Model Predictive Control for Cooperative Insertion or Exit of a Vehicle in a Platoon

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Abstract: Vehicle platooning has a central role in the road management by self-driving or autonomous vehicles (AVs). The main issues in this context are the agreement of communication and control instructions among vehicles in order to maintain a safe inter vehicular distance and a specific desired speed according to the planned travel. This paper proposes a longitudinal Model Predictive Control (MPC) to carry out vehicles' safe manoeuvres to let an external vehicle to be inserted in the platoon or alternatively to let a vehicle of the platoon to leave it. The control strategy considers a cooperative approach where the leader coordinates the exchange of information with the followers and with the vehicle which notifies its intent to enter (or to leave) the platoon. All the vehicles are equipped with technologies to monitor their own state in terms of position and speed while the leader receives, elaborates the data and, by the control process, distributes the optimal control decisions to the whole platoon. The proposed control algorithm minimizes the tractive forces and the square deviations of positions and speeds in respect to predefined references. The MPC longitudinal control of the vehicle, based on a non-linear cinematic model, provides the optimal control values related to the torques to be applied to vehicles' acceleration or deceleration in order to perform safe entering and exiting manoeuvring. The results of the simulations demonstrate the effectiveness of the proposed approach with reduced execution time.

1 INTRODUCTION

According to literature, an autonomous vehicle (AV) is defined as a car able to acquire data and information about the neighbour environment and it may drive for a prolonged period without human involvement.

To collect the progresses in AV research, SAE the Automotive Standardization Organization published the "SAE Information report" that formally defines six levels of automation for AV, ranging from Level 0 (fully manual) to Level 5 (fully autonomous) (SAE, 2014).

The possibility to perform automated tasks heavily depends on the capability to get enough correct and relevant data about the state of the surroundings. In the context of AV, one of the main challenges is the possibility to accurately acquire information about the environment and correctly represent the external conditions in which the vehicle operates (Provine et al., 2004).

In order to enhance the safety and the efficiency of the road traffic management, the AV may assume a cooperative driving set up. In this case, the AVs may proceed on the road forming a platoon. The AV platooning is a research area of the transportation field, which concerns the strategies to manage a group of vehicles travelling on the roadway and keeping a constant inter-distance among vehicles with a specific shared speed dictated by the safety and traffic condition. Due to those assumptions, the main important components which allow the implementation of a vehicle platoon is the adoption of the Adaptive Cruise Control (ACC), the use of reliable vehicle-to-vehicle (V2V) communication systems, and intelligent control strategies. The ACC has the function to maintain a constant speed and the

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control of the inter-distance between vehicles (Zhang, et al., 2020). The V2V allows communication among close vehicles according to the IEEE 802.11p standard in order to share relevant information about external environment and control (Gonçalves et al., 2020).

In addition, in real time, the environmental perception by the AV depends on the different kind of sensors the vehicle is equipped on. Key components are the sensors which allow to gain data and, by software elaboration, to extract crucial information about lanes marking, traffic signs, identifications of other vehicle or obstacles on the path (Watzenig D. and Horn M., 2017). In literature, different intelligent control strategies have been studied to manage the platoon behaviour. Recently, special interest has been dedicated to platooning control when a vehicle performs a "split" or "join" manoeuvres to exit from or merge a platoon (Hall, R., & Chin, C., 2005).

Rajamani et al. (2000) proposed the design and the implementation of lateral and longitudinal control systems, which work independently, to manage the request of a vehicle which makes an automated lane change to exit or enter in the platoon.

Lu et al. (2003) considered longitudinal control problem for automated vehicle platoon merging with a model based on the speed of the leading vehicle in the main lane. Graffione at al, (2020) implemented a longitudinal control model to optimize the safe inter vehicular distance among vehicle by operating on the torques to make positions and speeds close to reference values

Hussain et al. (2020) proposed a cooperative Nonlinear Model Predictive Control (NMPC)-based optimization method for implementing a highway lane merge of two connected autonomous vehicles. The authors considered three different scenarios of merging: the presence of a parallel acceleration lane, a tapered acceleration lane, and an auxiliary cloverleaf lane.

In Contet et al. (2007), the authors developed a multiagent based approach for the vehicle platooning problem with the possibility to merge new vehicle at the end of the platoon or exit from the train. In the proposed approach, each vehicle, implemented as reactive agent, relates only with the preceding one in the platoon.

