# Smart and Green ACC: As Applied to a Through the Road Hybrid Electric Vehicle

**Sagar Akhegaonkar, Sebastien Glaser, Lydie Nouveliere and Frederic Holzmann**

**Abstract.** The Smart and Green ACC (SAGA) or simply Green ACC (GACC) may be defined as a system which autonomously generates longitudinal control commands for a vehicle while balancing the safety and efficiency factors. In previous studies, the SAGA function is investigated as applied to a battery electric vehicle. As a continuation of the SAGA function development, this paper investigates the behavior of the autonomous longitudinal controller as applied to a "Through the Road" (TtR) hybrid electric vehicle. Given the presence of two power sources, the implementation of a SAGA system in HEV/PHEV has a higher level of complexity as compared to pure EV. As an autonomous longitudinal driver command generating system, SAGA acts as a surficial controller which is then combined with a core powertrain management system. The Equivalent Consumption Minimization Strategy (ECMS) is used to determine the optimum power split between the IC engine and electric motor.

**Keywords:** Driving assistance, longitudinal control, energy efficiency.

## 1 Introduction

Advanced driver assistance systems are primarily aimed at increasing road safety (e.g. lane keeping assistance) or reducing the driver fatigue by partially or completely taking over the driving task (e.g. cruise control). The Eureka PROMETHEUS project (PROgraMme for a European Traffic of Highest Efficiency

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and Unprecedented Safety, 1987-1995) [1] was one of the early demonstrators of the fully automated road vehicle. The significant advancement in on board computing capacity has enabled real time image processing such as object detection, recognition, classification, and tracking using vehicle mounted cameras. Combined with long and short range sensor data, a fairly satisfactory three dimensional virtual model of the real surrounding environment can be generated and updated in real time. This presents a possibility to apply automated lateral and longitudinal control for a road vehicle with significantly higher level of safety. Most of the time, this safety level exceeds that achieved during conventional human vehicle control.

While driver and pedestrian safety form an important part of human mobility, it is also imperative to balance it with environmental safety. Thus the newly coined term "Eco-driving" comes into existence. Research projects like eCoMove [2] and EcoDriver [3] have focused their efforts on coaching the driver to drive as efficiently as possible. However, for many individuals, their driving style closely resembles their personality and constant advice on driving style may often become irritating. The modern car is being loaded with so much technology that information, more than what a human brain can process at a time, is being presented to it every instant through the human machine interface. This might, on the contrary lead to reduced safety. Hence, in order to balance safety and efficiency, a more logical solution may be to eliminate the driver from the equation and load him with an easy supervisory task while the autonomous car controls itself laterally and longitudinally.

The SAGA function concentrates on autonomously generating the longitudinal control commands while balancing the safety and efficiency. The concept of SAGA and GACC is defined and elaborated in [4] and [5]. In [4] the authors describe the basic concept with a detailed strategy definition and system behavior in specific cases. In [5], dedicated system approaches towards city and highway scenarios are elaborated. In both these papers the SAGA system is investigated with respect to a battery electric vehicle (BEV) powertrain. This paper attempts to apply the SAGA concept to a hybrid electric vehicle (HEV). Because the SAGA system is basically a cruise control, it acts on a surficial level and only generates the acceleration and braking commands. But unlike the BEV, the HEV has two sources of power and must be appropriately controlled to maximize the efficiency. The Equivalent Consumption Minimization Strategy (ECMS) [6] is used to determine the optimum power split between the IC engine and electric motor.

The paper is structured as follows. In the second section a detailed description of the HEV model is given. The concept of ECMS is explained in the third section along with simulation results regarding fuel consumption comparisons to conventional IC engine vehicle. Finally the concept of SAGA system is investigated as applied to the HEV powertrain in fourth section followed by a short conclusion.

