

# Experimental Investigation of Underbody Thermal and Aerodynamic Flow-Field Features

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## ABSTRACT

Underbody vehicle flows are poorly understood given the comparatively small field of research to draw upon; even more so in the case of crosswinds. With the advent of electric and hybrid electric vehicles and their increased cooling demands, there is a need for a link between the aerodynamic flow field and the thermodynamic response. Thus underbody research considering a yawing vehicle was conducted on a Chevrolet Aveo5 hatchback. The vehicle was outfitted with a heat source to provide a baseline analysis along thermocouples, pressure probes and flow visualization tufts. The climatic wind tunnel at the University Of Ontario Institute Of Technology's Automotive Centre of Excellence provided video data of the tufts and thermal imaging data of the heat source. This study has demonstrated that there is a strong link between underbody aerodynamics and the thermal field; however the underbody aerodynamics are more dominated by the geometric turbulent effects due to the rough underbody as opposed to the yawing direction of the vehicle.

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## INTRODUCTION

The global decline in fossil fuel reserves, rising fuel prices and the damaging effects of global warming have necessitated the need to minimize fossil fuel consumption especially in the transportation sector which heavily depends on fossil fuels. Electric vehicle (EV) and Hybrid electric vehicle (HEV) technology offer huge potential to decrease our fossil fuel dependence. However, cooling the battery packs used in EVs and HEVs is still a challenge that requires innovative solutions. There are therefore aggressive research programmes that focus on different cooling techniques from phase-change material to liquid cooling, and natural and forced convective air cooling. Traditionally aerodynamics and thermodynamics (aero-thermal) studies on vehicles primarily focus on underhood. However, growing engine power demands, utilization of sophisticated underhood and underbody devices, and emission regulations have combined to make underhood and underbody aero-thermal management take an increasing role in the design process of new road vehicles. Although air penetration into the vehicle underhood improves cooling of the components, it also increases the overall aerodynamic drag of a vehicle.

In past, automotive aerodynamic research focused on the exterior shape and the underhood layout for optimizations. This was largely due to the vast improvements that could be made in these areas with respect to drag reduction and control of underhood temperatures. Earlier studies focused on improving the external body shape, such as the benefits of closed openings or rounded edges with regards to drag reduction [1]. Later studies looked at the interaction between external and underhood flow, such as optimization of the external airflow with air dams and ducts to improve the cooling flow through the radiator. Costa (2003) reduced temperature by 20% through this method [2]. There are many other studies which reported underhood analysis including the optimal positions of components relative to another, fan design and numerical modeling methods ([3], [4], [5]). Furthermore, all these studies were conducted without any cross-winds.

The majority of prior studies on underbody aerodynamics is split mainly into two distinct methods: research on highly generalized vehicle models, such as the Ahmed body [6], and research on a specific vehicle models. For example, Jowsey and Passmore reported a general design guideline for the optimal dimensions and geometry of an automotive underbody diffuser for low drag and high downforce using an Ahmed body [6]. On the other hand, research of an active diffuser that change shape depending on velocity was

performed by Kang et al. [7]. They reported up to 4% drag reduction on a Hyundai Sonata. Further underbody aerodynamic research involved the optimization of the flow in wheelhouses and around the tires [8]. The common theme in underbody aerodynamic research is to reduce overall drag and increase down force. Although research on underbody aerodynamics is limited, this is changing as optimizations with the exterior shape alone are becoming difficult to implement [1].

In addition, there is plenty of research that focusses on coupling thermal and aerodynamic research in the underhood, due to the high cooling demands of the engine ([9], [10], [11], [12]). There are also some components under vehicles that require cooling (e.g., differentials, battery packs). However, there is no real focus on how to link underbody aerodynamics to the thermal demands of these underbody components.

A vehicle can assume different yaw angles and inclinations, due to loadings, terrain, turning or cross-winds. These driving conditions significantly alter the airflow through the air inlets from their ideal design positions since the airflow entering a vehicle's underhood and underbody interacts strongly with the front geometries. Aero-thermal studies have traditionally been done based on three steady-state load cases: maximum velocity, trailer towing uphill and idle at a zero yaw angle [13]. Cross-wind effects, yaw and vehicle inclination in controlled environments are not fully understood.

The objective of this study was to investigate what automotive underbody thermal phenomena may be sensitive to cross-wind. To achieve this objective, an idealized heat source was used to approximate heat added to the air by the rear differential and wind tunnel measurements were employed to study the effects of cross-wind on thermal effects under a combination of ground speeds and cross-wind speeds. In particular the study examined the effects of cross-wind on heat convected from a controlled heat source at the rear axle of a real vehicle for different yaw angles, wind speeds and simulated road speeds. A 2005 Chevrolet Aveo5 was used as the test vehicle.

