DOI: 10.54254/2753-8818/2026.DL35585

Flow Separation and Wake Dynamics in High Reynolds Number Flows: Implications for Automotive Drag

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Abstract. Low pressure wake behind the body of a vehicle is the most important component of its aerodynamic drag at highway speeds, not the viscous friction along the body. In typical scales for vehicles, the Reynolds number is $O(10^6)$, which means that the boundary layer is turbulent and stays attached for the major part of the front and roof of the vehicle. The major problem is at the back where there is an adverse pressure gradient and the flow has a tendency to separate. So automotive drag is a more complex subject that is more related to a mechanism chain and not necessarily to speed. After separation a detached shear layer rolls up into coherent structures and a recirculating wake is formed. This wake size and structure will influence the mean base pressure and thus the drag. Based on the canonical Ahmed model, boundary-layer theory, separation criteria and wake scaling are used to demonstrate the order of variation in drag relative to relatively small changes in the rear geometry. From this point of view, the effective way of drag reduction is not to avoid separation, but to control the development of the separated wake and to enhance the pressure recovery.

Keywords: Flow Separation, Wake Dynamics, Ahmed Body, Pressure Drag

1. Introduction

The external flow around a road vehicle is a canonical high Reynolds number problem. At a characteristic vehicle length $L \sim 1.00\,m$ to $4.00\,m$ and freestream speed $U_\infty \sim 2.00e1\,m/s$ to $4.00e1\,m/s$, the Reynolds number is usually 10^6 or greater. Therefore, inertial transport dominates viscous diffusion almost everywhere except within very thin boundary layers and shear layers. In this regime, the front and roof of the vehicle design is relatively benign, but the rear is critical because it determines whether the flow can remain attached long enough to recover pressure before entering the wake. Therefore, automotive drag for bluff bodies is governed by the pressure deficit at the base rather than the skin friction along the body.

$$Re_L = \frac{U_\infty L}{v} \tag{1}$$

This point was made very clear in the pioneering wake studies of Ahmed et al. [1], who found that almost 85% of the body drag is pressure drag at the back of the model when he decomposes the drag of a simplified ground vehicle. They observed from the end of the model vehicle drag

DOI: 10.54254/2753-8818/2026.DL35585

measurement the pressure deficit in the base of the wake model vehicle drag measurement and this observation is a result of a specific sequence of non-linear fluid mechanics. A rear pressure gradient results in a low shear, the shear stress is low, the layer is detached, the detached layer is shear, and the wake behind the vehicle is low pressure and below the ambient freestream value. The aerodynamic drag is low and the pressure is low relative to the area the vehicle base.

Recent Ahmed-body literature demonstrates that the rear geometry influences the mean wake size, as well as the wake's topology, stability, and unsteadiness. For slanted back designs, a dominant concern is whether the flow over the roof reattaches to the backlight or if it completely detaches into the wake; for square back geometries, the dominant concern is often not generic separation, but rather a combination of spontaneous symmetry breaking and bistability of the recirculating bubble [2]. These issues are not small problems. They influence the mean base pressure, which affects potential reductions in drag done by passive or active controls.

Thus, the aim of this manuscript is to write the physics of automotive drag from the basics. The theoretical core is organized around boundary layer scaling, the momentum integral separation criterion, shear layer instability, and wake scaling. Experiment and calculation is based on a small group of vital benchmark studies. The synthesis target is the mechanism chain

$$\beta \uparrow \Rightarrow C_f \downarrow \Rightarrow separation \Rightarrow shear\ layer\ roll\ up \Rightarrow p_b \downarrow \Rightarrow C_D \uparrow \tag{2}$$

Where β is a non dimensional adverse-pressure-gradient parameter, C_f is the skin-friction coefficient, p_b is the mean base pressure, and C_D is the drag coefficient. The practical results are that the rear end design will be reduced when it raises the base pressure by delaying separation, changing the orientation of the separated shear layer, or suppressing the wake states that generate suction.

