An Autonomous Lane-Keeping Ground Vehicle Control System for Highway Drive

Ahmed Sharmin and Rahiman Wan

Abstract In this paper, a control system for lane-keeping ground vehicle is designed. Under the assumption of highway driving condition, with an uncertain road curvature, a lane keeping vehicle control system is developed. The closed loop control system is obtained by implementing a PID (proportional, integral and derivative controller) control strategy. For a MIMO (multi-input multi-output) vehicle model, a loop of PID controllers is designed to ensure the lane keeping criteria of the vehicle is satisfied. Several simulation results have demonstrated the functionality of lane-keeping feature of the vehicle.

Keywords Autonomous ground vehicle · Lane-keeping · PID

1 Introduction

An automated highway traffic has been of research interest since last two decades [1, 2]. Lane-keeping vehicles are the primary concern for an autonomous traffic system. Automated control of steering is the principal objective of a lane-keeping vehicle. A lane-keeping vehicle tracks a reference path, any displacement from the reference, forces the control system of the vehicle to steer back to the reference. The control input is the steering angle and the outputs are the displacement variables from the reference path. The design of a lane-keeping vehicle system with uncertain road

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curvature, is a disturbance rejection problem. Moreover, variation of velocity and road surface condition in highway drive, turns it into a robust control problem.

Different types of control strategies have been implemented for autonomous ground vehicle so far. PID control [3, 4], Sliding mode control [5], Predictive control [6] and more. An article in the recent release of IEEE Control Systems Magazine, reveals that PID hardware is now dominated by five major vendors ABB, Emerson, Foxboro (Invensys), Honeywell and Yokogawa, and this will probably affect the rapid take up of new PID control design concepts in PID hardware modules [7]. For the ease of calculation and implementation, in this research we have used classical Proportional, Integral and Derivative (PID) controller for the control of autonomous lane keeping vehicle.

Mathematical modeling of a dynamic system is the core element for a simulation study. Authors of this paper have used a mathematical model of the vehicle for this paper from their ongoing research. The PID control strategy is designed according to the need for lane-keeping feature and safe driving. Controller parameters are tuned according to the control objectives of the research. The control objective of this research is to reject the disturbance at any time instance. Considering the uncertain road condition due to raining and hot temperature in Malaysia, the designed control system is tested for different road surface circumstances. Simulation outcomes of the designed controller are presented in the experimental results section of the paper.

In the first section of this paper, mathematical model of ground vehicle with lateral dynamics is presented for lane-keeping system. Later, PID control strategy along with a regulator is implemented for the closed loop design. Finally, robustness of the system is validated via simulation in the experimental result section. Assuming that longitudinal velocity of the vehicle is $70\,\mathrm{kmh}^{-1}$ which is approximately $19.5\,\mathrm{ms}^{-1}$, the results for changing road curvature on different road surface conditions are shown.

2 Vehicle Mathematical Model

The mathematical modeling of ground vehicle has been widely studied so far. A number of dynamic and kinematic mathematical models of ground vehicles can be found in literature [2, 8]. The vehicle mathematical model used throughout this paper is inspired by previously developed [3, 9, 10] models of ground vehicle, which is based on "Bicycle vehicle model".

Let assume a vehicle with a longitudinal position x, a lateral position y, an orientation ψ, moving on a road surface with a constant longitudinal velocity, V_x. The distance of Center of Gravity (CG) from the front and the rear axle of the vehicle are respectively l_f and l_r. The vehicle side-slip angle and yaw rate is β and r respectively. The vehicle model is shown in Fig. 1 in terms of its parameters and forces. The road is having a radius, R at the look-ahead distance point.

