Trajectory Simulation Tool for Assessment of Active Vehicle Safety Systems

Chinmay S. Patil[1], Taehyun Shim[1][a], Jemyoung Ryu[2] and Seunghwan Chung[2]
[1]*Department of Mechanical Engineering, University of Michigan-Dearborn, Dearborn, U.S.A.*
[2]*Hyundai Kia Motors, South Korea*

Keywords: Simulation Tool, Path Planning, ADAS Test.

Abstract: Advanced Driver Assist Systems (ADAS) have been widely employed in the automotive industry to improve vehicle safety and to reduce the driver's workload. In addition, there are increasing efforts toward autonomous driving vehicles using enhanced ADAS technologies. For effective ADAS development, it is critical to test and validate these systems. This paper presents a vehicle simulation tool that can be used for various ADAS vehicle test scenarios in which it can generate vehicle trajectories and speed profiles that satisfy user defined test conditions. The proposed simulation tool is useful to design a test scenario in the simulation environment before the physical test. Thus, it can significantly reduce the time needed for the proper test scenario development.

1 INTRODUCTION

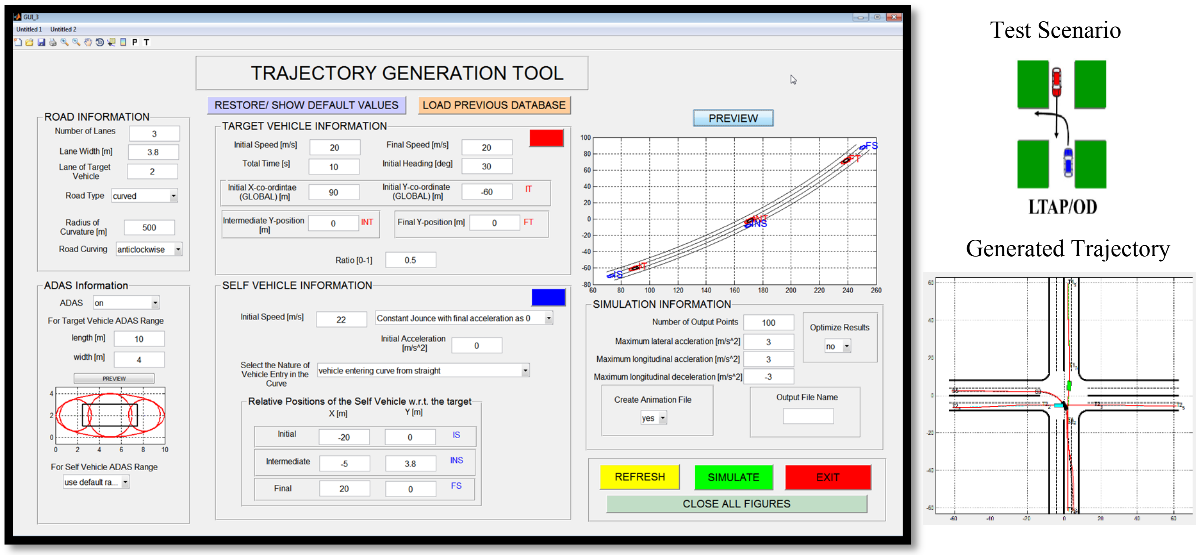
Active safety systems have been widely employed in the automobile industry in a recent effort to reduce vehicle accidents. These systems aim to prevent vehicle accidents by effectively controlling vehicle chassis components (brakes, steering, etc). With advent of fast computing power and cost effective sensors and actuators, more safety related systems have been developed and implemented in the latest automobiles. Advanced driver assist systems (ADAS), such as the lane departure warning (LDW), forward collision warning systems (FCW), lane keeping assist system (LKAS), and autonomous emergency braking system (AEB), etc., assist the driver in recognizing and reacting to potentially dangerous traffic situations by using environment sensors (e.g. radar, laser, vision). This has great potential to improve driving comfort and reduce the number of vehicle accidents.

However, since the design concept and method of ADAS are different from traditional automotive safety technologies, for the development of effective ADAS system, a testing scenario must consider real traffic information and drivers' reactions. A driverless vehicle with a steering and brake/acceleration robots is used for the testing of a vehicle equipped ADAS along with a soft target. For the effective usage of these systems, a proper (realistic) test scenario is essential. In the testing scenario, the inputs of vehicle trajectories and speed profile are required for the driverless vehicle. This paper presents a vehicle simulation tool that can be used for various ADAS vehicle test scenarios in which it can generate vehicle trajectories and speed profiles that satisfy user defined test conditions.

