Journal of Wind Engineering & Industrial Aerodynamics 177 (2018) 242–259

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Characterisation of the wake of the DrivAer estate vehicle☆

T. Avadiar *, M.C. Thompson, J. Sheridan, D. Burton **

Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, 3800, Australia

ARTICLE INFO

Keywords:
Automotive aerodynamics
Wind tunnel
Bluff body
Wake

ABSTRACT

To date, little information has been published on the time-averaged wake of the *estate* variant of the *DrivAer* vehicle type. In recent years, this generic automobile geometry has been put forward as a more realistic alternative to investigate vehicle aerodynamics than considerably more idealised geometries, such as the *Ahmed body*. In this paper, the time-averaged wake is experimentally investigated through wind-tunnel tests. Velocities maps and profiles, drag-force measurements and base pressure distributions are used to characterise and quantify the flow behind and around the vehicle. In particular, the combination of wake-velocity and base-pressure measurements provide insight into the wake behind an estate vehicle. The results indicate the near wake and base-pressure distribution is dominated by up-wash caused by flow exiting the smooth underbody diffuser.

1. Introduction

Progress in automotive aerodynamic development has been motivated by an increased demand for more energy efficient vehicles, for environmental and economic reasons. For a modern vehicle operating at highway speeds, aerodynamic drag contributes 60% of the overall resistive force (Heft et al., 2012a). In addition, aspects important to a vehicle's operation, such as stability and comfort, are also affected by its aerodynamic shape. There has been an increased consumer uptake of *Sports-Utility Vehicles* (SUVs) in markets such as Australia (Federal Chamber of Automotive Industries, 2017), and continued strong estate vehicle (also termed station-wagons) sales in Europe. Estate vehicles, by significantly increasing the backlight angle for a similar overall length, typically offer increased cargo area and versatile interior configurations. The wake of an estate will differ from an otherwise similar sedan, and as corollary so too will the aerodynamic drag.

The flows behind estates, hatchbacks and SUVs, which all share a similar rear-end configuration, have not been widely studied. The relevant previous studies can be divided into those that have used a simplified model but with a similar back angle and those that use a detailed model (i.e. a production car). These will be considered in turn.

Previously, detailed studies have primarily been focused on generic, simplified geometries, such as the Ahmed (square-back (0°) and 35°slant bodies) (Ahmed et al.), SAE (Cogotti, 1998), ASMO (Aljure et al., 2014), GTS (McArthur et al., 2016; Croll et al., 1996) or Windsor (Littlewood et al., 2011) models. The wake topologies of simplified models are typically fully separated from the base, and provide a good basis to analyse fundamental, large-scale flow structures, but results are not easily transferable to production cars. Indeed, due to the increased complexity and detail of the geometry of production vehicles, regions of high turbulence and general unsteadiness contribute to the complicated wake structure of such vehicles.

The Windsor and Ahmed models are typically rectangular cylinders with a slanted or rounded front geometry. Various rear slant angles are available for both models. The ASMO model has a square-back rear with a smooth surface, a boat-tail rear and an underbody diffuser. The Ahmed and Windsor square-back models typically have a large lower recirculating vortex driven by underbody flow and a standalone upper vortex formed from the rolling up of flow structures in the separated roof shear layer (Littlewood et al., 2011). For the Ahmed and Windsor geometries, a lateral bi-stability in the wake occurs on a time scale 500 to 1000 times longer than typical von-Karman shedding periods (Grandemange et al., 2013; Perry et al.). This feature is also found to be highly sensitive to small angles of yaw, favouring an asymmetric state (Grandemange et al., 2013; Volpe et al.). However, statistical averaging over a long time period yields a symmetric wake. Grandemange et al. (Grandemange et al., 2015) found an industrial-scale (or passenger vehicle scale) Ahmed square-back to exhibit a bi-stable behaviour after optimising the model's drag through the use of trailing-edge chamfers. The use of a vertical disturbance, or control cylinder was found to suppress the bi-stable

☆ A realistic, partially de-featured automobile geometry.

