

Aerodynamic Investigation of Cooling Drag of a Production Sedan Part 1: Test Results

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ABSTRACT

The airflow that enters the front grille of a ground vehicle for the purpose of component cooling has a significant effect on aerodynamic drag (engine airflow drag). Furthermore, engine airflow is known to be capable of influencing upstream external airflow (interference drag). The combined effect of these phenomena is commonly referred to as cooling drag, which generally contributes up to 10% of total vehicle drag. Due to this coupled nature, cooling drag is difficult to understand as it contains influences from multiple locations around the vehicle. A good understanding of the sources of cooling drag is paramount to drive vehicle design to a low cooling drag configuration. In this work, a production level Lincoln MKZ was modified so that a number of variables could be tested in both static ground and moving ground wind tunnel conditions. All tests were conducted at 80 MPH. The variables studied were: underbody shield coverage, heat exchanger resistance, cooling pack configuration, vehicle attitude, front-end sealing, exit path sealing, engine bay blockage and active grille shutter (AGS) configuration. In addition to overall vehicle drag coefficients, surface pressure taps, underbody velocity rakes and cooling pack mass flows were measured to provide better insight into the internal and external flow behaviour. This paper represents the first of a two-part series, with experimental and numerical foci respectively.

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INTRODUCTION

Automotive design challenges have grown significantly over the last few decades. Modern day vehicles must achieve the combination of: attractive styling, always-improving fuel economy, always-reducing emissions, high levels of performance and improved safety. Modern day customers also expect novel interface advancements to increase the driving experience, such as partial and one-day full-authority driver-assist technologies. Many of these design requirements inherently interfere with each other as well with areas such as packaging, weight and cost.

One of the previously mentioned attributes, fuel economy, is a measure of losses from various mechanical and chemical processes that occur in the operation of the vehicle, as well as driving habits. One of the mechanical losses is aerodynamic drag, which as [equation \(1\)](#) shows, increases exponentially with the vehicle speed and thus becomes most detrimental to fuel economy at highway speeds.

$$D = \frac{1}{2} \rho_{\infty} V_{\infty}^2 S C_d \quad (1)$$

The drag of a vehicle can only be designed for through frontal area (S) and drag coefficient (C_d). Furthermore, the drag can be divided into momentum loss around the body (external drag) and momentum loss through the body (internal drag). The dependence of these two classifications of drag on each other is referred to as interference drag

[1, 2, 3, 4]. External drag of a vehicle body is directly coupled with vehicle styling while internal drag interacts with cooling performance amongst others.

Generally, internal flow accounts for up to 10% of the total vehicle drag, which is determined through wind tunnel tests where the vehicle drag with an open and closed front grille is compared. This parameter is commonly referred to as cooling drag, shown in [equation \(2\)](#).

$$C_{d_{cooling}} = C_{d_{open\ grille}} - C_{d_{closed\ grille}} \quad (2)$$

Several strategies exist to mitigate cooling drag that have been discussed in the literature, these include: grille opening optimization, cooling fan/shroud optimization, active grille shutters (AGS), and heat exchanger ducting [5, 6, 7, 8, 9, 10, 11]. These strategies rarely only affect cooling drag, uniformity of heat exchanger flow or component thermal management may also be objectives.

The vehicle used in this study contains the AGS technology, herein AGS drag will be defined as shown in [equation \(3\)](#).

$$C_{d_{AGS}} = C_{d_{open\ vanes}} - C_{d_{closed\ vanes}} \quad (3)$$

The AGS efficiency can then be taken as the ratio between the AGS and cooling drag (4).

$$\eta_{AGS} = \frac{C_{d_{AGS}}}{C_{d_{cooling}}} \quad (4)$$

Given the complex nature of production vehicle internal air flow paths and their interactions with external air flow patterns, cooling and AGS drag have historically been difficult to understand. Several studies exist in the literature that provide insight into these phenomena. These studies can be categorized into two groups: simplified bodies and production-level bodies.

