

Evaluation of Impact of Active Grille Shutter on Vehicle Thermal Management

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ABSTRACT

Due to increased demand for improved fuel economy and reduction in CO₂ emissions, active grille shutter (AGS) has been considered as one option to increase fuel economy by reducing vehicle drag resistance. An AGS system will allow airflow through the grille when demand on cooling system or air conditioning system is high. Under conditions of light load and moderate ambient temperatures and humidity, the grille does not have to be fully open. A reduction in the effective grille size opening can be achieved by either partially or fully closing the grille through a stepped speed motor actuator. When the grille opening size is reduced, under-hood airflow will decrease. Therefore, the operating points for the grille shutter should take into account the effect of temperature rise for under-hood and underbody components and the performance of the cooling and climate control systems. In this paper, a series of tests have been designed and conducted to evaluate the effect of the grille shutter on the air conditioning (AC) system performance, and power train cooling as well as under-hood and underbody components temperatures. Tests have been designed to determine the impact of AGS on the AC compressor and fan power consumptions, cooling system and climate control system performance. Tests were selected to cover wide range of ambient temperature, humidity, vehicle speed, and climate control settings. In this paper, the experimental test results are analyzed and presented. Recommendations for the selection of the grille shutter operating points are based on these test results, functional requirements of vehicle systems and components, and overall fuel economy benefits.

INTRODUCTION

Grille shutters have been used on some vehicles as far back as the 1920's (e.g. 1929 Rolls Royce, 1930s-40s Packards) for primarily thermal warm-up benefits. The aerodynamic drag reduction benefits are a primary driver for modern active grille shutters (AGS). Although used primarily on luxury branded vehicles in recent times (e.g. Mercedes and BMW), almost all automobile manufacturers are currently investigating, and in some cases in the process of introducing them for production [1, 2, 3, 4, 5].

While the purpose of the grille shutter is to improve the overall vehicle fuel economy by reducing the overall drag resistance, it has an impact on the performance of climate control system, powertrain cooling system and under-hood components temperatures. The grille shutter will reduce the under-hood airflow and therefore, the under-hood components may exhibit higher temperature than normal conditions (when the grille is fully open). The rate of thermal degradation is directly related to the component temperature. Evaluation of the effect of thermal environment on automotive components requires early planning during the development phase of each program. Due to continuously increasing requirements to improve fuel economy and reduce emissions, vehicles are becoming more compact with less clearance for airflow.

ESTIMATION OF AERO DRAG REDUCTION

The aerodynamic drag was measured on a mocked-up part installed in the upper grille in a vehicle in the wind tunnel, first with grille shutters open and then with shutters closed. Aerodynamic force is proportional to velocity squared (Drag

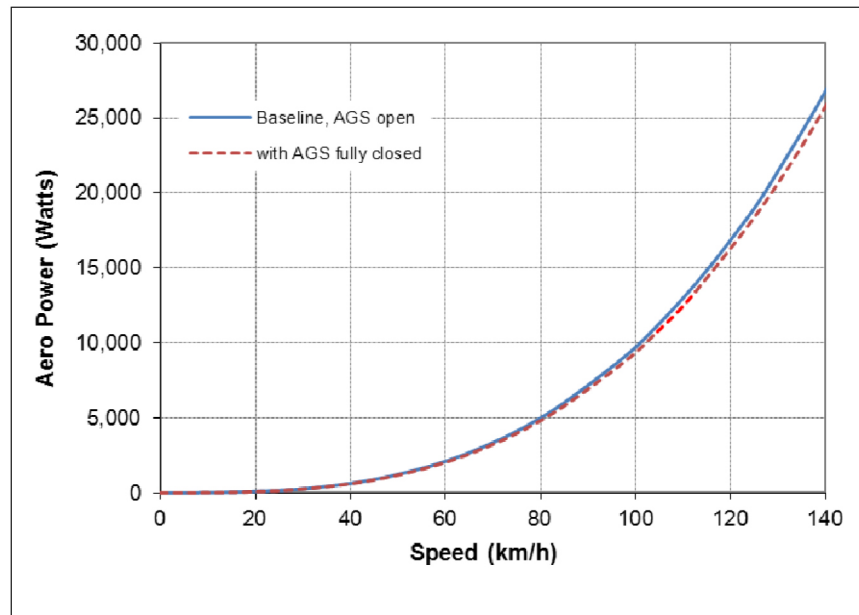


Figure 1. Aerodynamic Power for Vehicle without and with Shutters Closed at Various Speeds

= $CDA \cdot \frac{1}{2} \rho V^2$, where C_D = coefficient of drag, A = reference frontal area, and $\frac{1}{2} \rho V^2$ = dynamic pressure or q), and thus aerodynamic power results are proportional to velocity cubed (Power = Force $\times$ Velocity). Therefore, at higher speeds (> 80 km/h) the aerodynamic benefits become significant.

