Integrated model

Development and testing

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# Introduction

After the development of a virtual differential system and of an ESP control, for an all-wheel drive electric vehicle, it is fundamental to integrate the two, to study the combined effect when on a vehicle. The integrated system also requires integration with the complete vehicle model, devised appositely to support testing and validation of the developed system.

The integration requires special care, as it has to opportunely anticipate the behavior of the system which will eventually be implemented on car, to reduce development and testing costs and fasten up the individuation and correction of errors, also increasing the safety of real-world testing. The units integrated in the system shall be extensively tested, so that errors resulting from the interconnection can be more quickly asserted and solved.

The objective of this dissertation is to introduce the procedure used to integrate the subsystems and test the integrated model.

In the following there will be introduced:

* input signals used to interface with subsystems;
* output signals provided by the integrated system;
* interconnection between blocks;
* testing of the integrated system.

## System requirements

In order to interface with the model, the following software modules are required:

* MATLAB R2019b and Simulink
* Powertrain Blockset
* Vehicle Dynamics Blockset

# Input and output signals

The developed units, and the surrounding blocks necessary for a correct integration, require some signals to be retrieved from the vehicle model. On a real car, these signals would either be retrieved from on-board sensors, eventually following some elaboration procedures, or from signals produced by other ECUs.

The required input signals, used for subsystems integration, are:

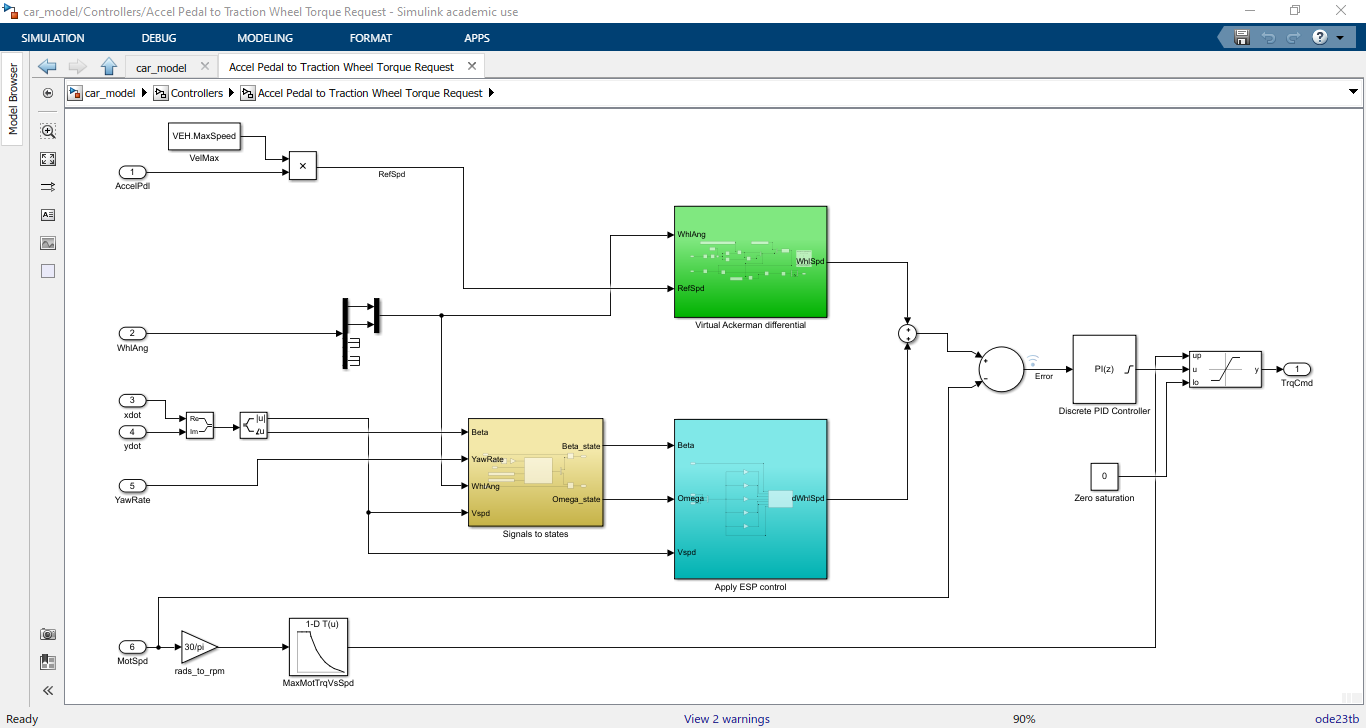
* **AccelPdl**: percentage of throttle pedal position, set by the driver and provided in the scheme by the Predictive Driver; it is required to determine the wanted reference speed.
* **WhlAng**: absolute rotation around vertical axis of each wheel, provided by the steering column; it is required to determine wheels’ speeds in ideal driving conditions.
* **Xdot**: longitudinal (along X axis) speed of the vehicle in vehicle refence frame, typically provided by on-board sensors, provided in the scheme by vehicle feedback loop; it is required to determine ESP control for increased stability.
* **Ydot**: lateral (along Y axis) speed of the vehicle in vehicle refence frame, typically provided by on-board sensors, provided in the scheme by vehicle feedback loop; it is required to determine ESP control for increased stability.
* **YawRate**: angular speed of the vehicle along the vertical axis, typically provided by on-board sensors, provided in the scheme by vehicle feedback loop; it is required to determine ESP control for increased stability.
* **MotSpd**: speed of each electric motor, provided by the electric machines; it is required to determine the control action of the on-wheel motors, as well as determining the maximum deliverable torque.

The integrated system provides some output signals:

* **TrqCmd**: torque requested to each electric motor, as an application of the control action; on a real vehicle, it is a command passed over in-vehicle network.

# Integration of subsystems

The scheme of the integrated subsystem is shown below. In figure, green block is the virtual differential, orange block is the translation of vehicle’s status to state space variables, blue block is ESP controller.



**Virtual differential block**

Virtual differential block requires front wheels’ angles and reference vehicle’s speed as input.

* Wheels’ angles are directly provided from the steering mechanism, which computes them starting from the steering angle on the steering wheel controlled by driver.
* Reference speed is computed from the throttle pedal position. The throttle pedal opening (in percentage) is multiplied by maximum vehicle speed to provide the reference speed as a fraction of the maximum vehicle speed. Therefore, throttle pedal linearly relates to the desired vehicle speed.

Virtual differential block provides the required wheels’ speeds in ideal driving conditions.

* The wheels’ speeds are computed according to ideal Ackerman steering geometry model and assumes ideal driving conditions. They are used to determine the torques required to on-wheels motors.

**Signals to states block**

The signals-to-states block determines the vehicle’s states as required by the ESP control system. Indeed, ESP control system applies optimal control on delta variables, computed as the difference between vehicle’s state variables and states at equilibrium condition.

The block requires some inputs for the correct computation of the states.

* Beta, current side-slip angle, angle between vehicle’s speed vector and vehicle’s longitudinal axis. It is provided by on-vehicle sensors.
* Yaw rate, current angular speed of the vehicle with respect to vertical axis passing through vehicle’s center of gravity. It is provided by on-vehicle sensors.
* Wheels’ angles are directly provided from the steering mechanism, which computes them starting from the steering angle on the steering wheel controlled by driver. They are required for the computation of the equilibrium condition.
* Current vehicle speed is directly provided by sensors. It is required for the computation of the equilibrium condition.

The block returns delta states as required by the ESP control system.

* Delta beta, computed as the difference between side-slip angle, from sensors, and the same angle at equilibrium according to current driving conditions.
* Delta yaw rate, computed as the difference between yaw rate, from sensors, and the same angular speed at equilibrium according to current driving conditions.

**ESP control block**

The ESP control block applies an optimal control strategy, based on the current state of the vehicle, to increase global stability of the car. This system helps in avoiding skidding when cornering or due to bad road conditions (i.e. ice on road).

