MathWorks

Introduction to Automated Driving System Toolbox:

Design and Verify Perception Systems

MATLAB Expo Germany 2017

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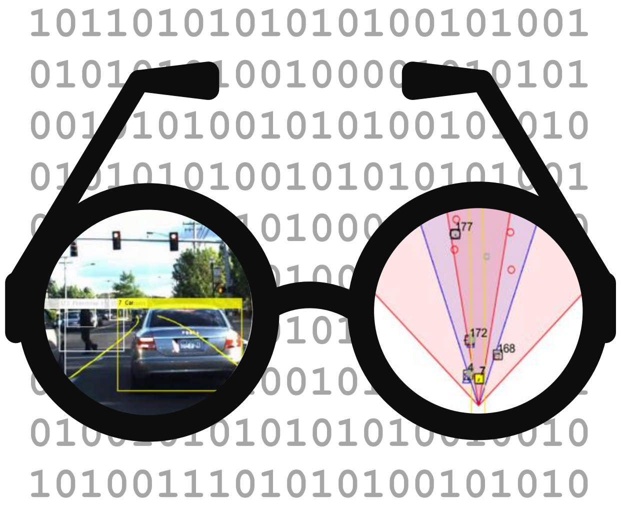
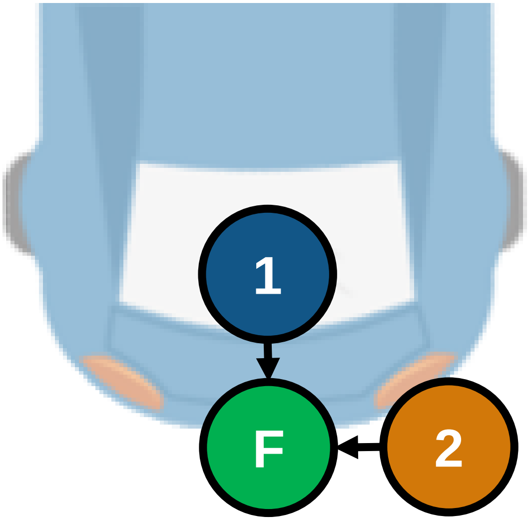
Some common questions from automated driving engineers



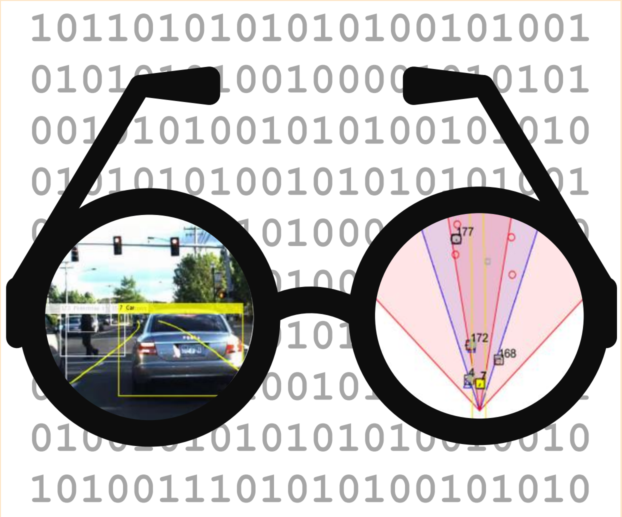
How can I visualize vehicle data?

How can I detect objects in images?

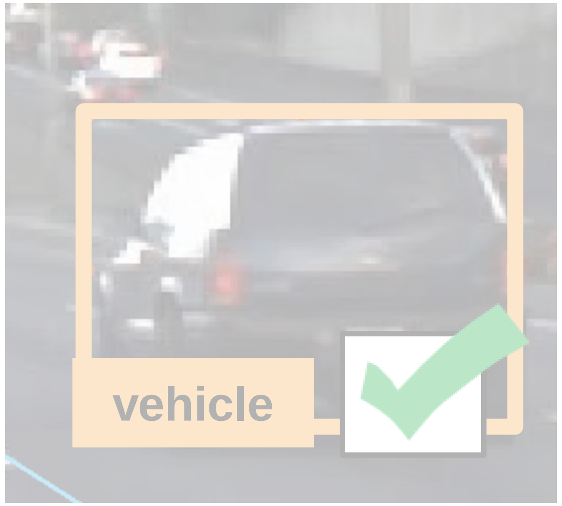


How can I fuse multiple detections?

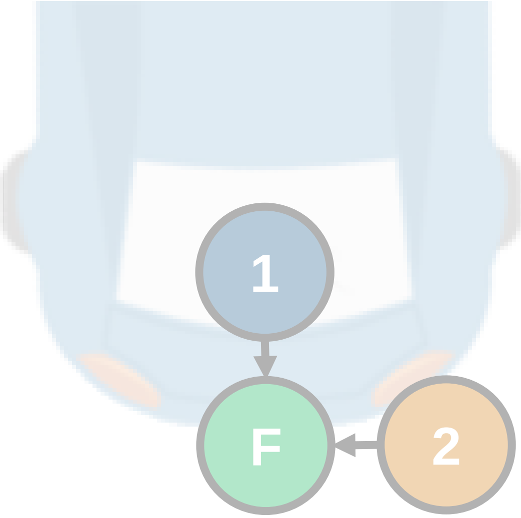
Some common questions from automated driving engineers



How can I visualize vehicle data?



How can I detect objects in images?



How can I fuse multiple detections?

Examples of automated driving sensors

Camera

Radar-based object detector

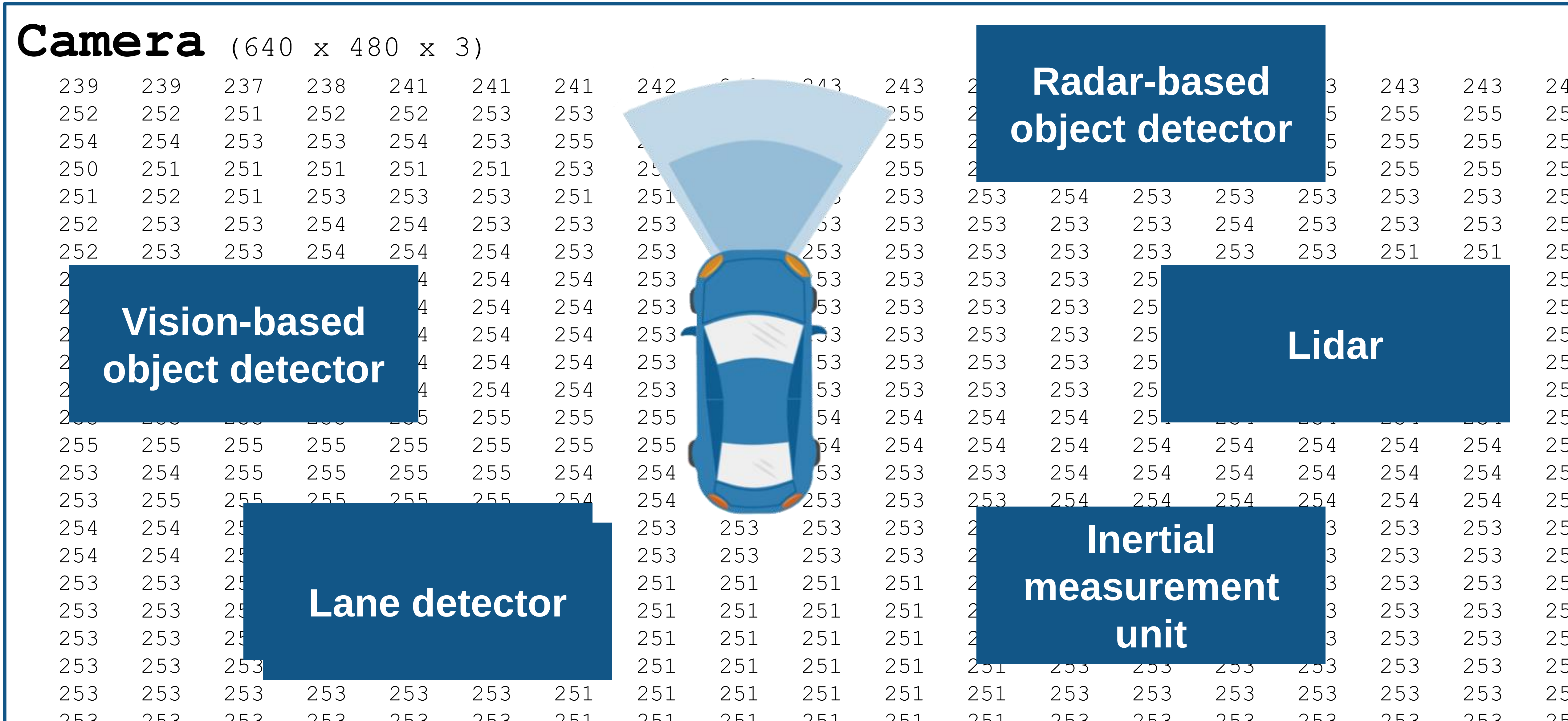
Vision-based object detector

Lidar

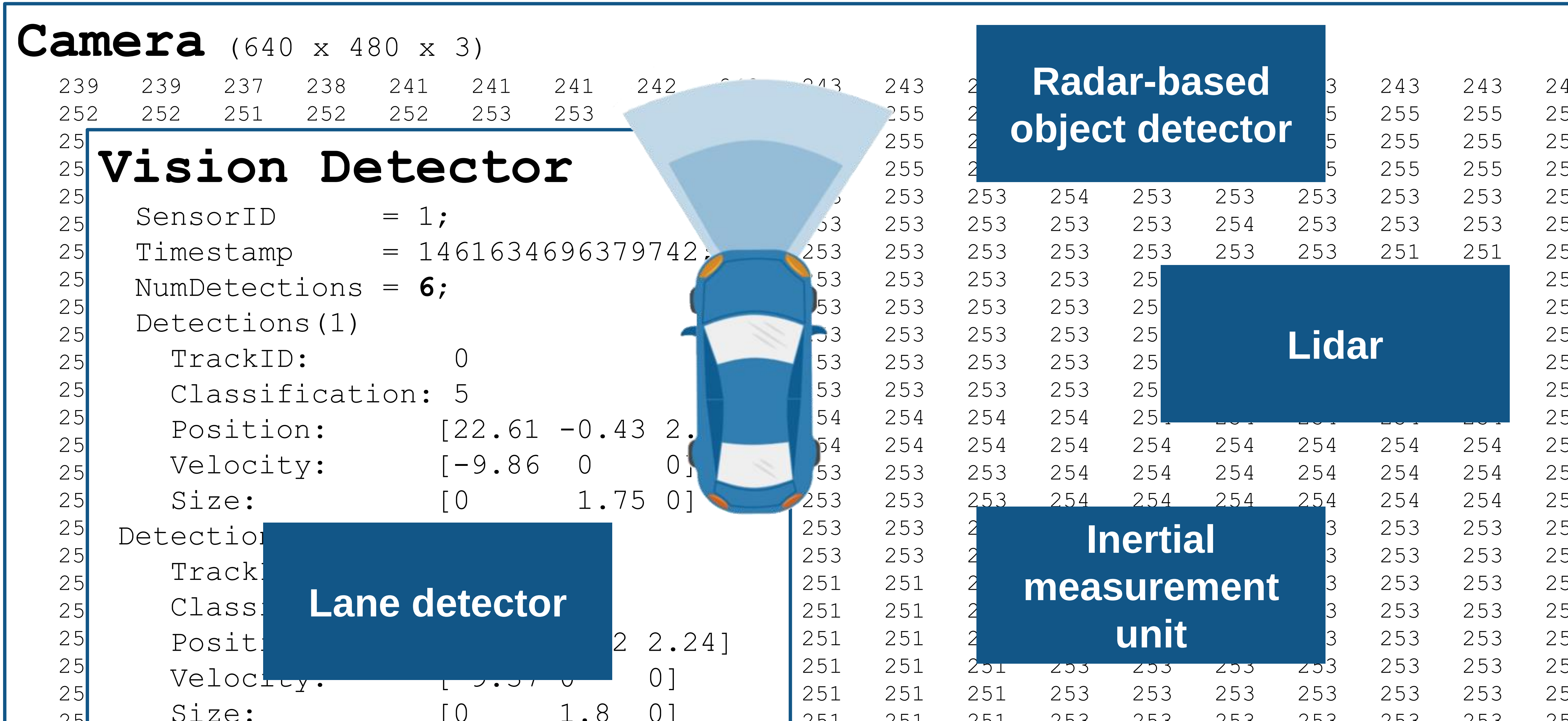
Lane detector

Inertial measurement unit

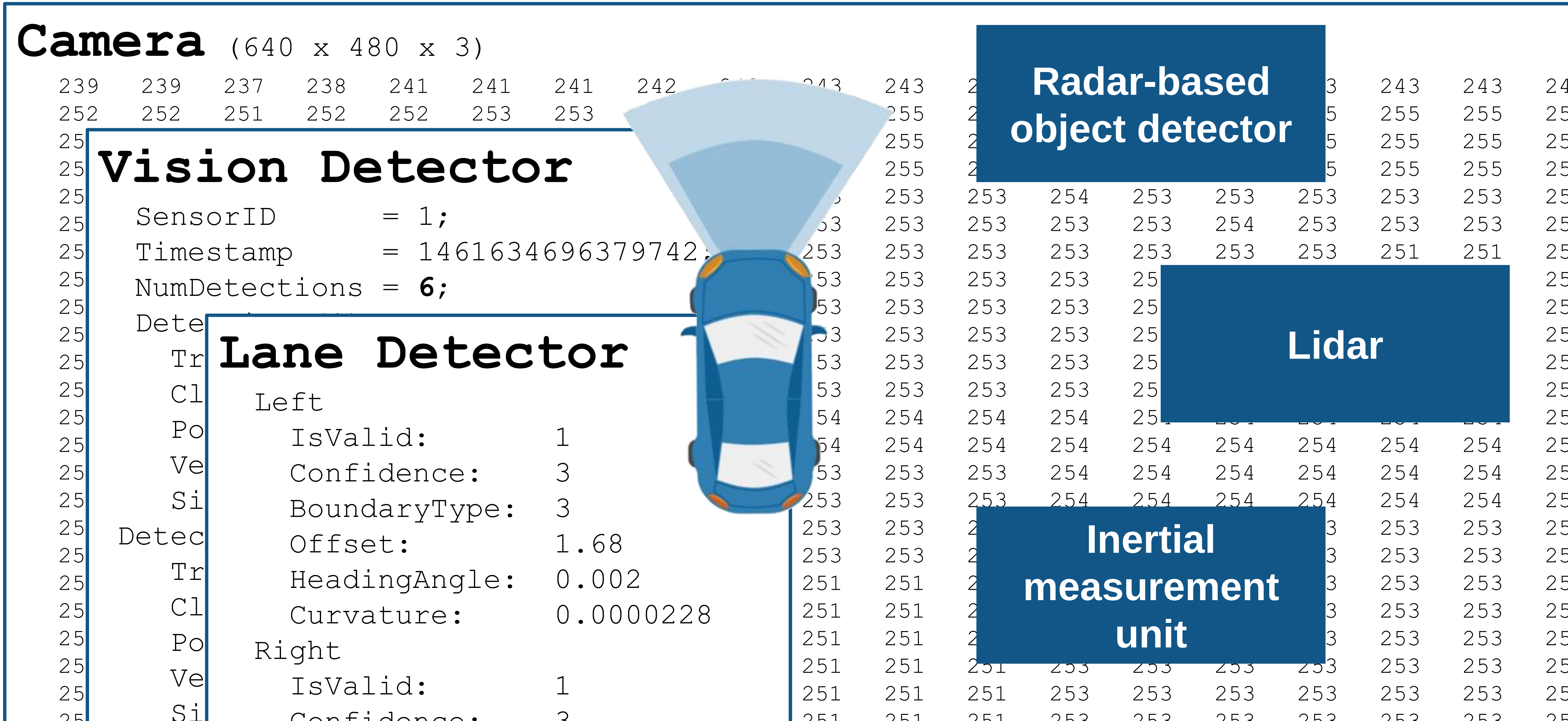
Examples of automated driving sensor data



Examples of automated driving sensor data



Examples of automated driving sensor data



Examples of automated driving sensor data

Camera (640 x 480 x 3)

```
239   239   237   238   241   241   241   242
252   252   251   252   252   253   253
25
25
25
25
25
25
25
25
25
25
25
25
25
25
25
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25
25
25
25
25
25
```
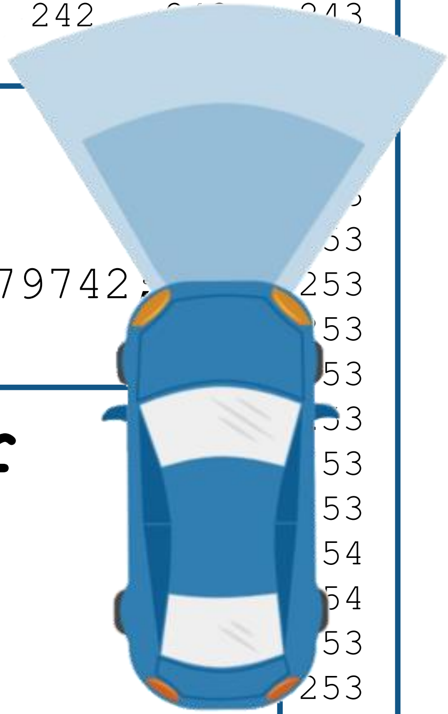

```
 243
 53
253
 53
 53
 53
 53
 53
 54
 54
 53
253
253
253
251
251
251
251
251
```

Vision Detector

```
SensorID      = 1;
Timestamp     = 1461634696379742
NumDetections = 6;
Dete
  Tr
  Cl
  Po
  Ve
  Si
Detec
  Tr
  Cl
  Po
  Ve
  Si
```

Lane Detector

```
Left
  IsValid:        1
  Confidence:     3
  BoundaryType:   3
  Offset:         1.68
  HeadingAngle:   0.002
  Curvature:      0.0000228
Right
  IsValid:        1
  Confidence:     3
```



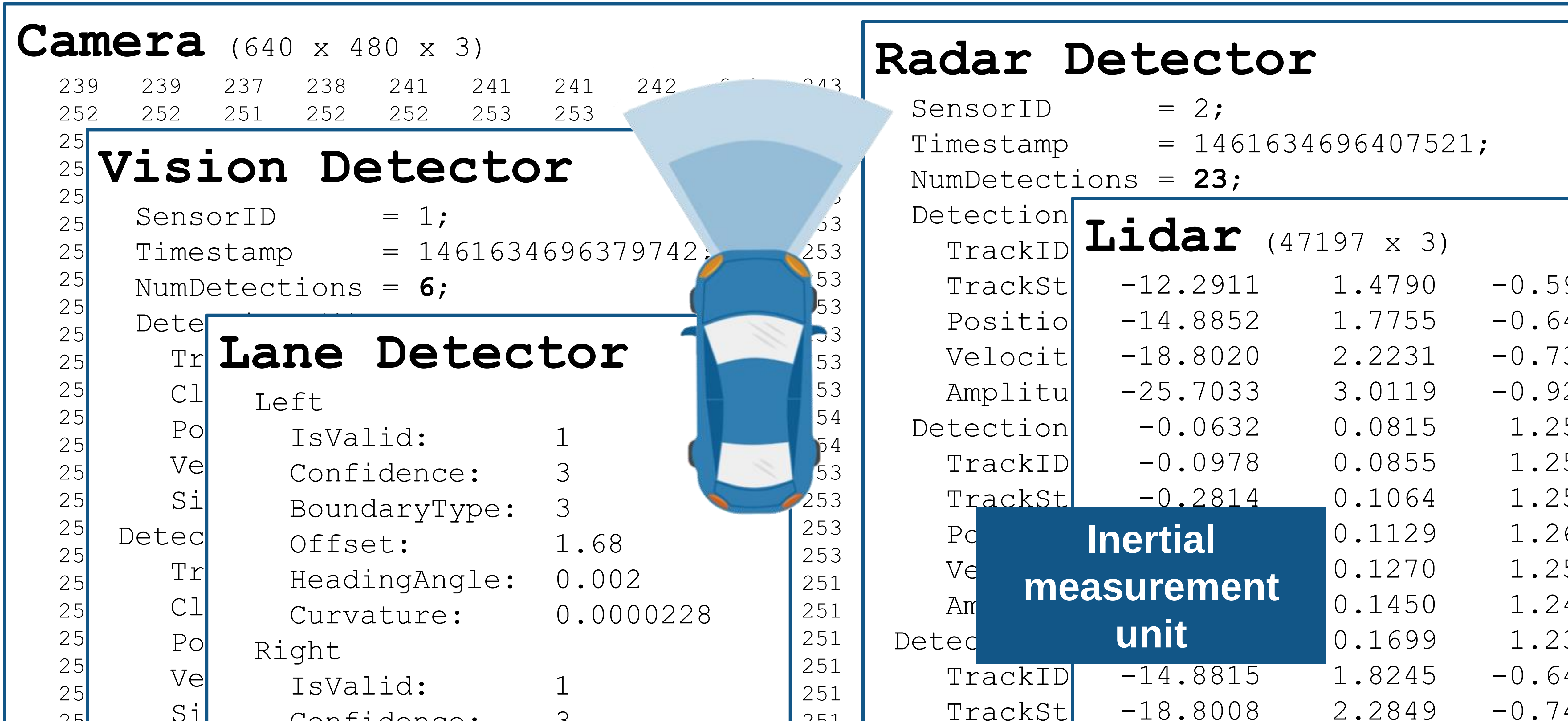
Radar Detector

```
SensorID      = 2;
Timestamp     = 1461634696407521;
NumDetections = 23;
Detections(1)
  TrackID:      0
  TrackStatus:
  Position:                      ]
  Velocity:
  Amplitude:
Detections(2)
  TrackID:      1
  TrackStatus:  6
  Po                 19.59 0.34]
  Ve                 4.92 0]
  Am
Detec
  TrackID:      12
  TrackStatus:  5
```

Lidar

Inertial measurement unit

Examples of automated driving sensor data



Examples of automated driving sensor data

Camera (640 x 480 x 3)

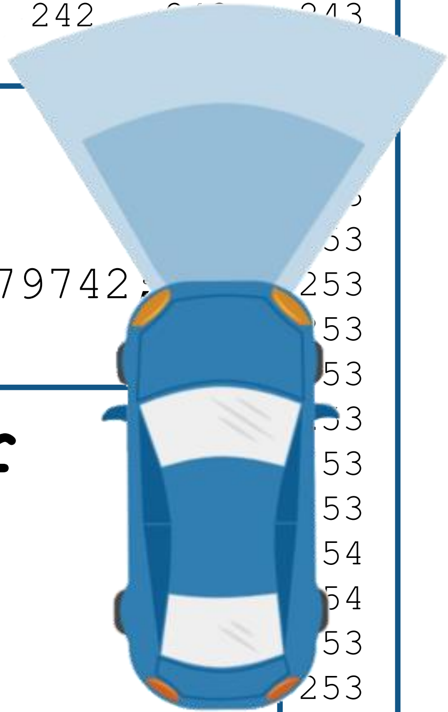
```
239   239   237   238   241   241   241   242   243
252   252   251   252   252   253   253
```

Vision Detector

```
SensorID      = 1;
Timestamp     = 1461634696379742;
NumDetections = 6;
```

Lane Detector

```
Left
  IsValid:       1
  Confidence:    3
  BoundaryType:  3
  Offset:        1.68
  HeadingAngle:  0.002
  Curvature:     0.000
Right
  IsValid:       1
```



Radar Detector

```
SensorID      = 2;
Timestamp     = 146163469640752l;
NumDetections = 23;
```

Lidar (47197 x 3)

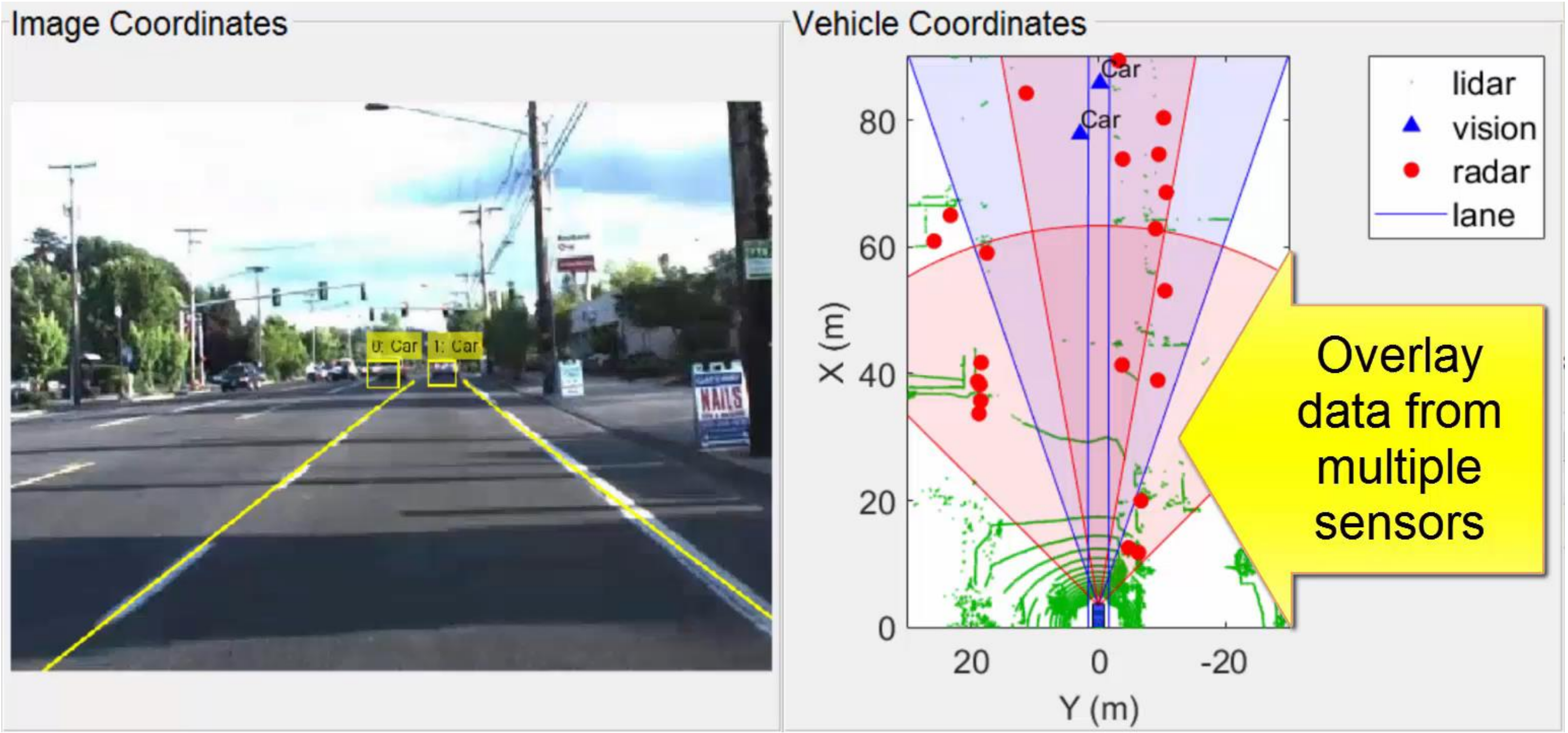
```
-12.2911   1.4790
-14.8852   1.7755
-18.8020   2.2231
-25.7033   3.0119
 -0.0632   0.0815
 -0.0978   0.0855
 -0.2814   0.1064
```

