Ecodriving

From processing the ideal speed profile to its use during driving activity

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ABSTRACT. *Nowadays, the eco-driving technique represents one possible mean to reduce the energy consumption and the pollutants emission of vehicles. Besides the very low investment needed for such an option, its suitability to be applied even to old vehicles makes its impact important and immediate. The work presented here aims to quantify the potential gain allowable by an eco-driving behavior for a given vehicle using numerical optimization methods (only the case of conventional ICE based vehicle is detailed in this paper). Then, an Advanced Driving Assist System (ADAS) based on the proposed optimization has been designed and tested. The design approach takes into account the different constraints that could appear like the traffic limitation, the safety, the pollution but also those related to the driver's receptivity and his ability to understand and apply the information given.*

RESUMÉ : *L'éco-conduite des véhicules représente aujourd'hui un des moyens pour réduire la consommation d'énergie et limiter les émissions de CO_2 dans l'atmosphère. En plus du coût d'investissement très faible de cette option, son application possible à des véhicules anciens rend son impact important et immédiat. Les travaux exposés ici visent à quantifier dans un premier temps les potentiels de gain permis par une éco-conduite pour un véhicule donné (ici le cas du véhicule conventionnel est détaillé) en utilisant des méthodes numériques d'optimisation. Ensuite, un outil d'aide à l'éco-conduite basé sur cette optimisation a été conçu et testé. La démarche de conception tient compte de différentes contraintes, celles qui peuvent apparaître, tels le trafic et la pollution, et celles dues à la réceptivité du conducteur et à son aptitude à assimiler les informations qui lui sont destinées.*

KEYWORDS: *eco-driving, vehicles, fuel consumption, assistance system, safety.*

MOTS-CLÉS : *éco-conduite, véhicules, consommation, système d'aide, sécurité.*

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1. Introduction

Eco-driving is an easy way to reduce the energy consumption and CO2 emission. Firstly, it does not induce an important additional cost of the vehicle like it is the case for electrification and hybridization for example. Secondly, it can be performed using a retrofitting of existing vehicles including the oldest ones.

The first studies aiming at reducing fuel consumption in transportation have been published in 1976 consecutively to the first petroleum crisis (Hinton *et al.*, 1976). The motivation was at that time purely economic. Nowadays, the environmental restrictions compel the automotive manufacturers to invest in a clean and efficient transportation (ACEA, 2013).

In this scope, some countries propose training periods to achieve eco-driving (FIA Brussels, 2007), when the future drivers pass the test for their driving license for example. These last ten years, several studies dealing with the interest of establishing eco-driving rules have been carried out, demonstrating the efficiency of such an approach (Fairchild *et al.*, 2009). However, some studies on the long term efficiency of the rule based training approach highlighted the limits in the time of their positive effect (Beusen *et al*., 2009). In fact, the driver went back progressively to his old driving habits. Consequently, it could be very useful to design assistance systems for the drivers in order to help them to achieve eco-driving practices in a sustainable way.

Using systemic modeling associated to numerical optimization techniques, the joint research work in this domain between the LTE, the LESCOT and Ampère laboratories aimed at quantifying, in a first step, the potential gain that could be allowed by an eco-driving behavior for a given vehicle (conventional, electric or hybrid). Then, to approach this ultimate gain in the real world, an ADAS has been designed and tested on a driving simulator. The implemented algorithms processes online the fuel optimization while taking into account different constraints, mainly those related to the driver receptivity and safety.

After giving the optimization principle that leads to the potential gain quantification for a giving trip, we will explain in this paper how constraints like traffic and pollutants emission could modify the calculated eco-driving potential. Then, an ADAS is designed to help drivers to achieve eco-driving behavior using the developed optimization algorithms. The system designed is tested and evaluated using a driving simulator with 20 recruited drivers.

In this paper a particular focus will be made on the scientific cooperation between Engineering Science teams (LTE and Ampère) and Human Science team (LESCOT) in order to design an efficient system that could be easily accepted by users.

2. Energetic optimization of the speed profile

Before designing and testing a new device for assisting drivers to achieve eco-driving behavior, it is important to have an idea about the potential energetic gain of such an investment. For this purpose, we will give in this section the elements that can constitute a reference of minimal energy consumption on a trip. Practically, it consists in searching the energetically ideal speed profile achievable by a given vehicle on a given route but actually unreachable by a driver in the real life.

2.1. Models used

In order to identify and compare the optimal functioning of different vehicles, we have modeled three representative vehicles, namely conventional, electric and hybrid vehicle. In this paper we will detail the case of the conventional vehicle as it is the one that has been tested with the assistance system presented in the following. In order to reduce the computation time and implement easily the vehicles' models in the optimization algorithms, we used inverse modelling instead of direct modeling. The advantages of such modeling approach are explained using the Figure 1.

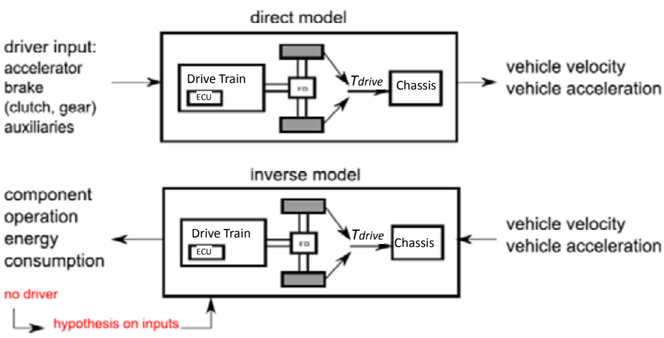

Figure 1. Direct vs *inverse modeling*

In fact, the direct simulation of a vehicle is based on inputs provided by the drivers that allow the calculation of the different parameters of the vehicle in a direct causal way following the power flow direction. The acceleration and the speed are determined using the driver pedals control and the vehicle dynamic model. On the other hand, we talk about inverse modeling when the functioning of the different sub-systems of the vehicle can be fixed while using both the speed and acceleration as inputs. The advantage of such an approach is to remove the driver from the calculation loop and get rid of possible errors that can appear due to the control loop simulating the driver behavior. In the inverse modeling, the driver is supposed to be a perfect controller with some assumptions concerning his behavior.