## 2 Vehicle Model

Since hybrid electric vehicles have two different power sources, various topologies are possible. The series hybrid vehicles completely isolate the engine from the task of actual vehicle propulsion. Hence the engine may run at the operating point of highest efficiency and the motor will produce the actual propulsion torque. This means that the motor must be powerful and oversized in the series topology. In the parallel hybrid, the relatively smaller motor assists the engine in order to avoid operating points of very low efficiency. While it is simpler, it does not provide the efficiency levels of series topology. A combination of series and parallel topologies can be realized in the power-split hybrid. This topology uses a planetary gear system to split the power requirement between two power sources. A through the road (TtR) hybrid may be classified as a sub-type of power-split hybrids which does away with the complex planetary gear device. Since the front and rear axle are mechanically isolated (except through the road), TtR hybrid offers more flexibility for engine and motor power split control. The Peugeot 3008 based on the PSA Hybrid4 technology is a TtR hybrid [7].

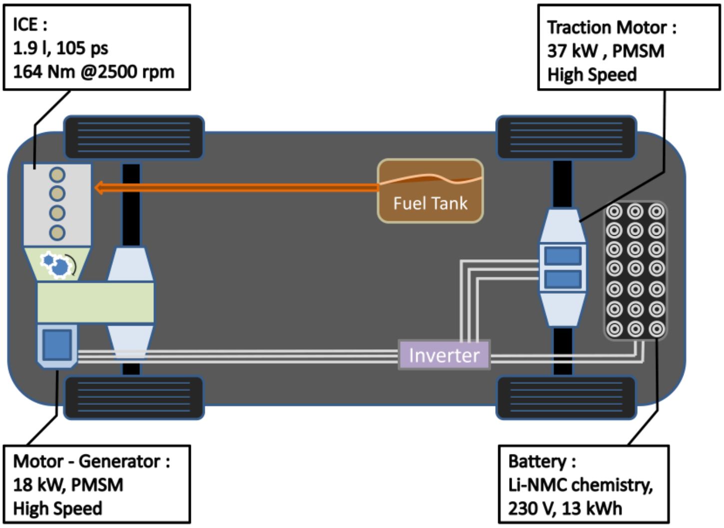


**Fig. 1** Through the road (TtR) hybrid topology

The above figure is a schematic representation of the vehicle model used in this paper. It is mathematically modeled using Simulink®.

### *2.1 Energy Model and Power-Split Definition*

A backward looking vehicle model is developed. It consists of two energy sub-systems, namely, mechanical (combustion energy) and electrical. A power-split block demands part of total required power from each of the power source. The required power is calculated as follows.

$$F_x = \left( \frac{C_w . \rho \cdot A \cdot v^2}{2} + M_v \cdot g \cdot f_r + M_v \cdot g \cdot sin\beta + M_v \cdot a \right)$$

where, $M_v$ is vehicle mass, $A$ is front area, $C_w$ is drag co-efficient, $f_r$is co-efficient of rolling resistance, $r$ is wheel radius, $a$ is vehicle acceleration, $v$ is vehicle velocity, $\rho$ is air density, $\beta$ is grade angle and $F_x$ is the required force at the wheel. The power-split is defined as follows.

$$u_{split} = T_{eM}/T_{total} \mid T_{total} = F_x \cdot r \mid T_{eM} = u \cdot T_{total} \mid T_{ice} = (1-u)\, T_{total}/g_{ice}$$

where, $u_{split}$ or $u$ is power-split ratio, $T_{total}$ is the required torque, $T_{eM}$is torque demanded from electric motor, $T_{ice}$ is torque demanded from I.C. engine and $g_{ice}$ is the gearbox reduction ratio. The energy supplied by the I.C. engine comes from fuel spent. Fig. 2 presents the base efficiency engine map containing the static 'sfc' (specific fuel consumption) in g/kWh for a 1.9 litre, 105 ps gasoline engine. It is used to determine the final energy consumption in litres/100 km.