The ESP control block requires the knowledge of the state of the vehicle.

* Beta is current side-slip angle, compared to current equilibrium condition. It is a state for the ESP control; therefore, it is multiplied by a gain to compute the control action.
* Omega is current yaw rate, compared to current equilibrium condition. It is a state for the ESP control; therefore, it is multiplied by a gain to compute the control action.
* Current vehicle speed is required to choose the proper gain to apply optimal control. It thus determines the gain matrix that will be multiplied by state vector.

The ESP control block provides the required wheels’ speeds difference due to non-ideal driving condition.

* Delta wheels’ speeds are determined, applying optimal control, as the angular speeds which should be added/subtracted to current angular speeds to compensate move a skidding vehicle back to a stable driving condition. They are used to determine the torques required to on-wheels motors.

**Wheels’ torques controller**

The on-wheels motors are torque-controlled. An outer control system is necessary to provide the control torque based on required wheels’ speeds.

A feedback control system is used to enhance the stability. A discrete PID is used to compute the requested torque.

The input for the controller is the difference between required and current wheels’ speeds (input vector with four elements). The output from the controller is the required torque to electric motors (output vector with four elements).

The design requirements for the controller are:

* Fast reaction to variations, to quickly actuate controls required by ESP for increased stability and safety;
* Small admissible overshoot and low ringing, to avoid unwanted accelerations/decelerations of the vehicle;
* Saturation on the torque according to maximum torque deliverable by the motors;
* Only positive torque, as braking torque is eventually handled by a regeneration system when braking;
* No requirements on settling time, as control system is ultimately in feedback with human driver who can adjust speed as wished.

For the above reasons, the PID has been designed having:

* High proportional gain, to fast react to variations in requested speed;
* Low integral gain, to have zero steady state error while reducing overshoots;
* No derivative gain, to reduce ringing;
* Saturation having maximum motor’s torque as upper limit, with anti-windup method;
* Saturation having zero torque as lower limit, with anti-windup method;
* Dynamic saturation to saturate torque according to current maximum torque delivered by the electric motor, with no anti-windup method since integral gain is small.