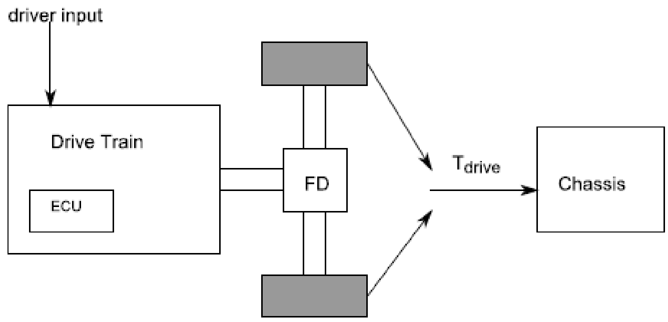

Figure 2. Vehicles modeling (ECU : Engine control unit, FD : Final Drive)

In general, all the vehicles models could be separated into a chassis and a drivetrain (Figure 2). Even if the drivetrain is different from a vehicle type to another, the chassis modeling remain a common element for all the vehicles and only model parameters will be changed according to the studied configuration.

In order to develop an energetic model of the vehicle, we have specified two assumptions concerning the chassis:

– Only the longitudinal motion is considered

– The pneumatic/road contact is perfect

Using these assumptions and the longitudinal motion equation, the torque provided by the drivetrain could be calculated in function of the vehicle speed (v) and the vehicle acceleration (a) as follows:

$$T_{drive} = J_{veh} \frac{a}{R_{tire}} + F_{res}(v) R_{tire} \quad (1)$$

Where J_{veh} is the equivalent inertia of the vehicle brought to the wheels and R_{tire} is the tires radius.

The resistance forces (F_{res}) are composed of the rolling forces due to the contact between the pneumatics and the road, the aerodynamic force and the gravity force due to the grade (Figure 3).

The resistance forces represent the losses of the chassis and are strongly related to the vehicle speed but they also vary with the vehicle weight and shape profile.

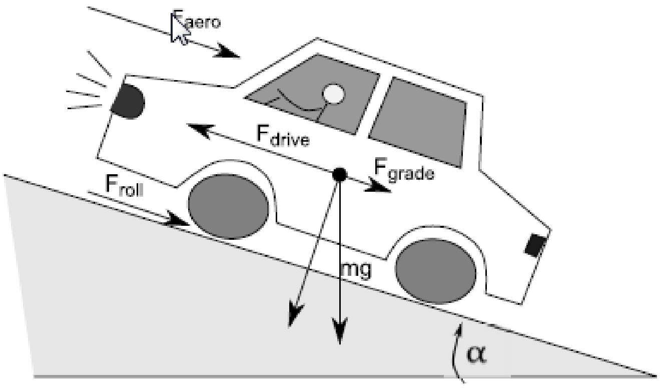

Figure 3. Resistance forces

The rolling resistance is a force generated by the pneumatic deformation during its contact with the road. Although this force depends on several parameters like the pneumatics pressure, their state of use and the road quality, we generally approximate this force by:

$$F_{roll} = C_r M_{veh} g \cos(\alpha) \quad (2)$$

With C_r the rolling resistance coefficient which depends on the vehicle weight and the wheel radius. g represents the gravitation acceleration and M_{veh} the vehicle mass including the chassis, the transmission, the drivetrain and the passenger. Besides, on a hilly road, the grade α should be taken into account in the rolling resistance force calculation because the reaction force due to the gravity is not orthogonal to the road surface. In the considered model, the rolling resistance is independent from the vehicle speed and acceleration and cannot be influenced by the driver behavior. However, it is obvious that this force changes with the vehicle onboard mass. The vehicle mass reduction would allow an energy consumption reduction by decreasing the needed energy to overcome the rolling resistance.

The aerodynamic resistance is a force for which a lot of work by researchers and manufacturers is continuously dedicated as it becomes the most important force at high speed. This force depends on the air density ρ, the drag coefficient C_d, and the front surface of the vehicle A. The aerodynamic resistance force varies with the square of the vehicle speed (in reality the relative speed of the vehicle and the wind, neglected here) according to the following equation:

$$F_{aero} = \frac{1}{2}\rho C_d A v^2 \quad (3)$$

When the vehicle is driven on hilly roads, the force due to the road grade should be taken into account in the resistance forces balance. When the road grade is α, the resistance force due to the gravity is calculated as follows:

$$F_{grade} = M_{veh} g \sin(\alpha) \qquad (4)$$

Naturally, the force due to the road profile acts as a traction force during a downhill and as resistance force during climbing phase.

In this work about eco-driving, different drivetrains have been studied. In this paper we will detail only the case of a conventional vehicle (Figure 4).

For all the rest of the paper, three assumptions have been considered:

– The gear shift is supposed to be instantaneous,

– No losses are considered in the clutch excepting the phases where the secondary shaft speed is lower than the idling engine speed,

– A constant auxiliaries consumption (P_{aux}) and a constant efficiency of the electricity generation system.