Inertial Measurement Unit

```
Timestamp:  1461634696379742
Velocity:   9.2795
YawRate:    0.0040
```

Visualize sensor data

Visualize differences in sensor detections



Explore logged vehicle data

- Load **video data** and corresponding **mono-camera parameters**

```
>> video = VideoReader('01_city_c2s_fcw_10s.mp4')
>> load('FCWDemoMonoCameraSensor.mat', 'sensor')
```

- Load **detection sensor data** and corresponding **parameters**

```
>> load('01_city_c2s_fcw_10s_sensor.mat', 'vision','lane','radar')
>> load('SensorConfigurationData.mat', 'sensorParams')
```

- Load **lidar point cloud data**

```
>> load('01_city_c2s_fcw_10s_Lidar.mat', 'LidarPointCloud')
```

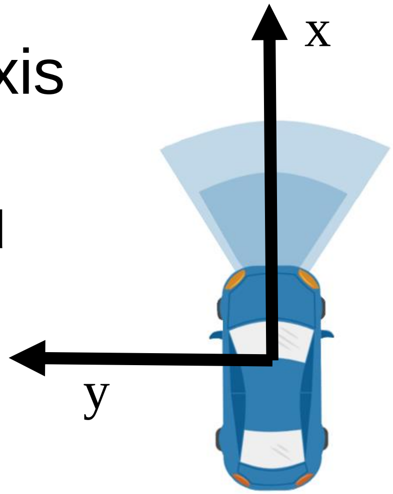
Visualize in image coordinates

```
%% Specify time to inspect
currentTime = 6.55;
video.CurrentTime = currentTime;

%% Extract video frame
frame = video.readFrame;

%% Plot image coordinates
ax1 = axes(...
    'Position',[0.02 0 0.55 1]);
im = imshow(frame,...
    'Parent',ax1);
```

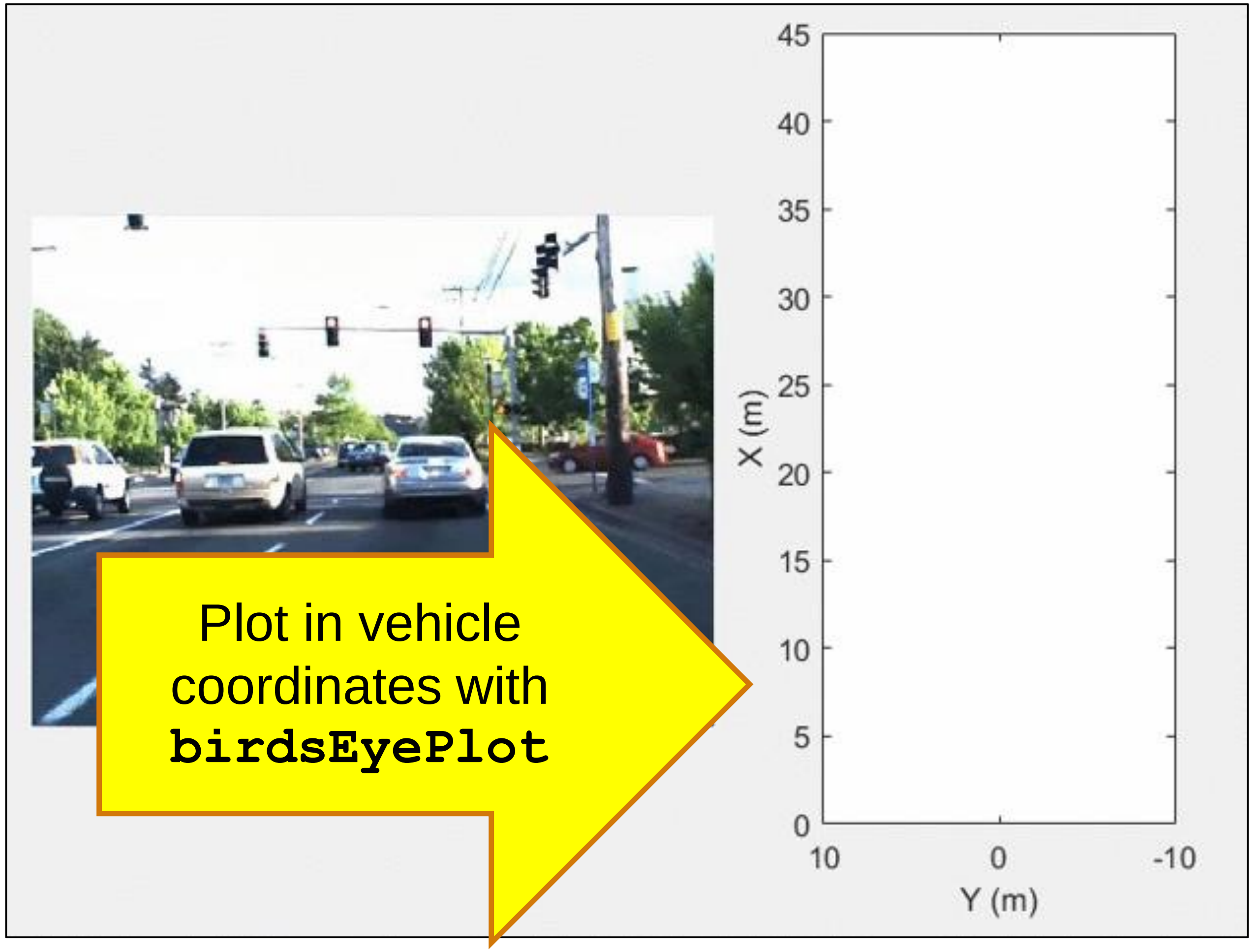
Plot in image coordinates using "classic" video and image functions like **`imshow`**

Visualize in vehicle coordinates

- ISO 8855 vehicle axis coordinate system
  - Positive x is forward
  - Positive y is left

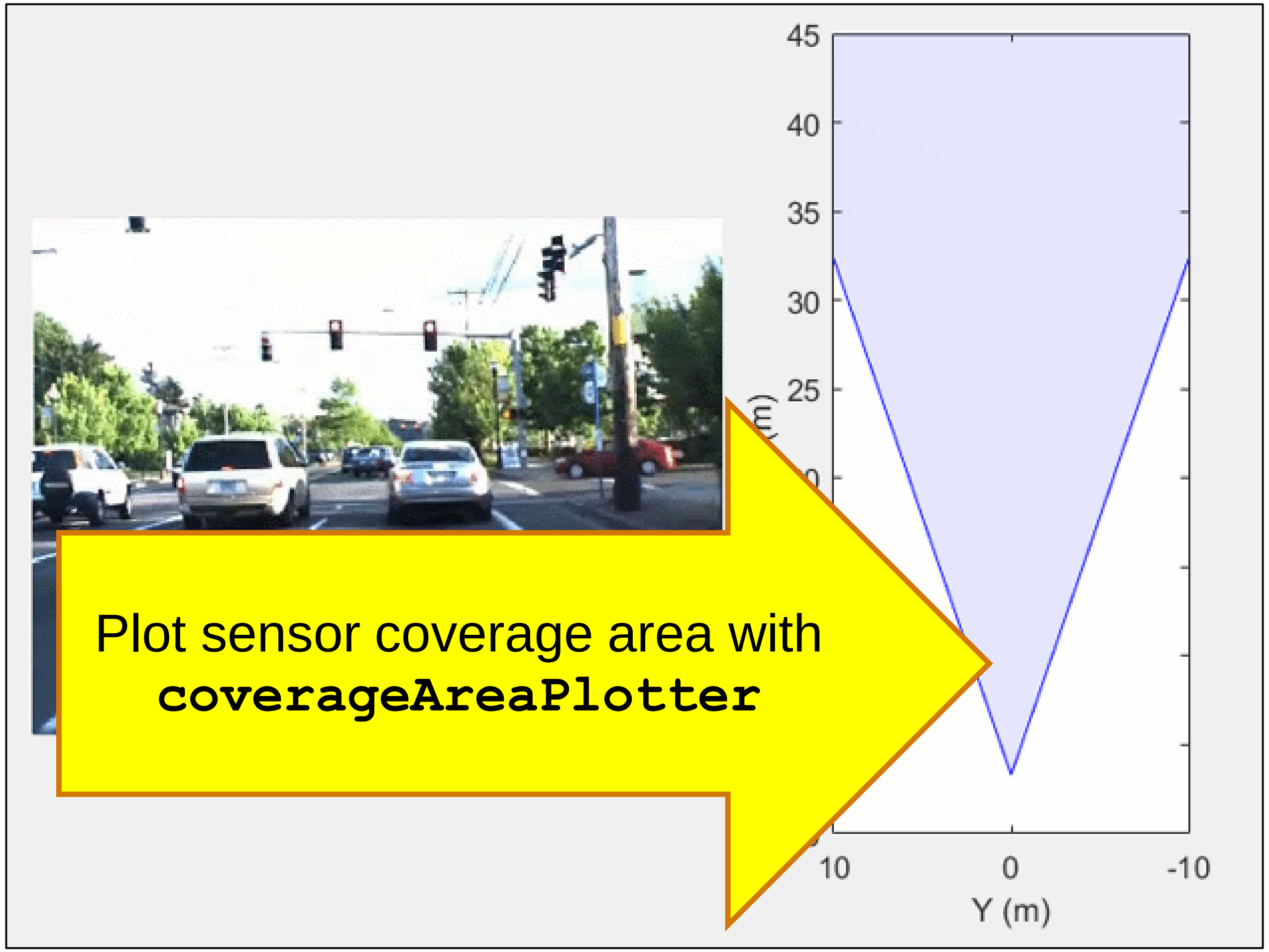



```
%% Plot in vehicle coordinates
ax2 = axes(...
    'Position',[0.6 0.12 0.4 0.85]);
bep = birdsEyePlot(...
    'Parent',ax2,...
    'Xlimits',[0 45],...
    'Ylimits',[-10 10]);
legend('off');
```



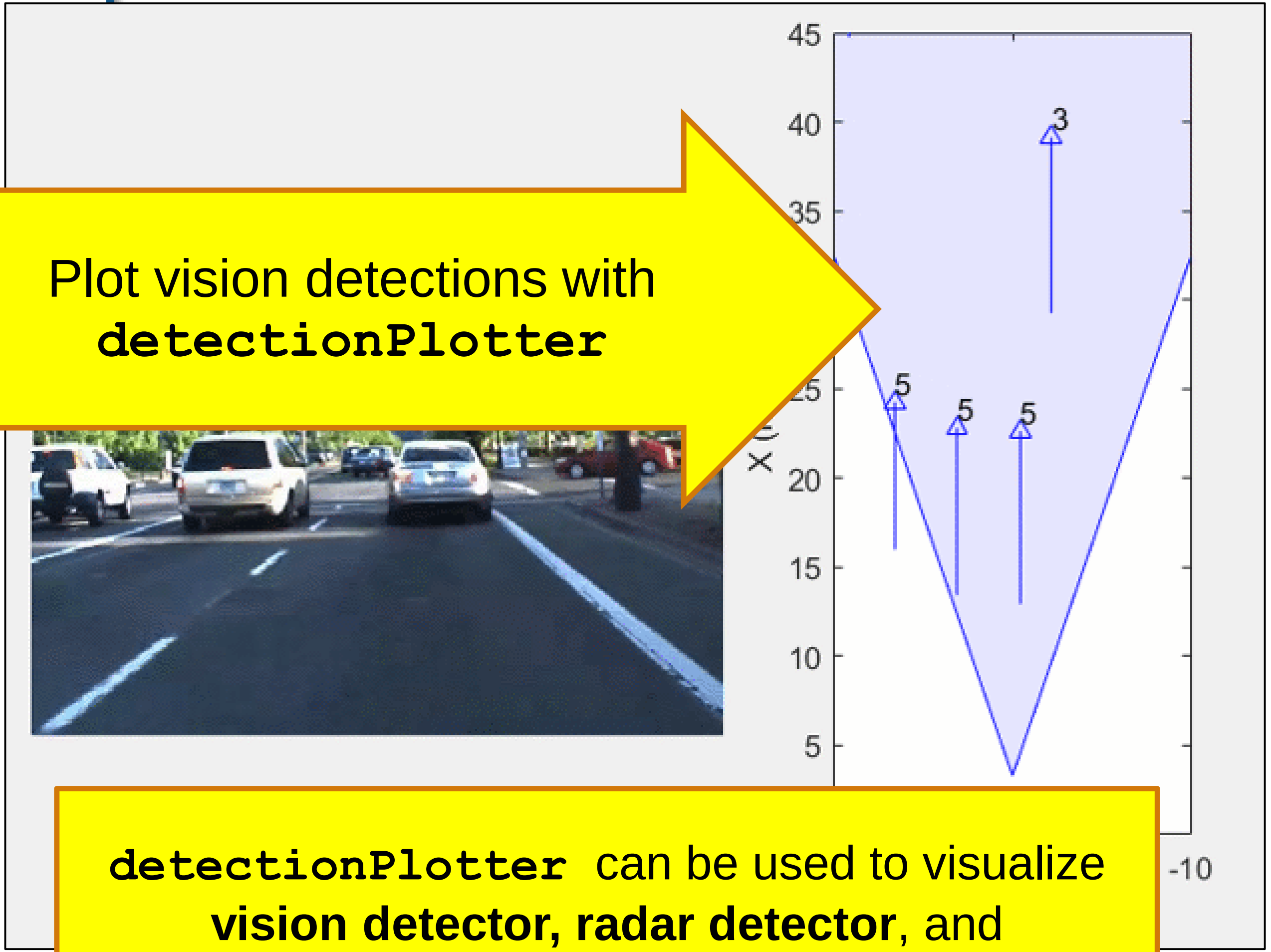
Visualize expected coverage area (vehicle coordinates)

```
%% Create coverage area plotter
covPlot = coverageAreaPlotter(bep,...
    'FaceColor','blue',...
    'EdgeColor','blue');

%% Update coverage area plotter
plotCoverageArea(covPlot,...
    [sensorParams(1).X ...  % Position x
     sensorParams(1).Y],... % Position y
    sensorParams(1).Range,...
    sensorParams(1).YawAngle,...
    sensorParams(1).FoV(1)) % Field of view
```



Visualize detections (vehicle coordinates)

```
%% Create detection plotter
detPlot = detectionPlotter(bep, ...
    'MarkerEdgeColor','blue',...
    'Marker','^');

%% Update detection plotter
n = round(currentTime/0.05);
numDets = vision(n).numObjects;
pos = zeros(numDets,3);
vel = zeros(numDets,3);
labels = repmat({''},numDets,1);
for k = 1:numDets
    pos(k,:) = vision(n).object(k).position;
    vel(k,:) = vision(n).object(k).velocity;
    labels{k} = num2str(...
      vision(n).object(k).classification);
end
plotDetection(detPlot,pos,vel,labels);
```

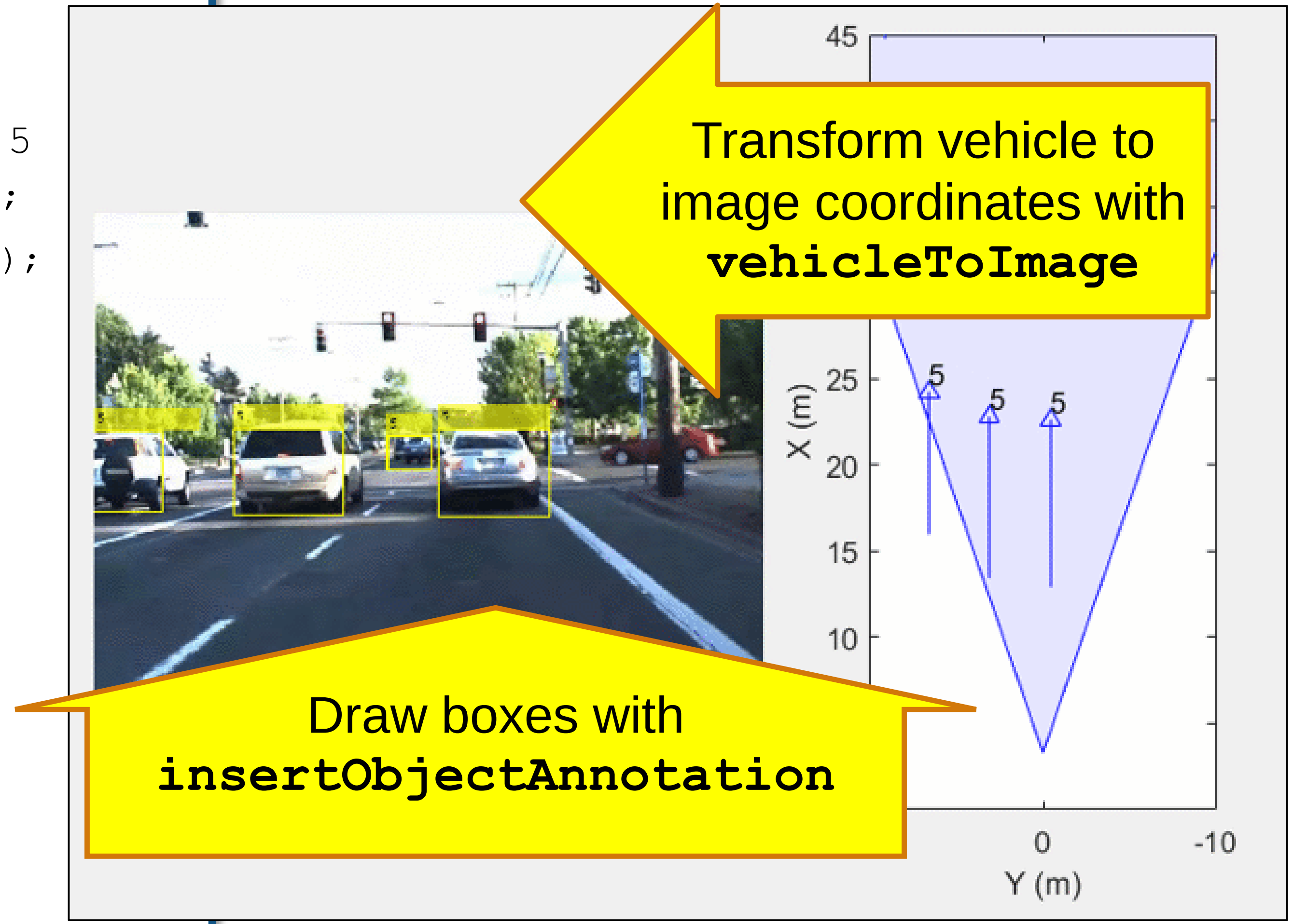


Plot vision detections with **`detectionPlotter`**

`detectionPlotter` can be used to visualize **vision detector, radar detector**, and **lidar point cloud**

Visualize detections (image coordinates)

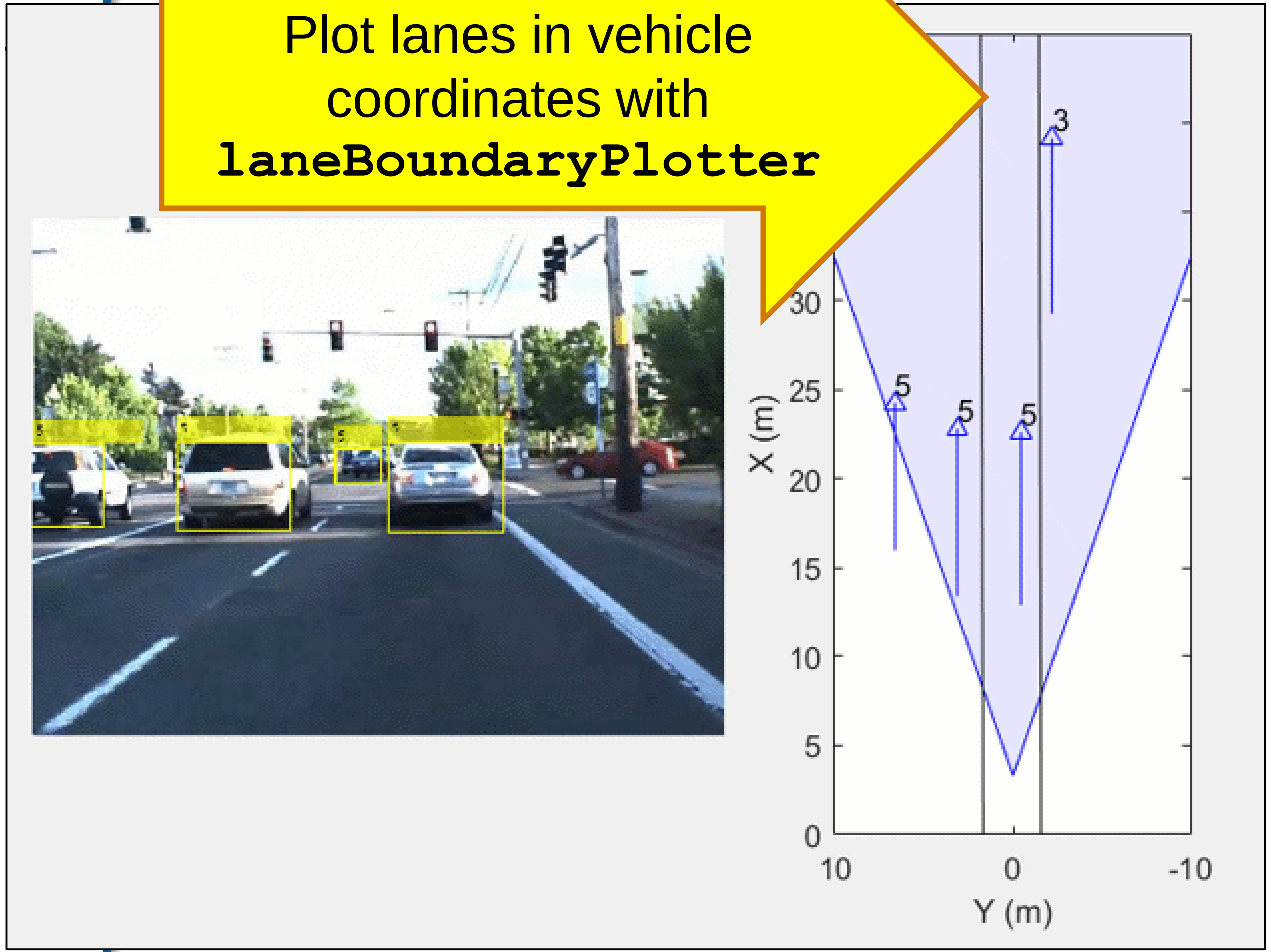
```
%% Bounding box positions in image coordinates
imBoxes = zeros(numDets,4);
for k = 1:numDets
  if vision(n).object(k).classification == 5
    vehPosLR = vision(n).object(k).position(1:2)';
    imPosLR = vehicleToImage(sensor, vehPosLR);
    boxHeight = 1.4 * 1333 / vehPosLR(1);
    boxWidth  = 1.8 * 1333 / vehPosLR(1);
    imBoxes(k,:)=[imPosLR(1) - boxWidth/2, ...
                  imPosLR(2) - boxHeight, ...
                  boxWidth, boxHeight];
  end
end

%% Draw bounding boxes on image frame
frame = insertObjectAnnotation(frame, ...
    'Rectangle', imBoxes, labels,...
    'Color','yellow','LineWidth',2);
im.CData = frame;
```



Visualize lane boundaries (vehicle coordinates)

```
%% Create lane detection plotter
lanePlot = laneBoundaryPlotter(bep, ...
    'Color','black');

%% Update lane detection plotter
lb = parabolicLaneBoundary([...
        lane(n).left.curvature,...
        lane(n).left.headingAngle,...
        lane(n).left.offset]);
rb = parabolicLaneBoundary([...
        lane(n).right.curvature,...
        lane(n).right.headingAngle,...
        lane(n).right.offset]);
plotLaneBoundary(lanePlot, [lb rb])
```