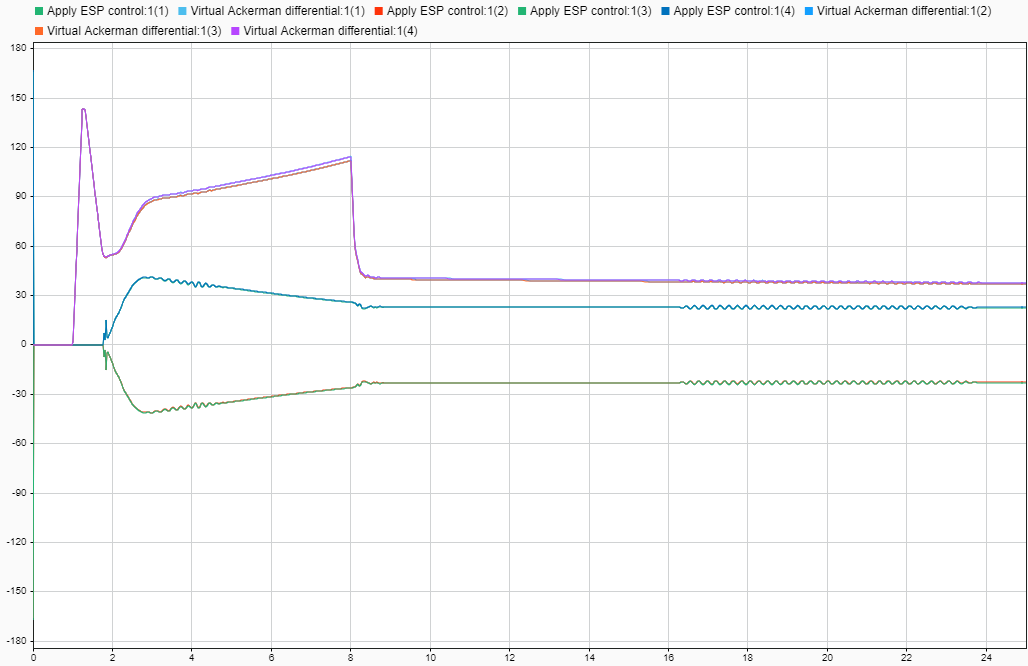
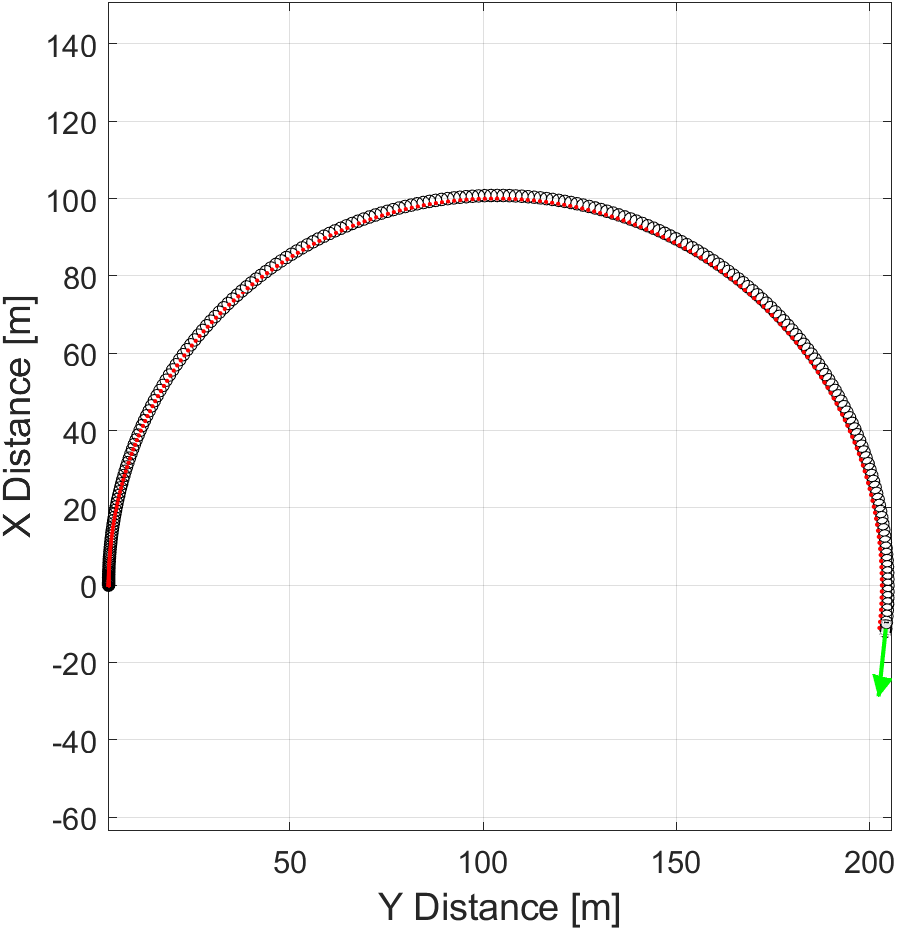
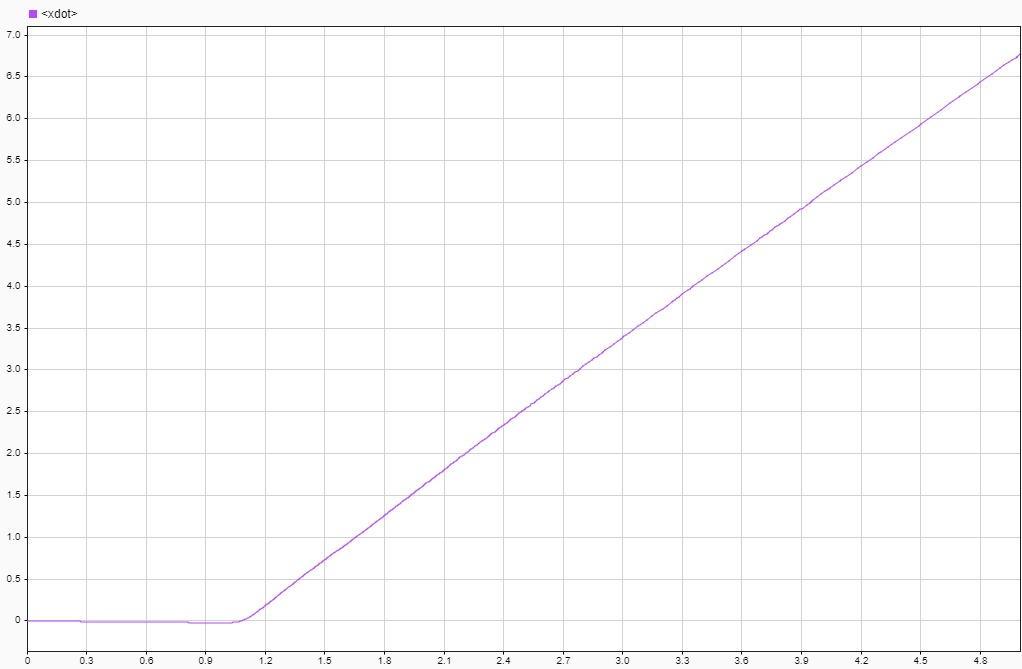
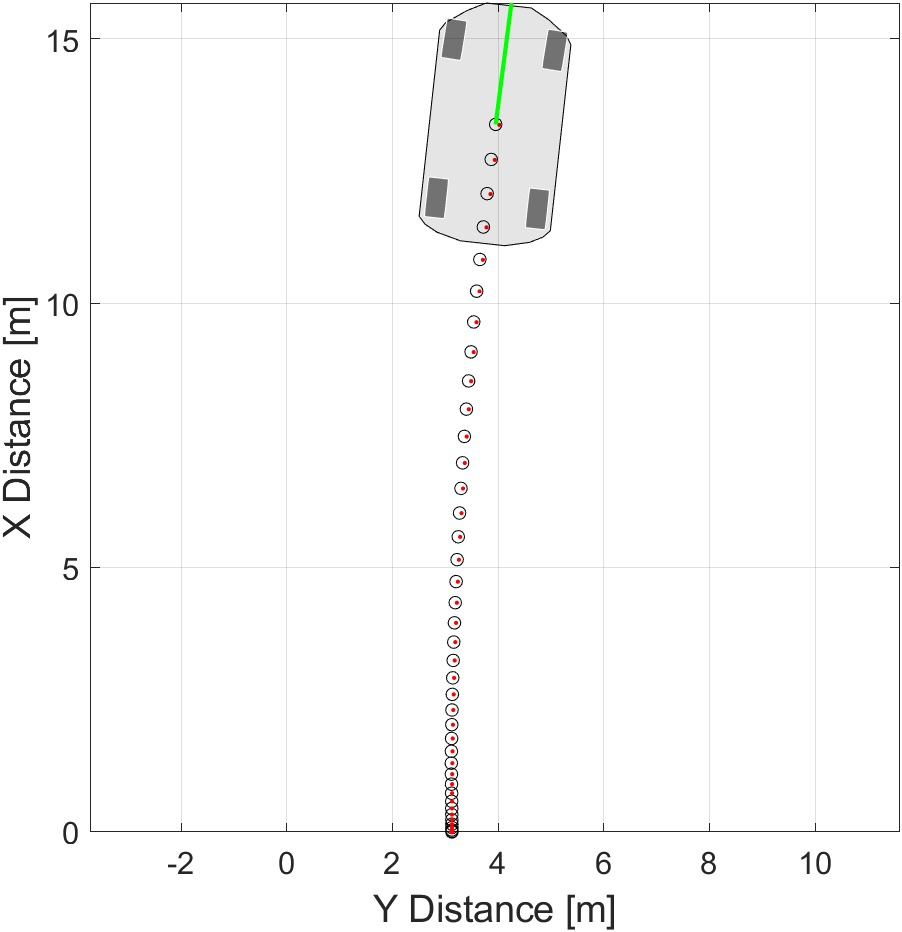
