

On the Cooperative Automatic Lane Change: Speed Synchronization and Automatic “Courtesy”

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Abstract—The recent ability of some vehicles to handle autonomously the lane change maneuvers, and the progressive equipment of roads and vehicles with ITS-G5 units motivate this paper to consider the case of road narrowing that requires a lane change because one lane is occupied by road works for maintenance, incidents and so on. This paper extends the approaches of cooperative speed synchronization at intersections. Because of the complexity of the overall system, it considers each automatic lane change as a mobile (unfixed) intersection in which vehicles synchronize their velocities. The wireless communication allows each vehicle to increase its field of view to negotiate its merging with the other equipped vehicles. Hence, the proposed approach introduces a kind of automatic “courtesy” between equipped vehicles. The paper defines the intersection point between each pair of vehicles and the suited protocol to safely reach the new lane. The protocol can be handled by the new work item (NWI) that has been created at ETSI to realize platooning and cooperative adaptive cruise control. Besides enhancing safety, the simulation results show that the main advantage of the approach is the energy saving by smoothing the traffic.

Index Terms—Advanced driver assistance systems; ITS-G5; V2V; automatic lane change; autonomous vehicles

I. INTRODUCTION

The infrastructure sharing between vehicles deserves a particular attention for safety and for energy saving. This has encouraged several authors to improve the intersection management, during more than half a century. Recently, to prepare the emergence of connected driver-less vehicles, many contributions have introduced new concepts that radically change our current approaches to manage traffic at intersections [1], [2], [3] and [4]. With Cooperative Intersection Management (CIM), the vehicles negotiate the right of way and even synchronize their speeds [5] to avoid stops and accelerations, greedy in terms of energy. Nonetheless, except some tests in particular contexts, the implementation of such technologies is difficult to achieve without a completely new generation of vehicles and of urban infrastructures.

The resource sharing problem raised by intersections, is also raised by the lane change maneuvers (LCM). So, it is interesting to extend CIM principles to LCM, to improve traffic safety and efficiency during lane changes.

Instead of considering the system as a whole, we rely on the enhancement of individual behaviors, and let the overall traffic improvement emerge from their interactions. Automatic courtesy should be introduced between equipped vehicles, to increase the opportunities of lane change. To

formally express this courtesy, this paper extends works on the CIM and on the speed synchronization to the case of lane change. Changes are required in the existing protocols because the “intersection” area is no longer a fixed place, and because the negotiation is inherently decentralized. Therefore in the following, an extension of a CIM protocol is proposed to manage lane change with speed synchronization, and simulation results are presented to show the potential benefits of this use of V2X (vehicle-to-anything communication) for lane change.

II. LANE CHANGE DESCRIPTION

A. Prerequisites

To implements the proposed lane-change improvement strategy, vehicles are required to be autonomous. When dealing with non-autonomous vehicles, standard lane-change strategies (as implemented in the Mercedes-Benz E class or the Tesla Model S) will be used as fallback, so not all vehicles are required to be autonomous.

The autonomous vehicles are equipped with sensors providing a sufficient field of view for a safe overtaking. To establish a cooperative lane change protocol using vehicle-to-vehicle (V2V) communication, we suppose that vehicles are also equipped with On-Board Units (OBU). Sensor data are prominent for a close neighbor whereas wireless communication extends the field of view of the sensors. The prominence of sensors is due to the fact that it cannot be expected that all cars will be equipped with these units. Moreover even an equipped vehicle could have a malfunction and ignore messages sent by other cars. So, a vehicle trying to change its lane using V2V must use obstacle detection systems to validate data coming from the communication, i.e. when the vehicle wants to overtake, if it detects another vehicle not signaled by V2V, it will interrupt the lane change procedure. Finally, vehicles need to be equipped with a precise positioning system (Differential GPS, Real Time Kinematic, Simultaneous Localization And Mapping, etc.).

B. Definitions

In the following, the definitions displayed in figure 1 are used to refer to the cars involved in the lane change operation. These definitions are similar to the ones in [6].