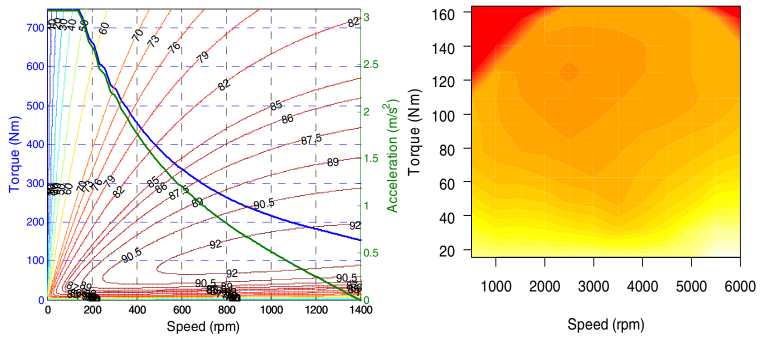


**Fig. 2** Motor characteristics (left) and engine base efficiency map in g/kWh (right)

## *2.2 eMotor*

An 18 kW PMSM e-Motor with 750 Nm peak torque is modeled. Front axle uses one motor as motor-generator whereas the rear axle uses two motors for propulsion. The motor model is based on look up tables which define the speed-torque characteristics and also the power losses corresponding to the operating point of the motor.

The motor model is supplied with speed (ω), torque request and battery voltage as inputs. The motor torque is calculated by adding the requested torque and power losses. Power required is the product of motor torque and speed. Since the voltage is known the current requirement for this power request is calculated. The calculated current value is supplied as an input signal to the battery. The torque speed characteristics for the e-Motor are shown in Fig. 2 along with the efficiency map and the maximum possible acceleration. Calculations are based on eFuture project [8] prototype vehicle described in [5].

### *2.3 Energy Storage System*

The Energy Storage System (ESS) is a lithium-ion (NCM chemistry) battery developed as a part of the eFuture project by Miljøbil Greenland AS. From the energy calculation point of view, the battery is an energy storage device which supplies or accepts the requested current at the present battery voltage and efficiency. The model is based on a virtual circuit as defined in [9] which represents the battery capacity, internal resistance and transient behavior of the battery. It is sought to keep a balance between accuracy and model complexity in order to reduce the computational load. Thereby, a temperature dependent internal resistance variation is taken into consideration while calculating the power loss and efficiency. Energy equations for the battery charging and discharging are as follows. Inverter losses are assumed negligible.

$$E_{batt.dis} = P_{eM} dt / (\eta_{eM} \cdot \eta_{batt.dis}) \qquad E_{batt.chg} = P_{eM} \cdot \eta_{eM} \cdot \eta_{batt.chg} dt$$

Where $E_{batt.dis}$, $E_{batt.chg}$ denote energy discharged from and charged to the battery respectively, $\eta_{eM}$ is the motor efficiency and $\eta_{batt.dis}$, $\eta_{batt.chg}$ denote the battery discharging and charging efficiencies respectively.

### *2.4 Transmission*

A 5 speed manual transmission is modeled which complements the I.C. engine torque-speed characteristics. Since gear selection is controlled by the energy management algorithm, it may as well be classified as a semi-automatic transmission. The gear ratios in increasing respect are 3.250, 1.950, 1.423, 1.033 and 0.730. The final gear ratio is 4.063 and it yields the $g_{ice}$ as a product with individual gear ratios.

## 3 Equivalent Consumption Minimization Strategy

The concept of ECMS (Equivalent consumption minimization strategy) was developed by G. Paganelli *et al.* in [6]. It is based on optimal control theory and can be derived from Pontryagin's Minimum Principle. In this paper, ECMS is used as a direct powertrain control algorithm in combination with the SAGA function for efficient autonomous vehicle control. The aim is to minimize the fuel consumption and sustain the battery charge level. It is explained as follows.

