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Authors
Swaroop, D.
Yoon, Seok Min

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D. Swaroop
Seok Min Yoon

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The design of a controller for a following vehicle in an Emergency Lane Change maneuver [1]

D. Swaroop, Seok Min Yoon
Department of Mechanical Engineering
Texas A&M University, College Station, TX - 77843-3123
dswaroop@usha.tamu.edu

Abstract

A lane change maneuver is one of the many appropriate responses to an emergency situation. The design of an Emergency Lane Change (ELC) maneuver for a platoon of two vehicles is considered in this paper. In response to the presence of a stationary or a slowly moving obstacle in the lane or any such emergency, the lead vehicle in the platoon designs an ELC trajectory on-line and broadcasts the trajectory curvature information in real time to its follower. The problem considered, in this paper, is the design of an integrated lateral and longitudinal controller that enables the follower to track the lead vehicle's trajectory, while maintaining a desired following distance. A sliding mode controller is developed for this purpose and its performance is demonstrated in simulations.

1 Introduction

Automatic lateral guidance of a vehicle involves:

1. the specification of a trajectory to be followed by a controlled vehicle, and
2. the design of a control system that regulates the lateral position of the vehicle about the specified trajectory.

The availability of lateral deviation from the specfied trajectory and the road preview information in control system synthesis affects the ride quality and tracking performance of a lateral vehicle guidance control system [14].

In a normal lane keeping task, the specified trajectory is the center of the lane. There are several approaches to sensing the lane center and road geometry. A vision system is used to sense the up-coming road geometry and objects in front of the vehicle [3, 10, 9]. With a vision system, road preview and lateral deviation from the center of the lane can be computed in real-time. Enabling the vehicle to sense the lane edge strippings of the road in varying road and weather conditions is a limiting factor of the vision system. Another alternative is an indirect sensing, where a reference for the lateral guidance control system is built into the road surface. A continuous reference gudieline using a wire

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was utilized and examined in [1]. A radar reflecting guard rail at the side of a lane was employed in the research at the Ohio State University [5]. In the California PATH program, permanent magnets are used as discrete markers in the road surface to delineate the center of the lane and encode the road preview information [16]. The information from magnetometers on-board the vehicle is processed to determine the lateral deviation from the lane center and to decode the road preview information.

Platoons typically involve short headway distances. In this paper, an architecture for an Automated Highway System (AHS) is assumed, where, in emergency situations, the leader of the platoon decides the most appropriate response for the situtation based on safety considerations. This response is based on the sensory and communicated information obtained regarding the surrounding vehicles and the environment. In this paper, it is assumed that the sensors, actuators and communication devices of all vehicles in the platoon are functioning properly. It is also assumed that the lead vehicle has the requisite sensing and accurate trajectory tracking capability.

One of the many appropriate responses to an emergency situation is an ELC maneuver. In the lane change scheme employed by Chee and Tomizuka in [2], every controlled vehicle in the platoon executes a preplanned lane change trajectory independently. The lateral deviation from the preplanned trajectory is estimated using a Kalman filter and on-board sensor information such as the magnetometer measurement, lateral acceleration and yaw rate measurements. While there are many possible ways of designing an ELC maneuver, the focus of this paper is the design of a vehicle following controller that tracks the trajectory of the vehicle ahead. Such a controller has the advantage of backing up as a lane keeping controller in the event of a failure in a magnetometer or a similar sensor. Unlike a lane keeping task, where the desired trajectory is prespecified and can be sensed, the desired trajectory in an ELC maneuver is not prespecified and evolves in time. Therefore, the absolute deviation from the preceding vehicle's trajectory is diffcult to sense and is impossible to infer, especially without any form of communication. The problem is compounded when the following vehicle maintains short headway distances, and its sensors are blinded by the preceding vehicle. One encounters similar difficulties in obtaining the requisite deviation and curvature information with a magnetometer on-board a controlled vehicle.

To circumvent these difficulties, a controller design for the following vehicle that relies on its motion relative to the preceding vehicle is sought. Such an information can easily be obtained using on-board sensors. However, associated with such a design is the problem of lateral stability in a multi-vehicle platoon, i.e., the amplification of lateral deviations from the specified path. Narendran and Hedrick [12] proposed an autonomous, sliding controller that tracks the vehicle in front using vehicle-to-vehicle range and azimuth measurements. The main drawback of this scheme is that it has nonzero steady state lateral deviations. Fujioka and Suzuki [6], in their trajectory follower scheme, estimate the trajectory of the preceding vehicle using a prediction and correction scheme. On-board sensory measurements are used to predict the trajectory of the preceding vehicle and communicated information is used to correct the estimate. The control task, then, is to track the estimated trajectory. In their simulations for a nine vehicle platoon, the steering effort profile actually increases with vehicle index.

The purpose of estimating the trajectory of the preceding vehicle is to determine the desired velocity and relative position of the controlled vehicle. In this perspective, the approach of Fujioka et. al. is indirect. In this paper, the approach for vehicle following lateral guidance control system design is direct. The desired position of the controlled vehicle is estimated directly from the sensory and communicated information. Although, this work concerns the design for only a two-vehicle platoon, the authors are hopeful that a proper extension to a multi-vehicle platoon results in smaller controller efforts than in [6].

The details of the algorithm development are given as follows: In section 2, the need for intervehicular communication in automated driving with short headway distances between vehicles, especially in emergency situations, is emphasized. In section 3, the vehicle model used in controller design is presented and the integrated lateral and longitudinal controller is developed. In section 4, simulation results are presented and section 5 summarizes the findings in this paper.

