Reactive Multi-agent approach to local platoon control: stability analysis and experimentations

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Abstract: This article presents a local control approach to linear platoons, systems of vehicles that displace together adopting a train configuration without any material coupling. Linear platoon technology is considered as a potential base for the definition of new urban transportation services. The main problems related to platoon systems is the geometry control: control of inter-vehicle distance and common trajectory matching. The geometry control problem is generally treated according to one of two approaches: global or local. This paper focuses on a local approach which does not require sophisticated sensors and/or costly road equipment. The objective of this local control approach allows satisfactory distance regulation and matching to any common trajectory, by using local perception capabilities of platoon’s vehicles. The basic perception capability consists in measuring the vectorial distance between a given vehicle and its predecessor. The behavior of each platoon vehicle is determined by a physics inspired interaction model based on a virtual spring-damper. Stability and other platoon safety properties are analyzed on the base of the physics inspired interaction model. Both simulation and experimentation have been used to measure trajectory error and to evaluate inter-vehicle distance during platoon evolution.

Keywords: Platoon, local control, stability proof, simulation, experimentation

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Franck Gechter obtained a Master in engineering and a Master in photonics and image processing from the L. Pasteur Strasbourg I
J-M. Contet and F. Gechter and P. Gruer and A. Koukam

University (France), F. Gechter received the Ph.D. in Computer Science from H. Poincare Nancy I University (France) in 2003, where he served as an assistant Professor from 1999 to 2004. He served as a researcher in INRIA (French Research National Institute for Computer Science and Automatic Control) (Nancy France) from 1999 to 2004. In 2004, he became associate professor of the Belfort Montbeliard Technological University (UTBM) and researcher of the ICAP Team of the Systems and Transportations Laboratory (Belfort France).

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1 Introduction

Embedded vehicle intelligence benefits from the development of computers, sensors and interfaces. Many applications based on new vehicle capabilities such as environment perception, communication, decision making and control are widely studied. Among them, we can mention linear platoons: systems of vehicles that displace together adopting a train configuration without any material coupling. Linear platoons are currently attracting research interest in the frame of energy, environment and security concerns. Linear platoons appear as the base technology upon which innovative urban transportation systems could be proposed. Approaches to linear platoons can be classified as either global or local. Global approaches use a decision making component with global perception capabilities, such as precise vehicle’s positioning. They also require inter-vehicle communication capabilities with a high level of reliability. Both requirements frequently lead to expensive road infrastructure. In this work, a local approach to linear platoon systems is proposed. It is based on vehicles with autonomous decision-making and control features. It requires local, well defined perception capabilities and does not need any inter-vehicle communication. Linear platoon structure emerges as consequence of self-organizing behavior of each vehicle. From this point of view, the local approach presented here can be considered as a reactive multi agent system, where each vehicle corresponds to an autonomous agent.

Linear platoon systems need to address the geometry control problem, including two aspects: controlling inter-vehicle distance and achieving single trajectory matching. The approach presented here addresses the geometry control problem by defining the behavior of vehicle as a result of their local perceptions, according to a physics-inspired interaction model.

This paper is structured as follow. The next section presents a review of the platoon control approach. Then, section 3 proposes the reactive and local approach, based on physics interaction model. Section 4 presents the stability analysis. Finally, simulation and experimentation results are presented and commented.

2 Platoon Control

2.1 Problem terms

The linear platoon geometry control problem has been defined as the set of functional capabilities for a vehicle to be able, on one hand, to control inter-vehicle distance and, on the other hand, to achieve single trajectory matching. Generally, the geometry control problem is addressed through two sub problems: longitudinal control and lateral control. Longitudinal control consists in controlling braking and acceleration in order to stabilize the distance between following vehicles. Lateral control consists in determining a vehicle’s direction according to platoon’s trajectory.
Most of the approaches presented in platoon literature can be classified as either global or local, as already stated. Next paragraphs present a rapid state of the art about both of them.

2.2 Global approaches

Global approaches require the presence of a decision-making entity, generally embedded in the head vehicle, which determines some reference information (trajectory points, steering and speed instruction, ...) and communicates them to each follower vehicles. Two examples of a global approach can be presented. The first one (11; 12) uses positioning systems such as GPS RTK to compute trajectory points to be visited by follower vehicles. In the second one (13), the leading vehicle broadcasts driving information (steering and speed) to each follower vehicle, as in the European Chauffeur project.

