IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: A Modi 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **148** 012021

IOP Conf. Series: Materials Science and Engineering **148** (2016) 012021 doi:10.1088/1757-899X/148/1/012021

Merging into platoons

A Modi[1]

[1]Warsaw University of Technology, SIMR, ul. Narbutta 84 , Warsaw ,Poland

E-mail: Abhishek.Modi@simr.pw.edu.pl

Abstract. Series of vehicles interacting with each other while driving in a straight line or while maneuvering is termed as a platoon of vehicles and known as platooning. This paper describes platooning and merging into platoons in general. The first part of this paper focuses on developing control strategies for automated driving. In this part a controller for longitudinal driving is designed and analysed. The second part of the paper focuses on the analysis of merging into a platoon on highways. This is done by validating experimental results by integrating a driver model with a single track bicycle model resulting in the calculation of merging path.

1. Introduction

Vehicle platooning or platooning in general can be described as a group of vehicles driving together where the interaction between these vehicles leads the driver to create a stable environment for driving. Platoon formation is the term used for a situation where two platoons (or a combination of a platoon and a vehicle or two vehicles) are combined into one platoon. An example of such a situation is illustrated in Figure 1 where vehicle number 4 accelerates in order to join the platoon (i.e. vehicles 1 to 3) [1].

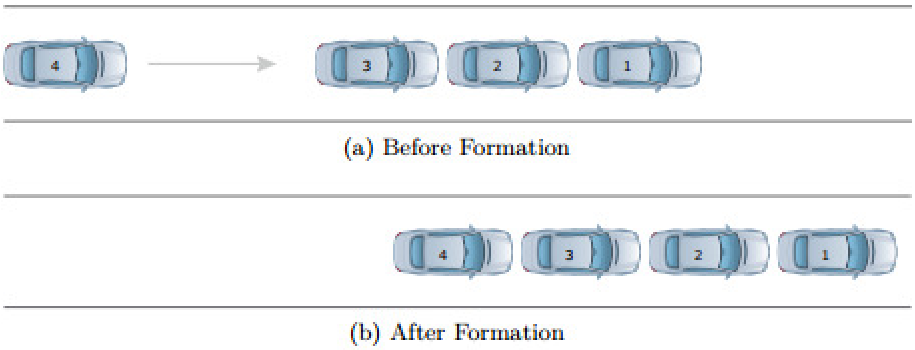

Figure 1. Platoon formation [1]

Traffic congestion is easily identified as a personal annoyance; however, the problem accumulates on a global scale. In 2015, the United States population alone spent 42 billion hours in traffic, wasting 10.7 billion gallons of gas and$78.2 billion (USD) [11]. There are over 600 million cars in operation in the world today, and by 2030, that number is projected to double [12]. With this influx of vehicles and the potential for increase in traffic congestion, it is important to look to a variety of social and technological solutions to help mitigate the problem. One unique solution to traffic management is the vehicle platoon.

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A platoon of driverless vehicles moves at high speeds along a dedicated lane of a highway. Each vehicle operates autonomously, accelerating or decelerating in response to local sensor measurements of velocity and position, as well as inter-vehicle communication, to maintain the platoon formation. Because the vehicles are automatically controlled, they can safely operate at higher speeds and closer inter-vehicle distances than human-driven vehicles, thus increasing the safety [14].

Parallel computing and a wide range of sensor networks are widely used and look to be the answer to the problem of vehicle platooning. Vehicle platoons help in the reduction of traffic congestion and have huge environmental benefits. A deep understanding of sensor accuracy will be required to perform intricate analysis which can lead us to the solution of vehicle platooning. From radars to magnets to radio communication systems, vehicle platooning systems have been found to be more efficient than most human drivers. Typical platooning systems consist of a longitudinal and lateral control system. These control systems are explained below.