2 Intervehicular communication and emergency lane change maneuvers

Consider a string of automated vehicles traveling on the right-lane of a straight section of a 2-lane highway as shown in figure 1. In this paper, obstacles that necessitate an evasive action to prevent the loss of human life or material damage are considered. In the presence of such an obstacle in the left-half of the right lane, every vehicle must register the presence of the obstacle, then plan and execute an obstacle-avoidance control action.

In such a situation, automated vehicles equipped with communication capabilities register the presence of an obstacle almost instantaneously. Autonomous vehicles, however, are, by definition, not equipped with inter-vehicular communication capabilities. As a result, they are completely blinded by their preceding vehicle (until somehow they get the information from roadside beacons or are close enough to detect the obstacle). It is assumed that an obstacle is not detected by a vehicle until half of the obstacle comes into the sensor range of the vehicle (for simplicity, sensor range is assumed to be cylindrical with a radius equal to a quarter of the vehicle's width). Until an obstacle is detected, an autonomous vehicle cannot distinguish between a genuine lane changing maneuver and an obstacle avoidance maneuver of its preceding vehicle and it continues to track the center of the lane, unless it detects an obstacle. Under these conditions, the safe spacing between autonomous vehicles is dictated by maximum negotiable road curvature and the maximum sensing range of the vehicle. To elaborate this point further, consider the situation described earlier where the string comprises of autonomous vehicles. For the sake of analysis, vehicle width is assumed to be two-thirds the lane width, W. The obstacle is assumed to be placed at a distance $W/6$ from the lane center and the width of the obstacle is $W/6$.

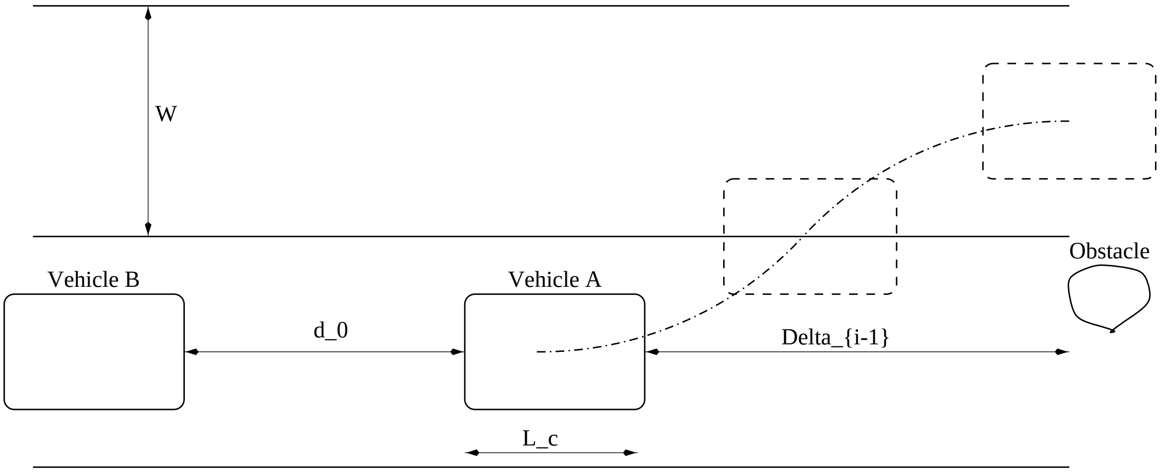

Figure 1: Obstacle avoidance scenario.

Figure 1 describes the situation under consideration. Δ_{i-1} is the distance of point of obstacle detection from the obstacle for vehicle A. Vehicle B is following vehicle A at a distance d_0. Obstacle will be detected by following vehicles, only when the right edge of vehicle A moves to the left by $W/3 + W/4 = 7W/12$. Accounting for loss of visibility due to yawing of the vehicle, vehicle A must move a distance $2W/3 = 8W/12$ from its lane center along the lateral direction to make the obstacle visible to its following vehicles. Assuming that the distance travelled longitudinally is proportional to the the lateral distance travelled, vehicle A travels $2\Delta_{i-1}/3$ distance longitudinally from its point of obstacle-detection. The distance of point of obstacle-detection, Δ_i for the following vehicle B, then becomes $d_0 + L_c + \Delta_{i-1}/3$. If vehicle A is considered as $i-1$ st vehicle and vehicle B as i th vehicle in a string, the distance between the obstacle and the point of obstacle-detection for vehicles sufficiently downstream becomes closer and closer to $1.5(d_0 + L_c)$, even if $\Delta_1 >> 1.5(d_0 + L_c)$. Therefore, from traffic capacity and safety points of view, it is critical to find out the minimum allowable d_0.

Let Δ_0 denote the minimum distance from the point of obstacle detection and the obstacle, for which a vehicle can perform a lane change maneuver for a maximum radius of curvature and ensuring acceptable ride quality. From the above calculation, it is easy to find that $d_0 + L_c = 2\Delta_0/3$ for safety and best static traffic capacity estimate.