The aerodynamic power curves for grille shutters open and grille shutters closed can visually be seen in the following graph:

The aerodynamic power benefits (which can then be translated into fuel economy benefits) can then be seen. In this case, the aerodynamics benefits were worth about 11 counts ($-0.011 C_D$) of drag reduction. [Figure 2](#) shows the aerodynamic power reduction (expressed as the delta power between the two curves) resulting from a prototype active grille shutter system:

In this case, the 3% aero drag reduction translates into 407 watts benefit (vehicle load reduction) at 105 km/h. This is considered significant, although the tradeoffs from the AC power consumption must then be taken into account. For some ranges of velocity and ambient temperatures, the increase in AC power consumption will become more than the aero benefits; and thus, the shutters should be opened.

EFFECT OF GRILLE SHUTTER ON POWERTRAIN COOLING

Initial plans for design of powertrain cooling systems are based on a specific set of test conditions that cover a wide range of scenarios. Typical test conditions include driving on grades at high ambient temperature and high loads. Other

tests include slow city traffic tests, and high speed tests (160 Km/h or higher) at high ambient temperature. These extreme test conditions are essential to determine the required airflow for cooling and cooling system configurations. Implementation of grille shutters will reduce the amount of air passing through the cooling modules. Therefore, the cooling system performance will be negatively affected by the grille shutter operating strategy. However, to improve the overall vehicle fuel economy benefits, the grille shutter operating points should be selected in a way that will maximize the fuel economy benefits while maintaining the engine coolant, engine oil and transmission oil below their temperature limits.

EFFECT OF GRILLE SHUTTER ON CLIMATE CONTROL SYSTEM PERFORMANCE

Implementation of the grill shutter can affect climate control system performance in several ways. As a result of reduced airflow through the condenser, the refrigerant temperature will increase. Therefore, the AC compressor will use more power to maintain the required panel air-out temperatures at the required settings. As a result, the AC compressor may end up using more energy than the benefits gained by aerodynamic drag reduction. In addition, electric fans may be running more often and at higher speeds than normal (when the grille is fully open). Therefore, the grille shutter operating strategy should be designed in a way that can maximize aerodynamic benefits and minimizes the additional power consumption by the AC compressor and cooling fans. On the other side, warm-up benefits can be gained when the grille shutter is fully closed during a cold start especially at very

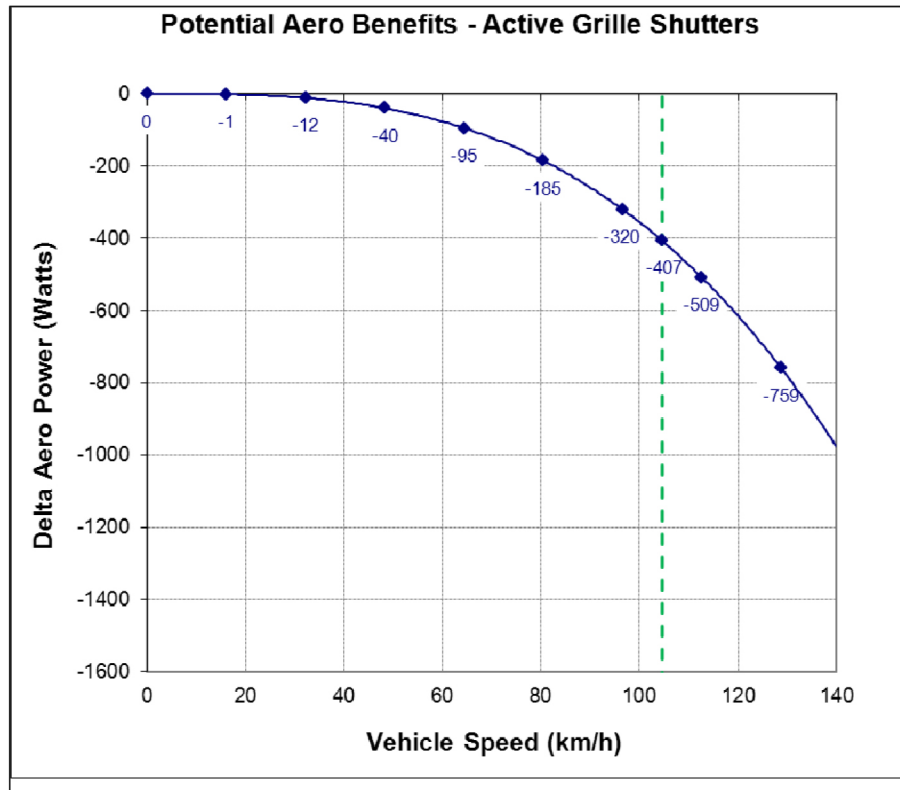


Figure 2. Potential Aero Benefits at various vehicle Speeds

low ambient temperatures. This will help the engine oil and transmission oil to warm up faster than when the grill is full open.