The mechanical transmission can be modeled simply using the gear ratio R_G of the selected gear the final gear ratio R_{FD} as well as their respective efficiency (η_G, η_{FD}). An engine map in the speed vs torque domain allows to calculate the fuel mass flow ($\dot{m}_{fuel}$) for a given mechanical functioning point (ω_{eng}, T_{eng}) (Figure 5). In order to calculate the torque T_{eng} provided by the engine at each time step, the following equation is used. It expresses the engine torque in function of the wheel torque calculated in (1).

$$T_{eng} = \frac{T_{drive}}{R_{FD}\eta_{FD}^{\psi} R_G(i_{gear})\eta_G^{\psi}(i_{gear})} + \frac{P_{aux}}{\omega_{eng}} + J_{eng}\dot{\omega}_{eng} \qquad (5)$$

J_{eng} is the engine inertia, i_{gear} is the gear number and ψ is the sign of the wheel torque.

The rotating speed of the engine is calculated using the wheel speed ω_{wheel}, deduced from the vehicle speed, and the gear and the final drive ratios according to the relationship (6).

$$\omega_{eng} = \max\left(\omega_{engidle}, \omega_{wheel} R_{FD} R_G\left(i_{gear}\right)\right) \qquad (6)$$

With $\omega_{engidle}$ the engine idling speed.

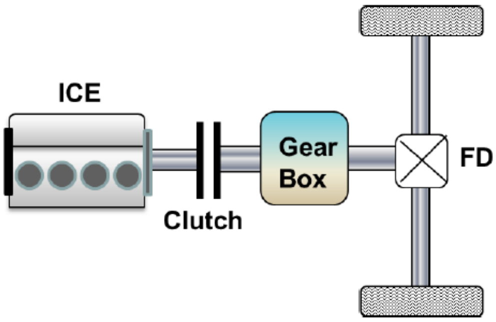

Figure 4. Simplified scheme of the conventional drivetrain

In the optimal trajectory search algorithm presented further, we assume that at each time, the selected gear is the one that minimizes the fuel consumption as expressed in (7):

$$\dot{m}*_{fuel} = \min_{i_{gear}} \dot{m}_{fuel}(T_{eng}(i_{gear}), \omega_{eng}(i_{gear})) \quad (7)$$

i_{gear} is the gear number.

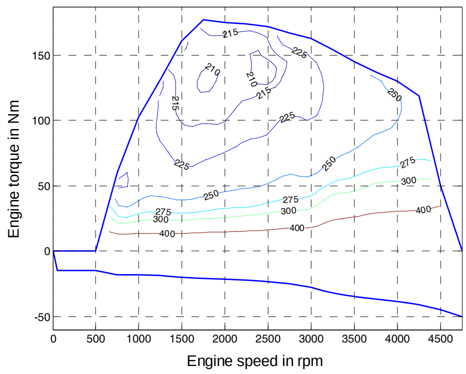

Figure 5. Specific fuel consumption map (in g/kWh) according to the torque and speed of the engine

2.2. The optimization method

In order to identify the optimal vehicle speed profile in terms of energy consumption for a given vehicle, we have applied optimization method on a given geographical trip. The vehicle displacement can be described by two state variables:

the distance d and the vehicle speed v. The discrete form of the motion equations are the following:

$$d_{i+1} = d_i + v_i \Delta t + \frac{1}{2} a_i \Delta t^2 \tag{8}$$

$$v_{i+1} = v_i + a_i \Delta t \tag{9}$$

where Δt is the time step with typical values between 0.1 and 1 s.

In order to determine the best speed profile to be used in eco-driving we will minimize the global energy consumption for the considered trip. The cost function is approximated by a sum over the whole trip of the instantaneous costs corresponding to the energy consumption at each time:

$$\mathrm{J} = \sum_{i=1}^{n} \gamma_{veh_i}(t_i \rightarrow t_{i+1})\ \Delta t_i \tag{10}$$

The instantaneous energetic cost $\gamma_{veh_i}(t_i \rightarrow t_{i+1})$ of a vehicle use depends on the drivetrain configuration. For the conventional vehicle, we will consider, as cost function, the fuel flow $\dot{m}_{fuel}$ used to go from the sample i to the sample i+1. The considered constraints are related on one hand to the vehicle capabilities (components performance, maximum speed and acceleration…) and on the other hand to the trip itself (initial and final values of the position the time and the speed, speed limits in different road sections, compulsory stops…). To solve this optimization problem with constraints, we have chosen to use the dynamic programming method. In fact, when an appropriate meshing of the considered domain is performed, this method allows finding the global optimum including constraints and possible saturation of the state variable. In order to apply the dynamic programming to our problem, we have first generated a 3D graph in the speed, distance and time domain. The oriented edges allow to go from a given speed at a time t_i to the speed at time t_{i+1} while performing a distance ($d_{i+1} - d_i$). However, in order to obtain a correct precision of the results, the mesh steps need to be small enough which leads to a very high computational time. This method is finally not suitable when we want to compute the optimum speed profile on a whole trip of some thousands of seconds.

In order to solve this problem, the time constraint is included using a weighting factor β, representing a penalty on the cost function when the trip time exceeds the planed final time (Equation 11).

$$\mathrm{J}' = \sum_{i=1}^{n} \dot{m}_{fuel}(t_i \rightarrow t_{i+1})\ \Delta t_i + \beta \Delta t_i \tag{11}$$

Consequently, the problem is reduced to 2 dimensions while controlling the time constraint by the mean of the weighting factor β.

Figure 6 describes the 2 D dynamic programming based algorithm that has been carried out. Firstly a meshing of the domain speed vs distance is performed leading to an oriented graph with an initial and a final position (X_0, X_f). To each edge linking 2 points of the graph, an instantaneous cost is associated, in our case corresponding to the terms of the sum in the Equation (11). An optimum search algorithm allows, for a given value of β, to find the optimal path corresponding to the minimum of the criterion J' on the whole trip (meshed domain). In an open loop approach, this optimum could lead to a non-controlled final time. In order to find the best speed profile for a giving final trip time, an iterative process using a dichotic search provides the appropriate value of the parameter β.