Now, it is important to determine Δ_0 from a vehicle's capability to negotiate a maximum curvature road. Let R_t represent the smallest radius of curvature a vehicle control system can successfully negotiate. Since the lane change ma-

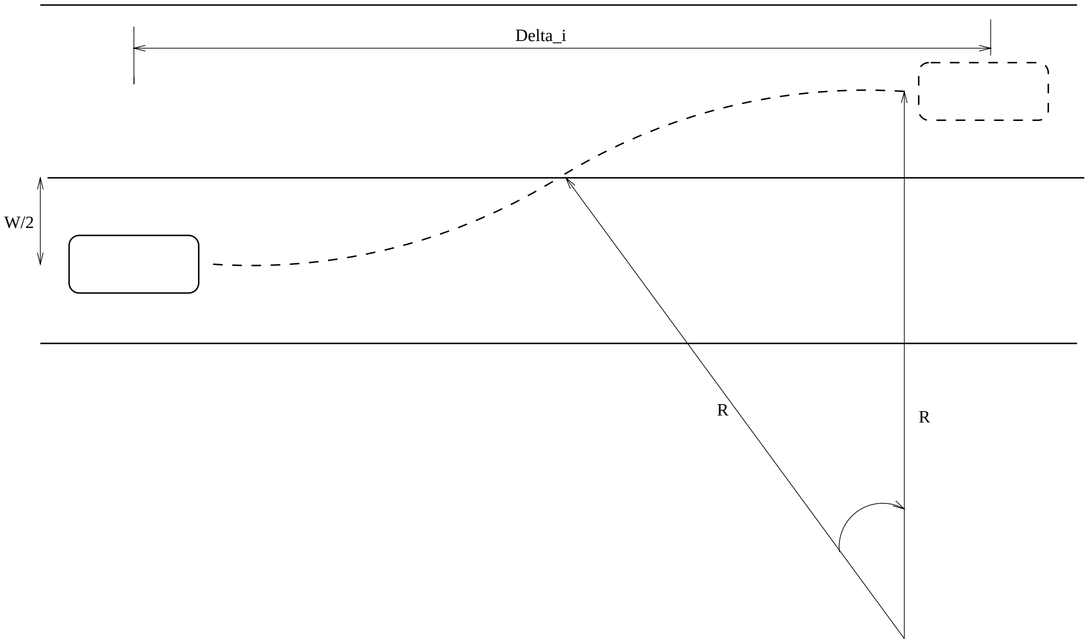

Figure 2: Lane change trajectory.

neuver trajectory is symmetric about the lane boundary and it has two curves of the same radius but of opposite sign, assuming the trajectory to be an arc of radius, R_t, geometry dictates that $(R_t - W/2)^2 + (\Delta_0)^2/4 = R_t^2 \Rightarrow R_t = \frac{\Delta_0^2 + W^2}{4W}$. This implies $\Delta_0 = \sqrt{4WR_t - W^2}$.

A vehicle is assumed to make atmost a 360m radius turn at 60 mph. Similarly, lane width is assumed to be 3m. This yields a $\Delta_0 = 65.66$m. Therefore, the minimum intervehicular spacing is $2\Delta_0/3 = 43.77$m (inclusive of vehicle length).

The need for intervehicular communication at headways shorter than $45m$ is very clear from the above calculation.

3 Control Law Development

While there are many possible ways of ensuring that vehicles in a platoon change lane, when they are required to, in response to an emergency, this paper is concerned with a possible lane change scenario where the lateral and longitudinal motion of a following vehicle is dependent on the motion of a vehicle or vehicles ahead.

3.1 Vehicle Model

The control law development is based on the following simplified (bicycle) model of a vehicle used in [16, 17, 15, 12].

$$\begin{aligned}
\dot{v}_x &= \frac{T_{net} - c_x v_x^2 - T_{rr}}{I_{eff}} + v_y \dot{\theta} &(1)\\
\dot{v}_y &= \frac{F_{tryf} + F_{tryr} - c_y v_v y^2}{M} - v_x \dot{\theta} &(2)\\
\ddot{\theta} &= \frac{1}{I_z}[l_1 F_{tryf} - l_2 F_{tryr}] &(3)
\end{aligned}$$

In the above set of equations, v_y, v_x are respectively the lateral and longitudinal velocites of the vehicle, T_{net} is the net engine/brake torque, and is the control input for the vehicle longitudinal dynamics; T_{rr} is the rolling resistance torque, c_y, c_x are respectively the lateral and longitudinal aerodynamic drag coefficients, M, I_{eff}, I_z are respectively the mass, effective longitudinal inertia and mass moment of inertia about the yaw axis passing through the vehicle's center of gravity. $\dot{\theta}$ is the yaw rate of the vehicle, F_{tryf}, F_{tryr} are respectively the cornering forces at the front tires and rear tires. l_1, l_2 are respectively the distances of the front and rear tires from vehicle's center of gravity. Some of the important assumptions made in obtaining the above set of equations are:

1. Roll, pitch and bounce dynamics of the vehicle are neglected. In effect, vehicle is only allowed translations in the longitudinal and lateral directions and a rotation about its yaw axis.
2. Throttle, brake and steering actuation dynamics and the engine manifold dynamics is neglected.
3. There is no slip between the vehicle tire and the ground, so that vehicle longitudinal velocity is always proportional to the wheel speed. It is also assumed that there is no slip across the torque converter.

A linear tire model is assumed for the simulations and is given by:

$$\begin{aligned}
F_{tryf} &= 2C_{sf}(\delta - \frac{v_y + l_1 \dot{\theta}}{v_x}) &(4)\\
F_{tryr} &= -2C_{sr}(\frac{v_y - l_2 \dot{\theta}}{v_x}) &(5)
\end{aligned}$$

Here C_{sf} and C_{sr} are respectively the cornering stiffness of the front and rear tires. δ is the steering angle input.

3.2 Kinematics

The control law is developed for the following vehicle of a two vehicle platoon. The extension to multiple vehicle platoons will be considered in our future work. In this work, the following measurements are assumed available for the following vehicle:

1. Relative Velocity and the following distance (shown as Δ in the figure 3).
2. Relative yaw angle, θ_r and the azimuth angle, ϕ.
3. Lateral velocity, $v_{y,l}$ and longitudinal velocity, $v_{x,l}$, of the lead vehicle.
4. Yaw rate of the lead vehicle, $\dot{\theta}_l$.
5. Longitudinal, lateral and yaw acceleration of the lead vehicle.
6. Road curvature information broadcast from the lead vehicle.