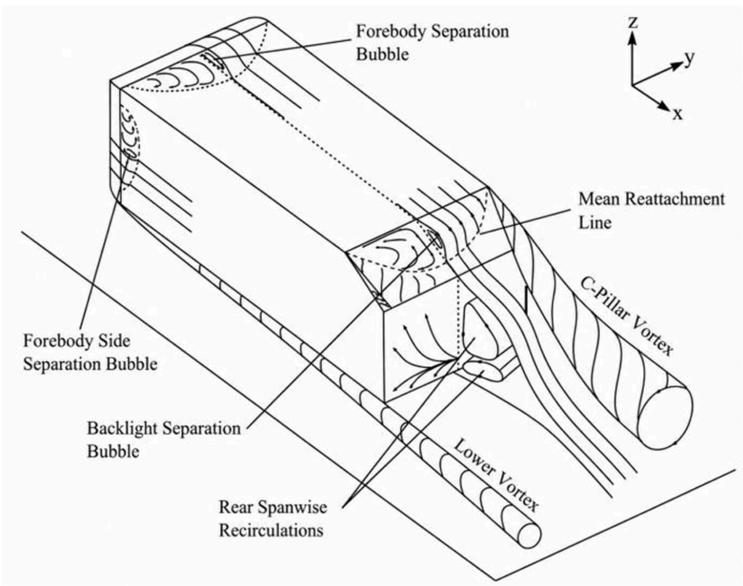

Figure 1. Separation bubbles, recirculation zones, and C-pillar vortices in the near wake

The physical structure of this mechanism chain is illustrated schematically in Fig. 1. The wake topology formed by the separated shear layers ultimately determines the low-pressure region responsible for pressure drag.

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2. Boundary-layer scaling and the separation criterion

The aerodynamic signature of separation appears directly in the surface pressure distribution. As shown schematically in Fig. 2, wake recirculation produces extended low-pressure regions over the rear surfaces, limiting pressure recovery and increasing pressure drag.

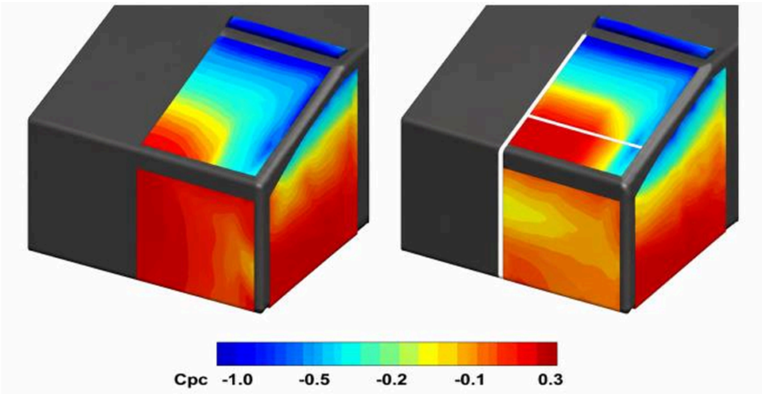

Figure 2. Surface pressure distribution on bluff-body geometries. regions of negative pressure coefficient Cp indicate wake recirculation and delayed pressure recovery associated with flow separation

The mathematical onset of separation can be understood from the boundary-layer reduction of the incompressible Navier-Stokes equations. Let $U_e(x)$ be the outer inviscid velocity imposed by the body shape and corresponding pressure field since $\partial p/\partial y \approx 0$ within the think boundary layer, the streamwise momentum equation may be written as:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_e\frac{dU_e}{dx} + v\frac{\partial^2 u}{\partial y^2} \tag{3}$$

with the outer-flow relation

$$\frac{1}{\rho}\frac{dP_e}{dx} = -U_e\frac{dU_e}{dx} \tag{4}$$

When $dU_e/dx < 0$, the outer flow decelerates and the gradient $dp_e/dx > 0$ is adverse. Because the low-momentum fluid near the wall has the least capacity to survive that deceleration, the near-wall velocity profile becomes fuller, then inflectional, and ultimately loses its positive slope at the wall.

