% Load pixel labels
classes = ["Sky";  "Building";...
  "Pole";  "Road"; "Pavement"; "Tree";...
  "SignSymbol";    "Fence";    "Car";...
  "Pedestrian";    "Bicyclist"];
pxds = pixelLabelDatastore(...
    labelDir,classes,labelIDs);

% Display labeled image
C = readimage(pxds, 1);
cmap = camvidColorMap;
B = labeloverlay(I,C,'ColorMap',cmap);
imshow(B)
```



pixelLabelDatastore
manages large collections
of pixel labels

Visualize distribution of labeled pixels

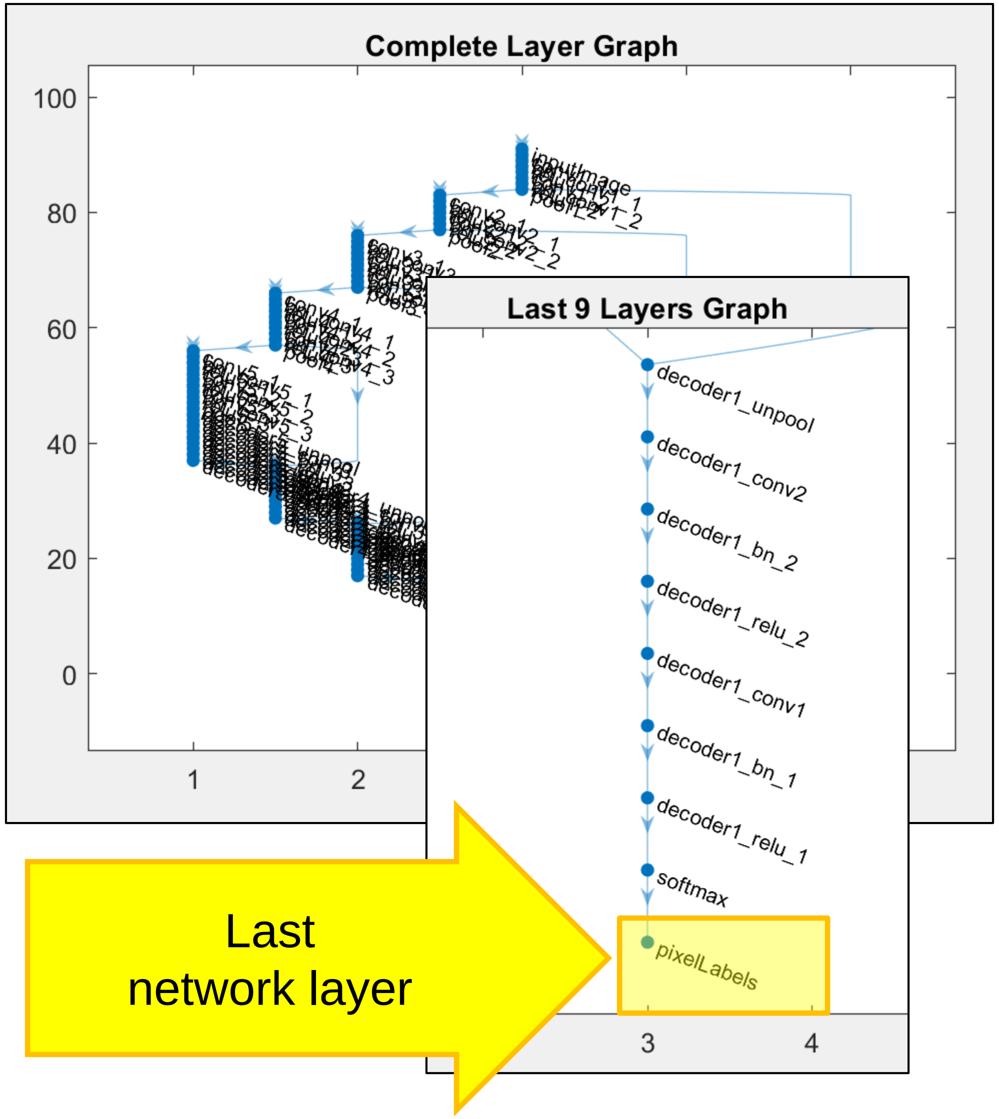
```
% Visualize label count by class
tbl = countEachLabel(pxds)

frequency = tbl.PixelCount / ...
            sum(tbl.PixelCount);

bar(1:numel(classes),frequency)
xticks(1:numel(classes))
xticklabels(tbl.Name)
xtickangle(45)
ylabel('Frequency')
```



Labeled pixels in this set are imbalanced

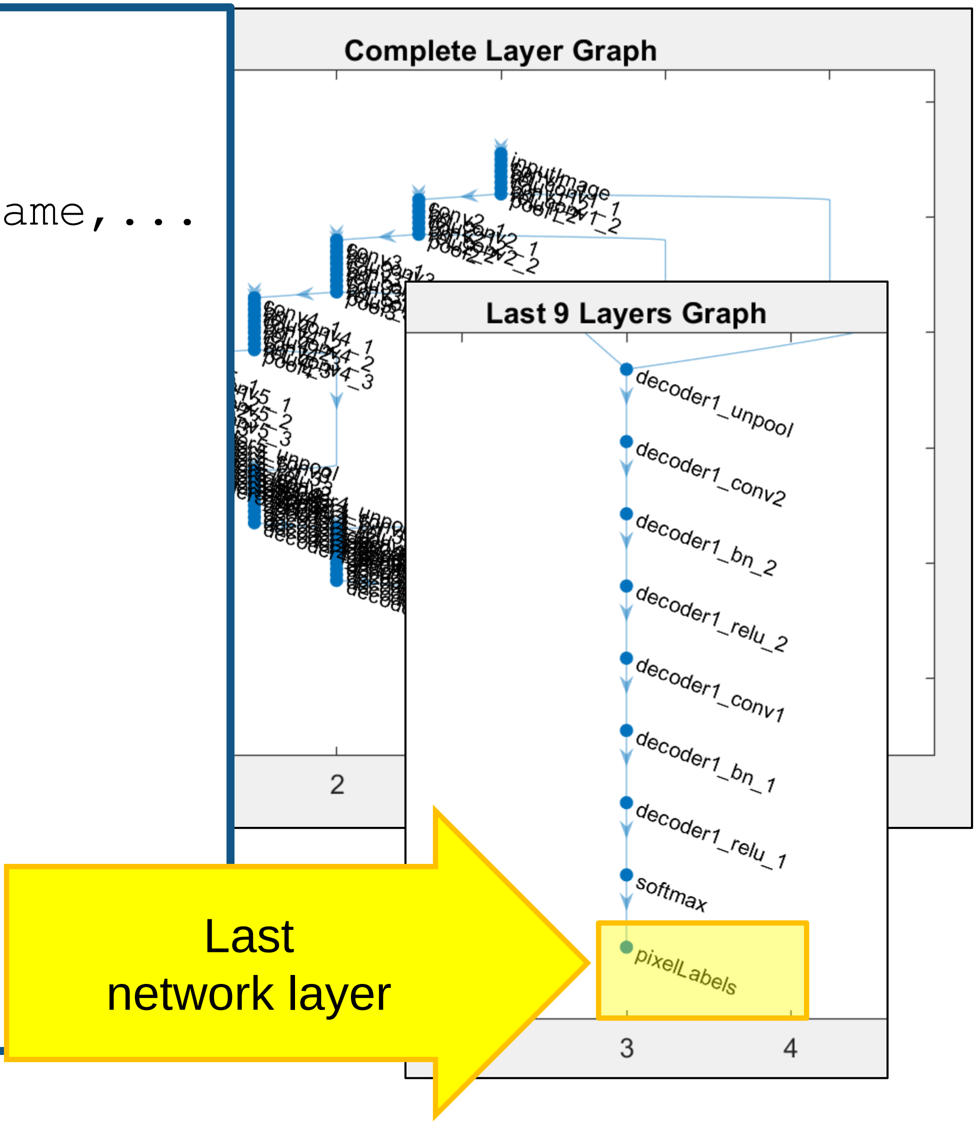
Create and visualize baseline network

```
% Create SegNet architecture
lgraph = segnetLayers(...
   imageSize, numClasses,...
   'vgg16');

% Display network structure
plot(lgraph)
title('Complete Layer Graph')%

% Display last layers
plot(lgraph); ylim([0 9.5])
title('Last 9 Layers Graph')
```



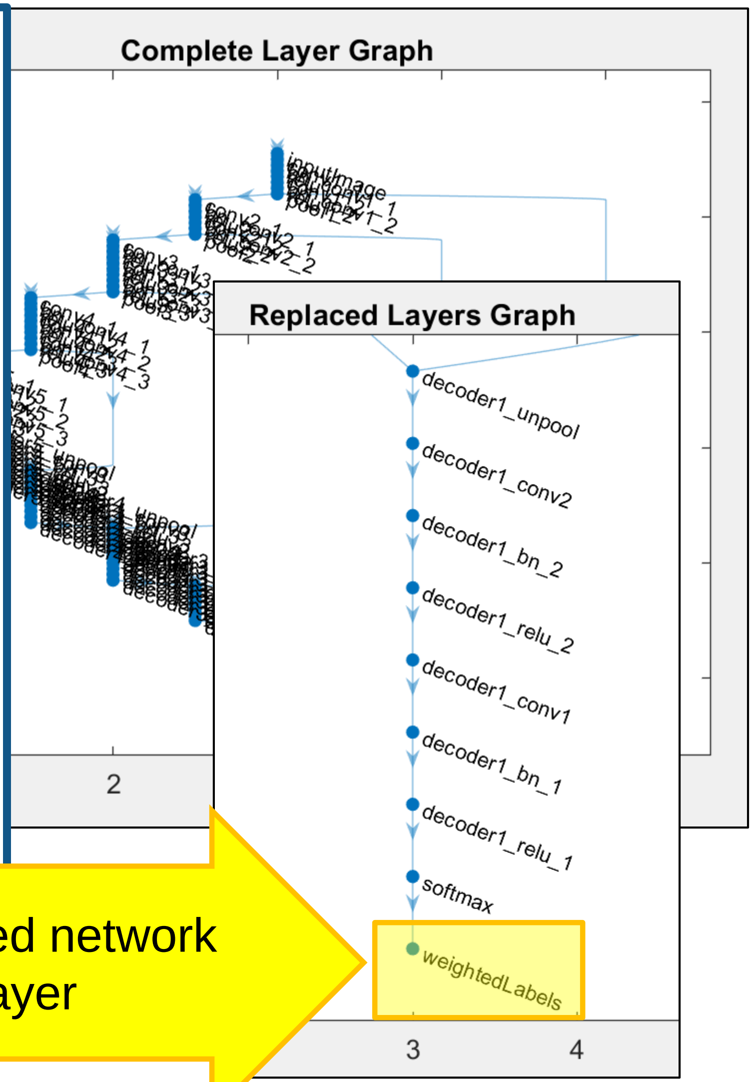
Add weighted layer to compensate for imbalanced data set

```
% Create weighted layer
pxLayer = pixelClassificationLayer(...
    'Name','weightedLabels', 'ClassNames',tbl.Name,...
    'ClassWeights',classWeights)
```



Add weighted layer to compensate for imbalanced data set

```
% Create weighted layer
pxLayer = pixelClassificationLayer(...
    'Name','weightedLabels', 'ClassNames',tbl.Name,...
    'ClassWeights',classWeights)

% Replace layer
lgraph = removeLayers(lgraph, 'pixelLabels');
lgraph = addLayers(lgraph, pxLayer);
lgraph = connectLayers(lgraph,...
    'softmax', 'weightedLabels');

% Display network structure
plot(lgraph); ylim([0 9.5])
title('Replaced Layers Graph')
```



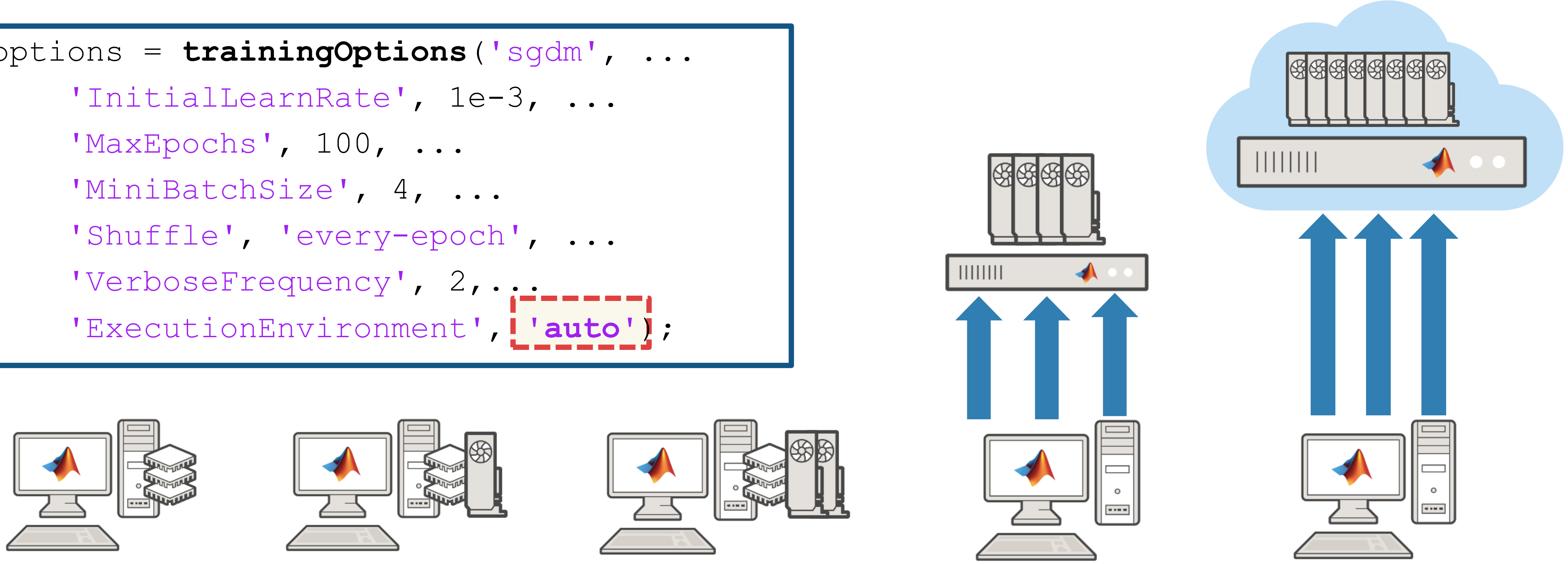
Replaced network layer

Augment images to expand training set

```
augmenter = imageDataAugmenter(...
   'RandXReflection', true,...
   'RandRotation',    [-30 30],... % degrees
   'RandXTranslation',[-10 10],... % pixels
   'RandYTranslation',[-10 10]);   % pixels

datasource = pixelLabelImageSource(...
   imdsTrain,... % Image datastore
   pxdsTrain,... % Pixel datastore
   'DataAugmentation',augmenter)
```

Deep learning on CPU, GPU, multi-GPU and clusters

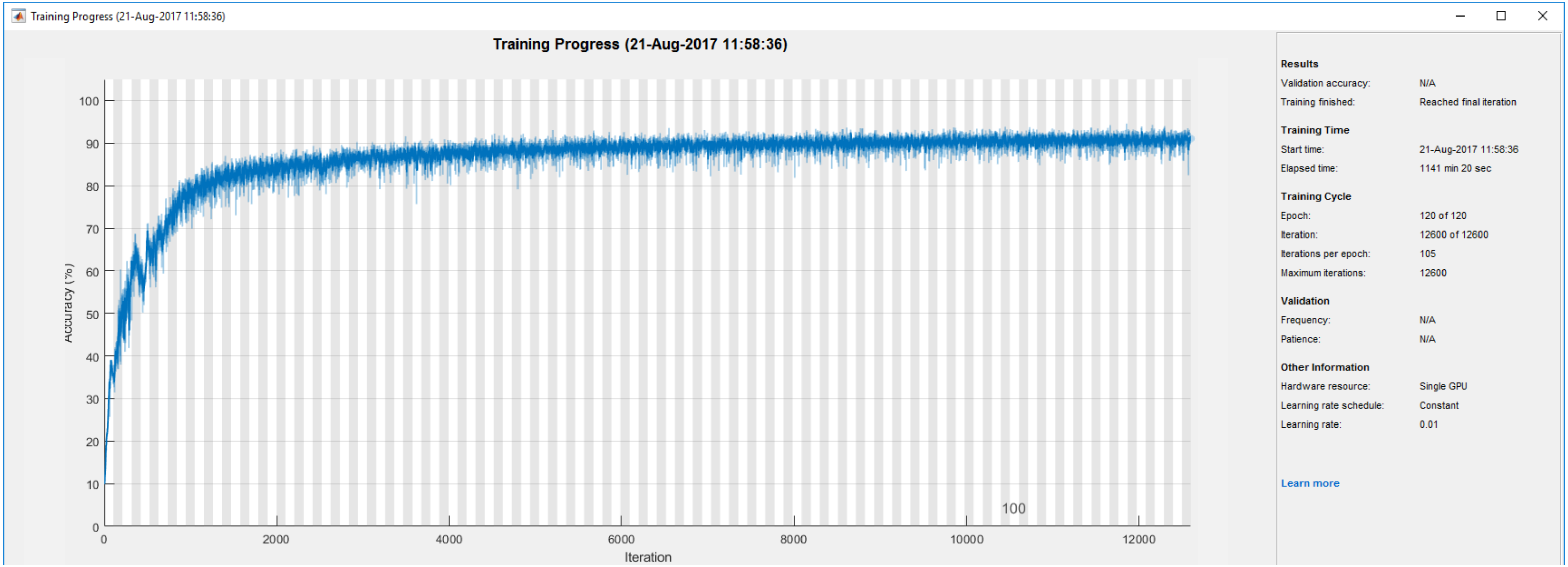
```
options = trainingOptions('sgdm', ...
     'InitialLearnRate', 1e-3, ...
     'MaxEpochs', 100, ...
     'MiniBatchSize', 4, ...
     'Shuffle', 'every-epoch', ...
     'VerboseFrequency', 2,...
     'ExecutionEnvironment', 'auto');
```



Single CPU	Single CPU Single GPU	Single CPU Multiple GPUs	On-prem server with GPUs	Cloud GPUs (AWS, Azure, etc.)
`'auto'`	`'auto'`	`'multi-gpu'`	`'parallel'`	`'parallel'`

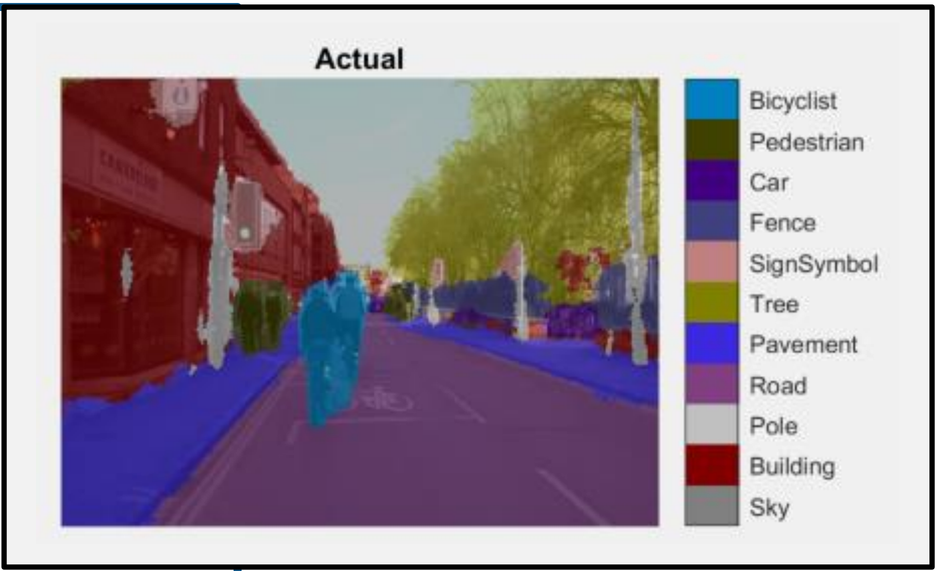
Train network and view progress

```
[net, info] = trainNetwork(datasource, lgraph, options);
```



Evaluate trained network on image

```
% Plot actual results
I = read(imdsTest);
actual = semanticseg(I, net);