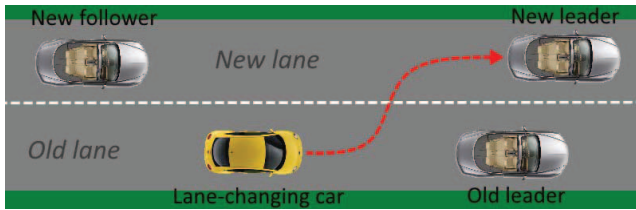


Fig. 1: Lane change definitions

C. Protocol basis

Using vehicular communication is a way to introduce exceptions to a radar-only lane change solution. In a first step, the vehicle analyzes the situation to find if it can safely change its lane according to data coming from sensors. If a lane change is not possible due to the presence of other cars, then the vehicle starts a negotiation to allow the lane change. The goal of this negotiation is to make the other cars adapt their speed (without exceeding their comfortable deceleration and acceleration bounds) to let the car merge in the other lane.

There are three independent points that must be precisely defined:

- What should trigger the lane change ?
- How to define that the car can make a lane change according to radar (or other physical sensors) ?
- How the V2V negotiation will allow lane change ?

To define if a car has to make a lane change, the four cases of lane change defined in [6] are used. Then to define if a car is allowed to make a lane change according to radar, the protocol relies on an underlying longitudinal model like IDM [7] or RT-ACC [8], and if the lane change does not make the lane changing car brake above a given value (for instance $-2m.s^{-2}$) and does not make the new follower car brake, then the lane change is allowed.

If the lane change is not allowed for the moment but the car has to make a lane change, then communication will be used to generate a situation where the cars will not have to brake above the given limit for braking, thus allowing a safe lane change.

III. COOPERATIVE LANE CHANGE

A. Lane change protocol

Once a car decides to make a lane change, it defines an intersection point which sets a limit for the lane change, i.e. the lane changing car expects to make its lane change before or at the intersection point, and notifies its intention to make a lane change to surrounding cars by broadcasting the intersection point coordinates and its data (current position and speed).

The new followers then decide if they shall accept to let the lane changing car make its lane change. If so, they notify the lane changing car and start to synchronize their speed to let it merge on their lane. The current leader of the closest new follower becomes the new leader of the lane changing car, and the lane changing car starts to synchronize its speed to merge behind its new leader without having to brake above

the limit. If there are no cars allowing the lane change, the car will set up a new intersection point and restart the procedure. If the lane changing car reach a point where it cannot continue without making a lane change, then it will stop and wait until the traffic allow this movement.

Multiple points must be clearly defined to get an efficient solution:

- The communication protocol, i.e. the type and the sequence of messages for the negotiation
- The criterion for the acceptance of the lane change by the new followers
- The ideal position of the intersection point

These points are detailed in the following parts.

B. Communication protocol

On the contrary to lane change policies designed for simulation, the issues of hardware have to be considered. To design a cooperative lane change communication protocol, the following assumptions have been made:

- Wireless communication is not perfect and there is no real-time guaranty that the message will be delivered
- Data contained in a packet may not be up-to-date due to network latency issues

The Transparent Intersection Manager (TIM) protocol [5] which is designed to overcome these issues is used as a basis and has been extended to integrate the notion of unfixed intersection. In the TIM protocol, vehicles approaching the intersection send an authorization request to an intersection server, this server then builds a sequence of vehicles and broadcast it to all vehicles. Vehicles synchronize their speeds with their leader in the sequence, and notify the intersection server once they leave the intersection.

In the adaptation to lane change, the lane changing car acts as an intersection server and broadcast the coordinates of a virtual intersection to the other cars. So the concerned cars should send a message to the "intersection server" to get a position in the sequence, and then synchronize their speed with their leader in the sequence. In the adaptation of this protocol to the lane change, five messages have been designed.

Three messages already defined by the TIM protocol and sent by the potential new-followers: authorization request, refresh message, and exit notification.

Two messages specific to the lane change and sent by the lane changing car:

- 1) The lane change request: sent by a car to notify its intention to make a lane change and thus creating a virtual intersection point
- 2) The lane change end: sent by a car to notify it has ended its lane change or that it has no more intention to make a lane change

In a typical scenario, a lane changing car will emit a lane change request message. If it has not already sent an authorization to another car, a new-follower may allow the lane change and emit an authorization request, thus explicitly giving the right to make a lane change to the lane changing

car. Both cars will then emit refresh messages to notify their current position and speed to perform speed synchronization.