At first scaling result comes from the thickness of the attached boundary layer for a laminar boundary layer, balancing $U_\infty{}^2/x$ against vU_∞/δ^2 yields the classical estimate.

$$\frac{\delta}{x} \sim Re_x{}^{-1/2}, Re_x = \frac{U_\infty x}{v} \tag{5}$$

For a turbulent boundary layer on a smooth body the momentum transport is enhanced by Reynolds stresses, and an empirical but robust scaling is enhanced by Reynolds stresses, and an empirical but robust scaling is:

$$\frac{\delta}{x} \sim 0.37Re_x{}^{-1/5}, C_f \sim 0.059Re_x{}^{-1/5} \tag{6}$$

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The physical content of (6) is that a turbulent boundary layer is thicker than a laminar one but has substantially more near-wall momentum. That is why turbulence often delays separation relative to laminar flow. Delay, however, is not immunity. Once the adverse pressure gradient is strong enough, even a turbulent layer must detach.

A more precise criterion follows from the von Kármán momentum-integral equation.

$$\frac{d\theta}{dx} + (2+H)\frac{\theta}{U_e}\frac{dU_e}{dx} = \frac{C_f}{2} \tag{7}$$

where θ is the momentum thickness and $H = \delta^*/\theta$ is the shape factor. Equation (7) shows that an adverse pressure gradient, $dU_e/dx < 0$, acts as a sink for boundary-layer momentum. In an attached flow this sink can be offset by the wall stress term on the right-hand side. As the gradient strengthens, however, Cf decreases. Separation is approached when

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0} \to 0, C_f = \frac{2\tau_w}{\rho U_e^2} \to 0 \tag{8}$$

The wall is then no longer extracting enough streamwise momentum from the outer flow to maintain attachment.

For adverse-pressure-gradient turbulent boundary layers, the standard nondimensional measure is Clauser's parameter.

$$\beta = \frac{\delta^*}{\tau_w}\frac{dp_e}{dx} \tag{9}$$

Although there is no universal threshold for separation in complex three dimensional vehicle flows, the physical interpretation is straightforward: increasing β means that the streamwise pressure force over the boundary layer thickness becomes large relative to the available wall stress. In automotive rear end flows, β grows sharply near the roof trailing edge, the upper corners of the base, the C-pillars, and the underbody diffuser exit or floor trailing edge, depending on the geometry. These are precisely the sites from which the detached shear layers that form the wake are born.

The Ahmed body makes this logic experimentally accessible because its front end is deliberately rounded to minimize upstream separation while its rear end is deliberately simplified 2 to isolate the separation physics [1]. Its rear slant angle then acts as a geometric control parameter for β. At a low slant angle the adverse pressure gradient is moderate enough that the roof flow may partially reattach on the slant. Near the critical slant range around $2.50e1^\circ - 3.00e1^\circ$ However, the separated structures on the backlight and C-pillars strengthen dramatically, and small geometric changes produce order-one changes in drag [1, 3, 4]. In that sense, the slant angle is not merely a geometric label but a control knob for the separation transition.

3. Shear-layer instability and wake scaling

Once separation occurs, the problem changes. The flow is no longer organized primarily by wall stress and displacement thickness, but by a free shear layer that encloses a recirculating wake. Immediately after detachment, the velocity profile across that layer contains a sharp inflection, so Kelvin--Helmholtz-type disturbances can grow rapidly, leading to vortex roll-up and large-scale wake unsteadiness characteristic of bluff-body flows [5]. If δ_w denotes the shear-layer vorticity thickness and ΔU the velocity jump across it, the near-field instability frequency sales as

DOI: 10.54254/2753-8818/2026.DL35585

$f \sim \Delta U/\delta_\omega$. Farther downstream, the slower coherent motions are instead set by the body scale and therefore scale with U_∞/L or U_∞/H.

The standard nondimensional measure of this unsteadiness is the Strouhal number.

$$St = \frac{fL_c}{U_\infty} \tag{10}$$

Where L_c is a chosen characteristic length. In the road-vehicle literature, that length is not unique: some authors use body height H, some use body length L, and some use $\sqrt{A_f}$ based on the frontal area. That variation is useful, because it shows that more than one large-scale mechanism is active in the wake. Some modes scale with the base dimensions and reflect the interaction of opposed shear layers, whereas others reflect broader bluff-body shedding or slow pumping of the recirculation zone. Sims-Williams et al. [3] found that the fastback wake showed only weak periodicity and limited coherence, yet it still contained identifiable large-scale structures with Strouhal numbers in the bluff-body range. Vino et al. [4] similarly showed that the near-wake shedding of the critical $-3.00e1^\circ$ Ahmed's body is analogous to classical bluff-body vortex shedding.