In Amoozadeh et al., (2015), the authors developed a platoon management protocols, based on V2V communication combined with longitudinal control system, referred to specific operations, such as vehicle entry, platoon leader leave, and follower leave. The control law is computed by the leader which transmits to the followers the throttle and/or brake commands required to track the desired acceleration.

In this paper, the AV cooperative platoon-driving problem is tackled focusing on the manoeuvring for a vehicle which merges or leaves an existing vehicle platoon coming from an adjacent lane according to the longitudinal control. The main contribution of this paper refers to the specific operations, which it considers in the platooning management and the application of the MPC approach in order to apply the state feedback control law. Besides, the objective function considers different components associated to the position: the speed, the safe inter-vehicular distance among vehicles and to the optimal tractive forces to be applied in order to avoid collision.

2 LONGITUDINAL CONTROL

The proposed control model aims at minimizing the square divergence among the current value for position r and the speed $\dot{r}$ in respect to the desired reference values a priori defined in order to maintain the safe intra-vehicular distance among vehicles in the platoon. The cost function J consists of quadratic terms with the goal to minimize the use of the tractive and brake force. Thus, this approach also implies to decrease the fuel consumption by solving the optimization problem (2) at each time instant. The related cost function J is defined as in (1).

$$
\begin{aligned}
J = \sum_{i=1}^{M-1} \omega_1\left(x_N^{(i)} - x_N^{(i-1)} - L_k^{(i)}\right)^2 \\
+ \omega_2\left(x_N^{(1)} - x_N^{(i)} - D_k^{(i)}\right)^2 \\
+ \omega_3\left(x_N^{(i)} - r_N^i\right)^2 \\
+ \omega_4\left(\dot{x}_N^{(i)} - \dot{r}_N^i\right)^2 \\
+ \sum_{k=0}^{N-1}\sum_{i=1}^{M-1} \omega_5\left(x_k^{(i)} - x_k^{(i-1)} \right. \\
\left. - L_k^{(i)}\right)^2 \\
+ \omega_6\left(x_k^{(1)} - x_k^{(i)} - D_k^{(i)}\right)^2 \\
+ \omega_7\left(x_k^{(i)} - r_k^i\right)^2 \\
+ \omega_8\left(\dot{x}_k^{(i)} - \dot{r}_k^i\right)^2 \\
+ \omega_9 \Delta\tau_k^{(i)2}
\end{aligned}
\tag{1}
$$

In eq. (1), the objective function is minimized for the overall fleet which consists in *M* vehicles in *N* time intervals. The terms $x_k^{(i)}$ and $\dot{x}_k^{(i)}$ indicate the longitudinal position and the speed for the *i-th* vehicle, with *i=1..M*, at time k, with *k=1..N*. The objective function considers the control application in the last time interval in the first four terms while, in the last four terms, it applies the control to the other time intervals. In (1), $L_k^{(i)}$ and $D_k^{(i)}$ are respectively the desired safety distance between the vehicles i and $i+1$ and the distance of the vehicle i from the leader. The square deviation of distance among vehicles is minimized in the first and fifth addenda in (1); the square error in the distance among the leader of the platoon and the *i-th* vehicle appear in second and in the sixth term for the last time internal *N*. Also, the deviation in respect to the reference position and speed are minimized, respectively, in the third and fourth terms for the last time interval, in the seventh and eighth terms for the time horizon. The last term is related to the minimization of the control variable $\tau_k^{(i)}$ associated to the torque applied to the vehicle *i-th* at the time interval *k-th.*

The weight parameters ω_i, *i*=1,..,9 allow to weight the different component in the objective function. The longitudinal model considers the forces involved during the acceleration and deceleration of the vehicle. Both forces are represented by the same control variable τ (torque) that can be both negative (brake) and positive (tractive).

The model is defined as follows:

$$m\ddot{x} = \frac{T_n}{r_w}\tau - \frac{1}{2}\rho C_{dA}\dot{x}^2 - (a - b\dot{x})m - mgsin(\theta) \tag{2}$$

where

- T_n is the number of tractive/braking wheels
- r_w is the wheel radius
- C_{dA} is aerodynamic drag coefficient for the frontal area A of the vehicle
- ρ is the air density [1.23 $\frac{Kg}{m^3}$]
- a and b are parameters for the rolling resistance defined as $R_x = (a + bV_x)m$ where V_x is the longitudinal speed
- m is the vehicle mass
- g is the gravity force
- θ is the road pitch

The equation (2) can be rewritten in matrix form with the state $X = [x \quad \dot{x}]^T$.