Global approaches yield good trajectory matching but global positioning with GPS or other technology requires road adaptation to avoid tunneling or canyon effects. Moreover, a safe, reliable communication network between vehicle is required.

Consequently, global control approaches produce adequate results, subject to strong constraints on sensors (high cost), road adaptation and communication reliability between vehicles.

2.3 Local approaches

Local approaches perform longitudinal and lateral control based only on each vehicle’s perception capabilities. Generally, vehicles are equipped with sensors which produce measures like inter-vehicle distance vectors. Each vehicle computes its own command references (acceleration and direction) only from it’s own perceptions (measures). Most of the lateral or longitudinal control strategies proposed within local approaches use the PID (Proportional, Integral, Derivative) controllers (14; 15; 16) or other regulation-loop based algorithm (17; 18; 19; 13; 25). Other approaches, propose are based on the model of a
particular physical phenomenon to determine vehicle’s control references. For instance, Gehrig and Stein (20) adopt a particle physics force model. Soo-yeong Yi and Kil-to Chong (21) model immaterial vehicle coupling by means of an impedance control mechanism. Those two proposals suffer from the anticipation error problem, defined later in this section, which handicaps the quality of trajectory matching.

The advantage of local approaches stems from the absence of a component with a critical role. Local approaches do not require expensive road infrastructure, neither they need inter vehicle communication. They can use less expensive and more reliable sensors. On the other hand, local approaches, as already mentioned, can suffer from poor trajectory matching but also from the so called accordion effect produced during platoon evolution.

This paper proposes a local platoon control approach which yields performance levels close to those obtained by global control. Performance is evaluated in terms of inter-vehicle distance error and of lateral error, both of which will be defined in section 5.3. Our approach bases on the capability of each vehicle to measure the vectorial distance to the vehicle immediately preceding it. The main cause of lateral error is the anticipation phenomenon, illustrated by figure 2: a vehicle tries to follow the direction of the distance vector to its predecessor. The local approach presented here minimizes the anticipation error taking into account local curve properties.

3 The interaction model

The local approach to linear platoons presented in this paper considers each vehicle as a reactive agent which determines its behavior from local perception capabilities. The focus is concentrated here on capabilities related to the main
platoon functions: longitudinal and lateral control. Other local perception capabilities, related to functions as obstacle avoidance, are presented in (7).

The proposed local approach is based on an interaction model using the local perception of the vehicle. In this model, interaction are enabled by forces which are computed from a virtual physical link. The virtual link is made by a classical spring-damper model as shown in figure 3 (a). Let consider the point of view of platoons vehicle $V_n$. In this approach, operation of $V_n$ bases on its perception of the preceding vehicle, $V_{n-1}$ in the train.

3.1 Principle

The interaction model proposed in this paper bases on forces, which are not materially exerted, but which are computed from a virtual physical interaction device relating vehicles $V_n$ and $V_{n-1}$. This virtual link connection is made by a classical spring damper model (C.f figure 3 (a)). Each vehicle $i$ is represented by its position $\vec{X}_i = [x_i, y_i]$. The distance between vehicles is $d = ||\vec{X}_{n-1} - \vec{X}_n||$. This distance is deduced from the inter-vehicle distance and the angle $\theta$. This virtual link parameters are stiffness $k$, damping $h$ and spring’s resting length $l_0$. Thus, forces involved are :

- Spring force $\vec{F}_s$:
  \[ \vec{F}_s = -k(||\vec{X}_{n-1} - \vec{X}_n|| - l_0)u_{n-1}n \quad (1) \]

  With $u_{n-1}n$ the unnitaire vector between the vehicle $n - 1$ and $n$ (since the numerotation start from 1 for the head vehicle and the preceding vehicle from the head one is $n - 1$).