Plot lanes in vehicle coordinates with **`laneBoundaryPlotter`**



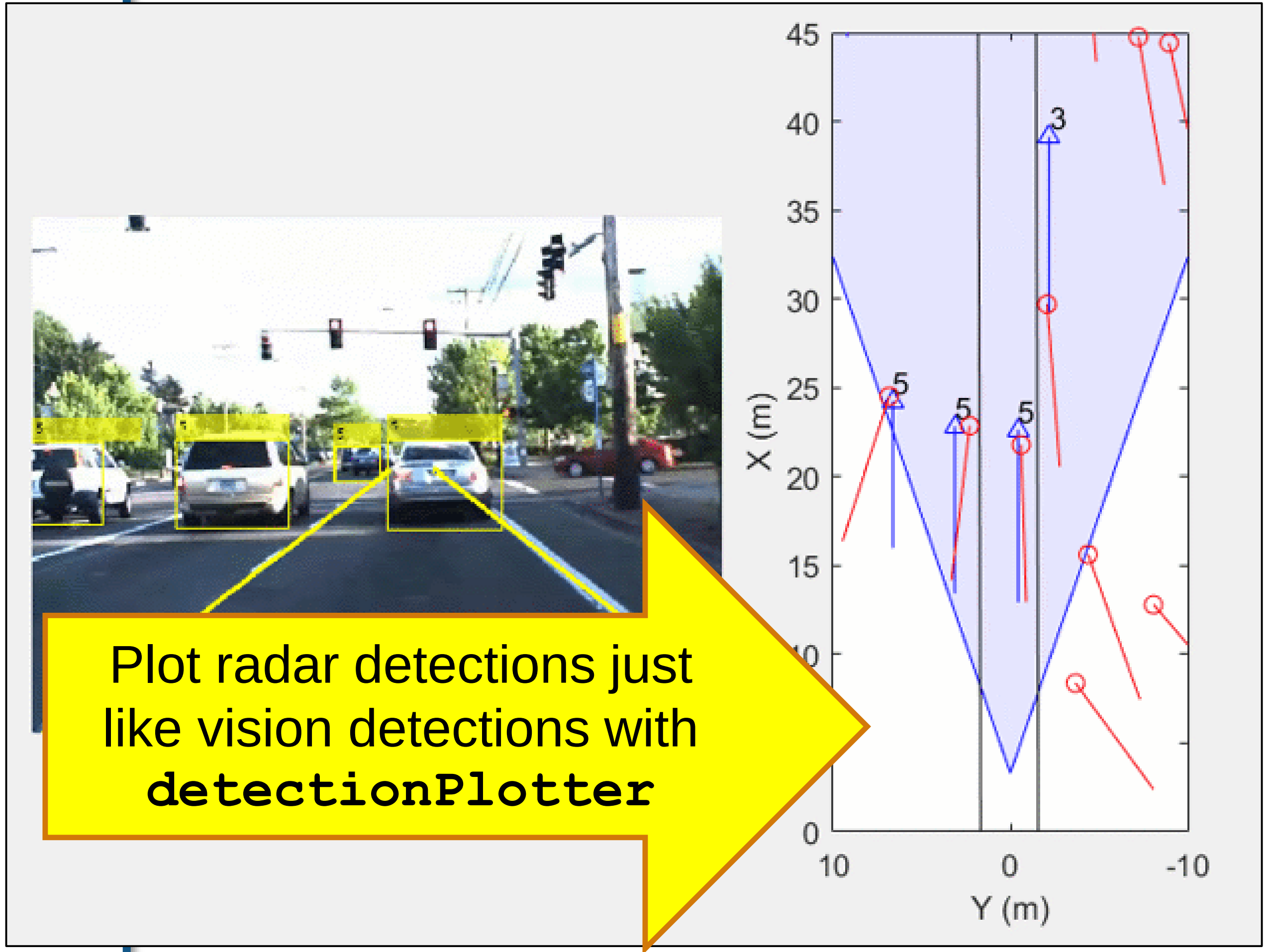
Visualize lane boundaries (image coordinates)

```
%% Draw in image coordinates
frame = insertLaneBoundary(frame, ...
     [lb rb], sensor, (1:100),...
     'LineWidth',5);
im.CData = frame;
```

Plot lanes in image coordinates with **insertLaneBoundary**

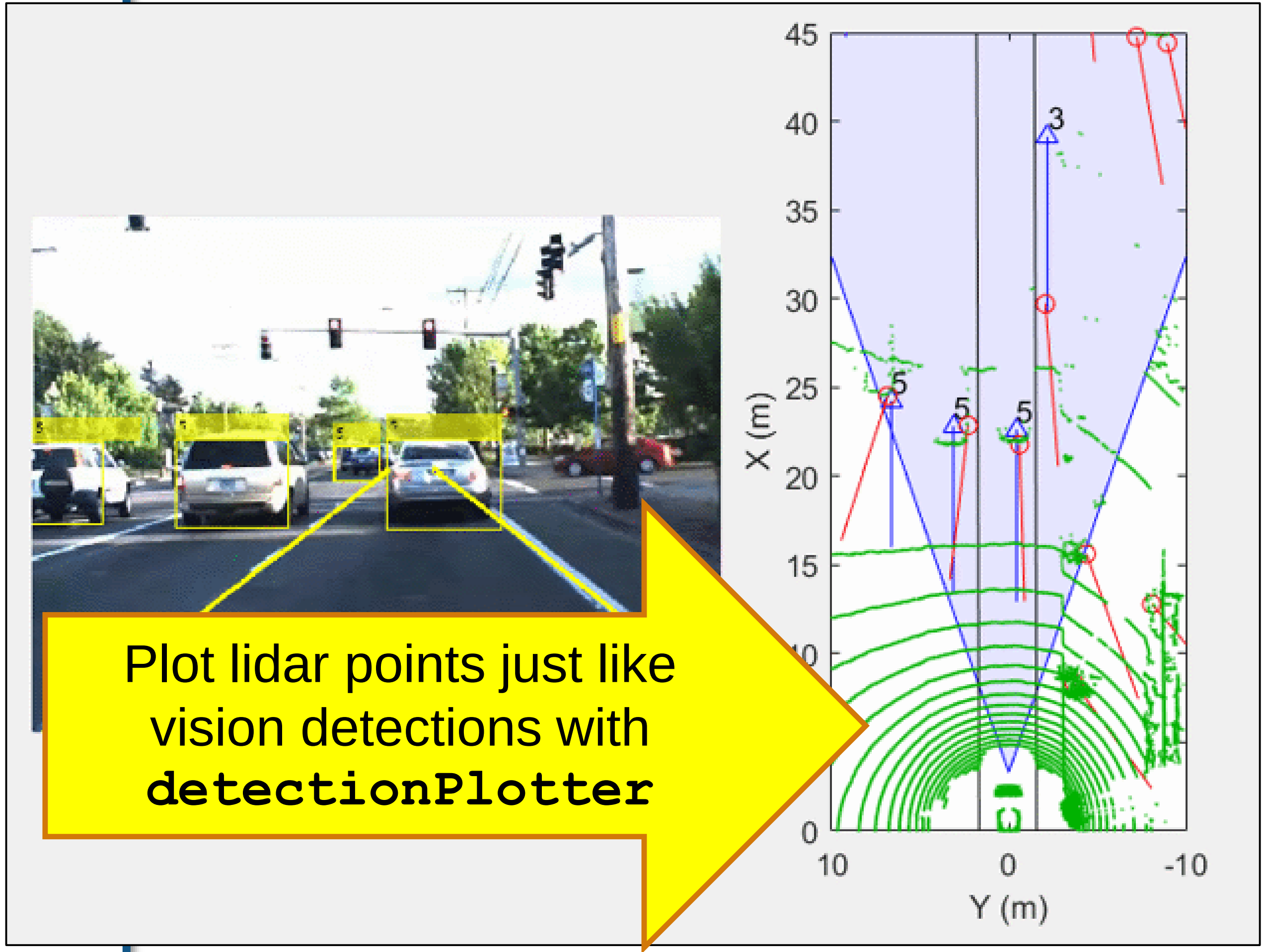
Visualize radar detections (vehicle coordinates)

```
%% Create radar detection plotter
radarPlot = detectionPlotter(bep, ...
    'MarkerEdgeColor','red',...
    'Marker','o');

%% Update radar detection plotter
numDets = radar(n).numObjects;
pos = zeros(numDets,3);
vel = zeros(numDets,3);
for k = 1:numDets
    pos(k,:) = radar(n).object(k).position;
    vel(k,:) = radar(n).object(k).velocity;
end
plotDetection(radarPlot,pos,vel);
```



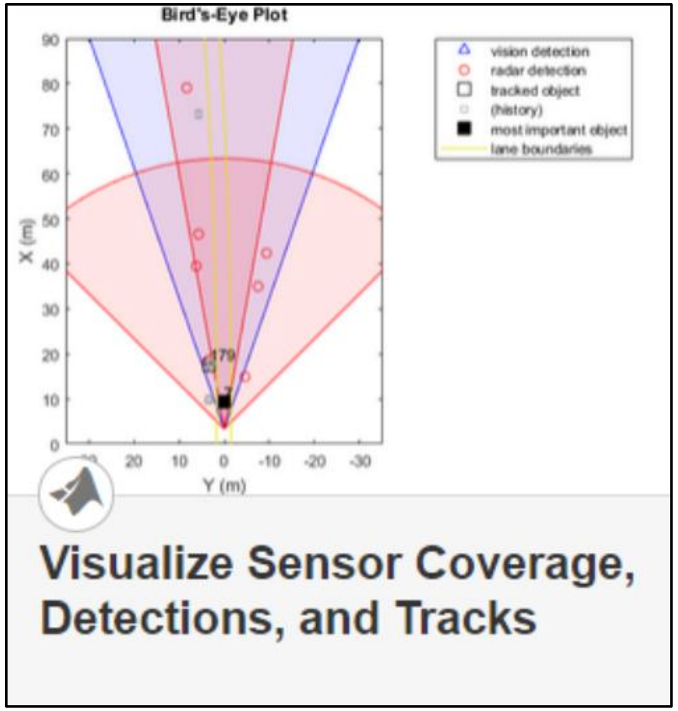
Visualize lidar point cloud (vehicle coordinates)

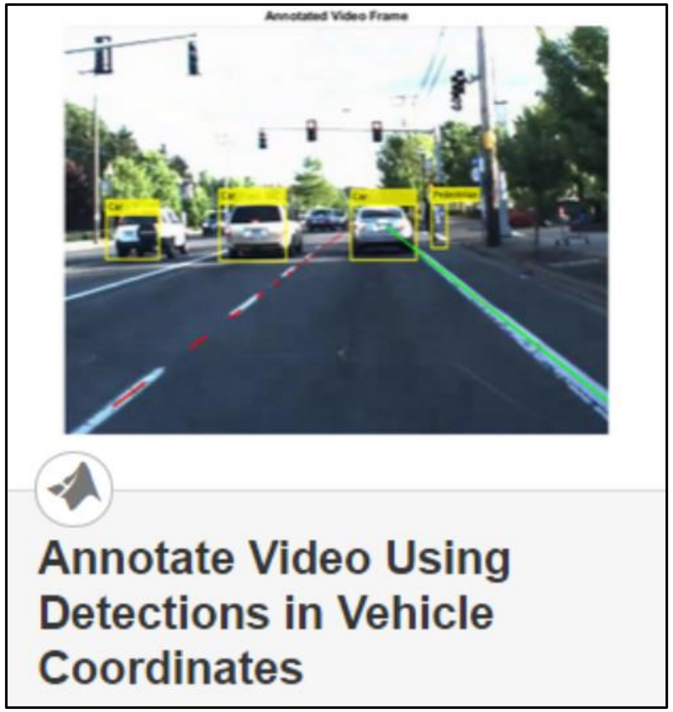
```
%% Create lidar detection plotter
lidarPlot = detectionPlotter(bep, ...
     'Marker','.',...
     'MarkerSize',1.5,...
     'MarkerEdgeColor',[0 0.7 0]); % Green

%% Update lidar detection plotter
n = round(video.CurrentTime/0.1);
pos = ...
  LidarPointCloud(n).ptCloud.Location(:,1:2);
plotDetection(lidarPlot,pos);
```

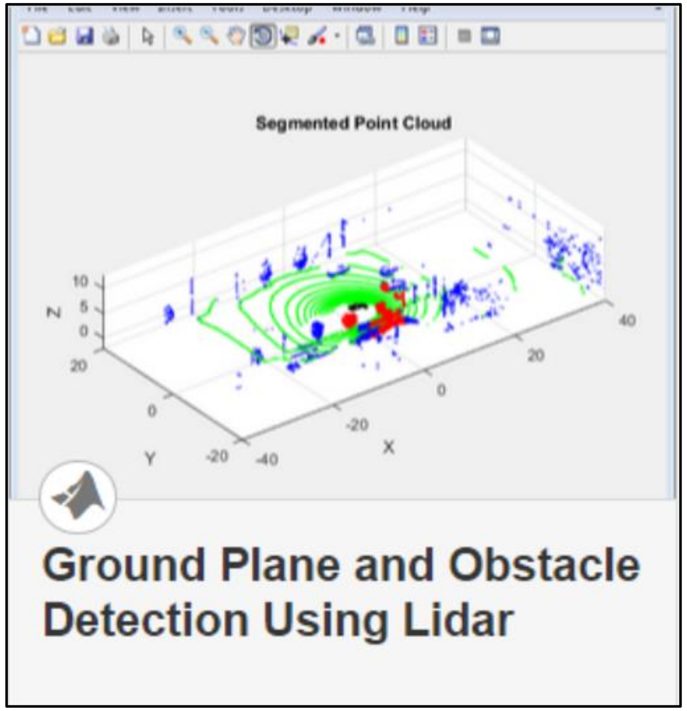


Learn more about visualizing vehicle data

by exploring examples in the Automated Driving System Toolbox





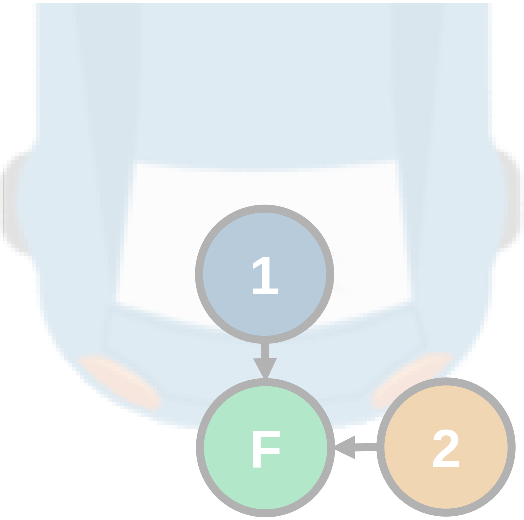


- **Plot object detectors in vehicle coordinates**
  - Vision & radar detector
  - Lane detectors
  - Detector coverage areas
- **Transform between vehicle and image coordinates**
- **Plot lidar point cloud**

Some common questions from automated driving engineers

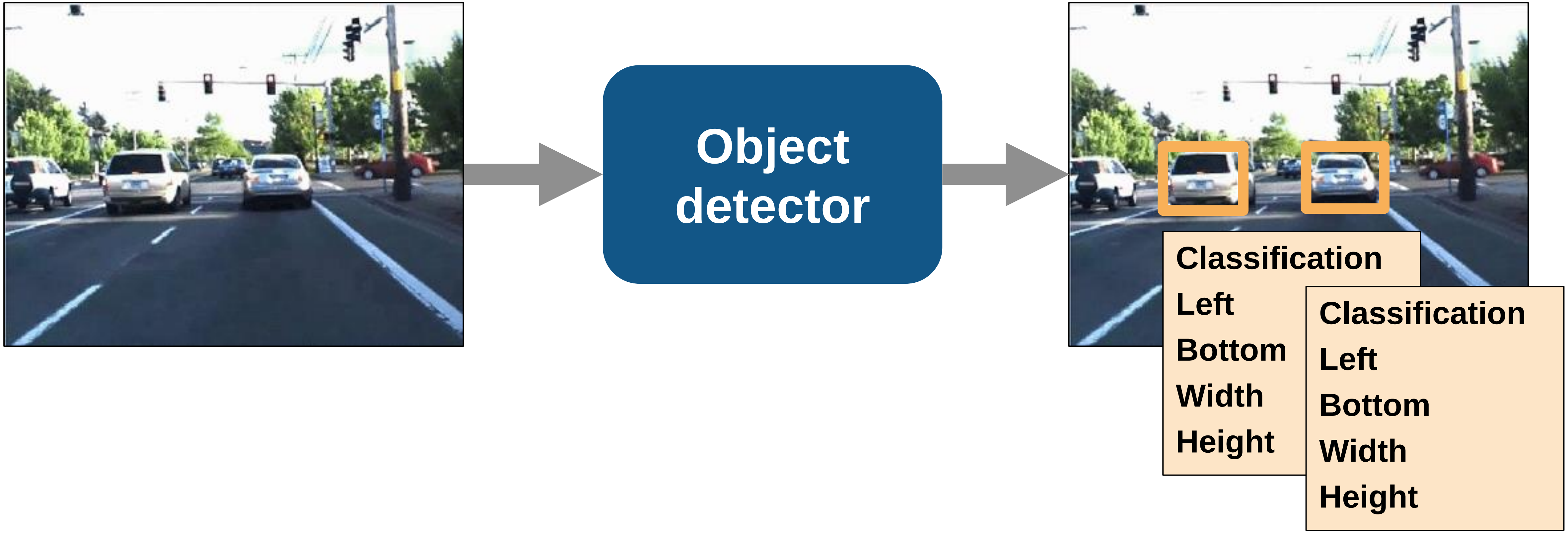
How can I visualize vehicle data?

How can I detect objects in images?

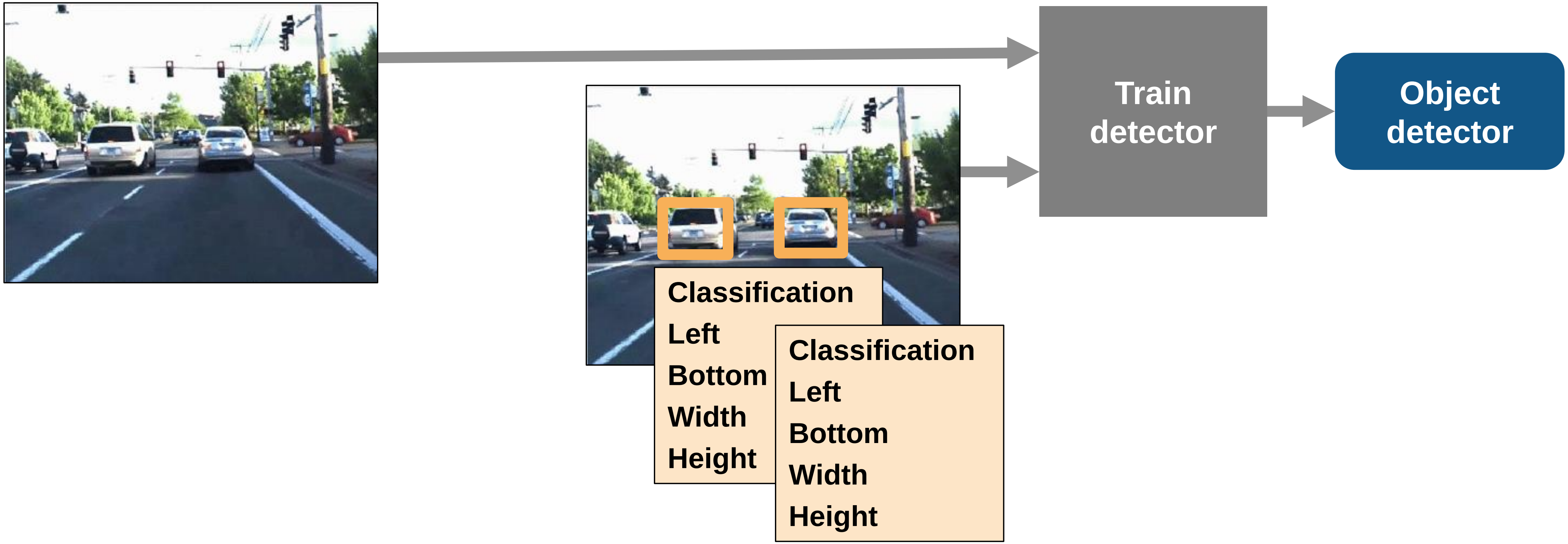


How can I fuse multiple detections?

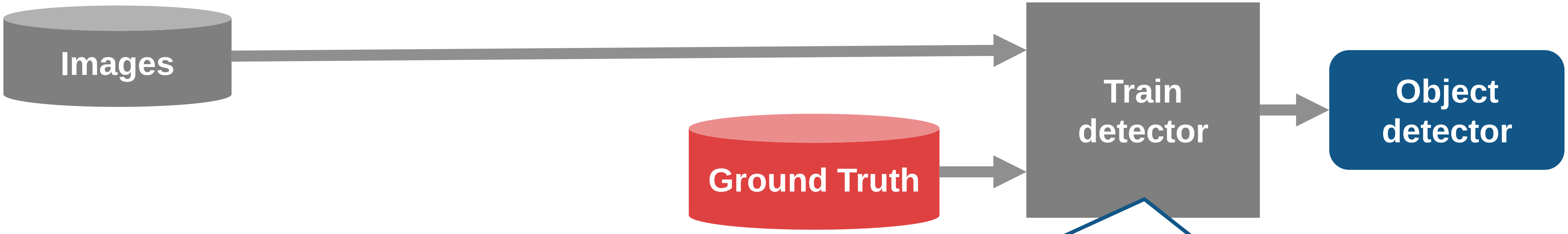
How can I detect objects in images?



Train object detectors based on ground truth



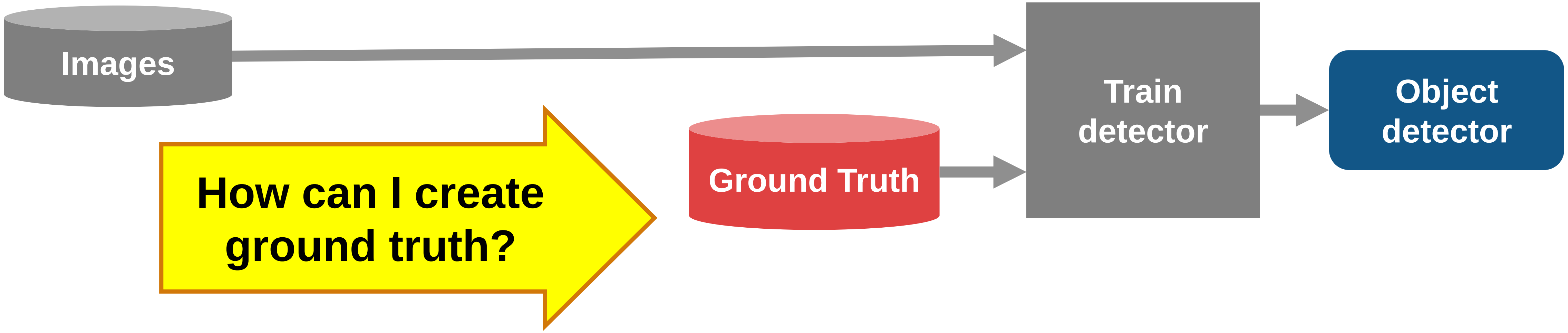
Train object detectors based on ground truth



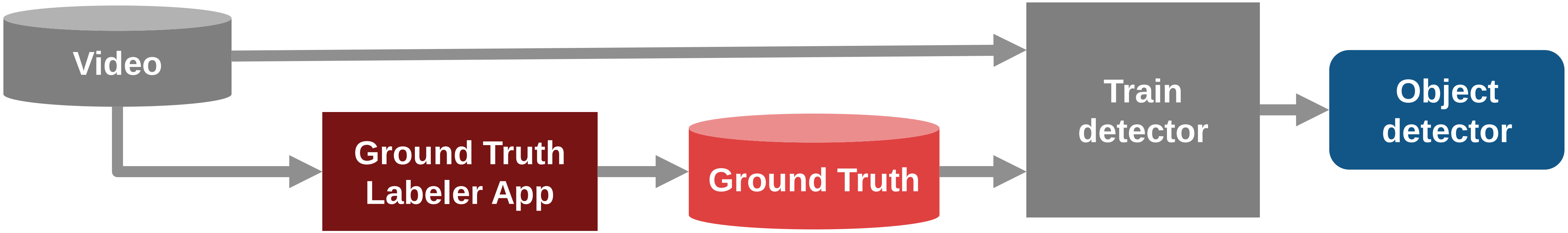
Design object detectors with the Computer Vision System Toolbox

Machine Learning	Aggregate Channel Feature	`trainACFObjectDetector`
	Cascade	`trainCascadeObjectDetector`
Deep Learning	R-CNN (Regions with Convolutional Neural Networks)	`trainRCNNObjectDetector`
	Fast R-CNN	`trainFastRCNNObjectDetector`
	Faster R-CNN	`trainFasterRCNNObjectDetector`