Given the equilibrium point $X_{e,k} = [x_{e,k} \quad \dot{x}_{e,k}]^T$ considered in the previous time instant, computing the Jacobian matrix and evaluating them at the point $X_{e,k}$, the following linearization of the system may be obtained:

$$\begin{bmatrix} x_{k+1} \\ \dot{x}_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & T_s \\ 0 & 1 - T_s b - \frac{T_s \rho C_{dA}}{m}\dot{x}_{e,k} \end{bmatrix} \begin{bmatrix} x_k \\ \dot{x}_k \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{T_s T_n}{m r_w} \end{bmatrix} \tau_k \tag{3}$$

The overall platoon system is

$$X_{k+1} = \begin{bmatrix} x_{k+1}^{(1)} \\ \dot{x}_{k+1}^{(1)} \\ x_{k+1}^{(2)} \\ \dot{x}_{k+1}^{(2)} \\ \vdots \\ x_{k+1}^{(M)} \\ \dot{x}_{k+1}^{(M)} \end{bmatrix} = \underbrace{\begin{bmatrix} A_k^{(1)} & & \\ & \ddots & \\ & & A_k^{(M)} \end{bmatrix}}_{\bar{A}} X_k + \underbrace{\begin{bmatrix} B_k^{(1)} & & \\ & \ddots & \\ & & B_k^{(M)} \end{bmatrix}}_{\bar{B}} \begin{bmatrix} \tau_k^{(1)} \\ \tau_k^{(2)} \\ \vdots \\ \tau_k^{(M)} \end{bmatrix} \tag{4}$$

The finite optimal control problem is defined as follows:

$$\min_{\Delta U_k} J(X_k, \Delta U_k) \tag{5}$$

$$s.t. \quad X_{k+1} = \bar{A}X_k + \bar{B}\Delta U_k \tag{5a}$$

$$Y_k = \bar{C}X_k \tag{5b}$$

$$k = k, \dots, k+N$$

$$\Delta U_{min,k} \leq \Delta U_k \leq \Delta U_{max,k} \tag{5c}$$

$$k = k, \dots, k+N_c$$

$$U_{min,k} \leq U_k \leq U_{max,k} \tag{5d}$$

$$k = k, \dots, k+N_c$$

$$X_{min,k} \leq X_k \leq X_{max,k} \tag{5e}$$

$$k = k, \dots, k+N_c$$

where the cost function $J(X_k, \Delta U_k)$ in (5) is the quadratic cost function (1) and the vector ΔU_k contains the torque $\tau_k^{(i)}$ for each vehicle *i*-th at the instant *k*-th.

The constraints (5a) and (5b) linearize the platoon model in (3) at each time step.

The constraints (5c) - (5e) give more efficiency to the system imposing minimum and maximum values for tractive/brake forces to be applied to each vehicle. These constraints may be also changed during the simulation according to the platoon state to increase safety and versatility.

As stated before, the cost function (1) consider the distance between two consecutive vehicles and from the leader to ensure safety space interval. In order to improve this aspect, a three-zone policy is implemented, which consists of a MPC approach that depends on the vehicle distances. The three-zone policy is usually used also in the rail context for the European Rail Traffic Management System (ERTMS) (Bersani at al., 2015).

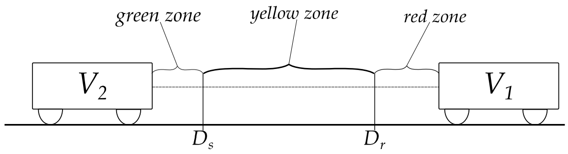

Figure 1: Three-zones distance. The space between two vehicles is divided into three areas: green, yellow and red. Each one consists in a different controller approaches.