Barnard conducted experiments on a ducted Ahmed body, with adjustable flow exits in either the base or underbody [12]. His results showed that thrust recovery due to underbody flow exit angle and exit location had a significant effect on cooling drag. Williams used the Probe IV aerodynamic concept vehicle (with base region cooling flow exits) to draw relations between cooling drag and cooling system resistance [4,13]. Lai et al. used a 1/8 scale simplified notchback model to study relations between cooling drag and ground clearance, rear diffuser angle, exit-flow inclination angles and locations of the cooling flow outlet [2]. Kuthada et al. presented a simplified SAE-Body which was later modified by Baeder et al. to incorporate an underhood region and the cooling drag dependence on cooling exit angle/location, and radiator resistance were studied [14–15]. A 1/4 scale DrivAer model was modified to allow underhood flow in a collaborative effort between TU Munich and FKFS [16–17]. The DrivAer model is a generic model based on the Audi A4 and the BMW 3-series and it features interchangeable rear ends (notchback, fastback and wagonback) [18]. The open-cooling DrivAer vehicle features a simulated radiator and simplified engine block, cooling air flow is allowed to leave through either the front wheel houses and/or the underbody.

The effects of ground simulation and rear-end shape were studied by Kuthada and Wiedemann and Wickern et al. on full scale vehicles [1,19]. It was determined through an extensive testing matrix of vehicles body styles that cooling drag tends to be higher in moving ground conditions than in static ground conditions. It was theorized that because stationary wheels have a larger drag than rotating wheels, the interference flow that impacts the front wheels would have a greater impact in moving ground conditions. The resulting front tire wakes then had a downstream influence on the body style. Tesch et al. studied the influence of cooling mass flow and cooling air flow outlet location on a scale model BMW 3-series and found that for a constant cooling mass flow the cooling drag varied widely depending on the outlet location [20]. The trend of cooling drag vs. cooling mass flow was also widely different depending on the outlet location, these phenomena were attributed to different mechanisms of interference effects depending on the outlet location.

The purpose of this study is to characterize the cooling and AGS drag behaviour of a production level C-Car sedan (2013 Lincoln MKZ) with respect to design considerations that may exist during the development of a program. As it has been previously shown that

cooling drag can be influenced by the road simulation technique, select cases were studied in both stationary and moving road conditions [19].

EXPERIMENTAL SETUP

Model Details

All experiments were conducted on a modified full scale 2013 Lincoln MKZ AWD 3.7L vehicle, see Figure 1. Modifications were made to study the influence of: AGS position, AGS sealing, heat exchanger resistance, cooling pack sealing, engine bay blockage, engine bay exit paths, vehicle attitude and underbody shielding. Apart from monitoring the integral coefficients of C_d and C_p , 80 (mostly) flush surface pressure taps were mounted along the vehicle, primarily along the: upper and underbody centrelines, hood and fascia near the suspected inlet interference zones, vehicle base, heat exchangers and engine bay. This vehicle's heat exchanger configuration consists of a condenser upstream of a radiator of roughly equal size. For select tests, an array of 15 vane anemometers was placed between the heat exchangers so that aligned air flow could be measured.



Figure 1. 2013 Lincoln MKZ test vehicle, shown here in a moving ground test condition.

The engine bay blockage was varied by removing the electrical system, air-intake system, engine cover, coolant reservoir and the engine location was made adjustable with fore/aft translation, see Figure 2. Cooling pack sealing was modified in several ways, the upper sealing was controlled by removing the beauty cover (see Figure 3) and the lower sealing was controlled by the underbody engine shield.



Figure 2. Engine translation mechanism, capable of moving the engine +/- 70mm for/aft.

The AGS system was modified in two ways; (1) the AGS to fascia seals were made interchangeable so that the degree of sealing could be adjusted, and (2) the AGS vanes were modified so that each quadrant could be moved forward or rearward independently, see Figures 4 and 5 for illustrations.

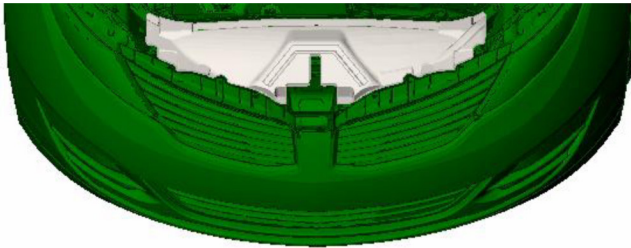


Figure 3. Beauty cover geometry, shown in white.

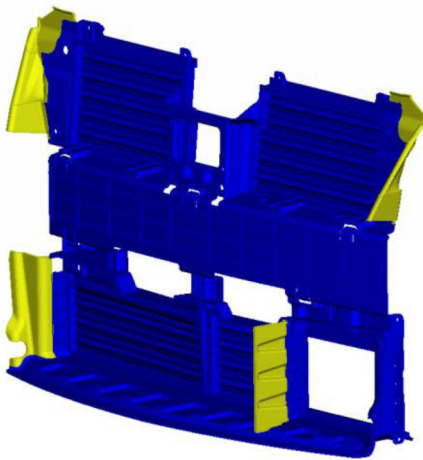


Figure 4. Side seals (yellow) that were interchangeable so that various percentages of sealing could be simulated. Above image is used for concept illustration purposes only and is not the physical article that was tested.

