Smart and Green ACC, Safety and Efficiency for a Longitudinal Driving Assistance

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Abstract Driving Assistances aim at enhancing the driver safety and the comfort. Nowadays, the consumption is also a major criterion which must be integrated in the driving assistances. Then, we propose to redefine the behavior of an ACC with energy efficiency consideration to perform a Smart and Green ACC. We apply our development to the specific use case of the electric vehicle that allows regenerative braking. The ACC, once activated, operates under two possible modes (speed control and headway spacing control). We define the behavior of the driving assistance under these both possible modes, focusing on the distance control. We present the efficiency of various strategies without trading off safety. We conclude on the efficiency by presenting several use cases that show the SAGA behavior.

Keywords Driving assistance · Longitudinal control · Energy efficiency

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1 Introduction

Daily traffic congestion or long trip on a highway brings up issues that the driver must face during his driving experience. However, these tasks may generate anger, stress or drowsiness. In a situation where the driver kept a constant clearance for a long time, and suddenly facing braking, his reaction time is higher and may lead to a collision. Automation, and automated driving seem to be one possible answer to these problems, by delegating partly or totally the driving task. Many projects during the 80's and 90's, have proved the feasibility of automated and autonomous (without driver interaction) driving systems. Eureka Prometheus project in Europe, or the US National Automated Highway System consortium conducted experiments on real road of automated driving or platoon. Even if the concepts were not fully adapted by car manufacturers, current vehicles benefit greatly from these research. Since 10 years, the driving assistances are booming. However these driving assistances present two major drawbacks:

- The optimization process behind the driving assistance aims only at maximizing the safety and/or the comfort of the considered vehicle,
- In order to work, the driving assistance relies only on the perception systems embedded in the vehicle: they are autonomous systems.

In today situation, the energy consumption is one of the major topic for the car users: electric vehicles still have a limited range and for conventional vehicles, the oil price has skyrocketed and the greenhouse gas emissions must be reduced. The consumption criterion must be taken into account in the definition of a driving assistance.

Moreover, communication devices and navigation devices become popular. In a vehicle, we can consider that we have access to these systems to exchange data with other vehicles and with the infrastructure. The driving assistance systems are now cooperative and the driving assistance systems can sense the environment behind the vehicle sensors range.

In the eFuture project, we focus on the shared control between the vehicle automated systems and the driver for electric vehicles. The driving assistance we propose, the Smart and Green ACC (SAGA), derives from a standard ACC (Adaptive Cruise Control). It aims at optimizing the common criteria and also the energy consumption. Moreover, the required variables come from the vehicle sensors and from a digital map which includes information on the upcoming road.

With an Adaptive Cruise Control system, the driver delegates the longitudinal control task. When the system is active, the vehicle speed is controlled automatically either to maintain a given clearance to a forward vehicle, or to maintain the driver desired speed, whichever is lower. Since 1997, car manufacturers propose this system on their high-end cars. However, research is still active. Researchers aim at evaluating the impact of the ACC on traffic, under congested situation [1] or with improved strategies [2]. They also extend the range of possible speeds, driver comfort, safety or road capacity [3, 4]. In 2006, the introduction of a vehicle to vehicle communication (cooperation ACC, C-ACC) allows to decrease drastically the clearance to a forward vehicle [5] and also to create stable vehicle platoon. The evaluation of the C-ACC [6, 7] shows promising results on road capacity and safety. An ISO standard now defines the intended performance of the ACC [8].

In the following, we develop the Smart and Green ACC function. In the next section, we define the function, the notations and the consumption model. Section 3 explains the two problems: speed control and distance control. This last point, being the main issue, as it means to handle both consumption and safety criteria, will be developed in Sect. 4. The Sect. 5 presents simulation results. In the last section, we conclude on this work.

2 Problem Definition

2.1 Adaptive Cruise Control

When an ACC system operates, the function is either in a speed control or distance control mode (Fig. 1). In the first case, there is no vehicle in front of the considered vehicle or in the distance of sensing. The vehicle aims at reaching a driver's desired speed. In the second case, a vehicle is in front of our vehicle. The system aims at maintaining a clearance defined by the driver, as soon as the lead vehicle speed is lower than the driver's desired speed.

The general variables are represented on the Fig. 1, along with the Table 1, for the description and units.

