

Evaluation of Fuel Economy Potential of an Active Grille Shutter by the Means of Model Based Development Including Vehicle Heat Management

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ABSTRACT

In the automotive field, reducing harmful pollutant, CO₂ emissions and fuel consumption of vehicles while increasing customer comfort is a continuous challenge that requires more and more sophisticated technology implementations. However, it is often difficult to anticipate the advantages and drawbacks of a technology without having its prototype parts and/or knowing the optimal control strategy. In order to meet these challenges, the authors have developed a vehicle thermal model in AMESim platform to evaluate the benefits of an Active Grille Shutter (AGS) on fuel economy when applied. The vehicle model was based on a C-Segment vehicle powered by a 1.4L Diesel engine. The complete oil and coolant circuits were modeled as well as a friction model based on engine coolant and oil temperature. The entire model was validated on the European homologation cycle (NEDC) at -7°C and $+25^{\circ}\text{C}$ ambient temperature and achieved an accurate estimation of the fuel consumption, coolant and oil temperatures. Then, an AGS model was developed and integrated into the vehicle thermal model in order to assess the control of the coolant temperature (radiator cooling efficiency) and the vehicle road load (drag coefficient). Several control strategies were investigated on an in-house country-highway driving cycle to clarify the best compromise among fuel consumption reduction, engine coolant temperature control stability and AGS durability. The model demonstrated a potential fuel economy of 1.7% and 2.0% at $+25^{\circ}\text{C}$ ambient temperature on NEDC and in-house country-highway driving cycles respectively. In addition, the model showed further fuel economy up to 2.4% on NEDC at -7°C ambient temperature thanks to the combined effects of reduced frictions and road load. Finally, simulation and experimental results were compared and the fuel economy predicted by the model achieved a deviation lower than 0.3%.

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INTRODUCTION

Simulation is taking a more and more important place in predevelopment phase of a vehicle and its powertrain, especially for vehicle and engine thermal management where real world fuel economy and customer comfort can be substantially improved [1][2][3][4]. The purpose of this study is to demonstrate the capability of Model Based Development (MBD) to pre-evaluate the potential of a new technology as well as its optimum control strategy before testing the first prototype in the vehicle, following left hand side of the known V-shape development diagram shown in Figure 1.

In this study, a multi-step Active Grille Shutter (AGS) was evaluated since it offers advantages such as a reduction of the vehicle drag coefficient [5][6][7][8][9] and a quicker engine warm-up thanks to the reduction of air flow through the front end of the vehicle toward the engine compartment. There are other advantages such as lower engine noise and heat retention and quicker cabin heat-up [9] in cold

conditions but they will not be addressed in this paper. However, the side effects of AGS are typically related to engine part thermal damage and over-heating, but these concerns are also not included in this paper.

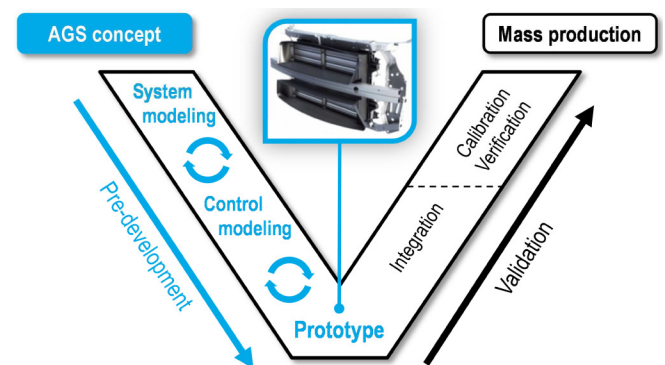


Figure 1. V-shape development diagram and usage of MBD for predevelopment activities

The first challenge with AGS is the difficulty to know the real fuel economy by doing vehicle chassis dynamo tests or on real driving conditions. On one hand, the chassis dynamo cannot dynamically adapt the vehicle road load during a test, based on instantaneous AGS position. On the other hand, despite having an accurate on board CO₂ measurement device, it is very difficult to drive the same car (or 2 cars in parallel) on real road by following the exact same speed pattern and by having the exact same environmental conditions. Therefore, the comparison of the fuel economy between cars with and without AGS would not be trustable when measuring a difference of nearly 2% which is close to the measurement accuracy.

The second challenge is the definition of the best control strategy to maximize fuel economy while keeping the coolant temperature in an optimum range for the engine thermal efficiency. Also, engine coolant temperature should not overshoot above a safe threshold when AGS is progressively closing. Finally, the AGS should be stable, meaning that the control strategy should avoid a continuous switch between several positions thus leading to a premature aging of the AGS's mechanical parts.