The green zone represents a safe distance according to the current speed to avoid collision among vehicles running the roadway. The yellow zone identifies a transition zone where the distance has to be accurately monitored in order to prevent accidents. Finally, the red zone means that two consecutive vehicles are travelling too close and they have to modify their speed in order to establish safe condition. In the green zone, the distance $D_s^{(i)}$ for the vehicle *i-th* is computed as:

$$D_s^{(i)} = \left(\frac{\dot{x}^{(i)}}{10}\right)^2 + S \qquad (6)$$

where $\dot{x}^{(i)}$represents the speed of the vehicle and S is a fixed distance from the front vehicle even when the platoon stops. Equation (6) is a simple way to compute the distance that lets the vehicle safely decelerate. Moreover, it overestimates the safety distance for higher speeds in respect to other standard techniques such as the "2 seconds driving rule". This latter considers that a vehicle should ideally stay at least two seconds behind the vehicle which precedes and it is recognized as a valid threshold to estimate the safety distance (Uribe, D., & Cuan, E., 2018). This approach does not take into account fuel consumption, which however may be enhanced by reducing the distance between cars which favours aerodynamic interaction. On the other hand, Equation (6) guarantees road safety and limited consumption thanks to the MPC which optimizes the torque forces. Besides the safety distance criterion may be varied according to the platoon goal.

In the red zone, the distance $D_r^{(i)}$ is computed as:

$$D_r^{(i)} = 0.25 * D_s^{(i)} + S \qquad (7)$$

and it depends on $D_s^{(i)}$ in (6).

3 MODEL PREDICTIVE CONTROL TO MERGE OR EXIT THE PLATOON

The MPC approach adopts a receding horizon approach. For each sample time, the longitudinal control model defines the optimal matrices that describe the state of the overall system computing the safety distance, speed, and acceleration. In the platooning standard configuration, according to the measurements received by sensors allocated to the vehicles, the MPC centralized control, managed by the leader, check the inter vehicular distances (*checkDistance*) and compute the related control values to be sent to the vehicles' actuators (*SendToVehicle)* in order to maintain the correct position and speed in the string formation.

The following schema (figure 2.a) represents the diagram flow of the control system. In the proposed approach, two different events may happen. In the first event, the leader may accept the insertion of a new vehicle, which notifies its intention to merge the platoon. In the second event, the leader may allow a vehicle to leave the platoon.

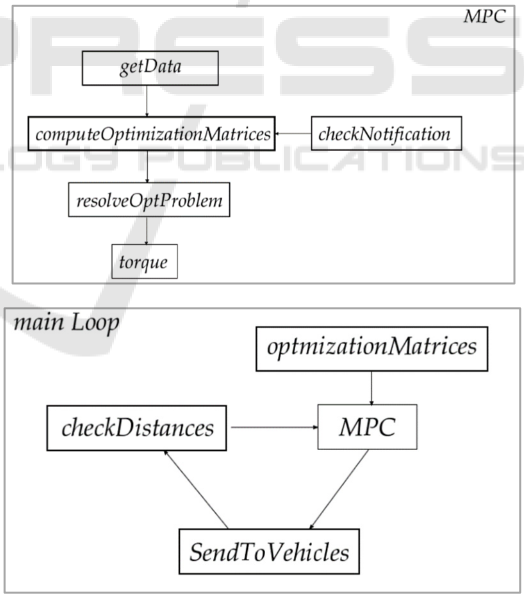

Figure 2: MPC control block diagram. In the top (a), the MainLoop is relative the basic cyclic operations of data acquisition – MPC controller – control application. In the bottom (b), the MPC block specifies that if the controller receive a specific message *checkNotification*, it will apply some changes to the MPC constraints.

In this case, (see figure 2.b), after the notification of the incoming event, the controller, by the MPC, has to recompute the control values related to the torques, for each time interval, induced by the longitudinal control, in order to assure the correct movements of the vehicles and to permit the new variations in the platoon configuration.

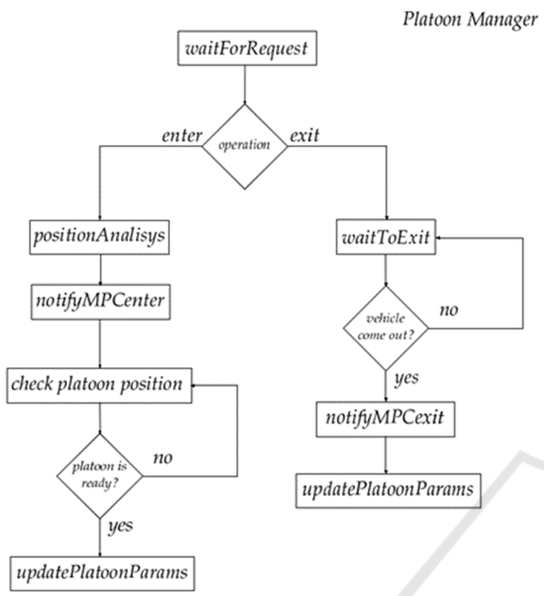

Figure 3: Control block diagram for merging or exiting requests.

