Formation analysis of soiling for side windows and the rear view mirrors of vehicle

D S Tsepo\textsuperscript{1}, N S Solomatin\textsuperscript{2}, A V Zotov\textsuperscript{2} and D A Rastorguev\textsuperscript{2}

\textsuperscript{1}PJSC AVTOVAZ, Zastavnaya Street, 2, Togliatti City, 445024, Samara Region, Russian Federation
\textsuperscript{2}Togliatti State University, Belarusian Street, 14, Togliatti City, 445020, Samara Region, Russian Federation

E-mail: sns@tltsu.ru

Abstract. The article provides a classification of soiling sources of side windows and rear view mirrors, taking into account different weather conditions. Criteria for assessing soiling degrees are presented. The analysis of soiling mechanisms from various sources is carried out. Visualization of the trajectories of liquid droplets in the air flow is presented. The processes of interaction of droplets with the car surface and the movement of fluid on given surfaces are considered. The main soiling sources of side windows and rear view mirrors have been identified. The results of modeling the precipitation of droplets on the front door glass are presented when analyzing the movement of flows overcoming obstacles in the form of two generations of rear-view mirrors. Two different designs LADA Kalina / Granta demonstrate a significant difference in their ability to prevent soiling.

1. Introduction
The quality of the view from the driver's seat through the glazing and rear view mirrors is one of the most important factors in ensuring traffic safety. Maintaining the outer surface of the glazing and the reflective surfaces of the exterior mirrors in a clean and / or dry state directly provides an overview of the driving process. As practice shows, the contamination of glass front doors and reflective surfaces of exterior rear view mirrors is directly related to the shape and mutual arrangement of the surfaces of the car body and exterior mirror housings.

Modeling of car windows soiling is a complex process. It uses various approaches to calculate the aerodynamic field around the vehicle, tracking the trajectories of droplets in the air field and, after the droplet impacts, simulate the movement of the water film along the car surface.

For the development of engineering techniques, AVL / Fire code was used to create an engineering tool which would allow one to take into account different soiling sources features using a digital vehicle at a concept phase.

The wide spectrum of road conditions and physical phenomena when soiling takes place and transient behavior of the mirror wake have become the main challenges to creation of the compact practical simulation tool.

2. Relevance
The process of designing a car begins with the determination of the body geometric proportions and the construction of basic style models. Further, there is a need to assess the influence of the body shape and
the exterior mirror housings on the ability to get dirty for the glazing and the working surfaces of the mirrors from water droplets or dirt that are present in the air flow in front of the car. Many articles are devoted to these questions [1-10].

Side windows are not as directly exposed to precipitation and mud drops as windscreen. Nevertheless, they together with outside mirrors often experience strict aerodynamic soiling caused by vortexes behind A-pillar and mirror shells, decreasing in side and rear visibility.

This becomes even more topical for roads in Russia due to very long season with temperatures around and below zero when roads are covered with the mixture of mud, deicing agents and melting snow almost constantly. In such conditions, driving for a short period of time in the wakes of trucks may lead to the total loss of side and rear visibility (Figure 1).

![Figure 1. Soiling of the side window after driving on motorway in winter conditions:](image)

Contrary to windshield, side windows are usually not equipped with outside cleaning assistance. For this reason preventing from soiling stays the only way to keep clearness in side and backward directions for driver. To decrease water and dirt deposition in view areas it is necessary to improve the shape of both car body and side mirrors, as well as their mutual position.

LADA engineers have been working hard on side window and mirror soiling prevention. Wind tunnel experiments stay the main tool for decades to improve the design of the vehicles. Providing just aggregate soiling pictures, this kind of experiment always took much time to find the good shape and position for side mirrors. Now shortening of designing phase requires doing such research already when digital mockup is available. On the other hand, testing engineers in the wind tunnel still want to know the mechanisms of soiling in detail to specify sources of dirt deposition.

3. Formulation of the problem

Practically, aerodynamic soiling occurs at quite wide spectrum of road conditions when many physical phenomena take place. Clear rain drops or mud aerosol can be captured by the air flow and thrown to the glass whereas they continue to interact with each other and to exchange with air flow, breaking up and vaporizing. The flow itself may result from driving in wind or in the presence of other vehicles.

