

Insights into Rear Surface Contamination Using Simulation of Road Spray and Aerodynamics

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ABSTRACT

Contamination of vehicle rear surfaces is a significant issue for customers. Along with being unsightly, it can degrade the performance of rear camera systems and lighting, prematurely wear rear screens and wipers, and transfer soil to customers moving goods through the rear tailgate. Countermeasures, such as rear camera wash or automated deployment add expense and complexity for OEMs.

This paper presents a rear surface contamination model for a fully detailed SUV based on the use of a highly-resolved time-accurate aerodynamic simulation realised through the use of a commercial Lattice-Boltzmann solver, combined with Lagrangian Particle Tracking to simulate droplet advection and surface water dynamics via a thin film model. Droplet break-up due to aerodynamic shear is included, along with splash and stripping from the surface film. The effect of two-way momentum coupling is included in a sub-set of simulations.

The simulations are qualitatively validated in terms of surface contamination distribution against full scale (climatic) wind tunnel experiments using a UV fluorescent dye in water introduced onto dynamometer rollers.

Three different contamination source configurations are examined: front tyres only, rear tyres only and all four tyres. The simulation is seen to recover the experimental rear surface contamination distribution, along with the trend in differences between these cases.

The rear tyres are seen to be the dominant source, with front wheel spray and front wheel rotation only making small relative contributions.

Two-way momentum coupling is seen to influence the rear surface contamination distribution.

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INTRODUCTION

Assessing the impact of design changes on the contamination of vehicle rear surfaces is an important and challenging problem. Rear surface contamination encompasses a particularly important sub-set of customer concerns, such as maintaining: vision through the rear glass, visibility of rear lights, the effectiveness of rear camera systems; as well as keeping the time between wash cycles reasonable. Whilst some part of the rear glass may be kept clean by a rear wash/

wipe system, excessive contamination will lead to long term degradation of the glass surface due to abrasion and premature wear of wiper blades.

Similarly rear camera cleaning systems, deployable cameras or advanced lens coatings may maintain camera function, but this comes at an increased cost to OEMs. Finally contaminated rear surfaces are unsightly and lead to the transfer of soil to the hands and clothes of customers as they operate rear closures and move goods in and out of the vehicle.

There are three general sources of contamination [1]: primary contamination from wind-driven rain; foreign (or third-party) contamination from other vehicles, and self-soiling from the road spray generated by the vehicle itself. Rear surface contamination is dominated by self-soiling.

The surrounding flow field is also dynamic: natural wind gusts and vehicle wakes generate extrinsic unsteadiness. Other boundary conditions are also influential, such as road and vehicle surface characteristics. Additionally, vehicle operating conditions such as speed, ride height and length of exposure to contamination sources are important.

Overall vehicle aerodynamic design influences the deposition of contaminants and their surface dynamics, through the flow structures that are generated. Conversely, small changes to the design of the under-body and wheel arches can be a significant influence.

Currently there are four main methods of investigating this issue: driving on-road, or on a test track (either a wetted road or graded gravel surface), wind tunnel testing and numerical simulation. Each of these methods has their own advantages and drawbacks.

All of these testing methods balance approximating real world conditions against repeatability, security and cost. For example road testing is the most realistic, but least repeatable method. It also requires a drivable vehicle that can be openly displayed in public. Test track methods offer better security for confidential prototypes and are more repeatable due to the removal of the influence of other vehicles and uniform road conditions. However, both suffer from providing sparse data and little insight into the mechanisms involved.

Wind tunnel approaches provide higher levels of repeatability and security. They can be used well before a drivable prototype is available and thus provide earlier design direction; but they are generally constrained to Climatic facilities with lower flow quality and poorer ground simulation than aerodynamic wind tunnels due to concerns over tunnel durability, as the water and other chemicals used during testing would be detrimental to aerodynamic force balances, floor boundary layer removal and moving ground equipment.

On the other hand, recent developments in numerical simulations have provided a predictive tool for investigating surface contamination earlier in the vehicle development process. Coupling particle and surface film models with time-accurate transient aerodynamics provides for the simulation of small-scale turbulent flow structures that drive the dispersion of particles, the impingement of particles on the vehicle surface and the transient motion of the surface film. These simulations contain a wealth of information not easily obtained with physical testing and make it easier to draw connections between design changes and their impact on rear

surface contamination. However, they only incorporate limited physics models and, to date, little systematic validation has been undertaken.

This study focuses on rear surface contamination of an SUV by self-soiling using wind tunnel testing and numerical simulation. The experiments were used to validate the results of the numerical simulations. The numerical simulations were also used to study the impact of choices made during wind tunnel testing. This includes the impact of front wheel rotation and the contribution of front tyre road spray.

Finally, this work provides important insight into the mechanisms of rear surface contamination, including: the relative contribution of front and rear wheel road spray, water film effects in the wheel arches and under-body, and the impact of front wheel rotation.

BACKGROUND

Investigations of the deposition of water on vehicle surfaces can be traced back to concerns over the loss of aerodynamic performance for aircraft in heavy rain. When considering this issue in 1941, Rhode [2] made an early observation of the dynamics of water on a vehicle surface:

"Visual observation in flight through rain indicates that some water accumulates at certain small regions, that some water adheres in the form of fine drops which are continually being forced back by the friction of the air stream, and that some water adheres in the form of large drops which move very little, if at all. Obviously, water cannot exist in any substantial depth except over limited areas where a balance of aerodynamic and gravitational forces on the water exists because it is either blown off by the air stream or flows off by the action of gravity."