Typically, the radius of curvature and the length of a trajectory required for a safe maneuver is typically much larger than the length of a two vehicle platoon. In that sense, it is reasonable to assume that the two vehicles in the platoon are traversing on a road of same curvature. However, such an assumption is not necessarily true for a multi-vehicle platoon. The longitudinal control objective here is that the following vehicle must maintain a constant spacing from the lead vehicle. The lateral control objective is that the following vehicle must track the lead vehicle's trajectory.

In order to determine the throttle, brake and steering commands, the desired lateral and longitudinal velocities of the following vehicle are determined from the above set of measurements in the following manner: Consider a mechanical tow or a link between the lead vehicle and the following vehicle. The two vehicles can be treated as mechanical links. Consider the planar motion of the three links such that the center of gravity of the first and last links is always on the desired circular trajectory. From kinematics, one can determine the tangential and normal velocities of the third link's center of mass from the tangential, normal and angular velocities of the first link's center of mass and the lengths of links. In an analogous manner, given the lateral, longitudinal and yaw velocities of the lead vehicle, and the desired following distance, the desired lateral and longitudinal velocities of the following vehicle can be calculated. The desired yaw rate of the following vehicle is the yaw rate of the lead vehicle. The desired relative yaw angle can be computed from the lengths of the following and lead vehicles, and the desired following distance.

In order to close the position loop, one must define the lateral and longitudinal position deviations. The deviations are shown in figure 4. Conceptually, the desired following position is the position of the third link in the above analogy. The desired longitudinal direction is the longitudinal direction of the third link (tangential to the desired circular trajectory). Geometrically, the longitudinal deviation, e_{long}, is the deviation in the following vehicle's postion from the desired following position along the desired longitudinal direction. The lateral deviation, e_{lat}, is the deviation in the following vehicle's position from the desired following position in a direction normal to the desired longitudinal direction as shown in the figure 4.

Let l_1, l_2 denote respectively the distances of the front and rear wheels of a vehicle from its center of gravity. Let R denote the radius of curvature of the road and the road curvature, ρ, is $\frac{1}{R}$. Let the desired yaw angle of the following vehicle relative to the lead vehicle be denoted by θ_{des} and let Δ_{des} denote the desired following distance of the following vehicle.

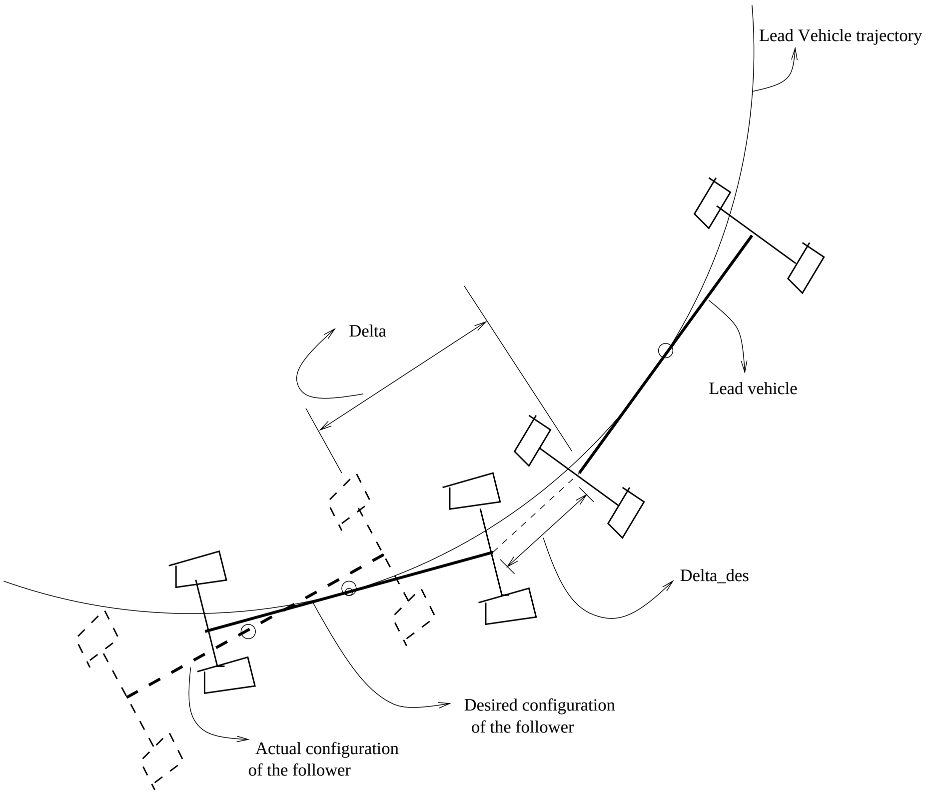

Figure 3: Desired and Actual positions of the following vehicle relative to the lead vehicle.

