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CityACC – On the way towards an intelligent autonomous driving

Thanh Binh To*, Marc-Michael Meinecke*, Frank Schroven*, Sergiu Nedevschi, Jörn Christian Knaup***

**Volkswagen Group Research, Volkswagen AG, Wolfsburg, Germany*
(e-mail:Thanh-Binh.To, Marc-Michael.Meinecke, Frank.Schroven & Joern.Christian.Knaup@volkswagen.de)

***Faculty of Automation and Computer Science, Technical University of Cluj-Napoca, Romania*
(e-mail: Sergiu.Nedevschi@cs.utcluj.ro)

Abstract: As comfort systems, the existing Adaptive Cruise Control systems **(**ACC-systems) function well on motorways and well-structured highways, but there are a lot of challenges for machine-supported driving in urban environments. This paper is aimed to introduce an innovative way to extension of the existing ACC-system for driving in the urban environments (so-called CityACC), where the secondary optical sensor (a stereo-camera) and an intelligent decision making algorithm are used for improving the performance of the whole system.

1. INTRODUCTION

Up to now driver assistance systems have been a very important topic of research and development due to their big potential for improved driving comfort and increased vehicle safety. For example, the full-speed-range ACC-systems based on 77GHz radar sensors have recently been commercialized successfully. The most important task of those systems is a partial automation of the longitudinal vehicle control and the reduction of the driver's workload by supporting the driver in a convenient manner and in dedicated traffic situations. The existing ACC-systems are well functioning on motorways and on well-structured highways. The most disadvantages of the existing ACC-systems can be characterized by the following facts:

- They can not be used in the most of urban driving scenes or in other complex traffic situations like this.
- The manoeuvre of the equipped vehicle (so-called ego vehicle) is recognized too late so that a current control object (vehicle) is released always with a big delay and a new control object can not be considered early for longitudinal control.
- Cut-in and cut-out situations of objects are often recognized late.
- Malfunctions may occur when driving very sharp curves.

Another well-known comfort system is the lane keeping system based on cameras. It works well in traffic jam situation by detecting the current lane and using the lane information for a lateral control. For improving the longitudinal and lateral control of the commercial vehicles, future driver assistance systems need comprehensive information about the vehicle surrounding field like the road and obstacle information. Individual sensor systems and sensor technologies do not meet this requirement any longer. Rather a common collection of the driving environment with different sensors is necessary. Since the collection of the driving environment is based on the measurements of vehicle and surrounding field sensors, the information is incomplete, uncertain and faulted.

The perception task will be more complicate and difficult for driving in the urban environments. Some challenges and special requirements on sensors and ACC-functionalities for the extension of the existing ACC-systems for driving in the urban environments will be discussed in Section 2. After analysing the special requirements in details, we introduce an acceptable sensor configuration with high value for money in an experimental vehicle in Section 3. Among an improved target object selection algorithm for the longitudinal control, a possibility to provide an advanced driver support with the lateral control will be considered in Section 4 by introducing a new automotive path planning. Section 5 is dedicated to a short description of our controller. The final section ends with a conclusion and an outlook on future works.

2. CHALLENGES FOR MACHINE SUPPORTED DRIVING IN URBAN ENVIRONMENTS

As mentioned before the complexity and density of objects in urban environments is much higher than in non-urban situations. In rural conditions only a small number of objects occur. In the most of these cases there are lanes with vehicles driving in the same direction as the ego vehicle is and other vehicles driving in the opposite direction. Mostly stationary targets are neglected.

In contrast to this, urban traffic has a total different character. In addition to the vehicles driving in the same and opposite direction there are a lot of crossing objects (e.g. pedestrians or bicyclists). Furthermore stationary targets (e.g. parked cars, traffic islands, curbs) become much more important. In Fig. 1 some examples of typical urban scenarios are depicted.

Fig. 1: Examples of typical urban scenarios

It is easy to understand that it is difficult to guaranty that the standard ACC functionality works properly in such scenarios. Due to the fact that the vehicle ahead (the so-called "relevant object") is relatively close to the ego vehicle the reaction capability of a CityACC system must be quite fast. Another requirement for city capable ACC is that objects in high curvature conditions must be detected and measured by the system continuously.