One of the key components needed for this tool is vehicle trajectory generation. There are various path planning methods in the literature. Popular approaches are potential fields combined with reactive control (Yuan and Qu, 2009), computational searching (Durali, et al., 2006), and parameterization (Dubins, 1957). The potential field approach and the reactive control are good only for low speed applications. The computational searching approach, due to the heavy computation requirement, is also limited to low speed applications. The parametrization approach in (Qu, et al., 2004; Shim, et al., 2012) based on the differential flatness approach (Fliess et al., 1994) uses kinematic models in generating polynomial trajectories. In the proposed simulation tool, path planning algorithm in (Shim, et al., 2012) is employed where the coefficient of the polynomials are determined by the boundary conditions of vehicle.

[a] https://orcid.org/0000-0002-7745-8998

Patil, C., Shim, T., Ryu, J. and Chung, S.
Trajectory Simulation Tool for Assessment of Active Vehicle Safety Systems.
DOI: 10.5220/0009567005410547
In *Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2020)*, pages 541-547
ISBN: 978-989-758-419-0



ROAD INFORMATION

Number of Lanes	3
Lane Width [m]	3.8
Lane of Target Vehicle	2
Road Type	curved
Radius of Curvature [m]	500
Road Curving	anticlockwise

ADAS Information

ADAS	on

For Target Vehicle ADAS Range

length [m]	10
width [m]	4

For Self Vehicle ADAS Range: use default ra...

TARGET VEHICLE INFORMATION

Initial Speed [m/s]	20	Final Speed [m/s]	20
Total Time [s]	10	Initial Heading [deg]	30
Initial X-co-ordintae (GLOBAL) [m]	90	Initial Y-co-ordinate (GLOBAL) [m]	-60
Intermediate Y-position [m]	0	Final Y-position [m]	0
Ratio [0-1]	0.5		

SELF VEHICLE INFORMATION

Initial Speed [m/s]	22
	Constant Jounce with final acceleration as 0
Initial Acceleration [m/s^2]	0
Select the Nature of Vehicle Entry in the Curve	vehicle entering curve from straight

Relative Positions of the Self Vehicle w.r.t. the target

	X [m]	Y [m]	
Initial	-20	0	IS
Intermediate	-5	3.8	INS
Final	20	0	FS

SIMULATION INFORMATION

Number of Output Points	100
Maximum lateral accleration [m/s^2]	3
Maximum longitudinal accleration [m/s^2]	3
Maximum longitudinal deceleration [m/s^2]	-3
Optimize Results	no
Create Animation File	yes
Output File Name	

Figure 1: GUI of the Trajectory Generation Tool and an Example Scenario.

The rest of the paper is organized as follows. Section 2 concentrates on the tool development by defining a co-ordinate system and vehicle positioning, followed by the path planning algorithm and the boundary conditions needed to use the algorithms. It also classifies trajectories into crash or crash-free and describes methods for finding the crash-free trajectory. Section 3 gives the simulation results and discusses them. Finally, Section 4 provides a conclusion.

2 SIMULATION TOOL DESIGN

Figure 1 shows a GUI of the proposed simulation tool. The proposed tool can be used to study various vehicle maneuvers involved in multiple vehicles. In this study, we have limited the vehicle maneuvers to those involved with two vehicles. The first and second vehicles are referred to the 'target vehicle' and the 'self-vehicle', respectively. In the proposed system, the user can define three points (initial, intermediate, and final) as shown in Fig.2 with specifications (position, speed, heading, etc.). The proposed tool can generate vehicle trajectories meeting the required specifications. The generated trajectories also pass through the three points on straight and curved road conditions and intersections.

In order to build test scenarios, the user can specify the following information:

- Roads: number of lanes, lane width, road type (straight, curved, or intersection), road curving (anticlockwise or clockwise) and initial lane of the target vehicle.
- Target Vehicle: initial and final speeds, initial heading and position, intermediate and final positions and ratio point.
- Self-Vehicle: Initial and final speed and acceleration, relative positions with respect to target vehicle.
- Simulation Information: simulation time, sampling points and the safety ranges around the vehicle.