In the design process, it is important to consider the worst case with the least effort. Thus, in order to judge the worst soiling picture, it is necessary to select the combination of the most unfavorable environmental conditions for digital modeling.

In fact, visibility decreases when either pure or contaminated water sticks to glass. The difference is that in the second case visibility doesn’t restore after liquid dries. Moreover, if the density of liquid phase in the air is not very high, the drops of dirt on the glass dry fast so the mud accumulates on their hitting spots. The amount of liquid in the air determines the type of droplet-to-surface interaction and can lead to different sprayed pictures. When the number of drops in the air is very low, vehicle surface may stay always dry due to evaporation, before next droplets hit it. In this case the dispersion of droplets reflected from A-pillar and mirror hull is wider, and the area of soiling on side windows may become bigger after long driving than one in the case of wetted surface. On the other hand, if there is a lot of
water in the air, the liquid can accumulate on mirror hulls charging the mirror wake with secondary drops, which, in turn, are sprayed onto the side window.

Drying dirty drops was considered as the most risky for the customers’ perception, as it will lead to the accumulation of contaminants on the window. Water accumulation in the view area next to A-pillar was considered as another risky case that had to be controlled. For the analysis three main driving situations were selected to model the most unfavorable visibility deterioration:

1) Soiling from dense spray of the mud made by vehicles close ahead on the wet road: car body and mirror hulls are constantly wet but dirty drops reaching the glass are implied to dry fast.
2) Soiling from sparse spray of the mud from cars traveling far ahead on a wet road: whole vehicle surface is constantly dry, dirty drops reaching the glass are implied to dry immediately.
3) Water deposition from moderate or heavy rain: whole vehicle surface is constantly wet, clear water drops reaching the glass splash or deposit to moving water shroud.

The case № 1 from above, basically, corresponds to experiments having been done in AVTOVAZ’s full scale wind tunnel with the aid of nozzle that provided colored water spray just in front of the vehicle or from its front wing. From the experience, such experiments usually gave a good agreement with lifetime vehicle average soiling seen in the road conditions.

4. Models and computational methods

Despite the importance of the problem, the publications found mainly reported on modeling the water flow over the vehicle surface or on the aerodynamic deposition of neutral solid particles [1-6]. In the latter case, the question of the droplet-to-surface interaction and sources of secondary droplets is not taken into account. At the same time, the results of the simulation, as well as the results of experiments, show that half of the total soiling was formed by secondary or reflected droplets, so those needed to pay the most attention.

In the present work, AVL / Fire software was used to calculate air flow around the vehicle. Spray and Wallfilm modules were used to simulate evolution of liquid particles including surface splash and their subsequent deposition onto side windows and mirror glasses using Lagrange approach. In addition to the factors listed above, crosswind, atmospheric turbulence and other passing vehicles can certainly influence the flow field and lead to different patterns of soiling. In addition, the concentration and composition of the solid phase in the droplets can affect their dynamics of splashing and movement, but these effects are intentionally left outside the scope of this work for simplification. A uniform low turbulent volumetric air flow \( U_0 = 100 \text{ km/h} \) was set in the vehicle’s coordinate system, so that the X-direction was downstream and the Z-direction was upward; clean water was chosen to replace all possible liquid contaminants.

The Maichle-Weigand / Urban submodel with moving water islands was used as a default solution to cover the entire spectrum of interactions between droplets and wetted walls. Looking fairly common and simple, this approach nevertheless revealed several problems that needed to be solved.

4.1. Transient wake of the mirror

An airflow field around a vehicle with a vortex amplitude depending on the balance of the airflow around the mirror hull results in a transient mirror wake. For some constructive forms, oscillations of the transverse air velocity in the wake can reach 50% of the incoming air velocity. Therefore, these fluctuations should be taken into account when calculating the droplets transfer to the windows. To do this, you must simultaneously integrate the Navier-Stokes transition equation and take into account the evolution of droplets. CPU time in this case would be unacceptable.