Therefore the additional requirements for a CityACC sensor system compared to a standard ACC system are:

- Wide field of view (high opening angle in azimuth).
- Detection capability of slowly driving vehicles and stationary objects.
- Target resolution capability (target separation capability) in range, speed and angle.
- Detection capability of lane markings and curbs, pillars, and other road side constructions.
- Detection capability of vulnerable road users (pedestrians, bicyclists).
- Quick target acquisition (e.g. when occluded objects become visible suddenly and become then relevant).
- Traffic light and traffic sign recognition is of interest for CityACC as well as the ability to give way or stop at red lights.

3. EXPERIMENTAL VEHICLE

3.1 Sensor systems

The existing ACC-systems are based on serial 77GHz radar with very small detection angle of 12° and the maximal detection range about 150m up to 200m. The radar sensor is mounted just behind the emblem and in the front of the engine cooling system. Using electromagnetic microwaves, radar sensors can detect well the moving and stopped objects. It measures the relative distance to the objects and the object velocity very precisely. Stationary objects can not be detected by existing radar sensors due to very difficult tracking tasks and difficulties in terms of discrimination of non-relevant targets (e.g. metallic manhole covers) and relevant targets (e.g. cars). For the extension of ACC functions for urban driving we use a stereo-camera system with a very wide detection angle (72°), which is mounted in the space between the wind-shield and the middle interior rear view mirrors (see Fig. 2).

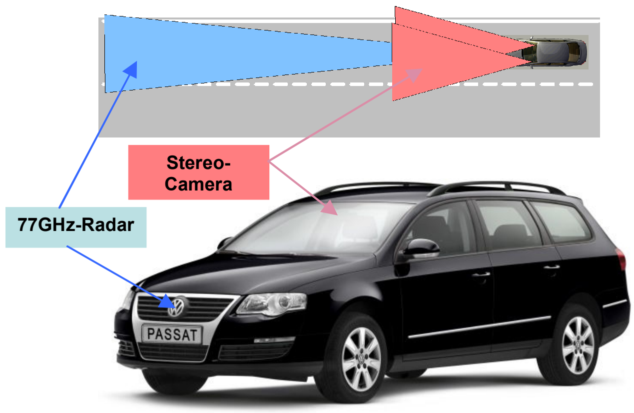

Fig. 2: Sensors system for CityACC

In our system, the stereo-camera based image processing module meets many requirements mentioned in the previous section, and is able to provide the following information about the driving environment (see Fig. 3, Nedevschi, S. and Meinecke, M.-M. and To, T.B. *et al.* (2007)):

- Information about the road geometry (e.g. lane width, the lane curvature and curvature changes etc.) as well as position and orientation of the ego vehicle within the lane. It also delivers lane markings. Due to very wide field of view, it can detect even very sharp curves.
- Estimation of the object geometrical data like object width, length and height as well as object orientation and object dynamics like velocity etc.
- It can detect traffic islands and even small curbs or poles.
- It can provide information about the drivable area in front of the vehicle after analysing the elevation map.

- It can recognize pedestrians that are close to the car.

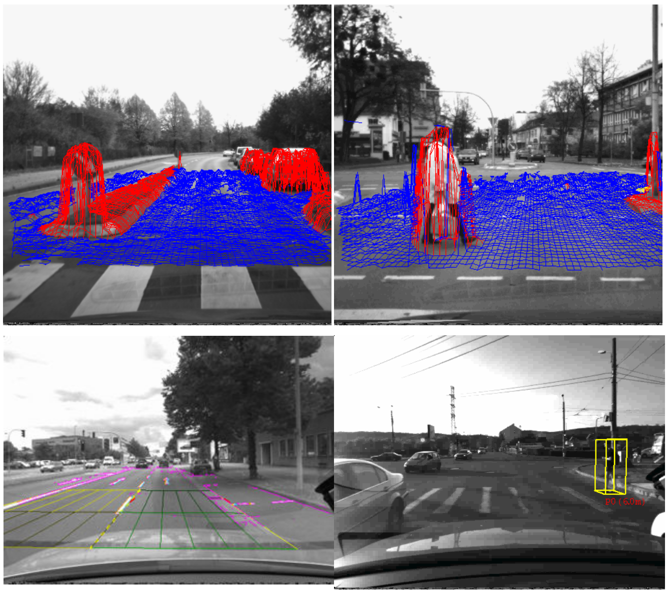

Fig. 3: Object and lane detection using stereo-camera systems

All data from the stereo-camera system (lane and object data), the data provided by the radar sensor and the dynamical data of the ego vehicle like velocity, acceleration, yaw rate are sent over a CAN-bus to a PC for sensor data fusion.

