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TRAFFIC CONGESTION REDUCTION AT TRAFFIC LIGHT INTERSECTIONS FOR TIME-SYNCHRONIZED AUTONOMOUS VEHICLES

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Abstract. Traffic congestion relates to an excess of vehicles on a portion of the road at a particular time, and generates slower speeds, longer trip times, pollution and increased vehicular queueing. Traffic congestions at intersection areas are a significant problem in many cities around the world. One aspect which can be taken into consideration for road traffic optimization is the moment the vehicles accelerate at traffic lights. Because most automobiles implement the standard AUTOSAR (Automotive Open System Architecture), the paper presents in the beginning a synopsis of the functionality and usability of the AUTOSAR time synchronization concept which allows each individual vehicle to have all the electronic control units time-synchronized within it. Therefore, each vehicle would be able to activate in an optimized way the acceleration feature. The MATLAB Simulink simulation results illustrate what is expected from the implementation of the concept in such a scenario: combining the advanced driver-assistance systems with the current concept would seem beneficial in reducing traffic congestion in traffic light intersections for autonomous vehicles by taking advantage of the knowledge of the precise time when the lights will change.

***Key words**:* autonomous vehicles, traffic congestion, time synchronization, simulation.

1. INTRODUCTION

The future of automobiles points into the direction of autonomous cars. Self-driving vehicles are currently being developed with the intention of constructing an intelligent automobile which senses, interacts and reacts to the environment [1]. This gives the opportunity to reduce the effects of the problems caused by traffic congestions such as fuel consumption, gas emissions, time delays, noise, road accidents, safety risks, and driver stress. Therefore, the future design of autonomous cars will require the concept of platooning. Vehicle platooning refers to a group of vehicles meant to be driven together and capable to accelerate or to brake simultaneously in order to increase road capacity. The vehicles can exchange relevant information with each other via wireless technologies. A vehicle inside the platoon acts as the leader and the other vehicles react to it. Artificial intelligence guided cars would also automatically join and leave platoons.

Several projects are deeply involved into making platooning possible, e.g., project ENSEMBLE (Enabling Safe Multi-Brand Platooning for Europe) strives to modernize the transport system with multi-brand truck platooning in order to improve fuel economy and traffic safety, project AutoNet 2030 (Cooperative Systems in Support of Networked Automated Driving by 2030) aims to develop a cooperative technology for fully automated driving in order to make vehicle manoeuvring efficient and reliable. This paper proposes the use of a standardized approach for the time-synchronized activation of the functionality embedded within each vehicle of the platoon without necessary depending on the information from the leader. Vehicle platooning increases the capacity of roads, provides a more steady-state traffic flow, reduces fuel consumption and accidents. On the other hand, long platoons may prevent other vehicles from changing lanes, the platoons are exposed to security issues, drivers might not have the necessary technology or skills to interact with platoons. Many research papers discuss vehicle platooning, e.g., a robust acceleration tracking control of vehicle longitudinal dynamics for platoon automation [2], an improvement for high-density platooning applications [3], a game-theoretic approach for vehicle platoon security from cybernetic attacks

[4], a platoon speed control to mitigate the shock wave effect using the traffic information [5], an artificial neural network used to generate the optimal path for locomotion avoiding obstacles [6].

The physical time and the real-time capability are very important for any vehicle system. They allow to determine when a past event has taken place and when a future functionality must be triggered. Therefore, a global time synchronization mechanism should be deployed within any vehicle, even if it is part of a platoon or not. The time synchronization mechanism within a vehicle can be diverse and with different strategies but considering that most automobiles implement the AUTOSAR standard, this paper refers to the global time synchronization concept implemented within this standard. AUTOSAR imposes the use of real-time operating systems and supports time synchronization over different communication buses to coordinate otherwise independent system clocks of in-vehicle ECUs (Electronic Control Units). Vehicle time synchronization provides high-precision synchronization of the underlying time bases in the ECUs required by many time-critical applications. It is a studied topic, e.g., a synchronized firefly model for autonomous vehicles with broadcast distribution of the time synchronization [7], an evaluation of the accuracy, stability, and robustness of the automotive time synchronization [8], a precise time synchronization mechanism for fog-based vehicular ad-hoc networks [9], a temporal relationship of the logged fault data across the vehicle using AUTOSAR global time synchronization [10].