Freezing of air flow before droplet injection is known as the simple decision. But freezing of the average flow field would eliminate extreme values of air velocities and, therefore, the most adverse effect on particles in the direction of windows. Instant freezing of flow could be even more incorrect if particles moved away from window so that soiling has considerably decreased. The decision is in freezing «distortion» of the flow field at which local air velocities are replaced with their extreme values during observation time chosen so that they most pushed droplets to windows.
Such artificial flow field satisfies neither the momentum nor the continuity equations. But this is not necessary if we count only the effect of the air flow on the liquid phase without full back coupling. At any given time, a droplet in such a «distorted» flow experiences aerodynamic force. This is the maximum force in the direction of the side window of all possible values during transition process. Therefore, each droplet has the maximum probability of reaching the glass along its path, as if it were the «the most soiling» particle in the oscillatory wake. As a result, on the dirt spot at the side window all possible drops will be displayed that can get to the surface from the mirror track during a very long observation.

4.2. Liquid phase dispersion

Another problem is a wide range of liquid phase concentration in front of the car, which can be found on the road [9].

To simulate impacts on the mirror body of rare drops at a frequency of one per second and which always have time to dry, it is necessary to use thousands of time steps to dry the remaining film before the next drops touch the surface. Instead, the density of droplets in the air was set to be quite high, corresponding to a precipitation rate of 78 mm/h. This is several times more than in heavy rain. But the surface is left dry, setting the multiplication factor for the evaporation rate of the film, equal to 10.000. With the particle interaction model disabled, it is allowed to simulate long-term contamination from rare drops in a short time using dense flow drops. The droplet flow was adjusted with an intensity of 400.000 parcel/(m²s) and 0.15 kg/(m²s) in front of the car from a position corresponding to the front view of A-pillar with an adjacent side mirror. The droplet diameters were evenly distributed between 0.1 mm and 0.4 mm, which corresponded to movement in the far wake of other vehicles according to [9], the observation time was set to 5 seconds.

Similar conditions have been applied to soiling imitation from dense flow of droplet, having just turned off evaporation from wall film and having established equal distribution of the size of drops from 0.5 to 2.5 mm. This is the whole range of droplet sizes that a car can take on a wet road. In this case interaction of droplet with surface was carried out on Maichle-Weigand / Urban's algorithm and always happened on wet surface as the feeder has been activated once prior to formation of droplets. In both cases all droplets reaching surface of side windows or mirror glass have been selected by means by Noparcel selections for visualization of the general contamination at the end of modeling.

4.3. Spray sourced from the liquid film

Finally, the ruptures of the thick liquid film on the surface of the vehicle provide about half of the total number of drops that eventually reach the glass. Under the influence of strong air flow and gravity, large drops and even flows are separated in places of accumulation of a liquid film, and then break and saturate the mirror trace with droplets. This process could be observed in the windtunnel or in the road conditions mainly on the tailing edges of mirror hulls (figure 2). The simulation of fire / Wallfilm could only predict where the liquid film thickness would increase (figure 3), but the initial assumption of a thin two-dimensional film could no longer work there. The film in the Wallfilm module cannot be detached to feed droplets to the Spray module. The built-in Entrainment option only took into account the instability of thin films and provided very small droplets smaller than 0.1 mm. It was found that the coverage by such droplets on the side window was very small, while the entrainment rate was very high for the current application due to the large surface areas, so the solver crashed with a huge number of parcels. The direct simulation of the film decay process with Volume-Of-Fluid Euler models would be reckless due to extreme high requirements for both space and time resolution. The only way to explain the soiling coming from the mirror wake fed by the detaching fluid was found. First, a complete Fire / Spray / Wallfilm combination on a wet surface was used to locate the film accumulation, and then another simulation was carried out with artificial droplet sources that had to be installed manually.

To simulate the disintegration of a liquid film into droplets, several nozzles were located only in those places where the film thickness on the wall was at least 2 mm. Full spray nozzles were used that
had the half-cone angle of 45° directed streamwise, a range of droplet sizes in the range of 1...2 mm and an initial velocity in the range from 5 % to 10 % of the flow rate U0.