To overcome the two above challenges, an already developed Vehicle Thermal Management model was modified to adapt the AGS model. This way, several control strategies could be evaluated to know their impact on fuel economy and coolant temperature control.

In this paper, a description of the experimental set-up and procedures will be introduced. Then, the modelling approach and the different evaluated AGS control strategies will be described. Finally the results will be explained and discussed to draw the final conclusions.

EXPERIMENTAL SET-UP & PROCEDURES

Vehicle Description & Instrumentation

For this study, a Toyota C-Segment vehicle (Auris) equipped with a 1.4L EU5 Diesel engine of 66kW power and 205Nm torque was selected. This vehicle was selected since it is C-Segment vehicle represents nearly 1/3rd of the European market share. Diesel engine was chosen since it has a large share of nearly 2/3rd in this segment and its lower temperature (cooling demand) compared to gasoline engine could potentially bring higher benefits with AGS technology.

The engine coolant temperature was measured from the original engine sensor and recorded via an open ECU and INCA acquisition system. The CO₂ emission were sampled and measured at the vehicle tail pipe using an HORIBA MEXA-7400 HLE analyzer connected to the dilution tunnel. Both instantaneous and bag CO₂ values were available in order to have the cumulative trace of the CO₂ with high accuracy and then calculate the fuel consumption from the fuel composition. Figure 2 shows the complete vehicle set-up on roller chassis dynamometer.

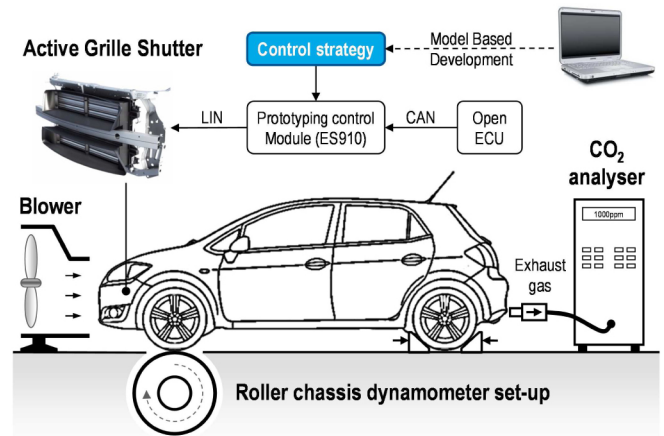


Figure 2. Vehicle test on chassis dynamo and main instrumentation to measure CO₂ and control AGS prototype

In addition, several measurements were done in a wind tunnel to clarify the benefit of the vehicle drag coefficient as a function of the AGS position. These measurements are described in the next sections of this paper.

Active Grille Shutter Prototype Installation

Figure 3 shows the two AGS prototypes designed together with a specialized supplier and integrated right behind the upper and lower radiator grille. To maximizing the drag coefficient reduction, the AGS sealing efficiency had to be optimized. To do so, the distance between front grille and AGS was minimized, air guides were added between the front grille and the AGS, and AGS flaps lips were selected with a soft rubber material. The reason of choosing two AGS was to study the cost/benefit of all possible configurations and be able to select the most appropriate layout. Each AGS was actuated by a three phase stepper motor offering up to 15 positions. Each actuator was connected to the vehicle electric supply and to a rapid prototyping module (ETAS, ES590) via a LIN bus. After pre-validation using MBD, the control strategies were coded and compiled using dedicated control logic softwares (ETAS, ASCET/Intecrio) and flashed in the rapid prototyping module to be tested with the real vehicle.

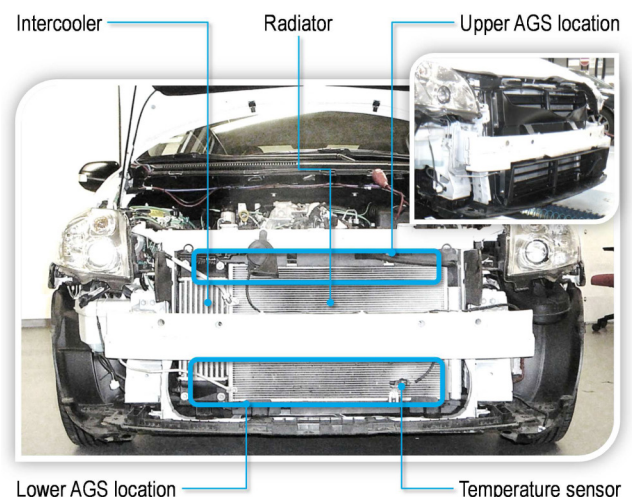


Figure 3. AGS prototype installation on vehicle

Evaluated Test Patterns and Conditions

In this study, the vehicle was evaluated under several driving cycles and ambient conditions to get the required input parameters for the models calibration and to be compared with simulation results for validation purposes.