For more details on the methods the reader could refer to (Mensing *et al.*, 2011).

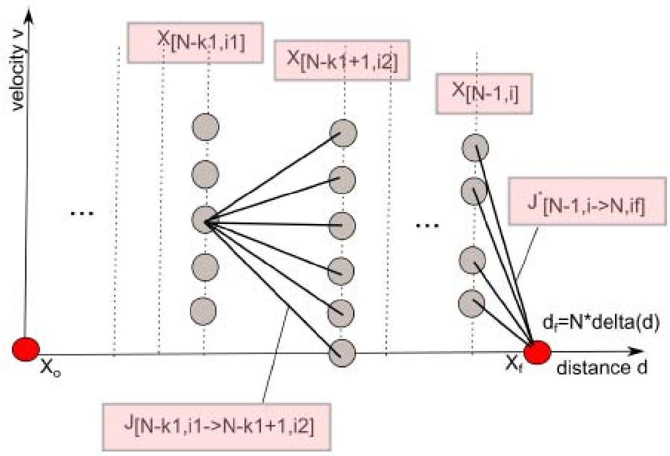

Figure 6. 2D graph used for dynamic programming

2.3. Eco-cycle generation

Using the developed algorithms and the vehicle model previously described we have calculated the optimal speed profiles for different registered driving cycles from European data bases. In order to fairly compare the original and the optimal results, the constraints inserted in the optimization process are calculated using the original cycle features (initial and final values for time, speed and distance, the stops are respected at the same points of the trip and with the same stop duration, the road section maximum speeds corresponds to the highest speed registered on the correspondent section of original drive cycle and saturated by the French maximum tolerated speeds values *i.e.* 30, 50, 70, 90, 110 and 130km/h). The identification of the potential gains of an eco-driving behavior is then obtained by comparing the fuel consumption of the two simulated cycles, namely the original cycle and the optimal cycle called also the “eco-cycle”.

The simulated driving cycles represent a selection with a wide variability of vehicle use ranging from the standard cycle (NEDC) to highway real use cycle (HYZAUTO) passing through urban (HYZURB) and suburban (HYZROUT) drive conditions.

The optimal speed profiles (eco-cycles) have been calculated using the previously described method *i.e* the 2D dynamic programming. In order to respect the time constraint (same final time than the original cycle), the closed loop calculation of the parameter β is activated. As an example, Figure 7 presents the original speed profile in blue and the eco-cycle in dashed red for the urban cycle HYZURB.

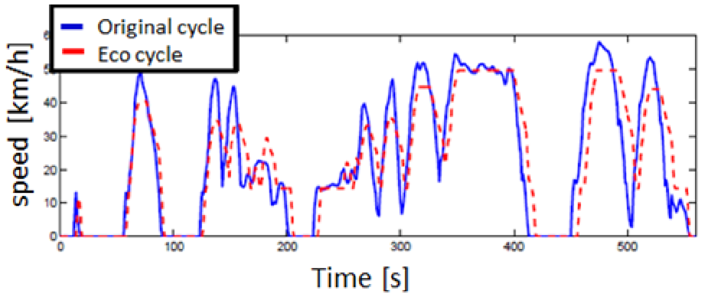

Figure 7. Vehicle speed vs time for the original and optimal cycles

In order to validate the results, the original cycles and the eco-cycles have been tested on an engine dynamic test bench. Based on Hardware in the loop (HIL) technique (Trigui *et al*., 2009), the vehicle model has been emulated while controlling in real time the ICE actually present on the test bench. The IFSTTAR facilities used also allow the measurement of the actual fuel consumption for each cycle while assuming a good validity of the vehicle model. The Table 1 presents the results for the original cycles and the eco-cycles. According to the cycle, the potential gain of an eco-driving behavior ranges from 7.9 to 27.2%. In the meantime, the results clearly show that an ideal driving behavior has more impact in urban and road conditions than in highway use.

Two factors have been identified as the main causes of the eco-driving potential gain:

– A better gear shifting strategy

– A better choice of the speed values and the acceleration rate of the vehicle.

Thanks to a higher gear ratio selection, the engine use efficiency is improved leading to lower fuel consumption. Moreover, the energy consumption decreases when an appropriate choice of vehicle speed and acceleration is done. For minimizing the fuel consumption under time constraint, a strong acceleration to reach a steady speed as soon as possible is recommended. In the deceleration phases, it is better to use the engine brake capability and only after that a strong mechanical brake should be applied in order to minimize the deceleration phase duration.

Table 1. Potential gain of eco-driving

Cycle	Gain in fuel consumption due to eco-driving
NEDC	17.9 %
HYZURB	27.2 %
HYZROUT	25.1 %
HYSAUTO	7.9 %

3. Insertion of other constraints

Until now, we have been interested in quantifying the potential gain of eco-driving in ideal conditions. In the following, we will discuss how the traffic and pollutant emission constraints have been considered in order to calculate more realistic gains.

