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Computational simulations of unsteady flow field and spray impingement on a simplified automotive geometry

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ABSTRACT

Accurately predicting vehicle soiling is important for maintaining a clear view for the driver and on board camera and sensor systems. In this work we study the soiling process on a scale model of generic SUV body, which is a vehicle type particularly susceptible to base contamination. The Spalart-Allmaras formulation of the IDDES model is used to compute the continuous phase and the dispersed phase is computed using Lagrangian particle tracking, both concurrently with the flow-field, and also as a post-processing approach using time averaged statistical information of turbulence in a stochastic dispersion model. The results are compared against experimental data and the discrepancies discussed with regard to the predicted and measured flow field and base pressure distribution. Good agreement with experiment is shown for the contamination pattern using the fully unsteady method, but the more economic stochastic model does not recover some important details. This is attributed to the role of spatially correlated flow structures around the wheel in entraining particles into the wake that the stochastic model cannot accurately represent. This leads to the conclusion that base soiling is a function of unsteady modes, elimination of which may potentially reduce spray deposition.

1. Introduction

Management of surface contamination is an increasingly important development objective for vehicle manufacturers as it can reduce vehicle visibility, driver's vision, sensor and camera systems performance; as well as compromising aesthetics. With the development of autonomous vehicles, which rely on sensor systems that must be kept clean, the need to understand and predict vehicle soiling processes is likely to increase in importance (Kutila et al., 2015; Shearman et al., 1998). In addition, contaminants can be transferred to hands and clothing on contact with the vehicle exterior, which can be a source of customer dissatisfaction. Three useful reviews of this topic have been published to date. Kuthada and Cyr (2006) provide a short general review, before focusing on calibrating a tyre spray model and simulating body-side soiling. Hagemeier et al. (2011) explored side-window water management, providing a comprehensive review of numerical techniques. More recently, Gaylard et al. (2017b) have provided a comprehensive general overview. The three sources of vehicle surface contamination are: rain (primary contamination); spray generated by other vehicles (third-party contamination); spray generated by the rotation of the vehicle's wheels (self--contamination) (Kuthada and Cyr, 2006). The work reported here focuses on the latter phenomenon and is particularly relevant for vehicles with blunt rear geometries, such as Sports Utility Vehicles (SUVs), estates (Station wagons), hatchbacks (Maycock, 1966), as well as bus bodies (Lajos et al., 1986). This is due to strong large-scale recirculating vortices generated by these vehicles that advect the spray and deposit it onto the base (Gaylard and Duncan, 2011).

Concerns over vehicle rear soiling had become evident by the mid-1960s, when Dawley (1965) had tested deflecting vanes at the rear corners of the vehicle body to provide clean air into the wake and thus minimize dirt impinging on the rear surface. It was later realized that applying these to the roof trailing edge, as proposed by Goetz (1971), was most effective for reducing base soiling. Nevertheless, this was achieved at the expense of increased overall drag. A deployable roof trailing edge deflecting vane was also studied by Costelli (1984), who linked the mechanism of rear-surface soiling with the pressure variation in the wake. He postulated that soiling tends to accumulate in regions of relatively high surface static pressure. However, recent simulations of rear face soiling for a relatively simple bluff body showed this to be a necessary though not sufficient condition and that local contaminant availability is also required (Jilesen et al., 2017). The work of Gaylard and Duncan (2011),Gaylard et al. (2014) and Jilesen et al. (2013)

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presented a comprehensive analysis of experimental and numerical base soiling results for a number of real vehicles. In the numerical approach, particles were emitted from the rotating wheels using the technique proposed by Kuthada and Cyr (2006). These studies showed that the main source of spray that gets deposited on the rear surface are rear wheels. In addition, the wakes of rear wheels contribute to the advection of droplets into the wake, which then transports them onto the base. It was also found that base contamination was better predicted using the fully unsteady particle tracking approach in Jilesen et al. (2013) rather than the one in which particles were post-processed for a number of frozen transient data frames and then superimposed to obtain the overall deposition, as was used in Gaylard and Duncan (2011)).

Most reported studies used detailed geometries of specific vehicles along with complex computational models, mainly focusing on the final outcome with regard to surface contamination. However, such an approach may not always be useful if one aims to understand the fundamentals of this phenomenon. This is due to the inherent complexity of the flow associated with geometric features and general level of detail of the physical model used. According to Jilesen et al. (2013), even small changes in the details of the vehicles' geometry can strongly influence contamination mechanisms. Although lacking the details and styling of specific vehicles, simplified bodies allow investigation of the relevant flow features in well characterised and repeatable settings, giving better insight into the studied phenomenon. In addition, they can be used to reveal trends due to design changes such as rear body shaping. The use of simplified, generic, vehicle bodies also allows soiling studies to be undertaken for cases for which detailed flow field data such as wake Particle Image Velocimetry (PIV) or base pressures is also known and publicly available. This, along with control of factors such as details of the contaminant source, allows the accuracy of simulation methods and the importance of modelling choices to be correctly assessed. One of the few examples of using a simple body in the studies of vehicle contamination is the study by Kabanovs et al. (2016), which used Computational Fluid Dynamics (CFD) and experiments to investigate rear surface contamination for a well known simple bluff body. This work showed that neither RANS nor URANS turbulence modelling is able to capture the relevant flow structures in the region of a strong pressure gradient, failing to accurately predict the flow field. This, therefore, resulted in an inaccurate prediction of spray dynamics and rear-surface contamination. High-fidelity eddy resolving methods have been used to produce encouraging predictions of the rear soiling of simple bluff body (Gaylard et al., 2017a; Kabanovs et al., 2017), the latter correctly predicting the trend in soiling pattern when the upper taper angle of the rear of a generic SUV geometry is changed.