This introduces the notion that droplets, large and small, adhere to the surface and exist in a dynamic balance with aerodynamic shear, surface friction and gravity. Also, the author raises the potential for this surface contamination to degrade the performance of instrumentation.

During the 1960s concerns over the impact of the road spray generated by commercial vehicles on visibility for both the driver and other road users gained increasing attention [3, 4, 5, 6, 7]. During one such investigation Maycock [8] noted that:

"The estate type of body tends to draw the spray-laden air into the region immediately behind it, a fact which is evidenced by the way the rear windows of these vehicles become obscured by mud."

The previous year Dawley [9], in a track-based experiment, reported on the use of a rear pillar turning-vane to reduce surface contamination on a station wagon rear screen. This

highlights that the problem of rear surface contamination for square-backed vehicles, such as station wagons was being treated seriously.

In the early 1970s Goetz [10] reviewed the topic of surface deposits on sedans and sport cars. He noted that, "Turbulence in the rear also causes deposits on rear vertical surfaces," and went on to discuss soiling of rear surfaces and lamps. From this it is clear that rear surface contamination is not just an issue limited to station wagons and other square-backed vehicles.

Larger square-backed vehicles have been the focus of the effort to model, simulate understand and mitigate rear surface contamination; such as bus [11, 12] and van [13] bodies. However, Hucho and Sovran [14] commented on the use of guide-vanes at the roof trailing edge of squareback cars to reduce dirt deposition on the rear window; pointing out that such devices carry a drag penalty. Also, Costelli's 1984 account of the aerodynamic development of the Fiat UNO includes a study of the reduction of rear screen soiling using a variable-attitude rear spoiler, along with an analysis of the deposition mechanism [15].

To this point efforts to understand and model the accumulation of contaminants on vehicle rear surfaces had been limited to road, track or wind tunnel testing. Hagemeyer et al. [1] provide a detailed review of both experimental and computational approaches to surface contamination measurement and simulation. Though focussing on the front side glass they provide a detailed account of numerical modelling approaches and emphasize the links between current approaches in the automotive industry and those used in aeronautical simulation.

However, it's most relevant here to consider the approaches taken to simulating rear surface contamination for road vehicles. Yoshida et al. [16] provide what the authors understand to be the first published example of CFD simulation for SUV body side and rear soiling. They used a "Dirt particle path" method based on the use of "particle streaklines" with distance-threshold surface capture; as well as a "Dirt concentration method", with contamination simulated by the diffusion of a passive scalar. Limited by the hardware and software capabilities of the time, the geometry used was highly simplified. Their conclusion that a time-averaged (or steady state) flow field gives the same soiling result as using an unsteady flow field has been overturned by subsequent investigations (see Pitman et al. [17], for example).

The accumulation of contamination on a station wagon was simulated by Roettger and co-workers [18, 19]. They described body side and rear surface soiling simulations using a combination of a Lattice Boltzmann solver (Exa PowerFLOW) and a Runge-Kutta particle tracer with adaptive step size control. This approach used a fixed (time-averaged) flow field and the particle tracking was essentially a post-processing activity.

The need to use unsteady flow solvers for rear soiling simulation has been demonstrated through two reports published in 2006 by Paschkewitz [20, 21]. The first examined dispersion of water droplets in the wake of a simplified tractor-trailer using a commercial RANS solver [20]. Water droplets were simulated using Lagrangian Particle Tracking, with models included for droplet break-up, spreading, rebounding, splash, coalescence and dispersion. The latter accounted for as an *ad hoc* addition of a random fluctuation velocity to the droplet velocity proportional to the local turbulent kinetic energy; it was hoped that this would remedy the lack of sensitivity of particles or droplets to small flow features seen in RANS simulations. The report highlighted that neither RANS nor URANS was likely to provide the best assessment for droplet advection in bluff vehicle wakes. It proposed that Large Eddy Simulation (LES) or hybrid RANS-LES approaches be investigated.

This proposal formed the basis of the second report [21], which reported a preliminary study of the dispersion of solid particles in the wake of a rectangular plane using LES. This was followed by simulating droplets in the wake of a simplified streamlined tractor-trailer using both LES and URANS turbulence modelling approaches. The particles were one-way coupled. It was observed that the LES simulations predicted a "finer-scale and more persistent wake structure" than URANS with resulting differences in the advection of low-inertia particles. The LES simulation of the tractor-trailer, though under-resolved, showed greater vertical dispersion of particles in the wake. Paschkewitz suggested that LES may be required to capture the dispersion of small, low-inertia particles or droplets.

This observation is relevant to the approach taken in this work, as it points to the need for highly-resolved unsteady flow simulation to capture small scale wake dynamics, if rear surface contamination is to be adequately simulated.

Paschkewitz's simulations did, however, use arbitrary assumptions on the size, location and velocity of particles introduced into the flow. Kuthada and Cyr [22] addressed this particular limitation as they explored the use of a Lattice-Boltzmann aerodynamic simulation with Lagrangian Particle Tracking for road spray driven off vehicle tyres. Their work includes an experimental validation for 'road spray' generated by a wheel in isolation, providing insights into the specification of the road spray boundary condition.

Drawing on the literature showing the viability of a combined Lattice Boltzmann and Lagrangian Particle Tracking method, along with the importance of using a time-resolved aerodynamic simulation, Gaylard and Duncan [23] presented simulations of body side and rear soiling for an SUV and saloon. An attempt was made to account for splashing and dripping using *ad hoc* particle emitters. Good agreement was demonstrated with body side soiling experiments. It was, however, clear that rear soiling prediction could be improved by the inclusion of additional physics