2. Control strategies for platooning

For automated driving in a platoon, design of longitudinal and a lateral controller is imperative and hence there is the need for a robust control methodology to suitably deal with uncertain non-linear time-varying systems. Therefore, introduced is a new driving assistance algorithm in order to make the automated vehicles capable of cooperating and navigating through urban traffic. This leads eventually to a more effective organization of the urban transport. The key functionality is that a platoon, which is composed of a leader followed by vehicles, should be able to travel at a close distance in a single line. Hence, a longitudinal control scheme is proposed for the platooning functionality. The proposed control schemes are based on the use of cameras and laser sensors which are mounted on the front of every car preceding the leading car. There are 2 control strategies proposed, a first order sliding model and a second order sliding model. But only the first order sliding model (FOSM) will be discussed. This FOSM is particularly suitable to deal with the uncertain nonlinear time-varying systems. Yet, FOSM controllers generate a discontinuous control action which has the drawback of producing high frequency chattering, with the possibly excessive mechanical wear and passengers' discomfort, due to the propagated vibrations throughout the different subsystems of the controlled vehicle. This will be proven in the following discussion of the system.

2.1. Vehicle model

Consider a platoon comprising of n+ 1 number of identical vehicles, where n is the total number of vehicles. The model of this platoon is represented by a single track bicycle model as shown below [2].

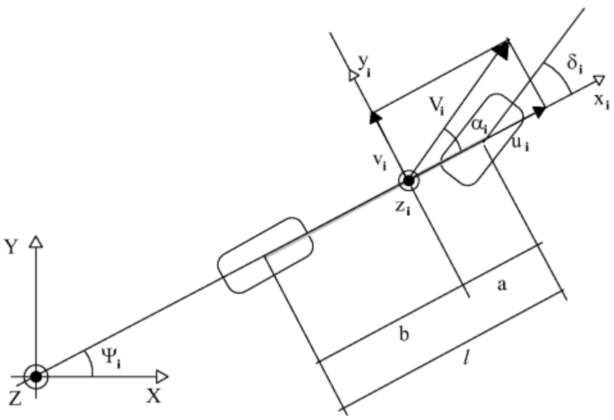

Figure 2. Bicycle model for sliding mode control [2]

Then, the model of the i-th vehicle is represented by the following equations [2],

$$\dot{u}_{\mathrm{i}} = \frac{1}{m}\left[mv_{\mathrm{i}}r_{\mathrm{i}} - mfg + u^2{}_{\mathrm{i}}(fK_1 - K_2) + C_f\left(\frac{v_{\mathrm{i}}+ar_{\mathrm{i}}}{u_{\mathrm{i}}}\right)\delta_{\mathrm{i}} + T_{\mathrm{i}}\right] \tag{1}$$

$$\dot{v}_{\mathrm{i}} = \frac{1}{m}\left[mu_{\mathrm{i}}r_{\mathrm{i}} - \left(c_f + c_r\right)\frac{v_{\mathrm{i}}}{u_{\mathrm{i}}} - \left(bc_r + ac_f\right)\frac{r_{\mathrm{i}}}{u_{\mathrm{i}}} + c_f\delta_{\mathrm{i}} + T_{\mathrm{i}}\delta_{\mathrm{i}}\right] \tag{2}$$

$$\dot{r}_{\mathrm{i}} = \frac{1}{Jz}\left[\left(bc_r - ac_f\right)\frac{v_{\mathrm{i}}}{u_{\mathrm{i}}} - \left(b^2c_r + a^2c_f\right)\frac{r_{\mathrm{i}}}{u_{\mathrm{i}}} + ac_f\delta_{\mathrm{i}} + aT_{\mathrm{i}}\delta_{\mathrm{i}}\right] \tag{3}$$

$$\dot{x}_{\mathrm{i}} = u_i\ \cos\varphi_{\mathrm{i}} - v_i \sin\varphi_i \tag{4}$$

$$\dot{y}_{\mathrm{i}} = u_{\mathrm{i}}\ \sin\varphi_{\mathrm{i}} + v_{\mathrm{i}}\cos\varphi_{\mathrm{i}} \tag{5}$$

$$\dot{\varphi}_{\mathrm{i}} = r_{\mathrm{i}} \tag{6}$$

Where, 'u_{i}', 'v_{i}' and 'r_{i}' are the longitudinal velocity, lateral velocity and the yaw rate respectively; 'x_{i}' and 'y_{i}' are the position coordinates in the centre of gravity. The 2 control signals are 'δ_{i}' the steering wheel angle and 'T_{i}' the traction force at the contact point between tire and road. 'm' is the mass of the vehicle and 'a', 'b' and 'l' are the distance from the front axle to the centre of gravity, distance of rear axle to centre of gravity and wheel base respectively. 'K_1' and 'K_2' are the control gains for front and rear respectively. For the control design a linearized decoupled model obtained from equation (1) to equation (6) is used.