3.1 Merge Manoeuvre

The merge manoeuvre is carried out in three phases: Request, Insert, Merge. Each phase consists of a bidirectional communication between the approaching vehicle and the platoon leader and among the leader and the followers. A block diagram that represents the operation flow is shown in the left side of the Figure 3.

During this manoeuvre, the new vehicle I is supposed to be equipped with appropriate sensors to detect obstacles, check its speed and position. However, if the vehicle is human-driven, it is supposed that the driver has a console that communicate to the platoon leader its purpose to be included in the platoon.

In the first phase, the new vehicle I which is approaching the platoon, sends a request to the leading vehicle (*waitForRequest*) to enter the platoon also transmitting information about its state such as speed and position. Then, it waits the response while remaining in the adjacent lane. Once the leader receives the request and the data, it decides where insert the vehicle I in the platoon (*positionAnalisys*) by analysing the position and speed of all followers. According to the acquired data, the leader communicates the new safety distances, generated by the MPC controller (*notifyMPCenter*) to two selected followers which have to admit the new vehicle. The distance requested to allow the joint is computed by doubling the safety distance D_S (equation (5)).

When the correct distance among the two vehicles which have to admit a new element is reached, the leader sends a signal to the waiting vehicle I and confirms the permission. The distance for the entering manoeuvre is allowed only if it differs from D_S for a limited error whose threshold is checked by the *checkPlatoonPosition* routine.

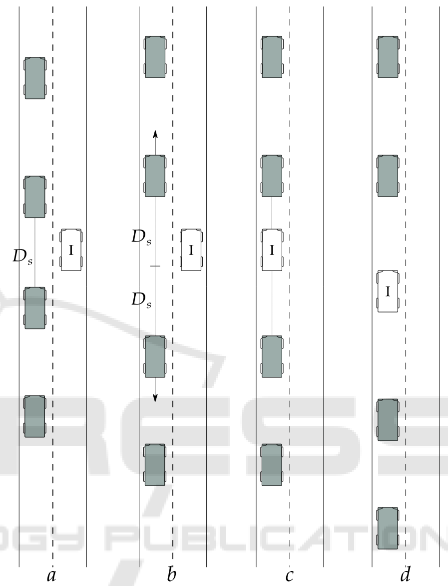

Figure 4: The three phases of the merge manoeuvre. A new vehicle approach the platoon (lane 4a), Request phase (lane 4b), Insert phase (lane 4c), Merge phase (lane 4d). The white vehicle "*I*" merges the platoon.

In the third phase, the platoon modifies its configuration according to the new parameters generated by the controller after the Request phase.

Once the vehicle I is included in the formation, it communicates to the leader that the manoeuvre was successfully and it's ready to follow the platoon rules. Thus, the system will update the platoon parameters (*updatePlatoonParams*) such as the number of vehicles, their position and the optimization matrices. At the end of this phase (Merge phase), the vehicle I is fully included in the platoon and in the centralized control of the leading vehicle. In case the vehicle I is too close to a vehicle, *checkDistances* (figure 2.a) will detect it and communicate to the MPC to take the appropriate actions according to the safety green zone (figure 1).

3.2 Exit Manoeuvre

In the exit manoeuvre, a member of the platoon notifies its desire to leave the formation and to continue on its own different path. The block diagram, which describes this phase, is shown in the right side of the figure 3. As in the Merge manoeuvre, it is supposed that the vehicle *O* has a lateral control that moves the vehicle away from the platoon (the architecture of the lateral control is not shown in this paper). Moreover, once it is disconnected from the leader, the vehicle will use its control system or gives the full control to the driver to continue its travel.

The first step of the algorithm consists in sending a request to the leader, asking to exit from the formation and from the leader control algorithm (*waitForRequest*). When the vehicle *O* has changed lane (*waitToExit*), it notifies it to the leader (Exit phase). The leader will proceed to update the MPC parameters to disconnect the vehicle from the control (*notifyMPCexit* and *updatePlatoonParams*).

In the last phase, the vehicle is disconnected from the platoon and the MPC of the platoon compute the correct control values to its members in order to define the new right position, speed and safe distance.