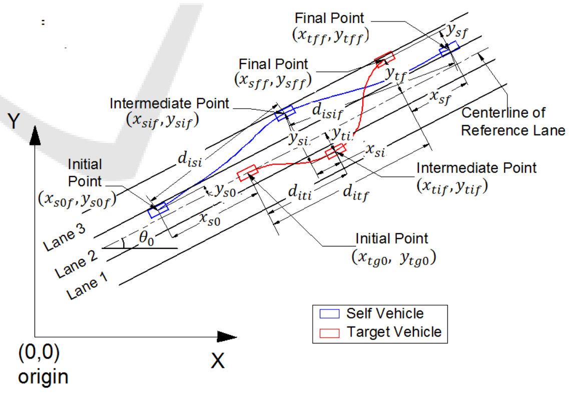


Figure 2: Vehicle Positioning for Straight Road.

The following sections explain vehicle coordinate systems and position information used for the trajectory generation.

2.1 Vehicle Position/Coordinate Systems

The target vehicle's initial position $(x_{tg0},\ y_{tg0})$ and heading (θ_0) are defined in the global coordinate system and considered as the reference to all positioning (Fig. 2). All the positions considered in this research represent the position of the center of gravity of the vehicles. Once the target vehicle is positioned and the road is built around it (a straight or a curved road with vehicle making clockwise or anticlockwise turn), the centerline of the target vehicle's initial lane is considered as the reference, also known as the reference lane. From the target vehicle's initial (v_{t0}) and final velocity (v_{tf}) and the simulation time (t), the longitudinal distance travelled for the total trajectory (d_{itf}) is calculated as

$$d_{itf} = v_{t0}\, t + (1/2) a_t\, t^2 \qquad (1)$$

To define the longitudinal location of the intermediate point, the variable known as the ratio point (r_{at}) divides the total distance d_{itf} into the ratio for both parts of the trajectory. Thus, the distance from the initial and the intermediate point can be obtained as:

$$d_{iti} = r_{at}\, d_{itf} \qquad (2)$$

Therefore the time to reach the intermediate position i.e. intermediate time (t_i) is calculated,

$$t_i = \frac{\sqrt{v_{t0}^2 + 2\, a_t\, d_{iti}} - v_{t0}}{a_t} \qquad (3)$$

For the target vehicle, the lateral deviation at the intermediate point (y_{ti}) and final point (y_{tf}) is considered at the distances d_{iti} and d_{itf} along the centerline of the lane. For a straight road, any distances to the left of the centerline in the direction of travel of the vehicle are negative and vice versa.

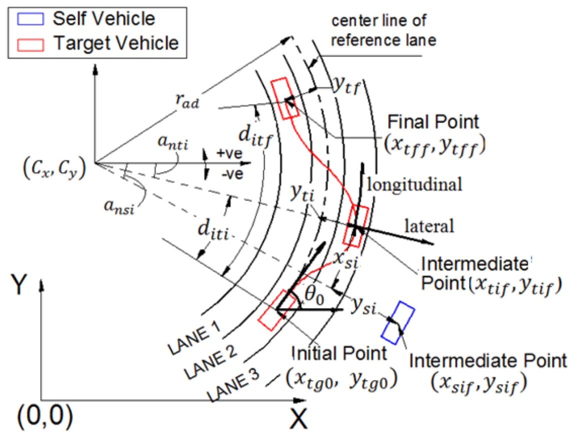

Self Vehicle
Target Vehicle
center line of reference lane
y_{tf}
r_{ad}
d_{itf}
Final Point (x_{tff}, y_{tff})
a_{nti}
+ve
-ve
(C_x, C_y)
a_{nsi}
y_{ti}
longitudinal
lateral
d_{iti}
x_{si}
Intermediate Point (x_{tif}, y_{tif})
θ_0
y_{si}
Y
LANE 1
LANE 2
LANE 3
Initial Point $(x_{tg0},\ y_{tg0})$
Intermediate Point (x_{sif}, y_{sif})
(0,0)
X

Figure 3: Vehicle Positioning for Curved Road.

In case of curved road, the lateral deviations (y_{ti}) and (y_{tf}) are considered along the radius. Any deviation radially inwards from the centerline is considered negative and vice versa.
The center (C_x, C_y) of the road can be found as

$$\begin{aligned} C_x &= x_{tg0} - r_{ad}\ \cos(a_{nt0}) \\ C_y &= y_{tg0} - r_{ad}\ \sin(a_{nt0}) \end{aligned} \qquad (4)$$

The co-ordinates of the intermediate (x_{tif}, y_{tif}) and the final point (x_{tff}, y_{tff}) for both type of roads can be easily found using co-ordinate geometry.