- Damping force $\vec{F}_d$:
  \[ \vec{F}_d = -h(\dot{\vec{X}}_{n-1} - \dot{\vec{X}}_n) \quad (2) \]

As a first approximation, longitudinal and lateral control references can thus be determined taking these three forces ($\vec{F}_s$, $\vec{F}_d$), and computed a new acceleration value. However, this model is not sufficient to avoid lateral error (6). This result is due to limitations of the linear impedance control model (Fig. 3 (a)). Figure 3 shows the acceleration anticipation and its consequence on the trajectory of $V_n$. To avoid this problem, the model has been improved by a new force introducing a flexibility of the spring-damper model in curves. The new force is aimed at compensate the acceleration anticipation. It is based on a virtual moment, result of a flexing spring and damping $\vec{M} = (k_m \theta - h_m \dot{\theta}) \vec{z}$ with $k_m$ the torsion spring, $h_m$ the torsion damping, $\theta$ the spring angle of flexion and $\dot{\theta}$ the spring torsion speed. This force is computed using the vectorial product of the distance between the moment application point and the preceding vehicle position (C.f Fig. 3 (b)). This moment has the same behavior as a spring damper but in rotation.
Let consider $\vec{M}A$ the vectorial distance between the front vehicle and the point of application moment $M$ (C.f Fig. 3 right). The mass of the vehicle is denoted as $m$ (vehicles are supposed to have the same mass).

The torsion force is:
- Torsion force $\vec{F}_{\text{torsion}}$:

$$\vec{F}_{\text{torsion}} = \vec{B}\vec{A} \wedge \vec{M}$$  \hspace{1cm} (3)

From now on, the vehicle acceleration can be computed using Newton’s law of motion in the preceding vehicle reference frame:

$$\begin{cases} 
m \cdot \ddot{X}_n = \sum_{\text{force}} \vec{F}_n \\
m \cdot \ddot{X}_n = -k(||\vec{X}_{n-1} - \vec{X}_n|| - l_0)u_{n-1} \hspace{0.5cm} n \\
- h(\dot{X}_{n-1} - \dot{X}_n) + \vec{B}\vec{A} \wedge \vec{M} \end{cases}$$ \hspace{1cm} (4)

Acceleration value can be computed using the equation 4. By discrete integration, speed and vehicle state (position and orientation) and then the command law can be determined. In this case, command law consists in vehicle direction and speed. The choice of a command law takes into account the characteristics of the test vehicle used in our laboratory.

### 3.2 Computation of interaction Model Parameters

The goal of this section is to present how the interaction model parameters can be computed taking into account the stability criterion. The interaction model introduces six variables, mass $m$, stiffness $k$, damping $h$, spring’s unstretched length $l_0$ (regular distance), $k_m$ torsion spring parameter and $h_m$ torsion stiffness parameter. Vehicle $n$ is taken as reference frame for coordinate values. So $\vec{Y} = [x, y]$ represents the difference between vehicles $n-1$ and $n$ taking into account the spring’s unstretched length. Similarly, $\dot{\vec{Y}}$ expresses the speed difference between vehicles $V_{n-1}$ and $V_n$. 

**Figure 3** Spring-damper based interaction model
The mass $m$ of an agent vehicle is set by the mass of the real vehicle.

In order to find the values of the other parameters, the platoon is supposed to be well formed ($\theta = 0$ the regular spring torsion angular). With this assumption, the Newton’s equation became

$$m \ddot{\vec{Y}} = -k(\vec{Y}) - h(\dot{\vec{Y}})$$

The solution is deduced using the critical damping case: $\varepsilon = 1 \Rightarrow \Delta = 0$.

$$\varepsilon = \frac{h}{2 \sqrt{k \cdot m}} = 1$$

Then damping parameter becomes:

$$h = 2 \sqrt{k \cdot m}$$

Spring tends to its rest length $l_0$. Thus, this parameters can be chosen to correspond to the expected inter-vehicle distance. According to the schedule equation, a condition can be defined on $l_0$:

$$l_0 > \frac{V_0^2}{2 \cdot \text{acc}}$$

$k$ represents the stiffness and therefore the vehicle capacity to follow the front vehicle. In order to have an adaptable virtual the link between vehicle, $k$ value can be linked to vehicle speed. Thanks to an energy study based on the spring and damping force, the following equation can be obtained:

$$E = E_{\text{potential}} + E_{\text{kinetics}} = \frac{1}{2} k (\vec{Y} \cdot \vec{Y}) + \frac{1}{2} m (\dot{\vec{Y}} \cdot \dot{\vec{Y}})$$

The system energy represents the system stability, so the condition $\Delta E = 0$ corresponds to the vehicle stability control, i.e. there are neither loss or gain of energy on both kinematics and potential points of view. Thanks to this condition, $k$ can be expressed using inter-vehicle speed difference:

$$k = \frac{m \cdot V^2}{Y^2}$$

With $V$ the inter-vehicle speed difference and $Y$ corresponding to the regular distance.