In this work we apply an eddy resolving simulation technique, namely the Detached Eddy Simulation (DES) method also used in Kabanovs et al. (2017)), to simulate the rear soiling of two configurations of the generic SUV and compare with detailed PIV measurements and rear soiling experiments. It has been shown in previous work (Gaylard et al., 2017a; Kabanovs et al., 2016) that a high fidelity eddy resolving method is required to correctly predict the mean flow field and that this is a prerequisite to accurate soiling predictions. However what is less clear is whether, given an accurate mean flow field, is this sufficient to allow accurate soiling predictions? i.e. Can soiling be predicted as a post-processing step if a suitable set of data is available? Hence, in this paper we also investigate the level of detail required in the simulation of the dispersed phase by comparing:

- A fully unsteady, time-resolved, spray simulation with post-processed spray tracking simulations using only the mean flow field.
- A fully unsteady, time-resolved, spray simulation with post-processed spray tracking simulations using the mean flow field with stochastic dispersion due to the time averaged turbulence field. The time averaged statistical information of the turbulence is available from the DES simulation and is used by a stochastic dispersion algorithm that models velocity perturbation seen by a particle advected through a time averaged flow field.

These post-processing methods represent a significant saving of computational time. The simulations are also used to investigate the mechanisms by which contaminant is entrained from wheel spray into the wake and then dispersed and distributed onto the rear surfaces of the vehicle. The influence of vehicle geometry on these mechanisms is investigated, both from the point of view of how this affects contamination, and how they should be modelled. Discrepancies between experiment and simulation are discussed together with suggestions for further improvements to the current methodology.

2. Experimental method and test geometries

A quarter scale generic SUV body was used in this study. The model is representative of a typical SUV and was designed within the department of Aeronautical and Automotive engineering at Loughborough University. The aft body has sharp edges while the leading edge radii are large to prevent separation. The model has configurable elements such as ride heights and the aft body. Four pins, attached to stationary wheels connect the model to the balance in the wind tunnel. The model gives a blockage ratio of 5.58% in a 2.5 m^2 working section. More information can be found in Wood et al. (2015). In this work, two configurations of this model were used. Both configurations had the ride height fixed at 0.065 m and the roof taper angle set to 0°. The angle of the diffuser, however, was set to 30° (configuration 1) and 0° (configuration 2). These two configurations were chosen on purpose, as they are recognized to produce very different wake structures and hence were expected to give unique soiling distributions. On the other side, geometries with bluff and square aft bodies such as configuration 2 are known to be very challenging to simulate, which is associated with the unsteady, sometimes bi-stable, wake of these models. For example, a number of experimental studies reported the presence of large scale (both in time and in size) lateral oscillations of the entire wake (flapping mode), accompanied by a ”breathing” mode of the mean recirculation region of the generic square-back SUV (Al-Garni et al., 2004), and other boxy geometries (Perry et al., 2016; Khalighi et al., 2001). Both configurations are illustrated in Fig. 1. It also shows the location of spray injector used in soiling experiments, discussed below.

Aerodynamics and soiling experiments were performed in the wind tunnel at Loughborough University. The wind tunnel has an open loop, circuit, closed working section configuration (see Fig. 2), full details of which can be found in Johl et al. (2004). All tests were carried out at a free-stream velocity of 40 m/s, giving a Reynolds number of 2.77 million based on model length. Full details of the experimental method, especially that used in soiling tests, can be found in Kabanovs et al. (2017) but important details are included in the two following sub-sections.

2.1. Aerodynamics tests

The experimental force and base pressure data used in this paper were collected for each configuration as part of two separate studies, reported by Wood et al. (2015) (configuration 1) and Varney et al. (2017) (configuration 2). The data taken for configurations 1 and 2 were sampled for 30 s and 300 s at a frequency of 300 Hz, respectively. The base pressure tappings were limited to one half of the base in the experiment that used configuration 1. The entire base of configuration 2 was populated with the pressure tappings due to a highly unsteady nature of the wake of this configuration. The pressure measurements were made with two 64 channel pressure scanners with samples triggered at 260 Hz. The pressure data and force coefficients presented in this paper account for blockage by applying a continuity based correction method shown in Eqs. (1) and (2), respectively (Littlewood and Passmore, 2010). In the equations, *TA* and *MA* correspond to the wind tunnel cross section area and the model frontal area, respectively. C_p and C_f are the pressure