The target vehicle's position and heading at each of the three point acts as the origin and axis direction for defining the self-vehicle position at that particular point. For the straight road case, the x-distance is considered in the longitudinal direction of the target vehicle and considered positive in the direction of motion. The y-distance is considered in the lateral direction and considered positive in the left hand side of the direction of motion. For the vehicles along the curved road, the longitudinal axis is considered along the circumference made by the radius of the circle at the target vehicle position, and the lateral direction is along the radius. It is assumed that at the three points, the vehicle headings are parallel to the road headings at that particular point.

2.2 Model-based Trajectory Generation

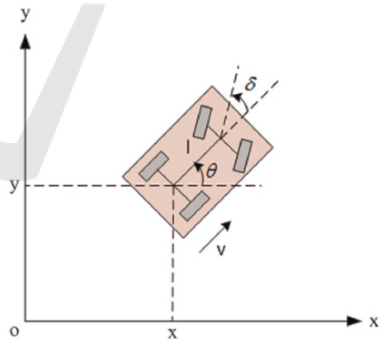


Figure 4: A Simplified Vehicle Model.

In Fig. 4, (x, y) are longitudinal and lateral positions of the reference point P (at the mid of the rear axle) in a global coordinate system, θ is the yaw angle, δ is front steering wheel angle, v is the longitudinal vehicle speed and L is the wheel base. The kinematic equations for such a vehicle are given by:

$$\begin{cases} \dot{x}(t) = v\cos\theta(t),\ \dot{y}(t) = v\sin\theta(t) \\ \dot{\theta}(t) = v\tan\delta(t)/L \end{cases} \qquad (5)$$

The initial and terminal conditions are:

$q_0 = (x_0, y_0, \theta_0, \delta_0, v_0, \dot{v}_0) \qquad q_f = (x_f, y_f, \theta_f, \delta_f, v_f, \dot{v}_f)$

Suppose the desired trajectory is $(x_d(t), y_d(t))$.

Then according to the vehicle model (5), the following constraints are imposed

$$\begin{cases} x_d(t_0) = x_0 \\ \dot{x}_d(t_0) = v_0 \cos\theta_0 \\ \ddot{x}_d(t_0) = \dot{v}_0 \cos\theta_0 - v_0^2 \tan\delta_0 \sin\theta_0 / L \end{cases}$$
$$\begin{cases} y_d(t_0) = y_0 \\ \dot{y}_d(t_0) = v_0 \sin\theta_0 \\ \ddot{y}_d(t_0) = \dot{v}_0 \sin\theta_0 + v_0^2 \tan\delta_0 \cos\theta_0 / L \end{cases} \tag{6}$$

on the trajectory at initial time:

At the ending time, a similar set of constraints are available. Therefore, both x_d and y_d have 6 constraints in parametric expressions, they need at least 6 free coefficients to accommodate these constraints. In addition, more parameters are needed to choose a collision-free path. With these considerations, the trajectory is parameterized by 6th order polynomials that have 7 coefficients.

$$x_d(t) = \sum_{i=0}^{6} a_i t^i, \quad y_d(t) = \sum_{i=0}^{6} b_i t^i \tag{7}$$

The coefficients can be determined as:

$$\vec{a} = L^{-1}(H_1 - Ma_6), \quad \vec{b} = L^{-1}(H_2 - Mb_6) \tag{8}$$

where,

$$\vec{a} = [a_0\ a_1\ a_2\ a_3\ a_4\ a_5], \vec{b} = [b_0\ b_1\ b_2\ b_3\ b_4\ b_5]$$
$$\begin{cases} H_1 = [x_d(t_0)\ \dot{x}_d(t_0)\ \ddot{x}_d(t_0)\ x_d(t_f)\ \dot{x}_d(t_f)\ \ddot{x}_d(t_f)] \\ H_2 = [y_d(t_0)\ \dot{y}_d(t_0)\ \ddot{y}_d(t_0)\ y_d(t_f)\ \dot{y}_d(t_f)\ \ddot{y}_d(t_f)] \end{cases}$$
$$M = [t_0^6\ 6t_0^5\ 30t_0^4\ t_f^6\ 6t_f^5\ 30t_f^4]$$

and

$$L = \begin{bmatrix} 1 & t_0 & t_0^2 & t_0^3 & t_0^4 & t_0^5 \\ 0 & 1 & 2t_0 & 3t_0^2 & 4t_0^3 & 5t_0^4 \\ 0 & 0 & 2 & 6t_0 & 12t_0^2 & 20t_0^3 \\ 1 & t_f & t_f^2 & t_f^3 & t_f^4 & t_f^5 \\ 0 & 1 & 2t_f & 3t_f^2 & 4t_f^3 & 5t_f^4 \\ 0 & 0 & 2 & 6t_f & 12t_f^2 & 20t_f^3 \end{bmatrix}$$