The two last parameters, i.e. torsion spring parameter $k_m$ and torsion damper parameter $h_m$ can be deduced from newton equation.
First, $k_m$ parameter can be deduced as follow:

\[
\begin{align*}
\dot{m} \ddot{Y} &= -k(Y) - h(\dot{Y}) + \dot{F}_{t\text{orsion}} \\
\|\ddot{Y}\| &= \text{acc}_{\text{max}} \\
Y &= \text{regular distance} \\
\dot{Y} &= \text{regular speed}
\end{align*}
\]

Thus, torsion spring parameter $k_m$ is equal to

\[
k_m = \sqrt{m^2\text{acc}_{\text{max}}^2 + k^2\text{regular distance}^2 + h^2\text{regular speed}^2}/\|M\| \times \theta
\]

(11)

From now on, according to the Newton dynamics equation, $k_m$ and $h_m$ can be linked using the following expressions, the interaction model being based on two moments:

\[
\begin{align*}
\text{Torsion spring} &= \begin{pmatrix} 0 \\ 0 \\ k_m \theta \end{pmatrix} \\
\text{Torsion damping} &= \begin{pmatrix} 0 \\ 0 \\ -h_m \dot{\theta} \end{pmatrix}
\end{align*}
\]

(12)

(13)

(14)

In this case, from the dynamics low of motion, $M = \text{Torsion spring} + \text{Torsion damping}$. Then, the following equation can be deduced:

\[
k_m \theta - h_m \dot{\theta} = 0
\]

(15)

According to these formulas, all model parameters are computed, following two steps: firstly, parameters’ values (stiffness $k$, damping $h$, $k_m$ torsion spring parameter and $h_m$ torsion stiffness) are recalculated from current value of speed and inter-vehicle distance. Secondly, new value of acceleration is computed.

4 Inter-Vehicle Distance Stability Analysis

Analysis of the interaction model by applying classical laws allows to prove that the interaction model satisfies a set of platoon stability properties. The next section presents two kinds of proofs: one applying a direct approach and the other using an energetic point of view.
4.1 Platoon Stability Based on Transfer Function

Platoon stability is treated following the “string stability” problem which has been studied in (10). A platoon is said to be stable if, under no other excitations, the error magnitude decreases as it propagates along the vehicle stream. This section proposes to prove the string stability relatively to longitudinal control (Consequently, elements link to lateral control (i.e. \( \theta = 0 \) and \( \dot{\theta} = 0 \)) are not considered in the demonstration). Formally speaking, if the transfer function of the system composed of two successive vehicles exhibits a magnitude less or equal to 1, string stability is obtained (23; 24). In order to verify this property, the control law of vehicles \( n-1 \) and \( n \) must be expressed with \( \theta = 0 \) (Longitudinal control):

\[
\begin{align*}
\dot{X}_{n-1} & = -kX_{n-1} - hX_{n-1} \\
\dot{X}_n & = -kX_n - hX_n
\end{align*}
\] (16)

From \( A(j\omega) \), \( A(s) \) can be computed, knowing that \( j\omega = s \), \( A(s) = \frac{h^*s + k}{s^2 + h^*s + k} \).

String stability is guaranteed only if: \( |A(j\omega)| \leq 1 \). This condition is verified with \( k \leq \frac{m\omega^2}{2} \). Thanks to the \( k \) value variation, this condition is \( \omega \geq \sqrt{\frac{2}{m} \frac{V}{Y}} \) (with \( V \) the inter-vehicle speed difference and \( Y \) the inter-vehicle distance). This study proof that our system is stable to any frequency. The error propagation will be attenuated through the platoon.