$$E_{total} = E_{ice} + E_{batt}$$

where, $E$ is energy. But all the energy ultimately comes from the fuel. Even the electrical energy $E_{batt}$ which is stored in battery is produced by the motor-generator powered by I.C. engine running at a specific operating point. If this operating point is known then there can be a direct comparison between fuel energy and electrical energy. This comparison factor is $s(t)$ and is called 'Equivalence factor'. For the rate of energy consumption it can be stated that,

$$\dot{m}_{fuel} = \dot{m}_{ice} + s(t) \cdot \dot{m}_{batt}$$

$$\dot{m}_{fuel} = \dot{m}_{ice} + s(t) \cdot \frac{E_{batt}}{Q_{lhv}} \cdot s\dot{o}c(t)$$

$$\dot{m}_{fuel} = \dot{m}_{ice} + s(t) \cdot \frac{P_{eM}}{Q_{lhv}}$$

where, $s\dot{o}c(t)$ is the change in battery state of charge, $m$ is fuel mass and $Q_{lhv}$ is the lower heating value of gasoline in MJ/g. The aim is to minimize the cost function '$J$' i.e. the total fuel cost $m_{fuel}$ subject to operational constraints as described below.

$$\text{Min } J\left(u_{split}, g_{ice}\right) = \int_0^T \dot{m}_{fuel}(t)dt$$

subject to,

$$P_{total} = P_{ice} + P_{eM}$$

$$P_{ice.min} \leq P_{ice}(t) \leq P_{ice.max}$$

$$P_{eM.min} \leq P_{eM}(t) \leq P_{eM.max}$$

$$P_{gen.min} \leq P_{gen}(t) \leq P_{gen.max}$$

$$SOC_{min} \leq SOC_{batt}(t) \leq \text{SOC}_{max}$$

In order to minimize the fuel consumption in the driving mission of time T, the global optimization problem is reduced to an instantaneous minimization problem by discretizing it into smaller time segments. For each segment the optimum values for $u_{split}$ and $g_{ice}$ must be determined such that optimum fuel consumption is obtained without violating the SOC constraints.

As stated earlier the equivalence factor allows a direct comparison between fuel and electrical energy for known engine operating point and overall system efficiency. Thus, if the $s(t)$ is high then the ECMS tries to penalize the use of electrical energy. On the other hand if $s(t)$ is low the use of electrical energy is encouraged. Since at any instant, the future operating point of the system is unknown, it is not possible to find the conversion between the electrical energy being spent which will be replenished by fuel energy at a later time or electrical energy being generated which will compensate fuel energy later. But if a driving cycle is known *a prori* then it is possible to find a lumped efficiency parameter for electrical and fuel energy conversion which is a characteristic of that particular velocity cycle. Such a method is described in [10] where two values of $s(t)$ are derived applicable to charging ($s_{chg}$) or discharging ($s_{dis}$) battery efficiencies. In [11], it is shown that only one equivalence factor suffices in ECMS. This $s(t)$ is always is located between $s_{chg}$ and $s_{dis}$ values. However, this $s(t)$ only offers optimum performance for the respective velocity cycle. Any deviation in the velocity cycle will result in sub-optimal and non-charge sustaining behavior. Pre-defined velocity cycles like NEDC, Artemis are hardly followed in real world situation. Hence a normal ECMS cannot be applied in real time.

In [11], an adaptive ECMS concept was introduced. Since then many different methods were introduced which used real time update for the equivalence factor. Such an algorithm facilitates constant adaptation of the strategy based on battery SOC status. One such method is described in [12].

$$s(t) = s_0 + s_0 \cdot K \cdot \tan\left(\frac{soc_{ref} - soc(t)}{2\pi}\right)$$

where, $s_0$ is the nominal equivalence factor. Since we know that equivalence factors lie between $s_{chg}$ and $s_{dis}$ the nominal equivalence factor may be derived as an average of the two. $K$ is a feedback factor, it decides $s(t)$ correction intensity related to the $soc$ deviation from $soc_{ref}$. $K$ is tuned manually to obtain an acceptable performance of the system.

The adaptive ECMS (A-ECMS) is implemented and tested for both charge sustaining normal HEV and blended mode Plug-in HEV. While for normal HEV the $soc_{ref}$ does not change, in a PHEV the aim is to use as much battery as possible. Hence the $soc_{ref}$ must be adjusted according to the distance covered. For a PHEV,

$$soc_{ref}(t) = \left(\frac{soc_{final} - soc_{init}}{D_{total}}\right) \cdot d(t) + soc_{init}$$

### *3.1 Simulation and Results*

The A-ECMS is developed as a Matlab s-function and implemented in the TtR hybrid Simulink model described in section 2. It acts as power-split and transmission gear controller. To test the assumption that the adaptive ECMS can be implemented in real time, the strategy is initially tuned for a WLTP

(Worldwide harmonized Light vehicles Test Procedures) class 3 cycle [13] and then tested with a completely different set of random velocity points which are recorded during real world driving [14].

