WARWICK
THE UNIVERSITY OF WARWICK

Original citation:
Gaylard, A. P., Kirwan, Kerry and Lockerby, Duncan A.. (2017) Surface contamination of cars : a review. Institution of Mechanical Engineers. Proceedings. Part D: Journal of Automobile Engineering.

Permanent WRAP URL:
http://wrap.warwick.ac.uk/86801

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work of researchers of the University of Warwick available open access under the following conditions.

This article is made available under the Creative Commons Attribution 4.0 International license (CC BY 4.0) and may be reused according to the conditions of the license. For more details see: http://creativecommons.org/licenses/by/4.0/

A note on versions:
The version presented in WRAP is the published version, or, version of record, and may be cited as it appears here.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

warwick.ac.uk/lib-publications

Automotive Aerodynamics Special Issue

Institution of MECHANICAL ENGINEERS

Journal of AUTOMOBILE ENGINEERING

Proc IMechE Part D:
J Automobile Engineering
1–17
© IMechE 2017
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0954407017695141
journals.sagepub.com/home/pid
SAGE

Surface contamination of cars: a review

Adrian P Gaylard[1,2], Kerry Kirwan[2] and Duncan A Lockerby[3]

Abstract

This review surveys the problem of surface contamination of cars, which poses a growing engineering challenge to vehicle manufacturers, operators and users. Both the vision of drivers and the visibility of vehicles need to be maintained under a wide range of environmental conditions. This requires managing the flow of surface water on windscreens and side glazing. The rate of deposition of solid contaminants on glazing, lights, licence plates and external mirrors also needs to be minimised. Maintaining vehicle aesthetics and limiting the transfer of contaminants to the hands and clothes of users from soiled surfaces are also significant issues. Recently, keeping camera lenses clean has emerged as a key concern, as these systems transition from occasional manoeuvring aids to sensors for safety systems. The deposition of water and solid contaminants on to car surfaces is strongly influenced by unsteady vehicle aerodynamic effects. Airborne water droplets falling as rain or lifted as spray by tyres interact with wakes, vortices and shear flows and accumulate on vehicle surfaces as a consequence. The same aerodynamic effects also control the movement of surface water droplets, rivulets and films; hence, particular attention is paid to the management of surface water over the front side glass and the deposition of contaminants on the rear surfaces. The test methods used in the automotive industry are reviewed, as are the numerical simulation techniques.

Keywords

Vehicle aerodynamics, multi-phase flow, surface contamination, soiling, exterior water management, computational fluid dynamics

Date received: 6 June 2016; accepted: 24 January 2017

Introduction

Automotive aerodynamics encompasses concerns that extend beyond the forces and moments experienced by a vehicle moving through the atmosphere. For example, the ability to operate vehicles safely in environmental conditions that include contaminants such as rain and road soil, the deposition of which on vehicle surfaces is strongly influenced by aerodynamic processes, has long been considered part of this discipline.[1,2]

Early surface contamination concerns included keeping windscreens clear of rain, which led to the development of the hand-operated ‘Rain Rubber’ and then integral windscreen wiper systems.[3] Subsequently, concerns extended to keeping windscreens clean (i.e. free of solid deposits) using washer systems.[4] Transparent air deflectors emerged as a potential solution to headlamp and windscreen soiling during the early 1950s, although they were not successful as they became obscured by a build-up of heavy dirt particles.[1] By the mid-1960s, manufacturers were developing turning vane systems to reduce the deposition of road soil on the rear windows of estate (station wagon) cars.[5] It was ultimately appreciated that applying these to the roof tailing edge was most effective for reducing surface contamination.[1]

By the end of the 1960s a wide range of surface contamination issues was being considered during the development of cars. These included the following: preventing overflow of the surface water from the windscreen on to the front side glass, or from the roof on to the rear screen; limiting contamination of the vehicle’s body, side glazing and rear lamps by solid contaminants picked up from the road surface by the vehicle’s own tyres.[1,2] However, some of the initial design

---

[1]Jaguar Land Rover Automotive PLC, Warwick, Warwickshire, UK
[2]WMG, University of Warwick, Coventry, Warwickshire, UK
[3]School of Engineering, University of Warwick, Coventry, Warwickshire, UK

Corresponding author:
Adrian P Gaylard, Jaguar Land Rover, Banbury Road, Gaydon, Warwickshire CV35 0RR, UK.
Email: agaylar1@jaguarlandrover.com

solutions became unpalatable. Deep rain channels (gutters) running along the outboard edge of the windscreen proved to be a significant aeroacoustic (wind) noise source, and some rear turning vanes increased the drag coefficient of vehicles by up to 20%.[1,6] Consequently, the focus has shifted on to developing solutions for these historic issues that minimise adverse impacts on the aerodynamic forces, the aeroacoustics or the aesthetics.

The importance of this topic, particularly rear-surface contamination, has increased as external camera systems have become commonplace. This started with their use as reversing aids and has extended with cameras now used to provide improved vision at junctions, moving-object detection, blind spot and lane-departure warnings. This trend has taken cameras from visibility aids to sensors for safety systems; hence, the need to mitigate surface contamination has become more acute. The external surfaces of current concern for a sport utility vehicle (SUV) are summarised in the schematic diagram provided in Figure 1.

There have been several useful reviews of this topic to date. Kuthada and Cyr[8] provided a brief overview of the main mechanisms and then focused on the development of a calibrated tyre spray model, which they used in numerical simulations of body-side soiling. In contrast, Hagemeier et al.[9] contributed a comprehensive review of front side-glass water management, including a detailed account of relevant numerical methods. This review provides a broader perspective, covering what is currently known about the nature of automotive surface contaminants, the mechanisms by which they are deposited on car surfaces and their impact on vehicle operation. The investigative tools available to the automotive aerodynamicist are also described, together with their strengths and their weaknesses. This highlights the current state of the art in both wind tunnel testing and numerical simulations. However, in common with these previous reviews, the focus here is on issues associated with vehicle operation on wet roads and in the rain; therefore, issues of dust and snow deposition or of water management for stationary vehicles are not considered.

The surface contamination problem

What is a contaminant?

Any substance may be considered a contaminant if it is foreign to a particular vehicle surface and degrades the vision of drivers, the visibility of vehicles, system performance or aesthetic appeal. The most straightforward contaminant is environmental water, with rain the primary source. Droplet diameters for natural rainfall range[10] from a minimum of 0.1 mm, with typical diameters of between 1 mm and 3 mm. Although relatively free of solid material, as rain falls on glazed surfaces, the droplets (together with the rivulets and surface films that they form) distort and obscure the vision of drivers.

In addition, road surfaces also contain a diverse range of solid contaminants, both natural and man made, which may be deposited on vehicle surfaces. Natural soil is an important source of the coarser particles (2.5–10 μm diameter) found on road surfaces and deposited by wind, water and the tyres of agricultural and construction vehicles.[11] Other natural contaminants include ocean salt, desert sand and biogenic material.[12] However, most of the fine particles deposited on roads are man made, from combustion sources such as the engines of cars and commercial vehicles.[11] This is largely carbon from diesel combustion, together with the components of fuels and motor oils.[13] Brake and tyre wear are also significant contributors, together

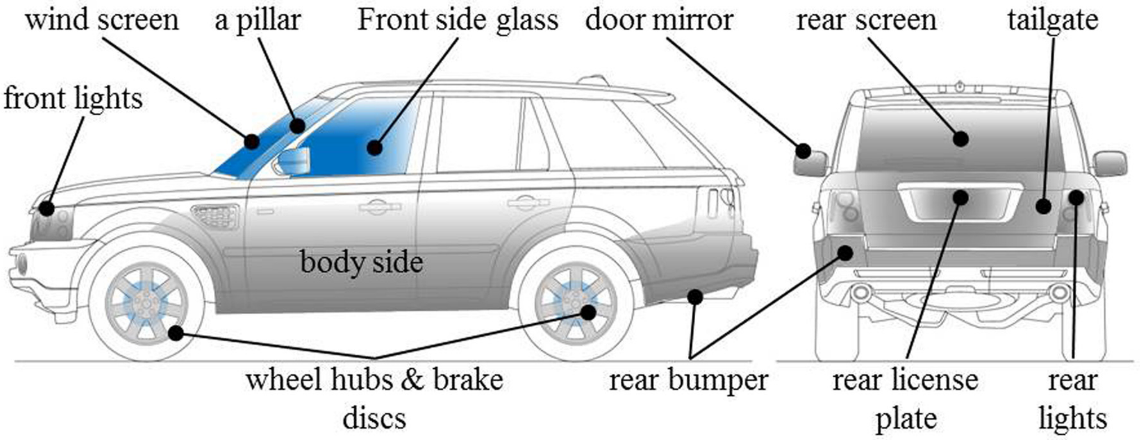

Figure 1. Key surface contamination regions illustrated for an SUV[7] (the surface-water-dominated zones are the windscreen, the A-pillar and the front side glass; the soiling-dominated zones are the front lights, the body side, the wheel hubs, the rear bumper, the door mirror, the rear screen, the tailgate, the rear licence plates and the rear lights).

with the debris generated by abrasion of the road surface itself.[14] De-icing salt and grit can also be applied to road surfaces in the winter months. Hence, road soil is a complex mix of both natural and man-made compounds. When it rains, these combine with water to produce a contaminant mixture that is thrown from the road surface by vehicle tyres, as a spray.

Vehicles also provide some of their own contaminants. Water mixed with cleaning agents carried for screen and lamp washing can be driven on to side glazing and painted surfaces. Additionally, braking generates dust that can soil wheel hubs and paintwork; soot from diesel engine exhausts can discolour bumpers.[15,16]

Sources of contamination

Contamination can be categorised as *direct soiling, third-party soiling* or *self-soiling*, depending on its source.[8] Rain provides direct contamination and tends to accumulate on the vehicle bonnet, windscreen, front side glass, roof and rear glazing. This contrasts with third-party soiling, where cars drive through the spray generated by both upstream and passing traffic. This mixture of water and solids generally accumulates on forward-facing surfaces, particularly the windscreen, front side glass, door mirrors and front lights. The spray caused by the vehicle's own tyres leads to self-soiling. Front-tyre spray generates a 'deposit zone' along the body side that extends from the front-wheel well to the rear wheel. Rear tyres generate a spray that is the dominant source for contamination on rear surfaces.