Platoon synchronization is generally solved by a networked controller which gives all vehicles a coherent behaviour. Extremely low latency and high reliability requirements generate a series of severe challenges for vehicles synchronization. Traffic light intersection handling is one of the problematic scenarios in this case. The GLOSA (Green Light Optimal Speed Advisory) service addresses this issue by predicting the green phases of the traffic lights and providing the drivers with information in order to increase efficiency and driving comfort. Rather than predicting the changes, this paper proposes the vehicles to know the exact moment of time when the traffic lights will change. Therefore, the paper suggests the use of the time-based synchronization described within AUTOSAR to achieve a synchronous start of the vehicles at traffic lights. The moment when the traffic lights will change must be received from the intelligent traffic lights system. Smart traffic lights combine traditional traffic lights with an array of sensors to intelligently route vehicle and pedestrian traffic in order to reduce the waiting time and the fuel consumption. Traffic lights in conjunction with autonomous cars have been investigated in many papers, e.g., a combination of V2X (vehicle-to-everything) communication and an adaptive fuzzy neural network algorithm for an intelligent traffic signal control system [11], a robust vision-based traffic light detection for different illumination and weather conditions [12], prediction of traffic lights signals using a Kalman filter [13], a system based on smartphones to recognize the traffic lights [14], a traffic light system optimization within two nearby intersections to deal with minimum traffic queue [15].

Vehicle platooning, vehicle time synchronization and smart traffic lights applications lay the foundation of the future autonomous driving. Each topic implies the realization of new standards, hardware equipment and requirements to be applied to vehicles and infrastructure. The main goal in this case is to reduce traffic congestion. In this paper, the AUTOSAR global time synchronization concept is proposed to support the vehicles synchronization with the traffic lights at intersections, as well as to coordinate the functionality among the vehicles. AUTOSAR is a well-known standard applied in automotive, its global time synchronization is a proven-in-use concept available on many vehicles already, it is easy to implement, and it allows all vehicles to be aware of the universal time.

The paper's structure is as follows. Section 2 presents a summary of the global time synchronization described in AUTOSAR. Section 3 presents through MATLAB simulations what is anticipated from using the time synchronization concept in autonomous vehicles. Section 4 presents the paper's conclusions.

2. AUTOSAR GLOBAL TIME SYNCHRONIZATION SYNOPSIS

The global time synchronization concept within AUTOSAR enables all in-vehicle network ECUs to synchronize their system clocks in order to operate and to execute in unison the required functionality. The concept can be implemented across different physical protocols, e.g., CAN, FlexRay, Ethernet and it is shaped through global time networks. A global time network, depicted in Fig. 1, consists of a global time master and at least one time slave. The master is capable to distribute the global time base using specific time synchronization messages. The slave can act as a time gateway distributing onto other buses the time information. Depending on the bus, the time synchronization messages encapsulate various time information.

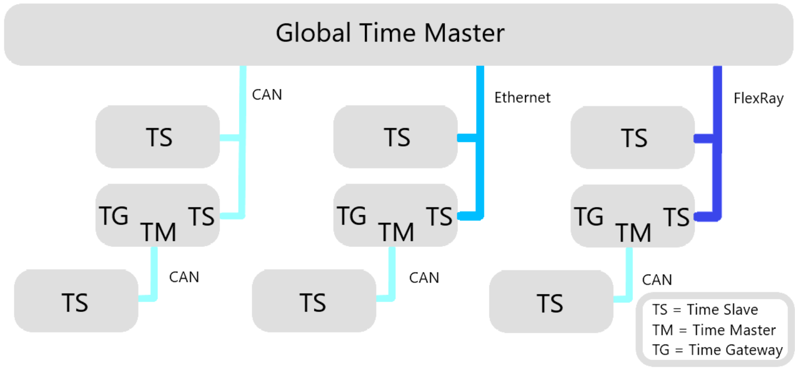

Fig. 1 – Global time network in AUTOSAR.