B = labeloverlay(I, ...
    actual,...
    'Colormap', cmap,...
    'Transparency',0.4);
imshow(B)
pixelLabelColorbar(cmap, classes);
title('Actual')
```

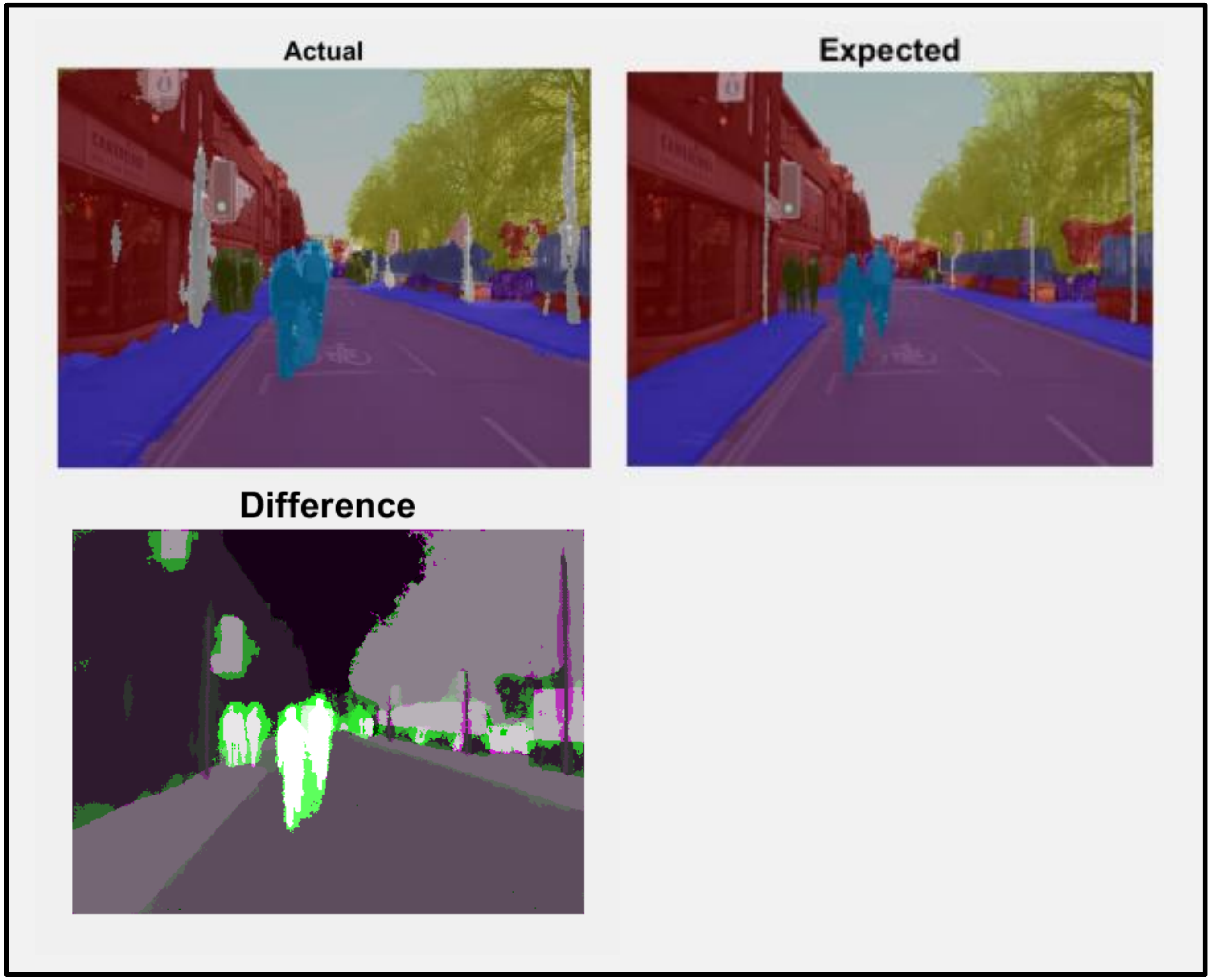


Visually compare actual with original labeled results

```
% Plot expected results
% using original labels
expected = read(pxdsTest);
E = labeloverlay(I,...
 expected,...
 'Colormap', cmap,...
 'Transparency',0.4);
imshow(E)
title('Expected');
```

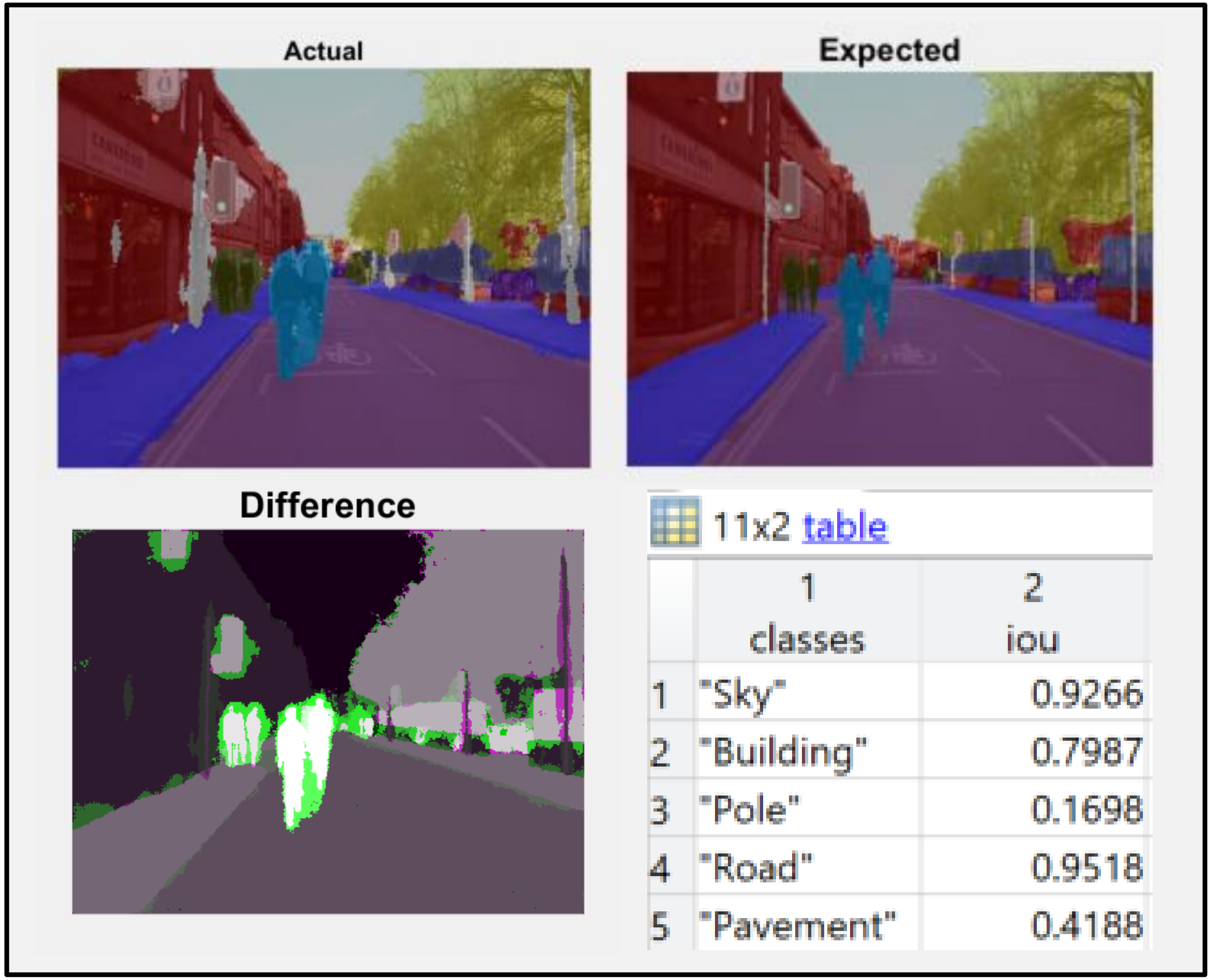
Visually compare actual with original labeled results

```
% Plot differences
imshowpair(...
 uint8(actual),...
 uint8(expected));
title('Difference');
```



Assess similarity using intersection-over-union (IoU) metric

```
iou = jaccard(actual,...
              expected);
table(classes,iou)

ans =
  11×2 table
      classes          iou
    ____________    ________

    "Sky"            0.92659
    "Building"        0.7987
    "Pole"           0.16978
    "Road"           0.95177
    "Pavement"       0.41877
    "Tree"           0.43401
    "SignSymbol"     0.32509
    "Fence"            0.492
    "Car"           0.068756
    "Pedestrian"           0
    "Bicyclist"            0
```



Evaluate trained network statistics

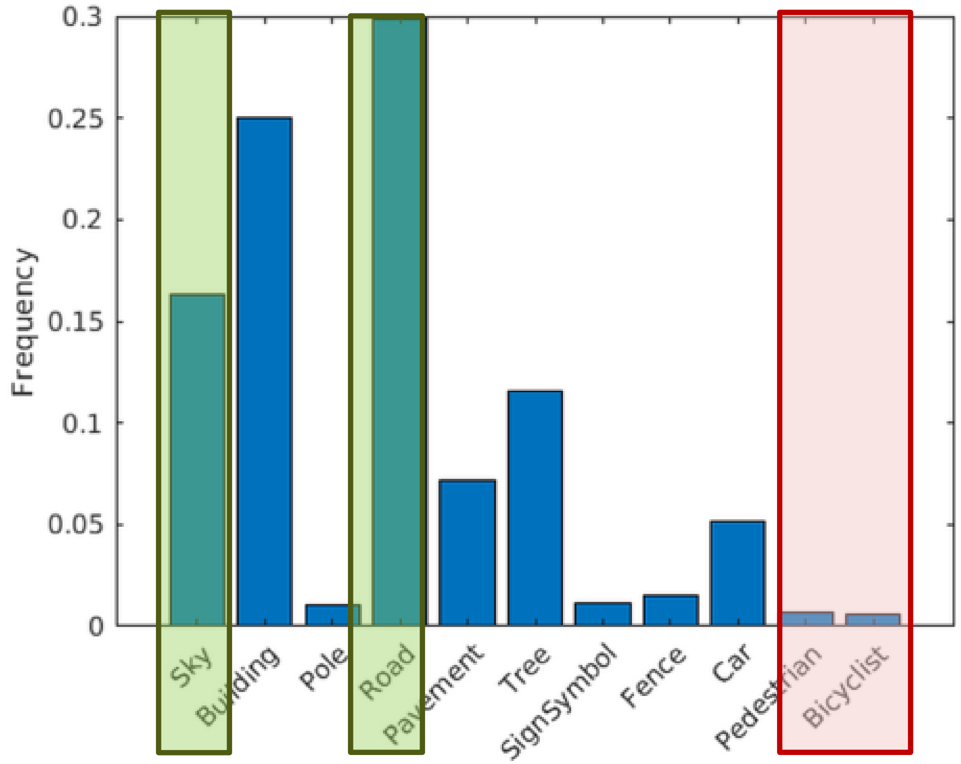
```
pxdsResults = ...
    semanticseg(...
      imdsTest,net,...
      'WriteLocation',tempdir,...
      'Verbose',false);

metrics = ...
    evaluateSemanticSegmentation(...
      pxdsResults,pxdsTest,...
      'Verbose',false);

metrics.ClassMetrics
```

Evaluation metrics of network

	Accuracy	IoU	MeanBFScore
Sky	0.93544	0.89279	0.88239
Building	0.79978	0.75543	0.59861
Pole	0.73166	0.18361	0.51426
Road	0.93644	0.90663	0.7086
Pavement	0.90624	0.72932	0.70585
Tree	0.86587	0.73694	0.67097
SignSymbol	0.76118	0.35339	0.44175
Fence	0.83258	0.49648	0.50265
Car	0.90961	0.75263	0.64837
Pedestrian	0.83751	0.35409	0.46796
Bicyclist	0.84156	0.5472	0.46933

Distribution of labels in data affects intersection-over-union (IoU)

Distribution of labels in original data set



Evaluation metrics of network

	Accuracy	IoU	MeanBFScore
Sky	0.93544	0.89279	0.88239
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Pedestrian	0.83751	0.35409	0.46796
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Underrepresented classes such as Pedestrian and Bicyclist are
not segmented as well as classes such as Sky and Road

Generate CUDA Code for Embedded Deployment