More attention has been paid to spray generated by heavy goods vehicles, rather than by cars, as it is a risk to the vision of other road users. It is useful to review its characteristics, as it is a source of spray through which cars are driven. Water lifted from the road surface by tyres can be categorised by the direction in which it is forced, the droplet size and the mechanism of its release from the tyre surface. For example, Maycock[17] distinguished between splash and spray in terms of droplet size, implicating the latter in both third-party soiling and self-soiling.

A more refined scheme was developed by Weir et al.,[18] who identified four primary categories:

(a) bow wave;
(b) side splash wave;
(c) tread pickup;
(d) capillary adhesion.

The first two categories are types of splash. The bow waves and side waves are made up of larger droplets that follow a ballistic trajectory and generally either impact on the underside of the vehicle or fall back to the road surface. These contribute little to surface contamination of the vehicle. The remaining two categories refer to spray. Tread pickup describes water that passes through the tread grooves and is thrown off early in the tyre rotation. This contrasts with capillary adhesion, where water is retained on the tyre surface and is subsequently released from the tyre later in its rotation. Weir et al.[18] estimated that droplets generated by tread pickup have diameters ranging from small (less than 1 mm) to relatively large (approximately 4 mm), with those released from the capillary film near the top of the tyre forming a very fine spray fraction containing an estimated 1% of the water volume picked up by the tyre tread. These two processes provide an important source of third-party soiling for cars.

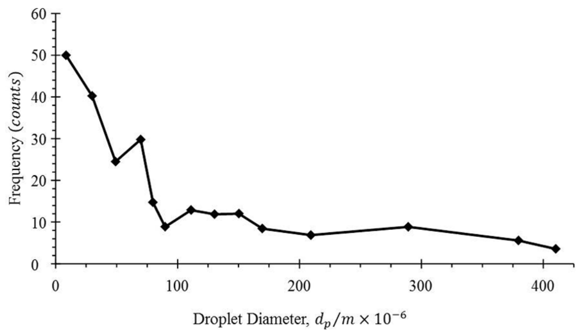

Figure 2. Distribution of the droplet diameters of the tyre spray measured by Shearman et al.[19]

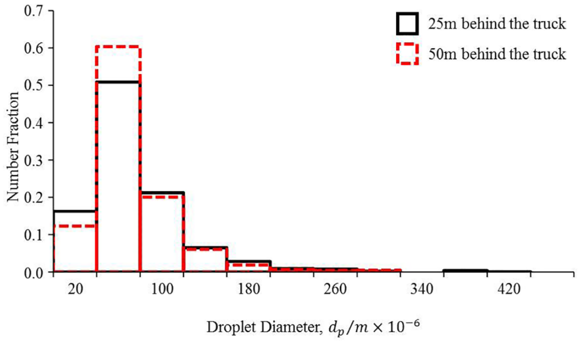

Figure 3. Distributions of the droplet diameters of the tyre spray measured by Borg and Vevang.[20]

Two notable efforts to quantify the droplet size distribution of this type of spray were made by Shearman et al.,[19] followed by Borg and Vevang.[20] Shearman et al. used a high-resolution laser-based measurement system to measure the droplet diameter distribution in a spray generated by a lorry travelling at 60 miles/h (96.6 km/h) on a wetted test track. Borg and Vevang employed hydrophobic plates to sample the droplet distribution in the wake of a truck driven on a wetted test track. The distribution measured by Shearman et al. is shown in Figure 2. It is dominated by droplets with diameters of less than 0.1 mm and peaks at the smallest diameter measured (9×10^{-6} m) with a number-averaged particle diameter $\bar{d}$ of 87×10^{-6} m. This is broadly comparable with the results obtained by Borg and Vevang, which are provided in Figure 3. This shows distributions with measured $\bar{d}$ values of

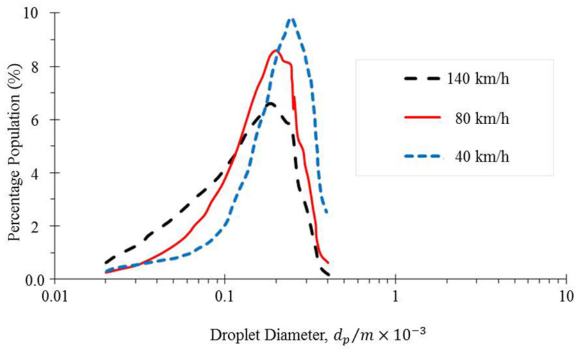

Figure 4. Distributions of the droplet diameters of the tyre spray measured by Bouchet et al.[21]

(75 ± 10) $\times 10^{-6}$ m and (70 ± 10) $\times 10^{-6}$ m at 25 m and 50 m respectively, behind a truck. However, the smallest droplet fraction appears to be missing; this is probably an artefact of the measurement technique used.

These experiments help to quantify the nature of the spray through which cars are driven, an important contributor to third-party soiling. However, measurements made by Bouchet et al.[21] of the spray generated by a car provide important insights into the source of self-soiling. Tyre spray was characterised 1 m behind the rear wheels of a test vehicle in a wind tunnel. The droplet diameter distributions measured at three equivalent road speeds are shown in Figure 4. For a vehicle speed of 80 km/h, the resulting distribution has an average (mode) droplet diameter of 0.2 mm. As the rotational speed of the wheel increases, the average droplet diameter tends to decrease and the percentage of the droplet population with smaller diameters increases. This suggests that droplet breakup is occurring at higher speeds. It also presents a very different distribution from that measured by Shearman et al.,[19] which favours smaller droplets. However, these measurements were made much closer to the vehicle, limiting the influence of processes that tend to reduce the presence of larger droplets, namely breakup and the tendency to fall back to the road surface.

The mechanics of water shedding from tyre treads have been explored in a laboratory setting. Radovich and Plocher[22] used a rig with two wheels, set side by side, with their idealised tyres touching. Water was introduced into the top of this ‘contact patch’, and high-speed photography was used to record the dynamics of water emptying from the grooves underneath the rig. This investigation suggested that higher rotational speeds favoured the formation of smaller droplets, consistent with the findings of Bouchet et al.[21] In a follow-up study, Plocher and Browand[23] found that grooves with smaller characteristic dimensions (i.e. shallower or narrower) drained more quickly and thus generated more spray at heights closer to the road surface, whereas tyres with deeper grooves took longer to drain and consequently lifted water further away from the road surface, releasing more spray higher up the rear face of the tyre. These trends suggest a potential dependence of self-soiling characteristics on tyre design. However, the simplified nature of the tyres, the representation of tyre-to-road contact by a symmetric tyre-to-tyre contact and the lack of vehicle aerodynamic effects in these experiments leaves this an open question.

The concept of the tyre as a soiling source has also been explored in isolated wheel experiments by Kuthada and Cyr,[8] followed by Spruss et al.[24] In both studies an isolated wheel was mounted on a stub axle in the Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart (FKFS) thermal wind tunnel. Insights into the spray structure generated at the tyre were obtained using laser light sheet illumination to visualise the spray in local planes around the wheel. Spruss et al.[24] also used a laser diffraction system to measure the relative droplet size distribution. These experiments provide a widely used calibration case for numerical simulations. For example, Kuthada and Cyr[8] also reported numerical simulations, where the diameter of the particles used to model the water droplets was varied until the experimentally determined spray topology was obtained. This occurred when a diameter of 0.2 mm was specified, aligning well with the direct measurements for mean droplet diameter behind a car tyre provided by Bouchet et al.[21] The use of calibrated tyre spray models, such as this, has provided a useful starting point for numerical simulations of self-soiling. However, they have a range of limitations, including the following: neglecting bow and side slash waves; not accounting for the different droplet size distributions caused by tread pickup and capillary adhesion; not capturing the effect of the tyre tread design. At present, the implications of these simplifications are unknown although the ability to simulate tyre spray generation explicitly by using numerical techniques which allow true tyre rotation (as opposed to using a rotational velocity boundary condition on the tyre surface) and capture the physics of water pickup and release may make these clear. However, this will incur a high computational cost.

Operational issues

The presence of these contamination sources causes a range of operational issues. A combination of direct soiling and third-party soiling can obscure the windscreen, side glazing, door mirror glass and front lights, reducing both the vision of drivers and the visibility of vehicles. At the rear of the vehicle, self-soiling also compromises both vision and visibility as contaminants accumulate on the rear screen, lights and licence plate. In addition, washer fluid applied to the front screen can be carried on to the side glass, where it may compromise the vision of drivers through the side glass and to the door mirror.

The performance of a range of vehicle systems may also be adversely affected by the presence of road soil. For example, wiper blades wear more quickly if high levels of solids are being removed from the windscreen. Rear camera systems are particularly vulnerable to contaminant accumulation on exposed lenses, particularly those installed on 'square-backed' vehicles: hatchback, estate and SUV body types. Finally, brake performance may be affected by the build-up of a water film on the brake discs.[25,26]

Aesthetic appeal

Although all road vehicles eventually become 'dirty', the rapid accumulation of surface contamination can be unsightly. This is particularly the case for self-soiling of the body side and the rear. A similar view may be taken on witness marks left by cleaning agent residue from windscreen and lamp washers. More persistent discolouration to the front fenders and body sides can be caused by brake dust, or to the rear bumper by soot discharged from the tailpipe of cars with diesel engines.[15,16] Further, the transfer of contaminants from the vehicle to the hands and clothes of users can reduce the appeal of a vehicle. For instance, contamination of the body side (including the door handles) by self-soiling can affect users accessing the cabin. Similarly, excessive accumulation on the rear bumpers, boot or tailgate can lead to the transfer of dirt to the hands and clothes of vehicle users accessing the rear load space.

In addressing these issues, it is helpful to subdivide surface contamination into contamination associated with the distribution of water over vehicle surfaces (exterior water management (EWM)) and contamination associated with the accumulation of solid material (soiling).