Figure 2 presents the CAN time synchronization messages [16]. The relative time t_r is calculated through the information contained in the synchronization (SYNC) and follow-up (FUP) messages. The absolute time t_a is computed by further analysing the information within the offset synchronization (OFS) and offset adjustment (OFNS) messages. The relative and absolute time are calculated as described by equations (1).

$$\begin{cases} t_r = (t_{3r} - t_{2r}) + s(t_{0r}) + t_{4r} \\ t_a = t_r + t_{5o} \end{cases} . \tag{1}$$

Figure 3 presents the Ethernet time synchronization messages [17], which employ the general Precision Time Protocol (gPTP) used to synchronize clocks throughout a network. The time base distribution is performed through the synchronization (SYNC) and follow-up (FUP) messages. The propagation delay measurement is implemented through the propagation delay request (PDELAY_REQ), propagation delay response (PDELAY_RES) and propagation delay response follow-up (PDELAY_RES_FUP) messages. The global time is computed each cycle as described by equations (2)

$$\begin{cases} \text{GlobalTime}_n = \left[T_{0_n} + T_{0diff_n} + \text{Pdelay}_n + \left(T_{fup_n} - T_{sync_n}\right)\right] \\ \text{Pdelay}_n = \left[\text{RateRatio}_n \times \left(T_{4_n} - T_{1_n}\right) - \left(T_{3_n} - T_{2_n}\right)\right]/2 \\ \text{RateRatio}_n = \left(T_{2_n} - T_{2_{n-1}}\right)/\left(T_{4_n} - T_{4_{n-1}}\right). \end{cases} \tag{2}$$

The notations seen in Fig. 2 and Fig. 3 are described in Table 1.

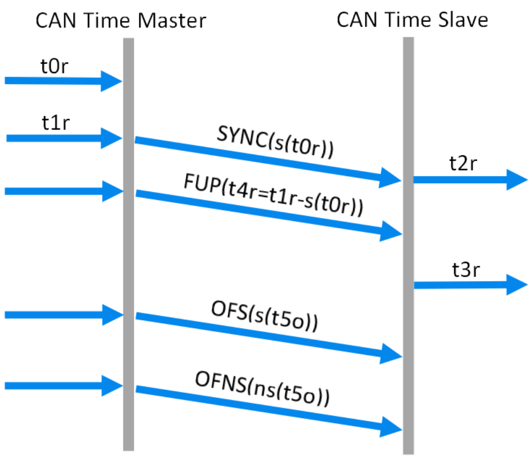

Fig. 2 – AUTOSAR CAN time synchronization messages.

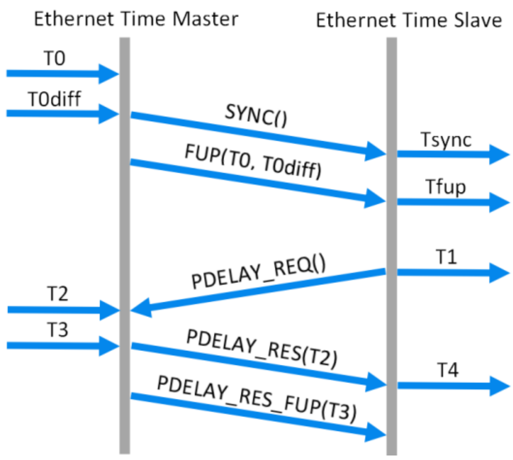

Fig. 3 – AUTOSAR Ethernet time synchronization messages.