4.2 Inter-Vehicle Distance Stability Proof Based on Energy

The goal of this section is to check if the stability (platoon stability is represented by the stabilization of the distance between each follower vehicle) of the system is kept in run time. To this end, Lyapunov stability of motion conditions are applied (9; 22). The system energy results from the addition of kinetic and potential energies. Vehicle \( i \) taken as reference frame, energy can be expressed as follow:

\[
E = E_{pot} + E_{kin} + E_{pot}(F_s) + E_{pot}(F_{torsion}) = \frac{1}{2} m (\dot{X} \cdot \dot{X}) + \frac{1}{2} k (X \cdot X) + \int_X \int_\theta \tilde{F} dY d\theta
\] (17)

By applying Lyapunov stability of motion conditions (9; 22), we assume that with \( V(x,y,\theta) = E \).

\[
\begin{align*}
V(x,y,\theta) & \geq 0 \\
\dot{V}(x,y,\theta) & < 0
\end{align*}
\] (18)

The first condition is filled since: \( ||\tilde{Y}||^2 \geq 0 \) and \( E_{pot}(F_{torsion}) \geq 0 \) with \( \theta \in [-\pi/2, \pi/2] \).

\[
E = E_{pot} + E_{kin} \geq 0
\] (19)
Reactive Multi-agent approach to local platoon control

The second condition:

\[ E(x, y, \theta) = E(x, y, \theta)_{\text{pot}} + E(x, y, \theta)_{\text{kin}} = E_{\text{kinetics}} + E_{\text{pot}}(F_s) + E_{\text{pot}}(F_{\text{torsion}}) \] (20)

Energy Proof, Starting from equation 4, we obtain:

\[
m \cdot \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = -h \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} - k \cdot \begin{bmatrix} x \\ y \end{bmatrix} + (k_m \cdot \dot{\theta} - h_m \dot{\theta}) \cdot \begin{bmatrix} x \\ y \end{bmatrix} \cdot \sin(\theta) \cdot \cos(\theta) \tag{21}
\]

Let’s assume that:

\[
\begin{bmatrix} \dot{x}_2 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \text{ and } \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{22}
\]

\[
\begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} \tag{23}
\]

\[
\begin{bmatrix} \ddot{x}_2 \\ \ddot{y}_2 \end{bmatrix} = -\frac{k}{m} \cdot \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} + \frac{k_m \cdot \dot{\theta} - h_m \dot{\theta}}{m} \cdot \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \cdot \sin(\theta) \cdot \cos(\theta) - \frac{h}{m} \cdot \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} \tag{24}
\]

\[
\begin{bmatrix} \frac{\partial E(x, y, \theta)}{\partial E_{(x, y, \theta)}} \\ \frac{\partial E(x, y, \theta)}{\partial E_{(x, y, \theta)}} \end{bmatrix} = \begin{bmatrix} \frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} \\ \frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} \end{bmatrix} \tag{24}
\]

\[
\begin{bmatrix} \frac{\partial E(x, y, \theta)}{\partial E_{(x, y, \theta)}} \end{bmatrix} = \begin{bmatrix} x_2^2(k_m \sin(\theta) - h) \\ y_2^2(k_m \cos(\theta) - h) \end{bmatrix} \tag{25}
\]

The derivative of Energy is negative if the angular \( h \cdot k_m \) is greater than 1 since \( \theta \in [-\pi/2, \pi/2] \). Applying Lyapunov stability of motion conditions as in (6; 4), shows that the system is stable when time tends to infinity. Thus, the distance between vehicles tends to the unstretched spring length when the platoon moves without environmental influence, if the condition on rotation angle (\( \theta \in [-\pi/2, \pi/2] \)) is verified.

5 Simulation and experiments

The physics inspired interaction model previously defined is the base to the specification of the local platooning control algorithm. Based on this algorithm, simulation and experimentation scenarios are designed and performed to check the platoon evolution particularly during lateral displacement situations and a set of safety platoon conditions.
5.1 Platforms presentation

This section shows the platforms used to test the platoon control algorithm. The first platform is a 3D simulator which incorporates a physics engine and sensors simulations, which allow to test realistic scenarios. The second platform is composed of modified GEM electrical vehicles automated by the laboratory SeT.