The longitudinal dynamics is given by equation (7) [3],

$$u_{\mathrm{i}} = 2u_{0\mathrm{i}}(fK_1 - K_2)\frac{u_{\mathrm{i}}}{m} + \frac{T_{\mathrm{i}}}{m} \tag{7}$$

While the handling dynamics are given by equation (8),

$$\begin{bmatrix}\dot{v}_{\mathrm{i}}\\ \dot{r}_{\mathrm{i}}\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}v_{\mathrm{i}}\\ r_{\mathrm{i}}\end{bmatrix} + \begin{bmatrix}b_1\\ b_2\end{bmatrix}\delta_{\mathrm{i}} \tag{8}$$

Where,

$$a_{11} = -\frac{(C_f + C_r)}{m\cdot u_0}; \qquad a_{12} = \frac{(bC_r - aC_f)}{(m\cdot u_0) - u_0}; \qquad a_{21} = -\frac{(bC_r - aC_f)}{J_z\cdot u_0}; \qquad a_{22} = -\frac{(b^2C_r - a^2C_f)}{J_z\cdot u_0}$$

$$b_1 = \frac{C_f}{m}; \qquad b_2 = \frac{aC_f}{J_z}$$

'C_f' and 'C_r' are the cornering stiffness at the front and the rear tyres and 'J_z', the polar moment of inertia.

2.2. Longitudinal control design

To understand the design of the controller we must first look into the leader of the platoon. The leader of the platoon has an arbitrary speed and acceleration [4]. The chosen sliding variable for the 0th vehicle is the error between the reference speed u_{ref} *(t)* and the actual speed u_o *(t)* of the vehicle represented by equation (9) [5].

$$S_o(t) = u_{ref}(t) - u_o(t) \tag{9}$$

The FOSM is given by equation (10),

$$T_o(t) = m\left[\eta_0 sign\big(S_0(t)\big) + \dot{u_{ref}}(t)\right] - 2u_{oo}(fK_1 - K_2)u_o(t) \tag{10}$$

The objective of this longitudinal control of the ith vehicle is to maintain a safe distance from the preceding vehicle. Here the Constant Time-Headway (CTH) is used, which is used primarily to describe the following vehicles implying the vehicles behind the leader and also used frequently to design the adaptive cruise control (ACC) [6].

CTH policy is explained by equation (11),

$$S_{d_i}\big(u_i(t)\big) = S_{d_0} + hu_i(t) \tag{11}$$

Where S_{d0} is the distance between stopped vehicles, and h is the headway time. The spacing error is expressed by equation (12) [6],

$$e_i(t) = S_{di}\big(u_i(t)\big) - d_i(t) = S_{d0} + hu_i(t) - x_{(i-1)}(t) + x_i(t) \tag{12}$$

Where, d_i(t) is the longitudinal distance between the ith vehicle and the (i-1)th vehicle. This distance can be measured by a laser sensor mounted on the front of the vehicle. So in this case the sliding variable is the spacing error, i.e. S_i (t) = e_i(t). Then the control law to make the sliding variable vanish in finite time is given by equation (13).

$$T_i(t) = \frac{m}{h}\left[-\eta_i \sin(S_i(t)) - u_i(t) - u_{i-1}(t)\right] - 2u_{0i}(fK_1 - K_2)u_i(t) \tag{13}$$

This control law guarantees that the vehicles correctly keep the desired distance and that the system is string stable i.e., the spacing errors never amplify along the platoon [7].