```
% Save network to MAT file
save('SegNet.mat', 'net’)
```

```
function out = segnet_predict(in) %#codegen
persistent mynet;
if isempty(mynet)
   mynet = coder.loadDeepLearningNetwork('SegNet.mat');
end
out = predict(mynet,in);
```

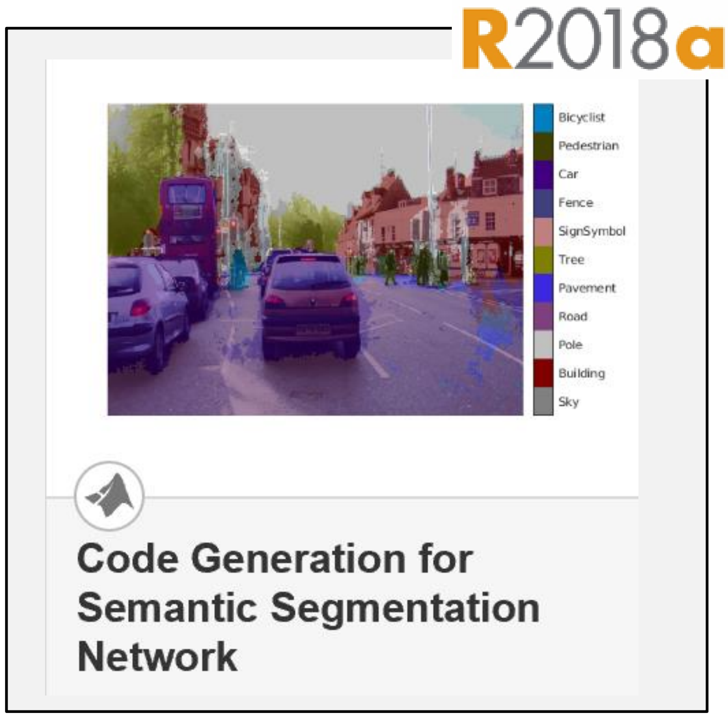
```
% Generate CUDA code
cfg = coder.config('lib');
cfg.TargetLang = 'C++';
codegen -config cfg segnet_predict -args
{ones(360,480,3,'uint8')} -report
```

Free Space Detection Using Semantic Segmentation

Learn more about developing deep learning perception algorithms with these examples

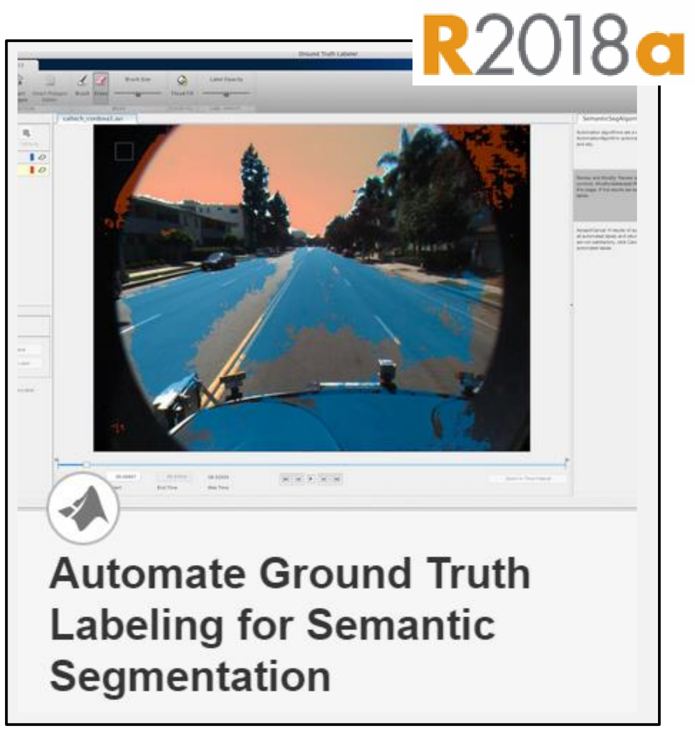
- **Train free space detection network** using deep learning

  Computer Vision System Toolbox™



- **Generate CUDA® code** to execute directed acyclic graph network on an NVIDIA GPU

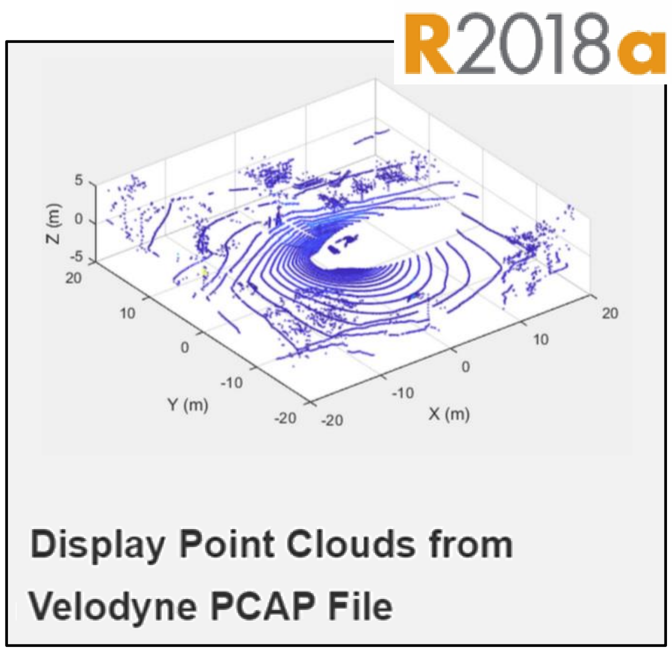
  GPU Coder™



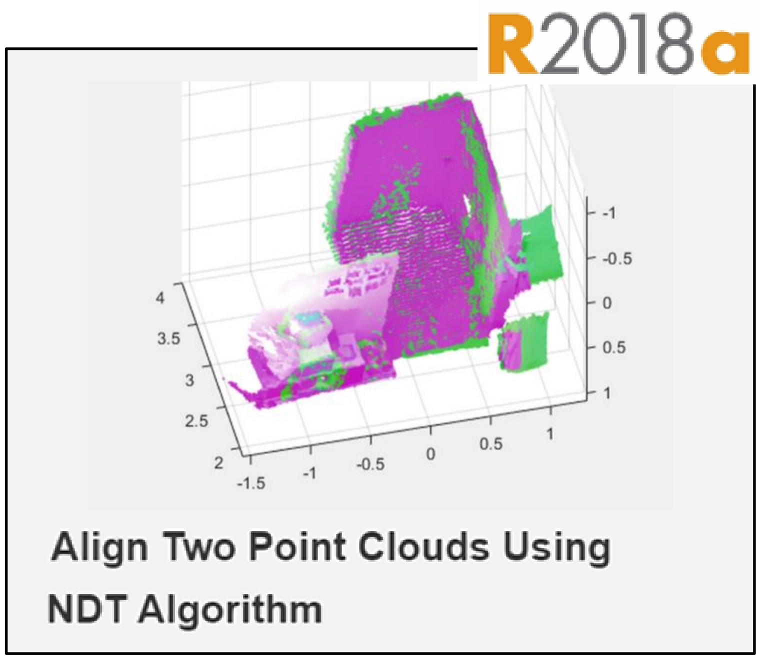
- **Add semantic segmentation** automation algorithm to Ground Truth Labeler App

  Automated Driving System Toolbox™

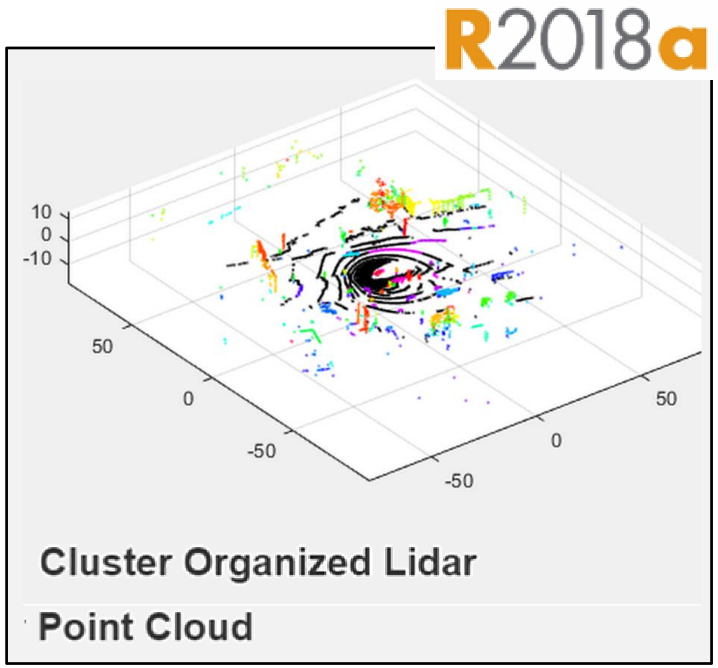
Learn about developing
lidar perception algorithms with these examples



- **Read Velodyne** files
  `velodyneFileReader`
  Automated Driving
  System Toolbox™



- **Register** point clouds with Normal Distributions Transform
  `pcregisterndt`
  Computer Vision System Toolbox™



- **Segment** lidar point cloud
  `segmentLidarData`
  Automated Driving
  System Toolbox™

How can you use MATLAB and Simulink to develop perception algorithms?

Deep learning

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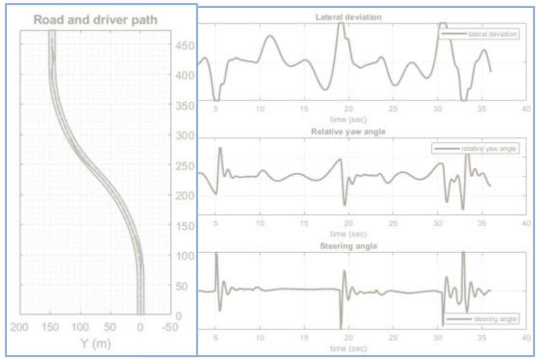