3.1. Traffic constraint

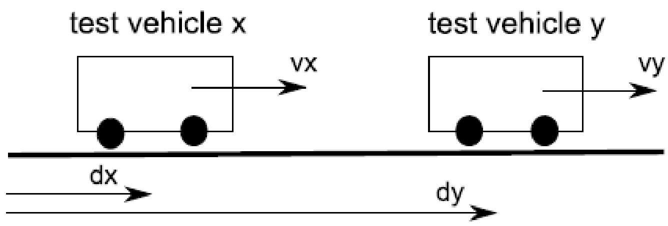

Figure 8. Traffic constraint expressed as a minimum inter-vehicular distance

The driver who intends to adopt an eco-driving behavior approaching an ideal speed profile could be constrained by the preceding vehicle to modify his speed and acceleration target. The implementation of eco-driving assistance systems in real time has to take into account the traffic in the close environment of the vehicle and has not to alter the driver safety. In order to evaluate the influence of the traffic on the potential of eco-driving, registered cycles where the preceding vehicle is detected have been used. In this way, we have performed the optimization algorithm to find the ideal speed profile for the vehicle x while respecting a minimum distance with the preceding vehicle y (Figure 8) (Mensing *et al*., 2013). We have studied three different parameters related to vehicle following in safe conditions:

– Safe braking distance: needed distance for a good braking behavior when the preceding vehicle brakes suddenly;

– Inter-Vehicular-Time (TIV): it is the time separating the passage of the two vehicles at the same point;

– Time-To-Collision (TTC): it is the time before a collision occurs if the two vehicles keep their current speeds.

The highway rules in France suggest respecting a TIV of 2 s for two vehicles driving on the highway. The TIV is an easy criterion for the driver to respect, however it does not take into account the preceding vehicle speed. In order to study the effect of the traffic on the eco-driving gains, we have defined two types of drivers: a high risky and a low risky driver. In order to specify the safety distance, the TTC criterion is considered with a value of 2s for a driving behavior with high risk and 4s for a safer driving behavior.

Using registered trips of vehicles equipped with cameras to identify the instantaneous relative position of the preceding vehicle, the optimal speed profile for an urban trip has been calculated with 2 assumptions corresponding to the two kinds of driver. The fuel consumption for each case is presented in Table 2. The reference consumption has been calculated without traffic constraint and leads to the highest eco-driving potential gain of 34 %. On the other hand, when considering the speed and acceleration limitation due to the respect of the considered TTC value, one can observe the gain decrease. In the case of a high risk driver the gain becomes about 28% and drops to 15% for a low risk driver. However, the lowest gain remains not negligible and leads to the conclusion that even in unfavorable conditions the eco-driving behavior is relatively efficient to reduce the fuel consumption.

Table 2. Fuel consumption according to the traffic constraint

Cycle	Constraint	Fuel consumption [g]	Gain [%]
Original cycle	Driver	97.36	-
Eco-drive cycle	-	64.10	34
Eco-drive cycle	TTC=2 sec	69.62	28
Eco-drive cycle	TTC=4 sec	82.30	15

3.2. Pollutants emission constraint

Generally, eco-driving is considered as an environment friendly behavior. However, and at our knowledge the most of the studies in the field are restrained to the energy consumption without considering the effect on pollutants emissions. In this part of the work, we have also been interested in the ecological aspects of the eco-driving (Mensing *et al*., 2014).

The engine test bench of IFSTTAR allows the measurement of instantaneous pollutants emission during the HIL simulation described in the section 2.3. In fact, the combustion inside the engine of a conventional vehicle is never perfect. The undesired products of such combustion are usually the water steam and CO2 but also the carbon monoxide (CO), the hydro-carbons (HC), the Nitrogen oxides (NOx) and particles. These pollutants contribute to the Green House Effect and to different negative impacts on the health. The motivation to work on this aspect has been grown since we analyzed the eco-cycle results of the experiment presented in 2.3.

In fact, the data presented in the Table 3 come from the tests of the original road cycle (HYZROUT) and the corresponding eco-cycle obtained while optimizing fuel consumption without traffic or pollutant constraints. The engine used in the experiment is the Peugeot 308 engine (EP6, gasoline) that respects the Euro IV norm for the pollutants emission values on the standard driving cycle (NEDC). The tests results are presented for the original cycle, the “eco” cycle and the Euro IV norm (Table 3).

Table 3. Consumption (l/100km) and pollutants emission (g/km) for the original and “eco” cycles

Emission in g/km	CO2	CO	NOx	HC	Fuel consumption [l/100 km]
Original cycle	207.0	2.06	0.0055	0.068	9.0
Eco-cycle	141.0	5.78	0.0016	0.12	6.5
Euro IV norm (NEDC)	-	1	0.08	0.1	-

The results show that if we apply the eco-cycle to the vehicle, we can decrease the fuel consumption from 9.0L/100km to 6.5L/100km. The CO2 emissions that are usually proportional to the fuel consumption have been also decreased. However, the CO and HC emission have increased drastically. In fact when the original cycle emits 2,06g/km of CO, the “eco” cycle causes an emission of 5,78g/km of the same gas. Moreover, The HC emission of the eco-cycle brings the values outside of the Euro IV norm tolerance while the original cycle allows a lower emission than this norm. Finally, the NOx measurement gives very low values for all the cycles and cannot be consistent for comparison. All these observations demonstrate that an economical driving behavior is not necessarily an ecological behavior and that we must take into account the pollutants' emission in the optimization algorithm.

In order to identify the causes of the over emissions of CO and HC observed previously, we have studied the engine functioning area. In fact, if we analyze the emission domains of the different pollutants according to the torque and speed area, we have identified a high density emission zone corresponding very high torque working points. This corresponds to the high acceleration rates imposed by the ideal speed profile together with the highest gear ration selection strategy. In order to determine the speed profile that also reduce the environmental impact, a new cost function is proposed:

$$J'' = \sum_i \dot{m}_{fuel}(t_i \rightarrow t_{i+1})\Delta t_i + \beta \Delta t_i + \lambda_i \qquad (12)$$

with

$$\lambda_i = \begin{cases} \lambda_0 \;\; si \;\; T_{eng} > (\chi \, T_{engmax}(\omega_{eng})) \\ 0 \;\; si \;\; T_{eng} <= (\chi \;\; T_{engmax}(\omega_{eng})) \end{cases} \qquad (13)$$

Taking into account the critical zone of over emission, the χ value has been set to 0.85. This new cost function leads to a restriction in the high torque values responsible for the main part of the over emission of CO and HC. From now on, we call eco^2 the cycle that minimizes the new cost function J'' for its reference to the interest for both aspects economic and ecologic. Using the same technique of tests than the previous section (engine test bench with HIL) a comparison between the original cycle, the eco cycle and the eco^2 cycle is detailed in Figure 9.