2.3. Simulation with Simulink

The considered platoon is composed by a leader vehicle and 2 follower vehicles. For the simulation realistic parameter are used. The leader of the platoon starts travelling with u_{ref} .We can see the longitudinal error in Figure 3 and we can note that the error is steered to zero in finite time. From Figure 4 we can observe that the safe distance is remained and adapted with variation of velocities. That becomes even clearer in Figure 5 where the distance of the follower vehicles is depicted with respect to the leader. So at a velocity of 14 m/s we see the gap is 16 m that implies a safety distance at standstill S_{d0}= 2 m and a headway time h = 1s, 2 m + 1 s . 14 m/s = 16 m. Finally, the traction input is reported in Figure 6, it's obvious to see the signal is not a smooth one. Hence, it is concluded that the sliding mode control has very robust properties against disturbances, model inaccuracies and parameter variations. The FOSM generates a discontinuous signal which causes a high actuator stress resulting in vibrations induced through the vehicle. Therefore this FOSM should be improved.

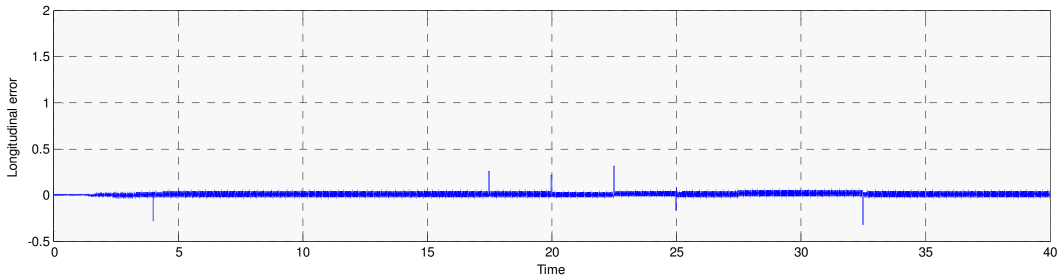

Figure 3. Longitudinal error FOSM.

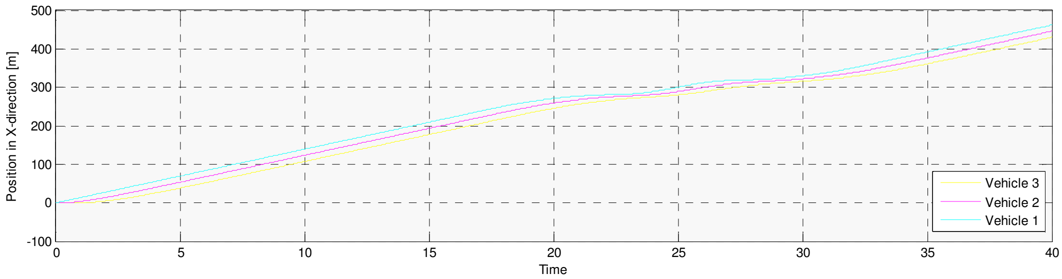

Figure 4. Position in X-direction FOSM.

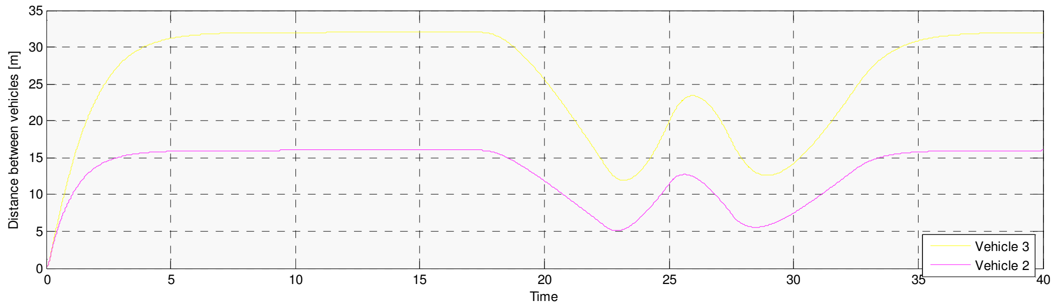

Figure 5. Distance between vehicles FOSM.