Table 1 lists the different driving test cycles and conditions depending on the purpose. It is important to note that most of the measurements were carried out to validate the model accuracy, but they would not all be required in a normal MBD approach to reduce time and cost.

Table 1. List of the test patterns and conditions evaluated in the present study

Purpose	Condition	Driving Pattern	EXP	SIM
Drag coefficient (Cd) characterization at various AGS positions (<i>Wind tunnel</i>)	Wind 120kph Tamb=20°C	Steady	Yes	No
Validation of: Fuel economy & coolant temperature (Tc) (<i>Chassis dynamometer</i>)	Tamb=-7°C	NEDC	Yes	←
	Tamb=25°C	NEDC	Yes	←
	Tamb=25°C	Country (<i>In-house</i>)	Yes	←
	Tamb=25°C	Highway (<i>In-house</i>)	Yes	←

Drag Coefficient (Cd) Measurement in Wind Tunnel

In order to have a very accurate measurement of the AGS aerodynamics benefit, the vehicle drag coefficient (Cd) was measured on a reference wind tunnel. This wind tunnel was selected for its good accuracy and repeatability but also for its moving belt underneath the vehicle which simulates the moving ground effect. The vehicle drag coefficient was measured at 13 (out of 15) AGS steps to have a detailed description of the relationship to be used later on as input for the AGS model.

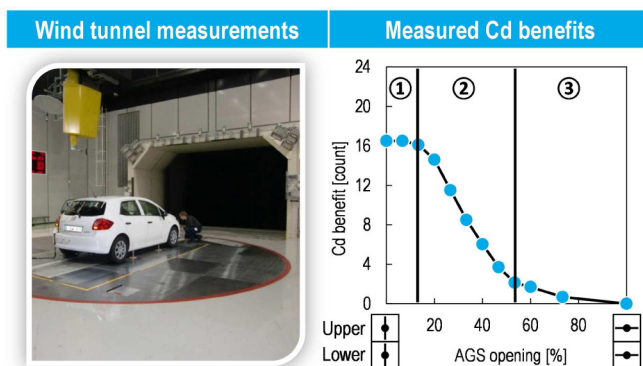


Figure 4. Vehicle measurement set-up in wind tunnel and characterization of the vehicle drag coefficient (Cd) benefit as a function of AGS opening position (120kph vehicle speed, Tamb=20°C).

Figure 4 shows the Cd reduction measured in the wind tunnel by actuating both upper and lower AGS simultaneously with the same angular position. The Cd reduction was up to 16.5 counts when closing both upper and lower AGS completely. The system achieved

a sealing efficiency of 78% compared to the max Cd benefit possibly achievable when putting a complete mask on both upper and lower grilles. Such a Cd benefit is in line with literature [7][8][9] and is remarkable compared to what is achievable with other vehicle aerodynamic improvements.

The relationship between AGS position and Cd reduction had a sigmoid shape. Three main ranges were distinguished and considered to develop the control strategy as described below.

- ①. Upper saturation of Cd reduction due to the high restriction of air flow. AGS flaps are almost closed so that air cannot go through anymore and this range does not require intermediate AGS position for control.
- ②. Quasi linear Cd reduction vs. AGS opening position. This is the best AGS position range for air mass flow control and intermediate positions must be added in this range.
- ③. Lower saturation of Cd benefit due to low restriction of air flow. AGS flaps are enough open to get the maximum air flow rate and this range does not require intermediate AGS position for control.

CFD simulation of air mass flow going through the AGS as a function of its position [2] showed a very similar physical behavior (especially for the ranges ② and ③) when compared to the Cd benefit. This means that the Cd reduction somehow decreases proportionally to the air mass flow going through the engine compartment.

AGS Control Strategy

Figure 5 describes the in-house developed AGS control strategy taking into account all possible vehicle usages. The key input parameters considered for the control strategy were the following:

- Ambient temperature
- Engine coolant temperature
- Vehicle speed
- Pedal position
- Diesel particulate filter regeneration demand
- A/C demand (not implemented since A/C was disabled)
- Radiator fan demand
- etc.

After starting the engine, a self-check sequence was implemented to make sure that both AGS were moving normally and a self-learning of the end position was made. In case of malfunctioning, a malfunction could be reported. Then, based on engine coolant temperature and ambient temperature, the control strategy decided the correct mode to operate the AGS. For instance, in case of low engine coolant temperature and ambient condition, the AGS was forced to be in "CLOSE" mode to improve the engine warm-up. When engine reached its target temperature, the control strategy switched to the "ACTIVE" mode to actuate the AGS position to its optimal position depending on engine coolant temperature. The number of positions could be changed to evaluate the different benefits for the engine coolant temperature control, fuel economy and