Table 1

Interpretation of the notations from Fig. 2 and Fig. 3

Figure 2		Figure 3	
$s(t)$	Second portion of time t	T_0	Current time base value of the time master to be transmitted
$ns(t)$	Nanosecond portion of time t	T_{0diff}	Transmission delay
t_{0r}	Current time base value of the time master to be transmitted	T_{sync}	Ingress timestamp of the SYNC on the time slave
t_{1r}	Egress timestamp of the SYNC from the time master	T_{fup}	Ingress timestamp of the FUP on the time slave
t_{2r}	Ingress timestamp of the SYNC on the time slave	T_1	Egress timestamp of the PDELAY_REQ from the time slave
t_{3r}	Current timestamp on the time slave	T_2	Ingress timestamp of the PDELAY_REQ on the time master
t_{4r}	Transmission delay + remainder from t_{0r}	T_3	Egress timestamp of the PDELAY_RES from the time master
t_{5o}	Offset time between relative and absolute time	T_4	Ingress timestamp of the PDELAY_RES on the time slave

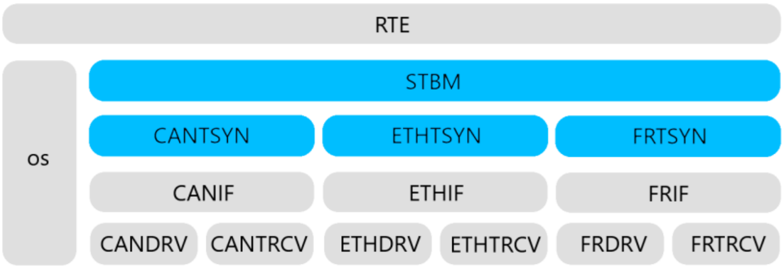

Fig. 4 – AUTOSAR time synchronization modules.

Figure 4 shows the AUTOSAR modules correlated with global time synchronization. The Synchronized Time Base Manager (STBM) collects and offers to applications above RTE (Runtime Environment) unique time base information, distributing the absolute or relative time values to customers [18]. STBM is also capable to synchronize application runnable entities within the entire network by triggering customers, thus STBM is aware of the required functionality. Time synchronization modules implement time base calculation and bus-specific protocols: CANTSYN (CAN), FRTSYN (FlexRay), ETHTSYN (Ethernet).

The AUTOSAR time synchronization concept is an independent process which takes place separately within every individual vehicle. Using this concept would not guarantee that all the vehicles are perfectly time-synchronized with each other because the synchronization accuracy depends on the global time master's precision within each vehicle. But this concept would allow for each separate vehicle to have all the in-vehicle ECUs time-synchronized, which would enable the optimal activation at a specified moment in time of a corresponding functionality, e.g., the acceleration. In the end, all vehicles would be in a very close-range of the universal time. The paper proposes the use of this concept to reduce traffic congestions at intersection areas because modern vehicles already incorporate it, although the concept is not yet used for such a scenario as presented in this paper. Therefore, the paper intends to use the existing AUTOSAR time synchronization concept to present a synchronization strategy between vehicles and traffic infrastructures.

3. SIMULATION OF THE PROPOSED CONCEPT

The expected outcome from the implementation of the AUTOSAR global time synchronization concept in such a scenario is depicted in Fig. 5. Due to the concept, each vehicle waiting at the stop lights has the current universal time. Therefore, all vehicles are time-synchronized. Using V2I (vehicle-to-infrastructure) communication protocols, the traffic light broadcasts to all the vehicles in the coverage area the time when its next state will change. The vehicles receive this information and decide when to trigger the acceleration, resulting in this case a synchronous start of the cars. The vehicles do not necessarily need to be part of a platoon for this functionality to work if they are autonomous vehicles. In case the column of vehicles exceeds the coverage area of the semaphore, it could be possible for the vehicles to exchange this information with each other using V2V (vehicle-to-vehicle) communication protocols.