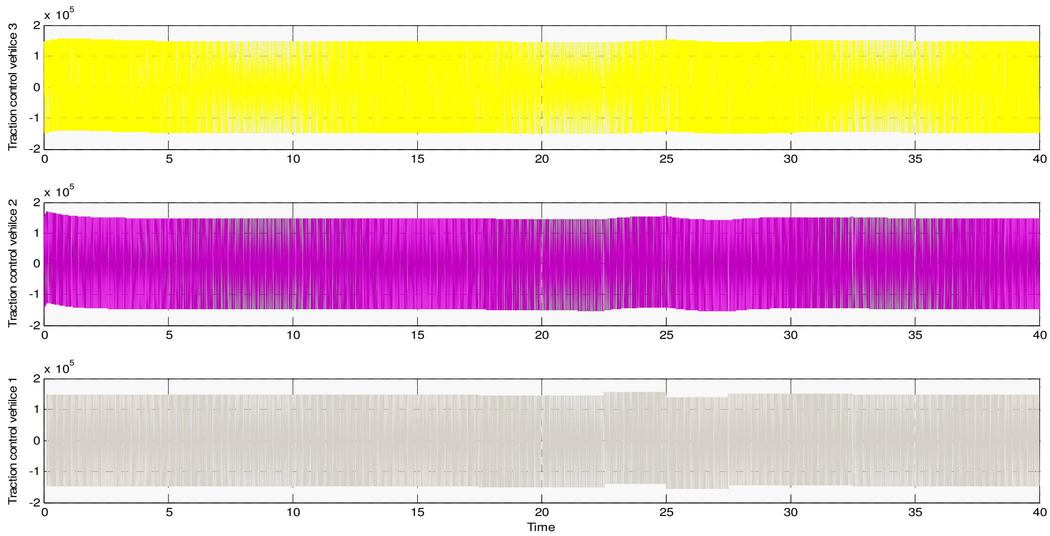

Figure 6. Traction control FOSM.

3. Experimental Validation of vehicle behaviour

The main objective of the experiment is to reconstruct a merging trajectory, more specific the merging that occurs when entering the highway. The car comes into the traffic from the right side, merging in between 2 cars driving in the lane. The merging manoeuvre was performed with three different longitudinal speeds and three different gap sizes to analyse the merging behaviour. The longitudinal speed during the merging process was maintained constant. Based on safety reasons and constant time-headway (CTH) policy the gap sizes were chosen as 25m. The desired constant speed was maintained by the front vehicle at 50km/hr. The second vehicle maintained the desired gap between the vehicles with the assistance of the view distance restriction on the front window. This distance was pre-set when standing still before each measurement and maintained constant during whole manoeuvre. For the objective evaluation and comparison of the results two different drivers were performing the merging manoeuvre. Both drivers repeated the measurement twice for each speed and each gap. For the purpose of validation a basic vehicle single track bicycle model integrated with a driver model was used which will be analysed in section 3.2.

3.1. Description of the experiment

The testing vehicle is BMW 320i equipped with the measurement system as described below. The coordinate system represented by axis X, Y and Z is pictured in Figure 1. The Z-axis points upwards. Acceleration sensors are mounted in the center of gravity and measure in X, Y and Z direction. Yaw rate sensor mounted is mounted at the Center of Gravity and measures angular velocity of the vehicle in degrees per second. Steering wheel sensor measures the steering angle and the steering moment which a driver applies.

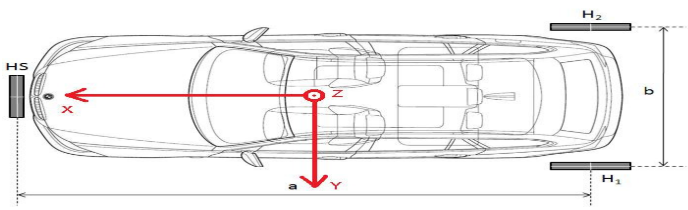

Figure 7. Sensor Position W.R.T Co-ordinate System [9].