Moreover, [8] also defines the operating range of the driving assistance. The assistance cannot be activated below a given speed V_{min}, which must be higher than 7 m/s. The average automatic deceleration of ACC systems shall not exceed 3.5 m/s^2, while the acceleration is limited to 2 m/s^2. the average rate of change of an automatic deceleration (jerk) shall not exceed 2.5 m/s^2. The ISO standard also defines the minimal performance of the perception system according to the possible value of the speed and of the time gap.

Then, we have to define the behavior of the SAGA function for these two modes: Speed Control and Distance Control.

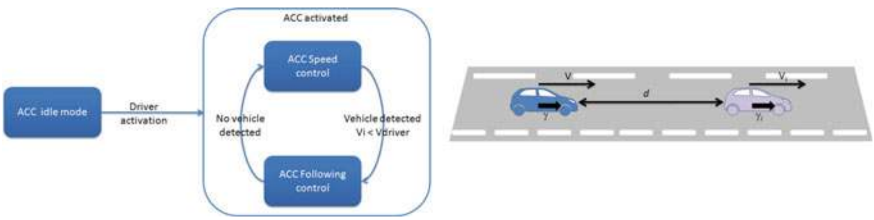


Fig. 1 ACC architecture and generic use case

Table 1 ACC related variables

Variables	Description	Units
d	Clearances to the lead vehicle	m
V, V_d	Speed of the ego vehicle, drive desired speed	m/s
γ	Acceleration of the ego vehicle	m/s^2
T, T_d	Time Headway ($T = d/V$), driver desired time headway	s
V_i	Speed of the lead vehicle	m/s
γ_{i}	Acceleration of the lead vehicle	m/s^2
ΔV	Relative speed ($\Delta V = V_{\mathrm{i}} - V$)	m/s

2.2 Consumption and Efficiency Model

The consumption model that we define here, is based on the evaluation of the torque needed, at each of the two motorized wheel, to overcome resisting forces and generate the desired acceleration. It could be defined as:

$$T = \frac{R_w}{2}\left(\frac{1}{2}\rho SC_x V^2 + MgC_{rr} + MG\sin\Phi_r + M\gamma\right) \tag{1}$$

where R_w is the wheel radius, the air volumetric mass, SC_x the air drag coefficient, V the current vehicle speed, M the vehicle's mass, C_{rr} the rolling resistance coefficient, ϕ_r the slope and γ the vehicle acceleration. The engine speed, supposing without sliding, is $w_e = {}^{V}\!/_{R_w}$. According with the torque definition, we evaluate the kinetic energy and the electric energy that is either consumed or regenerated during a period of time dt, depending on the value of the torque, in Table 2, where η_g, η_b, η are respectively the efficiency of the transmission, the battery and the motor. This last parameter depends on the torque demand and on the motor speed.

Using previous equations, we can then define the specific regenerative braking area for a given electric motor associated with the regenerated power. A real characteristic of regenerative deceleration is presented on the Fig. 2. It is obtained from the first prototype of eFuture project. At low speed, the regenerative braking is not high. The main reasons are technological choices and to avoid that a regenerative braking leads to a blocked wheel. However, at low speed, the energy that could be regenerated is low, because of the low speed of the motor.

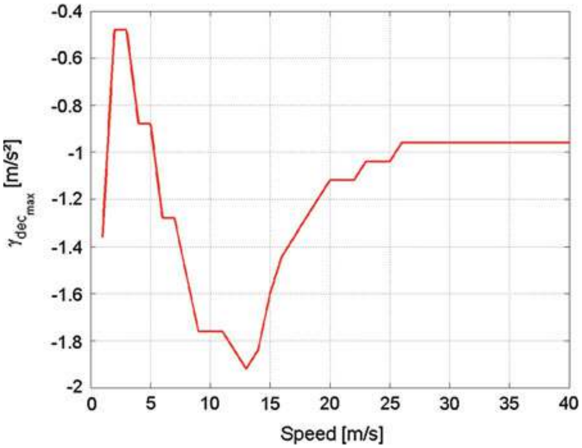
The regenerative braking area could be easily approximated by the following function :

$$\gamma_d(V) = \begin{cases} \gamma_{dec_1} : V < V_1 \\ \frac{A}{V} : V \geq V_1 \end{cases} \tag{2}$$

Table 2 Energy definition for the consumption model

Energy	Consumption	Regeneration
Mechanic	$E_m = 1/\eta_g T_e w_e dt$	$E_m = \eta_g T_e w_e dt$
Electric	$E_m = 1/\eta_b E_m \eta(T_e,\, w_e)$	$E_m = \eta_b E_m \eta(T_e,\, w_e)$

Fig. 2 Regenerative braking area for an electric motor



where A is a negative constant, γ_{dec_1} is the maximal deceleration below a given speed V_1.