* Corresponding author.
** Corresponding author.
E-mail addresses: terence.avadiar@monash.edu (T. Avadiar), david.burton@monash.edu (D. Burton).

https://doi.org/10.1016/j.jweia.2018.04.013
Received 12 October 2017; Received in revised form 30 March 2018; Accepted 11 April 2018

behaviour, reducing drag. For the square-back and 35° slant-angle bodies, their recirculation lengths range within 0.33–0.37 of the vehicle length behind the model (Volpe et al.; Lienhart et al., 2002). The ASMO model's time-averaged wake composes of a horseshoe toroidal vortex bounded by the roof and side flow, with slower underbody exit flow forming the recirculation bubble's lower vortex (Aljure et al., 2014). In addition, recent work by Venning et al. (Venning et al.) presented evidence the time-averaged flow structure at the base of an Ahmed body with 25°rear slant angle are a pair of horseshoe vortices whose legs point downstream. With the presence of modern underbody diffusers or body pillars (C or D-pillars) on which longitudinal vortices form, an augmentation to the wake may be present relative to the toroidal ring vortex found for square-back bodies.

Information regarding the time-varying nature of simplified geometries is widely available. The wake of a rectangular body of equal aspect ratio identified two main characteristic frequencies associated with different vortex shedding processes (Duell and George). Duell and George linked these motions with longitudinal pumping of the free-stagnation point and shear-layer vortex shedding, occurring at non-dimensional frequencies (based on height and freestream velocity) of $St_H = 0.069$ and $St = 1.157$ respectively. For the Ahmed square-back, dominant frequencies were found at $St_H = 0.13$ and 0.19; a resultant of von Karman-like shedding off the horizontal and vertical edges of the base. In addition, evidence of a near-wake pumping mechanism was also found at a frequency of $St_H = 0.07 - 0.09$. For the 35° slant-angle Ahmed body, a drag-reduction study using active flow control (Brunn et al.) highlighted the target non-dimensional frequencies of $St_H = 0.2$ and $St_H = 0.88$, associated with vortex shedding and shear-layer instabilities, respectively.

The bulk of experimental work on realistic vehicles has focused on the body forces and surface pressures. Drag-reduction efforts have been focused upon examining the effect of common modern passive geometries on the wake, such as roof spoilers (Kremheller, 2014), underbody roughness, rear diffusers (Aronson et al., 2000; Marklund and Lofdahl; Kahlighi et al., 2012), wheel wake control (Aronson et al., 2000; Marklund and Lofdahl), and optimizing the exit location of cooling flows (Kahlighi et al., 2012; Wittmeiere and Kuthada, 2015). These studies indicate the wake of estate-like vehicles with rear diffuser sections are heavily influenced by upwash from the underbody exit flow, convection of the wheel wakes towards the vehicle centreline, and may exhibit a strong lower recirculation region.

A partial solution to address the limitations of testing with highly simplified bodies is to introduce a reference geometry representative of modern production vehicles. The DrivAer model is a detailed generic car model (Heft et al., 2012a). The configurations available for this model include interchangeable tops (fastback, notchback and estate), two underbody geometries (detailed or smooth), wing mirrors, wheels, and recently, a mock power-plant system to simulate cooling and cavity flows (Wittmeiere and Kuthada, 2015).

Preliminary results and studies on the DrivAer geometry highlight differences of the drag coefficient for different vehicle body types. Ahmed's results (Ahmed et al.) show the square-back (0°) or 35° slant angle rear had drag coefficients less than that of the 25° case (commonly studied as a simplified fastback vehicle). Conversely, the initial time-averaged pressure and drag results for the DrivAer model's fastback or notchback configurations are typically 15–20% lower than the estate's drag (Heft et al., 2012a). Such findings indicate the flow topologies of over-simplified geometries are not fully transferable to detailed vehicles, with key flow structures and their interactions being different (Heft et al.; Heft et al.; Wieser et al., 2014).