The experiment was performed on Lelystad testing track consisted of two curves with constant radius R = 160 m and two straight parts with the length L=720 m. The speeds for merging were set to 50, 60 and 70 km/h in order not to exceed certain values of lateral acceleration since the tire behaviour is linear under $a_y < 0.4g$.The three sensors (HS, H1 and H2) measure the differences in height therefore the pitch and roll movements can be determined. The front sensor measures besides the longitudinal and lateral speeds. Distance of the sensor HS from the centre of gravity was measured as 2416 mm. The testing car was during test equipped with Vredestein Quatrac 3 225/45/17 tires. The Cornering stiffness on the front and rear axle C1 and C2 respectively is, 74000 N/deg and 128 000 N/deg respectively. The mass of the vehicle 'm' is 1650 kg and the wheelbase 'l' is 2.76 m. Yaw inertia of the vehicle 'J_z' is calculated by equation (14) which provides sufficiently accurate results for the simulation model.

$$\boldsymbol{J_z = m \times a \times b} \tag{14}$$

Where, 'a' is the distance from front axle to centre of gravity and 'b' is the distance from rear axle to centre of gravity.

3.2. Simulation of merging using an integrated single-track vehicle - driver model

For the simulation of vehicle behaviour, a simplified linear bicycle model and a driver model has been used which is represented in Figure 8 and Figure 9 respectively. This model provides relatively accurate results under non-extreme conditions. The following equations have been used to build the simulation model [9].

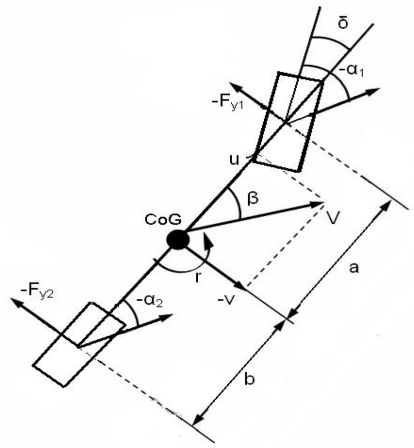

Figure 8. Bicycle Model [10]

$$m.a_y = m.(v + u.r) = F_{y1} + F_{y2} = -C_1.\alpha_1 - C_2.\alpha_2 \quad (15)$$

$$J_z.r = F_{y1}.a - F_{y2}.b \quad (16)$$

$$\alpha_1 = (v + ra)/u - \delta \quad (17)$$

$$\alpha_2 = (v - r.b)/u - \delta \quad (18)$$

Where *'m'* is vehicle mass, *'a_y'* is lateral acceleration, '*v*' is lateral speed, '*u*' is longitudinal speed, *'r'* is yaw rate, *'F_{y1}'* and '*F_{y2}*' are lateral forces, *'C_1'* and '*C_2*' are cornering stiffness's at the front and rear axle respectively, 'a' and 'b' are the distances from the front and rear axle to the centre of gravity , 'α_1' and 'α_2' are slip angles at front and rear respectively, δ is steering angle and J_z is yaw moment of inertia [9].

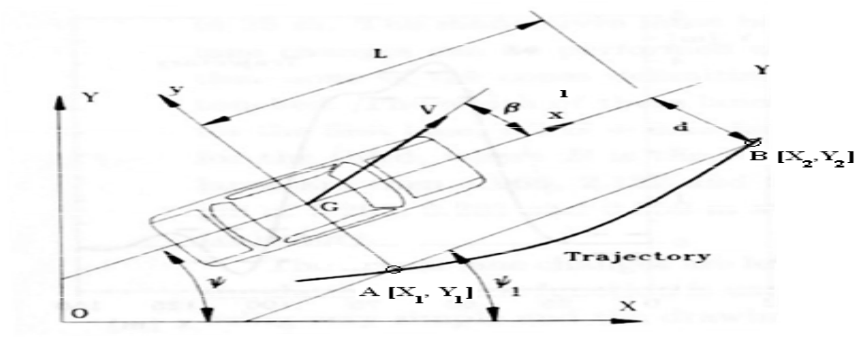

Figure 9. Driver Model [11].