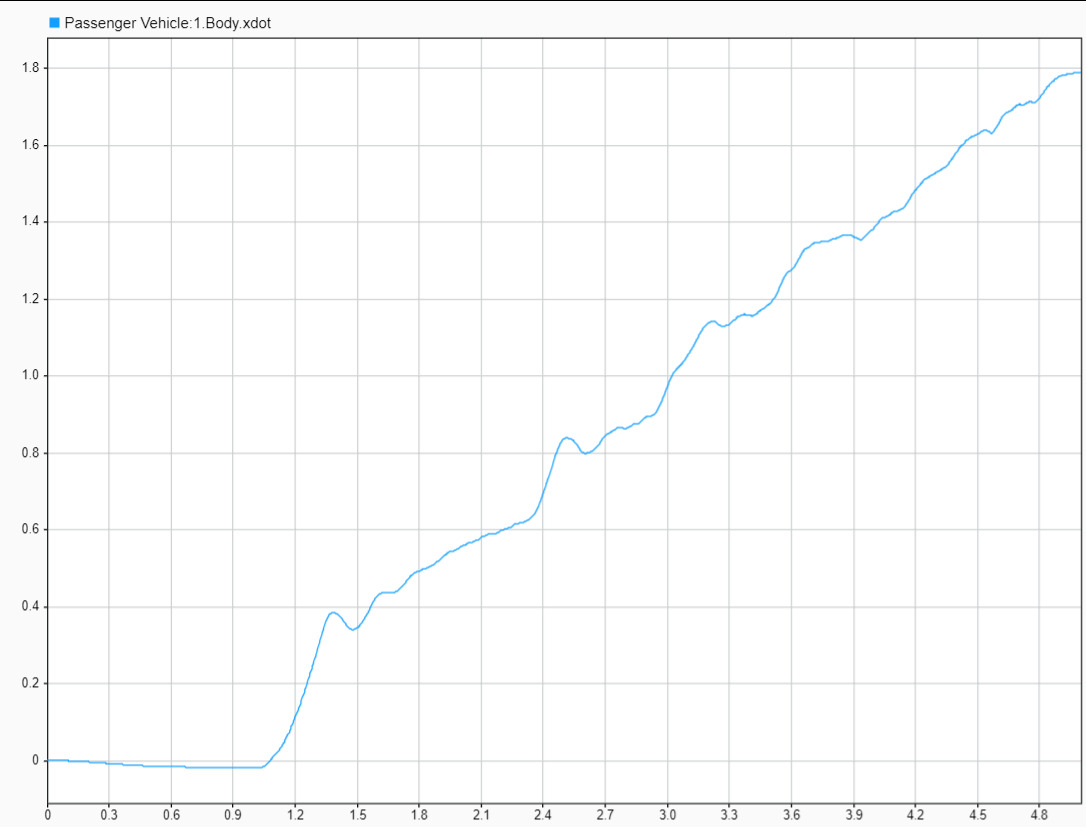
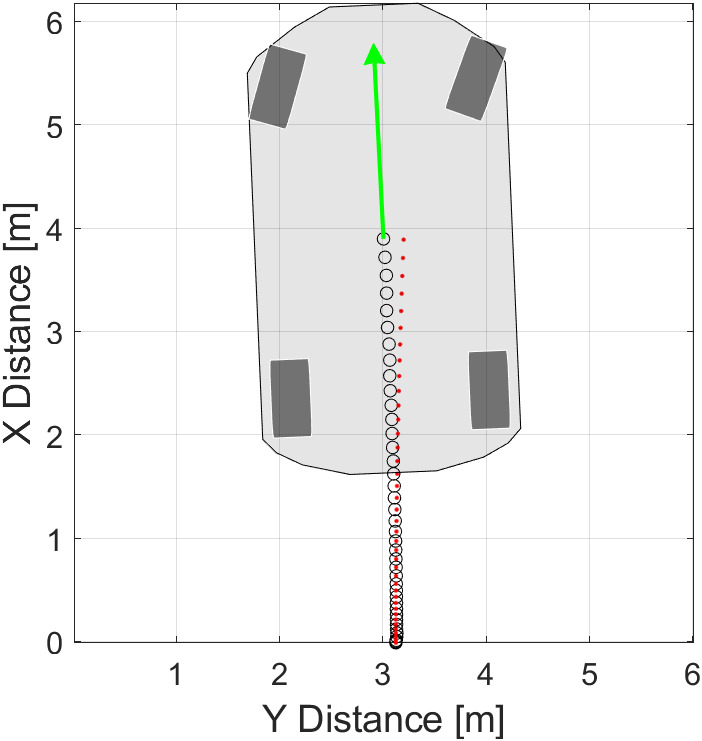
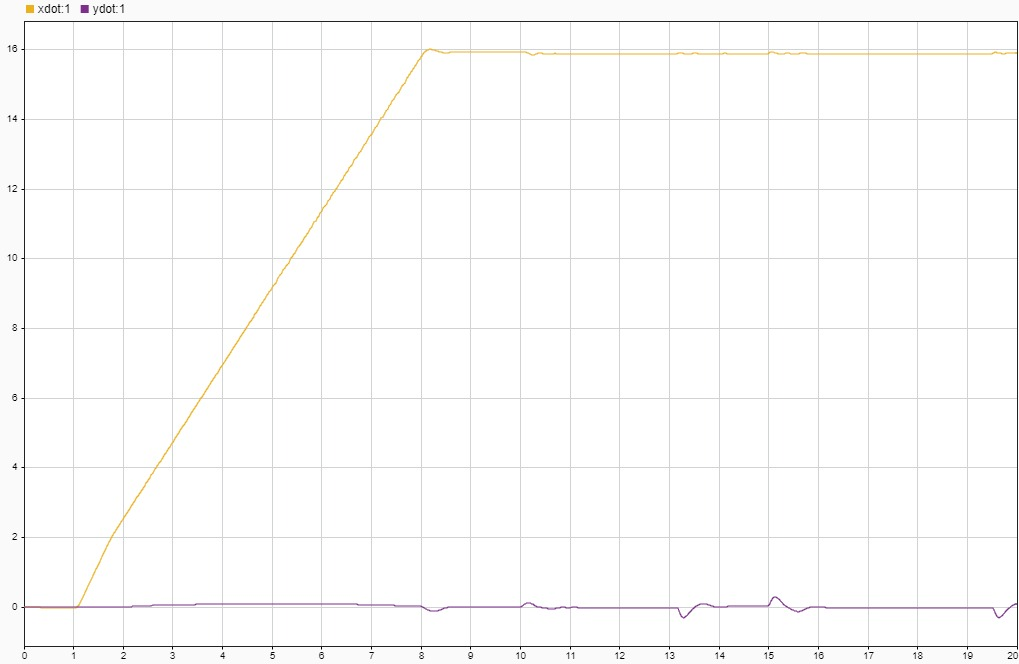
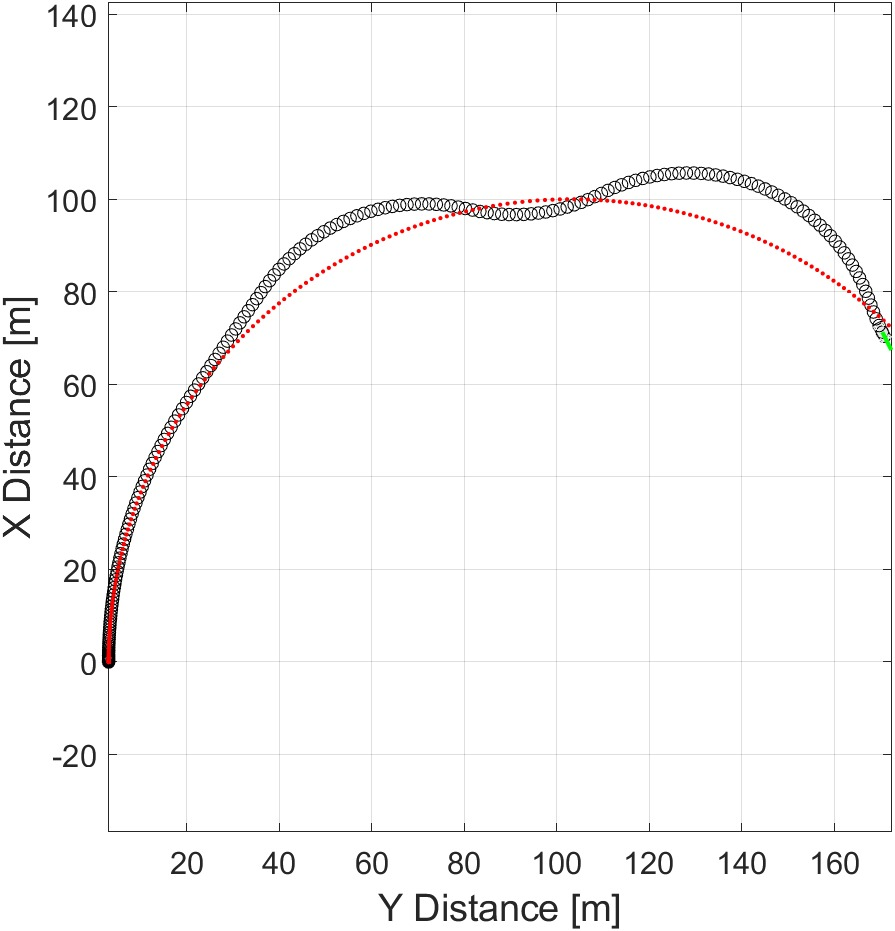