The following are the relevant kinematic relationships:

$$\theta_{des} = (l_1 + l_2 + \Delta_{des})\rho \quad (6)$$

$$\phi_{des} = (l_1 + \frac{\Delta_{des}}{2})\rho \quad (7)$$

$$\psi = \theta_{des} - \theta_r \quad (8)$$

$$e_{long} = \Delta_{des}\cos(\phi_{des}) - \Delta\cos(\psi + \phi) \quad (9)$$

$$e_{lat} = \Delta_{des}\sin(\phi_{des}) - \Delta\sin(\psi + \phi) \quad (10)$$

$$v_{x,des} \approx v_{x,l} \quad (11)$$

$$v_{y,des} \approx v_{y,l} + v_{x,l}\theta_{des} - (l_1 + \Delta_{des} + l_2)\dot{\theta}_l \quad (12)$$

The subscript l in $v_{x,l}, v_{y,l}$ indicate that they correspond to the lead vehicle. ψ_{des} is the desired azimuth angle. ρ is the curvature of the trajectory, and $R = \frac{1}{\rho}$ is the radius of curvature of the trajectory. In the above set of equations, it is assumed that θ_{des} is small. In other words, it is assumed that the desired intervehicular spacing is much smaller than the radius of curvature of the trajectory.

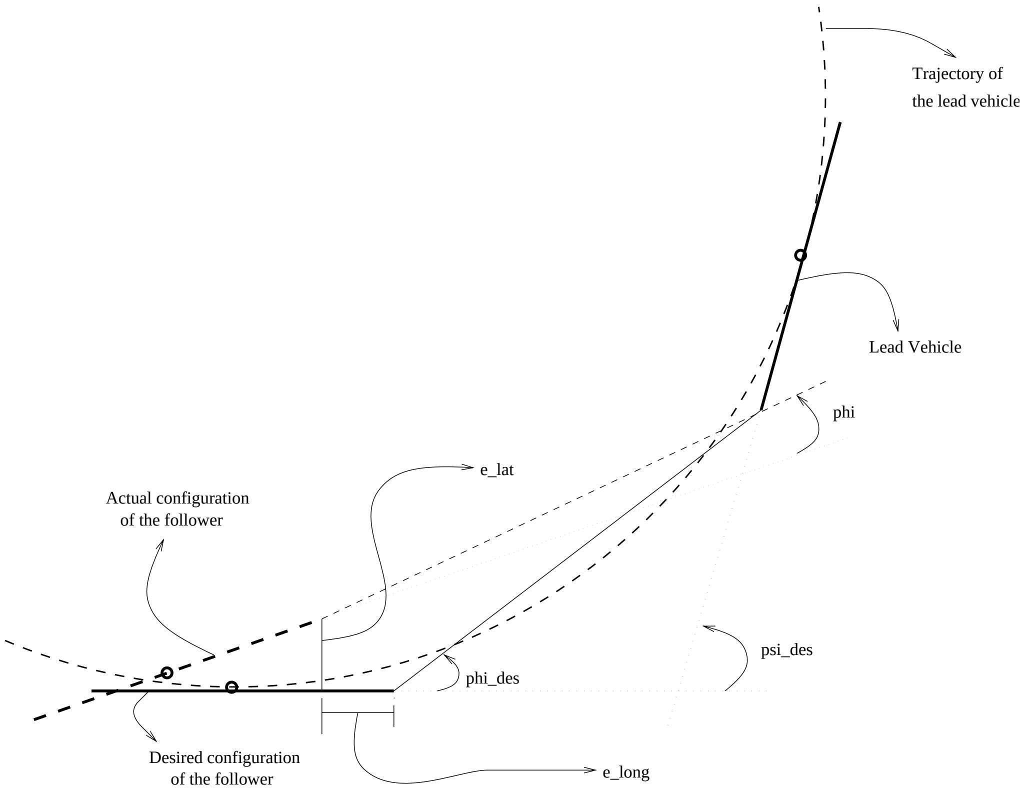

Figure 4: Illustration of the Lateral and Longitudinal position errors.

3.3 Control Algorithm

In developing a control algorithm, the lateral and longitudinal velocity of the following vehicle is matched with its corresponding desired value obtained from kinematic consideration. This allows for using the controller designed in [17]. From kinematics, the mismatch in the desired and actual longitudinal velocity of the following vehicle at the front wheels is

$$\begin{aligned} \tilde{v}_x &\approx v_x - v_{x,l} \qquad (13)\\ \tilde{v}_y &\approx v_y - v_{y,l} + l_1(\dot{\theta} - \dot{\theta}_l) - (v_{x,l} - R\dot{\theta}_l)\theta_{des} \qquad (14) \end{aligned}$$

Here, R is the radius of curvature of the desired trajectory and is obtained by communicating with the lead vehicle.

The auxillary error variables, S_{lat} and S_{long} are defined as follows:

$$\begin{aligned} S_{long} &:= v_x - v_{x,l} + \lambda_1 e_{long} + \lambda_2 \int_0^t e_{long}(\tau)d\tau \\ S_{lat} &:= v_y - v_{y,l} + l_1(\dot{\theta} - \dot{\theta}_l) - (v_{x,l} - R\dot{\theta}_l)\theta_{des} + \lambda_3 e_{lat} + \lambda_4 \int_0^t e_{lat}(\tau)d\tau \end{aligned}$$

In the above equation, λ_1, λ_2, λ_3 and λ_4 are positive constants and are design parameters. The throttle, brake and steering commands are chosen to drive the auxillary error variables to zero. The resulting control laws, following [18, 8, 17], are:

$$\begin{aligned}
T_{net,command} &= T_{rr} + c_x v_x^2 + I_{eff}(-v_y\dot{\theta} + \dot{v}_{x,l} - \lambda_1(v_x - v_{x,l}) - \lambda_2 e_{long} - \lambda_5 S_{long}) \\
F_{tyf,command} &= -\frac{1}{(\frac{1}{M}+\frac{l_1^2}{I})}[F_{tyr}(\frac{1}{M} - \frac{l_1 l_2}{I}) - \frac{c_y}{M}v_y^2 - v_x\dot{\theta} - \dot{v}_{y,l} - l_1\ddot{\theta}_l \\
&\quad -(\frac{\dot{v}_{x,l}}{R} - \dot{\theta}_l)(l_1 + l_2 + \Delta_{des}) + \lambda_3\dot{e}_{lat} + \lambda_4 e_{lat} + \lambda_6 S_{lat}]
\end{aligned}$$