For simulation a driver model represented by Figure 9 with a sort of a predictive behaviour from was used [10]. This driver model describes the human behaviour in a very simplified way but it gives satisfactory results in many cases. In the time domain the model is described by equation (19).

$$\tau\dot{\delta}(t)+\delta(t)=-K_d\left[\psi(t)-\psi_1(t)+\frac{y(t)}{L}\right] \tag{19}$$

Where, 'τ'- time delay of the driver, '$\delta(t)$' is the steering angle, 'K_d' is the gain of the driver, 'φ' is the yaw angle of the vehicle explained as the angle between X-axis and a line passing through two points of the trajectory at a preview distance 'L', 'y' is the lateral displacement of the vehicle .

For the simulation of the merging behaviour the measurement data with the velocity 50 km/h, the gap of 25 m and the driver 1was considered. Before the simulation the driver parameters were chosen. The common values for the time delay, the gain and the preview distance are 0.2 s, 0.3 and 25 m respectively [10]. For our simulation we assumed the value of the time delay of the driver to be 0.2 s the value of the gain to be 0.45 and the value of the preview distance to be 15 m because the driver has to look ahead in to merging into a gap of 25 m. Figure 10 depicts three curves representing the path. The red curve is the measured data of the position of the vehicle obtained from the GPS system, the blue is the input to the driver model which is definition of the path which the driver should follow and the green curve is the path from the vehicle model.

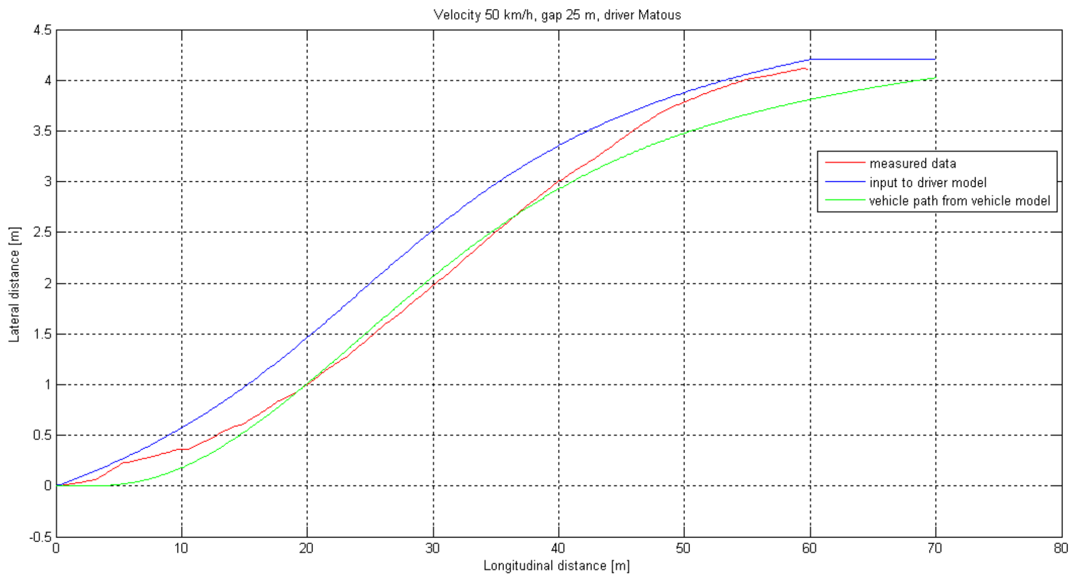

Figure 10. Simulation of the merging task using the driver model.

The results show that the driver model follows the input path with a certain delay, which is significant at the Beginning of the merging. In the middle part the simulated path is very similar to the driven one. In the last part the simulated path is differing more from the real one and it is not that quickly approaching the straight part of the input curve.

4. Conclusion

Our understanding and by comparing theoretical results and performance results we can gain a lot of valuable information into the development of control strategies for vehicle platoon systems. Firstly we conclude that a control strategy was developed which led us to the understanding of the error and therefore improvements can be made on the design by including a lateral controller alongside the longitudinal controller. Secondly, the understanding of the integrated vehicle–driver model led us to understanding merging behaviour at different speeds for different driver types. By varying the gain and time delay one can comprehend the age of the driver and the reaction times as well. There are many

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other issues that must be addressed to develop a complete platoon solution, including emergency actions such as obstacle avoidance and accommodation for vehicles that exit from the platoon. The investigation of strategies for these events is the subject of future work.