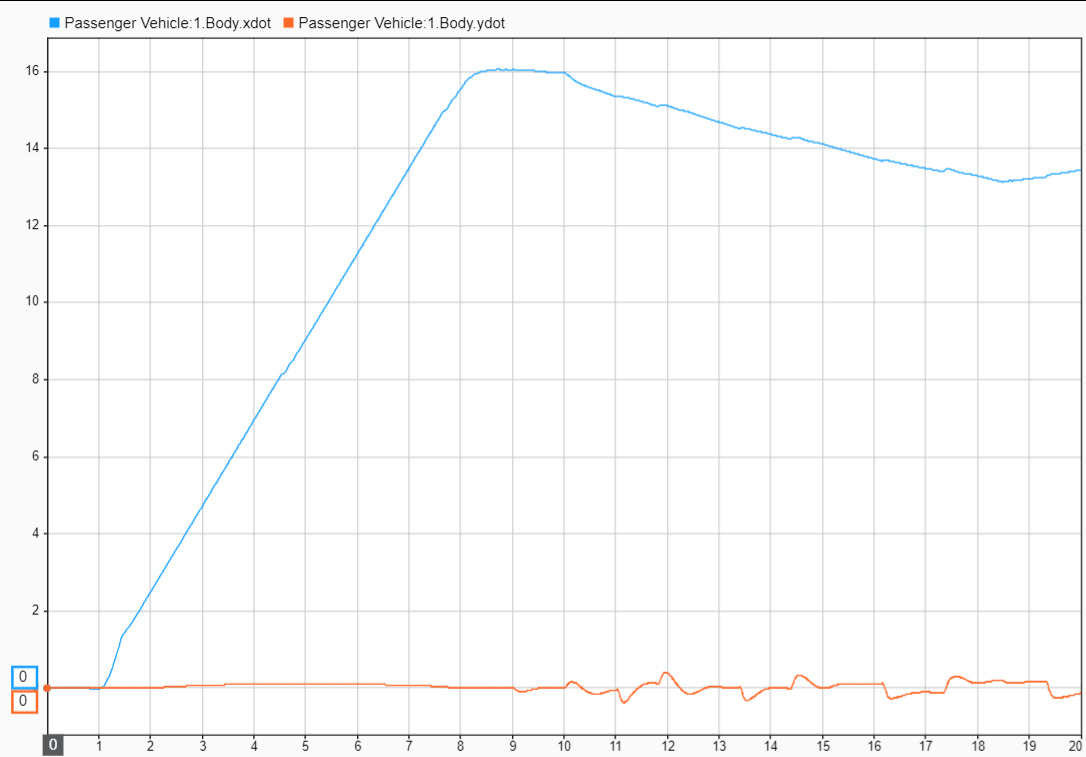
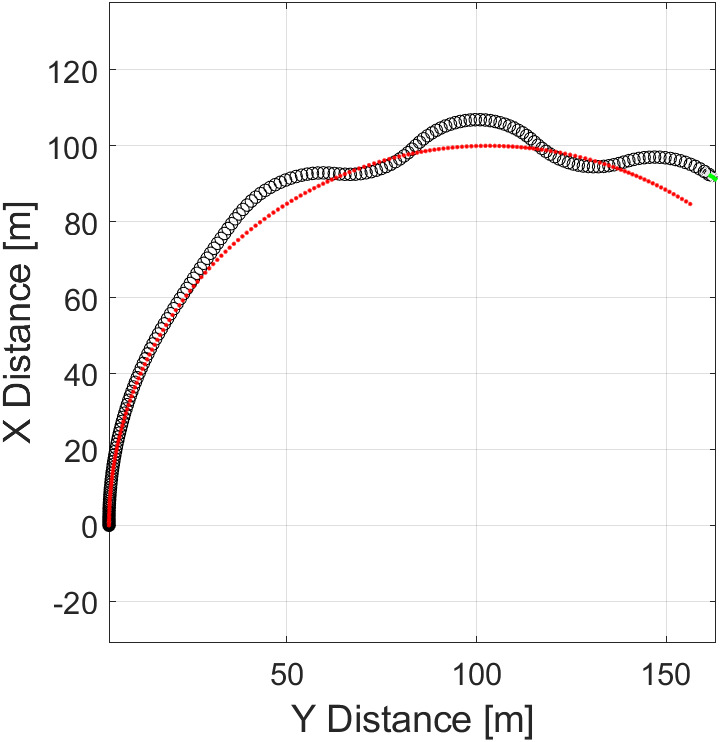
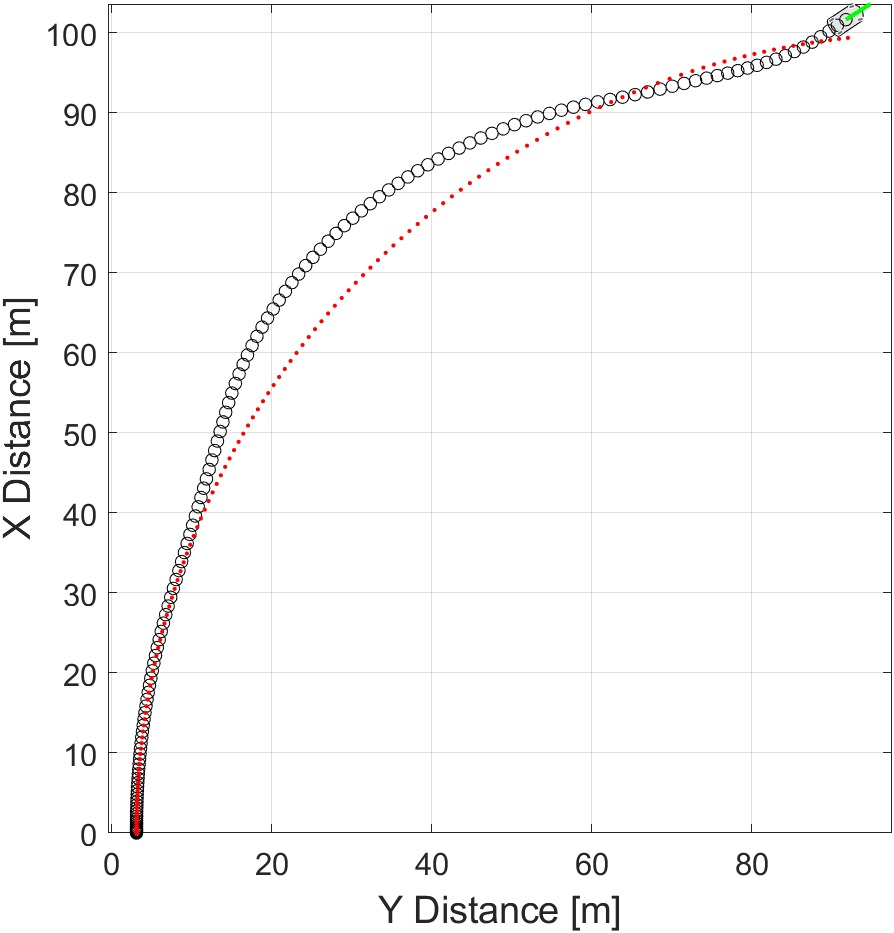
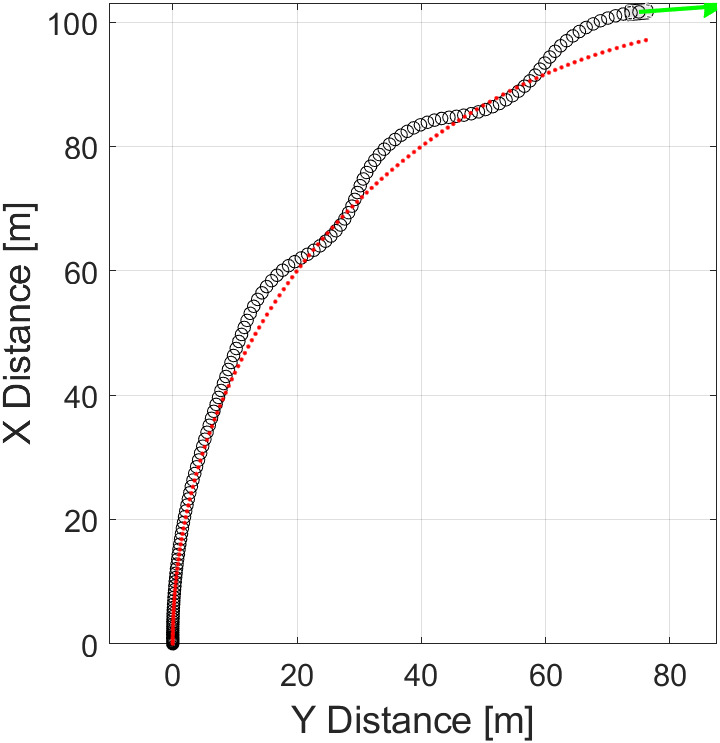
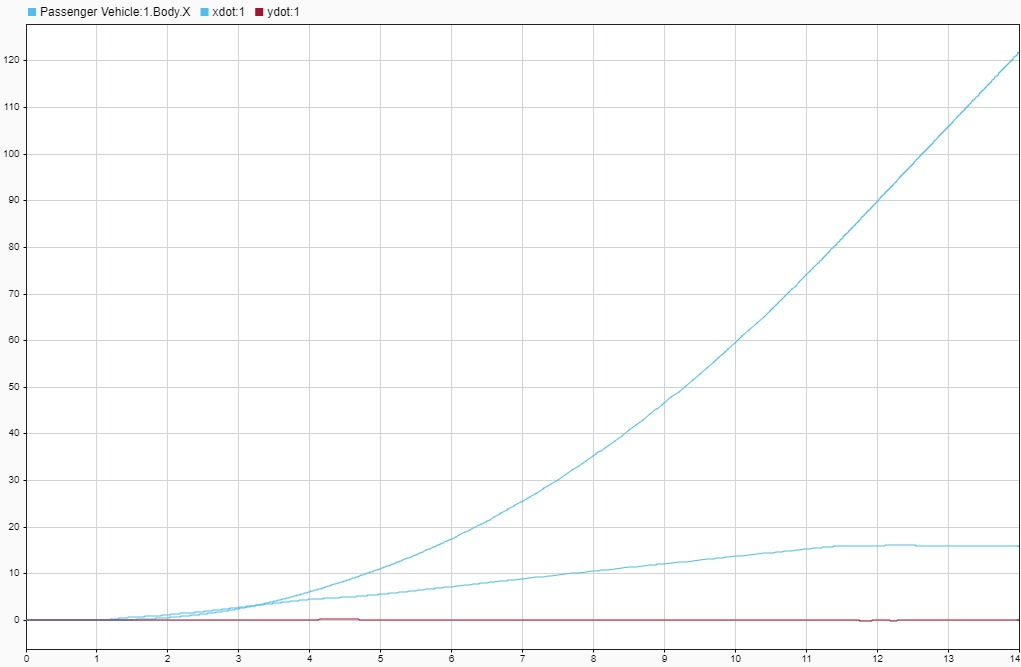