Simulation platform

The 3D simulation tool has been developed during CRISTAL project (http://www.projet-cristal.net/). This tool has been fully realized in the Systems and Transportations laboratory. The goal of this application is to simulate and study as fine as possible platooning solutions in regular conditions and also in the case of forbidden scenarios such as car crashes.

![Figure 4 3D simulator (Top) physics engine (Low)](image)

This tool can simulate the behavior of the following elements for each vehicle: perception, control law computation and vehicle physical reaction. The physics engine (cf. figure 4) simulates the interactions between vehicle components (wheels, shocks, ...) and stage (soil, ...) taking into account their physical properties (friction coefficient, spring rate, ...) and the nature of their mechanical connections (pivot, ...).

Experimental platform

Systems and Transportations Laboratory owns two electric vehicles (cf. figure 5 left). These vehicles have been automated and can be controlled by a onboard system.
Figure 5  SeT laboratory electrical vehicle (left), vehicle architecture (right)

Figure 5 shows the vehicle onboard system. The onboard computer receives perception information and sends direction and speed commands to the vehicle control device. The reactive local platoon system presented in this article has been implemented on this onboard computer.

5.2 Simulation and experimental protocol

Experiments were conducted on the Technopark site from the city of Belfort. The simulations were performed on a 3D geolocalized model of the same site built from Geographical Information Sources and topological data.

Figure 6  Simulation et experimentation path

Figure 6 shows the path (white curve) used for the simulation and experimentation. It was selected because it allows to move the train on a long distance in an urban environment using a trajectory with different curve radius.
In order to compare the simulation and the experimentation results, parameters were the same on simulation and real experiments. Thus, the perception of each vehicle is made by a simulated laser range finder having the same characteristics (range, angle, error rate,...) as the vehicle real sensor. The distance and the angle between vehicles are computed thanks to this sensor. To improve this measure, reflective beacons have been installed at the rear of the head vehicle (cf. figure 7).

Figure 7  Reflective beacon

This beacon is composed of three reflective rubbers. The middle position one allows to measure the distance between vehicles. The left and right are used to compute the angle $\theta$ (cf. 7).

Platoon characteristic values used are exposed in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Experimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>500 kg</td>
<td>500 kg</td>
</tr>
<tr>
<td>Max speed</td>
<td>8 km/h (2 m/s)</td>
<td>8 km/h</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.1 m/s$^2$</td>
<td>0.1 m/s$^2$</td>
</tr>
<tr>
<td>Deceleration</td>
<td>-0.1 m/s$^2$</td>
<td>-0.1 m/s$^2$</td>
</tr>
<tr>
<td>Max deceleration</td>
<td>-3 m/s$^2$</td>
<td>-3 m/s$^2$</td>
</tr>
<tr>
<td>Safety distance</td>
<td>50 cm</td>
<td>150 cm</td>
</tr>
<tr>
<td>Regular distance</td>
<td>180 cm</td>
<td>400 cm</td>
</tr>
</tbody>
</table>

Table 1  Parameters of vehicle model and platoon control

The algorithm used is the same for both simulations and real experiments. Moreover, the program runs on the same computer. Indeed a great attention has been paid on the fact that simulated vehicles should have the same communication interface as the real ones. Thus, passing from simulation to real vehicle relies only on unplugging artificial intelligence computer from simulator and plugging it on real vehicle. However, artificial intelligence program still need some minor adaptation to fit real vehicle specific parameters. Thus, experiments were performed with a more important regular distance in order to avoid collision that can lead to irreversible damage for vehicles. The regular distance has been established to 4 m and the safety distance to 1.5 m.
5.3 Simulation and experimentation scenarios

This subsection presents tests performed both in simulation and with real vehicles to assess the quality of platooning. The following cases were discussed:

- Evaluation of inter-vehicle distance: measuring the distance between two following vehicles, compared to the desired regular inter-vehicle distance during platoon evolution (cf. figure 8).

- Evaluation of lateral deviation: measuring the distance between the trajectories of the geometric center of a vehicle relative to the same path of his predecessor (cf. figure 8). For the measurement, points on the first vehicle trajectory were selected. Then, the normal trace of these points is drawn and a measure of the distance between the selected point and the point of intersection with the trajectory of its predecessor is made.