EFFECT OF GRILLE SHUTTER ON COMPONENT TEMPERATURES

Due to restrictions on emissions and the stringent requirements for improved fuel economy, the use of polymers and synthetic materials has been widely adopted in automotive applications. It is therefore critical to maintain vehicle components within their respective temperature limits. The typical temperature limits are defined as follows:

“Long Term Temperature Goal” is defined as the maximum temperature that the material can be exposed to for five hundred hours throughout the life of the vehicle without losing more than fifty percent of its performance.

“Short Term Temperature Goal” is defined as the maximum temperature that the material can be exposed to for fifty hours throughout the life of the vehicle without losing more than fifty percent of its performance.

The long term temperature goal applies to frequent driving conditions such as driving on freeways or during city traffic at gross vehicle weight (GVW).

The short term temperature goal applies to the less frequent driving conditions such as towing a trailer on a grade while driving at vehicle gross combined weight (GCW).

Several of the under-hood components such as the battery, engine mounts and rubber bushings usually have lower temperature goals that require thermal protection even though the grille may be fully open. These components are usually more sensitive to heat transfer by radiation from the exhaust manifold or the catalytic converters. Therefore, the steady state component temperature is a function of the heat addition by radiation and heat removal by air (convection). The heat removed by convection is therefore a function of the under-hood air temperature and airflow around each component. Any restrictions in the grille opening will restrict airflow in the under-hood compartment and will cause the radiator exit air temperature to increase. All these factors will cause an increase in component temperatures. The rate of thermal degradation of vehicle components is strongly related to the component temperatures and the vehicle duty cycle [9-10]. Therefore, the strategy of operating the grille shutter should consider the increase in component temperatures and its effect on component expected life.

THERMAL TESTING AND RESULTS

When planning the thermal testing, the following major points were considered:

- Historical test data and existing thermal profile for under-hood components suggest that the under-hood component temperature will exceed the temperature goals for the high load and high ambient conditions if the grille is fully closed or partially closed. Therefore, grade and trailer towing testing were not considered. An ambient temperature of about 30° C was considered as the maximum limit for testing with the grille closed (either fully closed or partially closed).
- Based on the above aerodynamic analysis, at low speeds of 55 Km/h or less, the aerodynamic benefits for the grille shutter do not justify having it closed. Therefore, test conditions were focused on vehicle speeds of 100 Km/h or higher.
- Since the AGS provides maximum benefits at higher speeds, a series of high speed tests at various ambient conditions were conducted for several positions of the grille shutter.
- To evaluate the impact of the grille shutter on AC compressor power consumption, a flow meter was used to measure the refrigerant flow rate. The change in the enthalpy of the refrigerant stream across the compressor was used to evaluate the AC compressor power consumption.
- In order to have valid comparisons of the cooling system and climate control performance at different grille shutter positions, the test plans were conducted in a thermal test cell where the test conditions can be easily controlled.

TESTING FOR COOLING SYSTEM PERFORMANCE

In this series of tests, the vehicle speed was increased, in increments of 16 Km/h, every 5 minutes. The starting speed was 110 Km/h. Test conditions are described as follows:

- Cell Ambient: 30° C
 - Vehicle speed: Vehicle speed was varied, from 110 Km/h to 208 Km/h, in increments of 16 Km/h every 5 minutes
 - Wind speed: Same as vehicle speed
- Vehicle was tested with the following positions for grille shutter :
 - Fully OPEN
 - 20° OPEN
 - Fully CLOSED

Several components temperatures, cooling system and AC system performance were measured. Vehicle speeds of about 208 Km/h can be maintained when the grille was fully open. When the grille was fully closed, the maximum vehicle speed was only 175 Km/h. Therefore, in addition to its impact on components temperatures and AC system performance, the grille shutter can affect the vehicle performance, as seen in [Figure 3](#). At the higher speeds, the engine coolant and engine oil temperatures approach their maximum limits. A protection strategy (de-rating strategy) will be invoked at that stage to protect the engine. The higher oil and coolant temperatures are a result of the limited airflow through the radiator when the grille opening is partially or fully closed. The following is a summary of the test observations during the high speed test trials:

- AC did not cut out at high speed of 208 Km/h
- Engine went into de-rating strategy under the following conditions:
 - At 208 Km/h with the grille shutter fully open
 - At 190 Km/h with the grille shutter 20° open
 - At 175 Km/h, with grille shutter fully closed
- Therefore, a completely closed grille above 160 Km/h may not be recommended
- AC discharge pressure is higher when grille is closed or partially closed
- Panel out temperature, sub-cool and AC discharge pressure are within acceptable limits

[Figure 4](#) illustrates the effect of the grille shutter on engine speed under the same test conditions listed above. At the high speed conditions, the engine speed (RPM) causes overheating of the engine oil which forces the vehicle into a protection mode that limits vehicle to lower speeds where the engine oil temperature can stay within acceptable limits.

[Figure 5](#) illustrates the effect of the grille shutter on engine coolant temperature. Although the engine coolant temperature was higher when the grille was fully closed than when the grille was fully open, there was a little difference in engine coolant temperature when the grille was about 20° open.