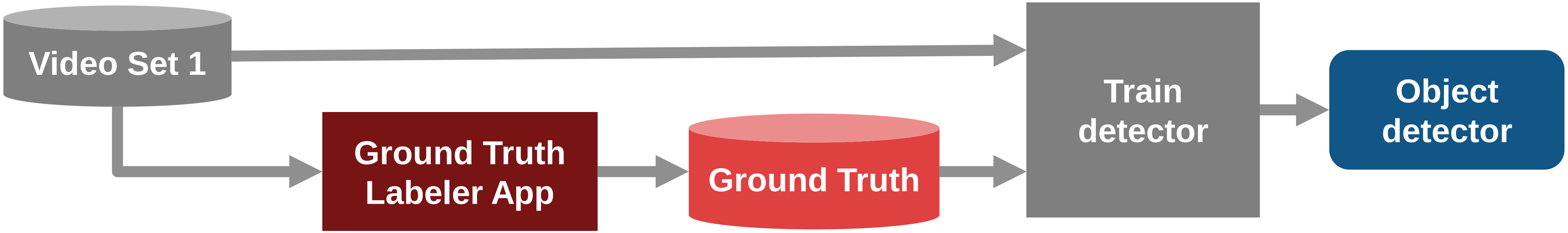
Specify ground truth to train detector



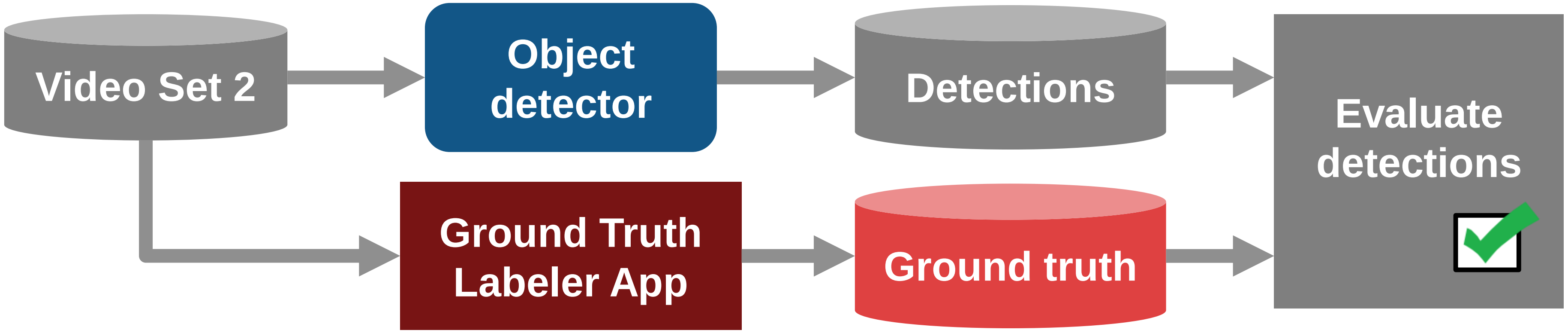
Specify ground truth to train detector



Specify ground truth to <u>train</u> detectors

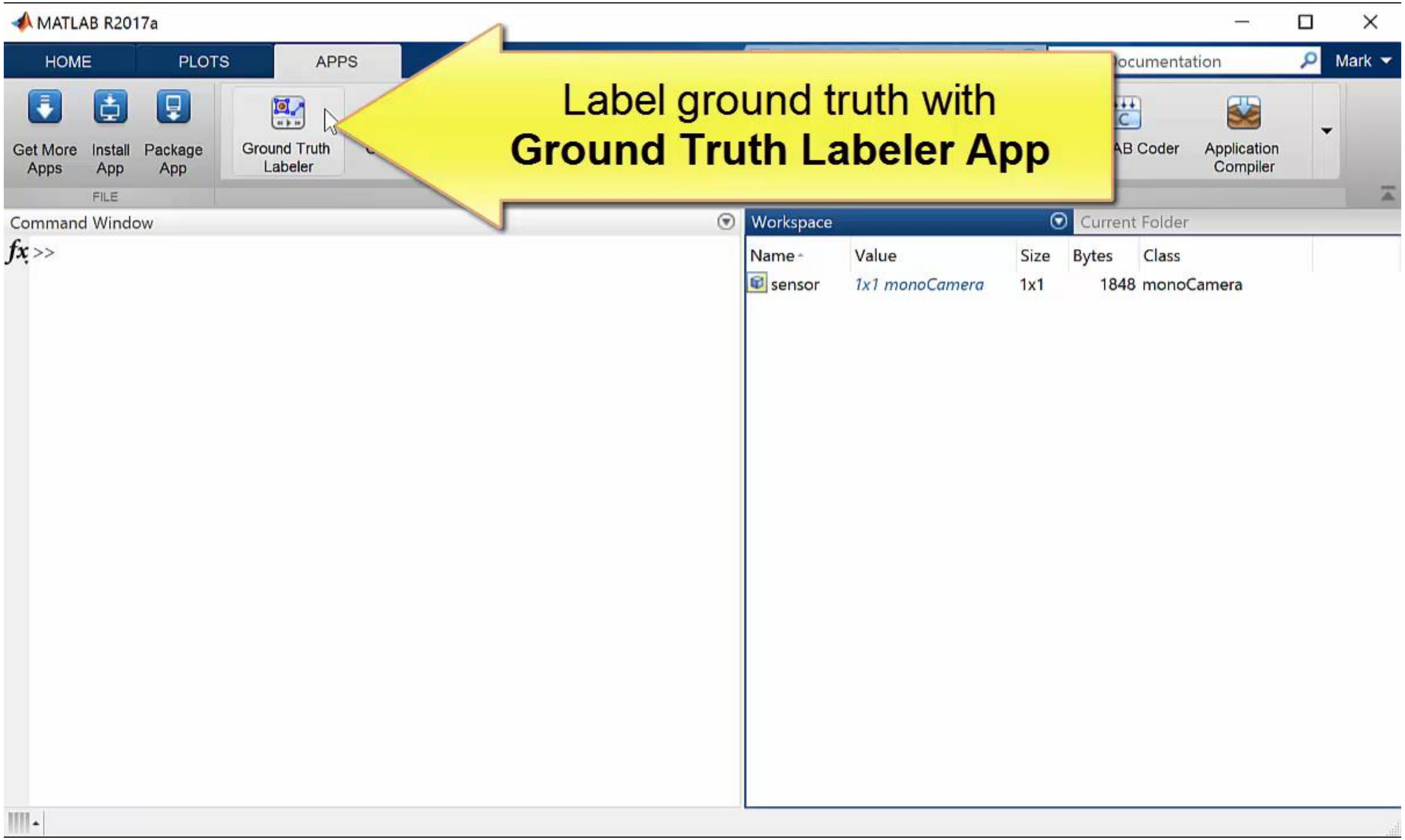


Specify ground truth to <u>evaluate</u> detectors



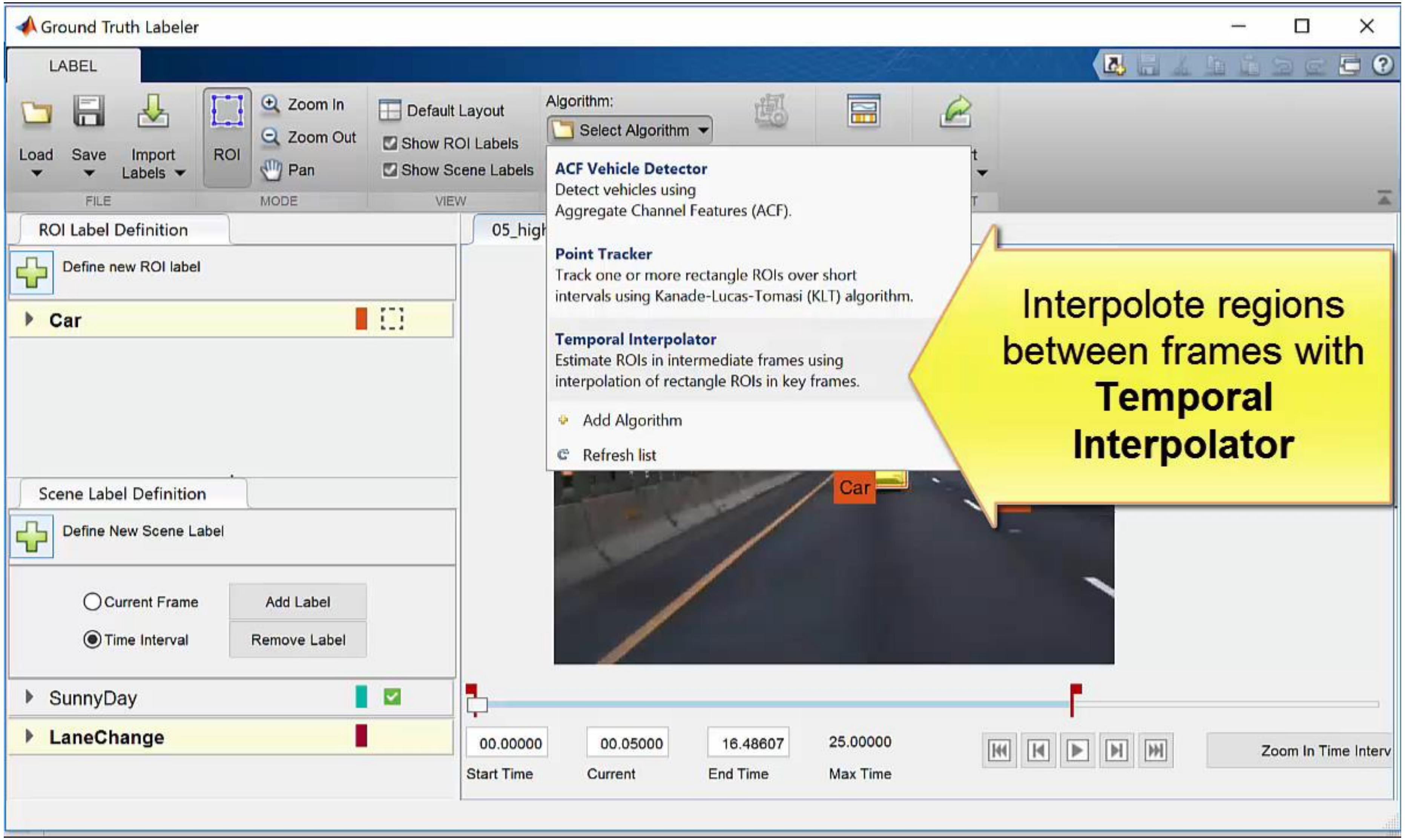
Manually label ground truth objects

with Ground Truth Labeling App



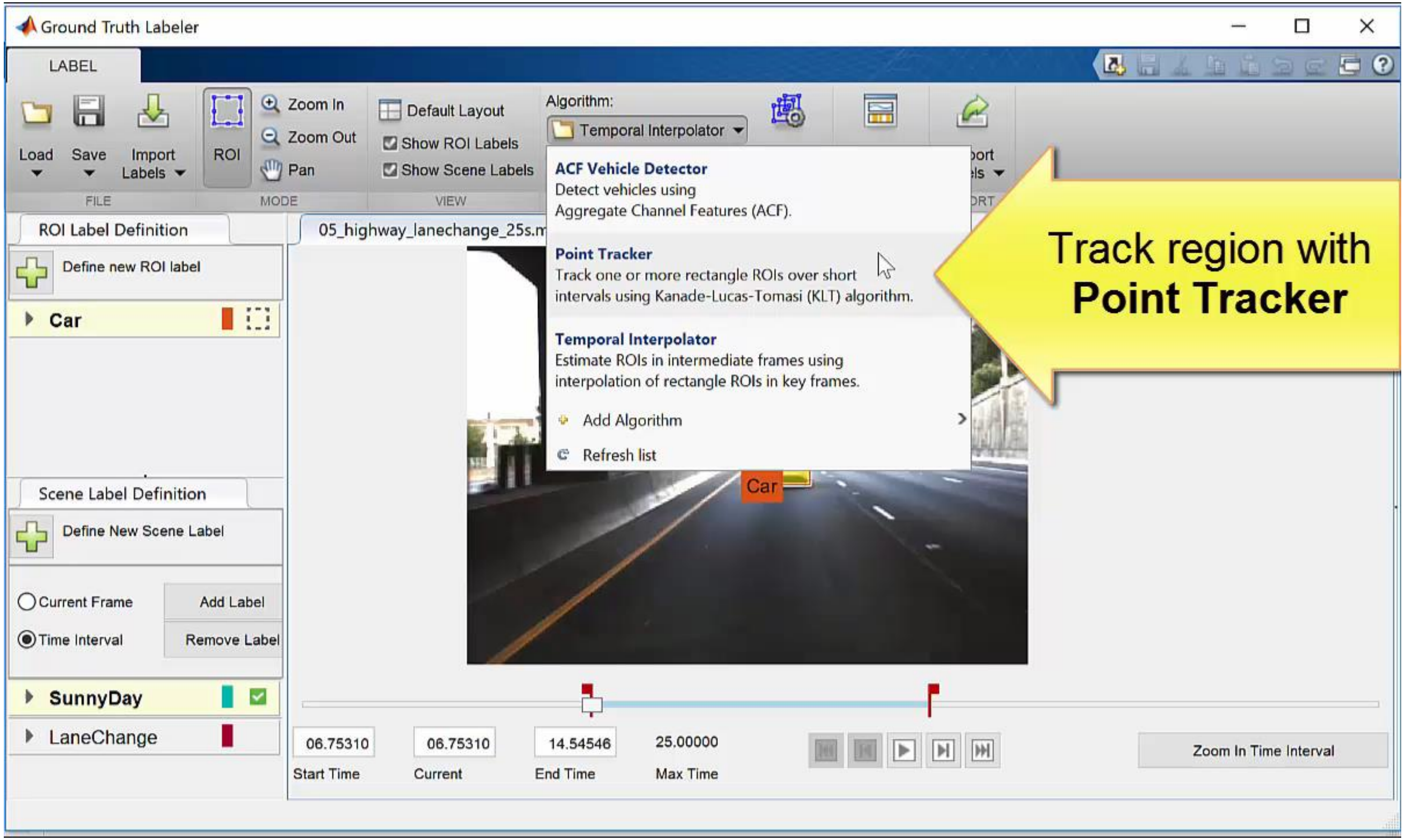
Automate labeling between manually labeled frames

with temporal interpolator



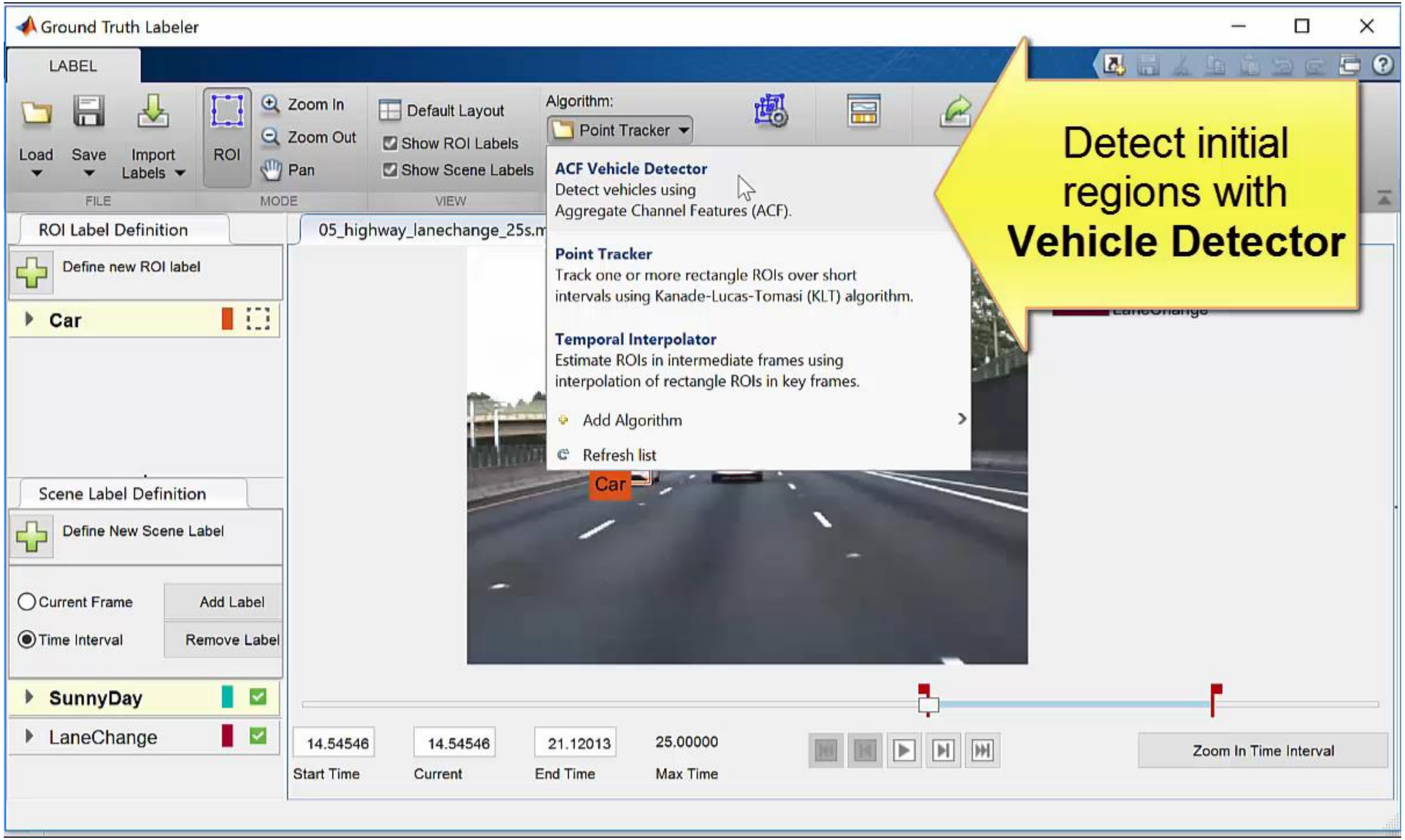
Automate labeling based on a manually labeled frame

with point tracker

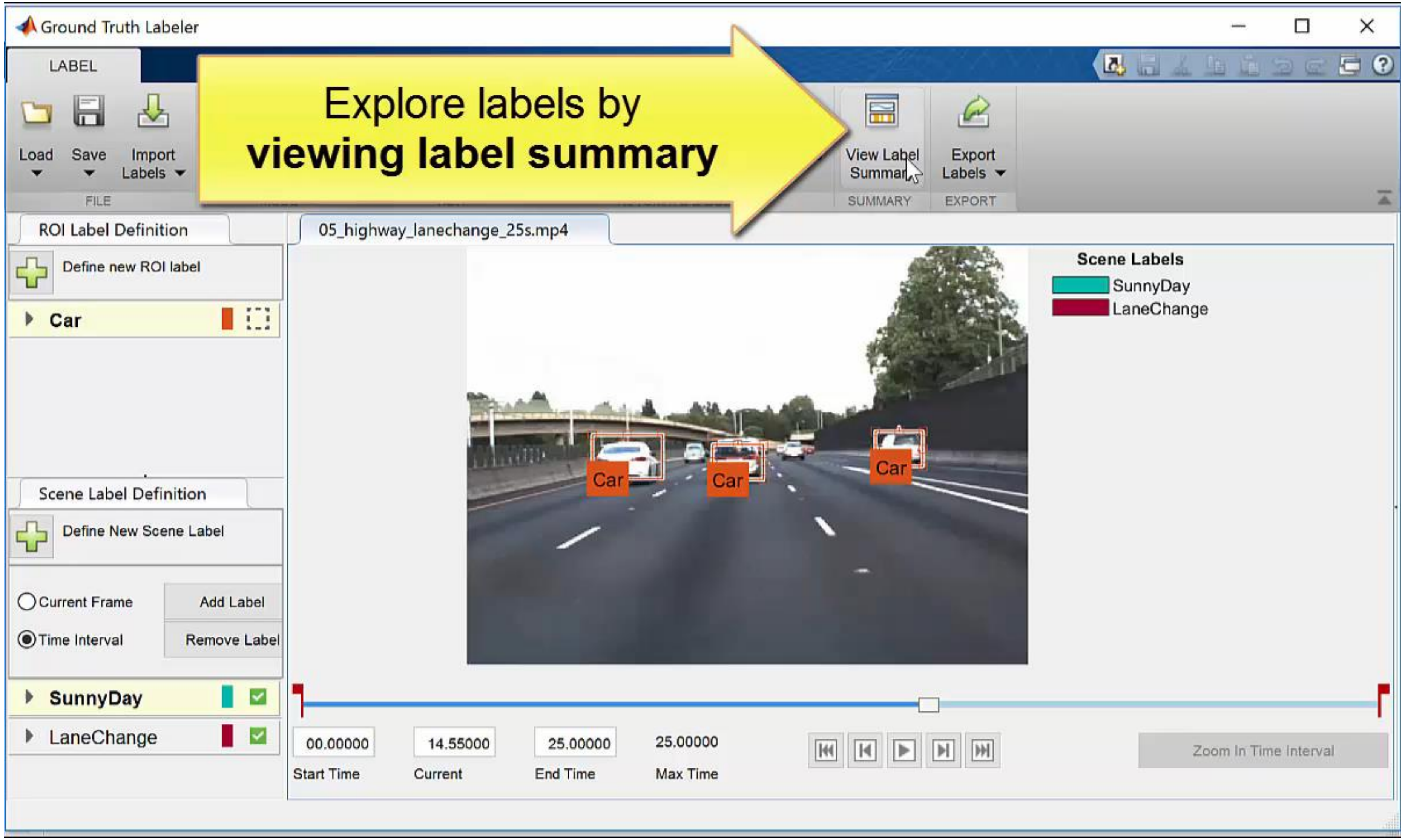


Automate initial ground truth of vehicles

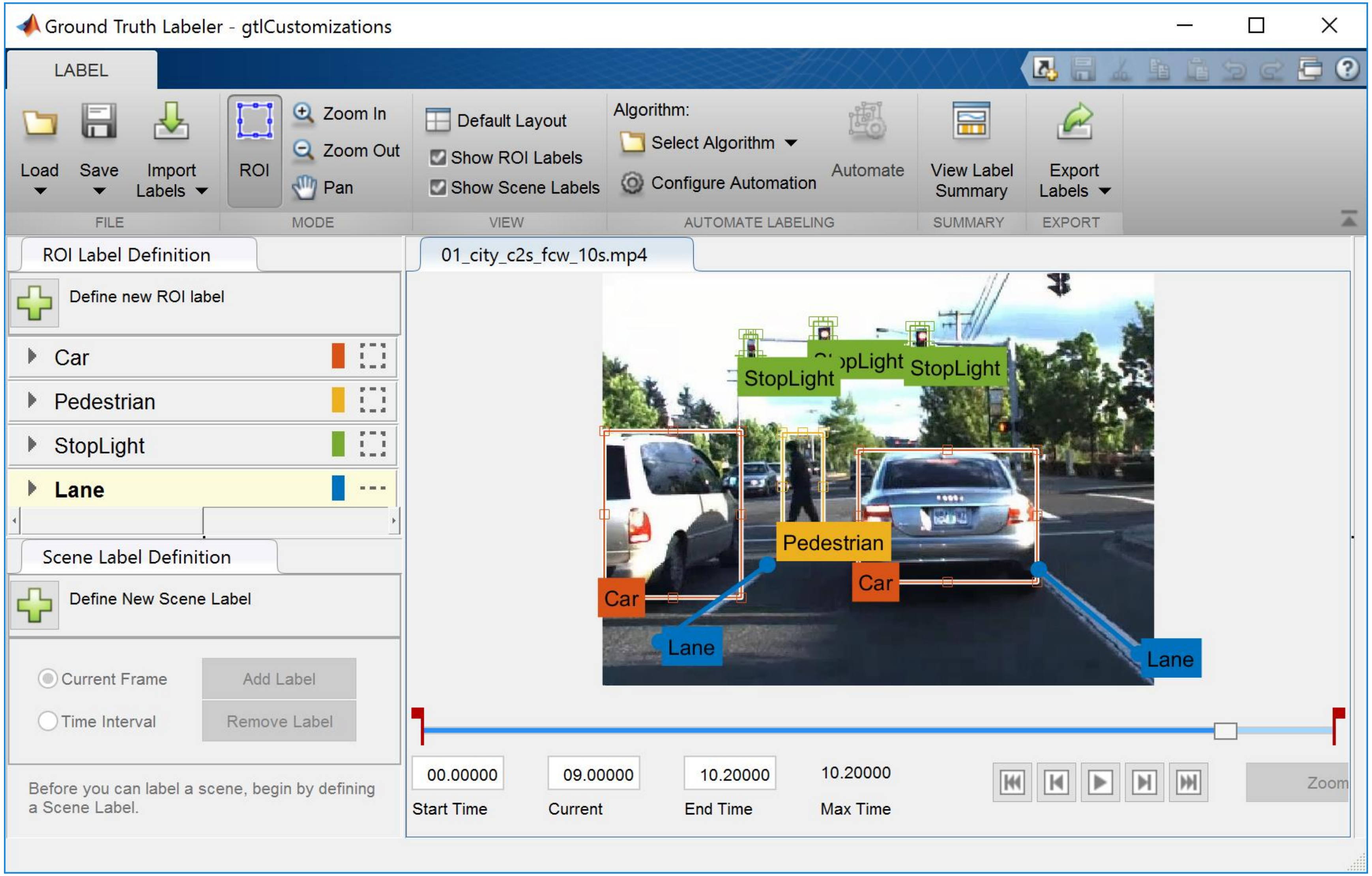
with ACF ground truth detector



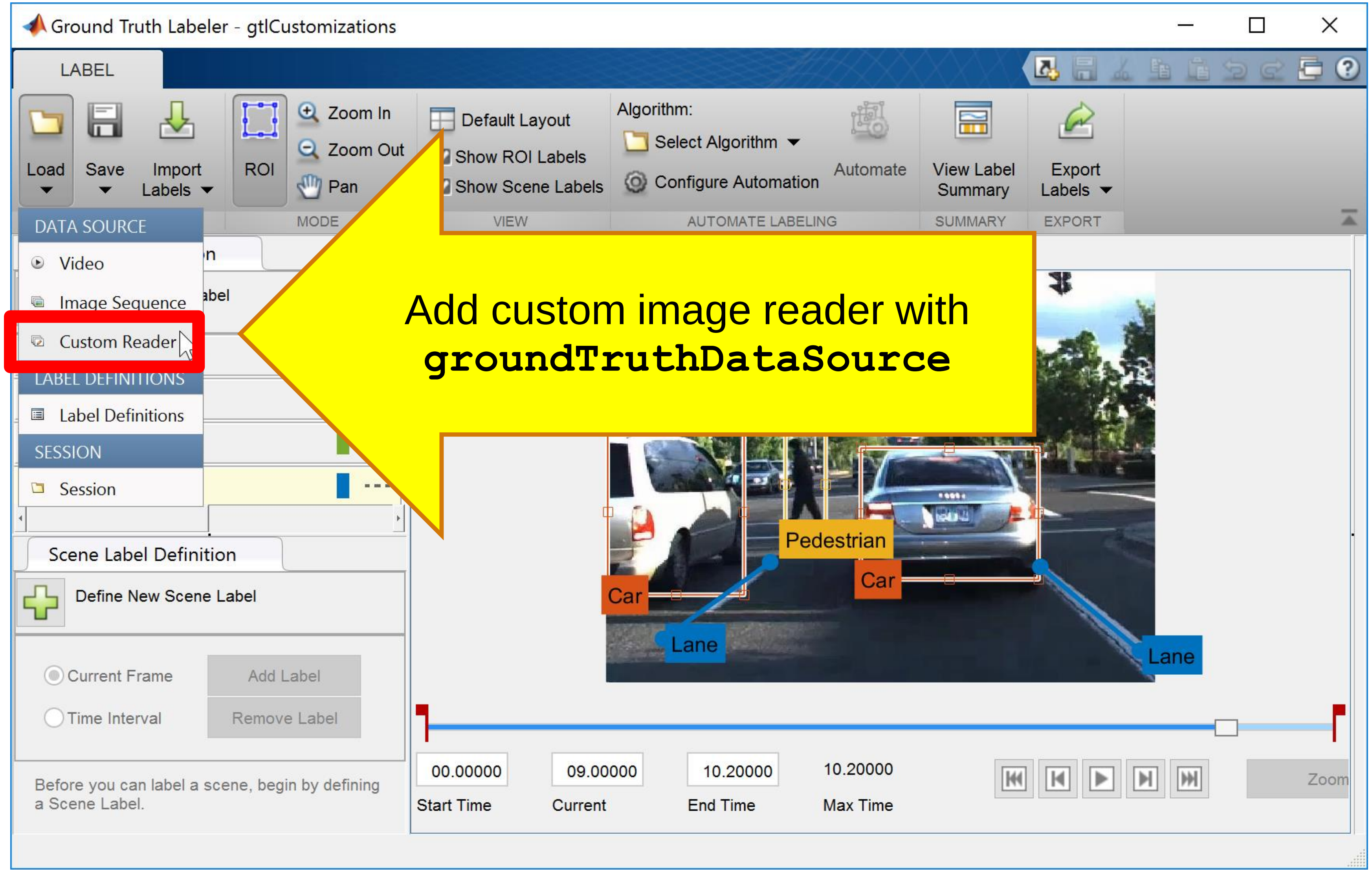
Export labeled regions as MATLAB time table