Exterior water management

Managing excess water on the windscreen is perhaps the oldest issue in surface contamination, with the oldest countermeasure: the windscreen wiper. As noted previously, the first example to be mass produced was Jepson's[3] hand-operated Rain Rubber. This occurred because John Oishei hit a cyclist with his car during a rainstorm. By 1917, Oishei had founded a company and was producing the Rain Rubber; that company later became TRICO and is still a major producer of wiper blades.[27] This technology has been refined, becoming first powered and then automated. Later, washer systems were added to aid the removal of solid contaminants. This example is emblematic of EWM as a whole: rain and spray have long been appreciated as an impediment, and engineering countermeasures have been progressively developed to manage the issues.

Moving beyond the windscreen, the surface water flows from the windscreen and on to the front side glass via the body structure that sits between them (the A-pillar) have historically been controlled by the use of water management features, such as steps from the windscreen, channels along the outboard edge of the windscreen or features associated with the door seals. However, these can cause boundary layer separation and support trapped vortices, generating wind noise. This has resulted in the use of more subtle water management features, which require significant design and development effort. Therefore, managing surface water in this region remains the main focus during vehicle development. This presents significant challenges, as the windscreen, front side glass and A-pillar form a region of geometric, engineering and fluid dynamic complexity.

As shown in Figure 5, aerodynamic complexity starts with the boundary layer flow separating from the bonnet, rolling up into a vortex that is situated at the bottom of the windscreen. This is followed by reattachment on to the windscreen and the formation of a radial flow over its surface; at the centre of the screen, this is aligned to the longitudinal axis of the vehicle and has a progressively stronger lateral component away from the centre-line. The flow over the windscreen is disrupted by the wiper structure. If in motion, wipers shed a vortex pair that convects over the windscreen and on to the roof;[29] this vortex system is swept from side to side by their movement. The windscreen surface flow either accelerates over the roof header or separates along the length of the A-pillar, rolling up into the eponymous A-pillar vortex, with the separated shear layer reattaching on the side glass. The flow over the side glass is further disturbed by the unsteady wake shed from the door mirror cap.[30] Furthermore, the flow may accelerate through the gap between the door mirror head and the side glass.[31]

The windscreen surface flow, A-pillar vortex, door mirror wake and the action of the wiper system all influence the distribution of water over this region. Rain and spray hitting the windscreen is forced towards the A-pillars by the periodic action of the windscreen wipers and the aerodynamic shear. If the resulting surface film is sufficiently deep, it may be driven over the A-pillar, breach water management features and flow on to the front side glass.[8] An example of a side glass water flow distribution is provided in Figure 6. This shows rivulets which breach the A-pillar. These interact with the A-pillar vortex; if this is sufficiently strong, then they may be held above the vision zones of the driver by the vortex. Otherwise the rivulets flow down the side glass, being driven backwards by the aerodynamic shear provided by the largely attached air flow on the side glass and downwards by the effect of gravity.

As noted, the main focus for controlling these surface water flows has been through geometry (e.g. steps and channels). In addition, hydrophobic glass coatings are now commonly used to supplement this strategy.

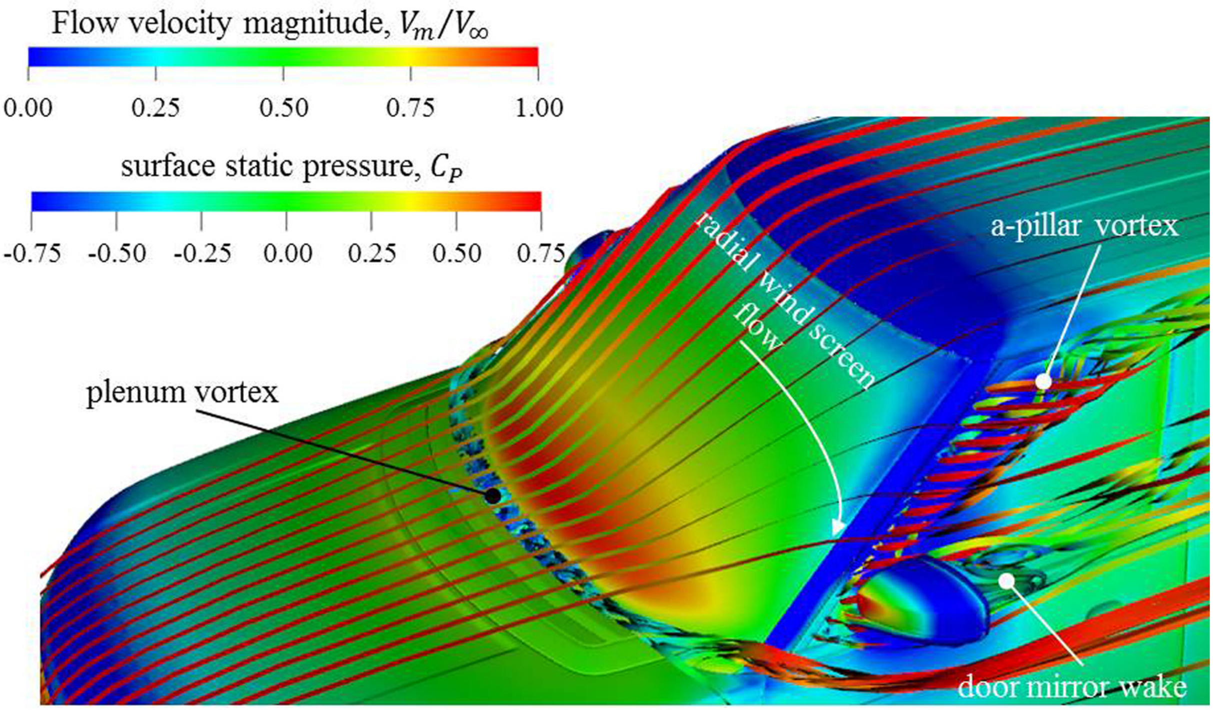

Figure 5. Key flow structures for EWM[28] (surface shaded according to the static pressure; streamlines shaded according to the flow velocity magnitude).

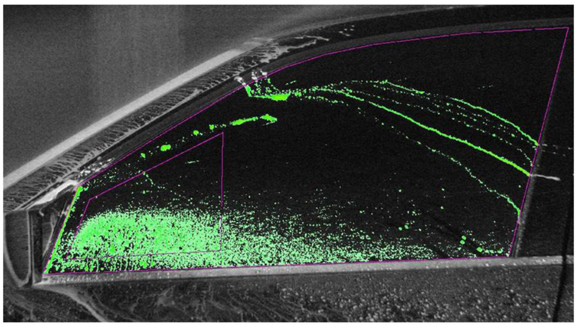

Figure 6. Water deposition on a front side glass.
Source: photograph courtesy of FKFS.

Surface soiling

Body-side soiling

'Road dirt' thrown into the air flow by the tyres of a vehicle causes a deposit zone extending from the front-wheel well along the side to the rear of the car.[1] This is largely an aesthetic issue; dirt accumulation on the door handles and the body side can be transferred to users as they access the vehicle. The extent of this zone can be reduced in height by reducing any favourable pressure gradient between the wheel house and the body side.[2,32] This implicates an outflow from the wheel house, incorporating the wheel wake, in the transport of material from the tyre to the body side. Furthermore, a mainly numerical study of body side and rear soiling by Gaylard and Duncan[33] provides evidence that small-scale vortex structures associated with this outflow advect contaminant on to the body side of the vehicle. Therefore, it is likely that improved aerodynamic treatment of the front corner of a car, including front-wheel house design, can mitigate this issue.

Figure 7 shows a typical body side soiling pattern for a saloon, obtained using an ultraviolet (UV) fluorescence technique. In this case, the deposit zone is situated well below the door handles, a key design objective.

Door mirror

The most comprehensive examination to date of the flow physics responsible for door mirror and subsequent side-glass surface contamination is that by Bannister.[30] From the use of wind tunnel and test track experiments, he deduced that airborne droplets which impact the door mirror housing break up and form a fine spray layer that can be deposited on the front side glass, obscuring the view of the door mirror. This work also demonstrated design changes that simultaneously improve the surface contamination performance and reduce the aerodynamic drag caused by the door mirror.

However, it must be noted that Bannister did not provide any direct evidence for the presence of the 'spray layer', although it is consistent with the 'ejecta fog' observed during droplet impact on the leading edge of a wing and hence is a physically plausible hypothesis.[34]

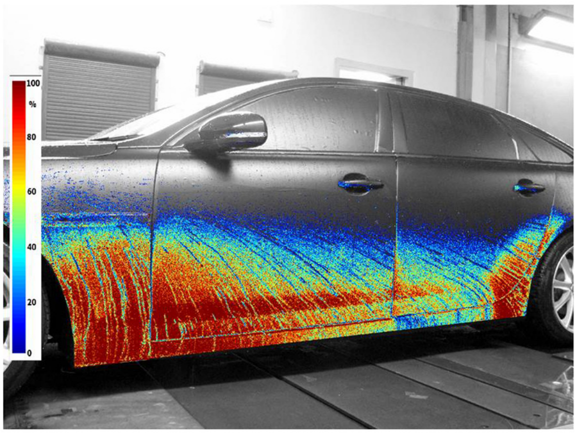

Figure 7. Deposit zone of body side soiling for a saloon car, obtained using a UV fluorescence method in the FKFS thermal wind tunnel.

Rear surfaces

The work of Maycock[17] on the spray generated by commercial vehicles also highlighted that square-backed cars, such as estates, are more vulnerable to rear-surface contamination than are other body types. The physical reasons for this have become clear; droplets mainly thrown off the rear tyres are carried into the wheel wakes from where they are transferred into the base wake, advected back towards the rear surfaces and deposited on them.[35] Accumulation is most acute where the surface pressure is relatively high.[36]

Countermeasures to date have mainly focused on turning relatively uncontaminated air either from high on the vehicle body side or from the flow over the roof using slotted spoilers, corner ducts or turning vanes to provide a 'clean' flow over the rear screen.[1,5,32] The disadvantages of these approaches have generally been an increase in both the vehicle drag and rear lift forces. However, Janson et al.[37] demonstrated a ducted rear spoiler on a Volvo V70 estate that gave a 15% dirt reduction on the rear screen with no increase in drag. This was achieved by stagnating the flow turned down the rear screen from the roof on the upper surface of the rear bumper, leading to a local pressure increase that compensated for the drag induced by turning the flow through the spoiler duct.