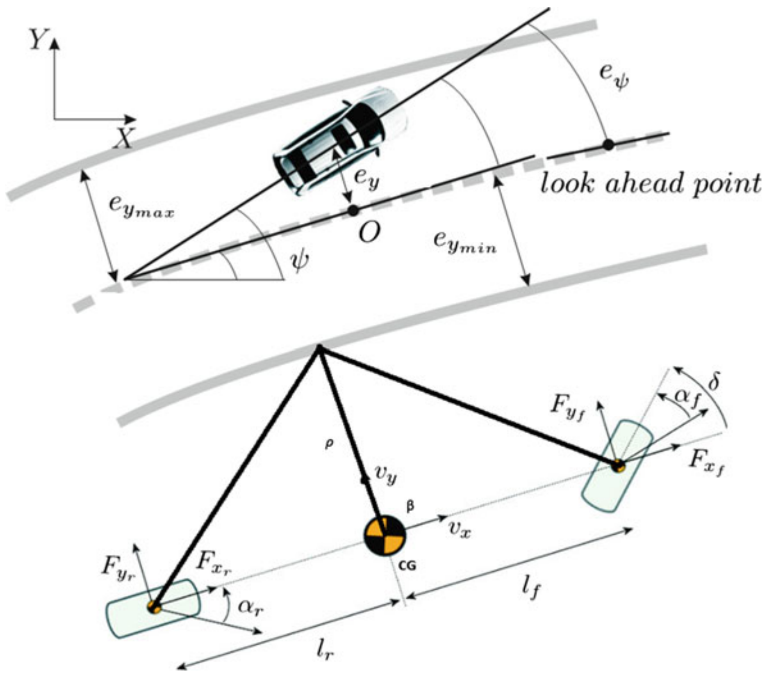


Fig. 1 Bicycle vehicle model

The vehicle equations of motion for bicycle model can be written as,

$$\dot{\beta}(t) = -\left[\frac{2C_{\alpha f} - 2C_{\alpha r}}{\tilde{m}}\right]\beta(t) + \left[-1 - \left(\frac{2C_{\alpha f}l_f - 2C_{\alpha r}l_r}{\tilde{m}V_x}\right)\right]r(t) + 2C_{\alpha f}V_x\delta(t) \quad (1)$$

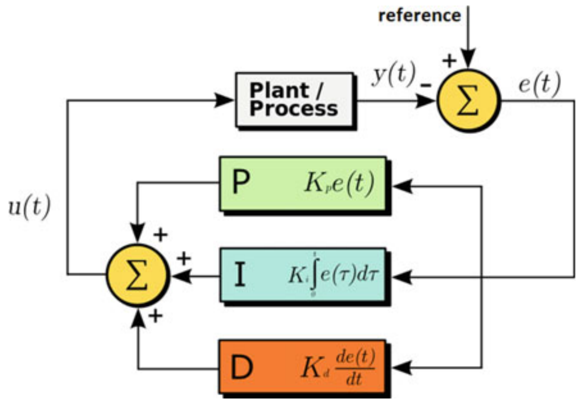
$$\dot{r}(t) = \left[-\frac{2C_{\alpha f}l_f + 2C_{\alpha r}l_r}{\tilde{I}_{zz}}\right]\beta(t) - \left[-1 - \left(\frac{2C_{\alpha f}l_f^2 + 2C_{\alpha r}l_r^2}{\tilde{m}V_x}\right)\right]r(t) + \frac{2C_{\alpha f}l_f}{\tilde{I}_{zz}}\delta(t) \quad (2)$$

$$\dot{e}_y(t) = V_x e_p(t) - V_y - V_x\rho L \quad (3)$$

$$\dot{e}_p(t) = -r(t) + V_x\rho L \quad (4)$$

where, C_f, C_r are respectively cornering stiffness of the front tire, cornering stiffness of the rear tire. $\tilde{m}$, $\tilde{I}_{zz}$ are the normalized mass of the vehicle, normalized yaw moment of inertia of the vehicle. The parameter mass and yaw moment of inertia are normalized with parameter μ, which is the road-surface coefficient. In (3) and (4), L is the look-ahead distance, along the longitudinal axis, from the vehicle center of gravity, shown in Fig. 2. ρ is the road curvature at the look-ahead point and it is the reciprocal of the road radius. From Eqs. (1), (2), (3) and (4) one a state-space rep-

Fig. 2 PID controller [11]



resentation of the vehicle can be formed where, the steering angle, δ is the control input of the vehicle and road curvature, ρ is the input disturbance; error variables e_y and e_p are the outputs of the system.

3 Closed Loop Lane-Keeping Vehicle Design

In order to develop a closed loop system for lane keeping feature of a ground vehicle we must have some control objectives. The objective of a lane-keeping ground vehicle is to keep the vehicle within the lane despite of change of curvature or uncertain road condition. On the basis of this objective of the paper a controller can be implemented.