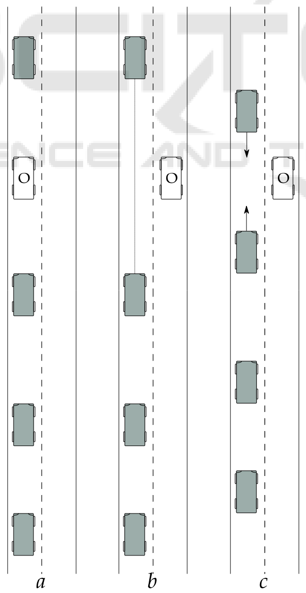

Figure 5: The three phases of the Exit manoeuvre. Request phase (lane 5a), Exit phase (lane 5b), Platoon disconnection (lane 5c). The white vehicle "*O*" leaves the platoon.

4 SIMULATIONS

The case study refers to an initial platoon of four vehicles which cover a rectilinear path with position and speed reference well defined. The values related to initial states of the platoon vehicles are displayed in the Table 1. Simulations have been performed using MATLAB environment.

Table 1: Initial state value for position and speed for the platoon vehicles.

Leader	Position: $30\ m$ Speed: $10\ m/s$
Follower 1	Position: $20\ m$ Speed: $10\ m/s$
Follower 2	Position: $15\ m$ Speed: $10\ m/s$
Follower 3	Position: $0\ m$ Speed: $10\ m/s$

After some instants from the simulation start, a new vehicle *I* approaches the platoon and asks to enter in the formation. The merge phase for the vehicle *I* will be realized by the algorithm described in the section 3.1.

After the merging phase of the vehicle *I*, the vehicle follower 1, called *O,* will ask to exit the platoon and it will use the Exit manoeuvre procedure introduced in the section 3.2.

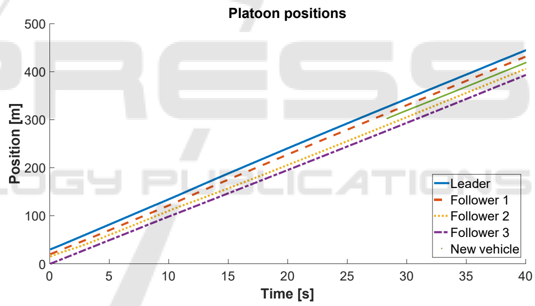

Figure 6: Platoon position during the Merge Manoeuvre.

Figure 6 shows the longitudinal positions of the vehicles that are in the platoon. During the merge and exit manoeuvres, the MPC controller has to satisfy various constraints. As stated before, the MPC parameters change in function of the zones where the vehicles are located. This modification in the platoon is subjected to the constraints related to the upper and lower bound for the change rates of the torque.

Table 2: Upper and lower bound for control variables (eq.5c).

Green Zone	$\Delta U_{max} = 25\ N/m$	$\Delta U_{min} = -25\ N/m$
Yellow zone	$\Delta U_{max} = 15\ N/m$	$\Delta U_{min} = -35\ N/m$
Red Zone	$\Delta U_{max} = -25\ N/m$	$\Delta U_{min} = -60\ N/m$

From Figure 6, it is possible to recognize each phase of the Merge Manoeuvre.

In the time interval [10, 25] the platoon creates space for the new vehicle, in [25, 30] the new vehicle enters the platoon between follower 1 and 2 and, from 30th interval, the vehicle *I* is fully included in the MPC controller.

Besides, it is possible to note that, due to the initial condition, the follower 2 brakes to increase the distance from the predecessor since it was in the red zone and, thanks to the centralized control, the last follower does not accelerate and waits for the follower 2 to fill the distances.

In the same time intervals, the Figure 8 and 9 represent the speeds values. They show how each vehicle adapts its speed to maintain the required distance (Figure 8).

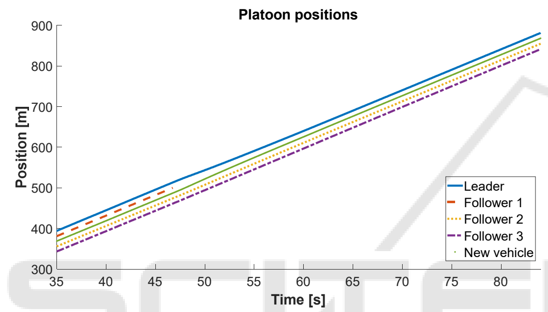

Figure 7: Platoon during the Exit Manoeuvre. Around 47 seconds, the follower 1 exit the platoon.