Substituting (5) into (4), the planned trajectory can be expressed as:

$$\begin{cases} x_d(t) = f(t)L^{-1}(H_1 - Ma_6) + a_6 t^6 \\ y_d(t) = f(t)L^{-1}(H_2 - Mb_6) + b_6 t^6 \end{cases} \tag{9}$$

where

$$f(t) = [1\ t\ t^2\ t^3\ t^4\ t^5]$$

In equation (9), a_6 and b_6 are left of free. Therefore, the trajectory (8) is to be determined by choosing a_6 and b_6. In this work, the optimal solution and trajectory are determined by choosing a_6 and b_6 that minimize the travel distance and collision avoidance condition. More detailed information can be found in (Shim, et al., 2012).

The problem with directly using this type of trajectory along the curved road is that it cannot be constrained to follow a particular radius of the road (Fig. 7). A solution to this was to find a trajectory for an equivalent scenario along the straight road and then bend the trajectory along the desired curvature. For the equivalent scenario, let the trajectory developed be $(x(t), y(t))$. This trajectory is to be curved by a radius of r_{ad} with vehicle initial heading as θ_0. The polar coordinate concept is applied in which the trajectory is curved along the center(C_x, C_y). The radial and angular components of this trajectory are:

$$r_c(t) = r_{ad} + (y(t) - y_{tg0})$$
$$\emptyset_c(t) = a_{nt0} + sgn\frac{x(t) - x_{tg0}}{r_{ad}} \tag{10}$$

Where sgn=1 stands for anticlockwise and -1 for a clockwise turning road. Now turning back this trajectory into Cartesian coordinates and shifting the center to (0, 0), the new equation of the trajectory obtained is:

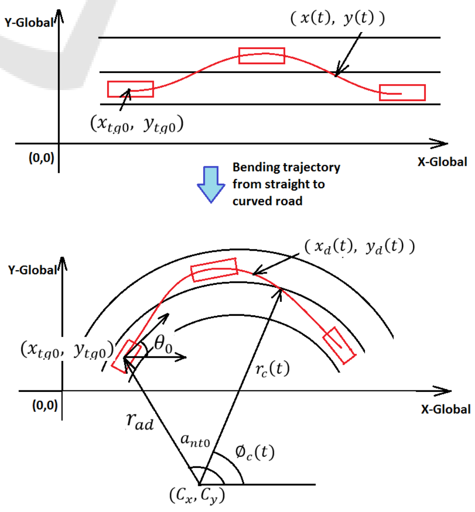


Figure 7: Bending an Equivalent Straight road Trajectory for a curved road.

$$x_d(t) = r_c(t)\cos(\emptyset_c(t)) + C_x$$
$$y_d(t) = r_c(t)\sin(\emptyset_c(t)) + C_y \qquad (11)$$

For the generation of collision free trajectory with obstacles, the following equations must be true in order to avoid the obstacles,

$$(r_0 + r_1)^2 \leq (x_d(t) - x_0)^2 + (y_d(t) - y_0)^2 \qquad (12)$$

where r_1 is the radius of the self-vehicle, and r_0 is the radius of the target vehicle located at (x_0, y_0).

2.3 Collision and Collision-free Trajectories

The proposed tool can generate two types of trajectories: collision and collision-free. The first type of trajectory can be developed deliberately to create a crash condition (referred as ADAS off trajectory) and the other one will generate collision free condition (referred as ADAS on trajectory). This will help the user to create crash scenarios using ADAS off trajectory and understand various ADAS's ideal behavior using the ADAS on trajectory.