**Figure 2.** Water detaching from the mirror in the windtunnel.

**Figure 3.** Pileup of the water in wallfilm simulations.

If the places of the thick wall film seemed to be elongated in shape, the surface selections were used to start the droplets at low speeds of 0.1 m/s from the surface. Since the detaching liquid flow rate could not be calculated, the fictitious values were used to adjust the flow rate of the liquid from the nozzles and from selections, the simulation results could only serve for qualitative tracking of the droplets on the glass.

Another practical case, when similar nozzles were located on the tailing edges of the mirror hull, regardless of how the fluid flows there, to assess the overall «contamination force» of the wake. The position and cones of injection of six nozzles were installed, as shown in figure 4, in order to uniformly saturate the route with drops, but in order to avoid direct hit of drops into the windows by inertia. Images of soiling from the simulation allowed one to see how different hull shapes spray drops. These are, for example, droplets delivered to the wake by wheels, side wind, or other overtaking or passing vehicles.

**Figure 4.** Standard nozzles to charge the mirror wake with droplets:
(a) top view; (b) – side view.

5. **Results and discussion**

All dirt deposition simulations have been done for the two reference shapes of the left side mirror mounted on the same vehicle body. Those were two generation of LADA-Kalina / Granta car side mirrors – the new mirror had replaced the old one in the production line in large part thanks to its better soiling protection behavior. Figure 5-6 show the pictures of colored water deposition on the side windows and mirror glass obtained in windtunnel for those two reference shapes.
Figure 5. Side window soiling: (a) LADA Kalina mirror (old version); (b) LADA Granta mirror (new version).

Figure 6. Soiling of rear-view mirrors: (a) LADA Kalina mirror (old version); (b) LADA Granta mirror (new version).

The difference in flow structure between averaged and “distorted” fields as well as difference in their soiling can be judged from figure 7 where the results of simulation for the old mirror are given. The regions with positive V air velocity component in the “distorted” flow field were more extended than in the averaged flow. All droplets in it are experienced the large integral impact towards the window along their trajectories. The droplets were sustained from falling down by maximized W-component and prevented from leaving the wake downstream and pushed towards mirror glass by minimized U-component of the air velocity in the “distorted” wake. As a result, the picture of drop deposition on the side window and on the mirror glass corresponded to maximum soiling after the long driving when all possible unfavorable trajectories of droplets had been realized. From figure 8 one can see that droplets coming from the averaged wake did not cover the regions on the driver’s shoulder level where soiling was observed in the reality (figure 5). In such studies, it is better to use the “distorted” flow field to account for the instability and to ensure cases of maximum contamination.

The amplitude of air flow unsteadiness in the wake varies for different shapes of mirror hulls so the difference between averaged and “distorted” flow can be big or small. This may become a measure to assess the quality of the air flow. The more oscillating wake will definitely produce more intense and wider scatter of drops on the window. Figure 9 shows the averaged and «distorted» flow fields in the wake of the second generation of LADA-Kalina / Granta side mirror. The new mirror has the wake calming down compared to the old one. This could be judged by the smaller difference between its averaged and “distorted” air flows. On the contrary, the “distorted” flow of the old mirror differs very much from averaged one, with streaklines turned distinctly up and towards side window (figure 7).
Figure 7. Difference between averaged (a, c) and “distorted” (b, d) flow fields for the old mirror of LADA-Kalina car; air velocity components: W in horizontal plane cut (a, b), V in vertical plane cut (c, d), plane cuts through the center of the mirror.

Figure 8. Difference in “soiling power” of the mirror wake (a, c) and in wet splash soiling (b, d) between averaged (a, b) and “distorted” (c, d) flow fields for the old mirror of LADA-Kalina car.
Figure 9. Difference between averaged (a) and “distorted” (b) flow fields for the new mirror of LADA-Granta car; air velocity component W in horizontal plane cut (top), plane cut through the center of mirror.