## EXPERIMENTAL SETUP

### Test Facility

The tests were conducted in the climatic wind tunnel (CWT) in the Automotive Centre of Excellence (ACE) at the University of Ontario Institute of Technology (UOIT). The CWT is the world's only full-range CWT that incorporates a dynamometer in a large turn-table for yaw testing. The vehicle was mounted on the 11.7 m turntable and the dynamometer. The nozzle of the wind tunnel can be expanded from a minimum of 7 m<sup>2</sup> to a maximum of 13m<sup>2</sup> in order to test a variety of vehicle sizes and shapes at a maximum speed of 250 km/h. The climatic aspects of the wind tunnel range the gamut from a 100°C temperature range (from -40°C to 60°C), relative humidity from 5-95%, a solar array to simulate the sun, and the capability to simulate driving or falling snow or driving rain [14].

The CWT is designed with a boundary layer removal system to reduce the size of the boundary layer for all possible configurations. Best et al. [14] investigated the boundary layer thickness at four different distances - 2120mm, 3210mm, 5343mm, and 7476mm - from the nozzle. The maximum boundary layer thicknesses at each of these locations were approximately 25mm, 50mm, 90mm and 135mm respectively. In addition, the static pressure variance across the nominal nozzle area is only 0.01 Pa and the temperature variance is a maximum of 0.2°C [14].

The 2005 Chevrolet Aveo5 was used as it is the available test vehicle at ACE. It was tested at two different temperatures, 10°C and 50°C, two wind speeds of 50km/h and 100km/h, and five different yaw angles: 0°, 8°, 15.6°, 29.2° and -29.2°. These test conditions were chosen to test the full range capabilities of wind tunnel from the minimum to the maximum. The vehicle was strapped down to the turntable using ratchet straps at the rear of the vehicle while at the front of the vehicle aircraft cable was used to anchor the vehicle down to minimize aerodynamic interference. Testing was done at various yaw angles in order to further understanding of the flow-field in cross-winds given the previously noted limited research currently available. Because of the large yaw angles, the 13m<sup>2</sup> (2.9m × 4.5m) nozzle was used for the tests. Figure 1 is a picture of the test vehicle in question in the climatic wind tunnel.



Figure 1. The test vehicle inside the climatic wind tunnel.

### Test Vehicle Instrumentation

The test vehicle was outfitted with a hot-plate affixed to the gas tank under the vehicle as shown in Fig.2. The hot-plate measured 20cm long by 20cm wide by 2.5cm thick and was made of aluminum. Four K-type thermocouples were embedded at each edge of the plate at approximately half the depth of the plate (12mm) to record the temperature. Based on preliminary tests the power supplied to the hot-plate was limited to 1000 W to avoid melting of the car's gas tank (made of acrylonitrile butadiene styrene)

In all 137 K-type thermocouples were installed around the hot-plate and vehicle underbody to measure the temperature distribution and changes due to the wind. A square array of thermocouples 10 cm apart covering the vehicle's underside from the front axle to the back side was used. Finer arrays of thermocouples at 3 cm apart were used around the hot-plate as shown in Fig. 2 for better capture temperatures close to it. All the thermocouples were placed 5 mm away from the surface of the underbody so they are approximately

inside airflow boundary layer. A few thermocouples were located at the radiator, hood, front bumper, side-view mirrors, the centre of the roof, in front and behind the rear wheel wells for reference. The thermocouples were connected to a bank of nine Ipetronik M-Thermo K-type 16 channel modules. These modules were then connected to a data acquisition system called TALENT Test Automation System supplied by ReACT Technologies Inc. The thermocouples were calibrated and each one checked in advance of the test by comparing their temperature readings to a known temperature. Figure 2 shows the position of the instrumented thermocouples under the body.