In the above equation, λ_5, λ_5 are design constants and are positive. In obtaining the above set of equations, $\dot{e}_{long}$ is approximated as $\tilde{v}_x$, and $\dot{e}_{lat}$ is approximated as $\tilde{v}_y$. From the commanded cornering force at the front tires, one can obtain the commanded steering angle by inverting the tire model. With the tire model assumed in this paper, the steering angle command is given by:

$$\delta = \frac{F_{tyf}}{2C_{sf}} + \frac{v_y + l_1\dot{\theta}}{v_x}$$

3.4 Simulation Results

In order to simulate a typical lane change maneuver, the desired lane change trajectory is assumed to consist of two circular arcs as shown in the figure. The length traveled in the direction of lane is $60m$ during the entire lane change maneuver and the lane width is assumed to be $3m$. From geometry, the radius of curvature of the circular arc is approximately $300m$. Figure 5 shows the trajectories of the lead and following vehicles. The lateral and longitudinal deviations are shown in figures 6 and 7. Notice that the errors are of the order of a few centimeters. The design constants used in the simulations are: $\lambda_1 = 0.2, \lambda_2 = 0.25, \lambda_3 = 2.5, \lambda_4 = 0.2, \lambda_2 = 5$ and $\lambda_6 = 8$.

Figures 8, 9 and 10 are the corresponding plots when the desired trajectory is a circle. Notice that the errors are significantly small.

In figures 7 and 10, there is a sudden jump in the lateral error from zero. The time at which such a jump occurs coincides with the onset of tracking a trajectory of non-zero curvature by the lead vehicle. At that instant, the desired configuration of the following vehicle changes instantly; it must be such that the centers of gravity of the following and lead vehicles be on a circular arc, the radius of which is determined by the lead vehicle at that instant and the length of which is approximately the desired following distance. This results in an instantaneous jump in the value of the lateral error.

3.5 Summary and Conclusions

In this paper, we demonstrated the need for intervehicular communication in emergency situations when the desired intervehicular distance is small. Then, we designed a lane change controller for the following vehicle that tracks the trajectory of the preceding vehicle. The advantage of this approach is two fold: the following vehicle does not require the absolute lateral deviation from the desired trajectory. It only depends on the lead vehicle information relative to itself. Secondly, the actions of the following vehicle are coupled to the lead vehicle and it enhances safety during a lane change maneuver. The satisfactory performance of the designed automated vehicle following controller is demonstrated at the end of this paper.

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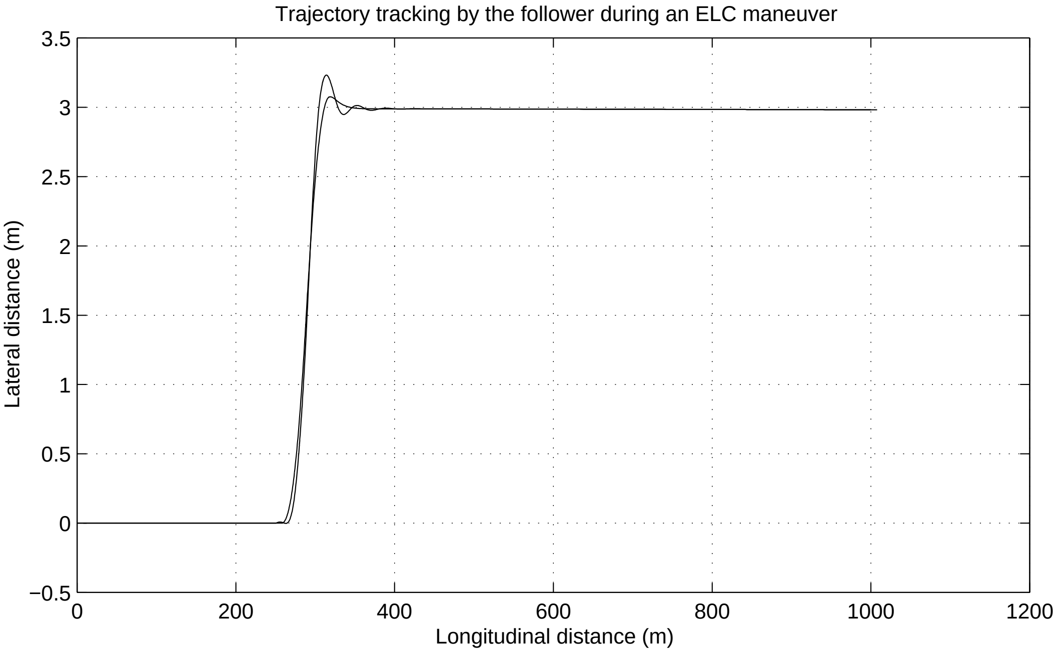

Figure 5: Trajectory of the lead and following vehicles for the ELC maneuver.