Wet or dry splashing of the droplets on the vehicle surface led to difference in number of reflected drops and to their different scatter. Figure 10 demonstrates the results of soiling simulation for two cases. The first one used the Maichle-Weigand / Urban model combined with the normal wall film splash calculation (always wet surface, dense flow of 0.5-5 mm droplets) while in the second case the wall film was forced to evaporate immediately after any drop deposited the liquid to it (always dry surface, sparse flow of 0.1-0.4 mm droplets). As a result, in the second case which corresponded to driving far behind other vehicles, splashing always occurred on dry surface and the area of deposition of reflected drops on the side window became wider. In the project work, both situations are explored to achieve better design of the vehicle.

Figure 10. Difference in soiling pictures between the cases of wet (a, c) and dry (b, d) drop-to-surface interaction for the old LADA-Kalina (a, b) and for the new LADA-Granta (c, d) side mirrors.

After the case of wet splashing finished, the wall film was analyzed to detect liquid pileup on the surface of the vehicle where it might become the source of secondary drops to the wake. Figure 11 shows the localization of wall film with the thickness values above 2 mm. This corresponds to the separation
of the water flow from the body of the mirror during the wind tunnel experiment. The nozzles and surface selection were installed in a similar manner on the mirror mounts and window seals to simulate the injection of fluid from a decomposing wall film. Figure 12 demonstrates the difference in soiling pictures reasoned by those sources of droplets for two reference shapes of LADA-Kalina / Granta mirrors. The new mirror proved to be better protected from both dangerous liquid piling up on the tailing edges of the hull and from blowing secondary drops onto side windows by the wake. The difference in general «soiling power» of two shapes is shown in figure 13.

![Figure 11](image1.png)  
**Figure 11.** Liquid piling up on the old LADA-Kalina (a, c) and new LADA-Granta (b, d) mirror hulls: the places where nozzles were setup.

![Figure 12](image2.png)  
**Figure 12.** Soiling picture on side window from nozzles imitating thick wallfilm detaching and breaking up for old LADA-Kalina (a) and new LADA-Granta (b) mirror shapes. Droplets captured on side window are colored by their source numbers.
Figure 13. Difference in “soiling power” of the mirror wake between the old LADA-Kalina (a) and the new LADA-Granta (b) mirrors.

Water deposition from the rain was simulated by introducing the initial droplets with start falling velocities of 4 m/s in front of the vehicle. As evaporation in this case was not essential the droplets on all vehicle surfaces were treated by Maichle-Weigand / Urban with Moving Islands model and allowed one to deposit to the wall film. The main attention was drawn to the water flowing over A-pillar as, with some shapes, it went down to the side window thus decreasing front visibility in the rain or in the dense droplets sprayed from vehicle ahead. After such simulation, the designer must check that the front part of the side window is free from the water penetrations, otherwise some drain measures should be allowed on the A-pillar and / or front door sealing. Different tilt angles of windscreen and also adjacent proportions may result in different intensity of the A-pillar vortex. More intense vortex may support the water and prevent it from tiding the side window as it is drained streamwise along the A-pillar surface up to the roof, like in the case of LADA-Kalina shown in figure 14a. In contrast to this, the air flow around LADA-Vesta A-pillar were not able to hold the liquid from tiding down the side window so, when the vehicle decelerated on the road, the dirt trickled down the windows (figure 14b).

Figure 14. Water propagation over A-pillar of LADA-Kalina (a) and of LADA-Vesta (b) vehicles. Leakage to the window is shown by the arrow.

6. Design evaluation criteria
To summarize, the cases are listed that made up the modeling tool:

1) Transient airflow around the vehicle, resolving the vortex shedding in the mirror wake; synthesis of a “distorted” flow field that needs to be frozen and used in the following cases to influence the evolution of a droplet.

2) Medium and large droplets hitting the wet surface of the vehicle, all drops reaching the side windows and mirror glasses are stopped to imitate dirt drying and accumulation; assessment of soiling mainly from reflected droplets may be done.

3) Like the case No. 2 but small droplets, always dry surface.
4) “Soiling power” of the wake – the wake saturated with secondary droplets by the standard nozzle set; soiling can be assessed with any droplets in the wake, no matter where they come from.