Understanding the processes behind EWM and surface soiling and then limiting their impacts rely on using a range of investigative tools. These include test tracks, wind tunnels and numerical simulations. The following sections describe both their strengths and weaknesses for assessing surface contamination.

Investigative tools

Test tracks

Test tracks provided the earliest tool for the systematic investigation of surface contamination. These preserve much of the on-road environment, but with control over the composition of the road surface and traffic in a more secure setting. They do, however, have many limitations, including: a driveable vehicle is required for testing; environmental conditions cannot be controlled; measuring contaminant deposition and surface water dynamics is difficult; confidential prototypes are still at risk of observation.

A substantial body of work using wetted test track surfaces exists for commercial vehicles, including the use of drive-through water troughs that allow control of and variation in the water depth.[18,38–42] This technique was carried into car development, as can be seen in the early studies by Maycock[17] and Goetz and Schoch.[43] In these studies, instrumentation was also attached to moving vehicles to obtain quantitative measurements. In the work by Maycock,[17] spray collectors were attached to frames mounted on the front of the test vehicles, sampling the spray through which the vehicles were driven for subsequent weighing; knowledge of the volume swept by the collectors allowed the spray density to be calculated. In contrast, Goetz and Schoch[43] used a planar 'light curtain' attached on the vehicle behind the wheels to visualise the spray for photographic analysis.[43] They also ran their tests at night to improve the contrast. Using this technique, they were able to demonstrate a substantial reduction in the spray generated by a car by using a grooved wheel arch liner and a deploying mud flap.

Test tracks have also been used to examine smaller areas of vehicle surfaces. Waki et al.[44] attached photosensitive paper to the door mirror glass of a car, spraying 'developing liquid' into the air flow to assess deposition on the mirror glass, whereas Bannister[30] used an upstream car with a spray grid attached to its rear to provide a spray source for his work on door mirrors.

Wetted gravel surfaces have also been used for self-soiling studies on the body side and the rear. For example, Dawley[5] used this type of facility together with a station wagon that had gridded acetate test panels fixed to the rear window, allowing a semi-quantitative assessment of soiling; Piatek and Schmitt[32] have provided a similar example.

Wind tunnel experiments

Although test tracks provide an environment closer to the experience of customers, wind tunnels allow more control over the test environment, particularly the air flow velocity, water flow rate and the ambient temperature. Vitally, the ability to use non-running test properties rather than driveable cars enables development work to start before any running prototypes are available. The use of a stationary test property also makes measurement and visualisation easier. Importantly, a closed test environment provides good security for confidential designs.

Some aerodynamic wind tunnels have been used extensively for surface contamination investigations, including the Rüstungs Unternehmen Aktiengesellschaft (RUAG) aerodynamic wind tunnel operated with its aerodynamic force balance removed, the environmental 'Jules Verne' wind tunnel at the Scientific and Technical Centre for Buildings in Nantes, France, and the Volvo passenger car wind tunnel (PVT) in Gothenburg, Sweden.[20,45–47] However, the requirement to use large quantities of water to simulate the sources for direct soiling, third-party soiling and self-soiling has limited the use of other aerodynamic facilities to less demanding investigations, such as washer fluid breaching of the A-post. For example, tyre spray is generally not compatible with aerodynamic ground simulation systems such as moving belts and floor boundary layer suction devices.

As a consequence, most facilities used for these experiments are climatic or thermal, rather than aerodynamic, wind tunnels. They are more robust to the presence of water, as they tend not to feature vulnerable ground simulation systems. This practical engineering compromise does mean that the aerodynamic mechanisms responsible for surface contamination are not represented with the same fidelity that an aerodynamic wind tunnel provides. In addition, the equipment required for their primary role (exhaust gas extraction systems, dynamometers and vehicle restraints) may further compromise the representation of aerodynamic mechanisms particularly wheel wakes and the vehicle base wake.

In addition, climatic wind tunnels typically have smaller test sections than their aerodynamic counterparts, in order to manage the plant and energy requirements needed to meet their thermal range of operation,[48] which can span –40 °C to + 60 °C. Therefore, the flow field around a vehicle mounted in a climatic facility is more affected by the presence of the test section boundaries.[49]

As the main focus for surface contamination has generally been windscreen and side-glass EWM, these limitations have been tolerable. However, the need to seriously consider rear and body side soiling during vehicle development means that this needs to be reconsidered. Therefore, it is encouraging that the aerodynamic representation provided by climatic wind tunnels is improving as new facilities are commissioned. For example, both The University of Ontario Institute of Technology (UOIT) Automotive Centre of Excellence climatic wind tunnel[48] and the BMW Energie- und umwelttechnische Versuchszentrum climatic wind tunnels[49] were developed with both boundary layer control systems and spray (but not tyre spray) simulation capability. In each of these cases there is a clear intent to improve the representation of the aerodynamic flow field in facilities which can also simulate direct soiling and third-party soiling. The ability to combine tyre spray generation with aerodynamic ground simulations (i.e. wheel rotation and the relative motion between the vehicle and ground) for self-soiling studies is still, however, an unmet need.

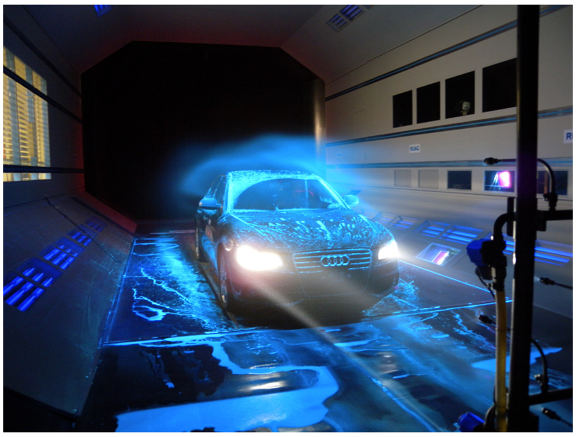

Figure 8. Typical wind tunnel spray grid experiment.
Source: photograph courtesy of RUAG.

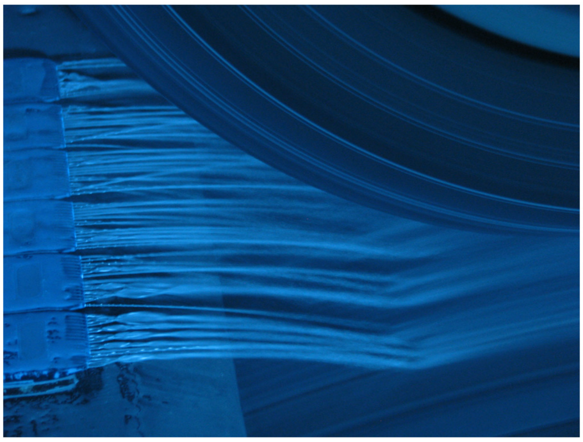

Figure 9. Water and UV dye introduced on to a dynamometer roller in the FKFS thermal wind tunnel to simulate the tyre spray.
Source: photograph courtesy of FKFS.

Contaminants are generally simulated using water dosed with a dye that absorbs UV radiation, re-emitting it in the visible part of the spectrum. This is introduced into the test section either using a spray grid in front of the vehicle, which simulates road spray or rain in the onset flow, or on to dynamometer rollers, which allows the vehicle's tyres to generate spray for self-soiling studies. Figure 8 shows a typical spray grid experiment in the RUAG wind tunnel, suitable for the assessment of third-party soiling on the windscreen, front side glass and door mirror. In contrast, Figure 9 shows the use of a dynamometer roller to simulate tyre spray for self-soiling experiments.

The area of interest is illuminated with UV lamps, providing intensity distributions showing areas of high and low contamination. As Spruss et al.[50] noted, these distributions can be used to determine the percentage coverage of the surface of interest (the degree of soiling) and the normalised mean intensity level (the average contamination factor). They also demonstrated

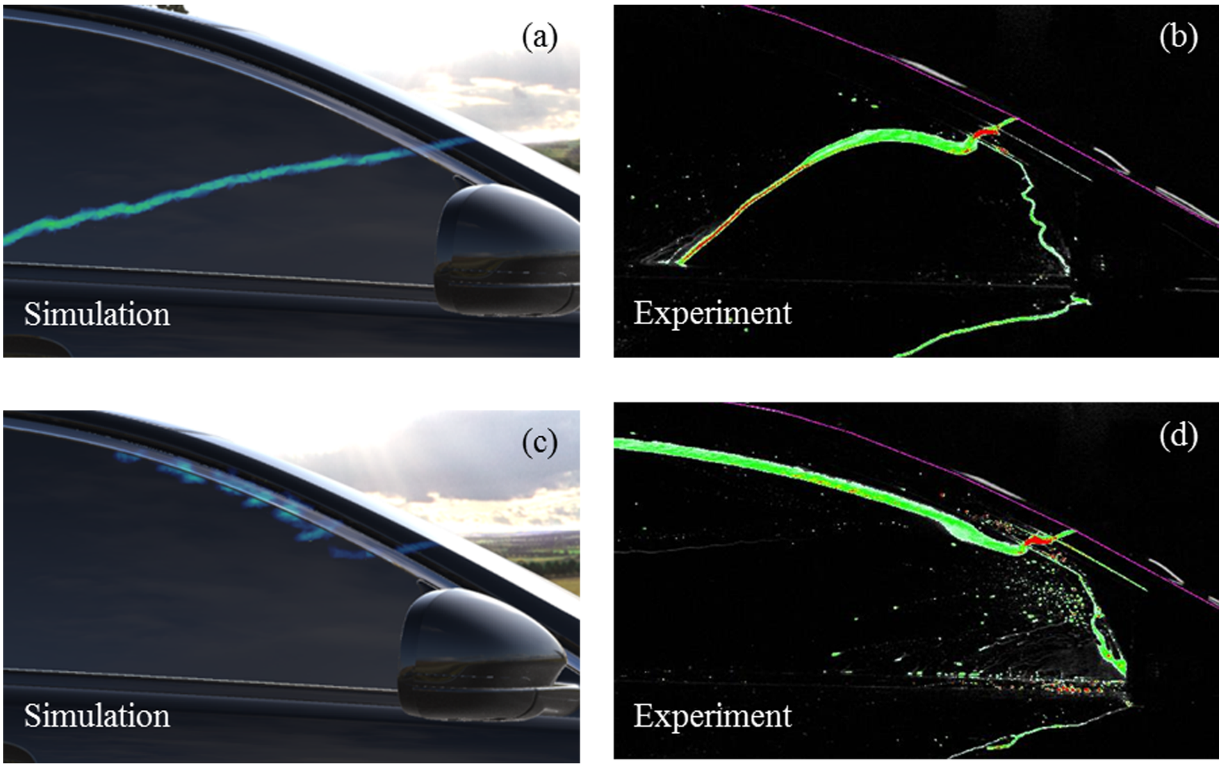

Figure 10. Single rivulet convection on to the front side glass of a saloon car obtained by (a), (c) simulations and (b), (d) experiments at (a), (b) 80 km/h and (c), (d) 100 km/h.
Source: after Jilesen et al.[52].

time-resolved measurements made over the front side glass for the intensity distribution, the degree of soiling and its gradient. Furthermore, Aguinaga and Bouchet[51] have demonstrated that surface film thicknesses can be measured on the front side glass and the body side using an intensity–depth calibration although, to date, these remain the only vehicle locations for which quantitative surface contamination data have been published.