### 3.1.1 Charge Sustaining (HEV) and Blended (PHEV) Strategy: WLTP

After an initial approximation using $s_{chg}$ and $s_{dis}$ values, the value of $s_0$ is finally manually tuned to 3.5. The value of $K$ was manually tuned to 0.7. $soc_{ref}$ is fixed at 60%. The performance of the A-ECMS for charge sustaining HEV operation is compared to that of a conventional I.C. engine vehicle.

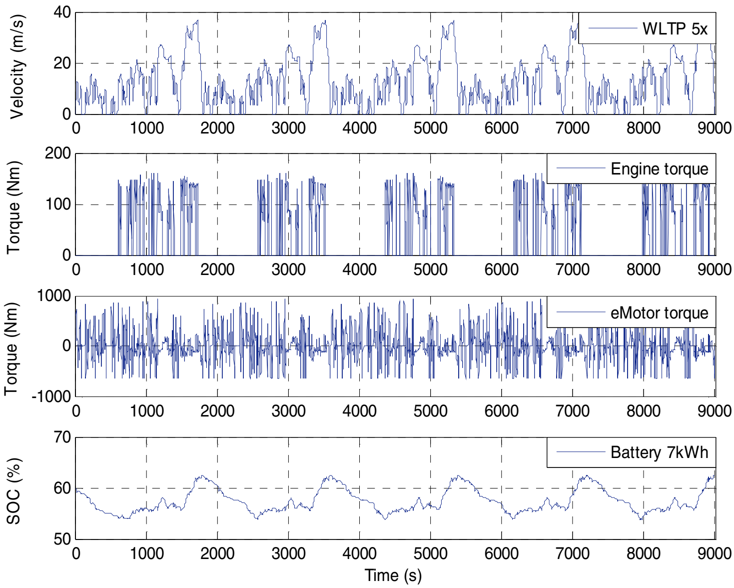


**Fig. 3** ECMS controller behavior (Charge sustaining HEV, WLTP 116 km, 7 kWh battery)

In Fig. 3 and 4, behavior of ECMS controller is shown as applied to WLTP class 3 cycle which is repeated 5 times for a total distance of 116 km. It can be seen that ECMS successfully sustains SOC within certain limits for a charge sustaining pure HEV. Whereas, for a plug-in hybrid, full utilization of battery energy between SOC levels 0.8-0.2 is ensured. For this it is necessary that the trip distance must be known beforehand. Apart from SOC regulation the aim of ECMS is to reduce consumption. ECMS actively avoids the engine operation points of lower efficiency as seen in Fig. 5 where a single run of WLTP cycle is compared for ECMS hybrid and conventional ICE.