Appendix A

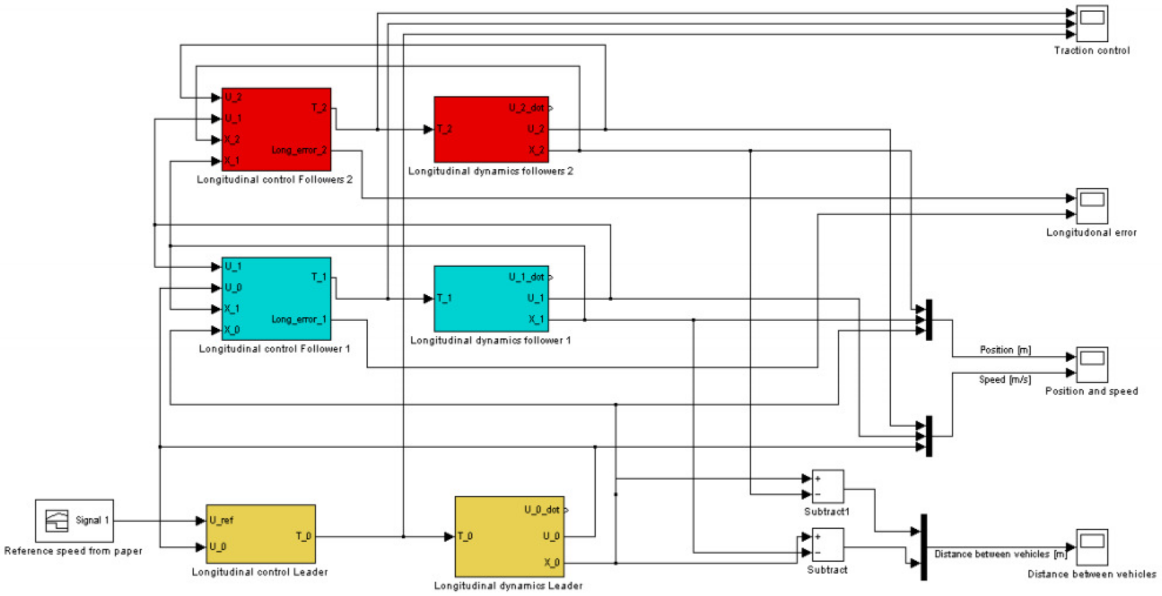

Figure A 1. Simulink Model of the longitudinal controller.

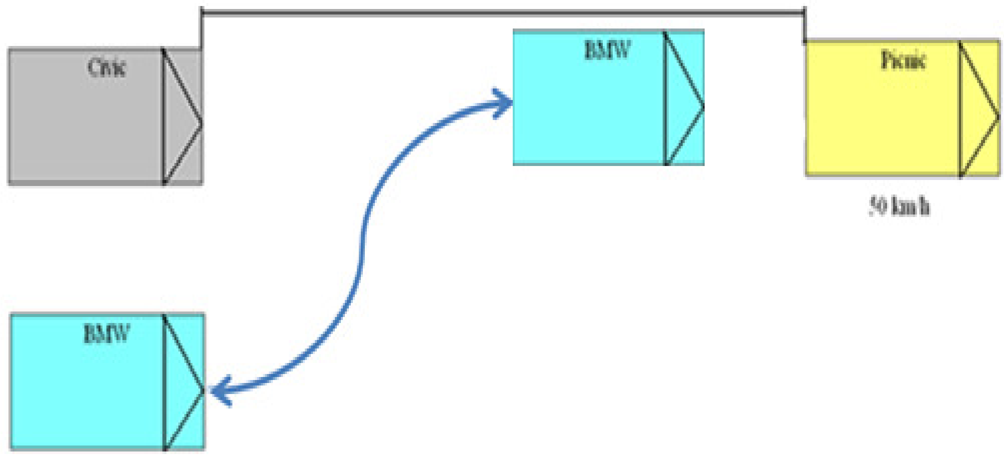

Figure A 2. Outlay of merging experiment.

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