The following key points are introduced by this protocol:

Accepted deceleration: When the lane change is authorized, the new-follower agrees to brake to let the lane changing car make its lane change, allowing it to merge in the new-follower lane even if it is not allowed by the radar-based lane change policy.

Default denial: Without an explicit authorization message from a new-follower car, the lane change is denied.

Improved safety: A new-follower can only give the right of way to one car, therefore it prevents more than one car to simultaneously merge in the lane before the new-follower.

Speed synchronization: Letting the new-follower car to know the position and the speed of the lane changing car allows the new-follower car to synchronize its speed with it, thus smoothing the lane change operation.

C. Intersection point coordinates

The intersection point is the limit point where the lane changing car must have made its lane change. This point is always in front of the lane changing car, so the position of the intersection point will be defined by its distance from the front of the car called d_i .

To compute the intersection point the assumption is made that the new lane is at full capacity (worst-case scenario), i.e. the inter-vehicular distance h is the minimum allowed by the longitudinal model and the current velocity v_0 of the vehicles. The goal of the negotiation is to increase this space to allow the lane changing car to merge into the new lane, without making the vehicles exceed their comfortable deceleration named b_f . Therefore, the intersection point must be far enough to let the time for the creation of an inter-vehicular gap in the new lane whose size will let a car merge in the new lane, and without forcing a car to brake above a fixed deceleration value.

The distance to this intersection point is given by:

$$d_i = \min(u, v_0 \times \left(\tau + \sqrt{\frac{h+l}{-b_f}} \right)) \quad (1)$$

Where u is a potential limit for the intersection point (e.g. the end of the insertion lane in the case of an insertion), l the length of the car and τ a reaction time, i.e. the estimated delay between the emission of the lane change request and the application of the speed synchronization by the new followers.

The safe distance between two cars in the new lane is supposed equal to h , to let another car merge between two cars, the distance must be changed to $2h + l$. It is supposed that the velocity of the leader car is constant, while the follower car is braking to b_f . Therefore, the position of the leader is $p_l(t) = p_l(0) + v_0 t$ and the position of the follower is $p_f(t) = p_f(0) + v_0 t + b_f t^2$. Then, $t \geq \sqrt{\frac{h+l}{-b_f}}$.

Which gives the time required to have the minimum inter-vehicular distance according to hypotheses. Then τ is added to this time for the sake of safety, and the distance traveled

during this total time is given by $v_0 \times (\tau + t) = v_0 \times \left(\tau + \sqrt{\frac{h+l}{-b_f}} \right)$.

If the safe headway time given by [9] is used, then the formula becomes:

$$d_i = \min(u, v_0 \times \left(\tau + \sqrt{\frac{v_0 t_r + \frac{k \times v_0^2}{2} \left(\frac{1}{a_f} - \frac{1}{a_l} \right) + l}{-b_f}} \right)) \quad (2)$$

D. Acceptance criterion

The acceptance criterion is the criterion used by a potential new-follower car to determine whether to allow a car to merge in its lane or not. The objective is to allow the lane change while minimizing self-deceleration or limiting it to a given value. Multiples parameters impact this decision: the distance to the intersection point, the relative velocities of the new-follower and of the lane changing car, and the headway between the new-follower and its current leader.

When the lane change request is received by the potential new-follower, it knows the coordinate to the intersection point relative to the lane changing car d_i , the position p and the current speed v of the lane changing car. Then it assumes that the lane changing car is its new leader and assumes a deceleration of b_f . It is also assumed that the speed of the lane changing car is constant.

The time required by the lane changing car to reach the intersection point is $t_i = \frac{d_i}{v}$.

The distance traveled by the new-follower during this time is $d = v_0 t + b_f \times t^2$ with $t = \min(t_i, \left| \frac{v_0}{b_f} \right|)$. If p_f is the position of the new-follower, then the new-follower will allow the lane changing car to merge if $p_f + d < p + d_i$. Therefore the acceptance criterion is summed up in (3).

$$p_f + v_0 t + b_f \times t^2 < p + d_i, t = \min(t_i, \left| \frac{v_0}{b_f} \right|) \quad (3)$$

E. Car behavior and speed synchronization

The default initial state of a car is "travel" which means that the car is just traveling on its lane with respect to inter-vehicular distance. From this state, two states can be reached: if a lane change is required according to the chosen lane change policy, then the lane change procedure is started, otherwise if a lane change request is received, the speed synchronization procedure is started.