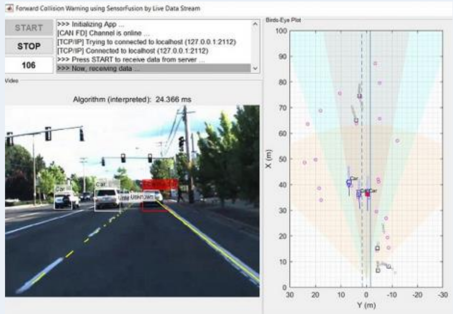
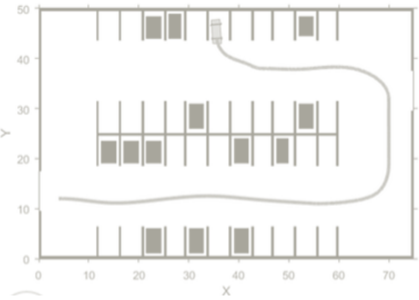
Sensor models &
model predictive control



Sensor fusion
with live data

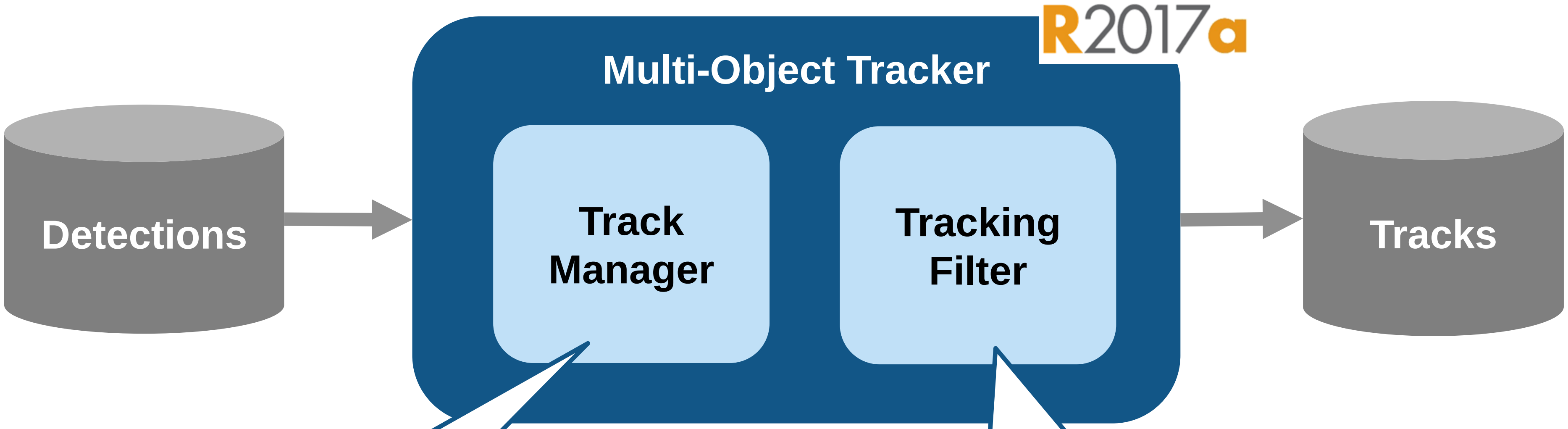


Path planning



Automated Driving System Toolbox introduced:

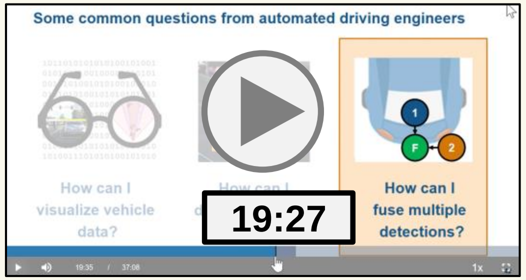
Multi-object tracker to develop sensor fusion algorithms



- Assigns detections to tracks
- Creates new tracks
- Updates existing tracks
- Removes old tracks

- Predicts and updates state of track
- Supports linear, extended, and unscented Kalman filters

Videos and Webinars

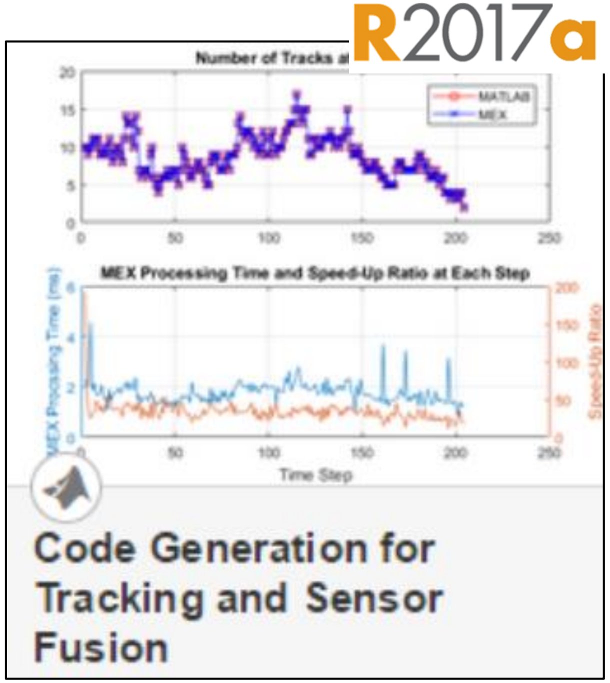


Introduction to Automated Driving System Toolbox

Automated Driving System Toolbox introduced examples to:

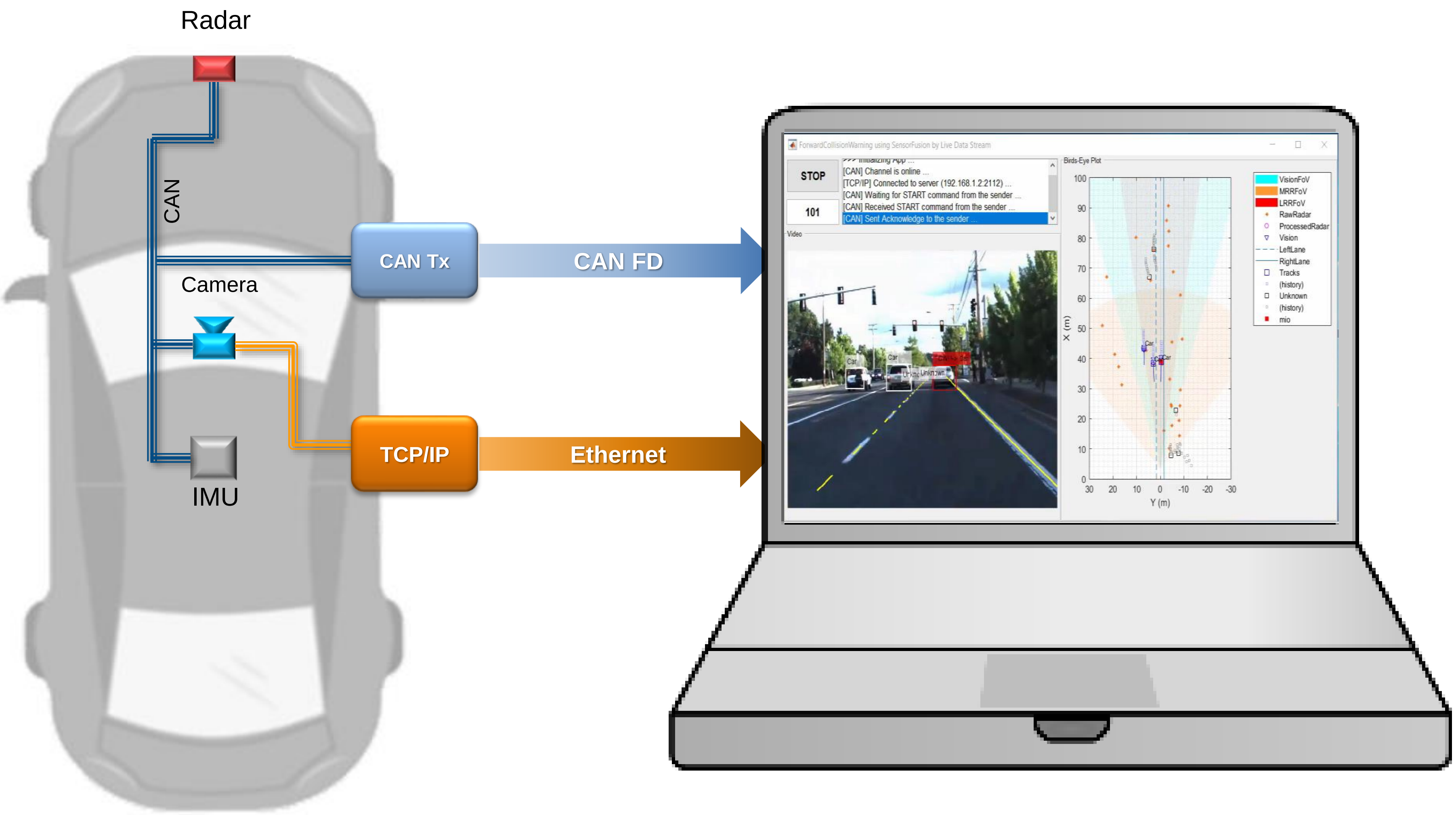
Develop sensor fusion algorithms with recorded data

- **Design**
  multi-object tracker based on logged vehicle data

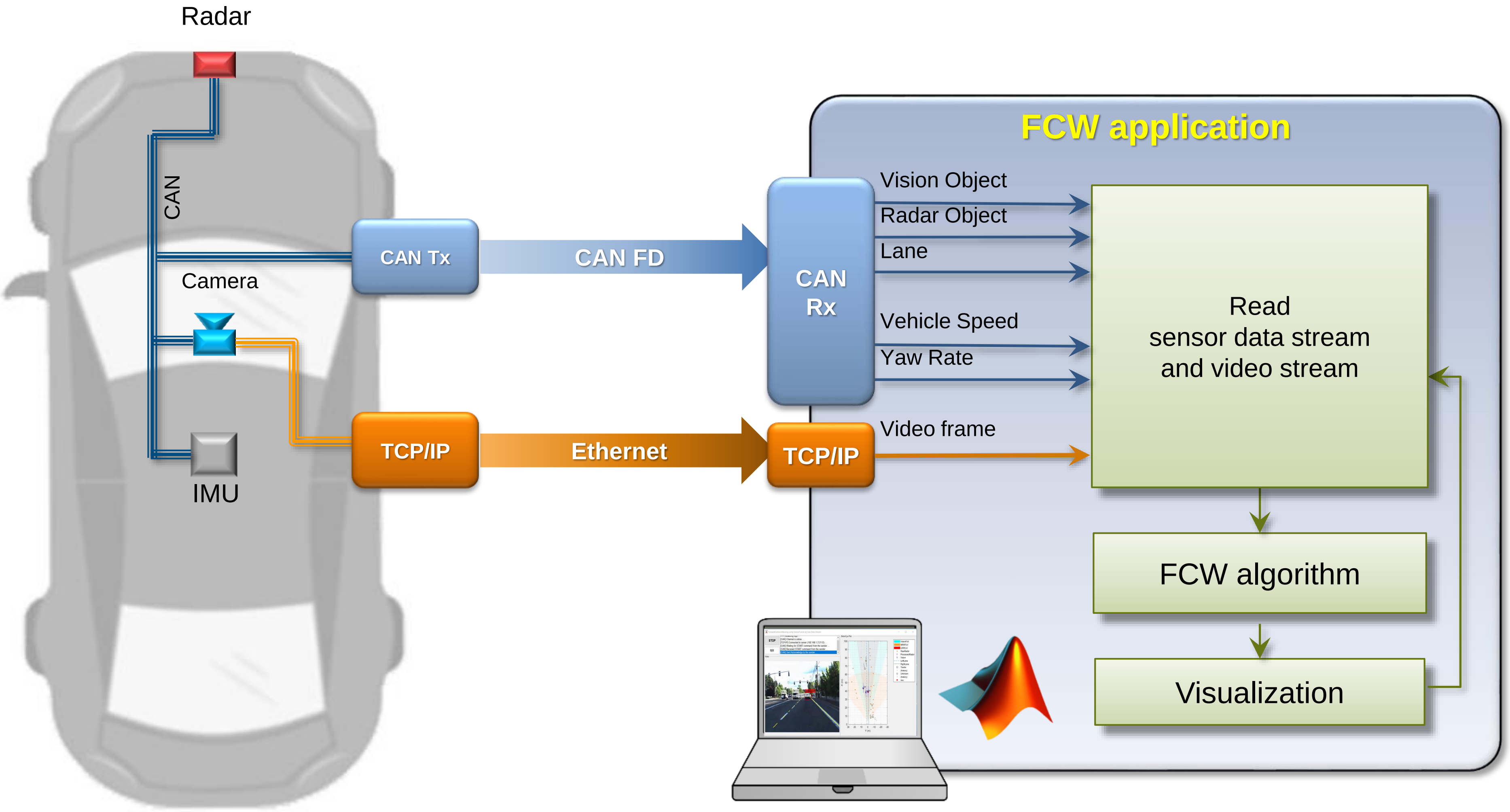


- **Generate C/C++**
  code from algorithm which includes a multi-object tracker

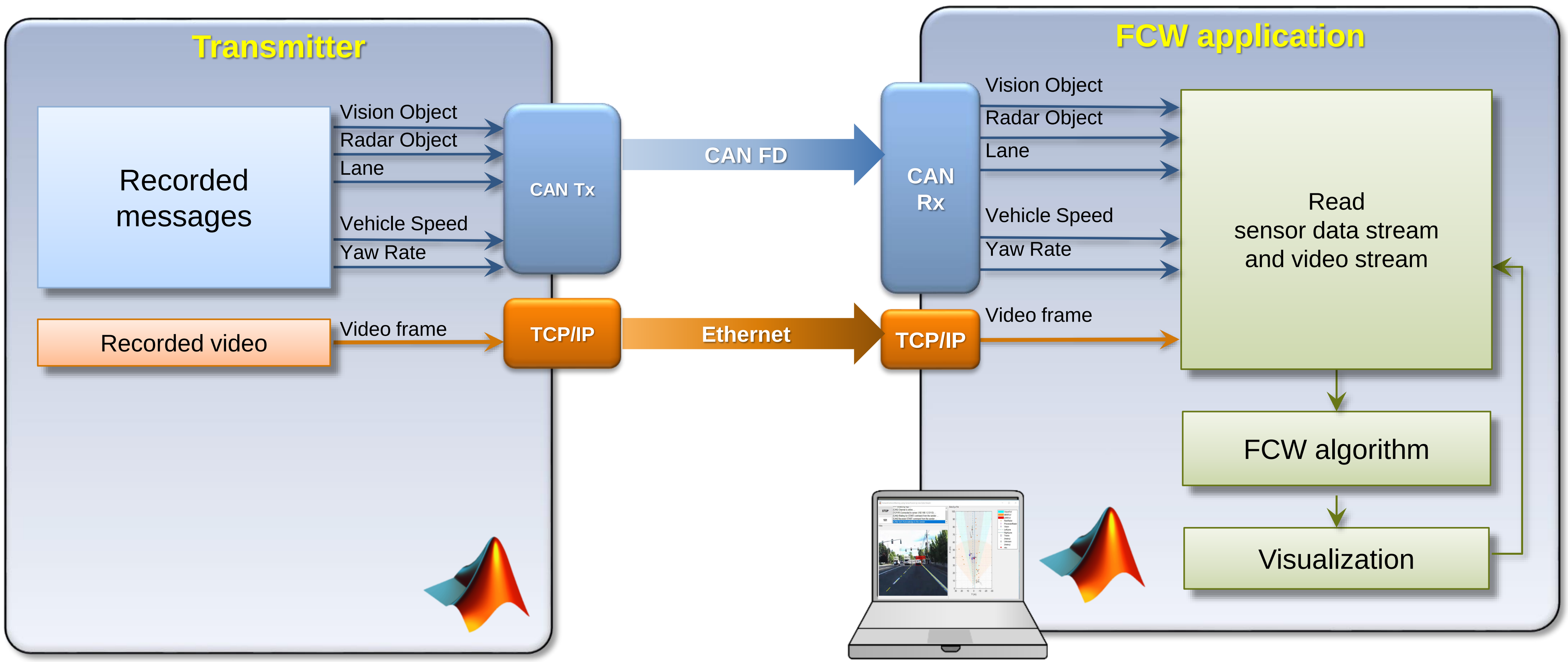
How can I test my sensor fusion algorithm with live data?



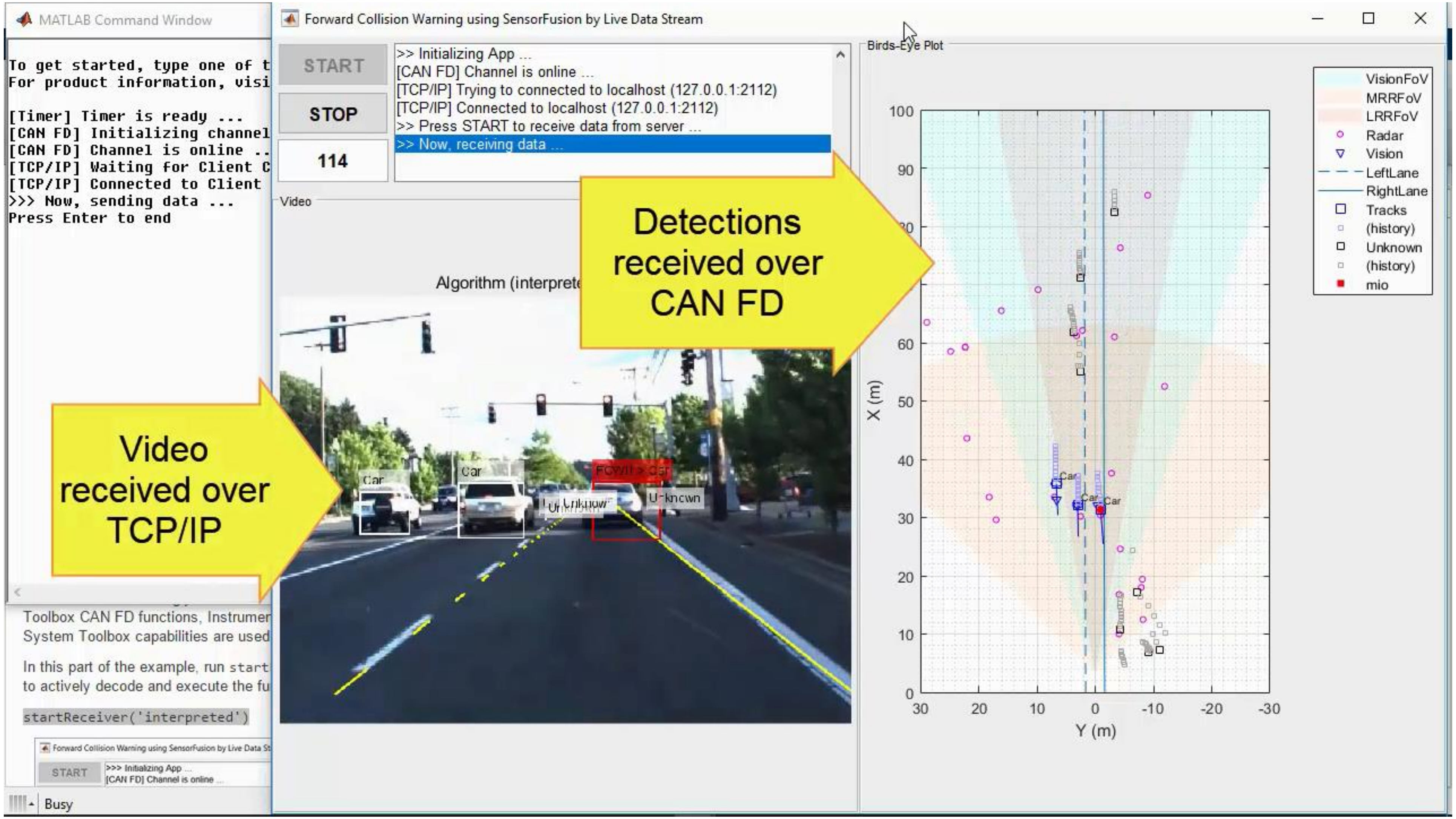
Test forward collision warning algorithm with live data from vehicle



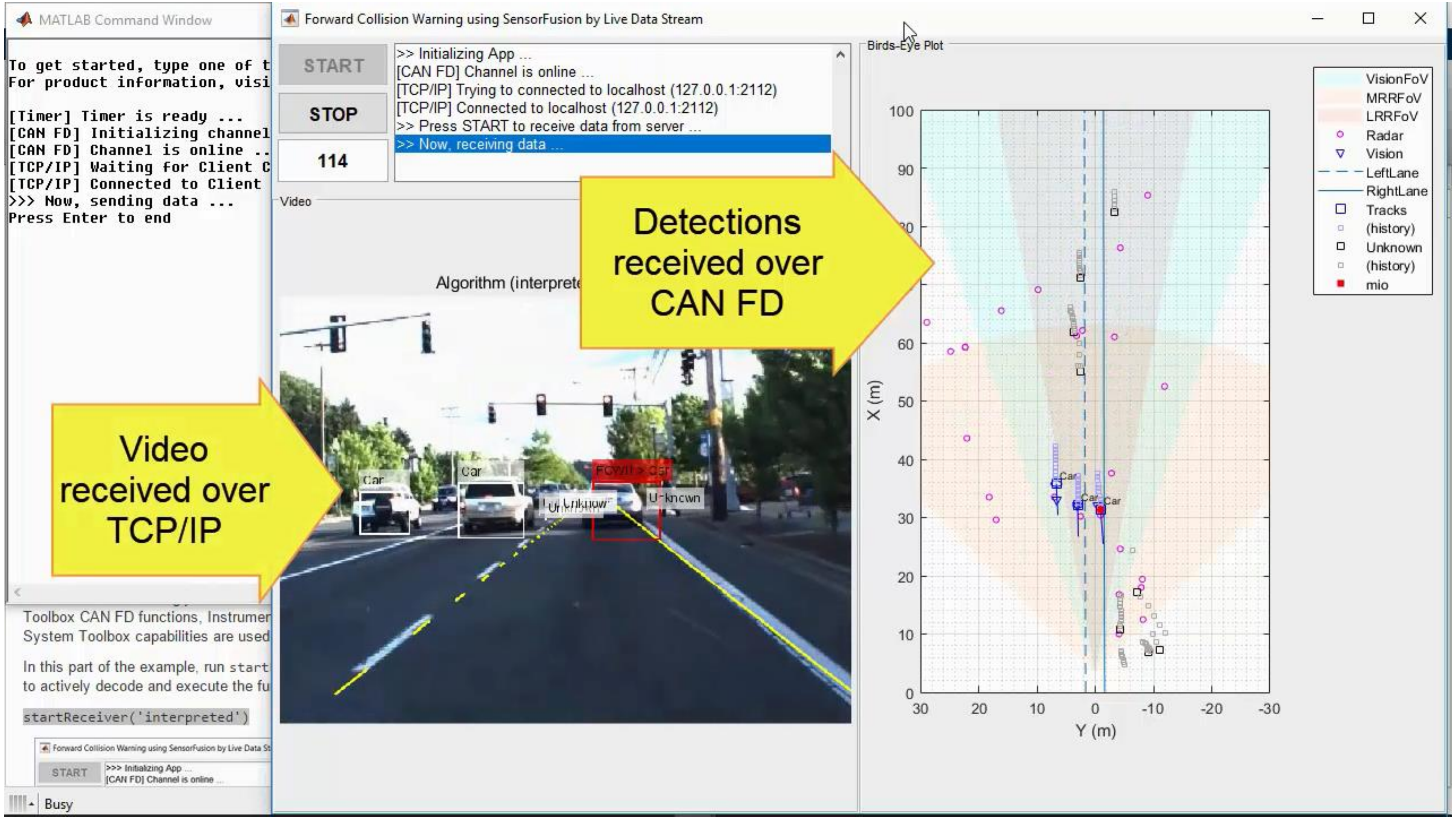
Test forward collision warning algorithm with live data from “surrogate” vehicle



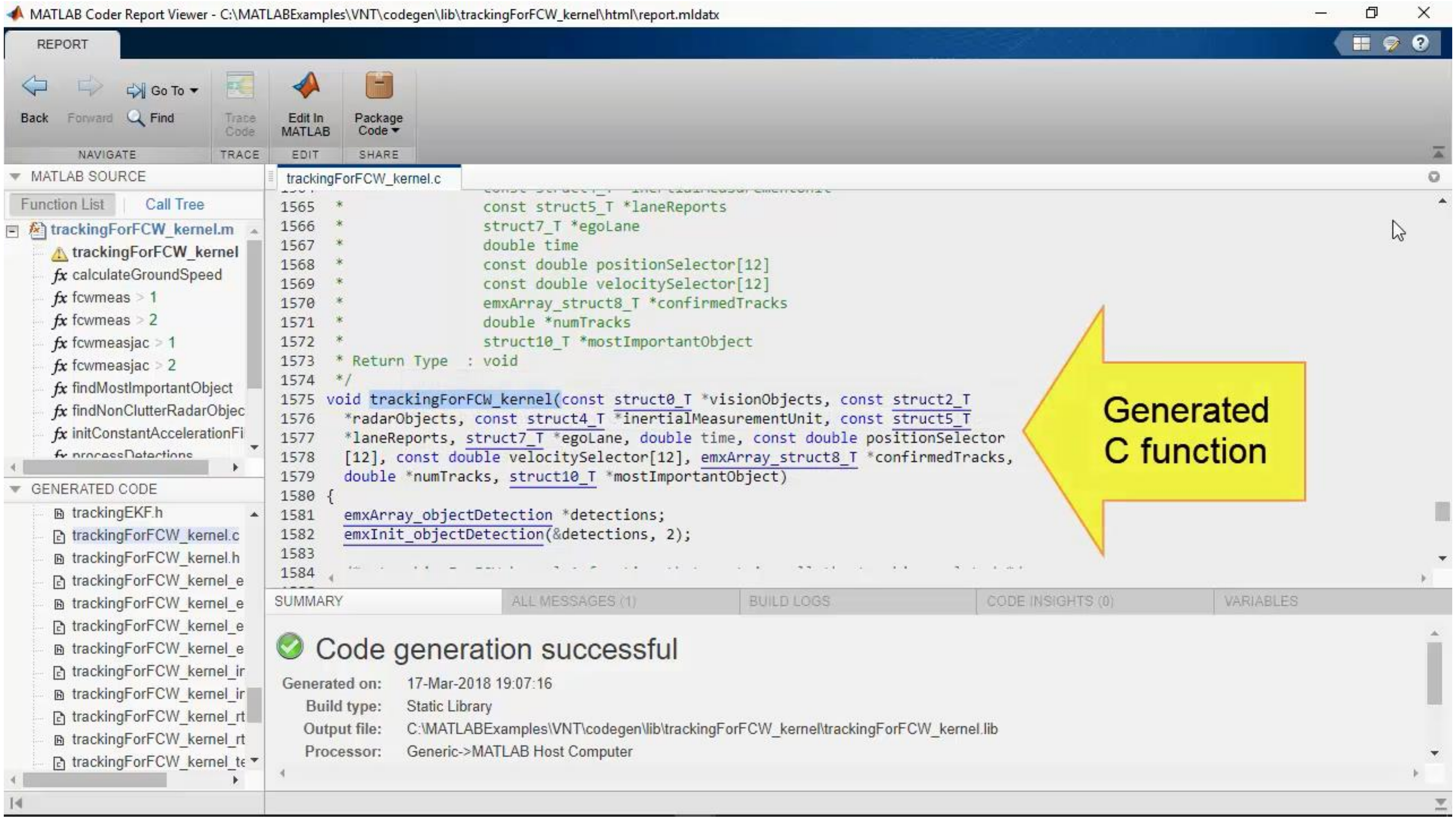
Send and live CAN FD and TCP/IP data



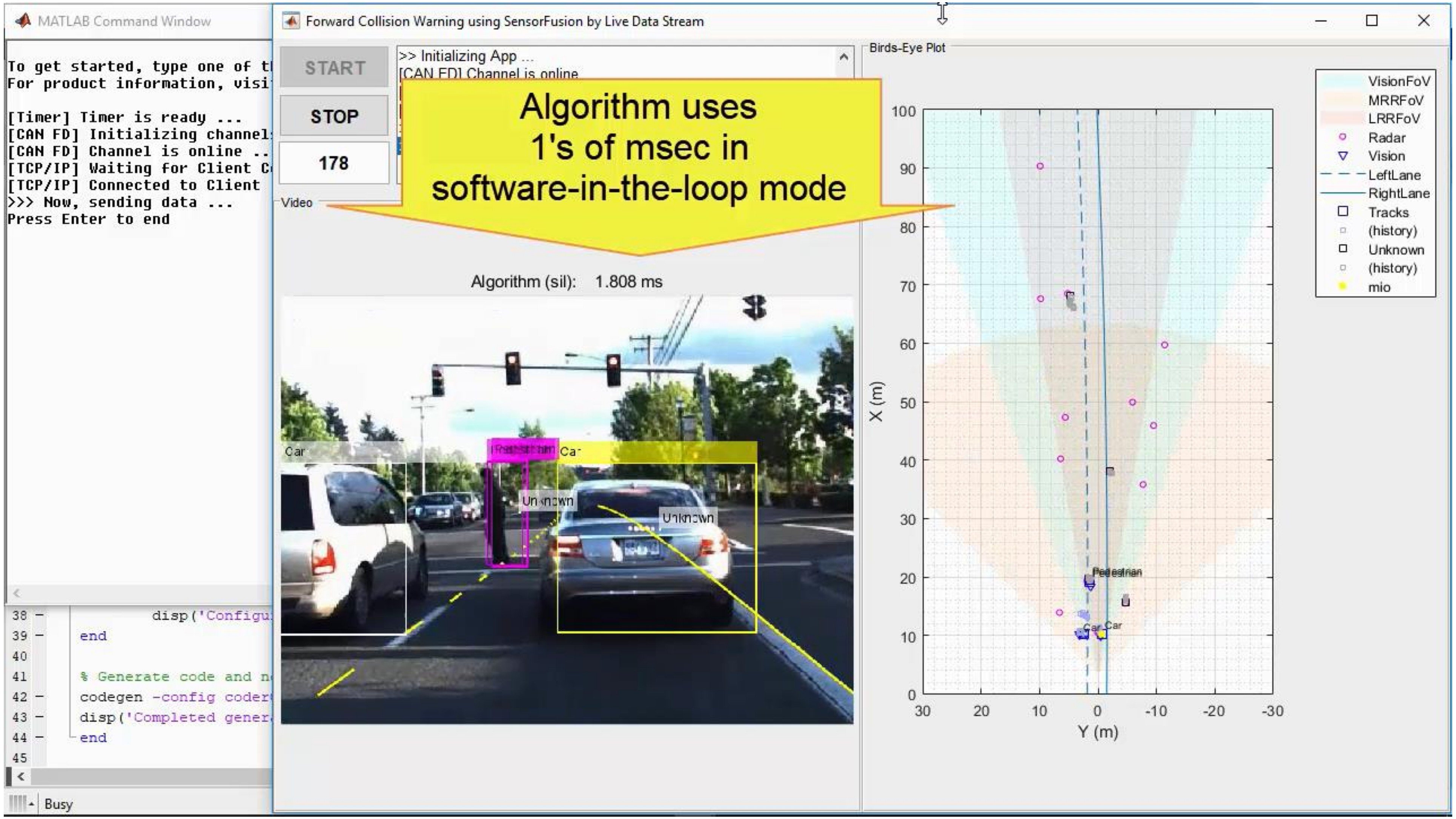
Receive live CAN FD and TCP/IP data



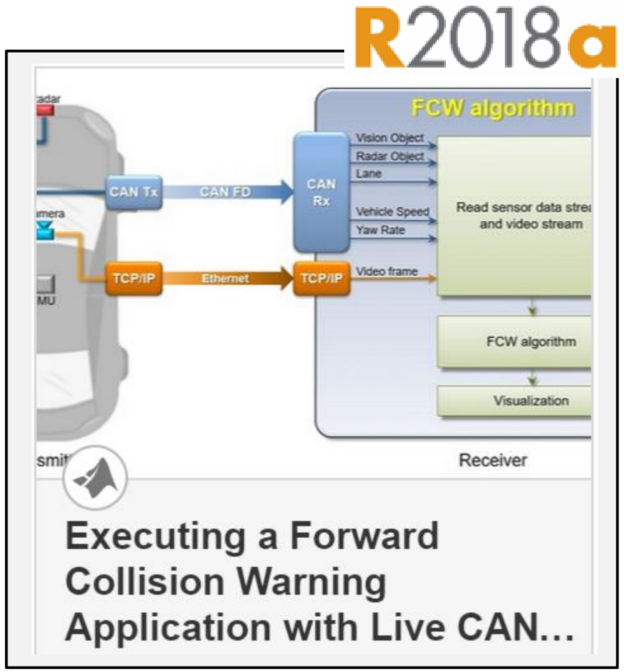