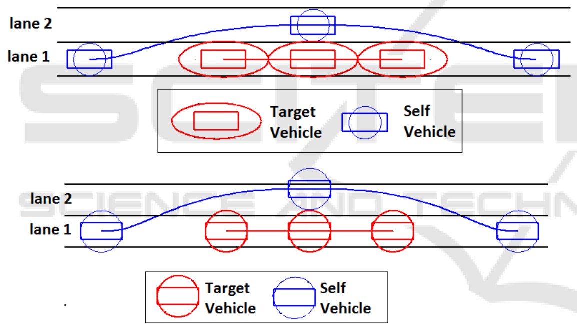


Figure 8: Dividing the Elliptical ADAS Range in Circles.

For the collision conditions, the collision avoidance criterion in eq. (12) was used. This condition requires both vehicles to be treated as circles with fixed radius which envelope the entire vehicle as shown in Fig. 8. Due to the possibility that the self-vehicle will be pushed out of the assigned lane if the radius of both the vehicle envelopes is greater than half the lane width (n_w), as shown in Fig. 8., the target-vehicle was considered as an elliptical envelope in which the length (r_{al}) and width (r_{aw}) can be controlled by the user and is referred to as the ADAS range. For the application of the collision avoidance criterion, the ellipse is divided into three circles which occupy most of the area of the target vehicle as shown in Fig. 8. The self-vehicle range/radius (r_s) is calculated from the lane width as:

$$r_s = \frac{n_w - r_{aw}}{2} \qquad (13)$$

The length and width of the ADAS range can be modified to get desired results. The collision avoidance criterion is tested between the self-vehicle circle and each of the three target vehicle circles. In case there is an overlap on the self-vehicle circle and target vehicle ellipse at the intermediate point, the self-vehicle is moved laterally out of the target vehicle ellipse until both the self-vehicle's circle and the target vehicle's ellipse are tangential.

3 SIMULATION

This section presents simulation results of the proposed tool. A few vehicle-to-vehicle test scenarios is generated by this tool.

3.1 Single Lane Change Cut-in Maneuver

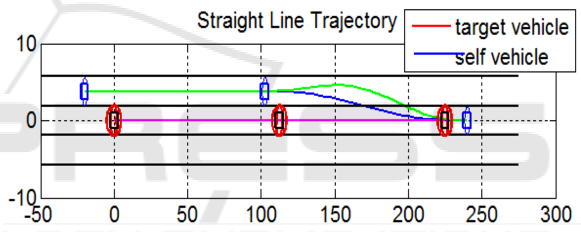


Figure 9: Single Lane Change Cut-in Maneuver.

In this case, the target vehicle is accelerating from 20 m/s to 25 m/s in 10 seconds. The Self-vehicle is moving in the adjacent lane with initial speed of 20 m/s and is 20 m behind. At the intermediate point set at ratio 0.5, the self-vehicle is 10 m behind and starts to change lanes. The blue trajectory in Fig. 9 shows the lane change trajectory without considering the possibility of crash with the target vehicle (ADAS off Trajectory). As the Crash is detected on this trajectory, the simulation tool plots an alternate trajectory (Green) that avoids the Crash. This case can be useful for evaluating the behavior of Lane Change Assist Systems.

3.2 Double Lane Change Maneuver

For this scenario, the target vehicle is moving at constant speed of 20 m/s for 10 seconds. The self-vehicle is moving in the same lane with initial speed of 22 m/s and is 20 m behind. At the intermediate point set at ratio 0.7, the self-vehicle is 10 m ahead of the target vehicle in the adjacent lane and at the final point is 20 m ahead in the same lane. The blue trajectory in Fig. 10 shows the lane change trajectory without considering the possibility of crash with the target vehicle (ADAS off Trajectory). As the Crash is detected in the first half of the trajectory, the simulation tool plots an alternate trajectory (Green) that avoids the Crash.

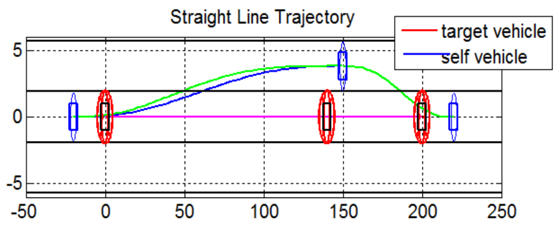


Figure 10: Double Lane Change Maneuver.

3.3 Trajectory Feasibility Evaluation

It is important to verify whether the trajectory developed by the tool can be followed by a realistic vehicle. Hence, the trajectory created was imported to PreScan, a physics- based simulation platform that is used in the automotive industry for development (Prescan, 2015). The PreScan Vehicle Models of None Dynamics and 3D Simple Dynamics were made to follow the trajectory and speed profile generated from the proposed tool for the double lane change maneuver (Section 3.2). Figure 11 shows vehicle speed profile and position information.