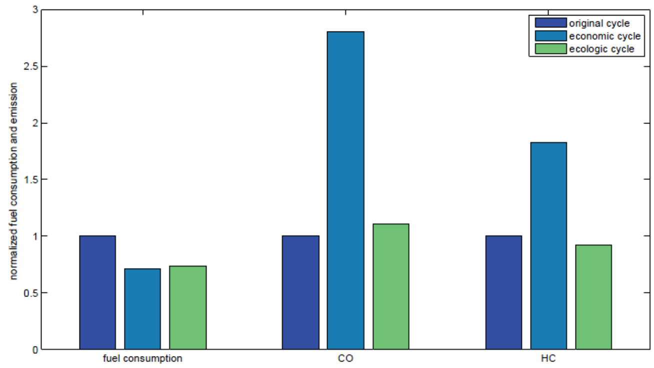

Figure 9. Consumption and emissions of the original, the eco and eco^2 cycles

We can note that after taking into account the pollution constraint in the minimization criterion, the CO and HC emission goes back to standard values similar to the original cycle values. In the same time, the consumption has registered only a very slight increase compared to the ideal eco cycle.

The instantaneous results show that the change in the speed profile between eco and eco2 cycles is almost imperceptible. However, the gear shift selection has notably changed.

4. Joint ES-HS design of an advanced driver ASSIST system for eco-driving

4.1. Problem formulation

As indicated in the introduction, the drivers taught to drive economically using simple rules or dedicated driving lessons are used to forget the eco-driving behavior after some months of practice and went back to their initial way of driving. An integrated assistance system or even a mobile application that help the driver keeping an eco-driving behavior could be an efficient solution.

In this scope, the optimization algorithms with the associated constraints described previously will be now integrated in an eco-driving assistance system that take into account the preceding vehicle and the emission constraints.

Classically, the design process of a system is based on technical specification and the system is often evaluated after its design which could lead to unusable or inefficient systems. For this reason, the design of a system dedicated to a human usage like the assistance systems should take into account some human constraints a priori. An eco-driving assistance system is particularly difficult to be accepted by a driver because it aims at modifying his behavior that is, in many cases, completely automated in terms of driving activity. It is thus interesting to have a coupled approach with a technical expertise of Engineering Science (ES) and psycho-social skills of the Human Science (HS) researchers.

In fact, the first idea of ES designers was to simply present the ideal speed profile as a speed target to be performed by the driver in real time. This proposal has immediately been brought face to face with human aspects pointed out by HS experts with mainly two questions:

– Is the information presented to the driver compatible with the time needed to treat and correctly understand the message? This time includes for the driver the time to get the information, to understand the message semantic and the integration of the information in his representation of the current situation in order to take into account the advices given to him.

– What is the impact of the information treatment on the safety of the driver and his environment? This impact obviously depends on the driving situations during which the assistance is presented.

The adopted solution after many discussions was to divide the information into two categories according to their complexity in order to better choose the instant they will be given to the driver. The first information type would be simple enough to be given during the driving activity and concerns the recommended vehicle speed and the optimal gear selection. In this type of advice the driver needs only to perceive the information and take the decision to accelerate, brake or shift the gear. The second type of information could be quite complex because it gives many details on the driving history and proposes to the driver to analyze his recent driving style according to the given advices. This cognitive effort is too important for the driver to be given during the driving activity. The advices will be then given during the vehicle stops.

4.2. The revised assistance system

The new algorithm of the designed ADAS revised after the human constraints study is based on a road segmentation logic. A segment could be defined as a part of the route between two intersections. When the driver is on an identified segment, the optimal speed and the advice for the best gear selection is displayed on the screen of the continuous advice. Along the whole segment, a detection of risky situations like a preceding vehicle too close for example is active. In case of positive detection of such situation, no advice is given to the driver in order to give the priority to the safety.

A colored gauge included in the speedometer is used to indicate the recommended speed area (and not speed value) according to the vehicle position in the segment. A gearbox scheme with arrows helped us to communicate the shift instant and the number of the most efficient gear. When the vehicle is approaching the end of the segment, the driving activity during the segment is evaluated. In order to keep the safety at its highest level, the results of the evaluation are displayed when the vehicle stops.

Three optimization algorithms have been implemented in the system logic:

– Gear shift continuous optimization

– Pre-segment optimization

– Post-segment optimization

The gear selection advice is calculated in a continuous way using the ICE best working points and the method presented in Section 2. A pre-segment optimization takes into account the initial vehicle state and an estimated final vehicle state in order to calculate the optimal speed profile on the considered segment. This algorithm applies the 2D dynamic programming. A weighting β factor (see Section 2) could be fixed for all the drivers. If the detected safety distance during the experiment does not allow the communication of the optimal speed target to the driver, the advice about the optimal speed area is inhibited until the near horizon of the vehicle is free again.

A post segment algorithm then uses the registered data along the past segment in order to analyze the driving behavior of the driver compared to the ideal behavior that includes eventual perturbations. The 2D dynamic programming method is again used, but this time it takes into account the safety distance according to the registered traffic as well as the time constraint respecting the actual final time. The results of this evaluation is transmitted to the driver using simple schematic representation for the acceleration phase, the steady speed phase, the deceleration phase and also for the gear choice.

