

Optimization of Active Grille Shutters Operation for Improved Fuel Economy

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ABSTRACT

The airflow into the engine bay of a passenger car is used for cooling down essential components of the vehicle, such as powertrain, air-conditioning compressor, intake charge air, batteries, and brake systems, before it returns back to the external flow. When the intake ram pressure becomes high enough to supply surplus cooling air flow, this flow can be actively regulated by using arrays of grille shutters, namely active grille shutters (AGS), in order to reduce the drag penalty due to excessive cooling. In this study, the operation of AGS for a generic SUV-type model vehicle is optimized for improved fuel economy on a highway drive cycle (part of SFTP-US06) by using surrogate models. Both vehicle aerodynamic power consumption and under-hood cooling performance are assessed by using PowerFLOW, a high-fidelity flow solver that is fully coupled with powertrain heat exchanger models. The fuel economy calculation is based on a quasi-static drive cycle simulation where the engine power is calculated to match drive cycle loads from aerodynamic forces, translational and rotational inertia, rolling resistance, transmission and tire slip losses, and auxiliary parts. The engine heat rejection is calculated from these same loads. The operation of AGS opening is determined by minimizing instantaneous vehicle aerodynamic power constrained by the radiator heat rejection requirement. The improved fuel economy of actively controlled AGS is then compared to the cases with fully open and scheduled operations. The approach in this study provides an effective framework for the design of fuel-efficient vehicles in earlier design stages.

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INTRODUCTION

With unprecedented higher pressure for improving vehicle's aerodynamic efficiency, it is inevitable to incorporate multiple performance attributes for the optimization of vehicle design. This is because the conflict between a single achievable goal, such as optimal aerodynamic design, and others, such as powertrain operation and cooling requirements, has never been more severe. As such trade-offs become more critical, traditional ways of vehicle design relying on sequential, iterative processes become not only inefficient but also incapable of providing desired design solutions. On the other hand, a design problem of concurrent optimization of multiple attributes can be much more challenging but at the same time provides higher potential for improving performance by incorporating conflicting goals in a single design frame.

Although the drag coefficient is still widely used as a key performance metric of aerodynamic bodies, the number alone hardly represents the real aerodynamic efficiency, such as actual energy consumption due to aerodynamic loadings. Such loadings include the aerodynamic drag of vehicle body, aerodynamic torque on wheels and parasitic forces related to various cooling airflows, which, unlike the nominal drag coefficient, usually vary significantly depending on a vehicle's operating conditions. For example, at different vehicle speeds, the wheel torque typically affected by underhood and wheel

ventilation flows as well as underbody flow may not scale in the same way as the external aerodynamic forces. At the same time the amount of flow for powertrain cooling differs significantly, where the flow through gaps and rotating parts involves various spatial and temporal scales.

Among various performance attributes, the fuel economy (or range for electric vehicles) is an inclusive representation of overall efficiency. Since most regulations for vehicle energy efficiency are based on fuel economy, it can be an objective of optimizing aerodynamic efficiency in vehicle design as a direct target. This system-level performance naturally incorporates all the constraints driven by other component designs. In particular, the trade-offs between aerodynamic and cooling performances of various parts should be accounted for as part of the solution.

In gasoline vehicles, where the engine and powertrain parts and their cooling modules are usually located under the hood, front-end cooling is one of the major constraints for reducing aerodynamic drag of the vehicle. For electric vehicles the motors, drivetrain, and batteries usually require cooling airflow for their operations. One of the challenges in improving the aerodynamic efficiency of a vehicle while meeting these cooling targets comes from a wide range of its operating conditions, such as drive cycle and ambient temperature.

Active grille shutters (AGS) can provide flexibility in improving a vehicle's aerodynamic efficiency by reducing excessive cooling airflow. However, the design of their management system and estimation of performance gains across different operating conditions, combined with parallel design efforts, can introduce elaborate design iterations. Subsequently, the assessment of the vehicle's aerodynamic efficiency becomes more subject to less-informed design decisions, more likely resulting in suboptimal design solutions.

This study illustrates an improved design framework for the development of a high-efficiency vehicle utilizing active cooling devices for powertrain or drivetrain. The concurrent optimization framework encompasses the potential for a more comprehensive design space along with advanced predictive models. As an example application the management of AGS units, i.e., optimizing the AGS control strategy, for a given drive cycle and ambient temperature condition is presented.