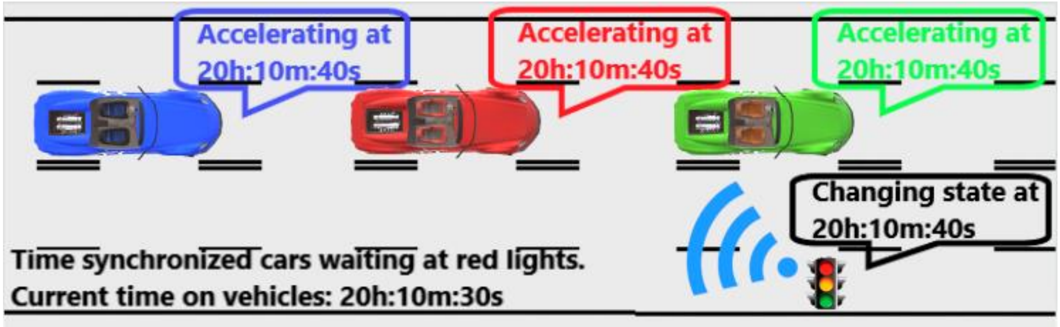

Fig. 5 – Time-synchronized vehicles informed about the next state change of the traffic lights decide when to start accelerating.

Figure 6 represents the Simulink block diagram used to illustrate what is expected from employing the AUTOSAR global time synchronization concept within vehicle platooning. The diagram contains three Vehicle Body 1DOF (one degree-of-freedom) Longitudinal blocks which simulate a 1DOF rigid two-axle vehicle body with constant mass undergoing longitudinal motion [19]. The configuration parameters of the vehicle body model blocks were left configured to the default MATLAB values but to simulate different types of vehicles, the body mass of each vehicle was configured as follows: $m_1 = 2\,000$ kg for the first vehicle, $m_2 = 1000$ kg for the second vehicle, and $m_3 = 1\,500$ kg for the last vehicle. The initial positions of the vehicles were configured to $x_{01} = 4$ m for the first vehicle, $x_{02} = 2$ m for the second vehicle, $x_{03} = 0$ m for the last vehicle, therefore a 2 m distance is between two adjacent vehicles. The controllers apply the same total longitudinal force on the front (FwF) and on the rear (FwR) axle, and the other inputs were not used. The vehicle centre of gravity displacement along earth-fixed X-axis was employed from the Info output, and the other outputs were not used.