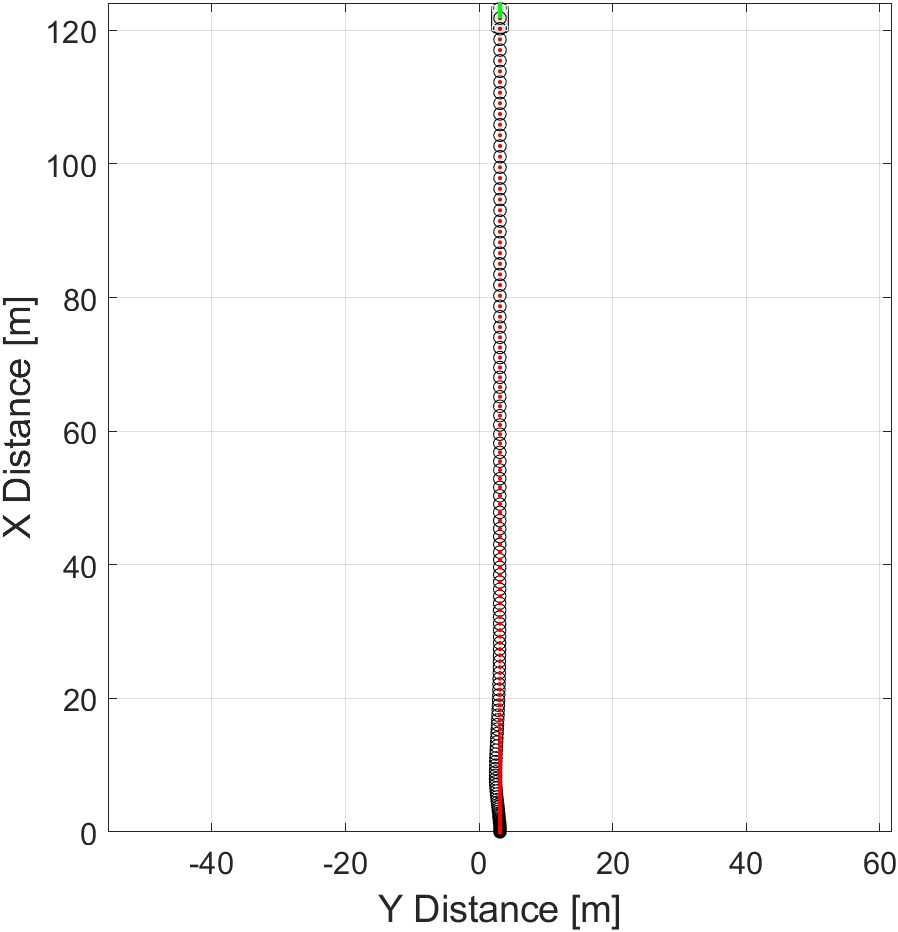
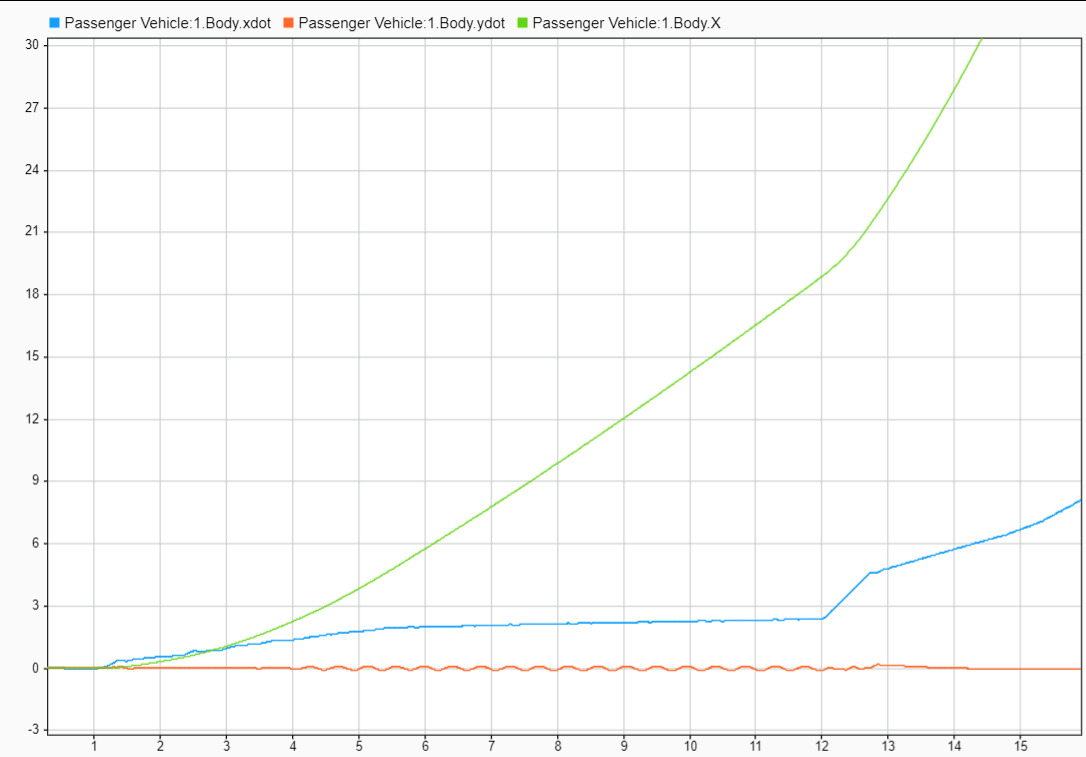
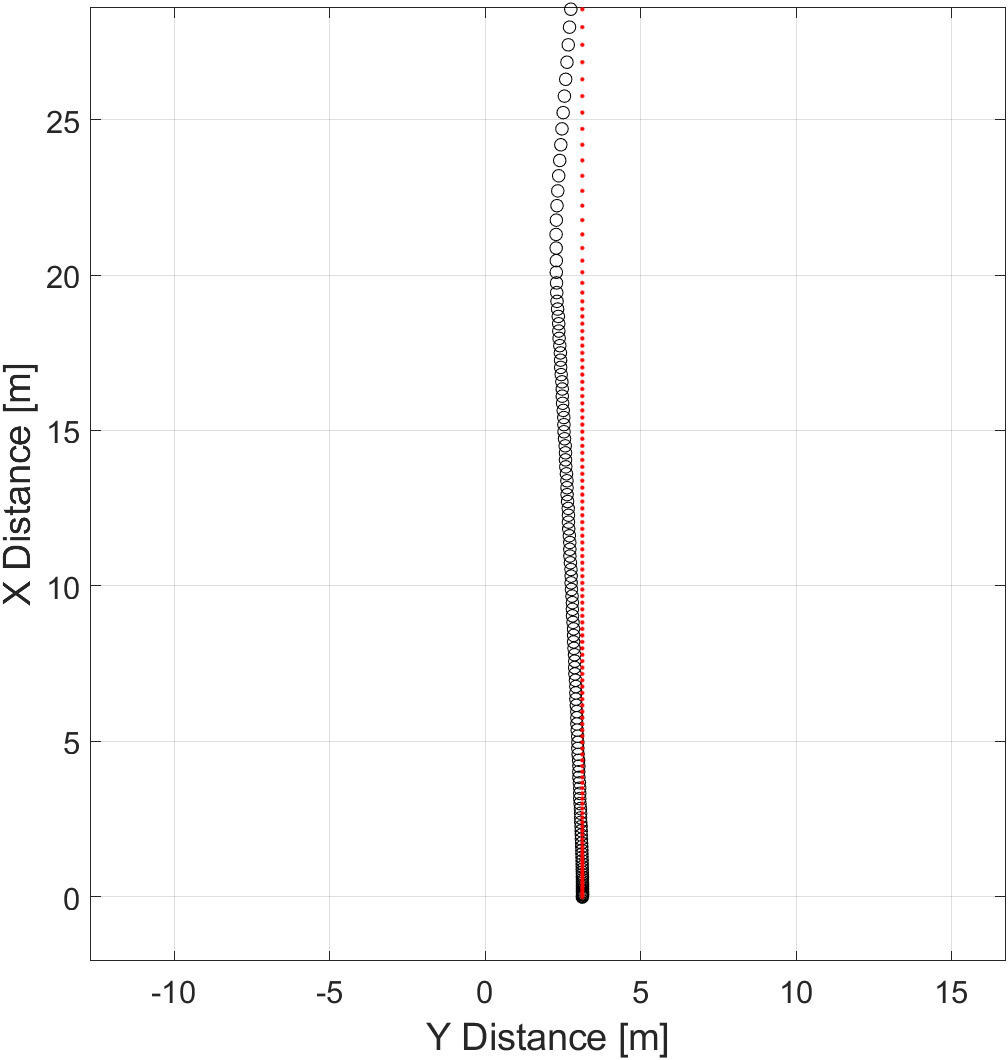
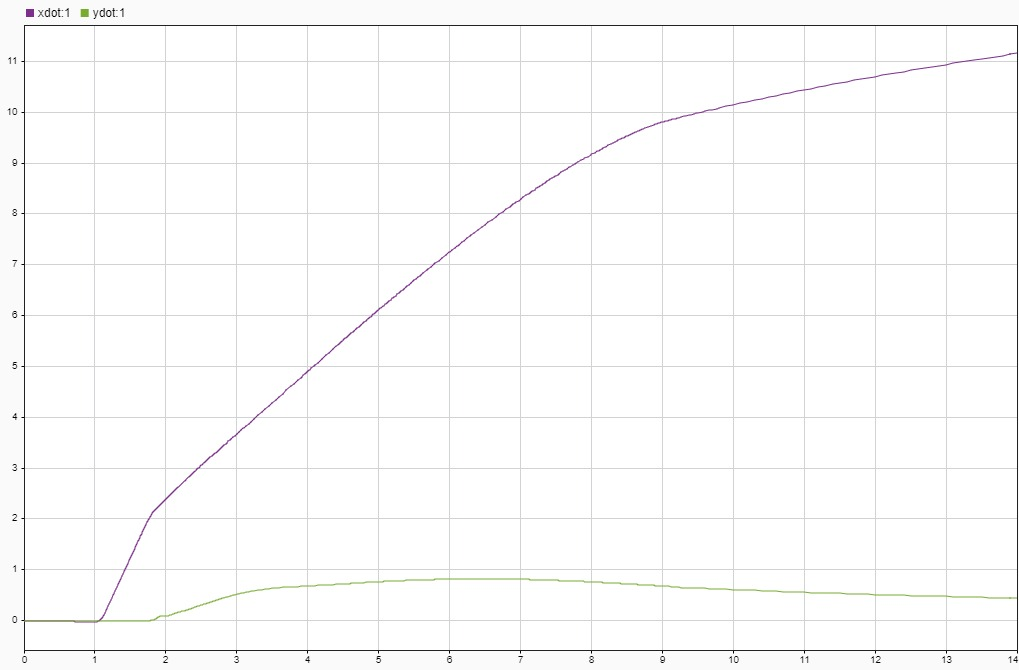