Generate C/C++ code for algorithm



Stream live CAN FD and TCP/IP data into compiled algorithm code

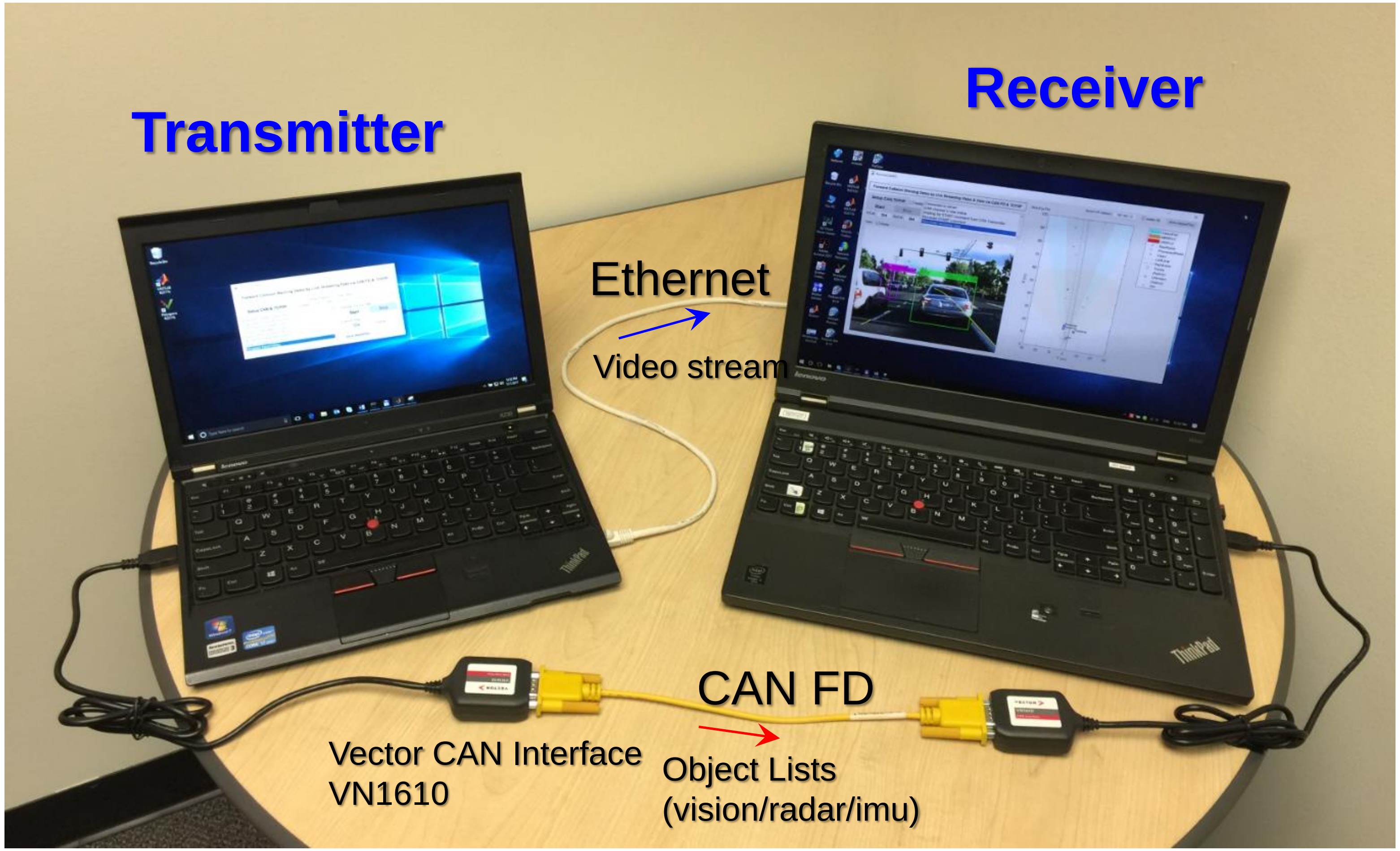


Learn about developing sensor fusion algorithms with live data using this example



- **Stream CAN FD** data to prototype algorithms on your laptop

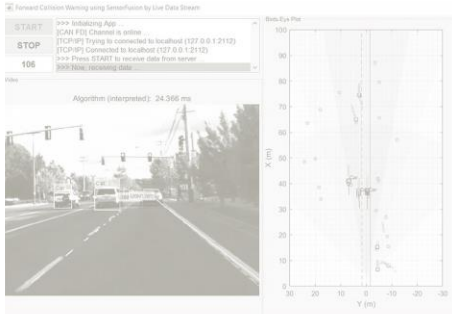
Vehicle Network Toolbox™



How can you use MATLAB and Simulink to develop control algorithms?

Deep learning

Sensor fusion with live data



Perception

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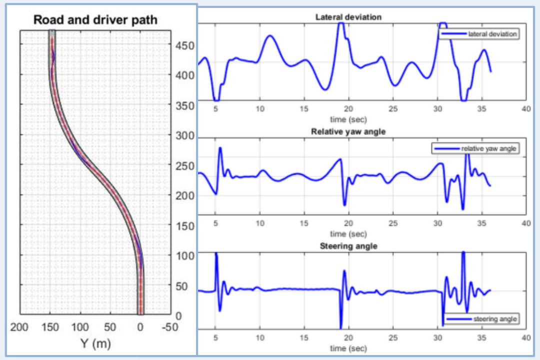
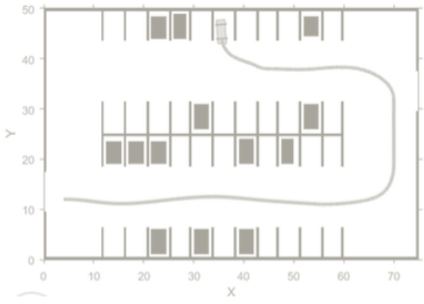
Sensor models & model predictive control

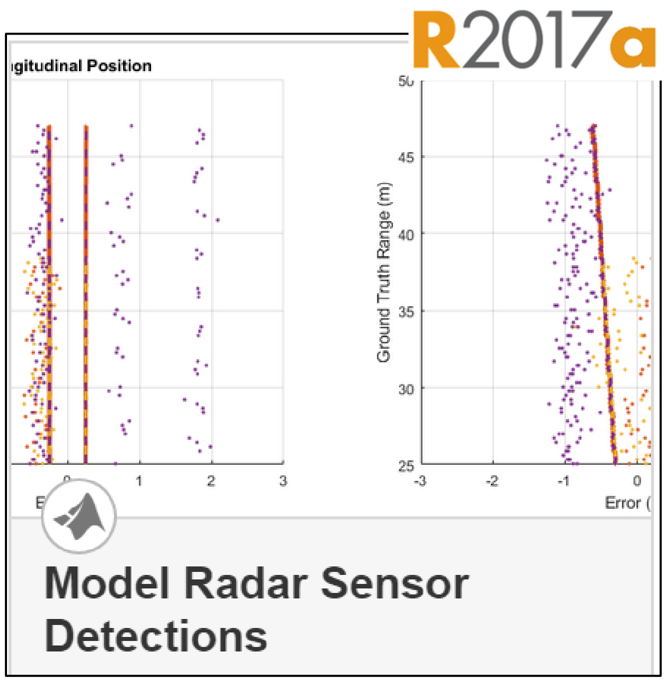


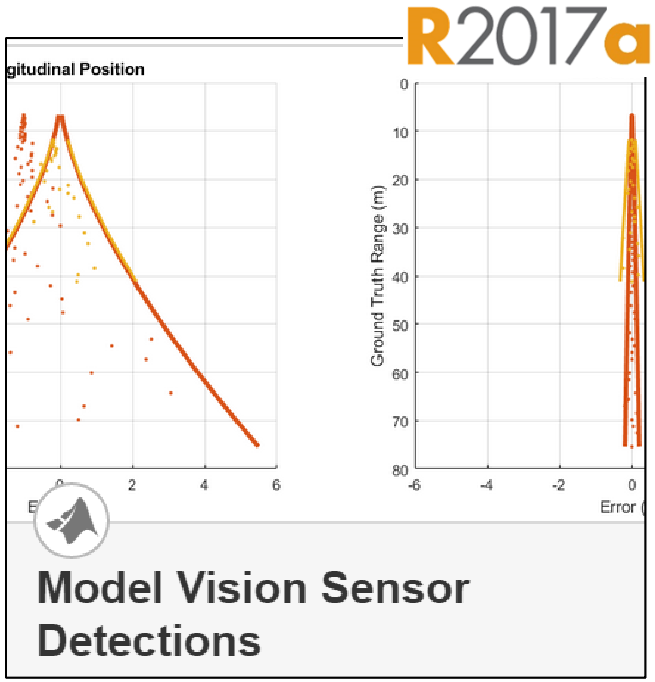
Path planning

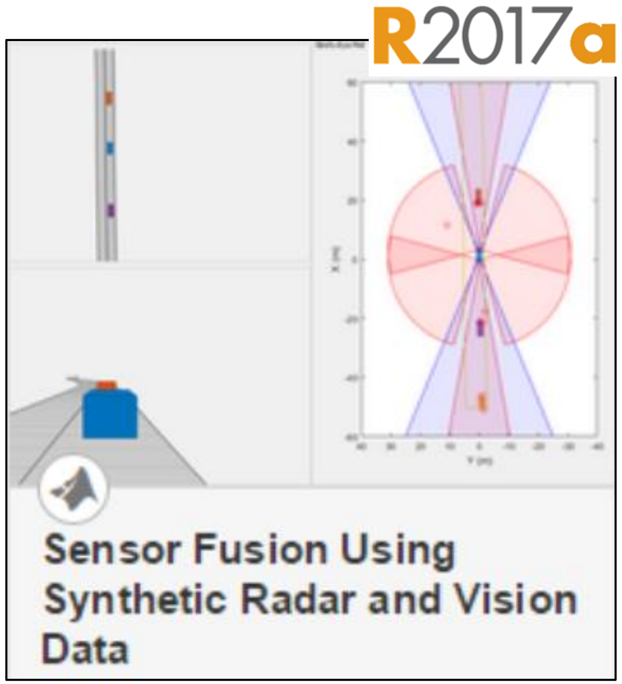


Automated Driving System Toolbox introduced examples to:

Synthesize detections to test sensor fusion algorithms



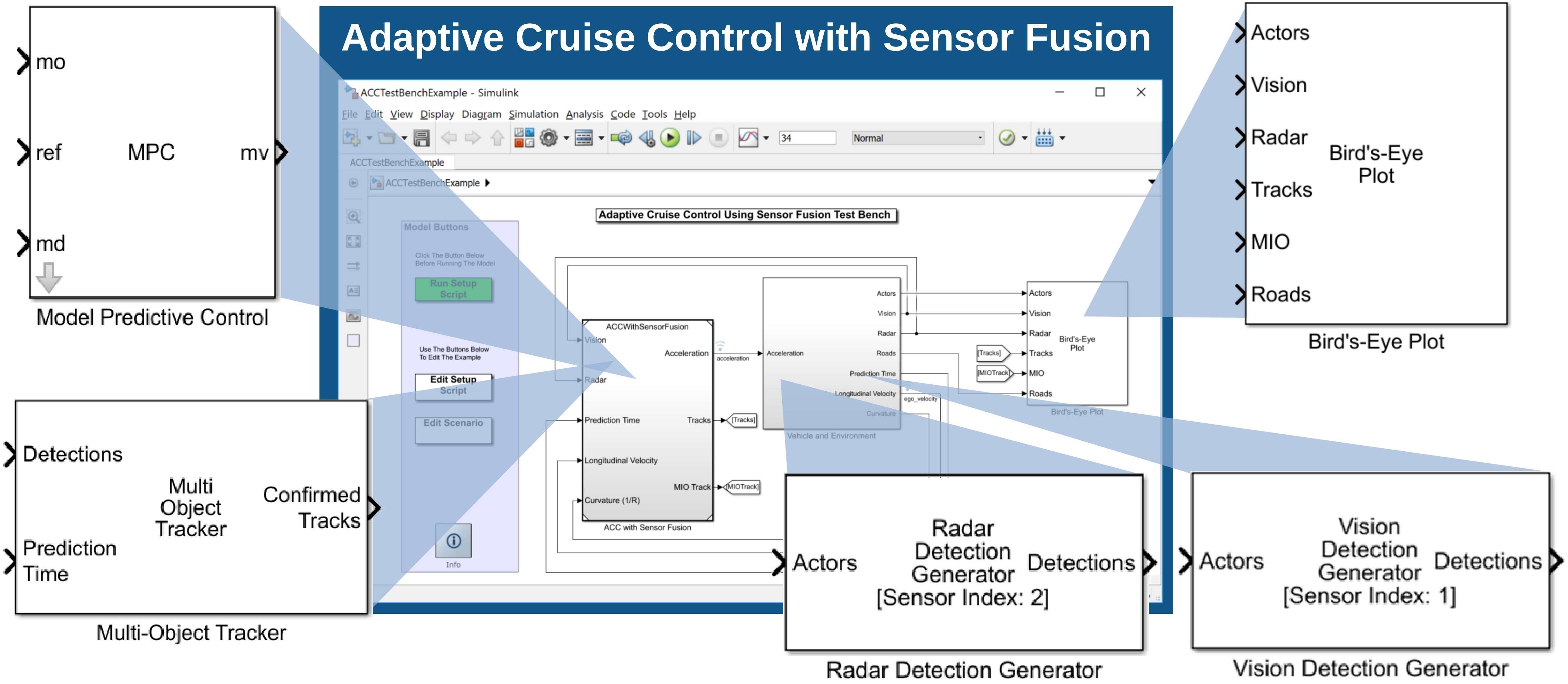




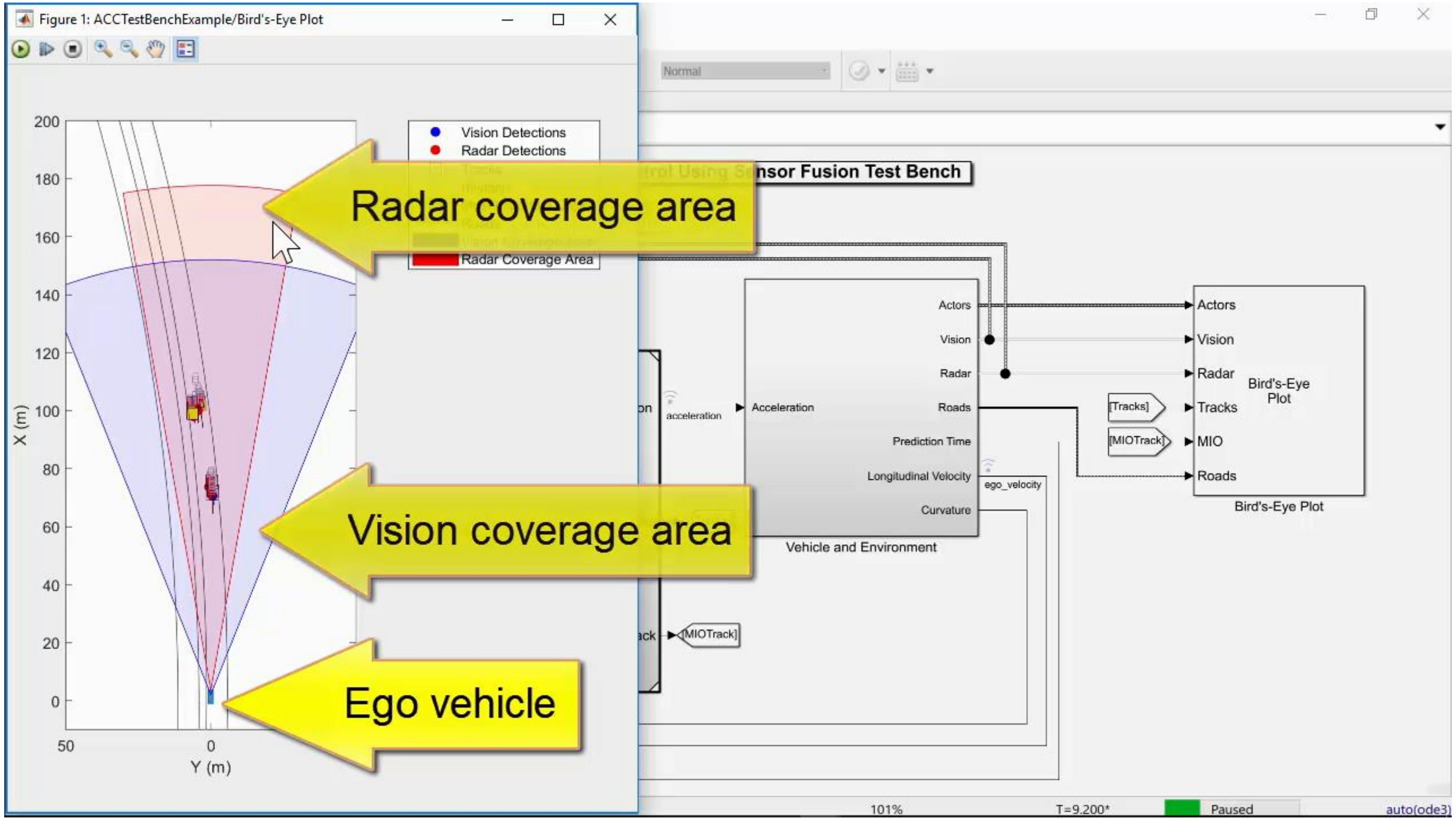
- **Synthesize radar** detections with probabilistic impairments
- **Synthesize vision** detections with probabilistic impairments
- **Synthesize scenario** to test multi-object tracker

Simulate closed loop system with radar/vision detections, sensor fusion, and model-predictive control

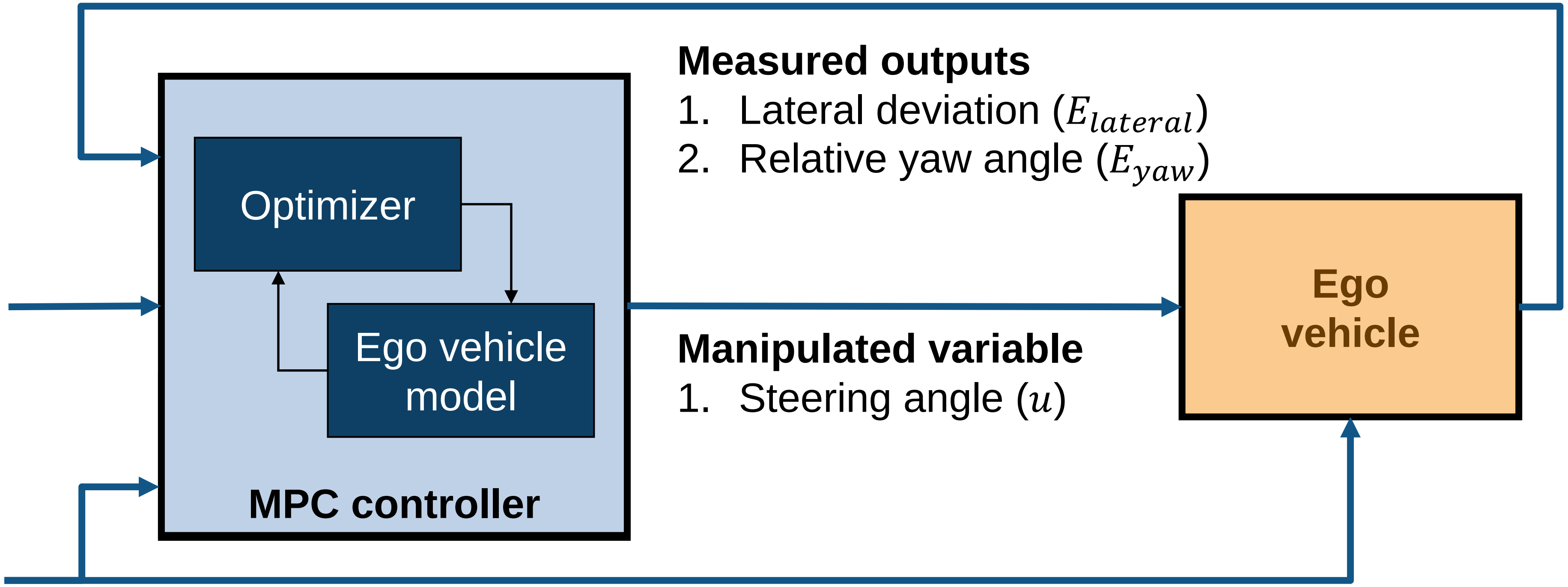
R2017b



Synthesize detections to test sensor fusion and model-predictive controller



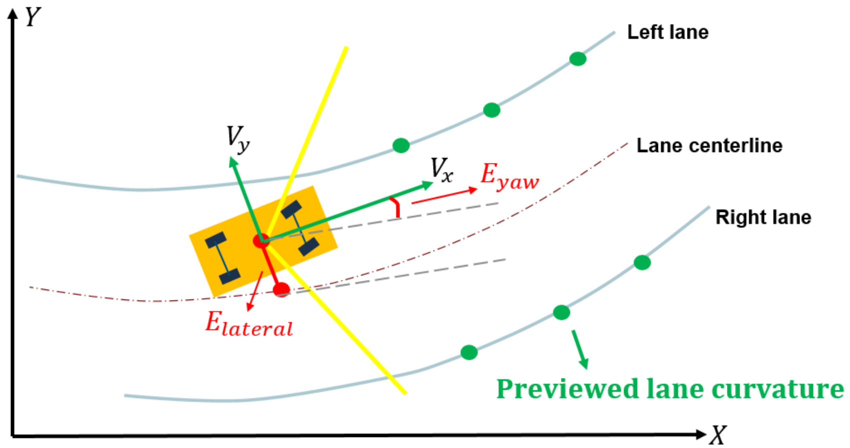
How can MPC be applied to lane keeping control?



References
1. For $E_{lateral}$ (0)
2. For E_{yaw} (0)