The UV fluorescence technique provides a practical tool for evaluating a range of surface contamination issues during vehicle development, including wiper performance, water management of the front side glass and door mirror, body-side and rear soiling (Figure 10), as well as brake wetting.

In contrast, Vollmer et al.[53] have described a new optical method, in which an opaque layer on the inside of the front side glass blurs the background but maintains the contrast of surface water films, rivulets and droplets as seen by a camera mounted inside the car. This opaque layer method provides time-resolved information on the surface water structure and coverage (but not on the depth). The main advantage is that fluorescent dyes are not required, allowing assessments to be made both in the wind tunnel and on the test track with natural rain. However, the field of view is limited to the glazed area visible from inside the car, and so A-post breaching locations cannot be identified.

Overall, a need remains for the development of quantitative measurement techniques which can be applied to vehicle development, whether extensions of those discussed here or new approaches. For example, Hagemeier et al.[54,55] have demonstrated that laser-induced fluorescence can be used to measure the depth of continuous water films, rivulets and droplets in open channels and on inclined plates. It may be, in the future, that this type of experimental technique can be applied to EWM measurements on vehicles or, more probably, used on simplified geometries to validate numerical models.

Currently, the wind tunnel is the main vehicle development tool for surface contamination. Generally, these facilities are well suited to the simulation of windscreen and side-glass EWM, and the new generation of climatic wind tunnels offers an improved representation of the aerodynamic flow field; however, the lack of moving ground-plane facilities capable of conducting body-side, and particularly rear soiling experiments, is a key limitation. The continuing development of experimental techniques has made quantitative measurement viable for surface water distribution over the front side glass and body side, although not over rear surfaces. Hence, there is still a tendency to rely on qualitative characterisation, which is an impediment to the validation of numerical simulations.

Numerical simulations

Overview. Numerical simulations offer the potential to gain deep insight into the physical processes at an early stage of product development. This can help to identify design changes before expensive tooling or prototype vehicles have been committed to, reducing the development cost and improving product quality. As the capabilities of computational fluid dynamics (CFD) codes have been expanded to include multi-phase flows and computational power has increased, numerical simulations have emerged as a viable tool.

As previously noted, a review of this topic, which mainly focused on surface film modelling for front side-glass and door mirror EWM, has been provided by Hagemeier et al.[9] They demonstrated that computational approaches used in automotive contamination studies derive from the aerospace industry. For example, Lagrangian particle tracking was used to represent airborne droplets in jet engines.[56] This approach was adopted in the automotive industry for in-cylinder fuel spray simulations.[57] Extensions to represent wall impingement, splash and droplet breakup were subsequently added.[58–61] Further advances included the representation of surface films, using either continuous formulations or discrete (particle-based) formulations.[62–64] These models form the foundation of the main approaches currently used in car surface contamination simulations.

Generally, an aerodynamic flow field is simulated using conventional CFD; airborne droplets are represented by Lagrangian particle modelling and surface water via thin-film models. This methodology has been used to investigate both EWM and surface soiling. The popularity of this approach derives from its relative computational economy.

In particular, thin-film models use a range of simplifying assumptions (sometimes referred to as 'the thin-film approximation'[65]) to make the representation of surface water dynamics tractable. These typically include the following assumptions: surface film thicknesses are small compared with the radii of surface curvature; film flow is laminar, tangential to the surface and varies linearly in the normal direction; in comparison with the surface film velocities, the air flow velocities over the film are sufficiently large for the surface still to be treated as solid for the purposes of the air flow calculation.

These assumptions allow the film to be represented by a simplified set of equations, where the behaviour of a surface film is described in terms of the balance between variations in total pressure, shear at the liquid–solid and liquid–air boundaries, together with the body forces (including gravity). If, as is the case in surface contamination simulations, the effect of droplets impacting the surface and contributing to the surface film needs to be modelled, then this is handled, first, by adding the tangential momentum lost by the Lagrangian particles as a tangential momentum source for the film and, second, by converting the normal component of particle momentum into an interfacial pressure on the film at the particle impact point. The physical significance of the latter is that, without it, particles impacting normal to the surface make no contribution to film inertia, irrespective of their velocity.[63]

Although providing a practical approach, thin-film modelling has a number of limitations relevant to its application for EWM simulations. On vehicle surfaces, the film thickness can become significant relative to the local surface curvature, violating a key assumption of the thin-film approximation. This is particularly evident at the vertical edges of the A-pillar, where the vehicle geometry steps up from the windscreen, and at the transition from the door frame to the side glass. Local boundary layer flow separation can also occur at these sharp edges, which results in droplet stripping from the film (re-entrainment). The breakdown of the thin-film approximation at these locations requires the use of additional submodels. In addition, the water film depth in heavily contaminated areas may become sufficient to contravene other assumptions (e.g. advection normal to the surface), thereby compromising the validity of this simplified approach. Finally, partial wetting is common in automotive surface water flows; e.g. both rivulet and droplet advection is a common feature of water flow over the front side glass. This implies diffusion tangential to the surface, counter to the thin-film approximation, which relies on the fact that it is negligible relative to that normal to the surface.[65] Nevertheless, this approach allows calculation of a film with various depths and velocities, without resorting to more demanding methods that explicitly resolve the film on the computational mesh.

As noted, the dispersed phase is typically modelled using a Lagrangian particle method. The advection is calculated via time integration of the Lagrangian equation of particle motion to obtain the instantaneous velocity vector for each particle.[66] The equation is a balance between the inertial force acting on the particle and the forces resulting from the aerodynamic drag, fluid pressure gradient, mass and gravity effects. This approach also requires the definition of a particle drag coefficient, which is typically treated as a function of the particle Reynolds number. The relationship proposed by Clift and Gauvin[67] has been frequently used in this context.[8]

In this relatively simple scheme, particles occupy no physical volume (i.e. are 'point particles').[68] In its most basic form, this approach is a tracking technique in which the fluid flow affects the particles, but the particles have no effect on the flow field (i.e. it is one-way coupled). However, extensions have been developed for a range of effects, including two-way momentum coupling,[69,70] providing a model for droplet advection which can accurately represent particle–flow interactions and is valid over a wide range of particle Reynolds numbers.[69] Finally, the computational burden may be reduced by tracking groups (parcels) rather than individual particles through the flow field.[68] This, however, represents a trade-off between computational cost and accuracy.

As is seen in the following sections, the combination of Lagrangian particle and thin-film models has enabled significant progress to be made in surface contamination simulations, particularly when the particle models are augmented to account for breakup and splash, and when film models address re-entrainment and partial wetting.

Exterior water management simulations. In an influential study of side glass water management during rain, Karbon and Longman[71] used a staged Euler–Lagrange approach to reduce the computational burden; a simulation of the flow over a complete car provided initial boundary conditions for smaller simulations limited to the flow around the front side glass, A-pillar and door mirror. Lagrangian particle tracking was used to model the airborne water droplets, and a thin-film model represented the accumulating surface water. The water film was solved transiently with a fixed aerodynamic flow field. A periodic surface water source was also included on the windscreen to represent the effect of windscreen wipers driving water over the A-pillar. A similar staged approach has been used by other workers, but with additional refinements. For example, Foucart and Blain[72] represented the periodic forcing of the windscreen surface water film by the wipers with a swept virtual plane. In contrast, Campos et al.[73] included a droplet stripping model based on wave instabilities in the surface film,[74] whereas Kruse and Chen[75] used a bespoke particle-based wall film model that included corrections for local wetting conditions.

The question of whether surface film models are necessary when investigating the impact of the door mirror design on the side-glass water management (and soiling) was explored by Borg and Vevang.[20] Their work is distinguished by the use of idealised door mirror geometry to undertake a fundamental validation before moving on to the more complex application; an underused technique in this field.

The importance of matching experimental boundary conditions can be seen in the work by Gaylard et al.,[76] who used an unsteady lattice Boltzmann (LB)–Lagrangian approach, with a surface film model, to simulate surface water flow breaching the A-pillar of an SUV. The flow domain represented the main features of a climatic wind tunnel test section (nozzle, plenum and test section flow outlets). The breaching position for two A-post designs appeared to match those obtained experimentally.

These studies have demonstrated that it is possible to simulate the gross features of surface water film accumulation on the front side glass and the influence of A-post and door mirror designs. Hence, numerical simulations can be a useful adjunct to wind tunnel testing. However, it is less clear whether current surface film models are able to represent sufficiently the important details of surface water flow over the front side glass, such as rivulet formation and dynamics, as they have a limited capability to account for droplet stripping, surface tension and capillary forces. Also, as previously noted, the film thickness at some locations may lie outside their range of validity.

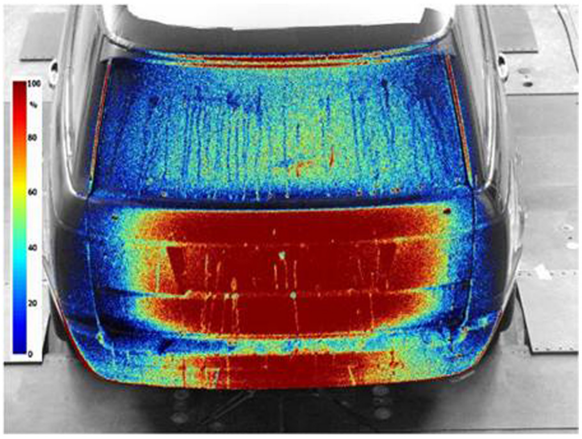

Figure 11. Accumulation of contaminant on the rear of an SUV after 75 s, obtained using a UV fluorescence method in the FKFS thermal wind tunnel.