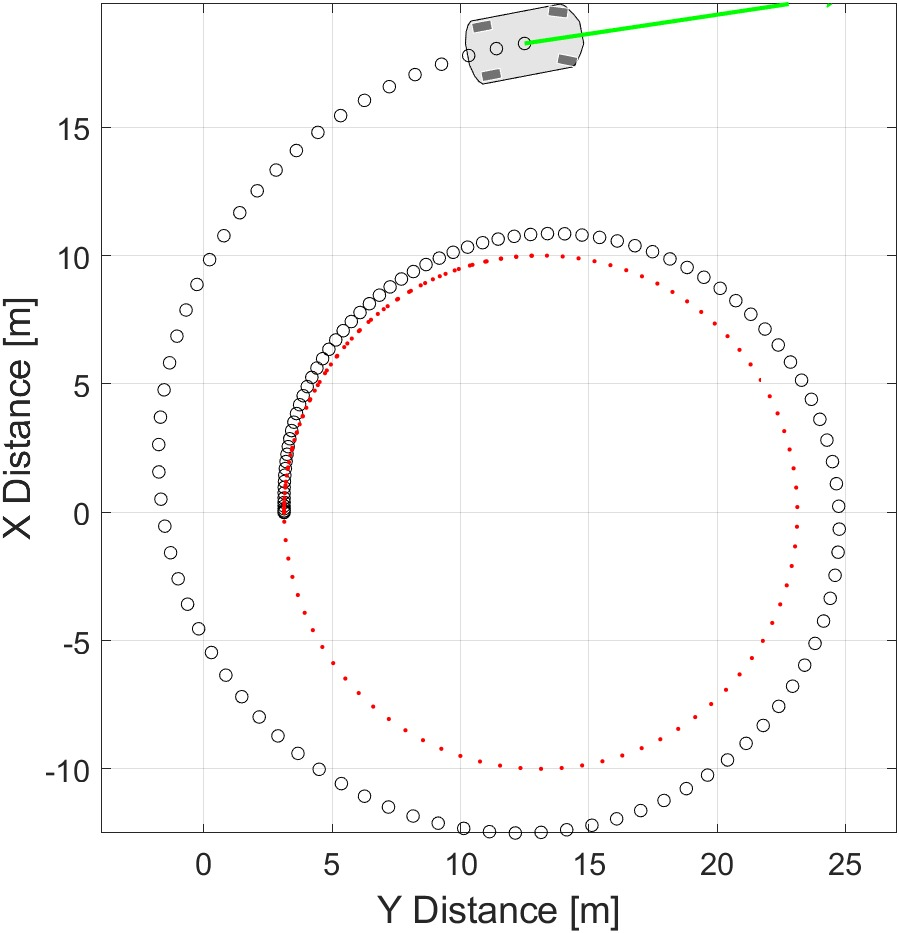
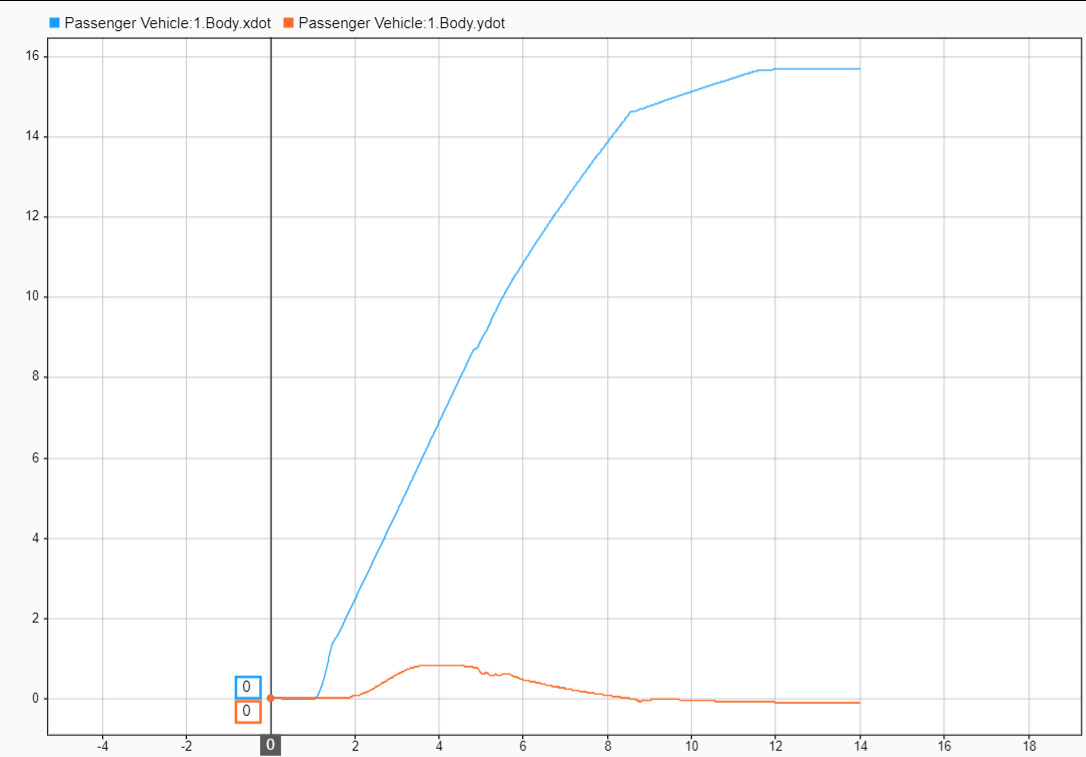
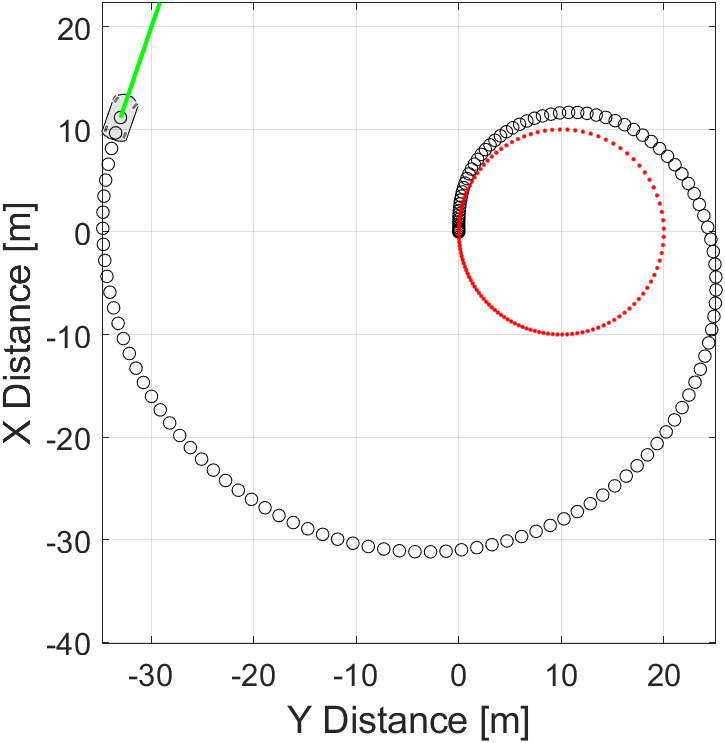
# Testing of the integrated system