On the other hand, in Figure 7, during the exiting phase, the platoon configuration is shown. Around second 45, the follower 2 leaves the platoon. In 15 s, the rear portion of the platoon recomposes the formation assessing the correct position/speed to fill the space generated by the exiting vehicle.

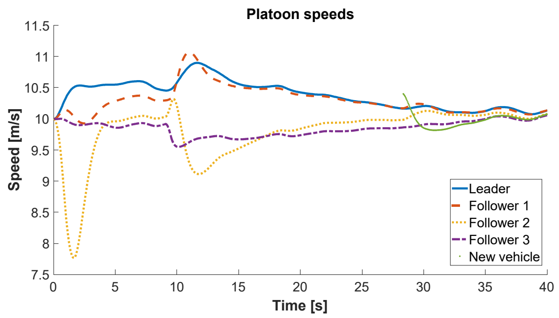

Figure 8: Platoon speeds during the Merge Manoeuvre.

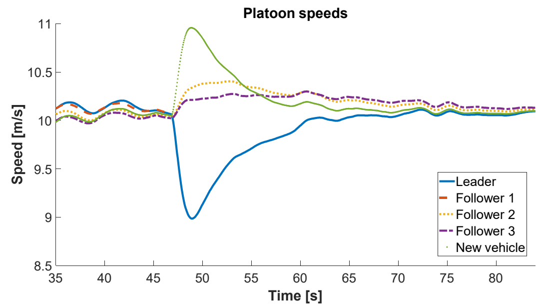

Figure 9: Platoon speeds during the Exit Manoeuvre.

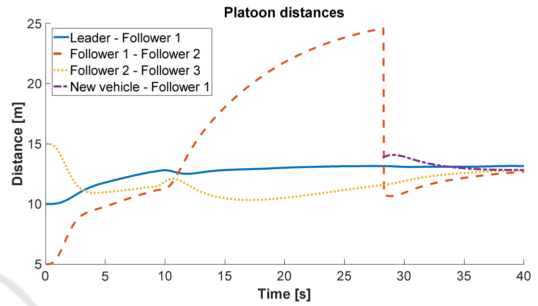

Figure 10: Platoon intra-vehicle distances during the Merge Manoeuvre.

In Figure 10, the variation of the intra-vehicular distance among vehicles is displayed. When the merge request comes (at time 10 s), the two groups of the platoon, in particular between follower 1 and 2, accelerate and decelerate to create the required space for the new vehicle *I* in a short time. In this case, the leader and the follower 1 increase their speed (follower 1 up about to 11 m/s) while follower 2 and 3 decreases it (follower 2 until 9 m/s) (See Figure 8). After the vehicle joints the platoon, the distance between the follower 2 and *I* drops since *I* is entered the platoon.

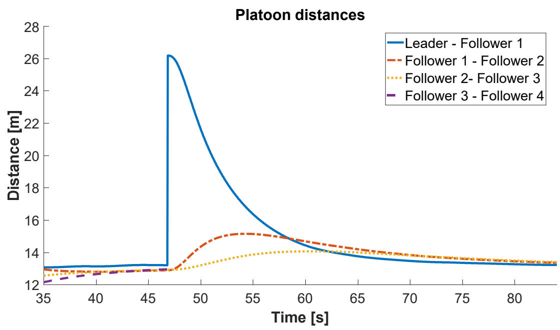

Figure 11: Platoon intra-vehicle distances during the Exit Manoeuvre. When the exit routine occurs, all vehicle “change” role so the Follower 2 became 1, Follower 3 became 2 and Follower 4 became 3.

In Figure 11, the behaviour can be analysed during the exit manoeuvre. At time 47, the empty space left by the follower 1 is rapidly occupied by the leader and the rest of the platoon with the minimum effort.

5 CONCLUSION

The paper addresses a centralized approach to model and control two main important tasks in a vehicle platoon management. The proposed MPC based longitudinal control model is consistent to carry out the specific manoeuvres for a vehicle which intends to merge or exit the platoon. By a bidirectional communication pattern, the control variables, associated to the torque to be applied to the wheels, have been transmitted, in each time interval, by the leader to the followers and to the vehicle which modifies the platoon assessment. In few seconds, the completion of the manoeuvres are successfully completed guarantying safety and avoiding collisions. In a next phase, a lateral and longitudinal control may be implemented by a robust distributed control model.

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