Nevertheless, as typified in the work of Jilesen et al.,[52] these simple models with suitable extensions can recover useful surface flow behaviour. Their work used a thin-film model coupled to an unsteady simulations of the surrounding air flow as well as a re-entrainment model.[35] As shown in Figure 11, they were able to predict the path taken by a single rivulet generated by fluid injection at the outboard edge of a vehicle windscreen, as it traversed the A-pillar and was carried on to the side glass. The correct sensitivity to the vehicle velocity was obtained, although significant differences were evident between the measured and calculated paths.

Other applications of water management simulation are emerging as the techniques become more capable. For instance, Schembri Puglisevich et al.[77] used a combination of an unsteady LB solver, Lagrangian particle model and thin-film models to simulate the wetting of front brake discs by tyre spray. These self-soiling simulations accounted for wheel (and disc) rotation using a sliding mesh. The changes in water deposition seen with the modification and removal of brake dust shields matched those obtained experimentally. This can also be seen as further evidence for the utility of tyre spray models derived from the work of Kuthada and Cyr.[8]

More advanced approaches that seek to explicitly resolve the liquid volume have been proposed but are currently prohibitively expensive. These include volume-of-fluid (VOF) methods. The first application of these methods to three-dimensional viscous flows was for hydrodynamic free-surface flows.[78,79] Unlike a thin-film model, they resolve the liquid content of the flow field on the computational grid. Cells containing an interface between air and liquid (*mixed cells*) have a liquid volume fraction f with a range $0 < f < 1$. In contrast, cells which do not contain an interface (*pure cells*) contain only liquid ($f = 1$) or only air ($f = 0$).[80] As the calculation is advanced, the volume fractions of the fluids are tracked across the grid. This 'volume-tracking' approach has a number of useful characteristics: it naturally conserves mass; it handles geometric complexity, together with the breakup and coalescence of liquid volumes.[81] This basic method has the disadvantage that the interface location is not tracked. Hence, an interface reconstruction algorithm is generally employed to approximate its shape. These are linear reconstructions which use piecewise constant, stair-stepped or linear functions to delineate between the liquid and air. However, the computational burden of explicitly resolving the liquid phase in EWM calculations has prevented their application to date, although Hagemeier et al.[9] suggested that coupling the thin-film method and VOF methods, with the latter activated where the film depth is significant, may be a productive approach. This type of hybrid approach could make VOF viable for use in vehicle-scale simulations.

Other hybrid approaches which may ultimately have some application to vehicle EWM studies include the combination of VOF and level-set (LS) methods.[82] The LS method uses a smooth function $\phi(x, y, t)$ to represent the interface; in this simple statement, the interface is on a two-dimensional x–y plane and its position changes with time t. This LS function takes values $\phi(x, y, t) > 0$ for liquid regions and $\phi(x, y, t) < 0$ for air. Hence the interface is implicitly represented by the set of points for which $\phi(x, y, t) = 0$.[83] This technique improves the accuracy and robustness of interface tracking by allowing the use of a larger number of grid points at the interface. The main disadvantage of LS methods is that they are not inherently mass conservative. Therefore, coupled LS–VOF methods have been proposed, combining the natural mass conservation of VOF with the more accurate and robust interface tracking of LS.[82] However, the main impediment to applying these to vehicle-scale problems remains the high computational cost.

Therefore, it is likely that the de facto standard of using an eddy-resolving aerodynamic flow solver with the addition of a Lagrangian particle model and a thin-film model to represent the liquid (water) phase will persist for some time to come. The most probable improvements are extensions to the thin-film scheme, or perhaps a coupled VOF–thin-film approach. In any case, for partially wetted surfaces where a contact angle is formed between the liquid regions and the surface, all these approaches require the use of additional models to represent this behaviour and thereby to recover realistic surface water dynamics.

Body-side soiling and rear soiling. The first published example of CFD applied to surface contamination was provided by Yoshida et al.,[84] who investigated body-side and rear soiling for an SUV, using Lagrangian particle tracking together with a simple Eulerian–Eulerian method. The geometry was highly simplified and a steady-state flow solver was used, reflecting the computational resources available at the time.

An alternative approach to providing economic body-side and rear-surface contamination simulations (excluding surface water film dynamics) was pioneered by Roettger et al.[85,86] They calculated the flow field using unsteady LB simulations and then tracked the movement of Lagrangian particles through a time-averaged flow field. The main limitation of this approach was that it did not include the effect of the unsteady flow generated by the vehicle on the particle paths. Unusually, their particle–surface interaction model also included electrostatic attraction. The significance of this force for deposition of environmental particulates on vehicle surfaces has not been explored further in the literature. Improvements to this method were reported by Kuthada and Cyr[8] who included a calibrated tyre spray model in body-side soiling simulations for a station wagon, releasing particles from the tyre face. Further, Gaylard and Duncan[33] applied particle tracking to a set of short-time-averaged flow fields and then summed the resulting particle distributions. This provided sufficient unsteady flow influence to produce a reasonable prediction of body-side soiling for a saloon and SUV; however, rear-surface soiling was not well predicted.

Substantial progress in predicting soiling patterns has resulted from including the particle simulation within the flow solver, sensitising particle paths to the unsteady flow, together with adding models for droplet breakup and splash. For example, Jilesen et al.[35] used a particle model incorporating empirical splash correlations[59,60] together with the Taylor analogy breakup (TAB) model of O'Rourke and Amsden.[61] The particle model was run concurrently with eddy-resolving unsteady aerodynamic simulations. The splash and breakup models were shown to increase the predicted extent of body-side soiling, in comparison with running the simulations without these enhancements. This was attributed to the generation of child particles with smaller Stokes numbers by surface splash and airborne breakup events. In turn, these were more readily advected by the turbulent flow structures generated by the front-wheel wakes and the wheel arch outflow than the initially emitted particles, increasing the number of surface collisions and spreading the contamination further up the body side. The concurrent simulation method also increased the extent of rear-surface soiling, improving on the results previously reported by Gaylard and Duncan.[33]

With the addition of two-way momentum coupling between the particles and air, this technique was able to predict rear-surface contamination patterns for an SUV together with the changes seen when spray was released at the front, the rear and all the wheels.[87] Figure 12 provides an example of a rear-surface contamination

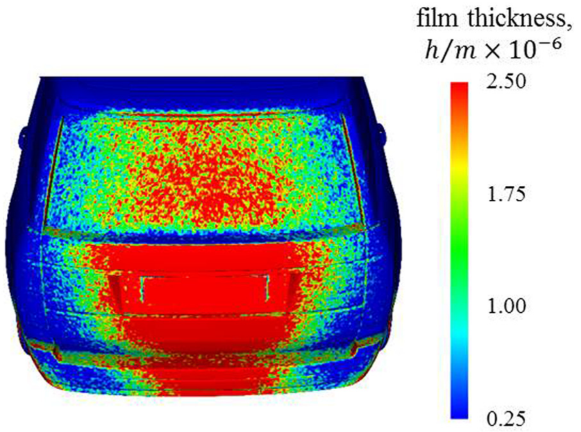

Figure 12. CFD simulation of rear soiling for an SUV, showing contaminant accumulation after 6 s.

pattern obtained with this method; a comparison with Figure 11 shows that, although deposition on the rear screen is overstated, the overall distribution of contaminant on the tailgate is well recovered. This represents a convergence between soiling and EWM simulation methodologies, i.e. solving the aerodynamic flow field using an unsteady eddy-resolving solver, representing the airborne droplets with a Lagrangian particle model and representing the surface water with a thin-film model.

For body-side and rear-surface soiling, it is clear that flow unsteadiness must be accounted for. This is evident in the improvement seen in the progression from tracking particles through a single time-averaged flow field,[8,85,86] to a sequence of short-time-averaged flow fields[33] and finally calculating their trajectories concurrently with the unsteady flow.[35]

In the case of rear soiling, the work of Paschkewitz[88] on particle dispersion in the wake of a commercial vehicle provided an early indication that eddy-resolving flow simulations would be necessary to address this issue. In comparison with an unsteady Reynolds-averaged Navier–Stokes (URANS) model, using large eddy simulations (LES) increased the vertical dispersion of the particles with the lowest inertia; for the particle fraction with diameters less than 5×10^{-5} m, the vertical dispersion distance increased by 35%. Hence, capturing the unsteady structures in the base wake is essential if a realistic distribution of particles through the wake is to be obtained.

Even before droplets enter the base wake of a car, they must be transported through the bounding shear layer. Computational investigation of droplet mixing in shear layers[89] has shown that simulating this process requires the use of methods which represent the relevant unsteady structures in the shear (mixing) layer. Therefore, it is important to use higher-fidelity turbulence modelling than that provided by either a Reynolds-averaged Navier–Stokes (RANS) model or a URANS model.

Hence, it is not surprising that Kabanovs et al.[90] found that neither the RANS nor URANS turbulence models, combined with a Lagrangian particle model, can provide satisfactory rear-surface deposition patterns for a simple car-like bluff body. This was also seen to be a result of the poor base pressure distributions predicted by these methods, an important aspect of the physical problem, as Costelli[36] observed a correlation between contaminant deposition and regions of relatively high surface static pressure.

If eddy-resolving unsteady CFD methods are used, the main features of both body-side and rear-surface contamination distributions can be predicted, together with broad trends in how they change as vehicle configurations are varied. Hence, numerical simulations can provide a viable although computationally expensive engineering tool and can be used to supplement wind tunnel testing.

Although CFD methods provide the opportunity to obtain detailed insights into flow mechanisms and to remove some of the other constraints of wind tunnel testing (wind tunnel boundary condition effects and the lack of a moving ground plane), significant challenges remain. From a vehicle development perspective, the most pressing is the computational cost to run simulations with adequate resolution for a sufficient time to obtain surface contamination and aerodynamic effects concurrently.