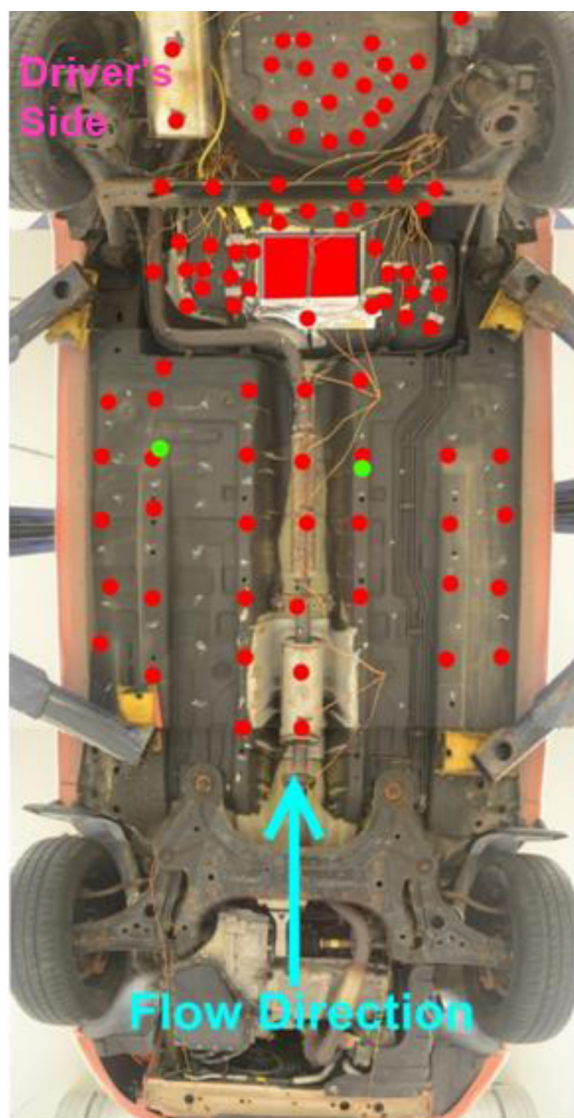


Figure 2. The vehicle underbody, showing the flow direction, position of the hot-plate (red rectangle), thermocouples (red dots) and probes (green dots). The left side is the driver's side.

Two Aeroprobe 5-hole pressure probes were also used to measure the wind speed and direction; one at the driver side of the vehicle and the other at the passenger side. Only two probes were used because they are the only ones available. The probes were mounted at the distance of 10 cm from the underbody surface. They were located approximately 1860 mm downstream of the front axle of the car, or approximately 4860mm downstream of the wind tunnel nozzle. The driver side probe was approximately 30 cm from the driver side edge

of the car while the passenger side probe was approximately 65 cm from the passenger side edge of the car, as shown in Fig. 2. In addition, tufts of approximately 5 cm long and 3 mm wide were affixed to the underside of the vehicle for flow visualization.

An infra-red camera (model IRXP 5000) with a wide angle (61.9°) lens was used to measure the surface temperature of the hot-plate to compare with the data from the embedded thermocouples in the hot-plate. This infra-red camera was mounted in a custom window in the turntable under the vehicle. A second custom window was made in the turntable for three video GoPro cameras for the flow visualization. The three cameras have the following specifications: One GoPro Hero Camera with 1280 × 960 pixels resolution and 170° angle of view and two Go-Pro Hero 3 Cameras with 1280 × 960 pixels resolution and of 149.2° angle of view.

### Test Matrix

As mentioned above, the experiments were conducted at a variety of yaw angles, wind speeds, tunnel temperatures. Table 1 contains the detailed test conditions. The number of tests conducted is 18.

Table 1. The test matrix. Tests marked with a \* indicated non-rotating wheels for that test.

| Test | Road speed (km/h) | Yaw angle (deg) | Test section temperature (°C) |
|------|-------------------|-----------------|-------------------------------|
| 1    | 50                | 0               | 10                            |
| 2    |                   | 15.6            |                               |
| 3    |                   | 29.2            |                               |
| 4    |                   | -29.2           |                               |
| 5*   | 0                 | 0               |                               |
| 6    | 100               | 0               |                               |
| 7    |                   | 8.0             |                               |
| 8    |                   | 15.6            |                               |
| 9*   | 0                 | 15.6            |                               |
| 10   | 50                | 0               | 50                            |
| 11   |                   | 15.6            |                               |
| 12   |                   | 29.2            |                               |
| 13   |                   | -29.2           |                               |
| 14*  | 0                 | 0               |                               |
| 15   | 100               | 0               |                               |
| 16   |                   | 8.0             |                               |
| 17   |                   | 15.6            |                               |
| 18*  | 0                 | 15.6            |                               |

## RESULTS AND DISCUSSION

### Temperature Data

Temperature data from the thermocouples were recorded every second by the data acquisition system. The system also recorded the ambient pressure, temperature, etc., for reference. The data was averaged over the entire test for analysis. For the infra-red thermal camera, a video was recorded for review.