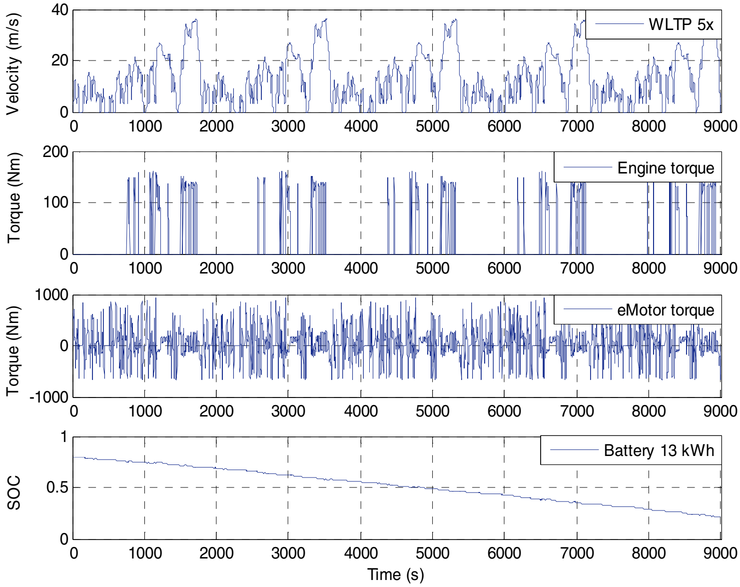


**Fig. 4** ECMS controller behavior (Blended Plug-in HEV, WLTP 116 km, 13 kWh battery)

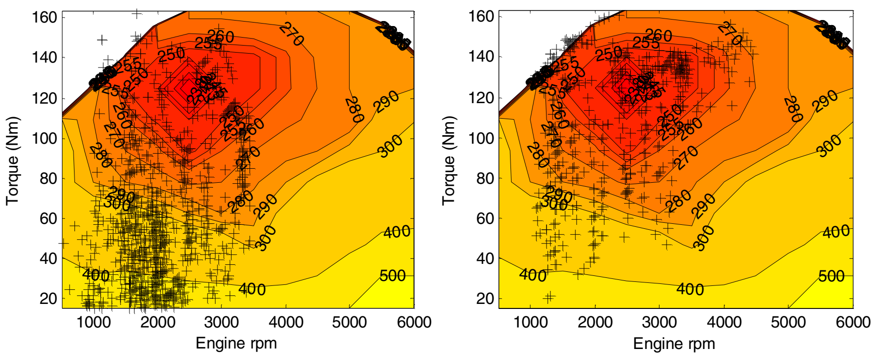


**Fig. 5** WLTP class3 cycle engine operating points, conventional ice (left), TtR ECMS (right)

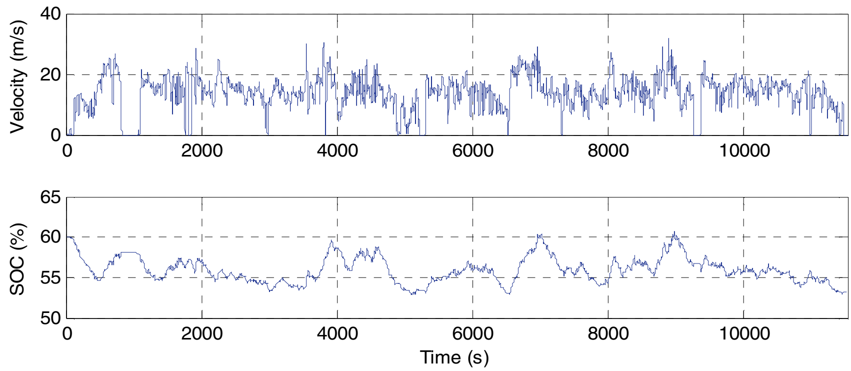


**Fig. 6** ECMS controller behavior on a real world recorded velocity session

**Table 1** Fuel consumption comparison for various powertrain configurations

| *Velocity cycle* | *Powertrain* | *Consumption(l/100km)* |
|---|---|---|
| *WLTP class3 (5x)* | Conventional ICE | 6.68 |
| *WLTP class3 (5x)* | Pure HEV (CS) | 5.52 |
| *WLTP class3 (5x)* | Plug-in HEV (Blended) | 3.23 |
| *Real world (A_M)* | Conventional ICE | 5.54 |
| *Real world (A_M)* | Pure HEV (CS) | 4.19 |
| *Real world (A_M)* | Plug-in HEV (Blended) | 1.96 |

In order to prove that the adaptive ECMS control which is realized on WLTP cycle is also applicable to real time situations, it is applied on actual recorded velocity session (Arco_Merano) [14] spanning about 157 km. It is observed in Fig. 6 that ECMS regulates the SOC within certain range and reduces the fuel consumption. Table 1 gives an overview of different consumptions figures for respective powertrains and cycles. A charge sustaining hybrid saves about 18% in WLTP cycle and about 24% in the Arco_Merano velocity session compared to the conventional ICE vehicle which is given an advantage of 200 kg and an efficient gear shifting algorithm which maintains the demand in most efficient engine map patch. It is not fair to compare the performance of plug-in hybrids since they use externally refillable electric energy.