3 SAGA Function

As described in the previous section, our SAGA function must cope with two operating domain. The first one corresponds to the speed control case, where the system must follow a driver's desired speed. The second one deals with the problem of distance control with a lead vehicle. The system must regulate the speed to maintain a constant clearance expressed as a driver desired headway time.

3.1 SAGA Speed Control Function

In this operating mode, there is not many safety related issues considering the interaction with the other road users, as, by definition, SAGA system operates in this mode when no vehicle is detected in front of our vehicle.

The main idea is then to supervise the conventional behavior of the ACC by defining a speed profile that includes the regenerative braking limitation and safety issues using a digital map to provide the needed data: legal speed limit if lower, can override the driver desired speed; approaching an intersection, the system automatically decreases the speed limit; using the curvature and slope information, a speed profile is defined to safely pass the curve. In this case, we extend the speed profile computation defined in [9, 10] with the deceleration limitation of the regenerative braking described previously.

3.2 SAGA Distance Control Function

The distance control function is far more critical as it directly deals with the interaction between vehicles. The objective of the ACC is to regulate the error on the clearance $e_d(e_d = d - T_d V)$ around 0. Depending on the sensors used to measure the distance, the algorithm may be more robust by integrating the error on the relative speed ΔV. The resulting acceleration is a function of this two errors, which is limited by the definition of the ACC. However, the regenerative braking is often below this threshold: with only a regenerative braking, we cannot ensure the same safety level of an ACC if we use the same strategy. Figure 3 shows the safety domain of a conventional ACC and an ACC which uses a regenerative braking. In this figure, we suppose that a front vehicle has a constant speed of 20 m/s and that the driver sets the time headway at 2 s.

The objective is then to regulate the acceleration of our vehicle to reach the point $(40\ \text{m}, 20\ \text{m/s})$. We can define a limit curve as being the points (d, v) which allow to reach this point with a given braking capacity. The points below this curve are in a safe area. As the regenerative braking is lower than the conventional ACC, the safe area is smaller. If we want to keep the performance in term of speed, the sensing range must be greater, at the opposite, if we want to keep the same performance on the sensors, then the maximal speed must be smaller. In the following, we suppose that we keep a constant maximal sensing distance and that we limit the maximal speed.

4 SAGA and Distance Control Problem

We must handle two specific situations for distance control:

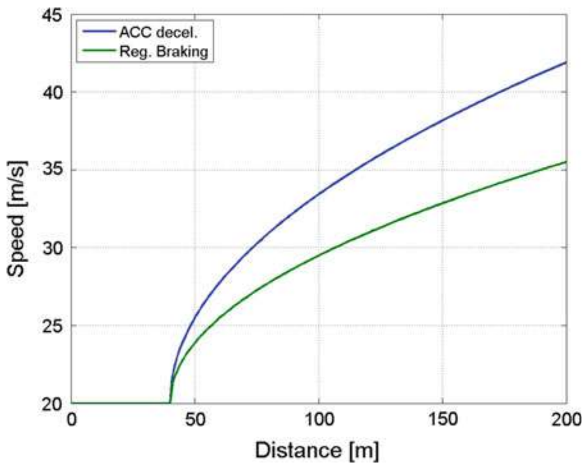


Fig. 3 Conventional ACC and regenerative braking safety domain

- We approach a slow vehicle, starting at a given distance and speed in the safe domain
- We follow a vehicle with an error e_d at zero. The lead vehicle start to decelerate with a deceleration that is greater than the possible deceleration.

For the first problem (see Fig. 4), we can suppose that the vehicle can either maintain a constant speed until it reaches the limit of the safe area, then decelerate at the regenerative deceleration (red path). Or that the vehicle starts to decelerate early to reach a speed that is slightly higher than the lead vehicle, and then it dece lerates slowly (orange path). Between these two extrema, we can tune the SAGA strategy.

The main drawback of the second strategy is that the gap between the two vehicles diminishes slowly. This situation allows a third vehicle to cut in our lane, leading to possible strong deceleration of our vehicle. If we follow the first strategy, and that the lead vehicle starts to decelerate, we may go out of the safe domain. For instance, if the front vehicle decelerates to 17 m/s (green curve in Fig. 4), our trajectory may quickly go out of the safe domain, losing the regenerative capacity, while the other strategy allows us to remain in the safe domain. Therefore, we need to define a tradeoff between these two strategies.