4.3. Experimental environment

In order to verify the efficiency of the developed ADAS, we have tested it experimentally using a driving simulator test set.

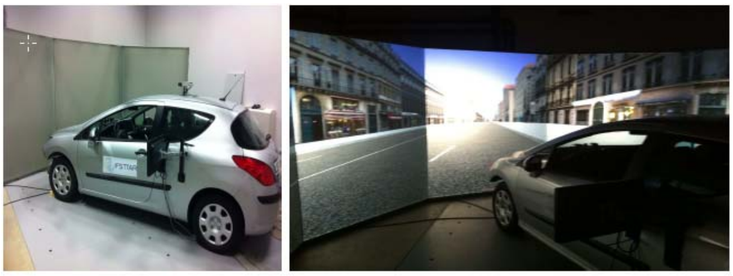

Figure 10. The driving simulator

Figure 10 represents the used IFSTTAR's driving simulator and Figure 11 depicts a general scheme of the experimental configuration where the designed ADAS is implemented. In the driving simulator, the driver is sitting in an actual vehicle but without engine. In this case, the vehicle body is used to transmit the driver commands to the simulated drivetrain and to the virtual environment. In the presented work, a multi-physics direct model under the VEHLIB software (Trigui *et al.*, 2003) of the Peugeot 308 is used. The vehicle model uses the pedals and the steering wheel outputs in order to calculate the current working point of the different subsystems of the drive train and estimate at each time the vehicle speed and position as well as the corresponding fuel consumption. With a predefined virtual environment, the vehicle position is displayed to the driver using the space coordinates. In our case, the virtual environment is displayed on a screen with a length of 220 cm a height of 165 cm providing a 180° horizontal view and a 47° vertical view. Even if it is difficult to reproduce very realistic feelings with the used driving simulator, it is possible to test an assistance driving system in controlled and comparable situations.

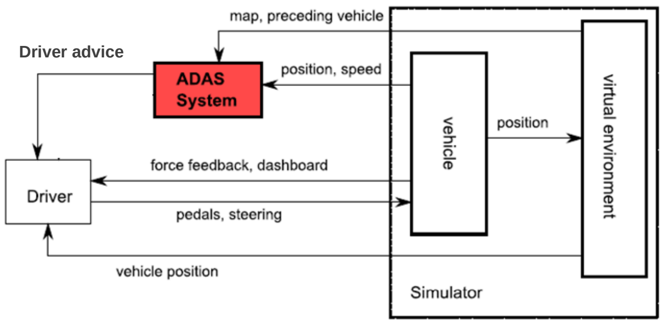

Figure 11. Experimental configuration global scheme

The ADAS system is integrated in the vehicle independently from the environment simulator. However, the ADAS takes into account inputs from the environment and the vehicle in order to generate the advice given to the driver. Moreover, it uses mapped data like the routes, the intersections and the maximum allowed speeds. As the vehicle is supposed to be equipped with radar, the environment transmits also to the ADAS the speed and the position of the preceding vehicle. In order to transmit an "eco^2" driving recommendation to the driver, two little screens have been installed onboard. The first screen displays a continuous advice for the optimal vehicle speed area and the optimal gear shifting. The second screen displays the driver behavior evaluation when the vehicle stops after achieving a road section (segment) drive. This information could help the driver to improve his eco-driving progressively.

4.4. Experimental settings

In order to evaluate the ADAS efficiency, we have tested it in the previously presented driving simulator with 20 actual drivers recruited to constitute a representative population. After a driving simulator training, the drivers performed a first trip without ADAS. The results of this test are used as reference to define a normal driving behavior for each driver. A first survey, filled in during a pause, allows identifying the parameters that describe the person and his vehicle use. After an introduction of the ADAS and its purpose, a second test is performed by the driver on a second route but this time with the ADAS. A second survey provides information about the driver understanding and appreciation of the ADAS. The two routes tested have been counterbalanced (half of the participants have performed the first route without system and the second route with, the second half did the opposite) so that the confusion between the ADAS effect and the route knowledge effect is minimized. Moreover, in order to not influence their driving style, the participants received the information about the objective of the experiment only after performing the first route without system.

4.5. Results and analysis

A statistical analysis of the personal parameters of the different drivers has shown that there were not significant differences in terms of fuel consumption between men and women. The age was also not a discriminant parameter. The sample was homogeneous for these two parameters and this for the two routes measured.

However, opposite to our expectation was the fact that stated mechanical knowledge of the participants does not induce any significant differences in terms of fuel consumption for the initial route as well as for the route with ADAS.

The statistical analysis of the results showed also that in average, the fuel consumption decreased when using the ADAS. In fact the consumption average decreased from 7.49 liter/100 km to 6.62 liter/100 km (Table 4) which constitutes 11.6 % of fuel economy.

Table 4. Statistical data for the 20 drivers for the test without ADAS (baseline) and the test with ADAS

	Consumption average [l/100km]	Samples number	Standard deviation	Mean error
Baseline	7.49	20	0.704	0.157
Test with ADAS	6.62	20	0.465	0.104

Table 5 presents the fuel consumption for 2 different simulated environments, namely urban and suburban environment. The limitations due to traffic allowed us to find that the eco-driving gains are higher in road driving condition than in urban environment. In fact, the fuel consumption reduction is about 9.4% for the urban trip while reaching 13.4% for the road conditions (decrease form 6.86 liter/100 km to 5.94 liter/100 km).