APPROACH

The schematic of the simulation framework is shown in Figure 1. The processes consist of two parts: one is the characterization of design space with an iterative design of experiments for aerodynamics and heat exchanger cooling simulations and the other is the drive cycle simulation. For the latter the aerodynamic loadings are calculated by iteratively optimizing the AGS openings and achieving the powertrain cooling target at the same time. This is done by enforcing the target radiator heat rejection to be the same as the total vehicle power consumption, which is composed of aerodynamic and non-aerodynamic components. The surrogate models from the first part bridge the two processes by calculating the aerodynamic power and radiator heat rejection.

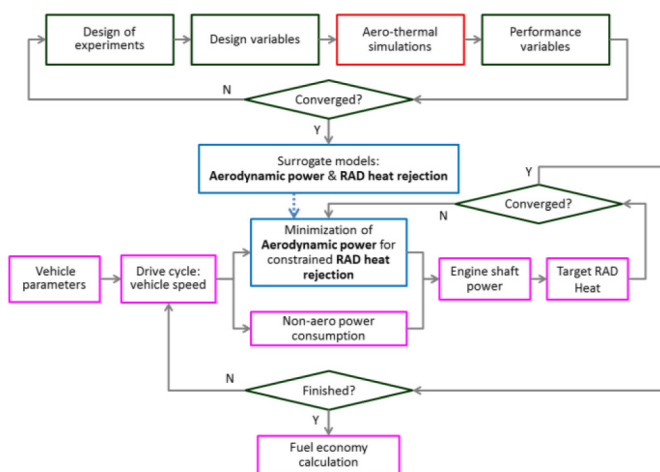


Figure 1. Process schematic for the optimization of AGS for fuel economy.

Aerodynamics and Heat Exchanger Cooling Simulation

The aerodynamics simulations of a generic SUV-type vehicle are done by using PowerFLOW, a lattice Boltzmann-based commercial software for the calculation of time-accurate unsteady aerodynamics. An open-road condition with clean upstream flow and moving ground is assumed. Heat exchangers are modeled by calculating the pressure difference with the inertial and viscous resistance coefficients and the heat transfer coefficients as functions of air and coolant mass flows based on measured or modeled component data. The thermal flow solver coupled with the heat exchanger models provide the cooling air temperature around heat exchangers. More details on the flow solver and its coupling for the calculation of thermal performance are available in [1].

The rotating motions of cooling fans and wheels are resolved by using the local reference frame approach. Time-averaged quantities such as aerodynamic forces and heat rejection rates are based on averaging their stationary unsteady data for 1.5 seconds.

The vehicle model incorporates generic parts of a passenger vehicle along with upper and lower grille openings in the front [2]. Upper and lower AGS units accept underhood cooling airflow with 6 and 7 grille members, respectively, which are angled in line with the local streamlines when fully open. Some key underhood parts, such as powertrain, heat exchangers, and auxiliary components, are located in the engine bay. Only vehicle radiator and charge air cooler (CAC) are modeled as active heat exchangers, i.e., coupled with the thermal flow solver whereas the condenser is a passive porous media corresponding to the conditions of air conditioner off. The modeled coolant mass flow rates of the radiator and CAC are proportional to the vehicle speed, and their inlet temperatures are set to 110°C and 150°C, respectively. Two synchronized 8-blade fans along with stators and sealed fan shroud are located downstream of the radiator. As described below, the fan rotation speed is an independent design variable. The scenarios of more generalized heat exchanger and cooling fan operation can be incorporated within the same modeling framework.

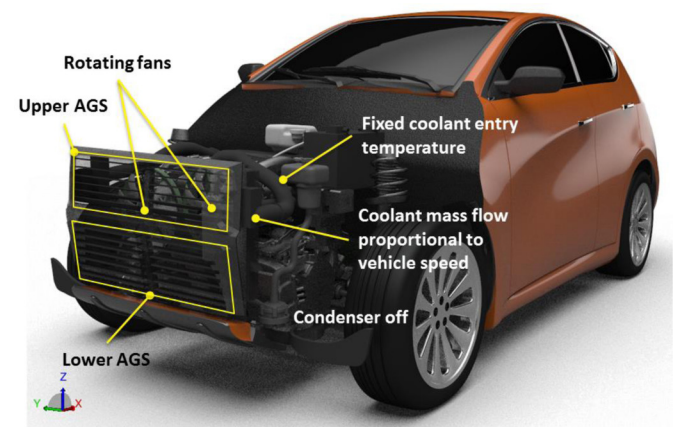


Figure 2. Underhood parts and heat exchanger cooling units of model vehicle.