3.1 Control Objectives

The main objective of this research is to control the error variables such a manner that the vehicle always remains within the lane even in the presence of disturbance. The disturbance is the curvature of the traveling road. Meaning that, the error variables shown in Eqs. (3) and (4), should be as small as possible even at a non-zero road curvature. The mathematical interpretation of such an objective can be done through a constraint on the output, lateral error variable, e_y. Besides, for the safe driving of the vehicle, constraint on the control input, steering angle is also important.
Steering angle input constraint for safety can be expressed as,

$$u_{min} \leq u \leq u_{max} \tag{5}$$

and the output constraint can be presented as,

$$e_{y_{min}} \leq e_y \leq e_{y_{max}} \tag{6}$$

On the basis of the usual lane width and car width the ideal values for lateral error variable should lie within, 1.8 m irrespective of the displacement direction (right or left), irrespective of the amount of road radius. For the passenger ground vehicle usually the maximum steering angle is 0.5 radian. For the sake of safe driving the maximum allowable steering angle in this research is 0.2 radian.

3.2 Controller Design

PID (proportional, integral, derivative) controller is a well-established classical method of controlling dynamic systems. This controller is a combination of three individual mathematical operators. Those are multiplier, integral and derivative. On the basis of the required objective of a control system, properties of the PID controller are chosen.

The basic working principle of a PID controller is shown in Fig. 2, here, $u(t)$ is the control input to the plant, $e(t)$ is the difference between the reference signal and the output of the system. k, k_i, k_d are the proportional, integral and derivative coefficients respectively. Mathematically the PID controller can be expressed as,

$$u(t) = ke(t) + k_i \int_0^t e(\tau)d\tau + k_d \frac{de(t)}{dt} \tag{7}$$

The vehicle model represented in Eqs. (1), (2), (3) and (4) is a two output, one input system, which is a SITO (single input, two output) plant model. As mentioned in previous section, the control objective of this research is to keep the vehicle within the lane in the presence of disturbance. In order to achieve this objective, we need to design a controller that keeps the lateral deviation and the angular deviation as close to the reference as possible. In this case, the reference is of zero magnitude for both of the output variables, e_y and e_p. Therefore, the controller to be used for the SITO vehicle model must be a TISO (two input, single output) controller. In this paper, the closed loop control system has also a regulator for the regulation of the control input. A regulator used in this paper is nothing but an Integral controller. The tuning of the controllers are carried out on the basis of response time and settling time of the system. The overall closed loop system design is shown in Fig. 3.

It can be observed in Fig. 3 that two PID controllers have been implemented for designing the controller. One of the controllers takes into account the output variable, e_y and the other controller responsible for variable, e_p. The control input generated by the controllers is then fed into a regulator, in order to tune the value of the steering angle. Therefore, the output of the regulator is a tuned steering angle that lies within the value of the constraint mentioned in (5). In the MIMO model presented in (1)–(4),

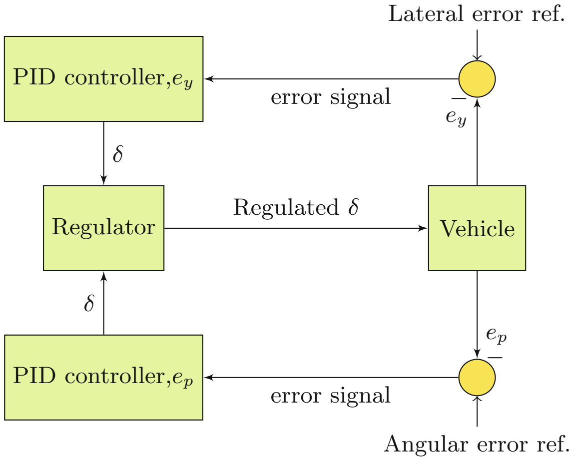


Fig. 3 PID controller [11]

there are two outputs and one control input. The second input is the disturbance input, road curvature, ρ. Since, ρ is a environmental parameter, it can not be controlled by a controller. Thus, for a 2-input 2-output, MIMO system two individual PID controllers are used, each controller responsible for one output.

4 Experimental Results

In the preceding section, a controller is designed along with a regulator for the mentioned mathematical model of the vehicle. In order to check that the control objectives mentioned in Sect. 3 are obeyed or not on this particular circumstances, the outputs of the vehicle are observed. The safety constraint on the steering angle is also a concern for safe driving. In this section of the paper, the simulation results for closed loop lane-keeping vehicle are shown. For three different values of road curvature, the outputs of the vehicle are witnessed in dry and wet road surface condition.