Geometric features such as wheels and their housings, mirrors, body pillars, and combinations of curved and sharp edges, are examples of such differences that influence external flow and the nature of flow separation. The external flow around the DrivAer body is influenced by the presence of detailed features such as the wheels, wheel-housing cavities, side mirrors, an underbody diffuser and the general vehicle geometry. Induced and separated flow structures around the DrivAer are of interest to research and industry to understand the losses associated with vehicle operation.

Flow features expected to be similar across the three main DrivAer geometry configurations, with a smooth underbody, will be considered. A-pillar vortices are formed by flow separating off the front windscreen, which is then transported onto the roof (Heft et al.). Remnants of these structures are observed to be present in the wake of the vehicle based on total pressure results (Guilmineau, 2014). Shedding off the wing mirrors also impart losses that are imprinted on the wake of the vehicle (Guilmineau, 2014; Yazdani, 2015), but the effects are of smaller magnitude than the influence from the A-pillar structures. This is possibly due to the collection of boundary layer vorticity of a single sign to feed into the A-pillar vortices on each side, while the wing mirrors have a more localised effect with net cancellation of vorticity of different signs as the fluid advects downstream. Additionally, the presence of the wing mirror is found to diminish the strength of the A-pillar vortices (Heft et al.), with formation no longer commencing at the root of the A-pillar. However, Heft et al. (2012a) note that the increased strength and closer proximity to the rear windscreen has little impact on the rear flow field of the vehicle. Exit flow from the smooth underbody exit of the DrivAer is attached, with large contributions of fluctuations and unsteady flow from the rear wheels being convected toward the center of the vehicle (Heft et al.; Yazdani, 2015) inducing upwash and some unsteadiness (Strangfeld et al., 2013) into recirculation region of the vehicle's wake. This is especially prevalent for the estate vehicle, where a lower vortex system is observed to be more dominant and induces reverse flow onto the rear windscreen of the estate (Yazdani, 2015).

Of interest to this work are studies of estates and similar vehicles (e.g. SUVs and hatchbacks). An experimental and numerical investigation on an SUV by Kahligi (Kahlighi et al., 2012; Kabanovs et al.; Marklund and Lofdahl; Blacha and Islam) characterized the wake flow in the symmetry plane as a largely symmetric wake, featuring a strong reversed flow region bounded by two shear layers beginning at the top and bottom trailing edges of the model. Experiments and numerical simulations of a detailed SUV showed a strong lower recirculation region and a large degree of upwash. An investigation into soiling on an SUV fitted with a rear underbody diffuser (Kabanovs et al.), showed the strong lower recirculating region that would influence the momentum of entrained flow on the vehicle's backlight. Marklund (Marklund and Lofdahl) conducted a numerical study comparing the performance of an underbody diffuser for a Saab 9-3 sedan and estate (referred to as a wagon) and found the wake of an estate to be dominated by upwash with the presence of an underbody diffuser. The wake of an estate was more symmetric in the vehicle's centreline in comparison to the downwash dominated flow of a sedan. Development of production vehicles such as the Audi Q5 SUV-estate crossover (Blacha and Islam) and Nissan Qashqai SUV (Kremheller, 2014) highlighted the changes to the flow field from geometric features mostly found on estate like vehicles. Time-averaged streamlines on the SUV's back light fitted with a roof spoiler show entrained flow moving up the rear windscreen, which then travels outboard below the spoiler and mixes back into the flow at the body pillar and spoiler interface (Kremheller, 2014). A corresponding increase and recovery in base pressure is observed below the spoiler. Similar pressure distributions exist for a hatchback and transport van, with recovery toward the top of the vehicle fitted with a spoiler (Bonnavion et al., 2017). Wake asymmetry modes were found for these transport van and hatchback vehicles by Bonnavion (Bonnavion et al., 2017), with evidence of both vertical and horizontal switching modes present when the vehicles are aligned with the flow. These modes were especially prominent in yawed conditions, with a substantial impact on the dynamics of the wake.

This paper presents a study of forces, pressures and velocity measurements, and quantities derived from such measurements (e.g. Reynolds stresses, vorticity and turbulence intensity) in the wake of a full-scale DrivAer estate vehicle. By providing a detailed characterisation of