A driver model in PreScan with a preview time of 0.8s has been used to follow the trajectories in the 3D dynamic model. Fig. 11 also shows the difference in parameters obtained from the Tool with the None Dynamic and the 3D model in form of errors. The None Dynamics model follows closely with the parameters generated by the Tool. The 3D model also follows the parameters closely. The larger error in the 3D PreScan Model can be associated with the driver model used in the PreScan. The higher heading and yaw rate error is due to the preview time variable in the driver model. The driver model also uses a PID controller for velocity control. A better tuned PID controller will lower these errors in velocity and accelerations. All the errors combined are responsible for the x-position and y-position errors.

4 CONCULUSION

A vehicle simulation tool that can be used for various vehicle test scenarios has been developed in Matlab/Simulink environment. The simulation tool

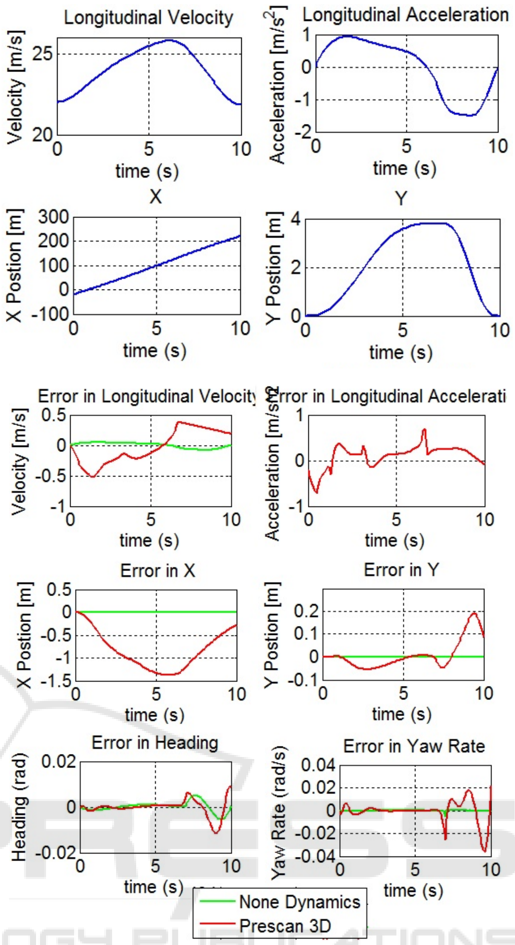


Figure 11: Parameters Developed by the Tool.

can generate vehicle trajectories using polynomial parameterization method. Using this tool, users can generate and evaluate two different trajectories (collision and collision-free) for various user defined test conditions. The user can design and pre-simulate a test scenario quickly and assure testing conditions before real vehicle testing.

REFERENCES

Yuan, H. and Qu, Z. (2009), Optimal Real-time Collision-Free Motion Planning for AUVs in a 3D Underwater Space, *IET Control Theory and Applications*, Vol. 3, No. 6, pp. 712-721.

M. Durali, G. Javid, and A. Kasaiezadeh (2006), Collision avoidance maneuver for an autonomous vehicle, *9th IEEE International Workshop on Advanced Motion Control*, pp. 249-254.

Dubins, L. E. (1957), On Curves of Minimal Length with a Constraint on Average Curvature, and with Prescribed

Initial and Terminal Positions and Tangents, *American Journal of Mathematics*, Vol. 79, No. 3, pp. 497-517.

Qu, Z., Wang, J., and Plaisted, C. (2004), A New Analytical Solution to Mobile Robot Trajectory Generation in the Presence of Moving Obstacles, *IEEE Trans. on Robotics*, Vol. 20, No. 6, pp. 978-993.

T. Shim, G. Adireddy, and H. Yuan (2012), Autonomous vehicle collision avoidance system using path planning and model-predictive-control-based active front steering and wheel torque control," *Proc. of the IMECE, Part D: Journal of Automobile Engineering*, pp. 767–778.

Fliess, M., Levine, J., Martin, P., and Rouchon, P. (1994), Flatness and Defect of Non-Linear Systems: Introductory Theory and Examples, *International Journal of Control*, Vol. 61, No. 6, pp. 1327-1361.

PreScan Help (2015), vol. PreScan R7.2.0. TASS, TNO.