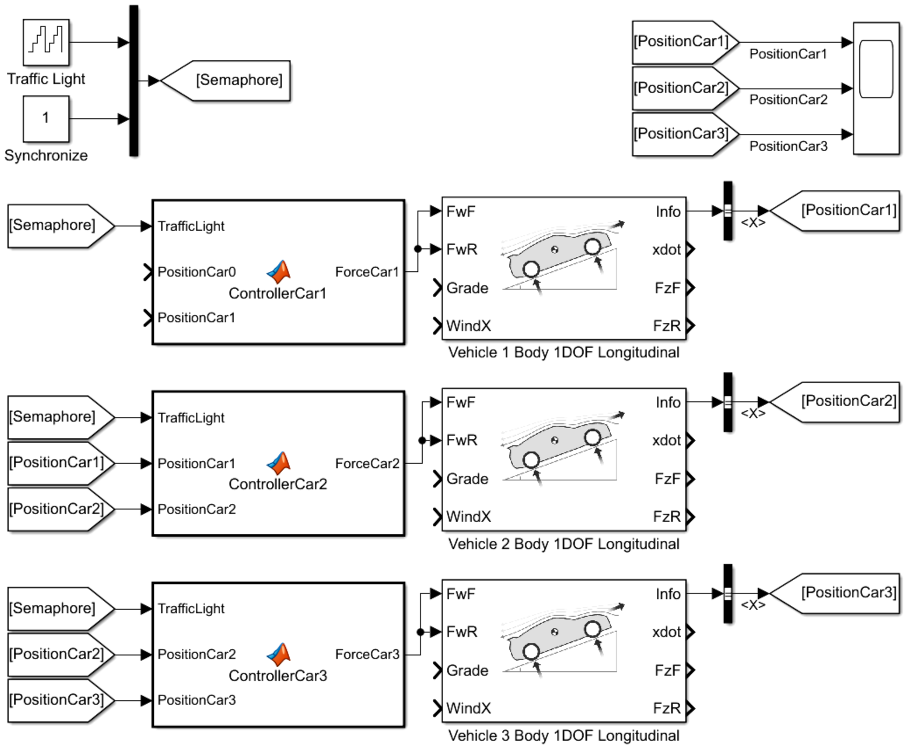

Fig. 6 – Simulation block diagram of three vehicles part of a platoon.

The three MATLAB functions control the acceleration of the vehicles based on the information received from the semaphore and from the radar or lidar sensor, e.g., the calculated distance between two adjacent vehicles. The functions have as input variables the information *TrafficLight* from the semaphore used to determine when the next traffic light state will change and the position *PositionCarX* of the car in front used to maintain a certain distance between the vehicles.

The traffic light is simulated using a free-running counter block *Traffic Light*. The block was configured to work on 32 bits and with a sample time of 0.0002 seconds. The traffic light is considered with only two states: green light state and red-light state with a duration of 10 seconds interval. The traffic light must be part of a V2X environment capable to distribute the time information to the vehicles. This information can either be related to the remaining duration of the current state, or it can represent the actual universal time when there will be a change in its state. To compare what is expected with and without the AUTOSAR global time synchronization, a constant block *Synchronize* was used to change between the two scenarios. The results are visualized on a scope block.

3.1. Experiment one

The first experiment observes the behaviour of the introduced vehicle model in case of vehicles moving at constant speed, and without additional information such as feedback of the distance between adjacent vehicles. The MATLAB implementation of all three controllers is similar and is described in (3). As expected, the results seen in Fig. 7 show there would be a collision between the first car with the second and the third car because it is the heaviest and therefore the slowest to move.

```
function ForceCar1 = ControllerCar1 (TrafficLight, PositionCar0, PositionCar1)
  persistent Movement;
  ForceCar1 = 0;
  if isempty(Movement) Movement = 0; end
  if (mod(TrafficLight(1), 5*1000*10) == 0) && (TrafficLight(1) ~= 0)
    Movement = 1;
  end
  if(Movement == 1) ForceCar1 = 2000; end
```
(3)