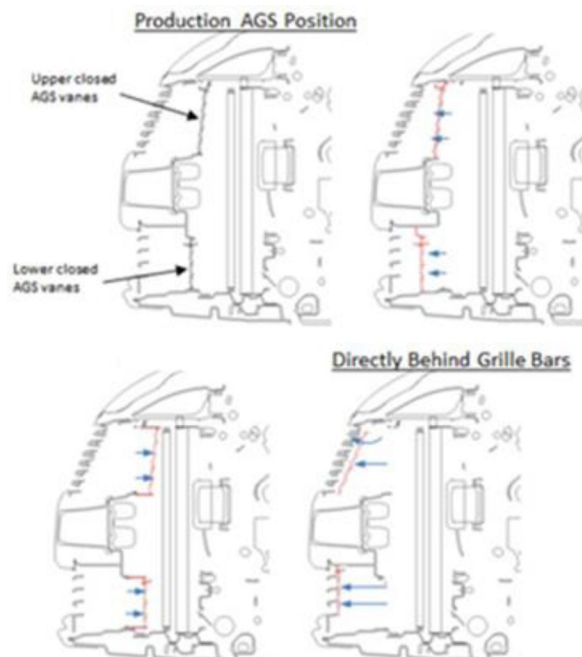


Figure 5. Adjustable AGS position, possible vane locations extended to directly in front of the condenser to directly behind the grille bars.

As previously mentioned, this vehicle features a condenser upstream of a radiator of roughly equal size. Each the condenser and radiator were made removable and perforated plates of various porosity could be added to the reverse side of the radiator. This setup allowed for the influence of heat exchanger presence and resistance on engine bay air flow to be tested. The available condenser and radiator configurations are shown in Figures 6 and 7 respectively.



Figure 6. Condenser configurations, (1) without core, (2) with core.

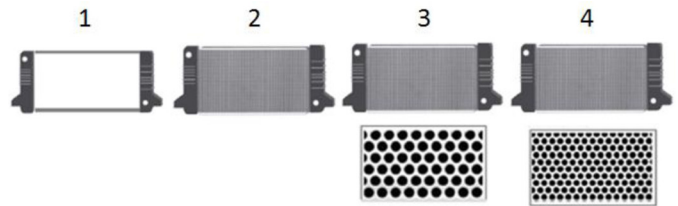


Figure 7. Radiator configurations, (1) without core, (2) with core, (3) core and additional porous plate, (4) core with additional porous plate with higher porosity.

An underbody shield package was constructed so that a completely flat, sealed underbody could be tested, and so that the air flow exit paths could be controlled through the underbody. Figure 8 shows the shield package that consists of: a rear diffuser shield, rear suspension shields, a centre tunnel shield, rocker shields and an engine shield. To force the engine bay air flow through the underbody of the vehicle the wheel liners could be sealed. Due to the complex geometry of the engine bay it was not pursued to perfectly seal the tunnel region in order to force the engine bay flow through only the wheel arches.

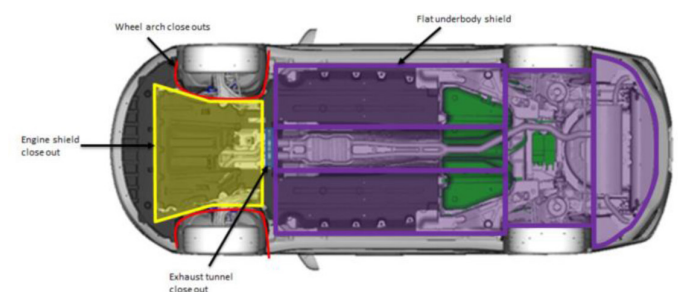


Figure 8. Flat underbody shield package where each shield could be removed individually.

The vehicles suspension was replaced with adjustable screw jacks so that vehicle attitude could be set consistently and so that attitude variation as a result of wind load could be minimized.

Test Facility Details

All static ground tests were carried out at the Ford DTF Wind Tunnel 8 (WT8) facility. WT8 is a full scale, $\frac{3}{4}$ open jet, closed return design with a 16.7 m^2 nozzle and a top speed of 54 m/s (120 mph). The Boundary Layer Control System (BLCS) consists of a tangential