Extensive testing has been performed to both asses the intended functionality of the subsystem and validate the correct integration of the subsystem with the car model.

In order to test the integrated subsystem under various working conditions, several simulative scenarios for the car model have been defined, some of which are introduced below. To validate the integrated system, the behavior of the developed car model, implementing the designed controller subsystem is compared to the original vehicle model as provided by Mathworks, implementing a mechanical differential and no ESP controller.

In the below images, when car position is shown, black circles indicate car position in time while red dots determine the reference trajectory, with abscissa and ordinate being the (X, Y) coordinates in inertial reference frame, (0, 0) being the position of the vehicle at the beginning of the simulation. On the other hand, when signals in time are shown, the magnitude of the signal against the time is reported. Some signals may be not visible as completely overlapped by other signals; units of measure comply with SI units and derived (e.g. m for positions, s for time, m/s for speed, rad/s for angular velocities, Nm for torques). Finally, when the behavior of the developed car model is compared with the behavior of the original car model, the latter is reported before the former. It is worth mentioning that the behavior of the car model is strongly influenced by the driver, set to be a predictive driver (acting to follow reference trajectory) during all the tests.

The testing scenarios and results are reported:

* Test of the integrated subsystem while turning.   
  The first series of tests had the aim of analyzing the behavior of the implemented controller subsystem during normal driving conditions, with the goal of verifying the correct integration as well as the functioning of the controller block. The results show, as expected, the ability of the system to accelerate the vehicle as requested by the driver and support the car while maneuvering. Movements of the vehicle during a 25 s time span and output signals of virtual differential (*Virtual Ackerman differential* signals) and ESP controller (*Apply ESP control* signals) subsystems are shown.   
  
* Ability of the controller subsystem to compensate for slippery road conditions.   
  One advantage of the virtual differential subsystem is its ability to distribute the torque on the wheels regardless of the conditions of the road, enforcing the working principle of a typical limited-slip differential system. The reported images show the movement and the speed (*xdot*) of the vehicle in a 5 s time span when two out of four wheels are on icy road, for both the original vehicle with a classical differential and the developed car model implementing virtual differential and ESP control. The developed system allows the vehicle to more easily move forward and accelerate in case of ice on the road.   
  
* Ability of the ESP controller to stabilize the vehicle when ice is found on road.   
  When ice is present when turning on a road, the vehicle tends to travel out of its original reference trajectory. The aim of the ESP control, in these cases, is to stabilize the vehicle, to avoid it starting to spin causing the driver to lose control. This action usually enlarges the turning radius of the car, but it allows the driver to re-gain control of the vehicle. The reported images show the movement of the vehicle for the original and the developed car model. In the former case, turning radius is reduced but oscillations are more frequent, causing a greater difficulty, for the driver, to re-gain control of the vehicle. The action of the ESP control also reduces lateral speed (*ydot*), and thus skidding, of the vehicle. It is worth mentioning that the nervous control by the predictive driver, forced to follow the reference trajectory, increase the instability of the system in both cases.   
    
  Another example of vehicle trajectory is reported, fort both original and developed vehicle models.   
  
* Straight trajectory with ice on road.   
  The combined action of the virtual differential subsystem and the ESP control allows the vehicle to both accelerate on icy roads and maintain a straight trajectory if required. The reported images show position (*X* signal), longitudinal (*xdot* signal) and lateral (*ydot* signal) speeds of the vehicle when ice is present on half of the road, meaning two skidding wheels and two wheels with high friction coefficient; behaviors for both original and developed car model are shown.   
  
* Cornering with small turn radius.   
  Another proven advantage of the developed controller system is its aid provided when cornering. The combined action of the virtual differential system and the ESP controller allows the driver to follow unconventional trajectories having a too small turn radius for the current vehicle speed. The reported images show the vehicle position in time and the longitudinal and lateral speeds (*xdot* and *ydot* respectively) for both original and developed car models.   
    
  The action of the ESP controller is also shown.   
  