For longitudinal velocity of $30\,\mathrm{ms}^{-1}$ or $70\,\mathrm{kmh}^{-1}$ in a highway, the vehicle model was subjected to different values of road curvature. The values of road curvature are selected based on the possible road radius in the standard highways. In Figs. 4, 5 and 6 the outputs and inputs of the vehicle are shown graphically, in these figures the light blue signals represent the outputs of the system, whereas the dark blue signals represent the desirable reference outputs, applied disturbance as road curvature and control input of the system. For all the three cases, the vehicle is assumed to be traveling in a straight path initially with a constant speed. At 4th second of the simulation a change of road curvature interrupts the vehicle. The observation of the results also begin at this instant. It is to be recorded from the outputs of the vehicle that is it possible for the vehicle to be within the lane while maintaining a safe value of steering angle at the change of road curvature. The simulation was performed in the MATLAB-Simulink environment.

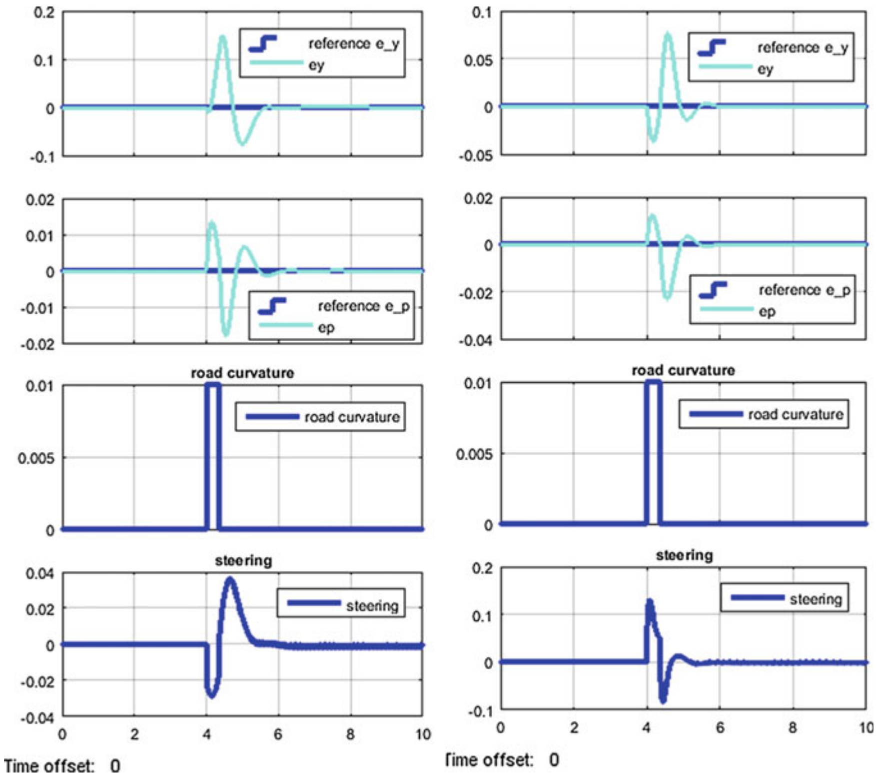


Fig. 4 Simulation result for closed loop vehicle system at 100 m radius, 19.5 ms^{-1} velocity, dry surface (*left*), wet surface (*right*), *y*-axis (e_y in m, e_p in radian, ρ in m^{-1}, δ in radian) respectively

In Fig. 4, the vehicle is subject to 0.01 m^{-1} road curvature (100 m road radius) from 4–4.30th second. The lateral error variable is within the maximum allowable value, so as the angular error variable. Again, the safety issue mentioned in Sect. 3, regarding the value of control input has also achieved desirable value under the disturbance of 0.01 $m^{-}1$ road curvature.

Again, in Fig. 5, 0.004 m^{-1} road curvature (250 m) has interrupted the vehicle outputs at 4th-4.30th second. The lateral error variable was within the allowable constraint, mentioned in Sect. 4. The steering angle has also managed to lie within the safe value under the disturbance.