Conclusions

The interaction of car surfaces with rain and road spray is an inevitable consequence of vehicle operation. This, in turn, leads to reductions in the vision of drivers and the visibility of vehicles, as well as compromising aesthetics. The use of external camera systems for both vision aids and safety system sensors has added further sensitivity to these processes. Hence, this topic needs to be carefully considered alongside aerodynamic performance throughout the development process. Only through an integrated approach can solutions be found that manage the surface water flows and reduce the deposition of soiling, without undue increases in aerodynamic drag, lift or wind noise.

EWM, particularly for the front side glass, remains the main focus for automotive manufacturers. This is evident in the availability of mature wind-tunnel-based test techniques. Indeed, these continue to be developed with both quantitative measurement of the thickness of the surface water film and time-resolved techniques in evidence in the literature, together with proposals for new methods. CFD approaches have been demonstrated although, as yet, are unconvincing as development tools. The main limitations appear to be accounting for surface–liquid interactions, surface tension and hydrostatic effects with sufficient computational economy to provide a viable engineering approach. However, recent progress suggests they may be a useful adjunct to experiments.

In contrast, surface soiling has received less focus until the emergence of camera lens cleanliness as an important issue. The UV fluorescence-based wind tunnel test approach used for surface water management provides a useful engineering development tool for investigation of body-side and rear-surface soiling. However, the lack of moving ground-plane test facilities capable of this type of testing is a significant issue. In addition, quantitative surface film thickness measurement has yet to be demonstrated for the rear surfaces of vehicles. Nevertheless, the rapid progress of numerical simulations, particularly for rear soiling, offers the potential to compensate for these shortfalls; however, this is more costly than standard aerodynamics simulations as the additional physics need to be modelled within the framework on an unsteady eddy-resolving CFD solution. In addition, the extent to which modelling rather than simulating tyre spray influences these calculations remains unclear.

Overall, there is still considerable scope to develop systematic insights into these topics. Until recently, most work has been carried out on vehicles with little recourse to the simplified geometries used in vehicle aerodynamics to elucidate key processes. The literature provides some examples that this approach is being used to understand the fundamentals of surface rivulet behaviour, door mirror soiling and rear-surface soiling. This foundation needs to be built upon, not only to develop insights into the fluid mechanics at work, but also to provide validation cases for numerical simulations.

In addition, both wind tunnel and numerical simulations represent contaminants using water free of any solid fraction (although a small amount of fluorescent dye is added in experimental work). This is taken as a surrogate for the range of contaminants that vehicles encounter. As noted, contaminants found in the road environment are a complex combination of water, natural and man-made solids. The effect on the distribution of contaminants over vehicle surfaces due to the differences between the physical properties of the simulation surrogate and real contaminants requires further research.

Solutions for surface contamination issues can be provided by adding additional systems to cars. Windscreen wipers and washers provide early examples of this approach. Recently, rear camera systems have been protected by deploying them only when needed or by providing washer systems for them. In addition, hydrophobic coatings are increasingly used to mitigate the impact of surface water on the front side glass. However, added systems increase cost and complexity; also, coatings can wear out. Perhaps new generations of dirt-repellent superhydrophobic surfaces may offer credible solutions to the full range of surface contamination issues in the future.

Acknowledgements

The authors would like to thank Timo Kuthada (FKFS) and Peter Aschwanden (RUAG) for providing the imagery used in this publication.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by Jaguar Land Rover and the UK Engineering and Physical Sciences Research Council (grant number EP/K014102/1) as part of the jointly funded Programme for Simulation Innovation and also by the UK Engineering and Physical Sciences Research Council (grant numbers EP/N016602/1, EP/K038664/1 and EP/I011927/1) for Duncan Lockerby.

References

1. Goetz H. The influence of wind tunnel tests on body design, ventilation, and surface deposits of sedans and sport cars. SAE paper 710212, 1971.
2. Hucho W-H and Sovran G. Aerodynamics of road vehicles. *A Rev Fluid Mech* 1993; 25(1): 485–537.
3. Jepson JW. *Wind-shield cleaner*. US Patent 1183463 A, 1916.
4. Anon. Spray gun to clean windshield is operated from dashboard. *Popular Mech* 1936; 65(4): 488.
5. Dawley MW. Aerodynamic effects on automotive components. SAE paper 650134, 1965.
6. Piatek R and Schmitt J. Function, safety and comfort. In: Hucho W-H (ed) *Aerodynamics of road vehicles: from fluid mechanics to vehicle engineering*. 4th edition. Warrendale, Pennsylvania: SAE International, 1998, pp. 331–332.
7. Gaylard A. Surface contamination main zones. *figshare*, https://dx.doi.org/10.6084/m9.figshare.4308209.v2 (2016, accessed 12 December 2016).
8. Kuthada T and Cyr S. Approaches to vehicle soiling. In: *4th FKFS conference on progress in vehicle aerodynamics and thermal management: numerical methods* (eds Wiedermann J and Hucho WH), Stuttgart, Germany, 2006, pp. 111–123. Renningen: Expert-Verlag.
9. Hagemeier T, Hartmann M and Thevenin D. Practice of vehicle soiling investigations: a review. *Int J Multiphase Flow* 2011; 37(8): 860–875.
10. Szakall M, Mitra SK, Diehl K et al. Shapes and oscillations of falling raindrops – a review. *Atmos Res* 2010; 97(4): 416–425.
11. Abu-Allaban M, Gillies JA, Gertler AW et al. Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles. *Atmos Environ* 2003; 37(37): 5283–5293.
12. Air Quality Expert Group. Particulate matter in the United Kingdom: summary. Report, DEFRA, London, UK, April 2005.

13. Pierson WR and Brachaczek WW. Particulate matter associated with vehicles on the road II. *Aerosol Sci Technol* 1982; 2(1): 1–40.
14. Thorpe A and Harrison RM. Sources and properties of non-exhaust particulate matter from road traffic: a review. *Sci Total Environ* 2008; 400(1–3): 270–282.
15. Gaylard AP, Lynch D, Amodeo J et al. The simulation of brake dust deposition. In: *8th MIRA international conference on vehicle aerodynamics*, Grove, Wantage, Oxfordshire, UK, 13–14 October 2010, pp. 271–287. Nuneaton: MIRA Ltd.
16. Martin W and Gilliéron P. Integration of fluid flow modelling in the vehicles renault development process. SAE paper 2001-01-0700, 2001.
17. Maycock G. The problem of water thrown up by vehicles on wet roads. Report 4, Road Research Laboratory, Ministry of Transport, Harmondsworth, UK, 1966.
18. Weir DH, Strange JF and Heffley RK. Reduction of adverse aerodynamic effects of large trucks volume I: technical report. Report FHWA-RD-79-84, Federal Highway Administration, Washington, DC, USA, September 1978.
19. Shearman EDR, Hoare EG and Hutton A. Trials of automotive radar and lidar performance in road spray. In: *IEE colloquium on automotive radar and navigation techniques*, London, UK, 9 February 1998, pp. 10/1–10/7. London: IET.
20. Borg A and Vevang R. On the prediction of exterior contamination with numerical simulations (simple Lagrangian particle tracking methods with and without wall film model). In: *6th MIRA international conference on vehicle aerodynamics*, Gaydon, Warwickshire, UK, 25–26 October 2006, pp. 380–388. Nuneaton: MIRA Ltd.
21. Bouchet JP, Delpech P and Palier P. Wind tunnel simulation of road vehicle in driving rain of variable intensity. In: *5th MIRA international conference on vehicle aerodynamics*, Warwick, Warwwickshire, UK, 13–14 October 2004. Nuneaton: MIRA Ltd.
22. Radovich C and Plocher D. Experiments on spray from a rolling tire. In: Browand F, McCallen R and Ross J (eds) *The aerodynamics of heavy vehicles II: trucks, buses, and trains*, Lecture notes in applied and computational mechanics, Vol 41. Berlin: Springer, 2009, pp. 403–417.
23. Plocher DA and Browand FK. Comparing spray from tires rolling on a wet surface. *Tire Sci Technol* 2014; 42(3): 145–165.
24. Spruss I, Kuthada T, Wiedemann J et al. Spray pattern of a free rotating wheel: CFD simulation and validation. In: *8th FKFS conference on progress in vehicle aerodynamics and thermal management* (ed Wiedermann J), Stuttgart, Germany, 5–6 October 2011, pp. 64–80. Renningen: Expert-Verlag.
25. Spruss I, Schröck D, Kuthada T et al. Aerodynamics as troubleshooting of wet fading. *ATZ Worldwide* 2010; 112(10): 22–25.
26. Spruss I, Schröck D, Widdecke N et al. Investigation of braking response under wet condition. In: *8th MIRA international conference on vehicle aerodynamics*, Grove, Wantage, Oxfordshire, UK, 13–14 October 2010. Nuneation: MIRA Ltd.
27. Rockwell MR. *John R. Oishei: Buffalo businessman and benefactor*. New York: John R. Oishei Foundation, 2004, p. 20.
28. Gaylard A. Vehicle aerodynamics, figshare, https://dx.doi.org/10.6084/m9.figshare.4308215.v1 (2016, accessed 12 December 2016).
29. Gaylard AP, Wilson AC and Bambrook GSJ. A quasi-unsteady description of windscreen wiper induced flow structures. In: *6th MIRA international conference on vehicle aerodynamics*, Gaydon, Warwickshire, UK, 25–26 October 2006. Nuneaton: MIRA Ltd.
30. Bannister M. Drag and dirt deposition mechanisms of external rear view mirrors and techniques used for optimisation. SAE paper 2000-01-0486, 2000.
31. Gaylard, AP. CFD simulation of side glass surface noise spectra for a bluff SUV. SAE paper 2006-01-0137, 2006.
32. Piatek R and Schmitt J. Function, safety and comfort. In: Hucho W-H (ed) *Aerodynamics of road vehicles: from fluid mechanics to vehicle engineering*. 4th edition. Warrendale, Pennsylvania: SAE International, 1998, pp. 335–336.
33. Gaylard AP and Duncan B. Simulation of rear glass and body side vehicle soiling by road sprays. SAE paper 2011-01-0173, 2011.
34. Thompson BE, Jang J and Dion JL. Wing performance in moderate rain. *J Aircr* 1995; 32(5): 1034–1039.
35. Jilesen J, Gaylard A, Duncan B et al. Simulation of rear and body side vehicle soiling by road sprays using transient particle tracking. SAE paper 2013-01-1256, 2013.
36. Costelli AF. Aerodynamic characteristics of the Fiat UNO car. SAE paper 840297, 1984.
37. Janson J, Darrieutort L, Bannister M et al. New development and working methods used in the aerodynamic development of the new large estate. JSAE paper 20005352, 2000.
38. Allan JW and Lilley GM. Reduction of water spray from heavy road vehicles. In: Dorgham MA and Businaro UL (eds) *International conference on impact of aerodynamics on vehicle design*, London, UK, 16–18 June 1982, pp. 270–307. St. Helier, Jersey: Interscience Enterprises, 1983.
39. Fujimoto T, Miyake N, Watanabe Y et al. Suppression of mud adhesion to the rear surface of a van-type truck. SAE paper 920203, 1992.
40. Manser MP, Koppa R and Mousley P. Evaluation of splash and spray suppression devices on large trucks during wet weather. Report HS-043 602, AAA Foundation for Traffic Safety, Washington, DC, USA, October 2003.
41. Clarke RM. Heavy truck splash and spray suppression: near and long term solutions. SAE paper 831178, 1983.
42. Olson ME and Fry PR. Highway tractor–trailer splash and spray reduction through aerodynamic design. SAE paper 881875, 1988.
43. Goetz H and Schoch R. Reducing splash and spray of trucks and passenger cars. SAE paper 950631, 1995.
44. Waki T, Tokumaru K, Nouzawa, T et al. Flow visualization around door mirror considering the adhesion of raindrops and wind noise. JSAE paper 963680, 1996.
45. Walthert L. Automotive soiling tests. Report, RUAG Aerospace, Emmen, Switzerland, 2001.
46. Hauser A. Rainmakers from Emmen. *Wind Tunnel Int* 2010; 73–75.
47. Gandemer J. La soufflerie climatique "Jules Verne". *J Wind Eng Ind Aerodynamics* 1992; 41(1–3): 43–54.
48. Best S, Komar J and Elfstrom G. The UOIT Automotive Centre of Excellence – Climatic Test Facility. SAE paper 2013-01-0597, 2013.