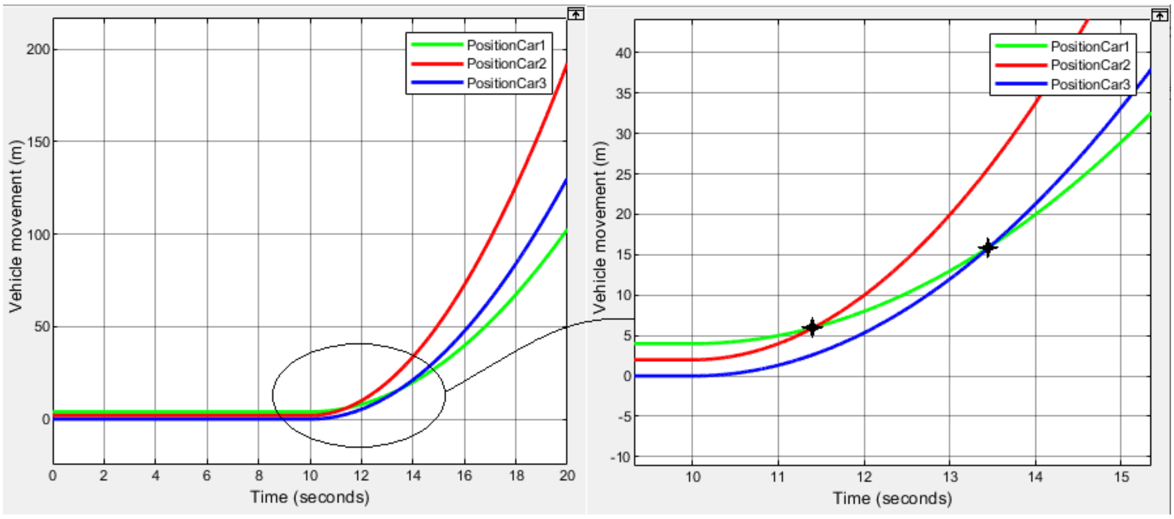

Fig. 7 – Simulation results of the vehicles having constant speed.

3.2. Experiment two

The second experiment observes the behaviour of the introduced vehicle model in case of vehicles moving with feedback of the distance between adjacent vehicles but without knowledge of the precise time when the traffic lights will change. The feedback is utilized within a simple closed-loop system with a proportional controller, where the reference desired is 2 m between vehicles and the proportional gain is $K_p = 1\,500$ for the second vehicle and $K_p = 550$ for the last vehicle. The MATLAB implementation of the first controller is the same as described in (3) and for the other two controllers is similar and described in (4). The results seen in Fig. 8 show that even if the first vehicle started to accelerate exactly when the light turned green, the second vehicle starts to move after approximately a second, and the third vehicle after two seconds because their actual movement depends on the distance of the car in front of them. The cars have no collision with each other in this scenario.

```
function ForceCar2 = ControllerCar2 (TrafficLight, PositionCar1, PositionCar2)
  persistent Movement;
  ForceCar2 = 0; Reference = 2;
  if isempty (Movement) Movement = 0; end
  if (mod(TrafficLight (1), 5*1000*10) == 0) && (TrafficLight (1) ~= 0) Movement = 1; end
  if(Movement ==1)
    if(TrafficLight(2)==0) Fs = 0; end
     Error = abs(Reference - abs(PositionCar1 - PositionCar2));
    ForceCar2= Fs + Kp * Error;
  end
```
(4)

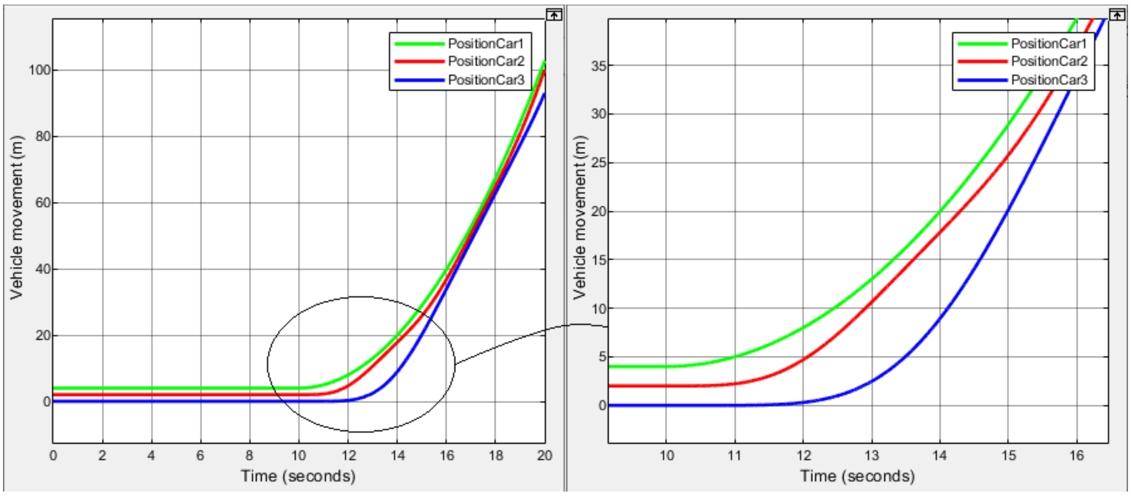

Fig. 8 – Simulation results of the vehicles having a feedback controller but without timing information.