3.2 Sensor data fusion architecture

Environmental perception through sensor fusion for automotive applications is an intensive research area. Since the advent of the first driver assistance systems researchers have worked on multi sensor systems that perceive the whole surrounding traffic scene. At Volkswagen Group Research various sensor and fusion configurations have been under examination over the last decade. The applied fusion architecture consists of four layers (see Fig. 4). The first layer is formed by the sensor network. All sensors transmit their tracked object data to the fusion layer. To avoid delayed data due to a different processing time, the data are queued and sorted before the global tracks will be fused into an environmental model. The environmental model (Weiss, K. *et al.* (2005)) is a combined description of the surrounding of the vehicle. It integrates models for tracked target objects, the road and the ego vehicle. At the interpretation layer the classification of driving manoeuvres of targets and traffic situations is performed. The aim of the situation classification is to describe the meaning of the perceived environmental model (To, T.B. *et al.* (2006)). The situation classification assesses motion and manoeuvres of objects in the background of the domain city way. The result of the situation classification is an abstract representation of the environmental model, but it is not intended as an input for a collision avoidance system. The current traffic situation is divided into several classes, like approaching, following or overtaking. A situation is determined for each detected object with respect to the ego vehicle.

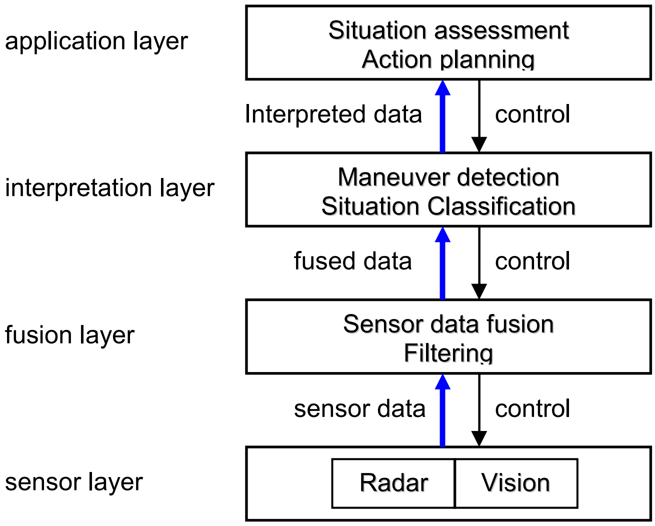

Fig. 4: Sensor data fusion architecture

Finally, the environmental model is considered as the common input for our applications, longitudinal and lateral control of the vehicle. The quality of the CityACC system on the one hand strongly depends on the quality of the longitudinal control strategy, but on the other hand also on how good an object in the front of the experiment vehicle is considered as the target/relevant object. In comparison with the serial ACC-system, the selection of the control object in our system is much better, especially in cut-in, cut-out situations of objects or in overtaking situations of the ego vehicle. A reason for the better performance is a better lane assignment and earlier lane change or manoeuvres detection for all objects and ego vehicle. For synchronizing the processing of the environmental server and for stamping the measurement data, a global time is distributed to all processing layers.

4. DECISION MAKING AND PATH PLANNING

4.1 Advanced Target Object Selection

After perceiving the driving environment, plans and decisions must be made to achieve an appropriate response (behaviour control) to the traffic situation. In other words, using the data of the environmental model in the sensor data fusion, the whole system has to analyse the current traffic situation and to make the following decisions and to send the appropriate data to the longitudinal and lateral controller, that are implemented in the rapid prototyping platform dSpace-Autobox (dSPACE Company, see Fig. 5):

- no object in front in the ego lane: *free mode*
- transition from following a vehicle to having no vehicle in front: *object cut-out*
- transition from having no vehicle to follow to a new vehicle in front: *object cut-in*

- potential relevant objects are not visible because of the limited field of view of the radar sensor (esp. on roads with high curvature): *limited perception*
- lane change of the ego vehicle: *ego lane change*

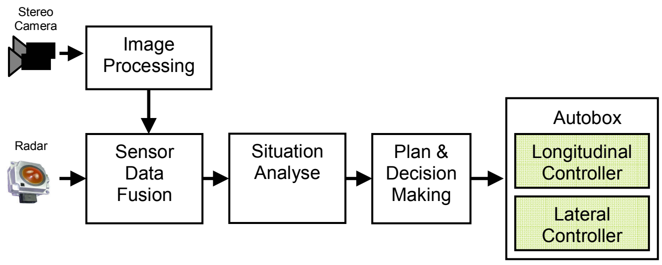

Fig. 5: System configuration

Using the rapid prototyping platform, development becomes very comfortable because the controller's parameters can be changed online without time consuming code generation or compilation.