For the third case, a 500 m road radius (0.002 m^{-1} road curvature) acting at 4*th* second of the simulation period. In this case also, the lateral error variables and the steering angle, all are within the allowable values for both wet and dry surface condition. The results are shown in Fig. 6. Thus, for three different input disturbance the controllers performance is ideal. Furthermore, the lane-keeping objective is satisfied on dry and wet surface at 30 ms^{-1} velocity.

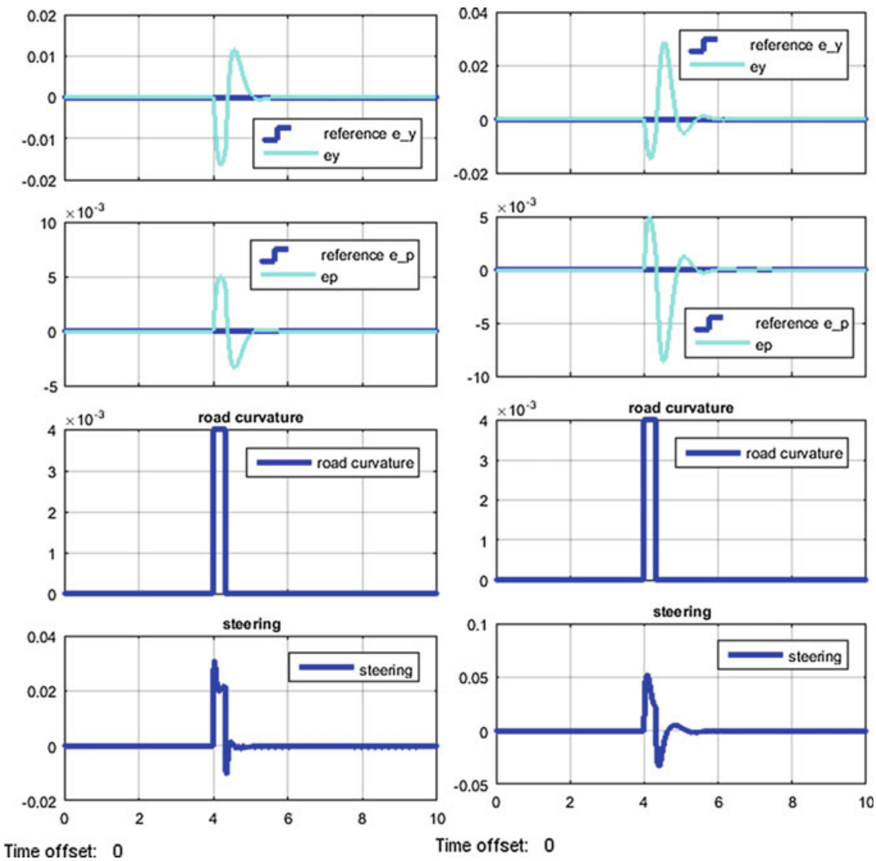


Fig. 5 Simulation result for closed loop vehicle system at 250 m radius, 19.5 ms^{-1} velocity, dry surface (*left*), *right* (wet) *y*-axis (e_y in meter, e_p in radian, ρ in m^{-1}, δ in radian) respectively

Besides the graphical results, the overall results of the experiments can briefly be expressed in Table 1. In Table 1, the maximum value of lateral error variable, e_y, the maximum value of angular error variable e_p, the peak value of steering angle δ are listed for different road curvature values. From the results, we can observe that, output variable, e_y and steering angle, δ, lie between the constraints mentioned in (5) (1.8 m) and (6) (0.2 rad). Therefore, it can be said that, the vehicle was able to remain within the lane in both dry and wet surface in the presence of different values of road curvature. The steering angle is also within the desirable comfortable values.

The vehicle parameters used in this paper are appropriate for a passenger car. The vehicle parameters used in this simulation are tabulated in Table 2. It is considered that throughout the simulation the longitudinal velocity of the vehicle is constant. For the dry and wet surface condition, the parameter, μ is varied. For a dry surface μ is assumed to be 1 and for wet surface μ is assumed to be 0.5.