![Figure 8](image)

**Figure 8** Longitudinal error (left) Lateral error (right)

5.4 Evaluation of inter-vehicle distance

This subsection presents the results of the evaluation of the inter-vehicle distance with a train of four vehicles in simulation and with a train of two vehicles in experimentation (Only two laboratory vehicles are available for the moment). As for simulations, the number of vehicles is determined by industrial partner requirements, however simulations with up to 10 vehicles have been successfully performed.

To evaluate the inter-vehicle distance, the train is submitted to critical operations such as starting, emergency braking and quick change of speed of the first vehicle.
5.4.1 Simulation

The figure 9 shows the distance variations between vehicles in relation to quick changes of the first vehicle speed.

- Starting: figure 9 part (a) shows the case of a quick start. The first vehicle accelerates to its maximum speed. The inter-vehicle distance increases and induces an overrun of 30% compared to the regular distance. Then, the inter-vehicle distance stabilizes to the regular distance. This variation is due to the dynamic response of vehicles, especially the first following vehicle.

- Quick changes of the first vehicle speed: The second case study is represented by critical changes, with a “sawtooth” shape, of the first vehicle speed (cf. figure 9). Parts (b) and (c) represent two cases of rapid speed change. The first case (b) is a decrease of 30% and an increase until the maximum speed whereas case (c) shows a decrease of 70%. In both cases, the inter-vehicle distance decreases then stabilizes at the regular distance and stay in any case above the safety distance (cf. table 2).

- Safety Stop: Figure 9 case (d) shows the most critical case. The first vehicle brakes with a maximum deceleration. Figure 9 shows that the value of the inter-vehicle remains above of the safety distance (cf. table 2).

<table>
<thead>
<tr>
<th>Vehicle speed variation in % in relation to 8 km/h</th>
<th>Inter-vehicle distance Variation in cm in relation to the regular distance (180 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 %</td>
<td>40</td>
</tr>
<tr>
<td>70 %</td>
<td>60</td>
</tr>
<tr>
<td>100 %</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 2 Variations of inter-vehicle distance in relation to quick changes of first vehicle speed
5.4.2 Experiments

Figure 10 shows the distance evolution between the two electric vehicles during the experiment.

- **Starting**: Figure 10 illustrates the same as what has been shown in simulation (Figure 9). Part denoted (a) presents the quick start. The first vehicle accelerates to its maximum speed (8 km/h). The inter-vehicle distance increases until an overrun of 55% compared to the regular distance. Then, the inter-vehicle distance stabilizes to the regular distance, set at 4 m for the experiments. This variation is due to the vehicle dynamic response, due to the time of 500 ms between sending speed commands and the reception control to the electric motor.

- **Rapid changes of the first vehicle speed**: Area (b) and (c) (cf. figure 10) represent two cases of quick speed change. As in simulation, the first case (b) is a decrease of 30% followed by an increase until the maximum speed. Case (c) shows a decrease of 70%. In both cases, the inter-vehicle distance decreases then stabilizes at the regular distance. Inter-vehicle distance never reaches a value above safety distance.

- **Safety Stop**: figure 10 case (d) shows a lead vehicle deceleration (Until now, an emergency braking with maximum deceleration cannot be performed because the latency between sending orders and executing them is too high (500 ms)). The value of the inter-vehicle distance remains above of the safety distance, set at 1.5 m.

5.4.3 Conclusion: Evaluation of inter-vehicle distance

Table 3 gives an overview of the inter-vehicle distance variation. We can observe that despite the very sudden changes in first vehicle speed, this value is above the value of the safety distance and stabilize rapidly to the regular distance.
<table>
<thead>
<tr>
<th>Critical case</th>
<th>Inter-vehicle distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td></td>
</tr>
<tr>
<td>Starting from 0 to maximal speed</td>
<td>Overrun of 30% compared to the regular distance</td>
</tr>
<tr>
<td>Speed variation of 30 et 70 %</td>
<td>Inter-vehicle distance variation 20 et 50 %</td>
</tr>
<tr>
<td>Safety stop from maximal speed to 0</td>
<td>Above the value of the safety distance</td>
</tr>
<tr>
<td>Experimentation</td>
<td></td>
</tr>
<tr>
<td>Starting from 0 to maximal speed</td>
<td>Overrun of 55% compared to the regular distance</td>
</tr>
<tr>
<td>Speed variation of 30 et 70 %</td>
<td>Inter-vehicle distance variation 30 et 50 %</td>
</tr>
<tr>
<td>Safety stop from maximal speed to 0</td>
<td>Above the value of the safety distance</td>
</tr>
</tbody>
</table>