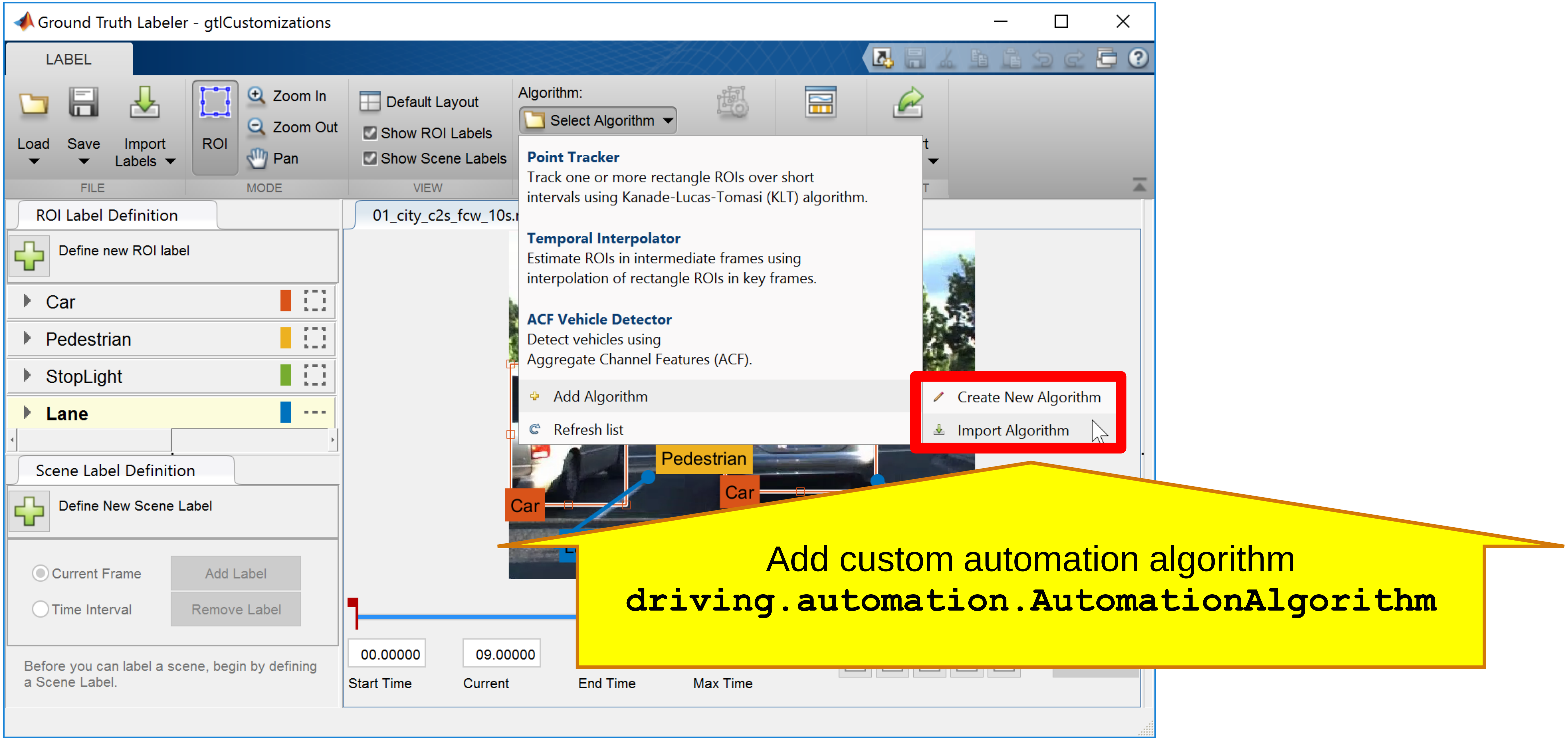
Customize Ground Truth Labeler App



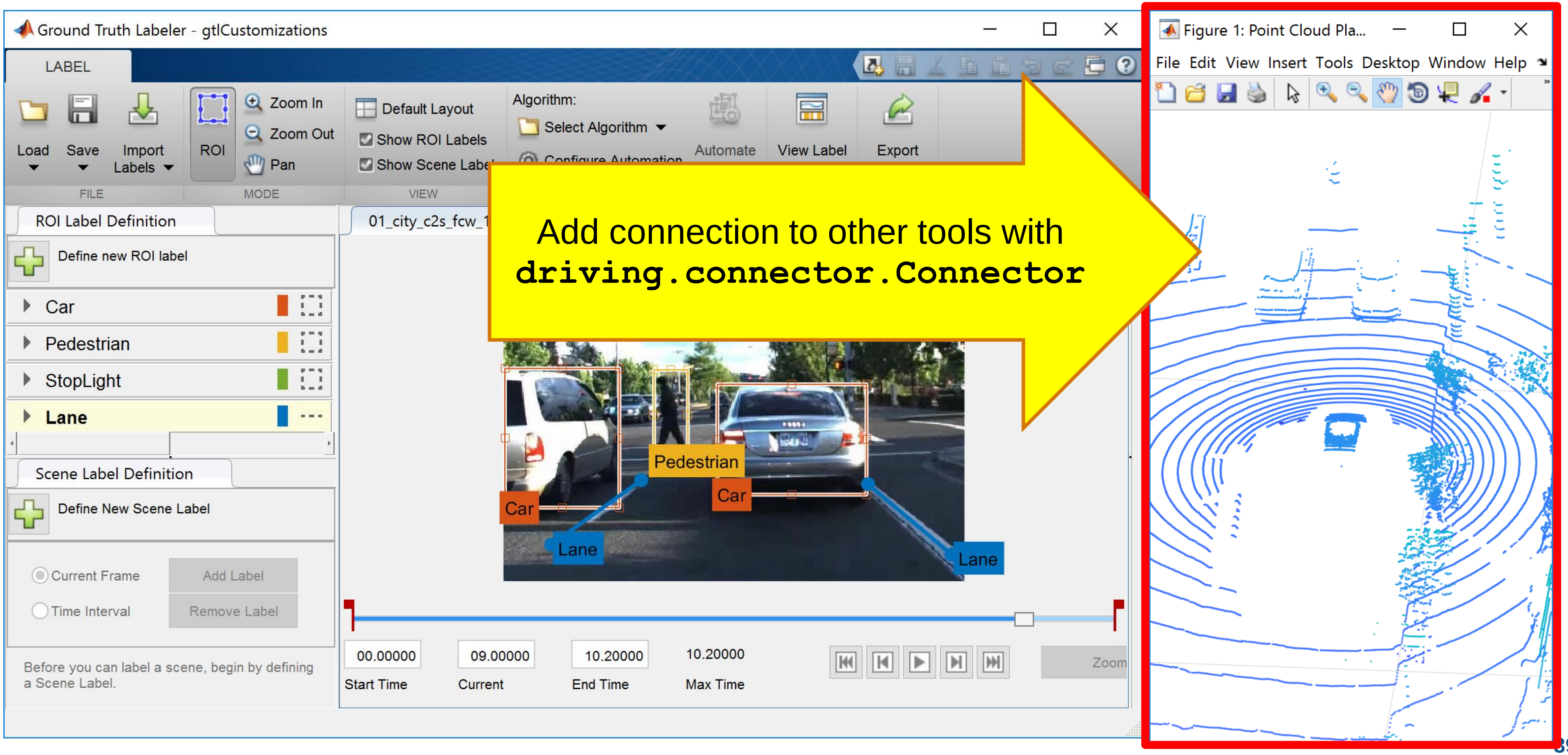
Customize Ground Truth Labeler App



Customize Ground Truth Labeler App



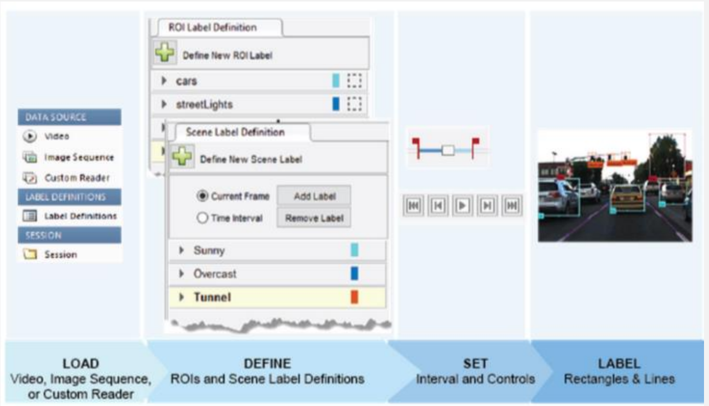
Customize Ground Truth Labeler App



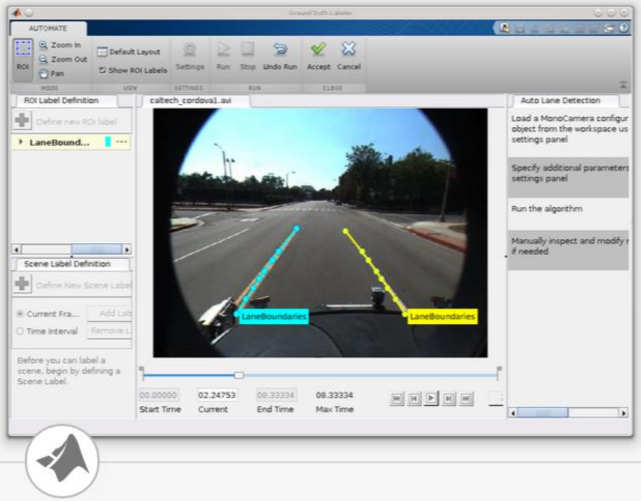
Add connection to other tools with `driving.connector.Connector`

Learn more about detecting objects in images

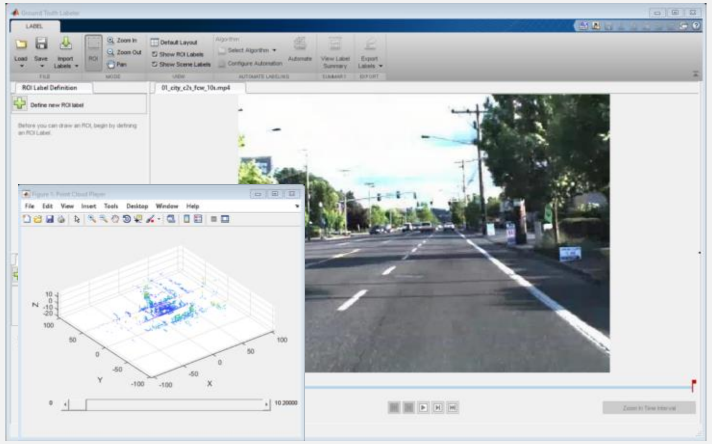
by exploring examples in the Automated Driving System Toolbox



Define Ground Truth Data for Video or Image Sequences



Automate Ground Truth Labeling of Lane Boundaries



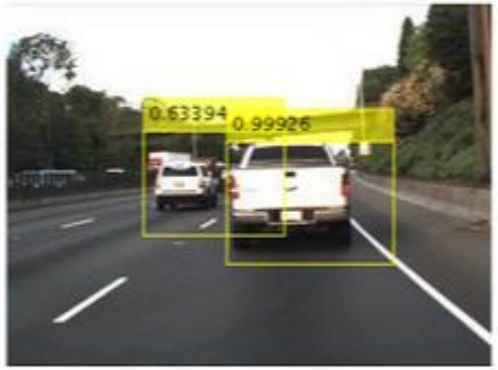
driving.connector.Connector class

Connect Lidar Display to Ground Truth Labeler

- **Label detections** with Ground Truth Labeler App
- **Add automation algorithm** for lane tracking
- **Extend connectivity** of Ground Truth Labeler App

Learn more about detecting objects in images

by exploring examples in the Automated Driving System Toolbox



Train a Deep Learning Vehicle Detector

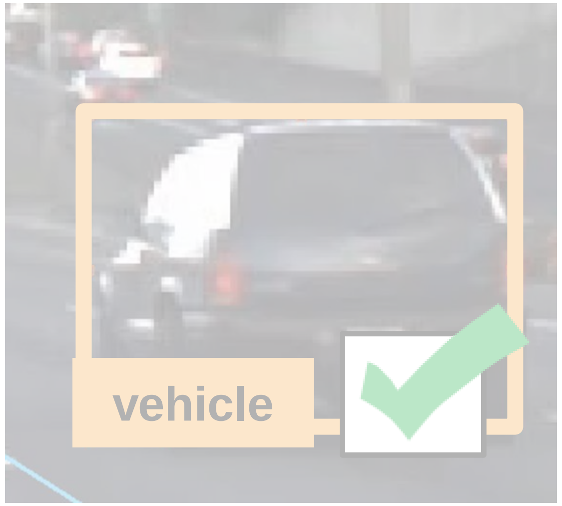
Track Pedestrians from a Moving Car

Visual Perception Using Monocular Camera

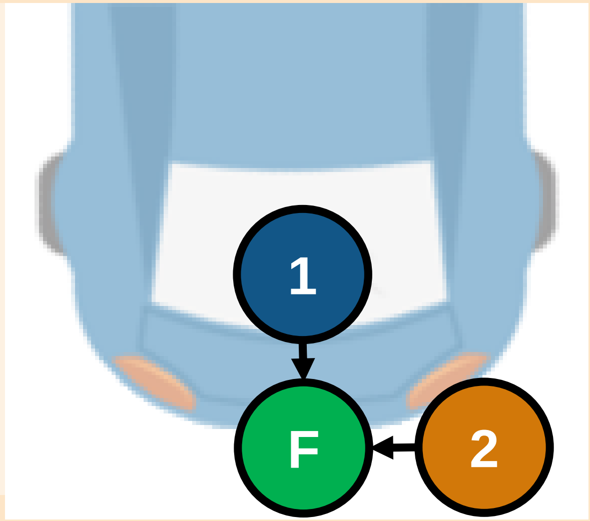
- **Train object detector** using deep learning and machine learning techniques
- **Explore pre-trained pedestrian detector**
- **Explore lane detector** using coordinate transforms for mono-camera sensor model

Some common questions from automated driving engineers

How can I visualize vehicle data?

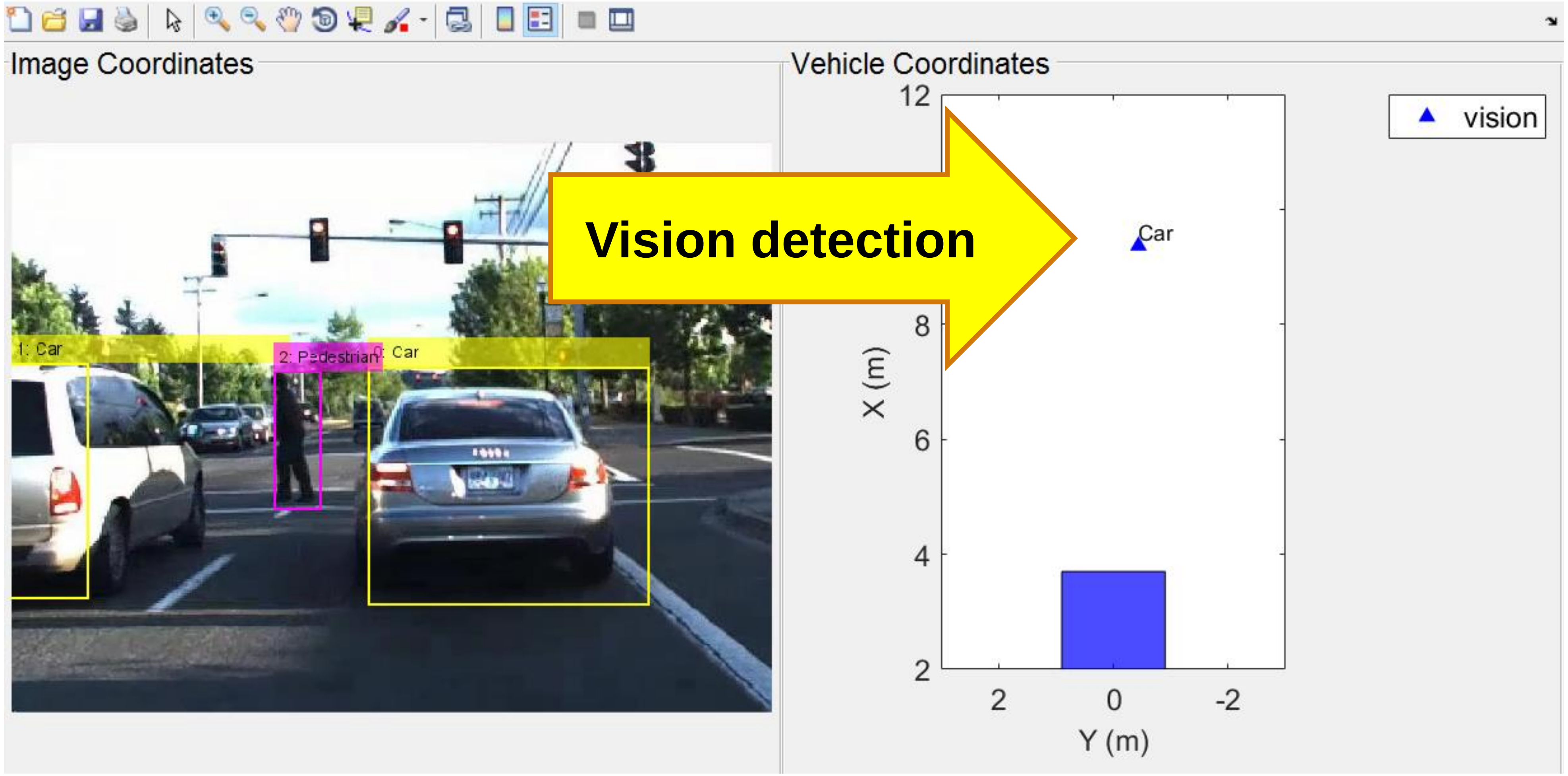


How can I detect objects in images?

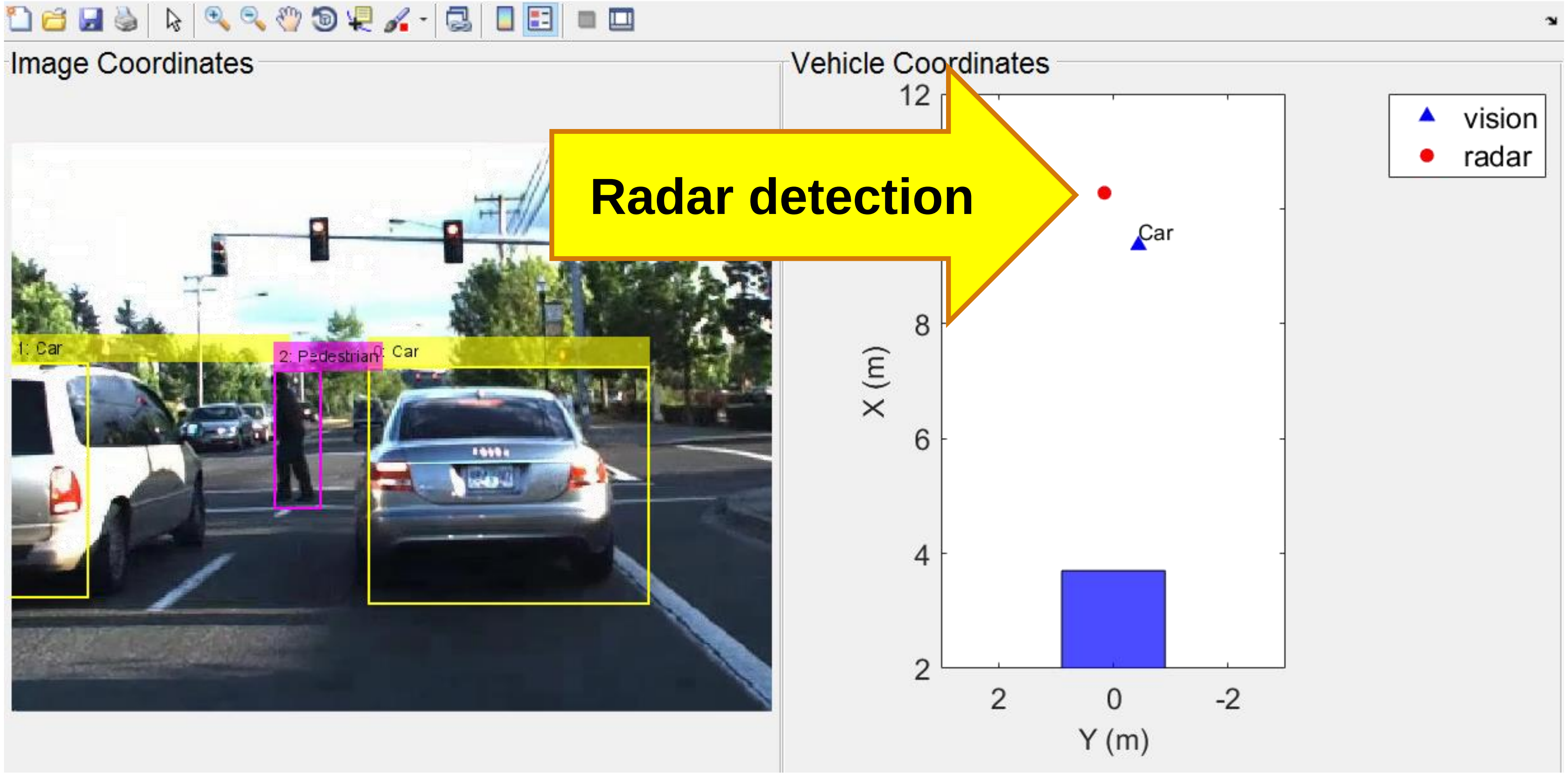


How can I fuse multiple detections?