For the second problem, we need, at least, to achieve at least the same safety than a conventional ACC. For instance, we consider the following use case: a lead vehicle that drives at 30 m/s, our vehicle is at the same speed and the time headway is set at 2 s. The lead vehicle decelerates with a given deceleration γ_i up to a speed of 7 m/s. The ACC system can achieve the deceleration without any collision for a large variation of the lead vehicle deceleration, even if the time headway drops to very low value (0.6 s for a considered deceleration of -8 m/s^2). Figure 5 represents the clearance when the vehicle reaches the same speed than the lead vehicle. Even for a very strong deceleration, the vehicle does not collide.

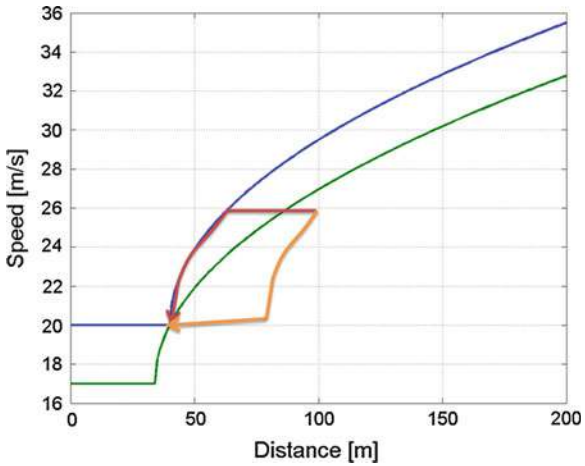


Fig. 4 Variation of the safe domain with a deceleration of the lead vehicle

Using the regenerative deceleration only, it is not possible to obtain the same safety level than a conventional ACC with the same use case (initial time headway of 2 s, speed of 30 m/s and final speed of the lead vehicle of 7 m/s). The possible solutions are:

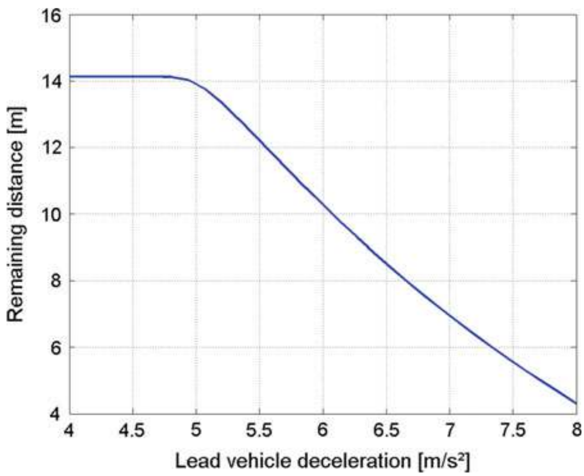
- To increase the minimal time headway that is defined by the driver. However, to obtain the same safety, we need to increase the minimal time headway up to 5 s. The resulting distance is hardly achievable as the sensor range is limited and other road user may cut in the space between vehicles.
- To switch to conventional braking if the time headway drops below a given threshold. For instance, we can maintain a collision free system, as for a conventional ACC, with an initial time headway of 3.7 s and an activation of a stronger braking at a threshold on the time headway of 1.5 s.
- To switch to an emergency braking if the deceleration of the lead vehicle and the distance drops below given thresholds. If the emergency braking can generate a deceleration of -6 m/s^2 when the time to collision (difference of distance divided by the difference of speed) is below 2 s, we can set the minimal time headway at 3 s.

As we want to use only the ACC system, then we choose the second option. However, we do not evaluate the acceptability by the user of the resulting clearance.

5 Simulation Results

In the following, we develop two different use cases to present the efficiency of the system. In a first scenario, our vehicle drives at the driver desired speed and it approaches a slow vehicle. The second scenario shows the reaction on a cut

Fig. 5 Final clearance as a function of the deceleration of the lead vehicle



in situation. The new target first decelerates slowly to increase the clearance with the previous lead vehicle, then accelerates to reach the traffic flow speed.

In the following, the ACC aims to regulate the distance at an headway of 2 s, the SAGA parameter is at 3.5 s. For SAGA, we use the conventional ACC if the headway drops below 1.2 s, and we start to control the vehicle with a 20 % longer distance.