**Table 3** Evaluation of inter-vehicle distance

5.5 **Evaluation of lateral deviation**

This subsection proposed to evaluate the distance between the trajectories of the geometric center of a vehicle relative to the same path of his predecessor. This lateral deviation may cause problems in curves as the friction of pavement and collisions with vehicles in the opposite direction.

5.6 **Simulation: evaluation of lateral deviation**

The simulation was performed with a train of four vehicles.

![Figure 11](image)

**Figure 11** Simulation: lateral error during exit station

Figure 11 presents the tracks of vehicles to measure the lateral error between each vehicle. The simulation was realized during exit station. In this case, the error is not greater than the width of a tire (i.e. 20 cm).
Wheel rotation (degree) | Curve radius | Medium error | Maximum error
--- | --- | --- | ---
5.73 | 18 m | 12 cm | 14 cm
11.46 | 9 m | 30 cm | 40 cm
17.2 | 6 m | 50 cm | 65 cm
22.9 | 4.5 m | 55 cm | 67 cm
28.65 | 3.6 m | 67 cm | 75 cm

Table 4  Simulation: trajectory error in curve

To see the maximum error then the train evolve, we plotted the lateral error in relation to the wheel rotation (cf. figure 12).

![Figure 12](image)

Figure 12  Simulation: lateral error in relation to the wheel rotation

Table 4 shows the maximum lateral error and average in relation to the radius of curvature of the lead vehicle. We note that in normal operation case (wheel rotation < 10 degrees), we have a lateral error less than 20 cm.

5.7 Experimentation : evaluation of lateral deviation

The experiment was realized with two electric vehicles from ScT laboratory. The measure has been realized thanks to the GPS RTK installed on vehicles to know their positions in centimeter.
To see the maximum error then the train evolve, we plotted the lateral error in relation to the wheel rotation (cf. figure 5).

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Wheel rotation (degree)} & \text{Curve radius} & \text{Medium error} & \text{Maximum error} \\
\hline
5.73\degree & 18 m & 30 cm & 45 cm \\
11.46\degree & 9 m & 40 cm & 52 cm \\
17.2\degree & 6 m & 46 cm & 56 cm \\
22.9\degree & 4.5 m & 55 cm & 70 cm \\
28.65\degree & 3.6 m & 70 cm & 90 cm \\
\hline
\end{array}
\]

Table 5  Experimentation: trajectory error in curve

5.8 Conclusion : evaluation of lateral deviation

Table 5 shows the maximum and average lateral error in relation to the radius of curvature from the lead vehicle. The results presented in the table show that the tracking error of the vehicle simulation is close to the experiment. Indeed, the results presented in the table 4 represent the average error between each car of the train, similar levels of values are found.
6 Conclusion

The aim of this article was to present a better local platoon control based on the bending of a virtual spring damper. In this paper, platoon control bases only on local perception capabilities. Each vehicle behavior is deduced from a physics inspired interaction model an embodied in a reactive agent architecture. The use of physics inspired forces enables an easier tuning of the interaction model parameters and the adaptation to any kind of vehicle. Besides, the physic model has been used to prove platoon stability, by using classic physical proof method: energy analysis. Analogously, another stability proof have been realized following a transfer-function approach. To assert the transition from abstract to concrete, simulations have been implemented to show the applicability of the theoretical model. Some simulations have been made on a 3D simulator which integrates vehicle dynamic properties (maximal speed and acceleration, ...). Simulation and experimentation scenarios are designed and performed to check the platoon evolution particularly during lateral displacement situations and a set of safety platoon conditions. These experimentations exhibit a little curved trajectory error during the platoon evolution and indicate that the presented approach improves platoon quality. Moreover, we are exploring the possibility of building formal specification models and exploiting them in order to verify by model-checking some safety properties (8).

References