Because no lane information is available in the existing radar-based ACC-system, the ego driving tube (estimated by the yaw rate, the velocity and the width of the ego vehicle) are used to make the decisions mentioned above. Due to the heavily fluctuation of the radar signals reflected from objects and due to the lack of the object width information, it is not easy to make a decision if the object will be in the current lane of the equipped vehicle. Especially in curves the current ACC systems suffer from the limited field of view of the radar sensors. In our system, the stereo-camera-based image processing module can also provide the lane data. If the lane markings are well (e.g. in the motorway and well-structured highway or in some urban streets), the lane data will be achieved with very high quality.

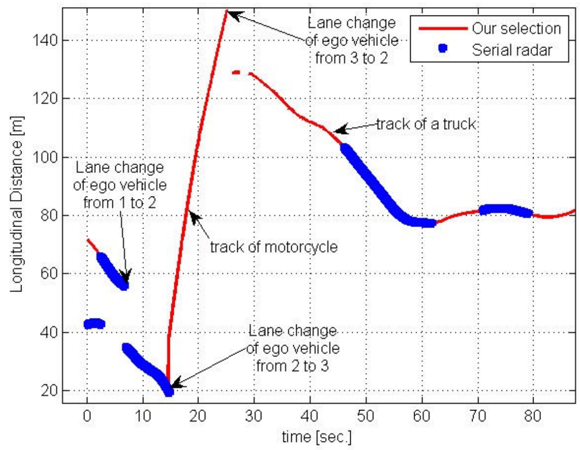

Fig. 6: Advanced Object Selection in a scenario in the expressway. The red (thin) and blue (thick) line describe the longitudinal distance of relevant objects detected by our system in comparison to serial radar

Based on an environmental perception system, our system is more robust than systems based on a single sensor perception. It can detect the following situations earlier:

- cut-in and cut-out situations of the selected objects,
- manoeuvres of the equipped vehicle (especially overtaking),

and therefore the system can react very quickly to the changing traffic environment. The advantages of our advanced selection of the relevant object are shown by considering a scenario in the 3-lane-motorway (see Fig. 6).

Here, at the beginning the equipped vehicle moves on the right lane (the first lane), a truck is in the second lane at a relative distance 40m and a car in the first lane at 70m. For all manoeuvres of the equipped vehicle like lane changing or lane keeping, our decision making module works well and robustly.

Unfortunately, for driving in the urban environment, the lane markings are not always and sometimes only partly available. For this reason, it is much more difficult to solve the decision making task for the urban driving than for the non-urban driving. An intelligent path planning can help us not only by solving this problem, but by introducing a new driver support possibility and by improving the collision avoidance.

4.2 Path planning

In the literature some path planning algorithms like Bug's algorithms (Lumelsky, V. *et al.* (1990)), artificial potential fields (Khatib, O. (1995)), the Vector Field Histogram (Borenstein, J. *et al.* (1991)) and elastic bands (Quinlan, S. *et al.* (1993)) are proposed and successfully used for robot controls.

For automotive applications, a few researchers modified the main concept of elastic bands and applied them for following a leader vehicle (Gehrig, Stefan K. (2001)) or for automatic collision avoidance systems (Brandt, T. *et al.* (2006)).

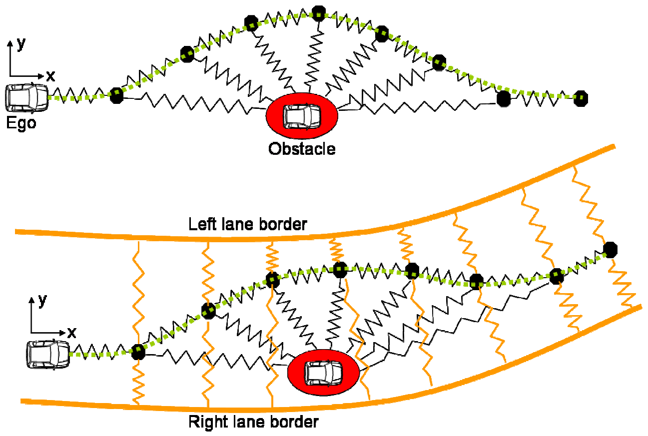

Fig. 7: Model of elastic bands

In our system we use the elastic band approach, which combine a real-time path planning with vehicle control aiming at a collision free motion to the goal. An elastic band is a deformable collision-free path. Whenever an obstacle is detected, the band is deformed according to an artificial force, aiming at keeping a smooth path and simultaneously maintaining the clearance from the obstacles (see Fig. 7).