5) Wake charged with nozzles and surface selections from spots of wall film pileup found in case № 2; an assessment of soiling from secondary droplets resulting from wall film detaching may be carried out.

6) Falling rain droplets forming the liquid film on the whole surface; assessment of the side window coverage by the rain water may be done with focus on the risk of leakage from A-pillar.

For the particular design, the analysis of soiling may be fulfilled when all the cases are done. The results may be scored with regard to reference shapes, which in experiments have shown good or bad results to prevent contamination of the side window. The end judgment upon the dirt soiling should be done upon the number of criteria that have been derived from the results of simulation for reference shapes. Criteria that have been found are listed below, while any user may contribute own invention as well.

1. The number of drops reflected from mirror’s housing and mount in the gap between the mirror and A-pillar or side window. Together with the regions of high V-component of air velocity in the gap, it determines the number of drops reaching the side window opposite the mirror, often just in driver’s view projection of the mirror. The result is strictly dependent on air flow critical point or line being in accordance to the leading edge of the mirror but it also depends on the wake symmetry and free flow of the air in the gap and along the side window. Two reference shapes demonstrate the difference: the old mirror has a bigger area exposed to incoming droplets that reflects drops in the gap towards the vehicle; in addition the air flow in the gap is deflected toward the window due to both confusor and the wake suction close to side window. As a result, the old mirror produces much more intense coverage by the reflected drops on side window, especially in the driver’s view projection of the mirror (figure 10). To do the analysis, cases No. 1, 2 and 3 must be simulated.

2. The liquid pileup on the mirror housing and its mount as well as on front door protrusions. As the liquid will gather somewhere on the mirror housing whatever its shape is, the target is to make it collect where it may leave the surface safely, not charging the wake with droplets. The tailing edges, especially their parts on the top and on the gap side of the housing, cannot be treated as good location. Having run the cases No. 2, the designer can see if the mirror housing needs drain or deflectors or total change in the shape to prevent from dangerous liquid pileup. Figure 11 shows that in the case of new design of the reference mirror the most liquid pileup were moved away from the tailing edge of the housing that together with favorable wake structure decreased soiling significantly (figure 12). The case No. 5 may help clarify the effect produced by wall film breakup on the side window and on the mirror glass.

3. The general «soiling power» of the mirror wake. It can be judged by the shape, position and unsteadiness of the wake and by the intensity of regions with high V and W-components of the air velocity (figure 7). The air flow may be evaluated by the case № 1 directly; also the cases No. 4 or 5 will show the result of respectively dummy or real droplet deposition on the side window and mirror glass from the wake. The difference in “soiling power” may be clearly seen for two reference shapes in figure 12 and in figure 13 where the new LADA-Granta mirror produces almost zero soiling on the window due to its good shape and lower turbulence of the wake.

7. Conclusions
The selection of AVL / Fire Solver, Spray and Wallfilm simulation cases was successfully used as the practical tool allowing to estimate vehicle side window and mirror soiling caused mainly by dirty water dispersions coming from the road during driving. In addition, the rain water deposition on side window from A-pillar might be estimated.

The transient behavior of the air flow behind the mirror had to be captured otherwise the soiling would be underpredicted. Reduction of the transient vortex shedding to the frozen «distorted» flow field was found to be acceptable technique to stay within reasonable CPU time and to keep maximum droplets effect from the transient airflow at the same time. The hand-made sources of liquid stream such as nozzles and selections for it mounting were used to charge the mirror wake with droplets and thus to
imitate thick wall film detachment. A thick wall film breakup model not yet present in AVL / Fire stayed in great demand to automate the simulation of soiling by secondary drops.

The validation of the approach was illustrated by visible agreement between numerical and physical tendencies for soiling for two reference shapes of the side mirror. Also reference shapes must be used to assess the particular design during the project work to range the result of simulation between bad and good scores. As a result of the work, the deterioration of side and rear visibility in wet road conditions might be purposefully decreased using DMU in the development process before going into the windtunnel with proto. The visualization of soiling mechanisms provided by simulation tool would help the aero-engineers tune the shape of the mirror knowingly later in the windtunnel.

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