3.3. Experiment three

The third experiment observes the behaviour of the introduced vehicle model in case of vehicles moving with feedback of the distance between adjacent vehicles and with knowledge of the precise time when the traffic lights will change. The feedback is utilized within a simple closed-loop system with a proportional controller, where the reference desired is 2 m between vehicles and the proportional gain is $K_p = 1\,000$ for the second vehicle and $K_p = 500$ for the last vehicle. In addition, because the vehicles are informed about the precise moment when the traffic lights will change, the second and the third car have a reasonable supplementary force right from the beginning, $F_s = 1\,000$ N for the second vehicle and $F_s = 1\,500$ N for the last vehicle. The MATLAB implementation of the first controller is the same as described in (3) and for the other two controllers is similar and described in (4). The results from Fig. 9 show that a synchronous start of all the vehicles has been achieved. The cars have no collision with each other in this scenario.

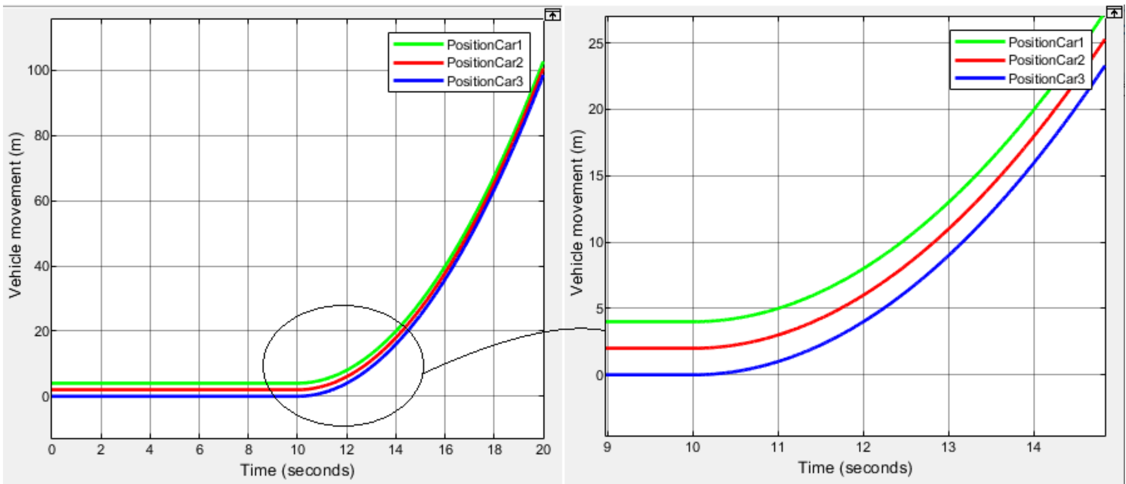

Fig. 9 – Simulation results of the vehicles having a feedback controller with timing information.

4. CONCLUSIONS

The automotive field demands high-precision time bases for time-critical applications such as advanced driver assistance systems (ADAS) and multimedia systems based on real-time audio and video. One solution is AUTOSAR global time synchronization which is capable to achieve the required demands.

The paper proposes the use of the time synchronization concept described within AUTOSAR to achieve a synchronous start of the vehicles at the traffic lights. The approach wants to corroborate the existing vehicle platooning solutions to reduce traffic congestion at intersections. For the proposed approach to work, intelligent traffic lights must be available and capable to exchange the time information related to their states in a V2X environment. The vehicles can benefit from the global time synchronization for other applications such as synchronously changing the platoon's formation, dividing at some point in time the platoon in one or more platoons or even allowing the vehicles to activate the same functionality at a precise moment in time. This research can be extended in future works with a complete intersection that operates under near-saturated traffic demands, possibly using a microscopic traffic simulator.

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