In our implementation, an elastic band consists of many nodes, connected among each other, to the road borders and to obstacles by springs. The first node is fixed to the ego vehicle and the last one can be placed on the road along the planned path. A collision-free path is a smooth path (e.g. splines) coming through all nodes of elastic bands. For making elastic bands useable for automotive collision avoidance systems, we use the concept of the elastic bands (Brandt, T. *et al.* (2006)) with the following modifications:

- Every obstacle is modelled as a safety ellipse instead of a safety circles (see Fig. 8). This is because all objects or obstacles are detected and tracked in the sensor data fusion module. Object data like position, velocity and geometrical parameters (e.g. width, length and height) are calculated with the given uncertainties (measuring variances). The safety ellipse is placed exactly on the object position, whereas its axes length is set to the lateral and longitudinal position uncertainties. This new representation of obstacles is more natural than in the former concept and therefore it allows us to find a feasible collision-free path along very long road objects like trucks or traffic islands, whereas no feasible paths can be found using safety circles.

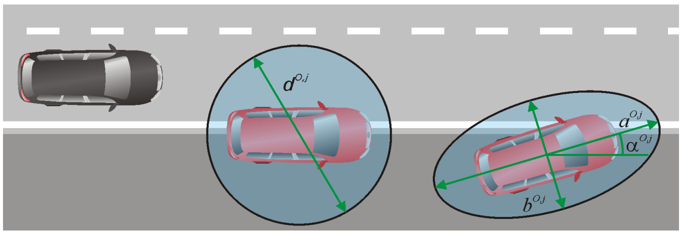

Fig. 8: Safety ellipses instead of safety circles

- Because ACC-systems are comfort systems, a collision-free path must be calculated so that the manoeuvre around obstacles is acceptable by drivers. In the control language, the lateral acceleration of the ego vehicle must be lower than a maximal value, what depends on the ego velocity. For this reason, the restriction on the lateral acceleration must be considered by searching for a collision-free path.

- To accelerate the path finding process (also searching process for stable states of elastic bands) each node can be moved only in the lateral direction (see Fig. 9). This modification is for us very important, because the searching process is very time-consuming especially if the number of nodes is big. Using this modification, the calculation time is reduced heavily, so that our path planning can be done well in the test bed vehicle.

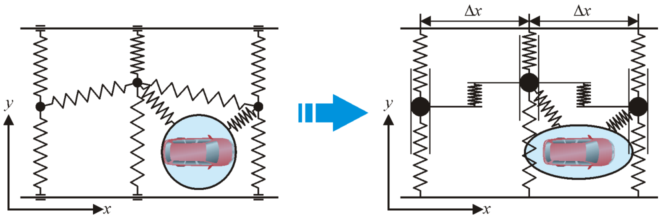

Fig. 9: Lateral motion direction of a node

The following figures show some simulation results of the path planning/executing for collision avoidance situations, what are often met in the urban environment. A simple driving situation is driving around traffic islands in the middle of a road (modelled by two black rectangles on the bottom of Fig. 10) or around a car parked on the road right side (a blue rectangle on the top of Fig. 10). Those simulation cases clearly show an advantage of the novel path planning and decision making. By following a moving object vehicle in those situations and at the time point, where the obstacles (traffic islands or parked cars) are between the ego vehicle and the moving object vehicle, the existing ACC-systems do not consider those obstacles as the relevant control object and the ego vehicle equipped with those ACC-systems can hit those obstacles. In contrast to the existing ACC-systems, our system can detect even traffic islands and plan a new path (violet lines in Fig. 10) to avoid any collision with obstacles.