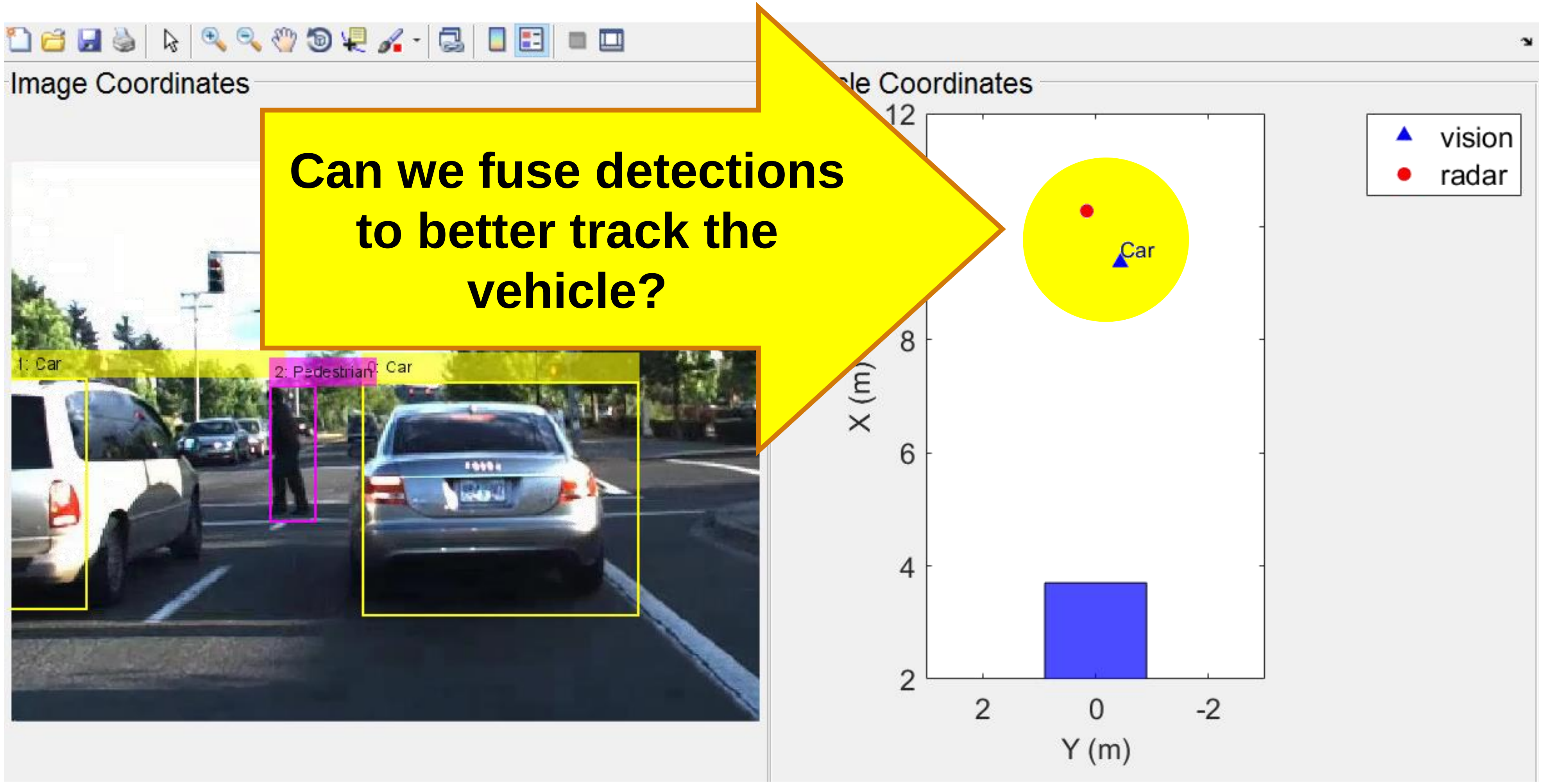
Example of radar and vision detections of a vehicle



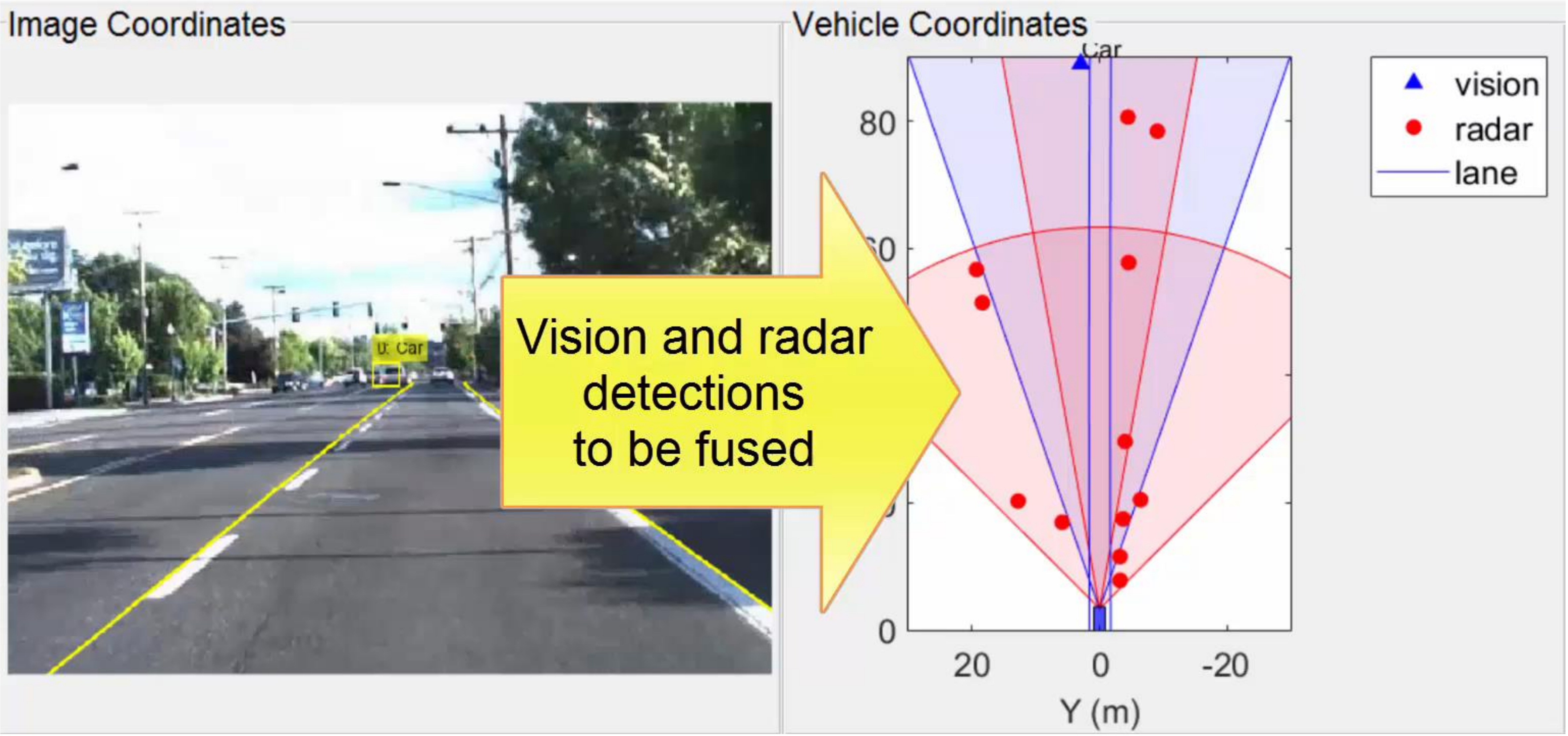
Example of radar and vision detections of a vehicle



Example of radar and vision detections of a vehicle

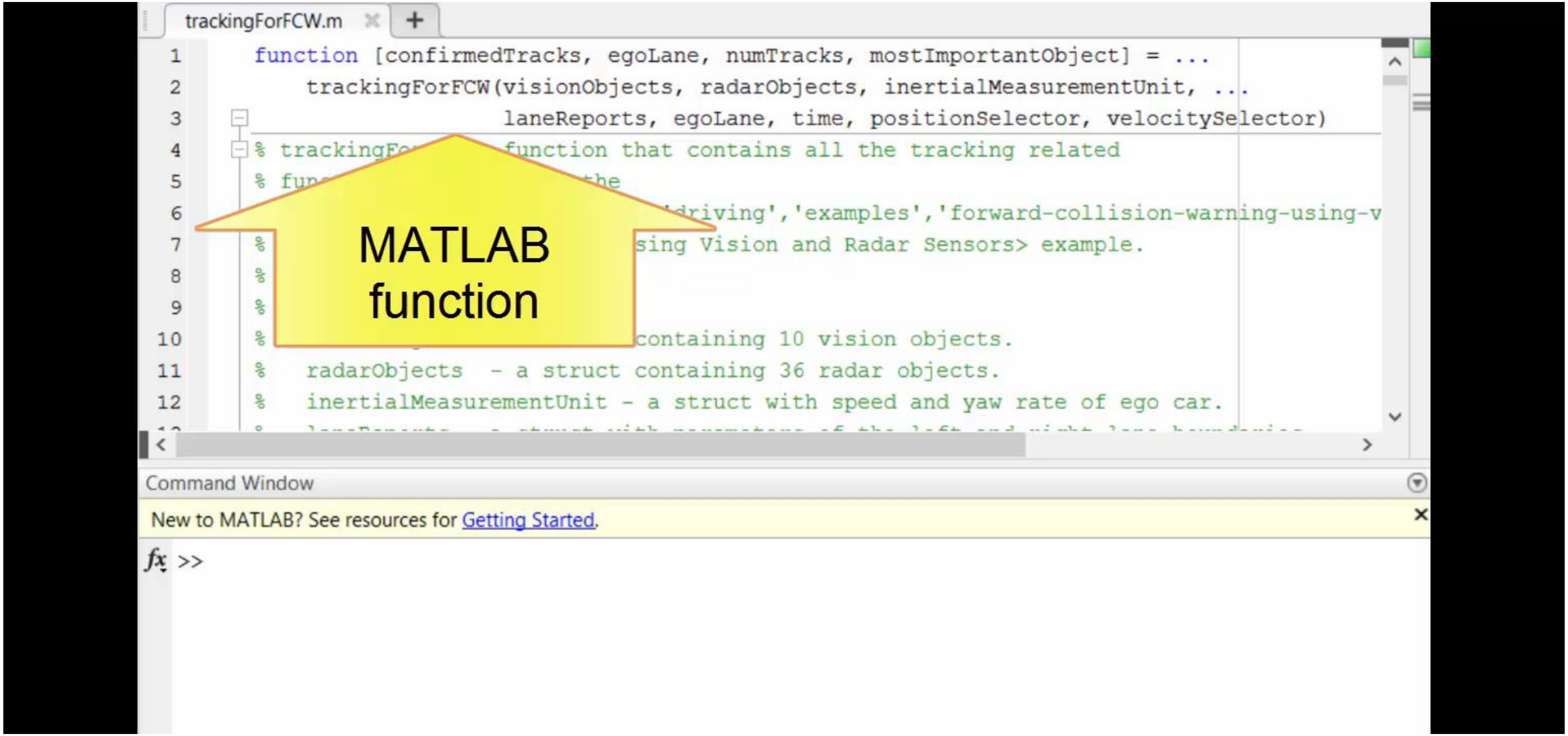


Fuse detections with multi-object tracker

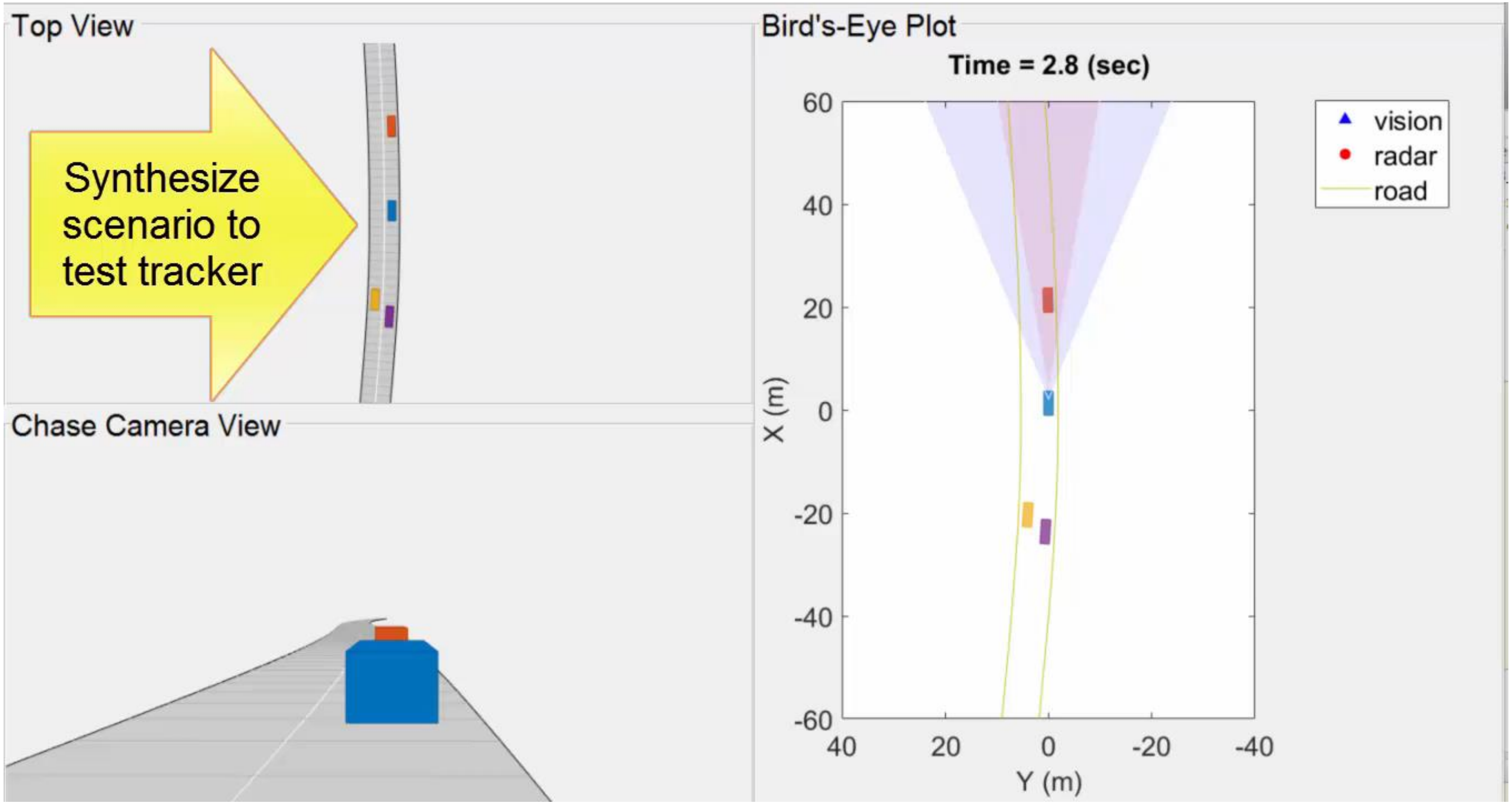


Integrate tracker into higher level algorithm

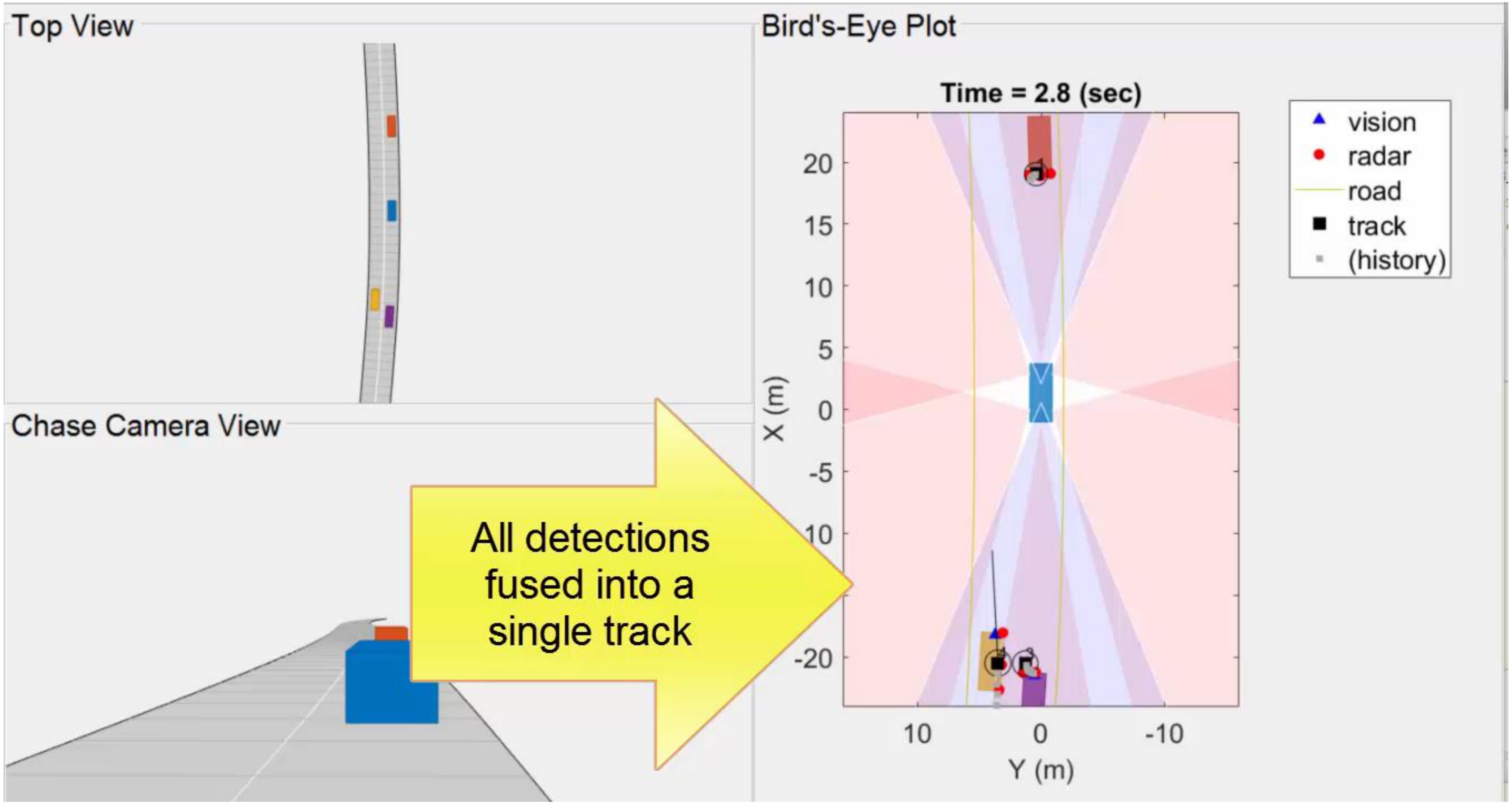
Generate C code for algorithm



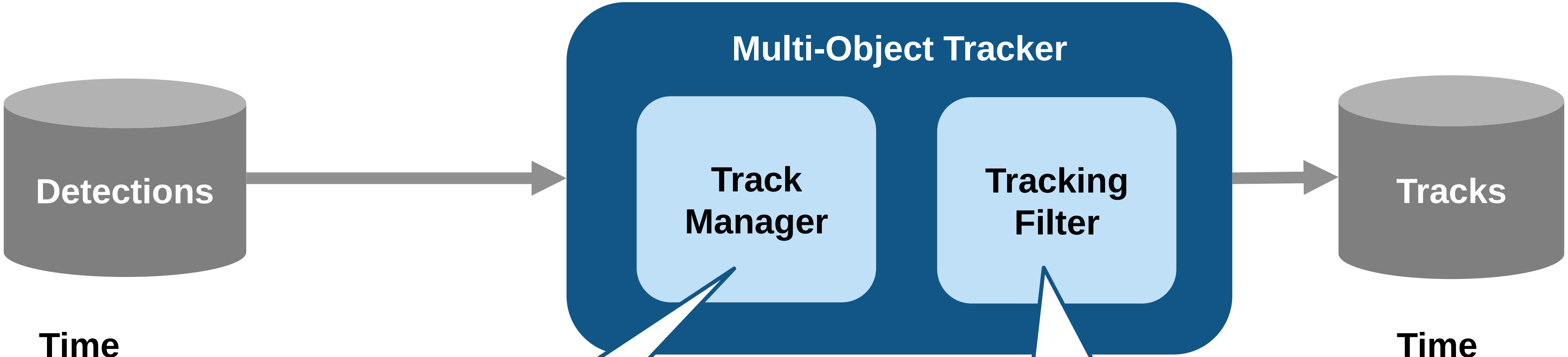
Synthesize scenario to test tracker



Test tracker against synthesized data



Track multiple object detections



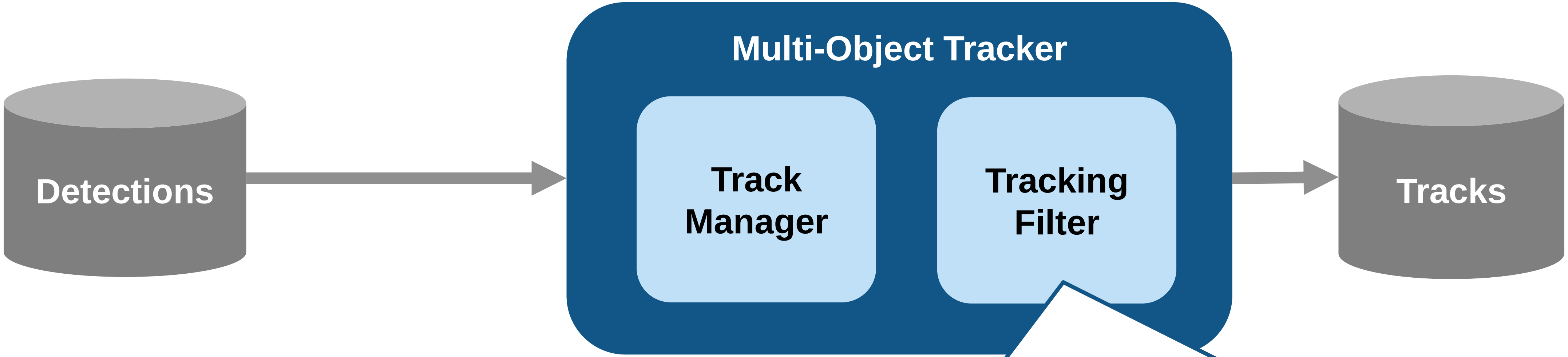
Time
Measurement
Measurement Noise

- 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

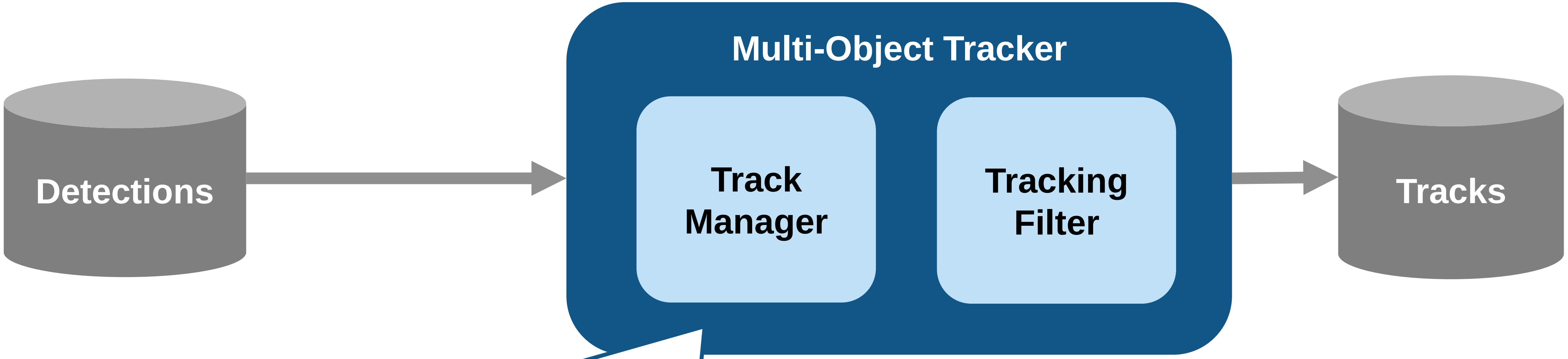
Time
State
State Covariance
Track ID
Age
Is Confirmed
Is Coasted

Examples of Kalman Filter (KF) initialization functions



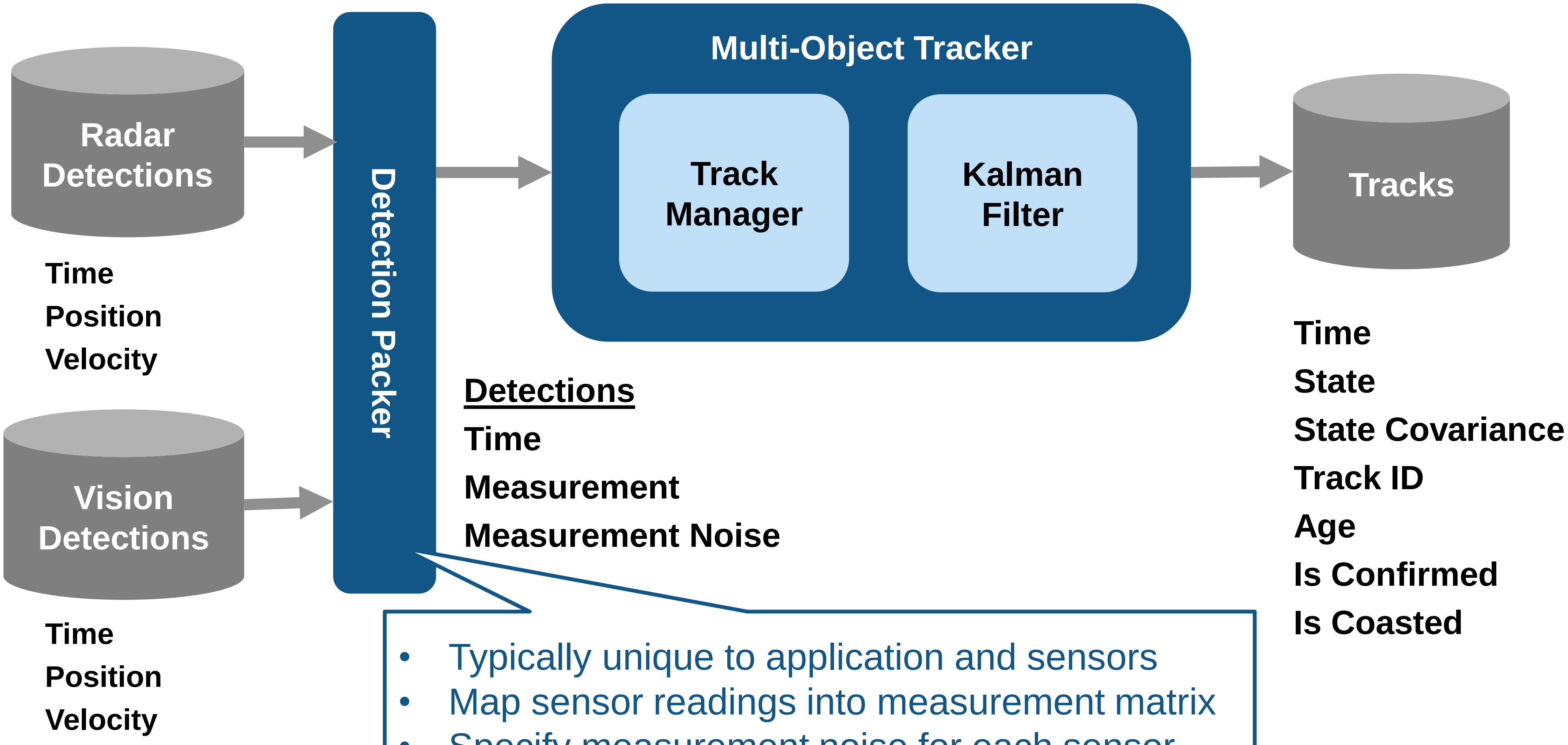
	Linear KF (`trackingKF`)	Extended KF (`trackingEKF`)	Unscented KF (`trackingUKF`)
Constant velocity	`initcvkf`	`initcvekf`	`initcvukf`
Constant acceleration	`initcakf`	`initcaekf`	`initcaukf`
Constant turn	Not applicable	`initctekf`	`initctukf`