5.1 Approaching a Slow Vehicle

In this scenario (see Fig. 6), we suppose that the lead vehicle is at 150 m in front of our vehicle. The lead vehicle's speed is constant and equal to 20 m/s. SAGA takes into account this front vehicle very early and decelerates slowly to reach the same speed and the correct clearance. The clearance decreases slowly and the complete maneuver takes more than 12 s. For the ACC, the same result is achieved in 8 s. During this maneuver, the State of Charge (SoC) increases of 0.07 kw for the SAGA, while it decreases of 0.05 kw for the ACC.

5.2 Vehicle Cut In

In this use case (see Fig. 7), we suppose that our vehicle follows a lead vehicle at a speed of 20 m/s with a time headway of 3.5 s. At $t = 1$ s, a vehicle inserts at a distance of 20 m in front of our vehicle. Its speed is 20 m/s and it decreases slowly to 18 m/s in order to increase its gap with the lead vehicle. At $t = 1$ s, our vehicle starts to decelerate, first with a regenerative deceleration, but as the new lead vehicle may be dangerous, the system shift to a conventional ACC, without regenerative capacity. During this deceleration, the vehicle's speed drops to

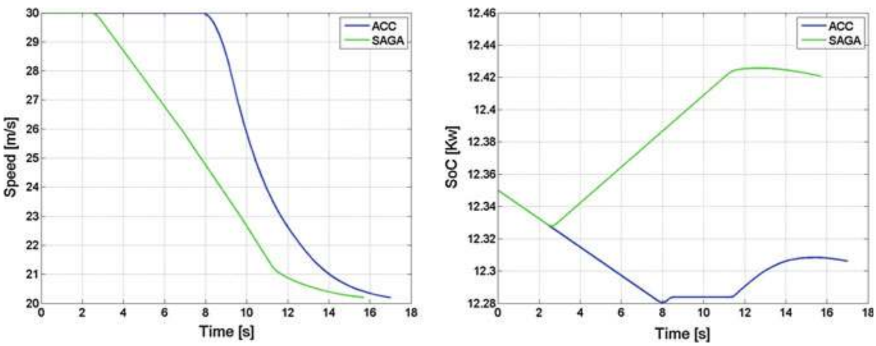


Fig. 6 Approaching a vehicle, comparison of SAGA and ACC outputs on speed and state of charge

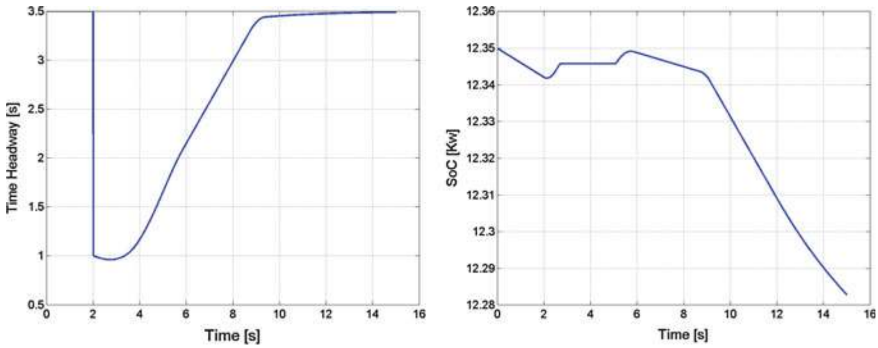


Fig. 7 Evolution of the time headway and the SoC during a cut in use case

12.7 m/s. In the last phase the vehicle has to accelerate to reach the lead vehicle speed and the driver desired time headway. The system manages this dangerous situation without any collision.

6 Conclusion

In this article, we have presented the Smart and Green ACC, namely SAGA. This application enhances the conventional ACC for electric vehicle with regenerative capacity. The main aim of the application is to deliver, at least, the same level of safety than a conventional ACC, and to integrate a consumption criteria. Given the motor specification, and the possible deceleration, the tradeoff is to increase the clearance and to replace the regenerative deceleration with a conventional braking if the clearance drops below a low value. Moreover, the deceleration has to start early to allow a regenerative braking when the vehicle approach a slower vehicle. This behavior could maintain a large clearance for a long time, allowing a third vehicle to cut in the gap. On daily situation, the driving assistance shows to be efficient, increasing or at least maintaining the state of charge of the battery. We demonstrate the efficiency and the safety of our application on two use cases.

However, the behavior of the driving assistance has a huge impact on the acceptability: increased clearance, long deceleration and resulting smaller time headway, which need to be evaluated under the user point of view.

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