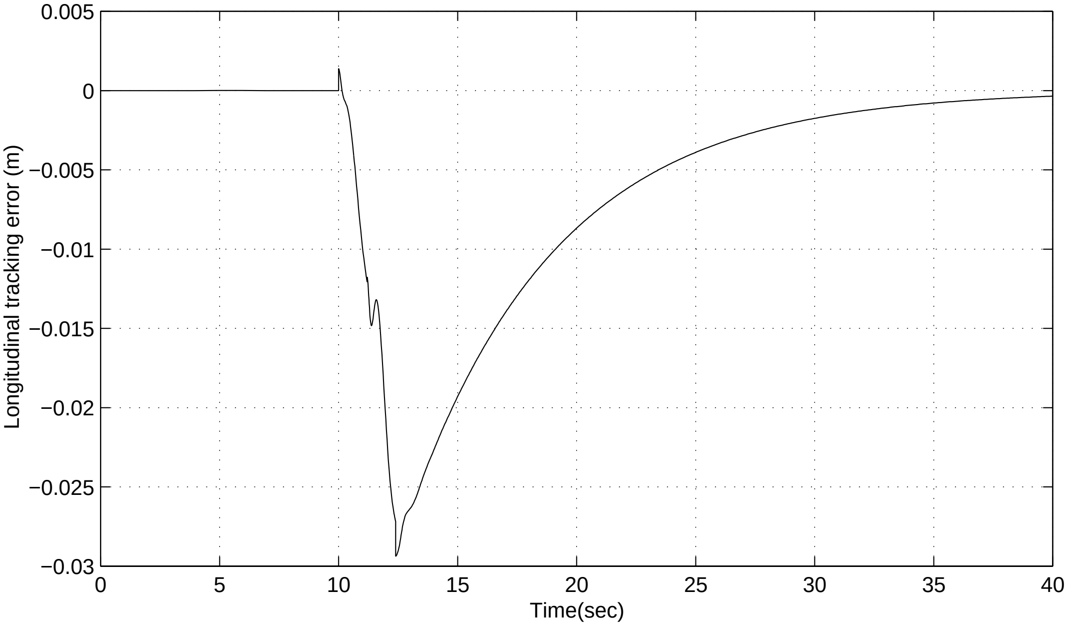

Figure 6: Longitudinal error in vehicle following during an ELC maneuver.

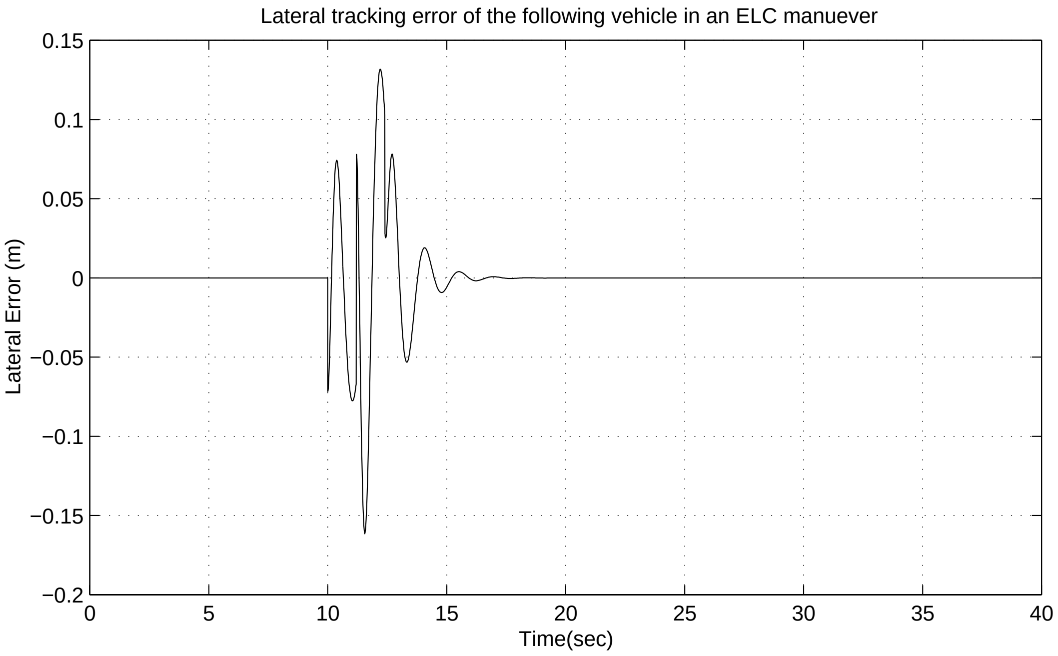

Figure 7: Lateral error in vehicle following during an ELC maneuver.