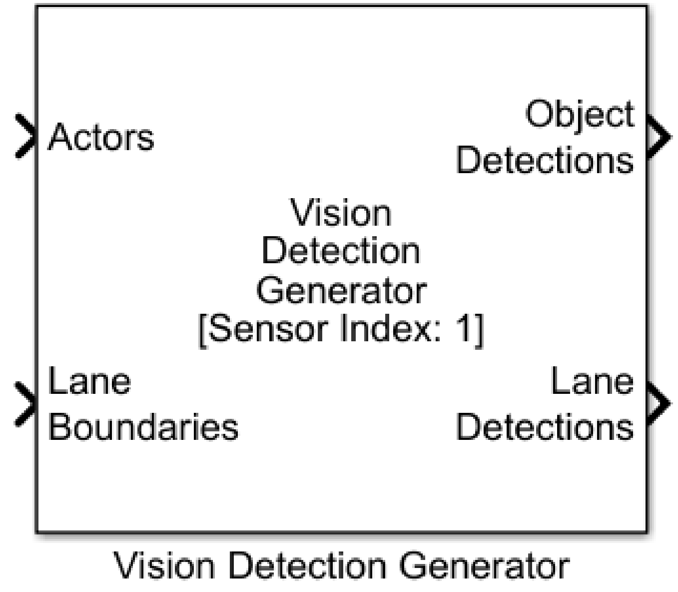
Measured disturbance
1. Previewed curvature

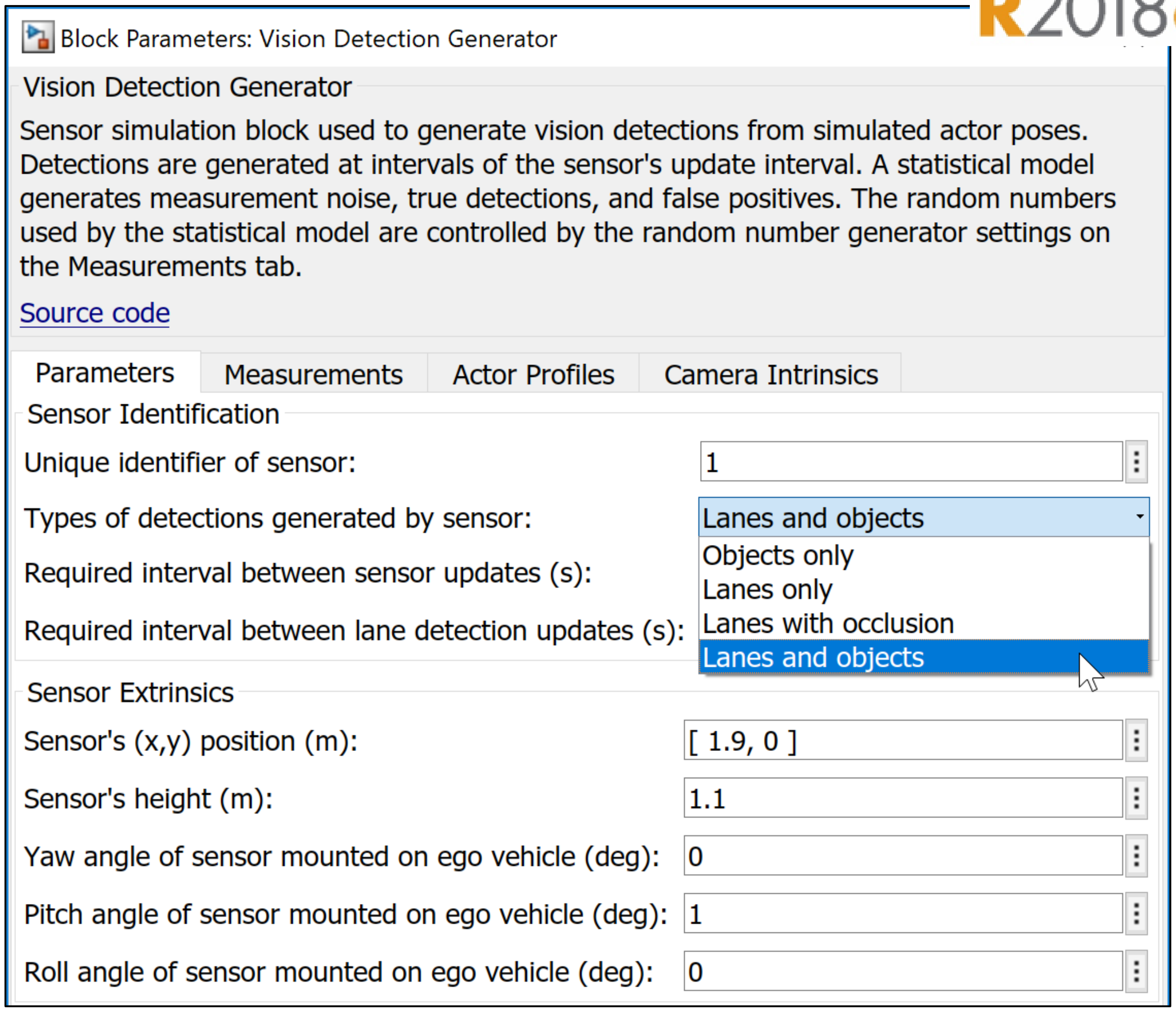
minimize: $|E_{lateral}|^2 + |E_{yaw}|^2$
subject to: $u_{min} \leq u \leq u_{max}$



Vision Detection Generator models lane detection sensor

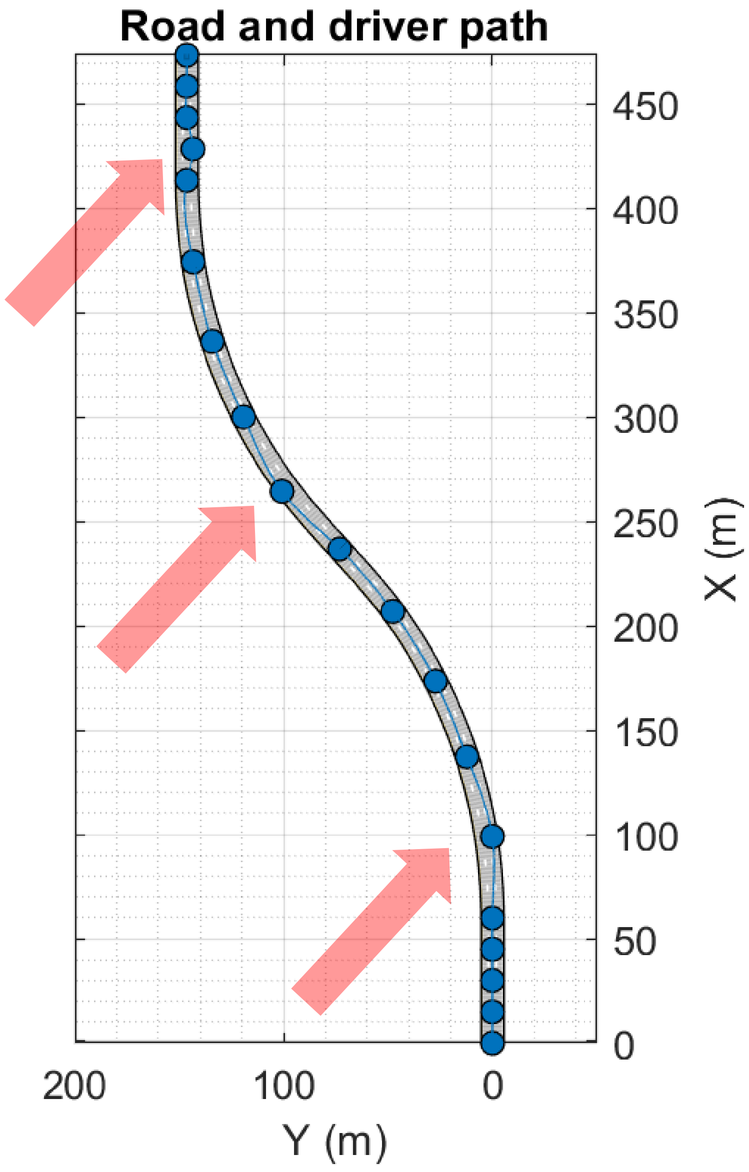
R2018a

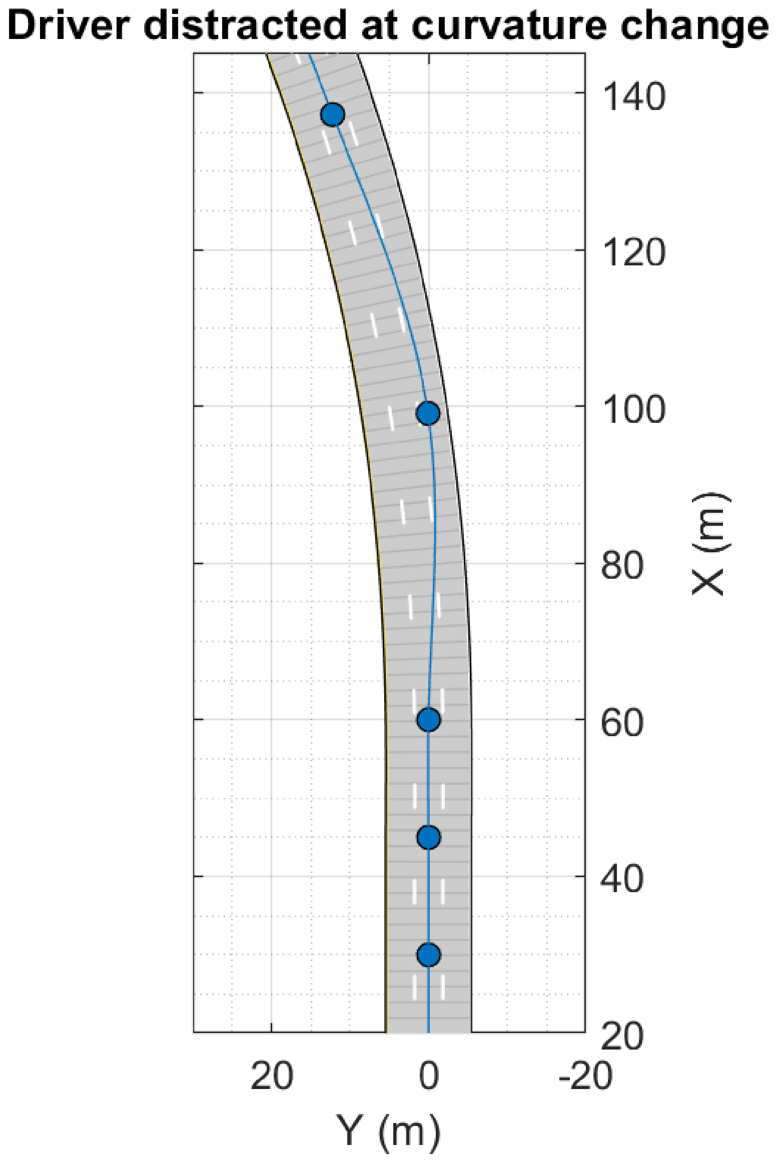




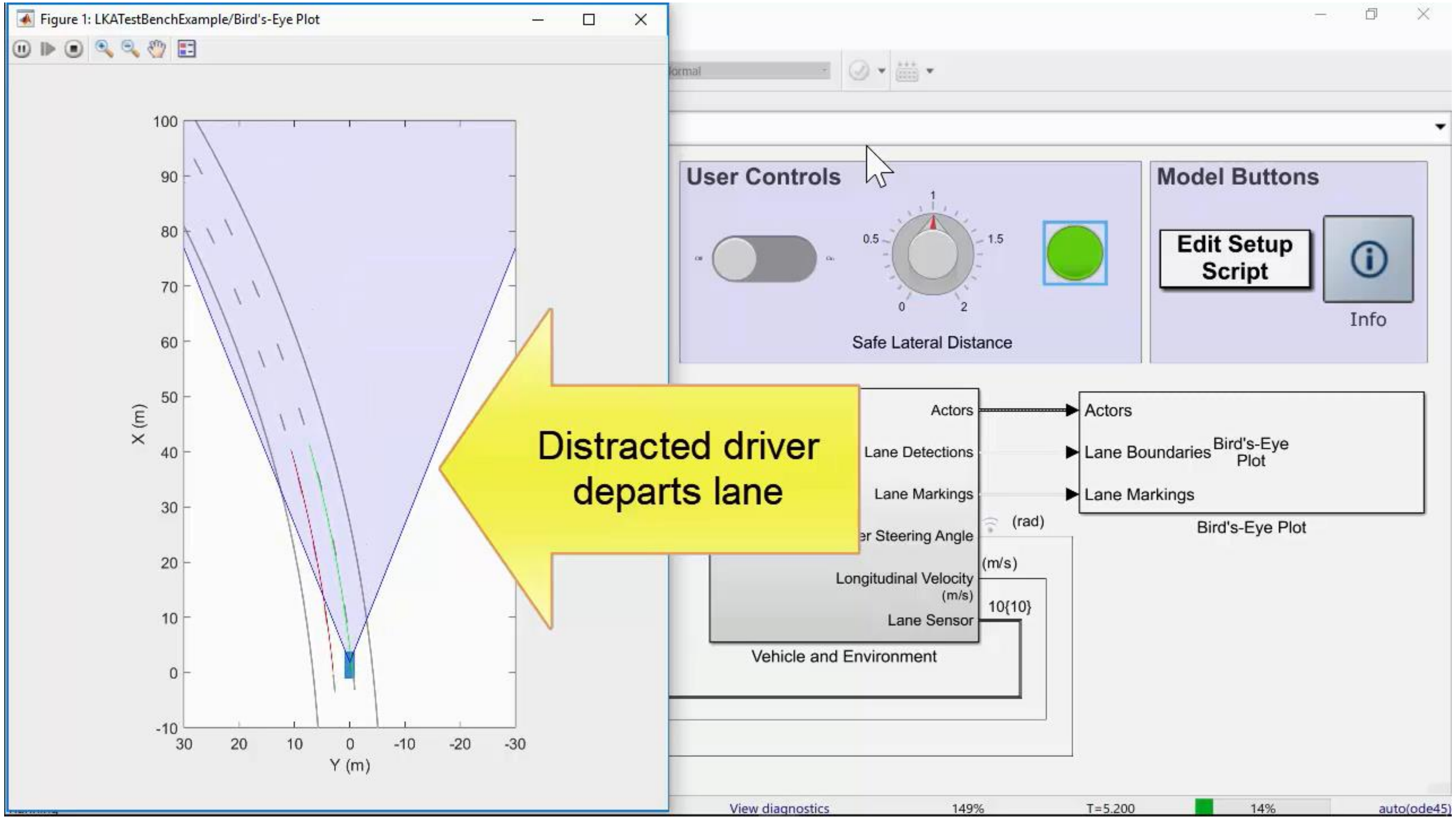
Create highway double curve with drivingScenario

- Driver waypoints simulate distraction at curvature changes

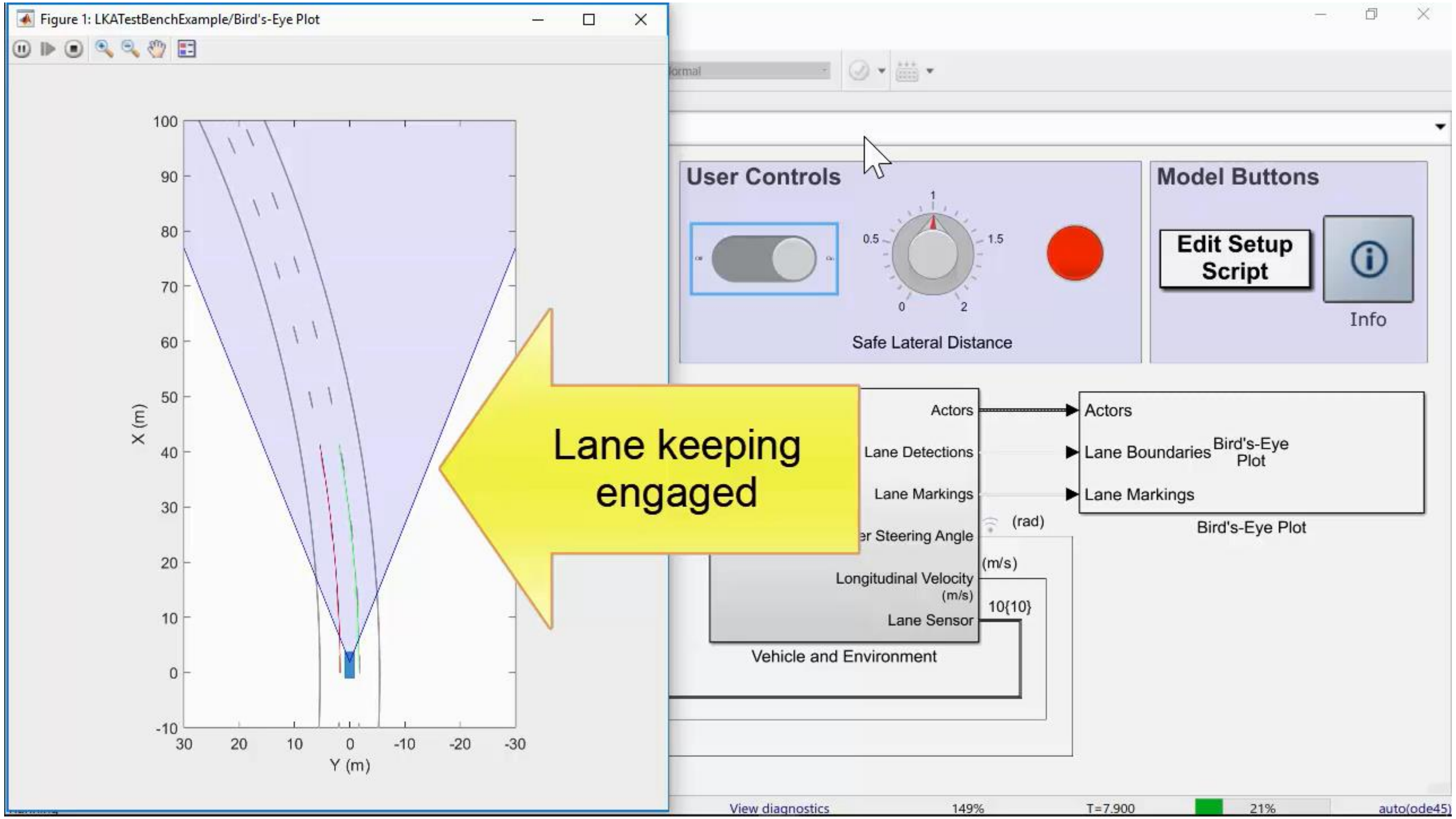




Simulate distracted driver

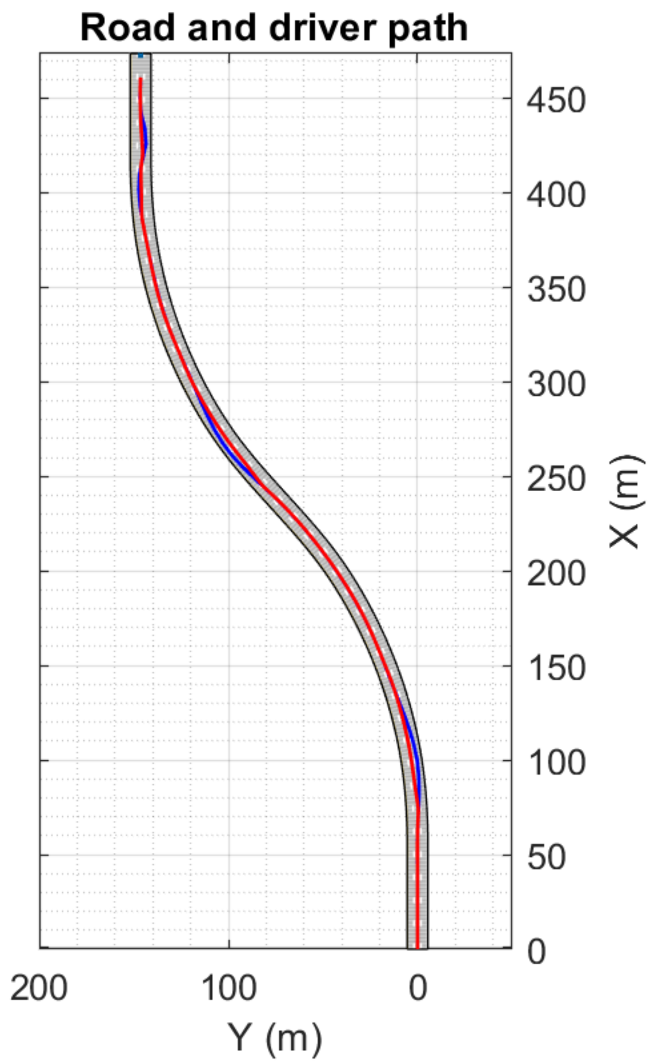


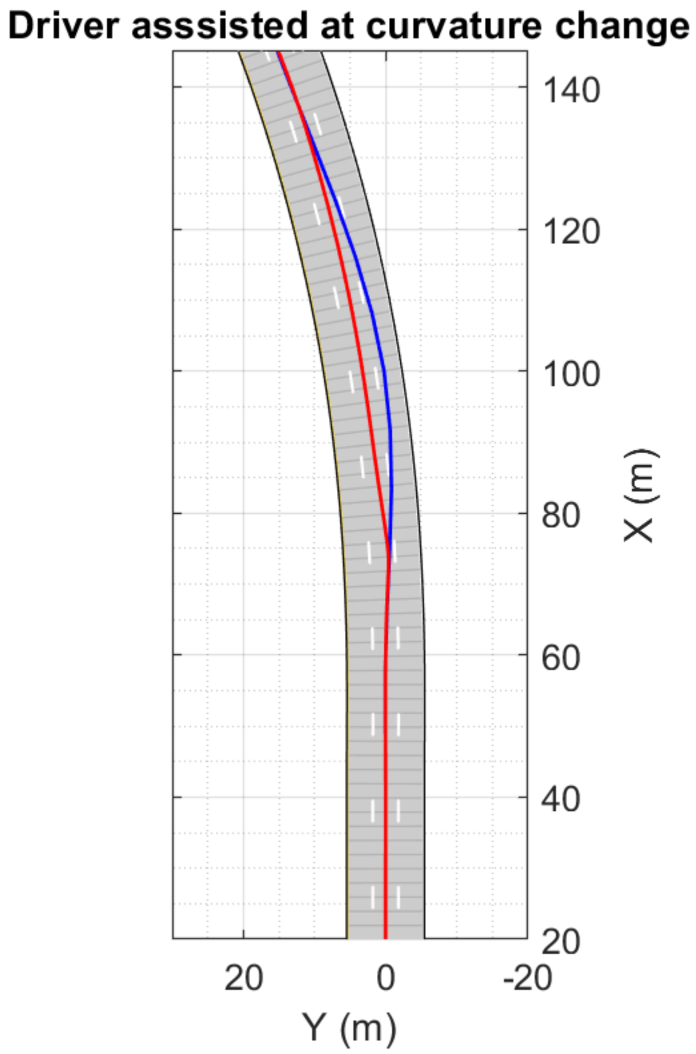
Simulate lane keep assist at distraction events



Compare distracted and assisted results

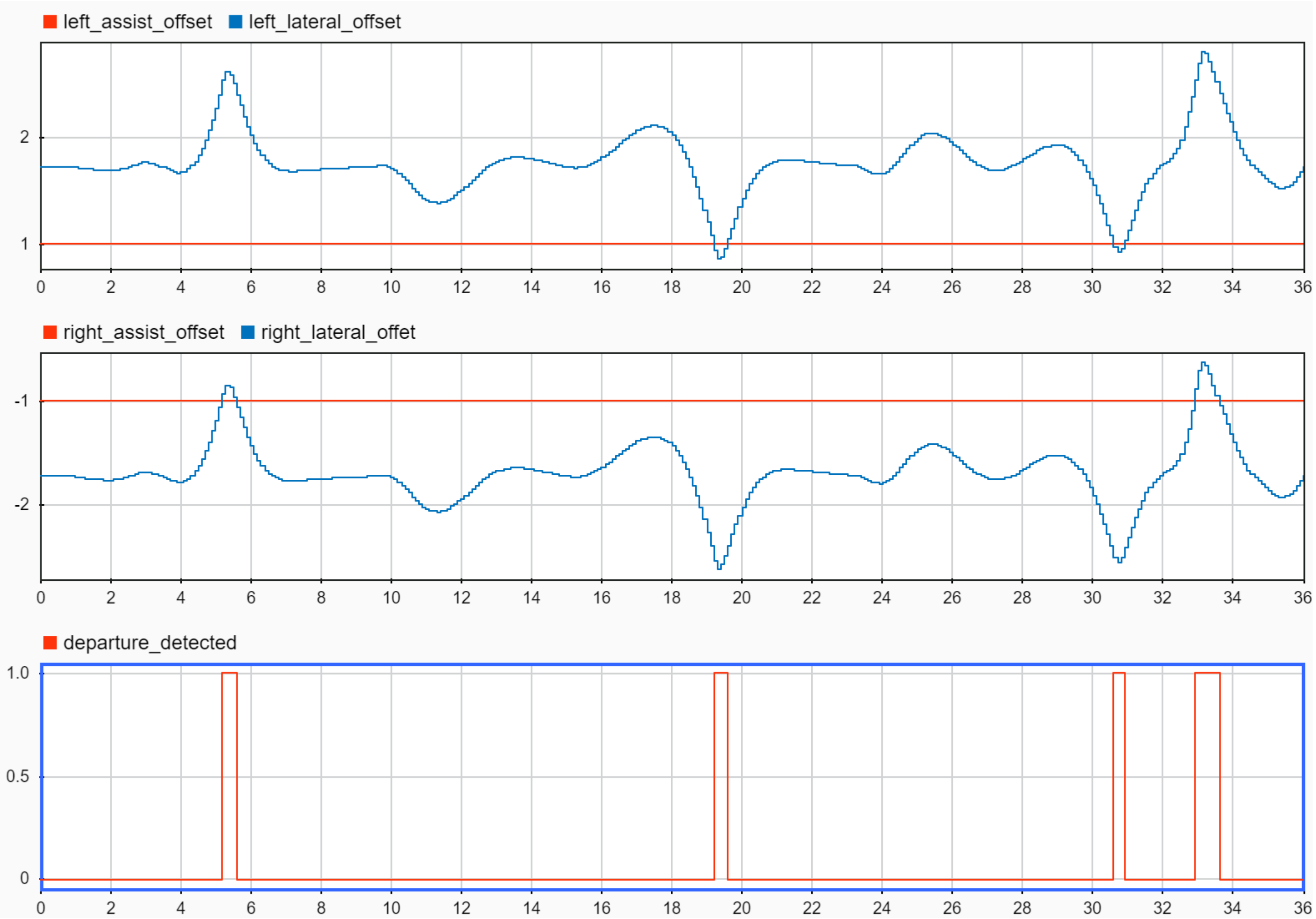
- Detect lane departure and maintain lane during distraction



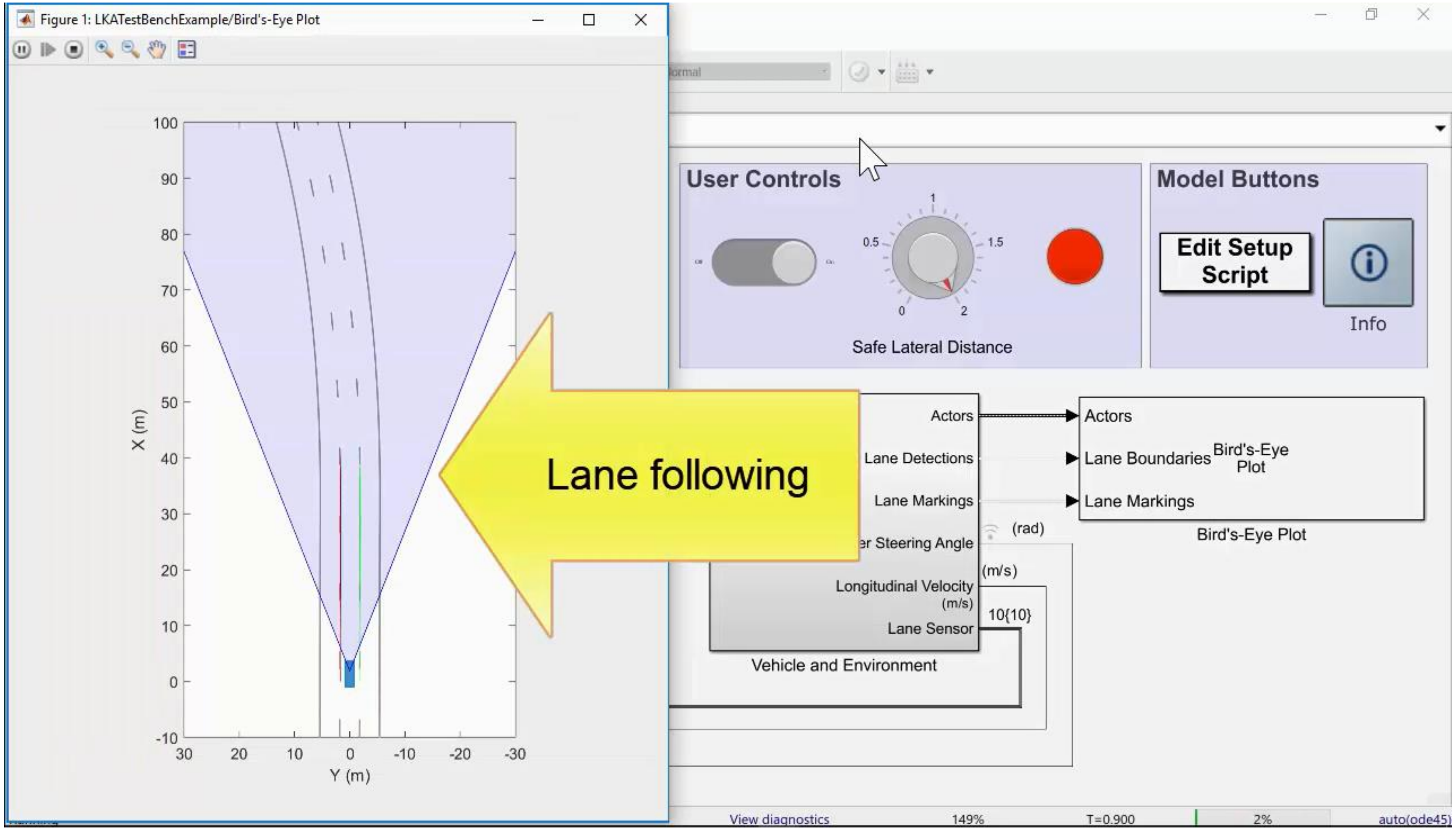


Detect departure based on lateral offset to lane boundary

Max Safe Lateral Distance from Lane Boundary

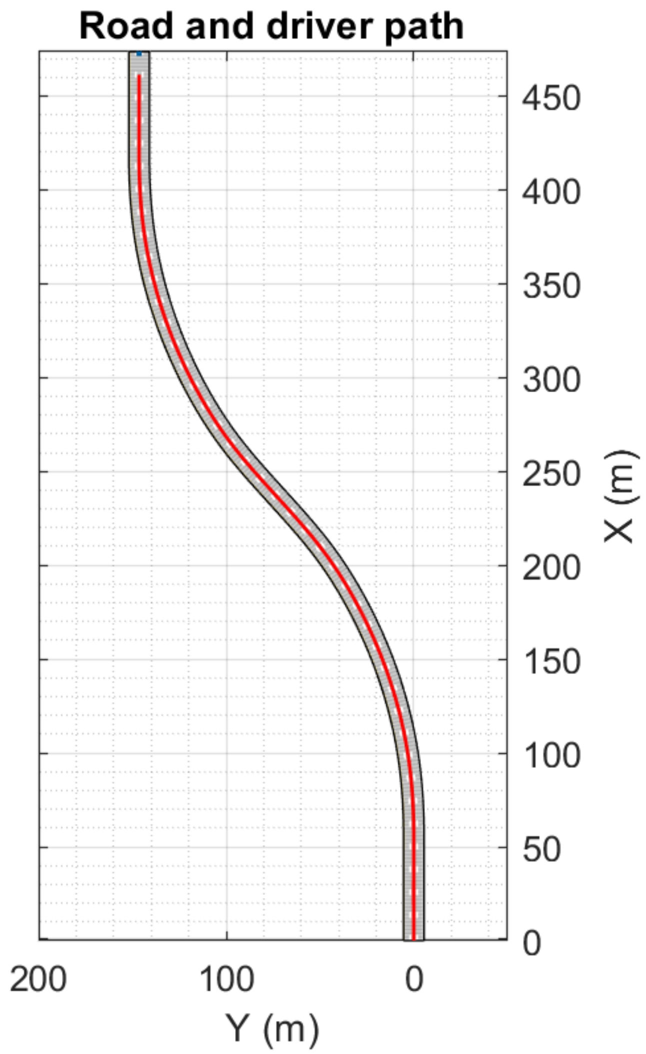


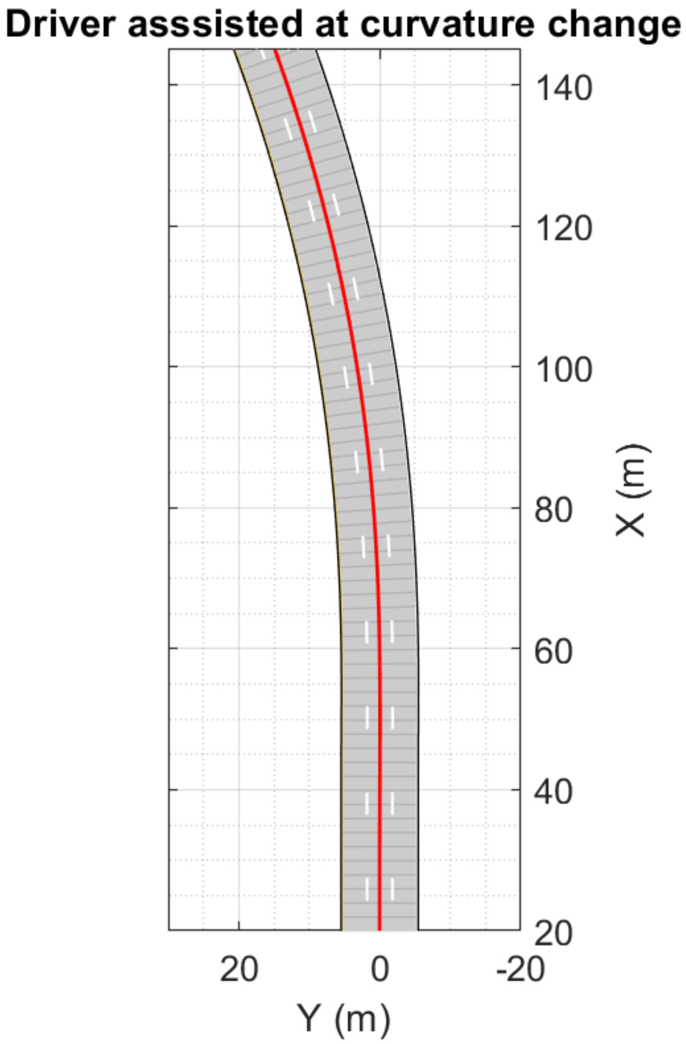
Simulate lane following by increasing minimum safe distance



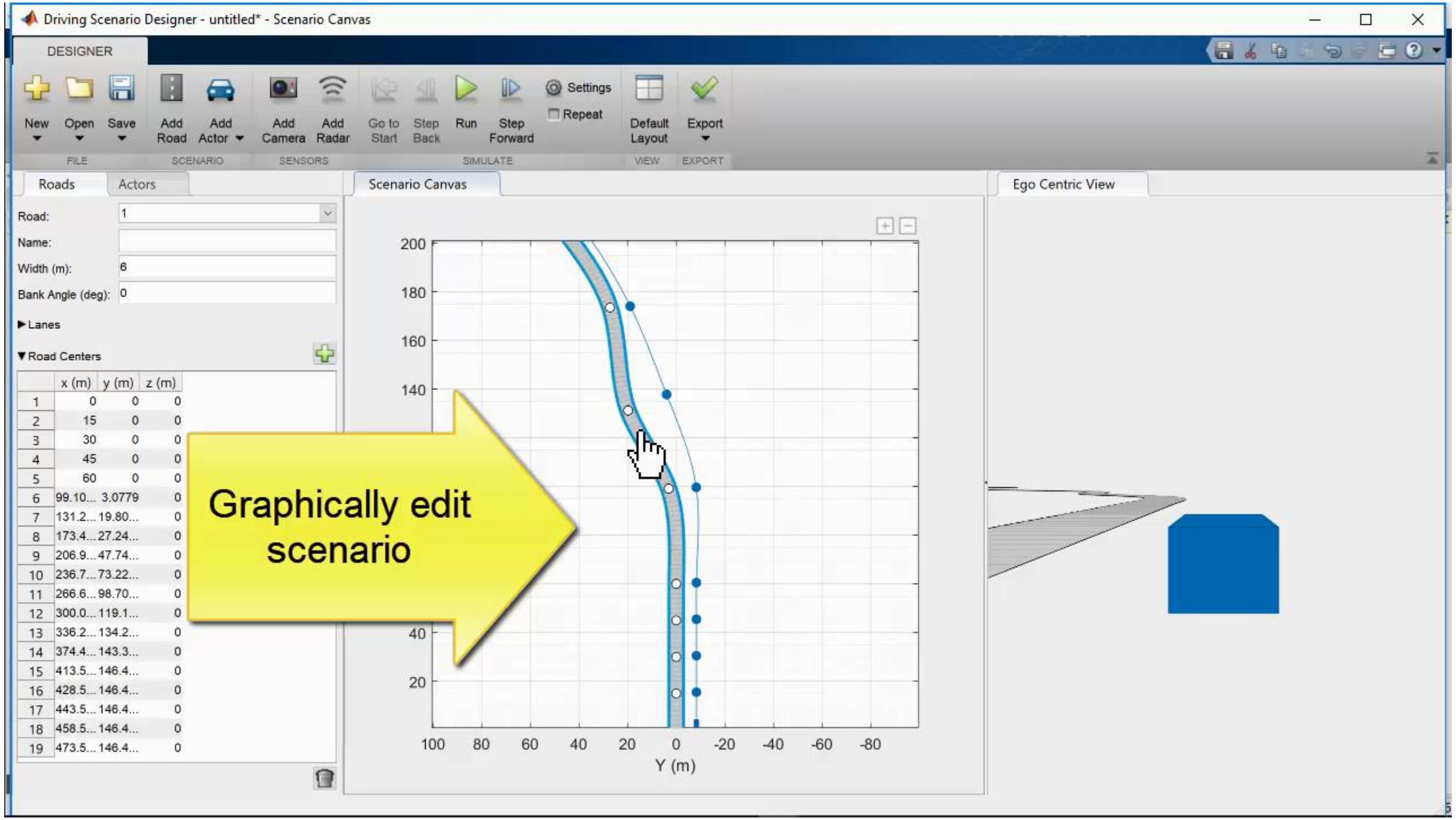
Explore lane following results

- Vehicle stays within lane boundaries

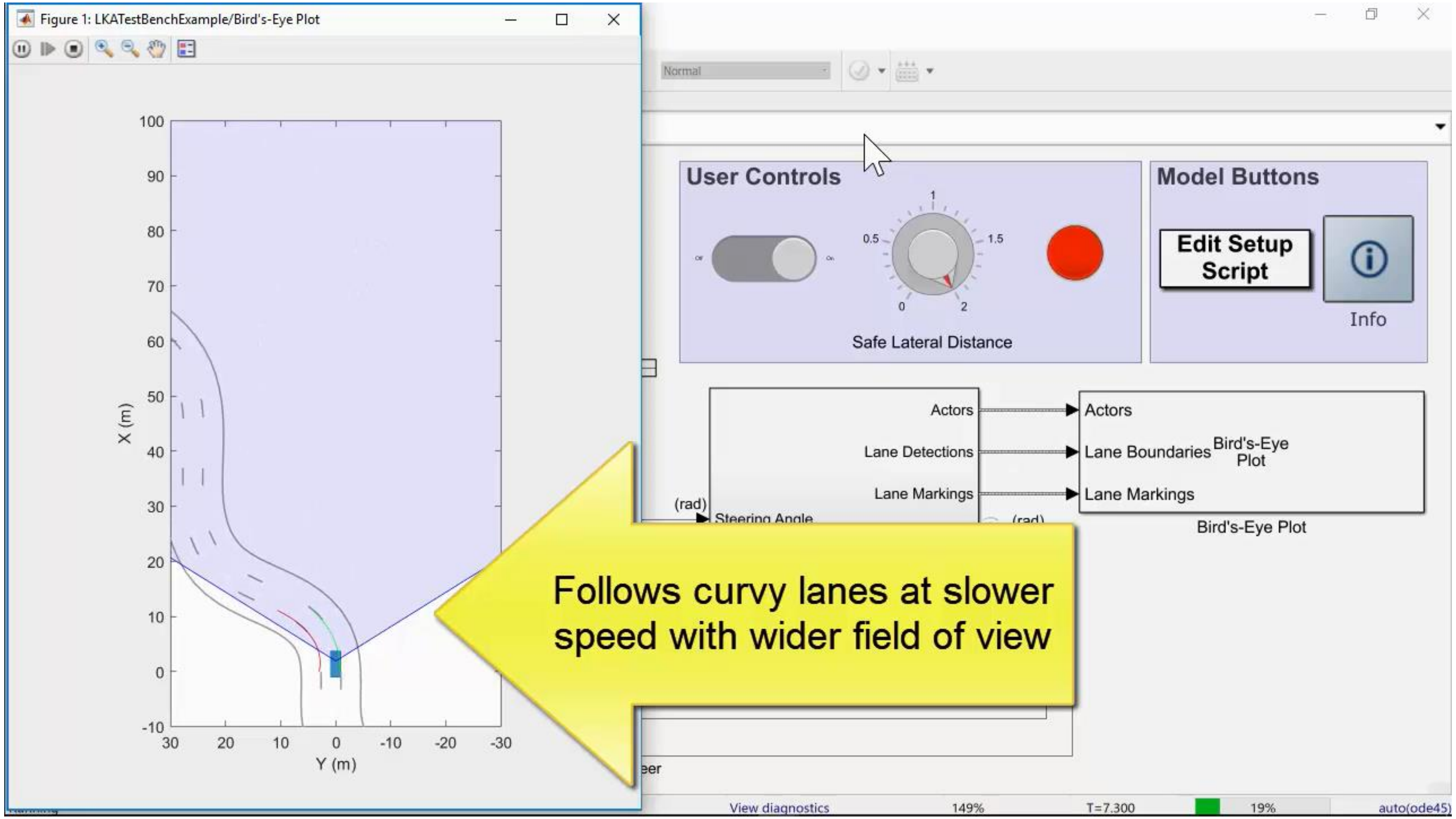




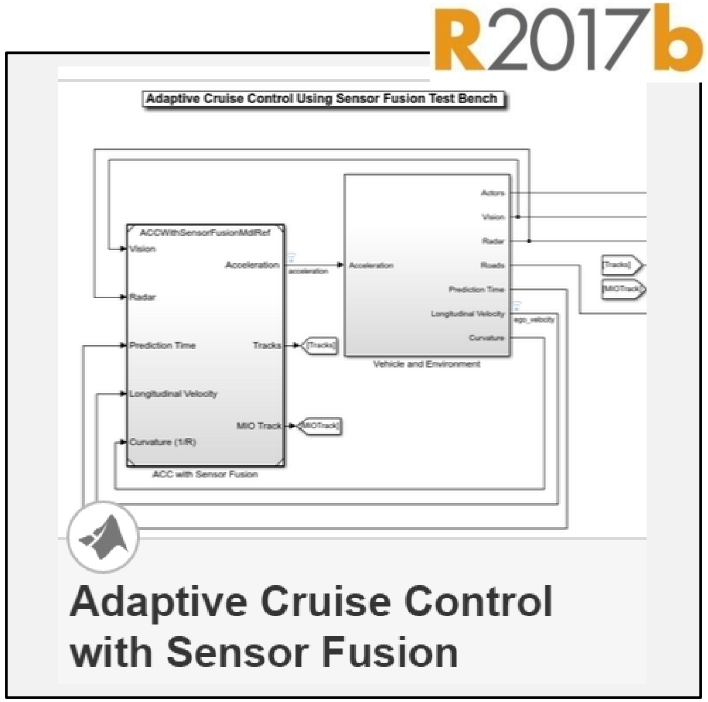
Graphically edit scenarios with Driving Scenario Designer



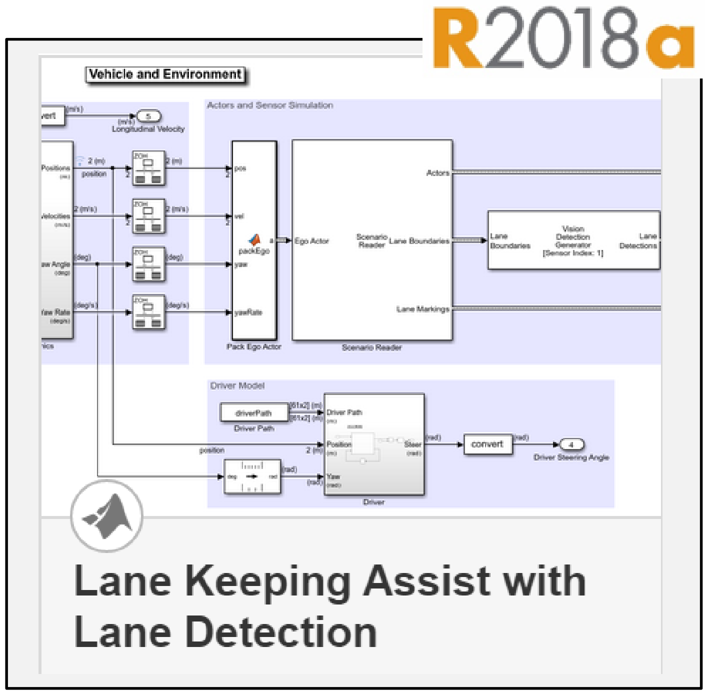
Explore what is required to follow high curvature paths



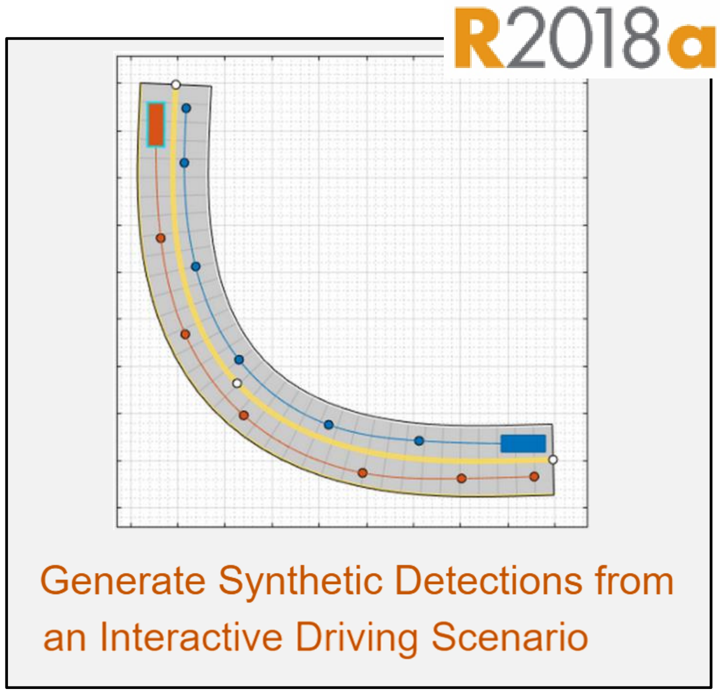