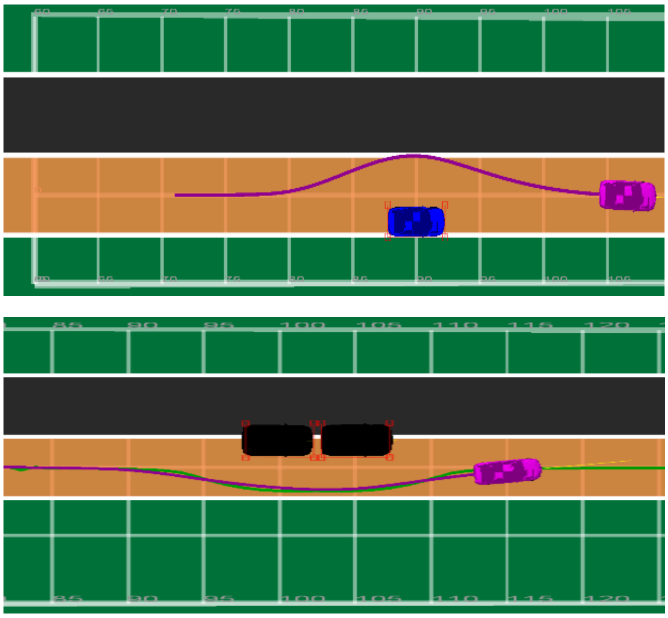

Fig. 10: Driving around a traffic island (bottom) and a parked car (top)

Fig. 11 shows the effectiveness of our path planning for a more complex situation on a curve with two lanes and some stationary obstacles (blue rectangles). Even in this case, a human-like collision-free path (represented as a green line) can also be found.

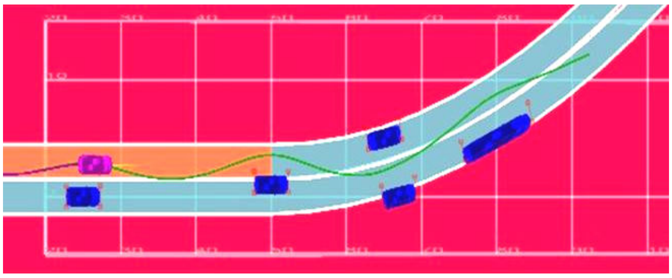

Fig. 11: Path planning on the left curve

5. LONGITUDINAL VEHICLE CONTROL

The longitudinal vehicle control can be split up into a velocity controller and a distance controller. When no leading vehicle is present (free mode) the system accelerates up to the driver's desired speed. In follow mode the distance controller keeps the driver's set time gap to the object ahead. The controller's output is an acceleration request that is handled by the car's engine and brake ECU (Electronic Control Unit).

Especially when driving in urban environment different scenarios have to be treated in different ways to meet the driver's expectation. When the leading car for example accelerates after standing, the controller has to distinguish a takeoff from a red traffic light from a smooth drive within traffic congestion. Therefore a variable controller structure is used that can easily represent different driving patterns. Fig. 12 shows an example of the described situation.

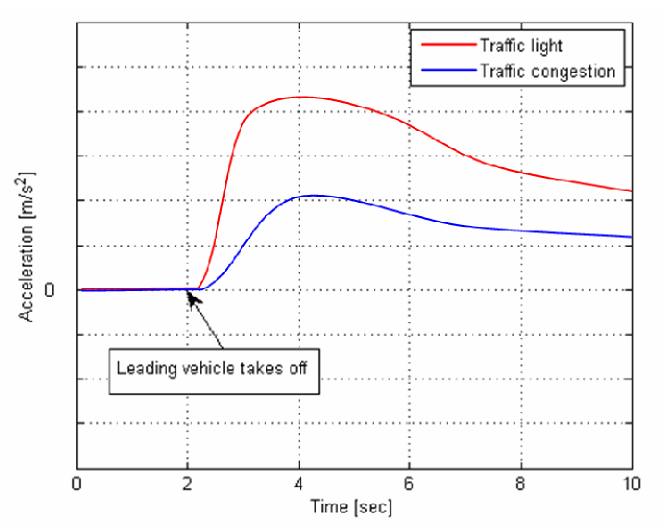

Fig. 12: Desired longitudinal vehicle acceleration for different driving scenarios

6. CONCLUSIONS AND FUTURE WORKS

In this paper, we introduce an innovative way for making the existing ACC-systems available for urban environments. A stereo-camera system plays hereby a decisive role for better understanding the complex urban environments, whereas an intelligent path planning provides excellent human-like supports for comfortable driving in some complex urban traffic situations. Although our CityACC works now well under many conditions it may fail sometimes due to environmental conditions, sensor faults or other reasons, which is certainly a further issue for research.

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