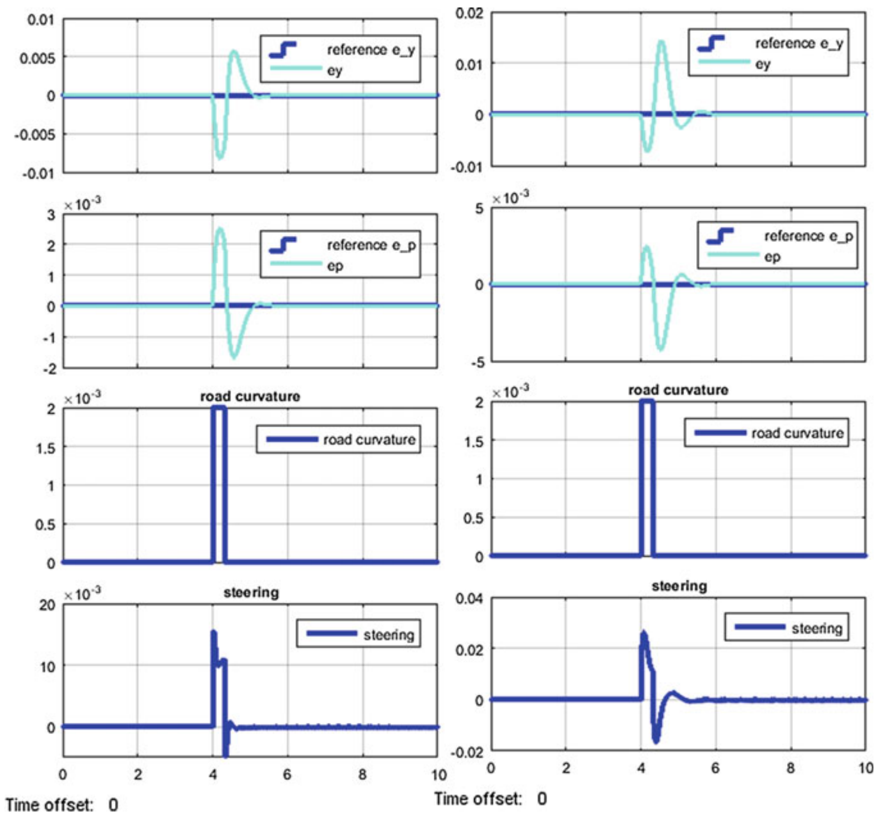


Fig. 6 Simulation result for closed loop vehicle system at 500 m radius, 19.5 ms^{-1} velocity, dry surface (*left*), wet (*right*) y-axis(e_y in m, e_p in radian, ρ in m^{-1}, δ in radian) respectively

Table 1 Simulation results for output and input variables on different road condition at varying disturbance

Disturbance	Max.e_y	Max.e_p	Max.δ	Road condition
m^{-1}	m	m	radian	$\mu = 0.5$ or 1
0.01	0.15	0.018	0.038	Dry
	0.07	0.021	0.13	Wet
0.004	0.015	0.0005	0.03	Dry
	0.03	0.0008	0.05	Wet
0.002	0.008	0.0025	0.015	Dry
	0.015	0.0021	0.018	Wet

Table 2 Parameters of ground vehicle

Symbol	Nomenclature	Value	Unit
$C_{\alpha f}$	Cornering, stiffness of the front tire	35000	Nrad^{-1}
$C_{\alpha r}$	Cornering, stiffness of the rear tire	70000	Nrad^{-1}
l_f	Distance c.g., to front axel	1.4	m
l_r	Distance c.g., to rear axel	1.4	m
m	Vehicle mass	2000	kg
I_z	Yaw moment of, inertia	3500	kgm^{-2}

5 Conclusion

It can be concluded that the overall performance of the controller was robust and reliable. Despite of the constant velocity, changed road condition and sudden change in road curvature, the controller was able to keep the vehicle within the lane. Even though the results are satisfactory for lane-keeping feature but there are some limitations in this paper. For example, this lane-keeping vehicle system was tested only with 70 kmh^{-1} speed on highway driving conditions. Again, the value of the disturbance implemented in the simulation is suitable only for highway drive. The contribution of this work, lies on two facts, that is, the mathematical model used in this paper for lane-keeping accounts for road surface condition, road curvature and includes side-slip angle as one of the degree of freedoms of the vehicle. Moreover, the PID loop strategy along with regulator is also a robust design compared to other conventional control methods used for lane-keeping. However, the robustness of the system can be analyzed further with different longitudinal speed. In future, the implementation of this controller in prototype ground vehicle can validate the design.

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