Table 5. Consumption statistics according to the environment

Test		Average	N	Standard deviation	Mean error
First group	Urban baseline	8.28	20	0.796	0.178
	Urban w ADAS	7.49	20	0.822	0.184
Second group	Road baseline	6.86	20	0.742	0.166
	Road w ADAS	5.94	20	0.399	0.089

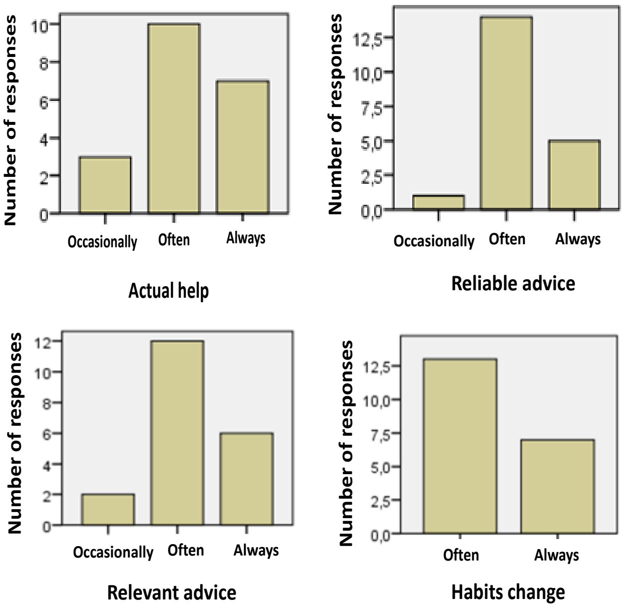

Figure 12. Drivers' confidence about the ADAS

For the drivers confidence in the system, (Figure 12), 60% of the participants stated that the advices given are often relevant where 30% found them always relevant and 10% relevant occasionally. In the same way, 25% of the drivers found the advices always reliable 70% often and only 5% occasionally. Most of the participants think that the system help them to drive in a more economical way (35% always, 50% often and 15% occasionally) and that it could change their driving habits after a long period use (35% always, 65% often).

With the results obtained in this study, we can conclude that the designed ADAS present a real added value. In fact, we can note that the experiment participants expressed a good degree of confidence in the system and performed a statistically significant fuel economy when using it.

5. Conclusions

Optimization algorithm applications together with a comprehensive understanding of the driver capacity and acceptance have been coupled to design an efficient and safe eco-driving assistance.

Firstly, an inverse modeling method has been applied to perform a systemic simulation of a conventional vehicle with a gasoline engine. Taking into account the route constraints, an optimization problem has been defined in order to minimize the fuel consumption for a given trip. The dynamic programming method has been used to solve the problem including a weighting factor to respect the final time constraint. Considering an original registered speed profile (cycle) the developed algorithm could be used to generate what we call an eco-cycle corresponding to the ideal speed profile while respecting the original cycle constraints (stops positions, maximum speed, arrival time). On the other hand, an integration study of the traffic and pollutants emission constraints has been conducted. It was found that the potential gain of an ideal eco-driving behavior decreases with the traffic density but remains significant enough. By taking into account emission constraints, a trade off could be found in order to avoid possible over emission while keeping an almost optimal gain in terms of fuel consumption. The eco-driving behavior could thus be economic and ecologic in the same time.

Finally, the implementation of the optimization algorithms in an Advanced Driver Assist System (ADAS) efficient and secure has been successfully tested on a driving simulator. Among the 20 people recruited as driver for a test with and without the ADAS, none of them found the system completely useless or unreliable. More than 80% found it often helpful and pertinent. The experiment showed globally that an optimized system but simply presented could be efficient and in the same time well accepted by the users.

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Bibliography

ACEA (2013) (European Automobile Manufacturers' Association). Reducint CO2 emission: Working together to achieve better results, 2013. http://www.acea.be.

Beusen B., Broekx S., Denys T., Beckx C. (2009). Using onboard logging devices to study the longer-term impact of an eco.driving course. *Transportation Research Part D,* vol. 14, n° 7, p. 514-520.

Fairchild R.G., Brake J.F., Thorpe N., Birrell S.A., Young M.S., Felstend T., Fowkes M. (2009). Foot-LITE: using on-board driver feedback systems to encourage safe, ecological and e_cient driving: The foot LITE project. *AISB 2009 Convention: Adaptive and Emergent Behaviour and Complex Systems*.

FIA Brussels (2007). Ecodriving as a policy; highly cost-effective CO_2 emission reductions, 2007. URL: http://www.fiabrussels.com/download/projects/ecodriven/english brochure august 2007.pdf.

Hinton M.G., Forrest L., Duclos D.P., Davey T.H., Sheahan R.R., Swan K.B. (1976). Survey of driver aided devices for improved fuel economy. Technical Report DOT-TSC-OST-76-45, Department of Transportation.

Mensing F., Bideaux E., Trigui R., Jeanneret B., Ribet J. (2014). Eco-Driving: An Economic or Ecologic driving style? *Transportation Research Part C: Emerging Technologies,* 38, p. 110-121.

Mensing F., Bideaux E., Trigui R., Tattegrain H. (2013). Trajectory optimization for eco-driving taking into account traffic constraints. *Transportation Research part D.* 18, p. 55-61.

Mensing F., Trigui R., Bideaux E. (2011). Vehicle Trajectory Optimization for Application in Eco-Driving. *IEEE Vehicle Power and Propulsion Conference,* September 2011, Chicago, Illinois.

Trigui R., Jeanneret B., Badin F. (2003). Systemic modelling of hybrid vehicles in order to predict dynamic performance and energy consumption. Building the VEHLIB library of models. (text in French with abridged version in English), *RTS,* November 2003.

Trigui R., Jeanneret B., Malaquin B., Plasse C. (2009). Performance Comparison of Three Storage Systems for Mild-HEVs using PHIL Simulation. *IEEE Transaction on Vehicular Technology.* Vol. 58, n° 8, October, p. 3959-69.

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