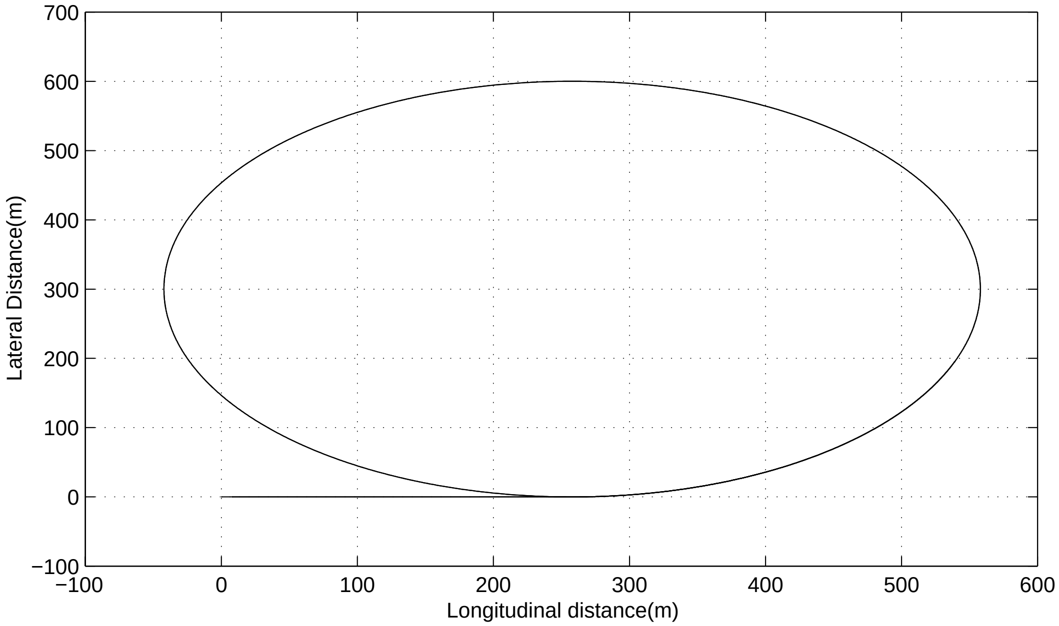

Figure 8: Trajectory of the lead and following vehicles when tracking a circular trajectory.

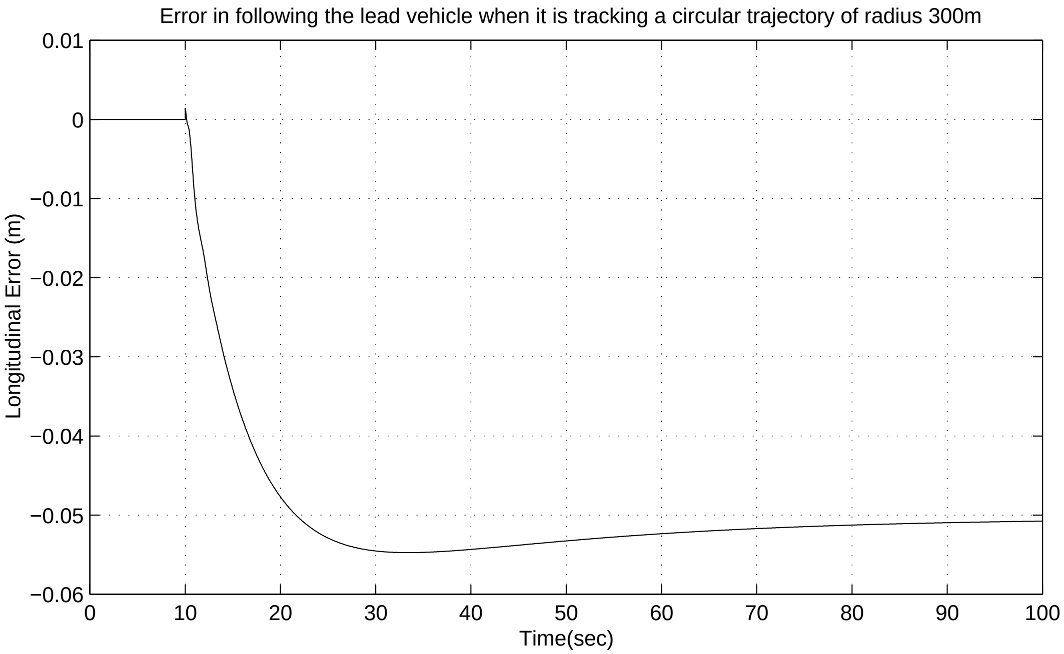

Figure 9: Longitudinal error in tracking a lead vehicle that traverses a circular trajectory.

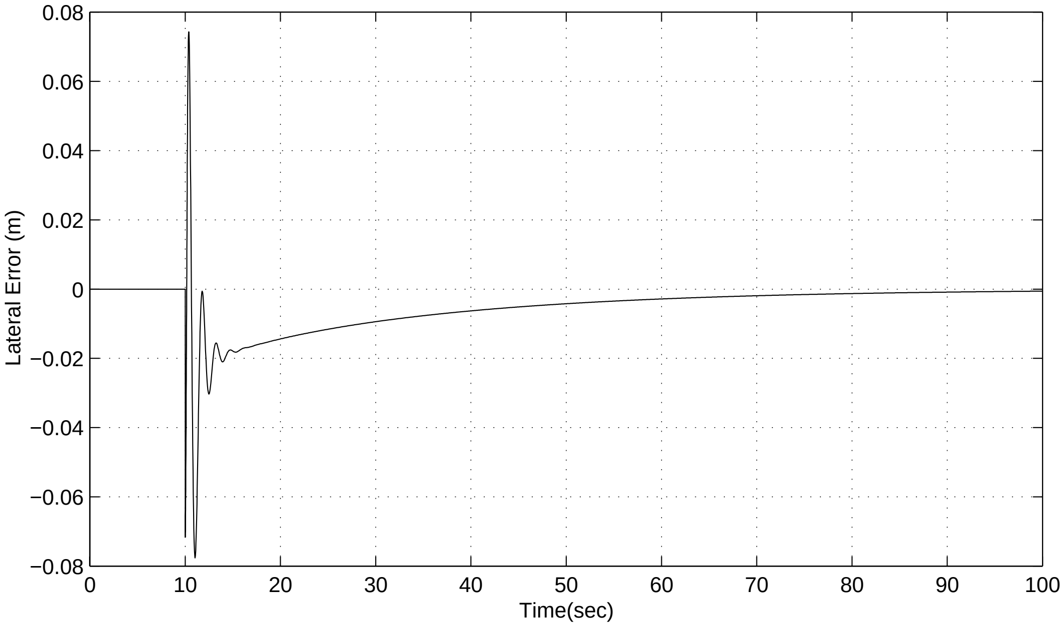

Figure 10: Lateral error in tracking a lead vehicle that traverses a circular trajectory.