## 4 SAGA as a Supervisory Controller

The SAGA which is basically a green cruise control function, operates in speed control and distance control (vehicle following) modes. In the speed control mode, the controller determines the acceleration depending on the difference in desired and actual speed. It is limited at 2 m/s$^2$. 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 where, $d$ is the headway spacing from front vehicle, $V$ is the speed of ego vehicle and $T_d$ is desired time headway. Depending on the sensors used to measure the distance, the algorithm may be more robust by integrating the error on the relative speed $\Delta V$. The resulting acceleration is a function of these two errors. During the deceleration phase, the aim of SAGA is to regenerate as much energy as possible. For this, it tries to use exclusive motor braking taking into consideration the speed dependent limited braking torque offered by the motors.

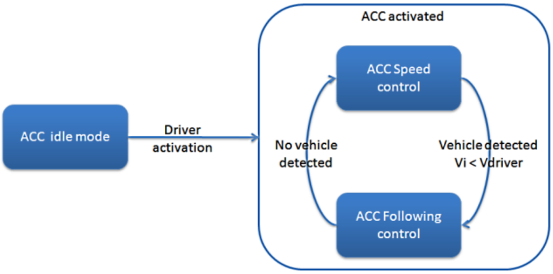


**Fig. 7** Operation domains for a SAGA controller

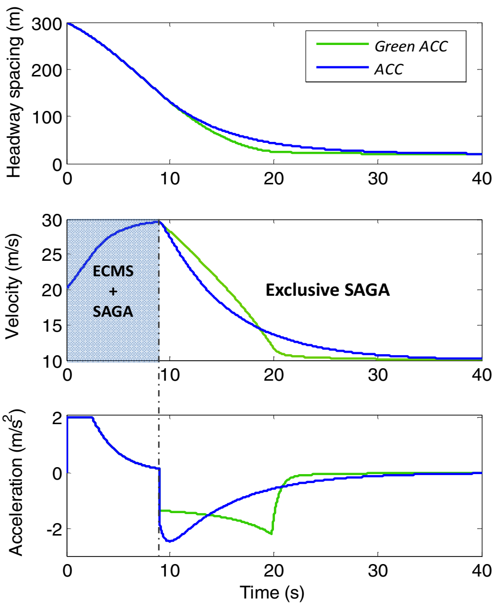


**Fig. 8** Definition of SAGA and ECMS operation domains

Fig.8 demonstrates a maneuver where the desired set speed is 30 m/s and actual speed is 20 m/s. The front vehicle is 300 m ahead and sensors range is 150 m, so the SAGA function determines an acceleration value in speed control mode. The approximate amount of torque to achieve the specified acceleration is calculated and passed on to the ECMS function. Dependent on the system parameters, ECMS determines the power-split, transmission gear and amount of torque to be generated or consumed (stored as electrical energy) for each powertrain component. In short, for the acceleration domain SAGA acts as a surficial command generator whereas ECMS manages the actual powertrain activity.

At headway spacing of 150 m SAGA senses the front vehicle and shifts into distance control mode. The front vehicle is moving at 10 m/s. SAGA determines if the motor braking capacity is sufficient to achieve the required deceleration within safe headway distance. Otherwise the service brakes are engaged as seen in case of normal ACC. ECMS is held dormant during this time and SAGA directly controls the regenerative power components. When the speed of ego vehicle is equalized with front vehicle, the objective is to follow the front vehicle speed. In this operation domain characterized with constant speed and intermittent acceleration, SAGA again performs the supervisory control with ECMS as the active powertrain controller.

## 5 Conclusion

Autonomous driving may become reality sooner than projected predictions. While the main ounce for development is on safety, it presents a significant opportunity towards Eco-Driving. This paper presents an autonomous longitudinal control system where a combination of a Green ACC function and a powertrain management system is employed to control a TtR hybrid vehicle. For future development, real time simulator test runs are planned for an investigation of reliability of such a system.

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