Learn about synthesizing sensor detections to develop control algorithms with these examples



- **Simulate and generate C++** for model-predictive control and sensor fusion algorithms

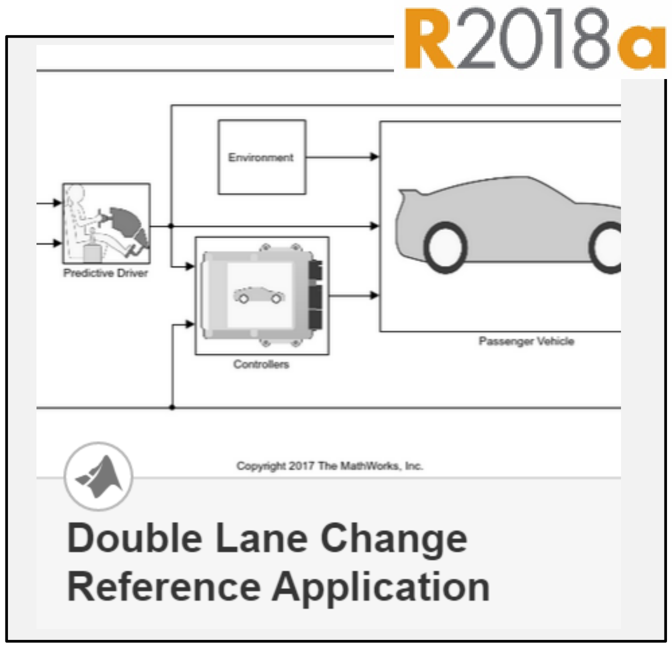


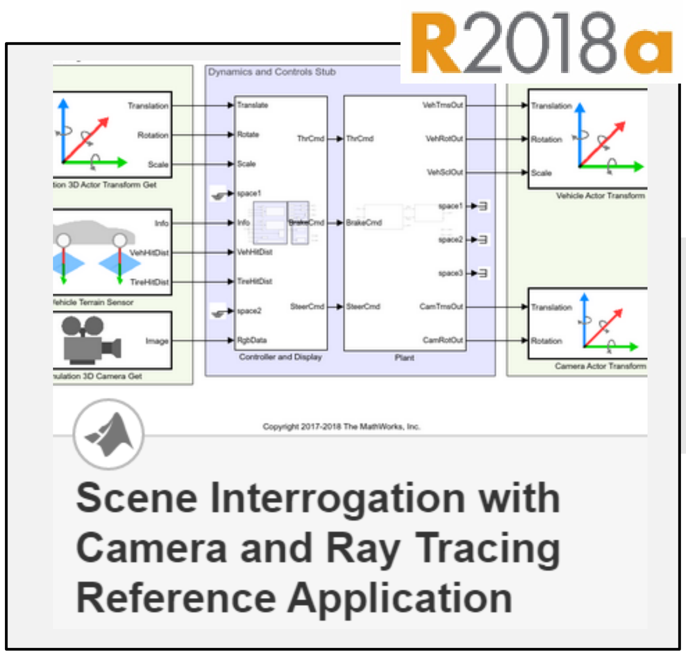
- **Simulate and generate C++** for model-predictive control with lane detections

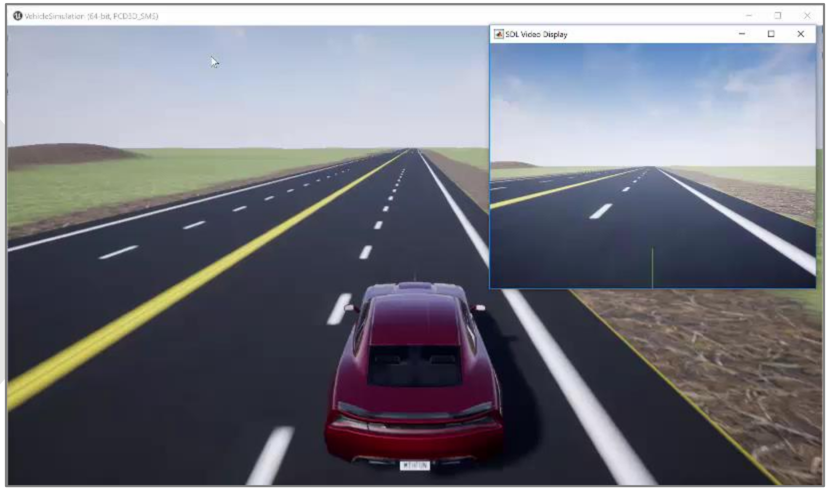


- **Edit roads, cuboid actors, and sensors** with Driving Scenario Designer App `drivingScenarioDesigner`

Learn about modeling vehicle dynamics to develop control algorithms with these examples







- **Simulate vehicle dynamics** for closed loop design

  Vehicle Dynamics Blockset™

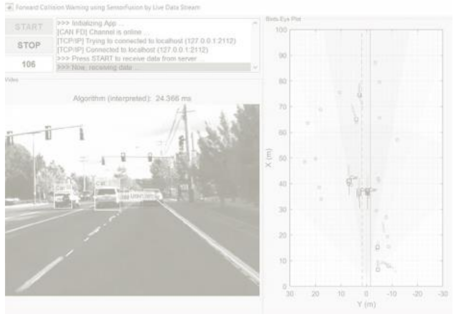
- **Co-simulate with Unreal Engine** and to set actor positions get camera image

  Vehicle Dynamics Blockset™

How can you use MATLAB and Simulink to develop planning algorithms?

Deep learning

Sensor fusion
with live data

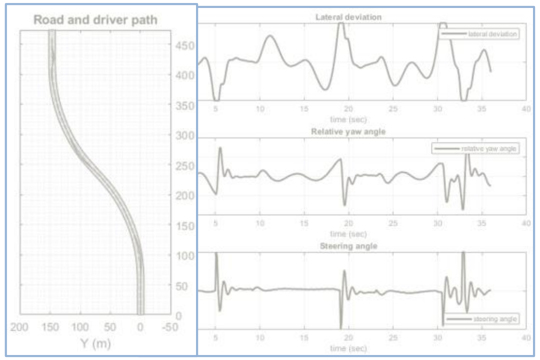


Perception

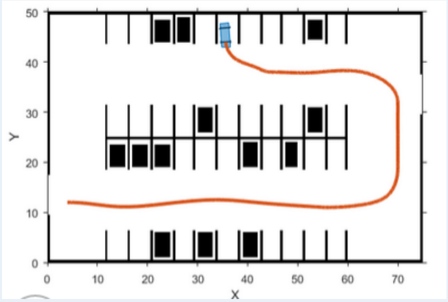
Control

Planning

Sensor models &
model predictive control

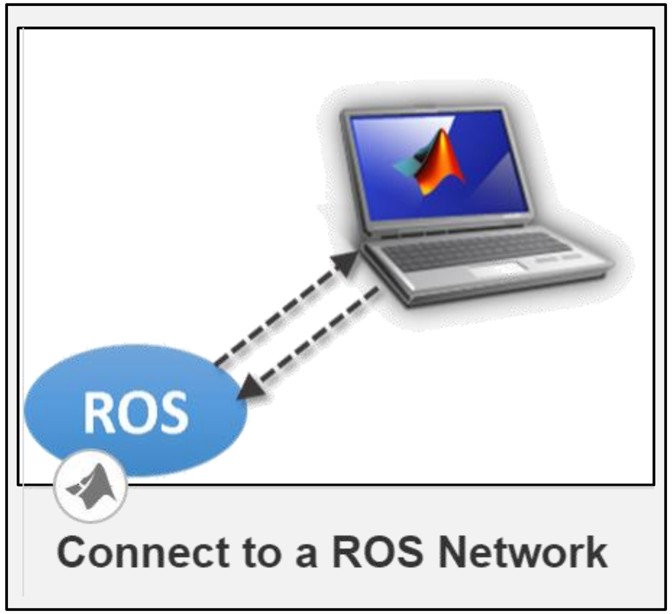


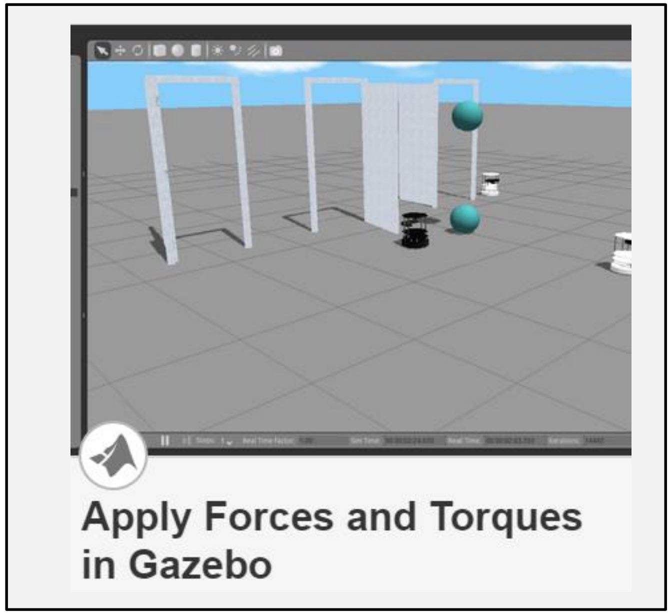
Path planning

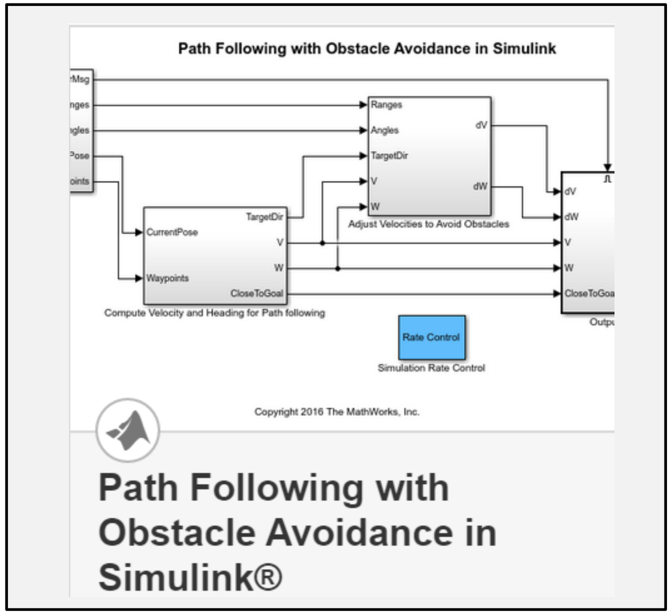


Robotics System Toolbox introduced:

Connectivity with the ROS ecosystem

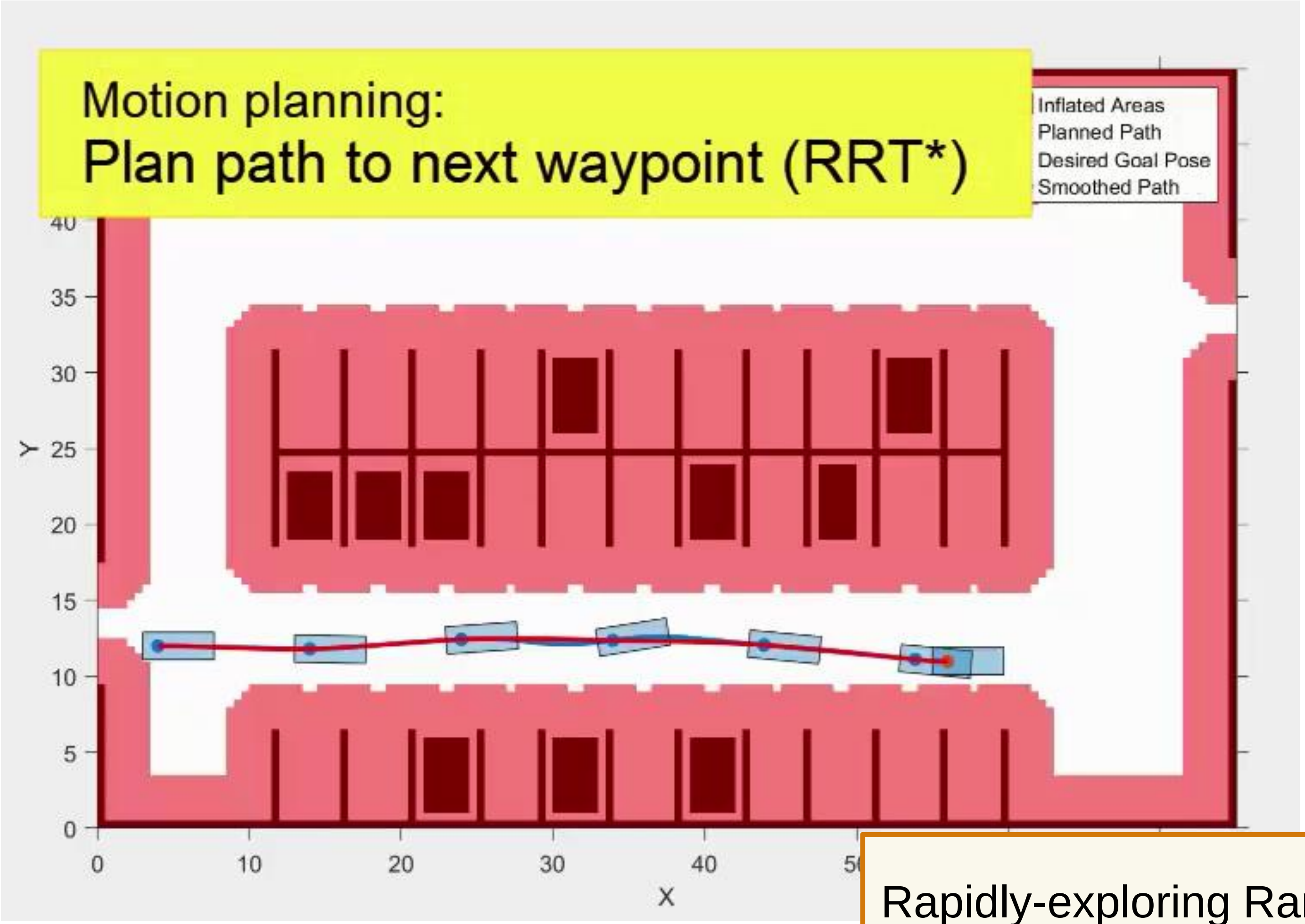






- **Communicate via ROS** to integrate with externally authored ROS components
- **Communication with Gazebo** to visualize and simulated system
- **Follow path** for differential drive robot with ROS based simulator

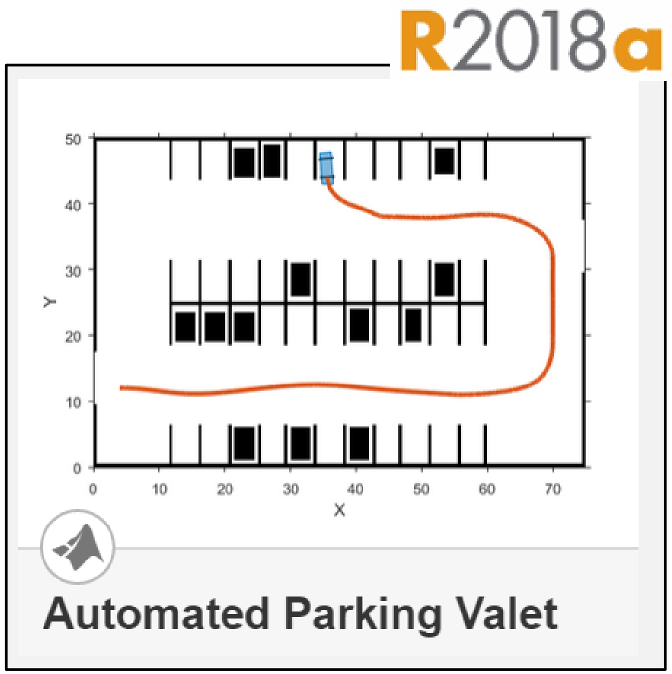