Design Space Characterization

As shown in Table 1, the design space incorporates 5 design variables, two for operating conditions and three for cooling modules, which is the same as [2]. In particular, only the highway speed range is considered in order to focus on the conditions with the largest impact of aerodynamic efficiency. The design space is resolved by coupled aerodynamics and heat exchanger cooling simulations based on a sequence of sampling strategies, which includes the Uniform Latin hypercube (ULH) and Adaptive Space Filler algorithms [3] available in modeFRONTIER. The surrogate models for objective functions are based on the Kriging model also available in modeFRONTIER. For 23 training samples the root-mean-square leave-one-out error is 2 counts for the aerodynamic drag coefficient and 5 kW for the radiator heat rejection rate.

In addition to the four objective variables, surrogate models for a number of other quantities are considered for the purpose of analysis too, such as front and rear lift coefficients, underhood cooling air mass flow rate, and air flow rate through rim openings for front and rear wheels.

The total aerodynamic power can be calculated by the following.

$$P_{aero} = P_{body} + P_{wheel} + P_{fan} \quad (1)$$

Table 1. Design space and objectives.

Design variables	Lower bound	Upper bound
T_{amb} : Ambient temperature [°C]	-10	40
V : Vehicle speed [mph]	60	100
α_U : AGS upper closure ratio	0	0.95
α_L : AGS lower closure ratio	0	0.95
ω_f : Fan rotation speed [rpm]	0	3000
Objectives		
P_{body} : Aerodynamic power on body [kW]		
P_{wheel} : Aerodynamic power on wheels [kW]		
P_{fan} : Aerodynamic power on cooling fans [kW]		
H_{RAD} : Radiator heat rejection rate [kW]		

Constrained Optimization of AGS for Minimizing Aerodynamic Power Consumption

For the quasi-steady modeling of vehicle operation, it is assumed that at each time instance the total power consumption and target powertrain cooling requirement for radiator are balanced. With fully open AGS the cooling package tends to allow more-than-necessary cooling airflow, increasing aerodynamic power consumption. In order to minimize the redundant cooling airflow the AGS openings can be determined by minimizing the aerodynamic power consumption while satisfying the cooling requirement at each operating condition.

Since the aerodynamic power consumption and cooling requirement are coupled through the fuel economy model below, the optimization problem needs to be solved iteratively at each time instance.

The optimizer adopts the objective and constraint functions from the surrogate model of total aerodynamic power and radiator heat rejection rate, respectively. This constrained optimization problem is solved by using the Sequential Least-Squares Quadratic Programming (SLSQP), where a nonlinear constrained optimization is replaced by a standard quadratic program with a quadratic approximation of the Lagrange function and linear approximation of the constraints [4]. The SLSQP optimizer in Python's pyOpt library is used in this study.

Fuel Economy Simulation

A simulation model is built to calculate the vehicle fuel economy on a given dynamic drive cycle. The dynamic drive cycle is divided into discrete time steps, in which a quasi-steady state calculation is performed to assess the instantaneous fuel consumption rate based on the vehicle speed, road load, tire slip loss, transitional and rotational inertia, the engine efficiency as well as transmission ratio and efficiency. The fuel consumption is calculated by integrating the instant fuel rate throughout the drive cycle divided by the distance, resulting in a vehicle average fuel economy for the drive cycle [5].

For an instantaneous vehicle speed from the drive cycle, the road load consists of the rolling resistance and vehicle aerodynamic drag, or equivalent total aerodynamic drag, i.e.,

$$F_{road} = mgC_{rr} + \frac{P_{aero}}{V} \quad (2)$$

, where m is the vehicle mass, g is the gravitational acceleration, C_{rr} is the rolling resistance coefficient, and V is the vehicle speed [6].

In addition, the transitional and rotational inertia forces can be calculated as the following.

$$F_{inertia,trans} = m \frac{\delta V}{\delta t} \quad (3)$$

$$F_{inertia,rot}(\omega_w) = \frac{I_p \delta \omega_w}{R_w \delta t} \quad (4)$$

, where I_p is the effective powertrain rotational inertia from the view point of driving wheels, ω_w is the wheel rotational speed, and R_w is the effective rolling radius of wheel. The rotational inertia is a function of wheel rotational speed.