49. Bender T, Hoff P and Kleemann R. The New BMW Climatic Testing Complex – The Energy and Environment Test Centre. SAE paper 2011-01-0167, 2011.
50. Spruss I, Landwehr T, Kuthada T et al. Advanced investigation methods on side glass soiling. In: *9th FKFS conference on progress in vehicle aerodynamics and thermal management* (ed Wiedermann J), Stuttgart, Germany, 1–2 October 2013, pp. 167–181. Renningen: Expert-Verlag.
51. Aguinaga S and Bouchet JP. Quantitative assessment by UV fluorescence of rain water flow on vehicle body in the Jules Verne climatic wind tunnel. In: *7th FKFS conference on progress in vehicle aerodynamics and thermal management* (ed Wiedermann J), Stuttgart, Germany, 6–7 October, 2009, pp. 127–142. Renningen: Expert-Verlag.
52. Jilesen J, Gaylard A, Spruss I et al. Advances in modelling A-pillar water overflow. SAE paper 2015-01-1549, 2015.
53. Vollmer H, Gau H, Klußmann S et al. Comparison of on-road and wind tunnel testing of side window soiling using a new method. In: *10th FKFS conference on progress in vehicle aerodynamics and thermal management* (ed Wiedermann J), Stuttgart, Germany, 29–30 September 2015, pp. 276–288. Renningen: Expert-Verlag.
54. Hagemeier T, Hartmann M, Kühle M et al. Experimental characterization of thin films, droplets and rivulets using LED fluorescence. *Exp Fluids* 2012; 52(2): 361–374.
55. Hagemeier T, Bordás R, Zähringer K et al. Two-perspective fluorescence analysis of droplets creeping down a tilted plate. *Exp Fluids* 2014; 55:1639.
56. El Wakil MM, Ueyhara OA and Myers PS. A theoretical investigation of the heating-up period of injected fuel droplets vaporizing in air. Report TN 3179, National Advisory Committee for Aeronautics, Washington, DC, USA, 1954.
57. Borman G and Johnson J. Unsteady vaporization histories and trajectories of fuel drops injected into swirling air. SAE paper 620271, 1962.
58. Bai C and Gosman A. Development of methodology for spray impingement simulation. SAE paper 950283, 1995.
59. Mundo C, Sommerfeld M and Tropea C. Droplet–wall collisions: experimental studies of the deformation and breakup process. *Int J Multiphase Flow* 1995; 21(2): 151–173.
60. O'Rourke P and Amsden A. A spray/wall interaction submodel for the KIVA-3 wall film model. SAE paper 2000-01-0271, 2000.
61. O'Rourke P and Amsden A. The TAB method for numerical calculation of spray droplet breakup. SAE paper 872089, 1987.
62. Bai C and Gosman A. Mathematical modelling of wall films formed by impinging sprays. SAE paper 960626, 1996.
63. Ahmadi-Befrui B, Uchil N, Gosman A et al. Modeling and simulation of thin liquid films formed by spray–wall interaction. SAE paper 960627, 1996.
64. O'Rourke P and Amsden A. A particle numerical model for wall film dynamics in port-injected engines. SAE paper 961961, 1996.
65. Meredith KV, Heather A, De Vries J et al. A numerical model for partially-wetted flow of thin liquid films. In: Mammoli AA and Brebbia CA (eds) *Computational methods in multiphase flow VI*. Southampton: WIT Press, 2011, pp. 239–250.
66. Elghobashi S. Particle-laden turbulent flows: direct simulation and closure models. *Appl Sci Res* 1991; 48: 301–314.
67. Clift R and Gauvin WH. The motion of particles in turbulent gas streams. *Proc Chemeca* 1970; 1(1): 14–28.
68. Elghobashi S. On predicting particle-laden turbulent flows. *Appl Sci Res* 1994; 52(4): 309–329.
69. Subramaniam S. Lagrangian–Eulerian methods for multiphase flows. *Prog Energy Combust Sci* 2013; 39(2–3): 215–245.
70. Dukowicz JK. A particle–fluid numerical model for liquid sprays. *J Comput Phys* 1980; 35(2): 229–253.
71. Karbon KJ and Longman SE. Automobile exterior water flow analysis using CFD and wind tunnel visualization. SAE paper 980035, 1988.
72. Foucart H and Blain E. Water-flow simulation on vehicle panels by taking into account the calculated aerodynamic field. SAE paper 2005-01-3572, 2005.
73. Campos F, Mendonca F, Weston S et al. Vehicle soiling simulation. In: *6th MIRA international conference on vehicle aerodynamics*, Gaydon, Warwickshire, UK, 25–26 October 2006, pp. 358–367. Nuneaton: MIRA Ltd.
74. Maroteaux FF, Llory DD, Le Coz JF et al. Liquid film atomization on wall edges – separation criterion and droplets formation model. *J Fluids Engng* 2002; 124(3): 565–575.
75. Kruse N and Chen KH. Exterior water management using a custom Euler–Lagrange simulation approach. SAE paper 2007-01-0101, 2007.
76. Gaylard A, Fagg M, Bannister M et al. Modelling A-pillar water overflow: developing CFD and experimental methods. SAE paper 2012-01-0588, 2012.
77. Schembri Puglisevich L, Gaylard A, Osborne M et al. Application of CFD to predict brake disc contamination in wet conditions. SAE paper 2016-01-1619, 2016.
78. Nichols BD and Hirt CW. Methods for calculating multi-dimensional, transient, free surface flows past bodies. In: *1st international conference on ship hydrodynamics*, Gaithersburg, Maryland, USA, 20–22 October 1975, pp. 253–277. Bethesda, Maryland: Naval Ship Research and Development Center.
79. Hirt CW and Nichols BD. A computational method for free surface hydrodynamics. *Trans ASME, J Pressure Vessel Technol* 1981; 103(2): 136–141.
80. Rider WJ and Kothe DB. Reconstructing volume tracking. *J Comput Phys* 1998; 141(2): 112–152.
81. Pilliod JE and Puckett EG. Second-order accurate volume-of-fluid algorithms for tracking material interfaces. *J Comput Phys* 2004; 1999(2): 465–502.
82. Sussman M and Puckett EG. A coupled level set and volume-of-fluid method for computing 3D and axisymmetric incompressible two-phase flows. *J Comput Phys* 2000; 162(10): 301–337.
83. Sethian JA and Smereka P. Level set methods for fluid interfaces. *A Rev Fluid Mech* 2003; 35: 341–372.
84. Yoshida M, Yamatani A and China H. Prediction of dirt contamination on vehicle body surface. *JSAE Rev* 1998; 19(3): 257–262.
85. Roettger S, Schulz S, Bartelheimer W et al. Automotive soiling simulation based on massive particle tracing. In: *Joint Eurographics–IEEE TCVG symposium on visualization*, Ascona, Switzerland, 28–30 May 2001, pp. 309–317. Vienna: Springer.

86. Roettger S, Schulz S, Bartelheimer W et al. Flow visualization on hierarchical cartesian grids. In: *3rd international FORTWIHR conference on high performance scientific and engineering computing* (eds Breuer M, Durst F and Zenger C), Erlangen, Germany, 2001, pp. 139–146. Berlin: Springer.
87. Gaylard A, Pitman J, Jilesen J et al. Insights into rear surface contamination using simulation of road spray and aerodynamics. SAE paper 2014-01-0610, 2014.
88. Paschkewitz JS. A comparison of dispersion calculations in bluff body wakes using LES and unsteady RANS. Report UCRL-TR-218576, Lawrence Livermore National Laboratory, Livermore, California, USA, 1 February 2006.
89. Yang WB, Zhang HQ, Chan CK et al. Large eddy simulation of mixing layer. *J Comput Appl Math* 2004; 163(1): 311–318.
90. Kabanovs A, Varney M, Garmory A et al. Experimental and computational study of vehicle surface contamination on a generic bluff body. SAE paper 2016-01-1604, 2016.