We are investing in design and simulation of path planning for automobiles

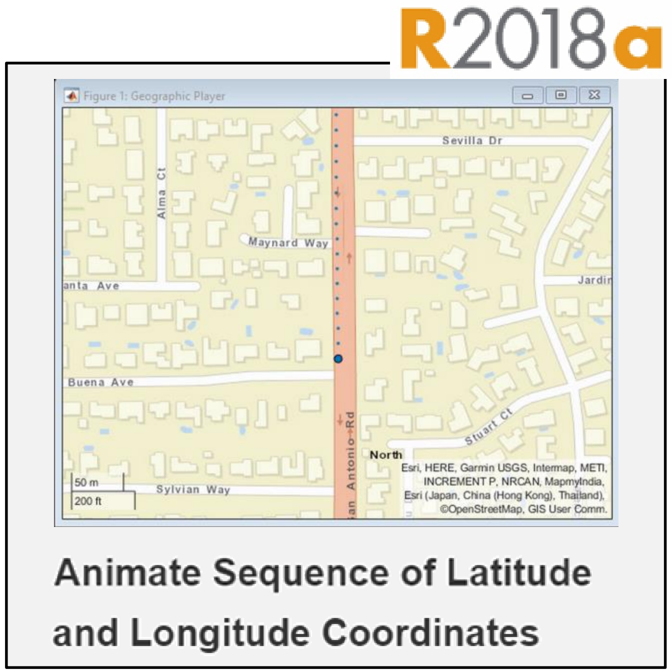


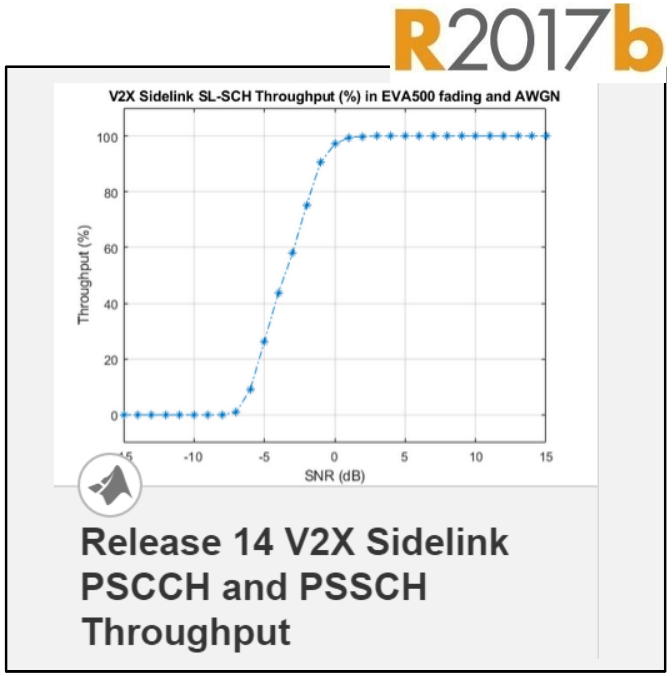
R2018a

Rapidly-exploring Random Tree (RRT*)

Learn about developing path planning algorithms with these examples







- **Plan path** for automobile given pre-defined map

  Automated Driving System Toolbox™

- **Plot map tiles** using World Street Map (Esri)

  Automated Driving System Toolbox™

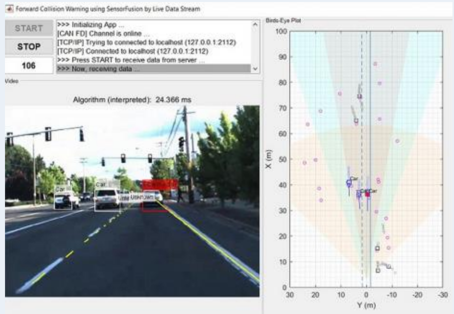
- **Simulate V2X communication** to assess channel throughput

  LTE System Toolbox™

Examples of how you can use MATLAB and Simulink to develop automated driving algorithms

Deep learning

Sensor fusion
with live data

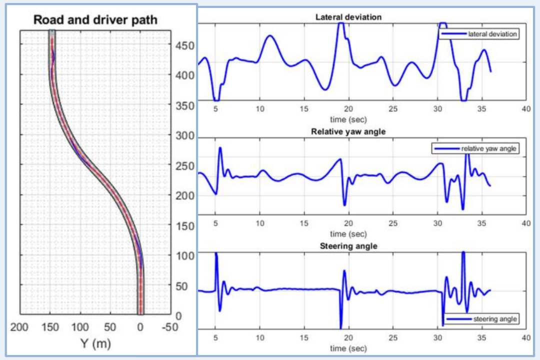


Perception

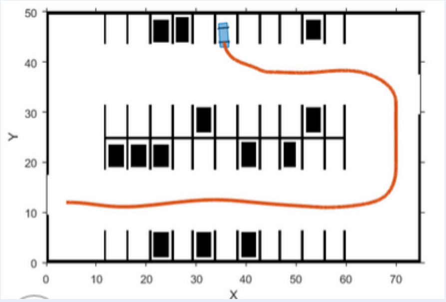
Control

Planning

Sensor models &
model predictive control

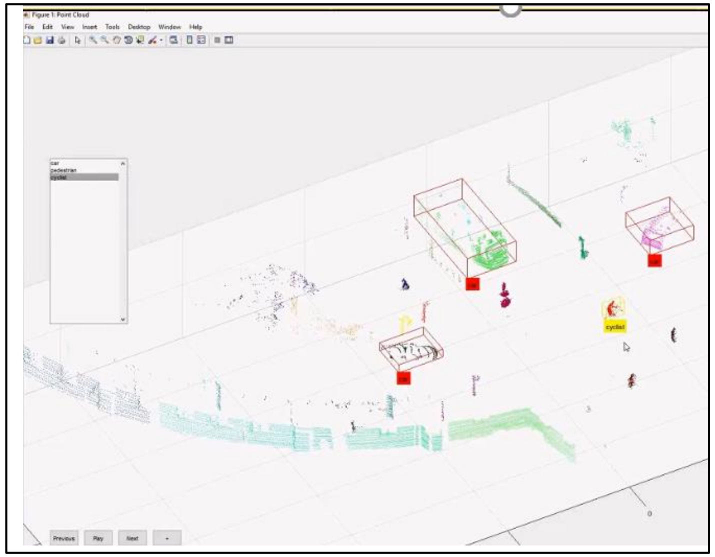


Path planning

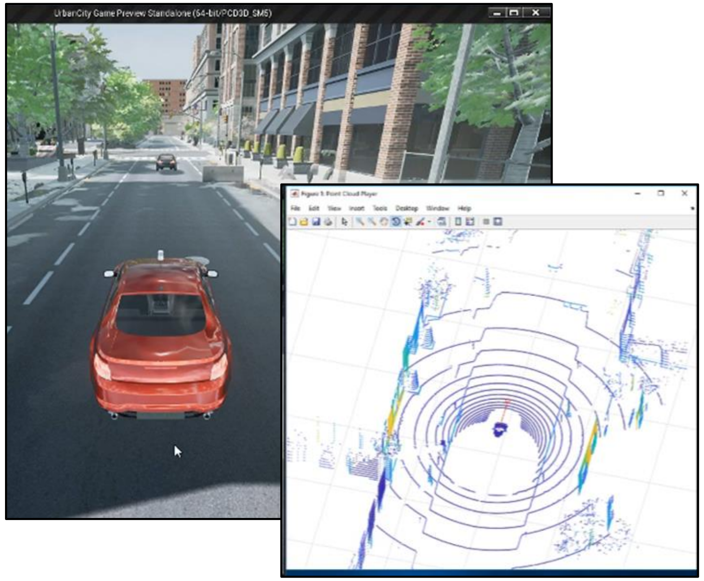


MathWorks can help you customize MATLAB and Simulink for your automated driving application

- **Web based ground truth labeling**
- Consulting project with Caterpillar
- [2017 MathWorks Automotive Conference]



- **Lidar ground truth labeling**
- Joint presentation with Autoliv
- 2018 MathWorks Automotive Conference (May 2nd, Plymouth MI)

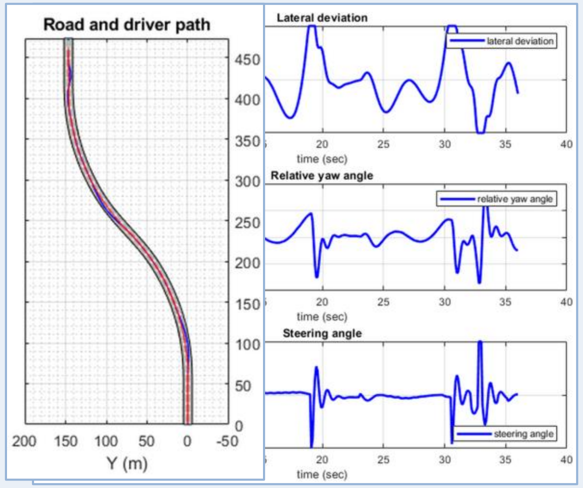


- **Lidar sensor model for Unreal Engine**
- Joint paper with Ford
- SAE Paper 2017-01-0107

How can we help you can use MATLAB and Simulink to develop automated driving algorithms?

Perception

Control



Planning