Example of configuring multi-object tracker



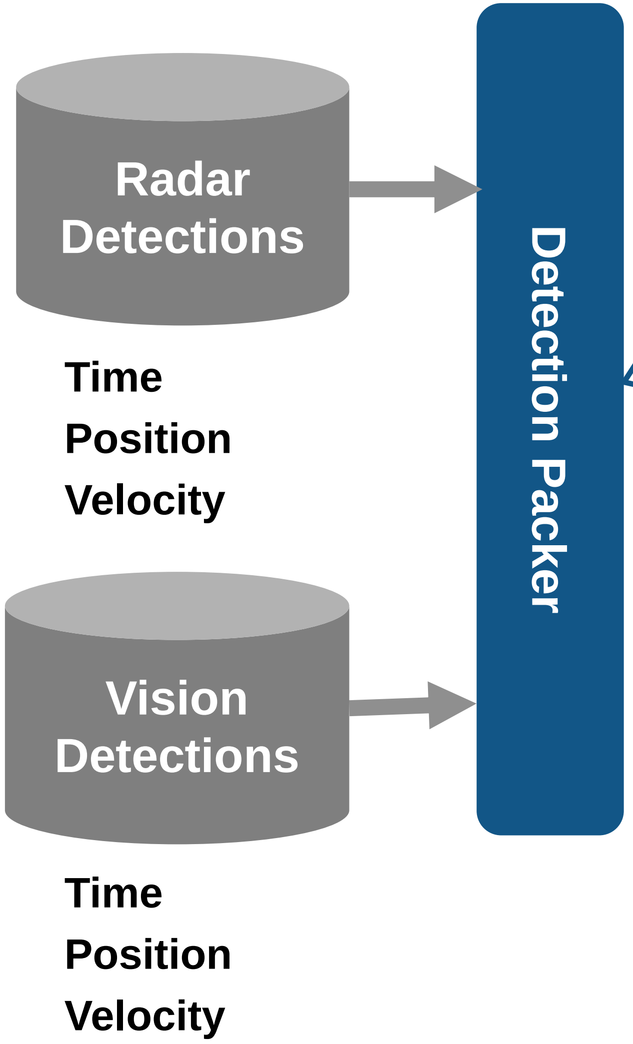

```
tracker = multiObjectTracker(...
    'FilterInitializationFcn', @initcaekf, ... % Handle to tracking Kalman filter
    'AssignmentThreshold',     35,... % Normalized distance from track for assignment
    'ConfirmationParameters',[2 ...   % Min number of assignments for confirmation
                               3],... % Min number of updates for confirmation
    'NumCoastingUpdates',      5);    % Threshold for track deletion
```

Fuse and track multiple detections from different sensors



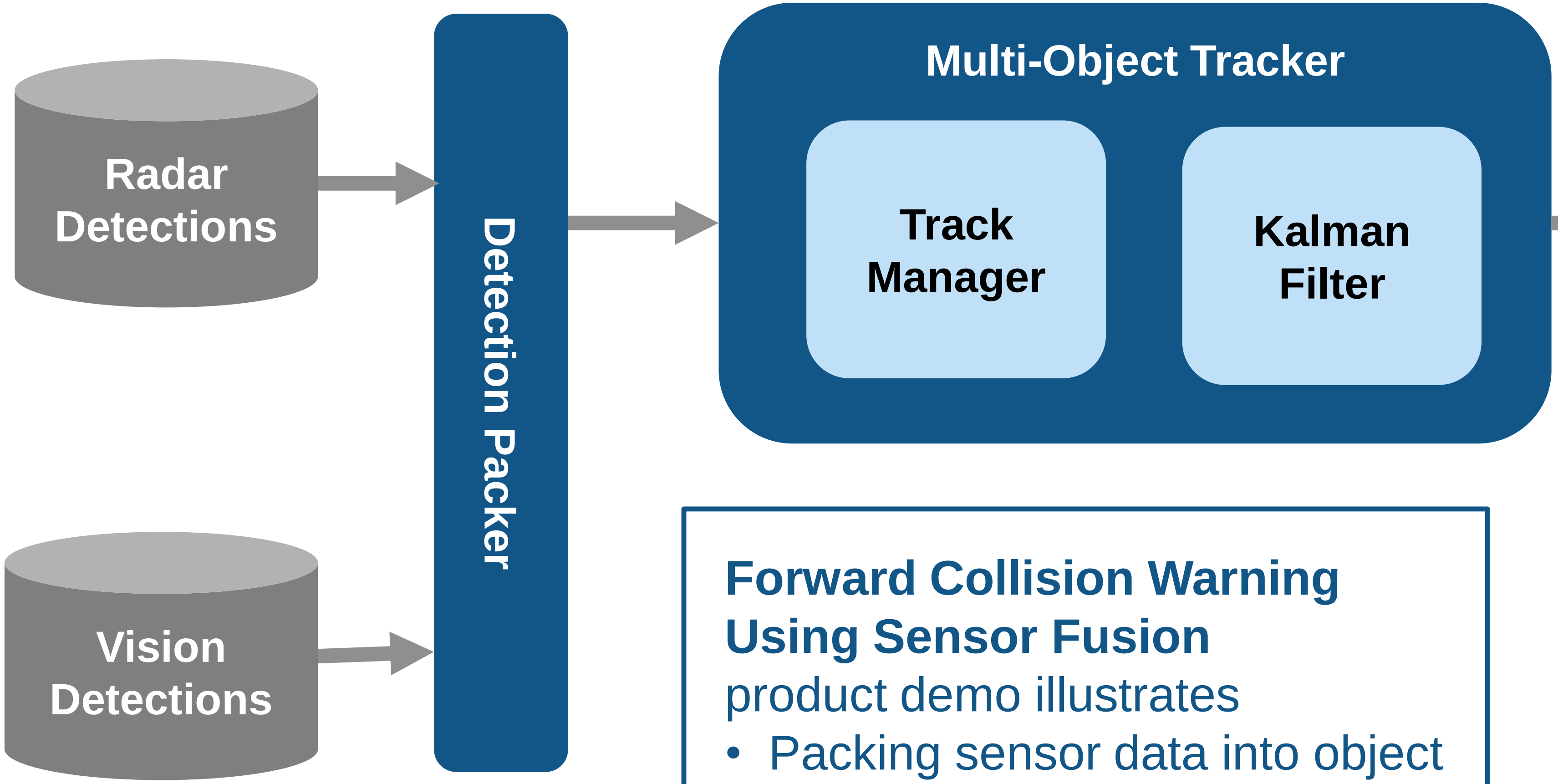
- Typically unique to application and sensors
- Map sensor readings into measurement matrix
- Specify measurement noise for each sensor

Example of packing sensor data into detection measurements

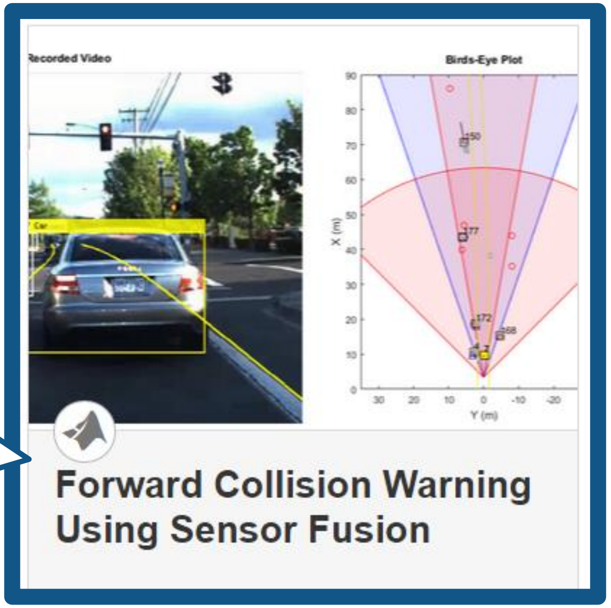



```
% Example sensor data
radar.Time          = 0.049;       % (sec)
radar.Position      = [10 0.5];    % [x y]  (m)
radar.Velocity      = [4.4 0.1];   % [x y]  (m/sec)
vision.Time         = 0.051;       % (sec)
vision.Position = [11 0.1];        % [x y]  (m)
vision.Velocity = 4.1;             % [x]    (m/sec)

% Pack to constant acceleration measurement format:
%  [positionX; velocityX; positionY; velocityY]
packedDetections(1) = objectDetection(radar.Time,...
    [radar.Position(1); radar.Velocity(1);...
     radar.Position(2); radar.Velocity(2)],...
    'MeasurementNoise', diag([1,1,2,10]));

packedDetections(2) = objectDetection(vision.Time,...
    [vision.Position(1); vision.Velocity(1);...
     vision.Position(2); 0],...
    'MeasurementNoise', diag([2,1,1,10]));
```

Explore demo to learn more about fusing detections



Forward Collision Warning Using Sensor Fusion
product demo illustrates
- Packing sensor data into object detections
- Initializing Kalman filter
- Configuring multi-object tracker



Generate C code for algorithm

with MATLAB Coder

trackingForFCW_kernel.m

```matlab
function [confirmedTracks, egoLane, numTracks, mostImportantObject] = ...
    trackingForFCW_kernel(visionObjects, radarObjects, inertialMeasurementUnit, ...
    laneReports, egoLane, time, positionSelector, velocitySelector)
```

Generate C code with **codegen**

File: trackingForFCW_kernel.c

```c
 */
void trackingForFCW_kernel(const struct0_T *visionObjects, const struct2_T
  *radarObjects, const struct4_T *inertialMeasurementUnit, const struct5_T
  *laneReports, struct7_T *egoLane, double time, const double positionSelector
  [12], const double velocitySelector[12], emxArray_struct8_T *confirmedTracks,
  double *numTracks, struct10_T *mostImportantObject)
```

Generate C-code for algorithm
with MATLAB Coder

```
%% Create variables that will be used to specify example input arguments
[visionObjects, radarObjects, imu, lanes] = ...
    helperReadSensorRecordingsFile('01_city_c2s_fcw_10s_sensor.mat');
egoLane = struct('left', [0 0 0], 'right', [0 0 0]);
time = 0;
positionSelector = [1 0 0 0 0 0; 0 0 0 1 0 0];
velocitySelector = [0 1 0 0 0 0; 0 0 0 0 1 0];

exampleInputs  = {visionObjects(1), radarObjects(1), imu(1),...
                  lanes(1), egoLane, time,...
                  positionSelector, velocitySelector};

%% Generate code for sensor fusion algorithm: trackingForFCW_kernel
codegen trackingForFCW_kernel -args exampleInputs -config:dll -launchreport
```

Install patch to generate C code from multiObjectTracker

- https://www.mathworks.com/support/bugreports/1546972

1546972

Summary

Code generation fails for multiObjectTracker in 'lib' or 'dll' configuration

Description

Code generation of a function that uses multiObjectTracker fails under some conditions with the following error message:

```
??? Property 'pSampleDetection.Measurement' is undefined on
some execution paths but is used inside the called
function.
```

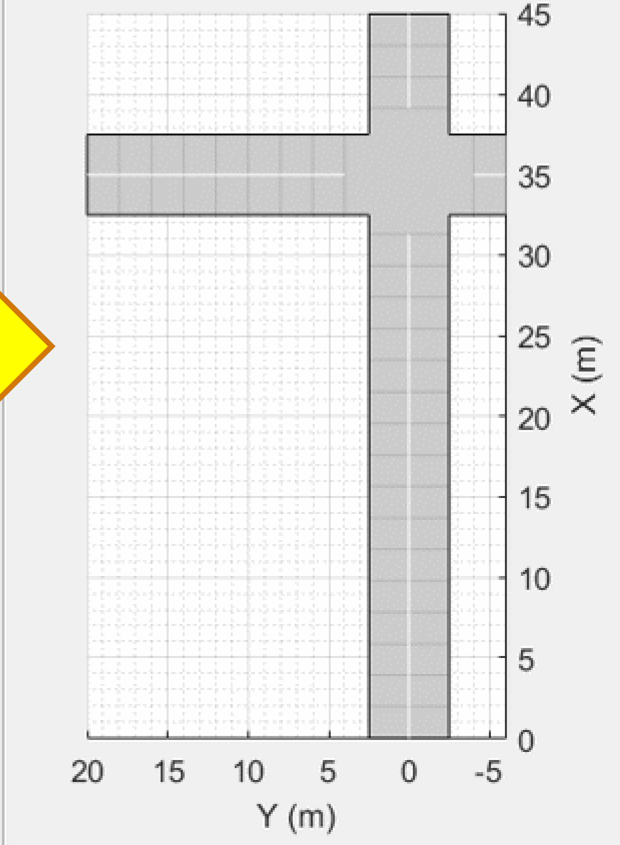
Workaround

Installation instructions

Specify driving scenario and roads

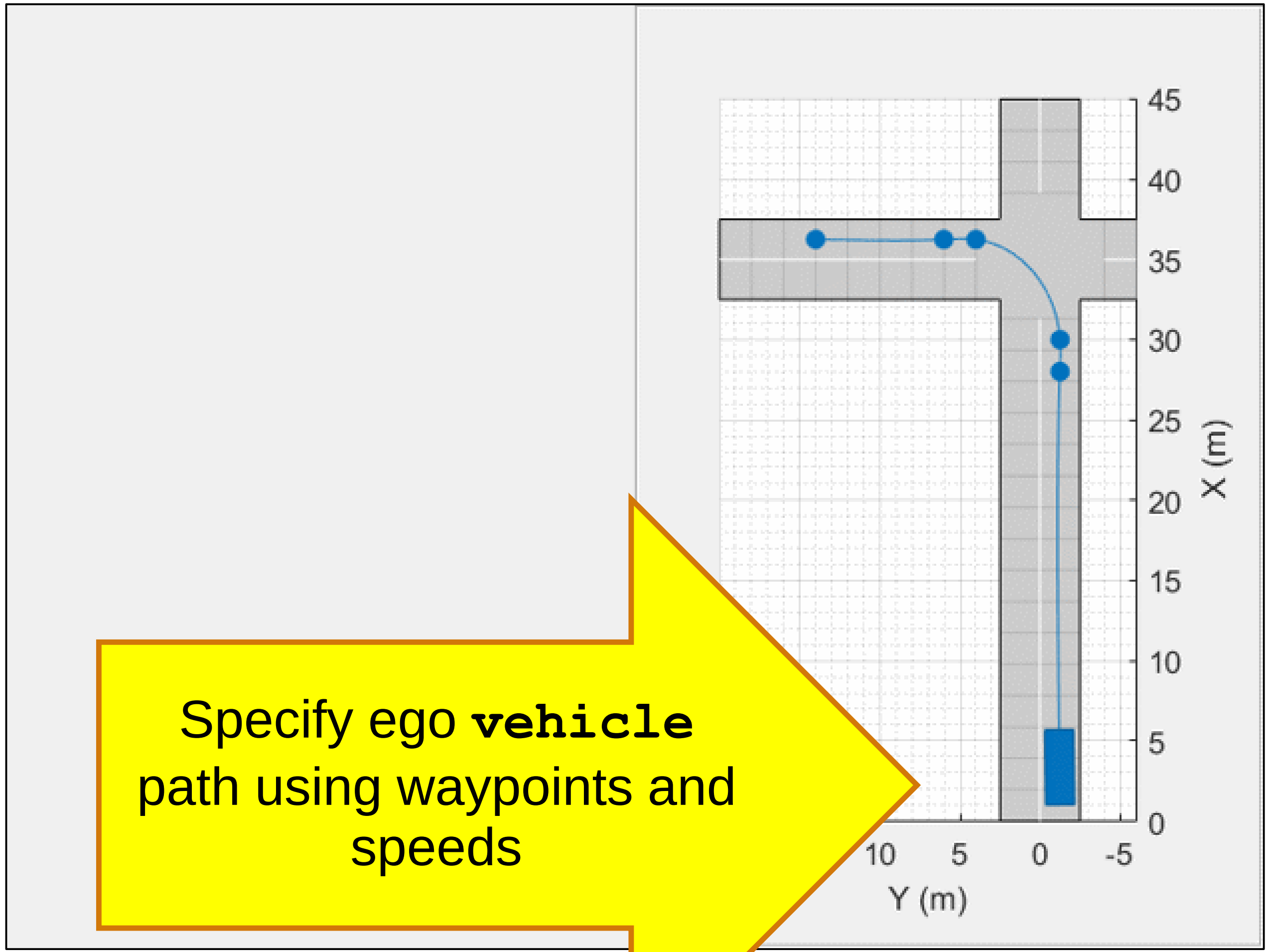
```matlab
%% Create a new scenario
s = drivingScenario('SampleTime', 0.05);

%% Create road
road(s, [ 0  0; ...  % Centers [x,y] (m)
          45  0],...
          5);          % Width (m)
road(s, [35  20; ...
          35 -10],...
          5);

%% Plot scenario
p1 = uipanel('Position',[0.5 0 0.5 1]);
a1 = axes('Parent',p1);
plot(s,'Parent',a1,...
    'Centerline','on','Waypoints','on')
a1.XLim = [0 45];
a1.YLim = [-6 20];
```

Specify **road** centers and width as part of a **drivingScenario**



Add ego vehicle

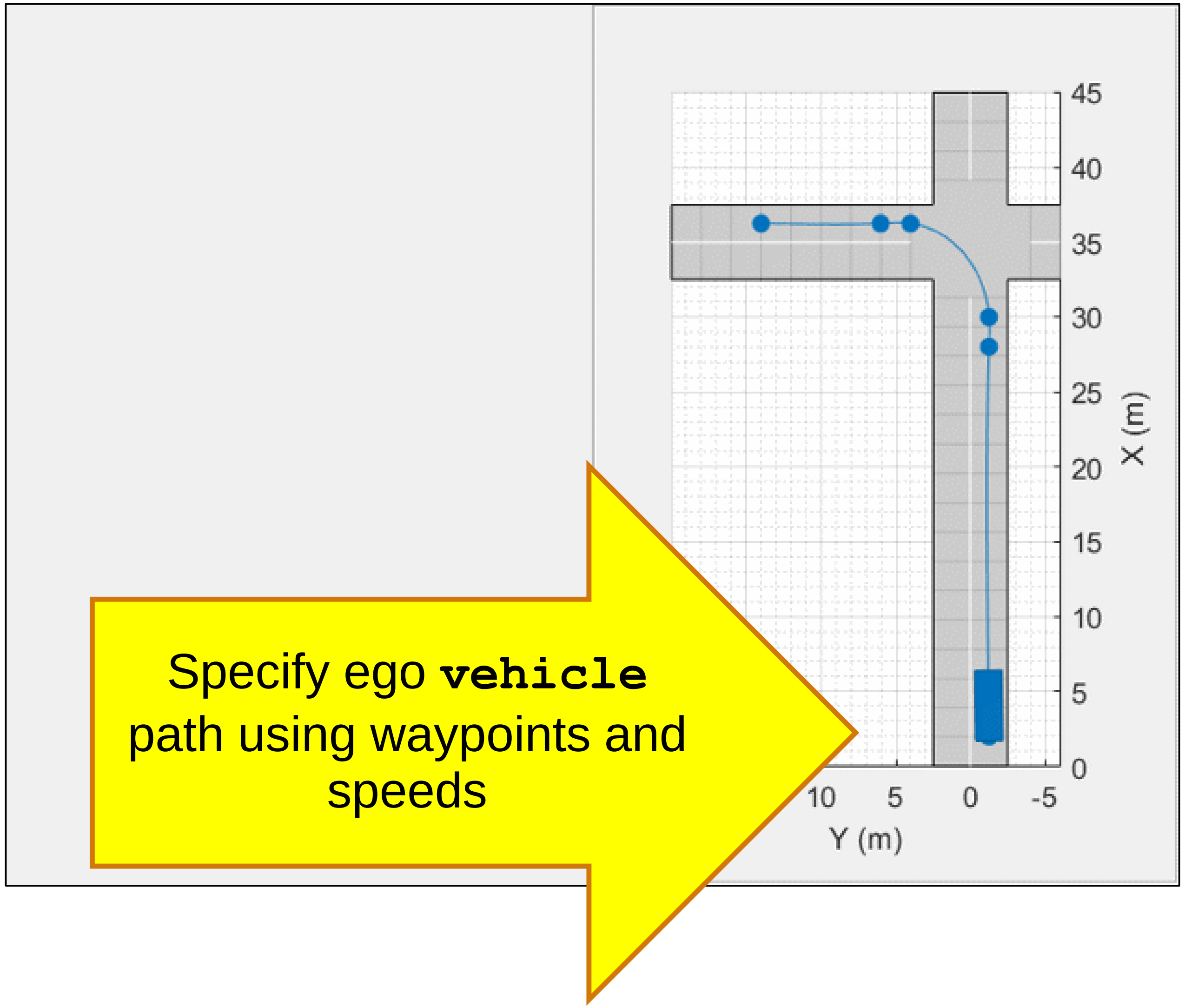
```
%% Add ego vehicle
egoCar = vehicle(s);
waypoints = [ 2   -1.25;... % [x y]  (m)
             28   -1.25;...
             30   -1.25;...
             36.25   4;...
             36.25   6;...
             36.25  14];
speed = 13.89; % (m/s) = 50 km/hr
path(egoCar, waypoints, speed);
```



Specify ego **vehicle** path using waypoints and speeds

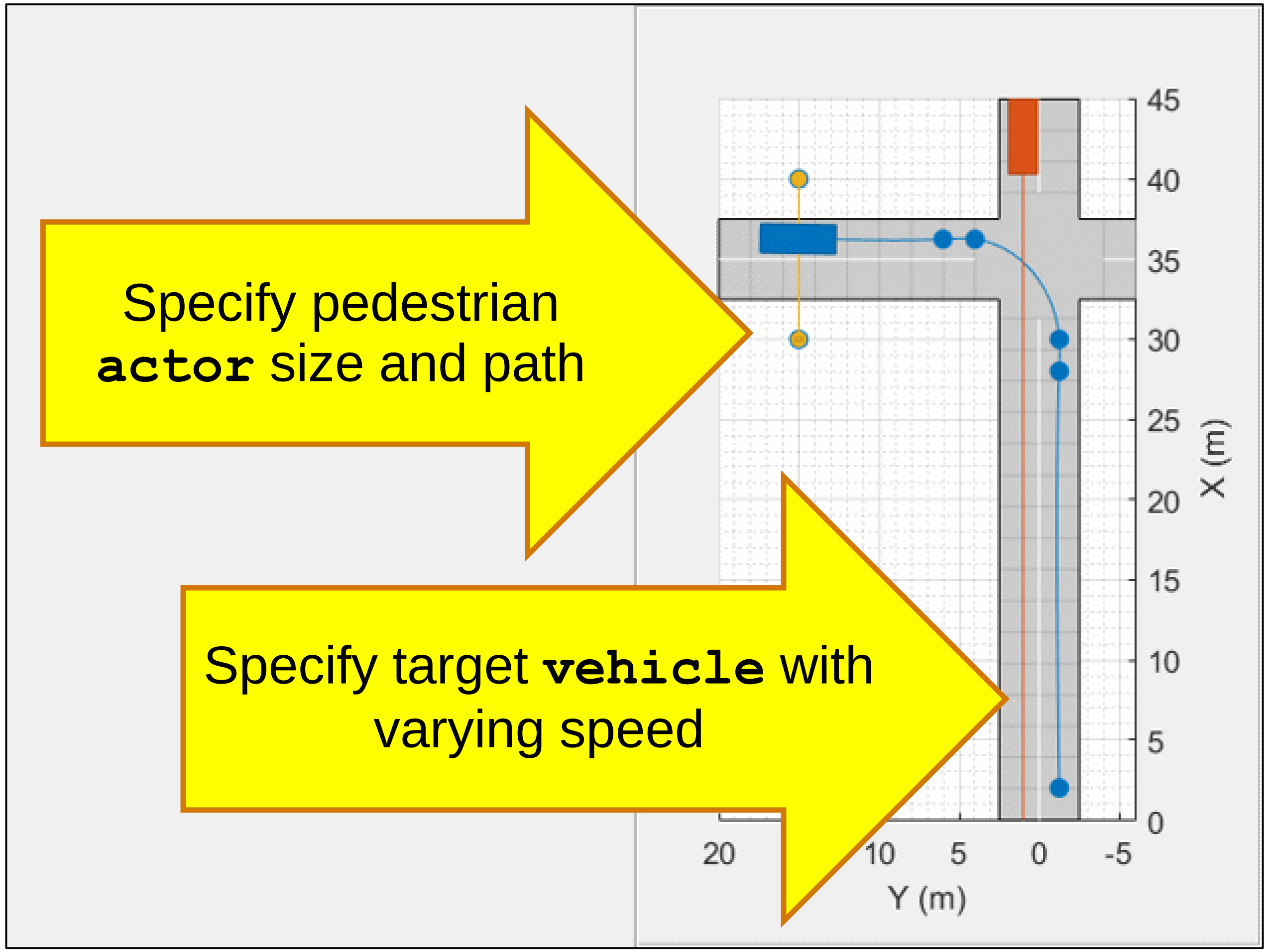
Add ego vehicle

```
%% Add ego vehicle
egoCar = vehicle(s);
waypoints = [ 2   -1.25;... % [x y]  (m)
             28   -1.25;...
             30   -1.25;...
             36.25    4;...
             36.25    6;...
             36.25   14];
speed = 13.89; % (m/s) = 50 km/hr
path(egoCar, waypoints, speed);

%% Play scenario
while advance(s)
    pause(s.SampleTime);
end
```