To synchronize its speed with a lane changing car, the new-follower will start braking (using its accepted deceleration value) until the distance between it and its new leader (the lane changing car) is safe. This safety is estimated using an underlying longitudinal model: if the deceleration value computed by this model knowing the distance between the cars and their speed is more important than the accepted deceleration, the situation will not be considered as safe.

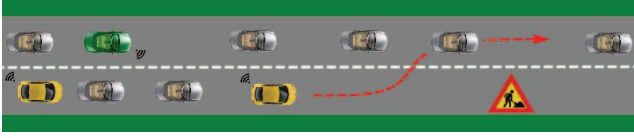


Fig. 2: Simulation scenario

IV. SIMULATIONS

A. Tests

To evaluate the interest of the solution, a specific simulation scenario has been designed: on a road with two lanes, the right lane is closed, the cars on the right lane have to merge on the left lane to go further (it is similar to an insertion). Each car has a specific target speed randomly chosen.

There are two comparisons of 10 simulations of each scenario. The first one compares the introduced strategy (Cooperative lane change-CLC) with MOBIL [10] strategy for simulating the automatic lane change without using V2X. The number of vehicle is set to 60 during 240s ($q = 0.25$ veh/s). Different indicators have been measured: the average speed and the output to estimate the global performance of the system, the G value (indicator of the traffic quality and the energy consumption see (4)) [11] and the average stop time.

$$G = \frac{\sqrt{\frac{\int_0^T (a(t) - a_{avg})^2 dt}{T}}}{v_{avg}} \quad (4)$$

The simulation was realized using a dedicated simulator following the principles of multi-agent based systems, where each car was controlled by an independent agent, whose knowledge of the environment was restricted to data acquired from virtual sensors.

B. Results

The tables I and II show respectively the measures made for a V2X based lane change policy and a radar-only lane change policy.

	Avg speed	Avg G	Stop time	Vehicles out
Mean	8.072	$2.18e^{-2}$	0.198	43.62
σ	0.361	0.002	0.135	0.701

TABLE I: Measures using V2X for lane change negotiation with 0.25veh/s for 240s

	Avg speed	Avg G	Stop time	Vehicles out
Mean	8.170	$2.44e^{-2}$	5.999	43.27
σ	0.354	0.002	2.557	1.009

TABLE II: Measures using only radar for lane change with 0.25veh/s for 240s

A slight reduction of the average speed when using V2X (-1.21%) can be observed, though the number of vehicles out

is not significantly reduced. Indeed, slower vehicles initially located in the right-lane are able to merge in the left-lane thus reducing the average speed of the left-lane. In the scenario the traffic flow is limited by the number of lanes, so a traffic flow improvement cannot be expected by the use of communication. Moreover, we can see a small improvement for the G value (-10.64%) meaning a better traffic fluidity.

Finally, the most significant change is the reduction of the stop time (-96.7 %). Indeed, without negotiation the cars on the right-lane were frequently stuck behind the obstacle in the left-lane. When using V2X negotiation, the cars in the right-lane were flawlessly merging in the left-lane and almost never had to stop behind the obstacle.

V. CONCLUSION

This paper presents a cooperative lane change policy using vehicular communication to allow velocity synchronization of cars. The purpose of this policy is to introduce a form of courtesy among autonomous vehicles to allow a better road sharing among these vehicles. To achieve this, a specific protocol based on CIM is defined and detailed. Finally, results of simulation are presented showing a better fluidity, and a reduction of the average stop time without a significant impact on the traffic flow.

The proposed protocol relies on the definition of a virtual intersection point corresponding to the expected location of the lane change, and on the definition of an acceptance criterion stating if a new-follower car will let a lane changing car merge before it. The encouraging results of simulations invite to explore new policies to define system parameters that potentially enhance the traffic throughput.

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