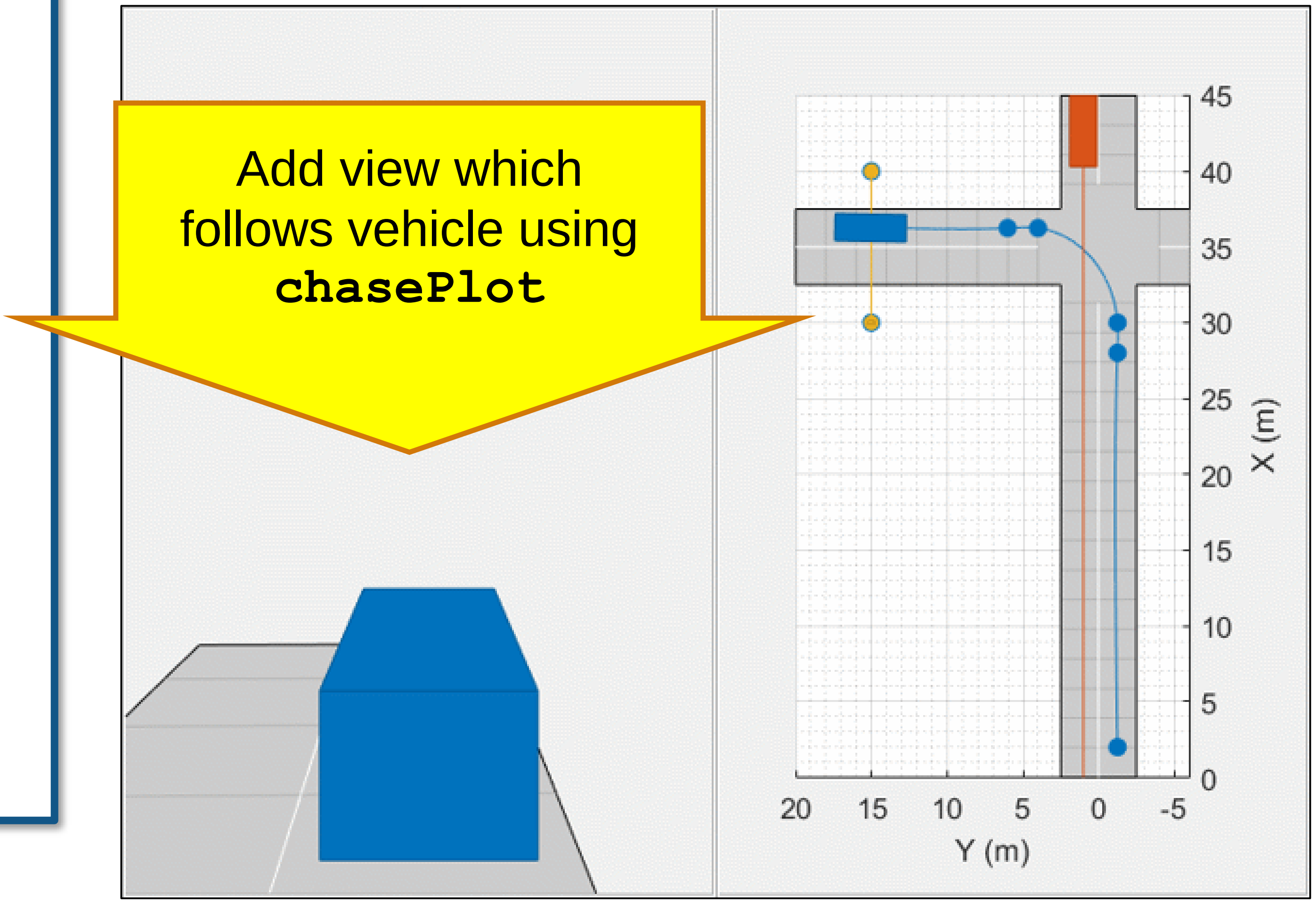
Add target vehicle and pedestrian actor

```
%% Add Target vehicle
targetVehicle = vehicle(s);
path(targetVehicle,...
      [44 1; -4 1],... % Waypoints (m)
      [5  ; 14]);      % Speeds (m/s)


%% Add child pedestrian actor
child = actor(s,'Length',0.24,...
                'Width',0.45,...
                'Height',1.7,...
                'Position',[40 -5 0],...
                'Yaw',180);
path(child,...
    [30 15; 40 15],... % Waypoints (m)
    1.39); % Speed (m/s) = 5 km/hr
```



View scenario from behind ego vehicle

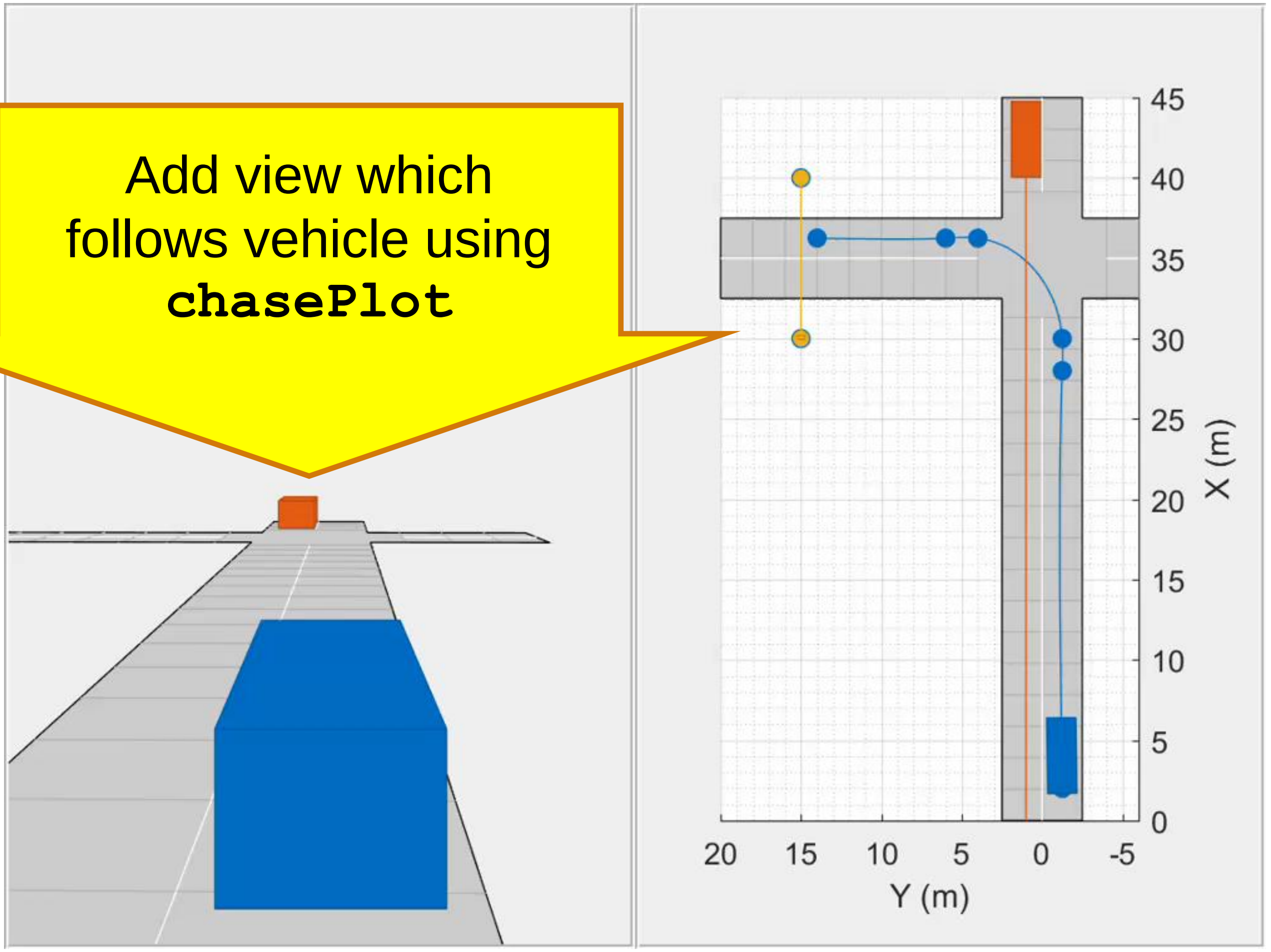
```
%% Add chase view (left)
p2 = uipanel('Position',[0 0 0.5 1]);
a2 = axes('Parent',p2);
chasePlot(egoCar,...
    'Parent',a2,...
    'Centerline','on',...
    'ViewHeight',3.5,...      % (m)
    'ViewLocation',[-8 0]); % [x y]  (m)
```



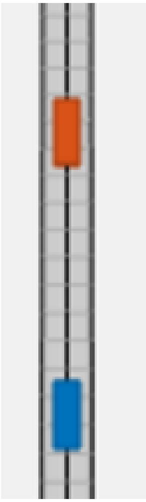
View scenario from behind ego vehicle

```
%% Add chase view (left)
p2 = uipanel('Position',[0 0 0.5 1]);
a2 = axes('Parent',p2);
chasePlot(egoCar,...
    'Parent',a2,...
    'Centerline','on',...
    'ViewHeight',3.5,...     % (m)
    'ViewLocation',[-8 0]); % [x y] (m)

%% Play scenario
restart(s)
while advance(s)
    pause(s.SampleTime);
end
```

Add view which follows vehicle using **`chasePlot`**



Simulate effects of vision detection sensor

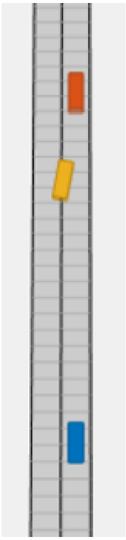


Range effects

- Range measurement accuracy degrades with distance to object
- Angle measurement accuracy consistent throughout coverage area

Road elevation effects

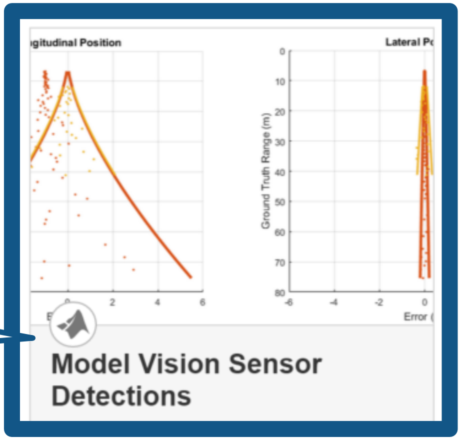
- Objects may not be detected if they appear above the horizon line
- Large range measurement errors can be introduced for detected objects at different road elevations



Occlusion effects

- Partially or completely occluded objects are not detected

Model Vision Sensor Detections
product demo illustrates these effects



Model vision detection sensor

```
%% Create vision detection generator
sensor = visionDetectionGenerator(...
    'SensorLocation', [0.75*egoCar.Wheelbase 0], ...
    'Height', 1.1, ...
    'Pitch', 1, ...
    'Intrinsics', cameraIntrinsics(...
        800,...             % Focal length
        [320 240],...       % Principal point
        [480 640]), ... % Image size
        'RadialDistortion',[0 0], ...
        'TangientialDistortion',[0 0]), ...
    'UpdateInterval', s.SampleTime, ...
    'BoundingBoxAccuracy', 5, ...
    'MaxRange', 150, ...
    'ActorProfiles', actorProfiles(s));
```

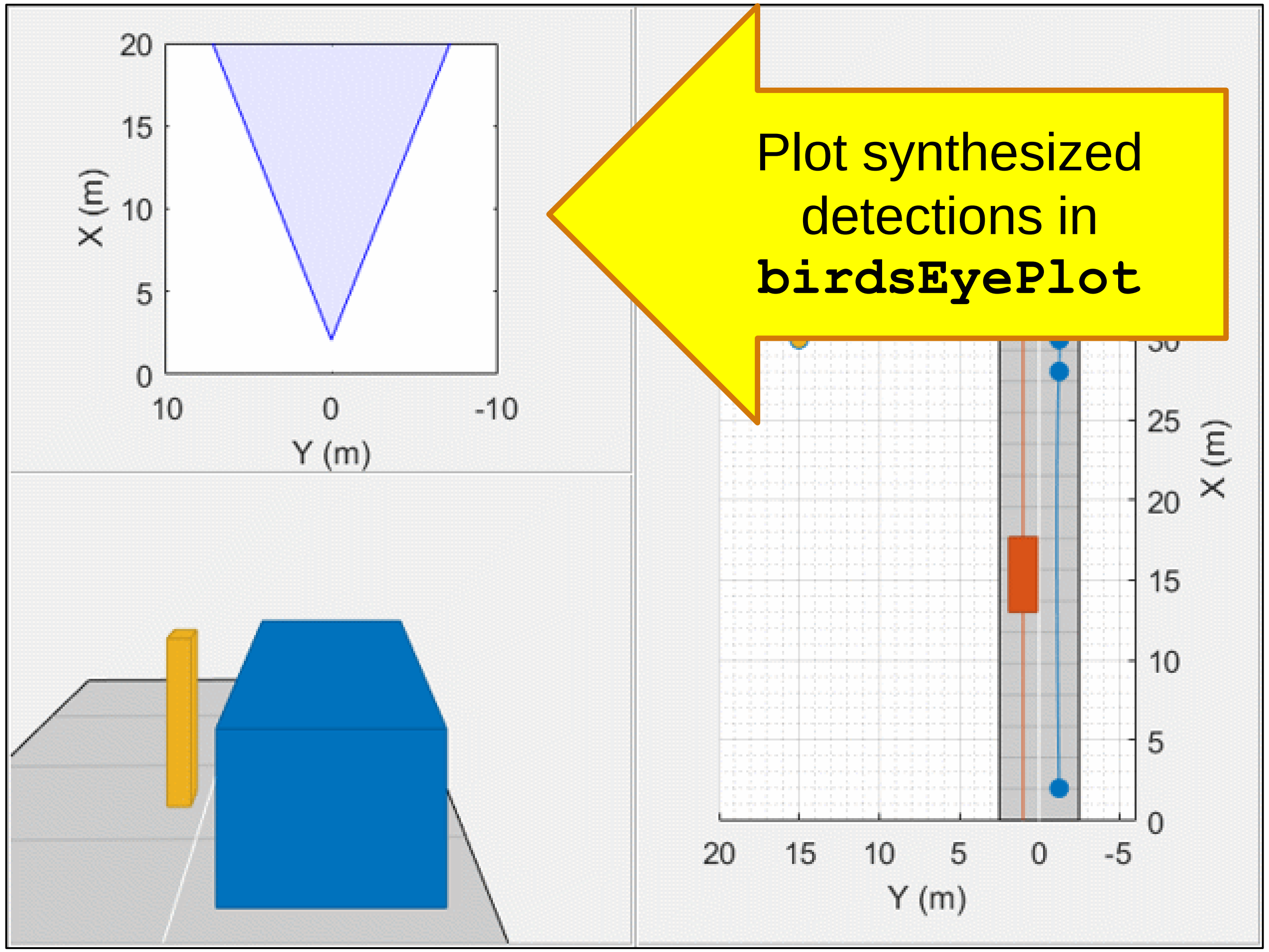
Extrinsic mounting parameters

Coverage area is determined based on **`cameraIntrinsics`**

Model radar detection sensor using **`radarDetectionGenerator`**

Create birds eye plot to view sensor detections

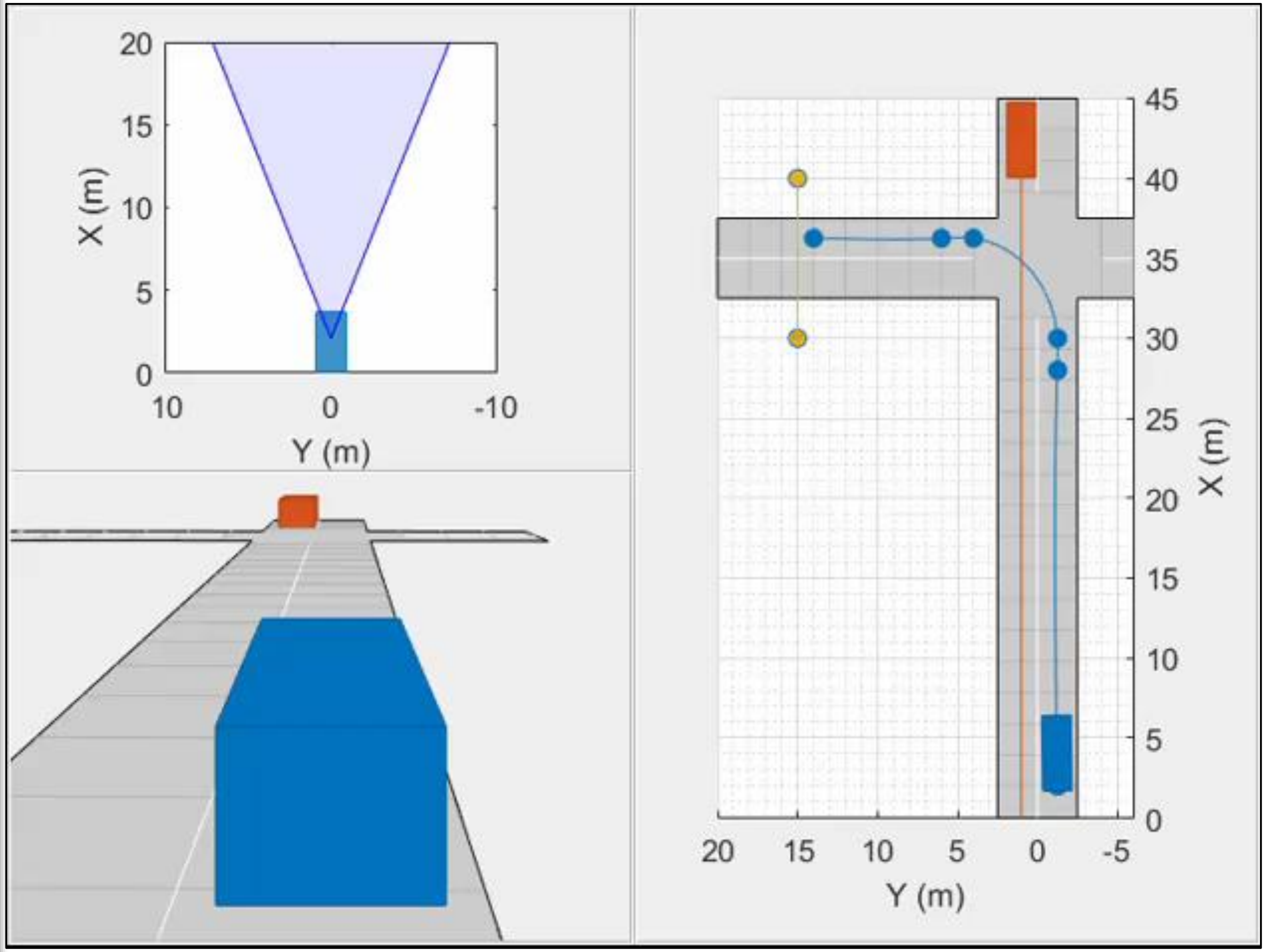
```
%% Add sensor birds eye plot (top left)
p3 = uipanel('Position',[0 0.5 0.5 0.5]);
a3 = axes('Parent',p3);
bep = birdsEyePlot('Parent',a3,...
    'Xlimits', [0 20],...
    'Ylimits', [-10 10]);
legend(a3,'off');

% Create plotters
covPlot = coverageAreaPlotter(bep,...
    'FaceColor','blue',...
    'EdgeColor','blue');
plotCoverageArea(covPlot,...
    sensor.SensorLocation,sensor.MaxRange,...
    sensor.Yaw,sensor.FieldOfView(1))

detPlot = detectionPlotter(bep,...
    'MarkerEdgeColor','blue',...
    'Marker','^');

truthPlot = outlinePlotter(bep);
```



Plot synthesized detections in **birdsEyePlot**

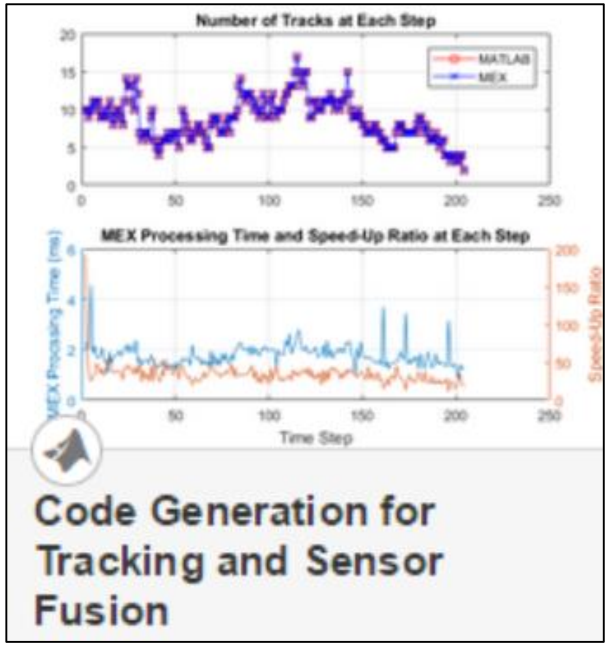
Play scenario with sensor models

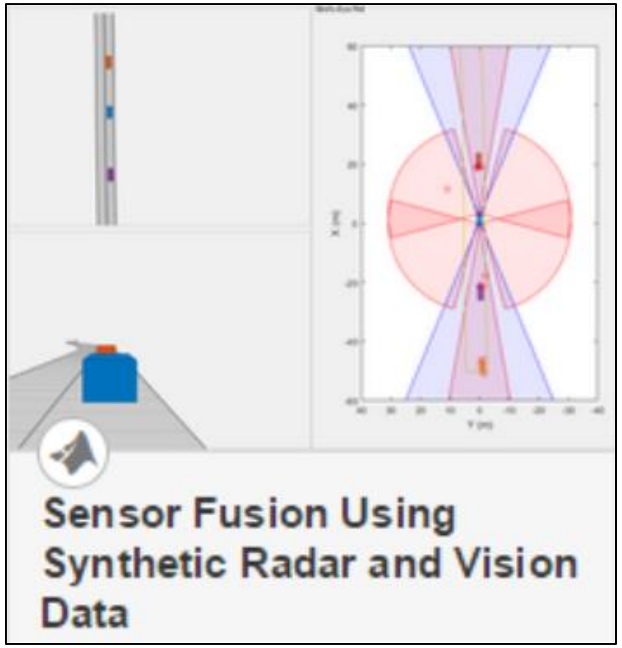
```
restart(s)
while advance(s)
   % Get detections in ego vehicle coordinates
   det = sensor(targetPoses(egoCar),...
                 s.SimulationTime);
   % Update plotters
   if isempty(det)
       clearData(detPlot)
   else % Unpack measurements to position/velocity
       pos = cellfun(@(d)d.Measurement(1:2),...
                 det,'UniformOutput',false);
       vel = cellfun(@(d)d.Measurement(4:5),...
                 det,'UniformOutput',false);
       plotDetection(detPlot,...
           cell2mat(pos')', cell2mat(vel')');
   end
   [p, y, l, w, oo, c] = targetOutlines(egoCar);
   plotOutline(truthPlot,p,y,l,w,...
       'OriginOffset', oo, 'Color', c);
end
```



Learn more about sensor fusion

by exploring examples in the Automated Driving System Toolbox



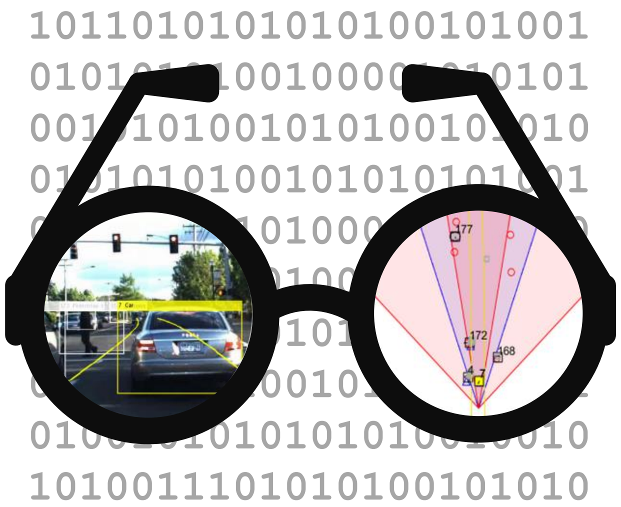


- **Design**
  multi-object tracker
  based on logged
  vehicle data

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

- **Synthesize**
  driving scenario
  to test
  multi-object tracker

The Automated Driving System Toolbox helps you…

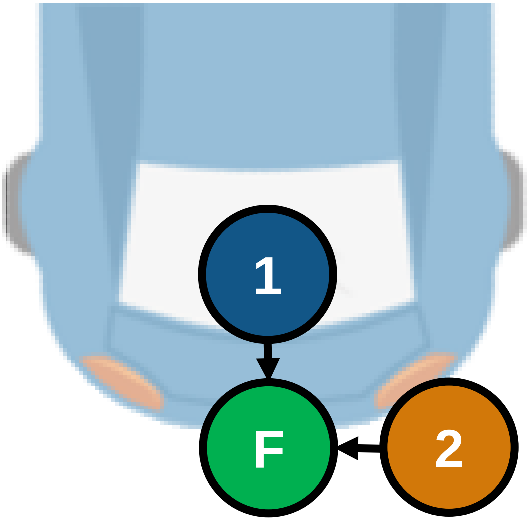


Visualize vehicle data

- Plot sensor detections
- Plot coverage areas
- Transform between image and vehicle coordinates

Detect objects in images

- Train deep learning networks
- Label ground truth
- Connect to other tools



Fuse multiple detections

- Design multi-object tracker
- Generate C/C++
- Synthesize driving scenarios