This unsteadiness matters because it helps set the mean base pressure. The exact drag force is:

$$F_D = \int_S (-pn_x + \tau_x) ds \tag{11}$$

But for a rounded-nose, blunt-tailed vehicle the dominant contribution comes from the pressure integral over the rear-facing surfaces and the wake-induced suction zone. One may therefore write, to leading order.

$$C_D \approx C_{D,p} + C_{D,f}, C_{D,p} \approx -C_{p,b}\frac{A_b}{A_f} \tag{12}$$

Where A_b is the base area, A_f is the frontal area, and $C_{p,b} = (p_b - p_\infty)/\left(\frac{1}{2}\rho {U_\infty}^2\right)$ is the mean base-pressure coefficient. Equation (12) becomes more concrete when the rear-surface pressure field is examined. As the pressure coefficient C_p indicates in Fig. 2 it is still strongly negative over a large portion of the rear slant and base. The low pressure patch is a sign of separated flow where wake recirculation prevents pressure recovery.

It is important not just that this low-pressure area forms, but its size and how far below sea level it gets. The configurations that result in a more diffuse and more uniform recirculation region tend to be associated with a larger pressure deficit, or more drag. On the other hand, small geometric modifications which change the direction of the shear layer or increase the entrainment rate can significantly increase the mean base pressure.

The pressure map is the manifestation of that mechanism chain in (2) in that sense. The separation process is initiated by the adverse pressure gradient and the final pressure field is determined by the behavior of the detached shear layers, their rolling up, interaction, and entrainment of the surrounding fluid. The wake is not only the consequence of separation, it is the most important part of the flow that determines the majority of the drag. This is in agreement with the experiments where wake topology changes rather than separation itself are more strongly affected by changes in rear geometry. The differences in interaction at the shear-layer and in efficiency of entrainment are the direct causes of the differences in mean base pressures. For this reason drag-reduction methods need to focus not only on the viscous effects but also on the wake organization.

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A practical example of such an empirical result is the square-back wake studies of Grandemange et al. [2] which demonstrated that the wake can have two reflectionally asymmetric states and that the wake base pressure is also coupled to the recirculation structure on long time scales. The correlation that they report between base suction and recirculation length can be expressed as an empirical power law in the form.

$$-C_{p,b} \propto \left(\frac{L_r}{H}\right)^{-0.41} \tag{13}$$

With a characteristic recirculation length L_r. The exact prefactor does depend on the geometry and wall configuration, but what matters more is that the drag does not only depend on the location of flow separation, but on how the separated wake evolves subsequent to separation.

The dominant vortices are not the same for Ahmed configurations with a slantedback as for a squareback wake. Ahmed et al. [1] and later Vino et al. [4] demonstrated the C-pillar vortices and the arch-like separated flow over the slant can either be augmenting or reducing the basepressure deficit, depending on the rear angle. It is important, therefore, to note that it is not simply that the flow separates that is the key feature of the highdrag regime: all relevant cases involve separation, but what matters most is that it is a separation that increases the suction over the slant, and makes the wake pressure deficit deeper. This is an important aspect in design. The objective is not normally to completely remove the separation, as this is usually not possible for a short bluff rear end, but to modify the separated structures, thereby causing the wake to close in a more gentle manner and increasing the mean base pressure.

4. Experimental and computational basis

A good physics argument for the drag on an automobile is based on a few basic canonical measurements, each of which isolate a piece of the mechanism chain. Table 1 shows some representative studies that are still fundamental.

Table 1. Representative benchmark studies for Ahmed-type and related bluff-boddy vehicle wakes

Study	Geometry	Reynolds Number	Key Finding
Ahmed et al. [1]	Canonical Ahmed body	Re_L=4.29×10^6	Established the Ahmed body as a standard automotive wake model.
Grandemange et al. [2]	Square-back wakes	Re~105	Demonstrated wake bi-stability and asymmetric switching.
Sims-Williams et al. [3]	Ahmed and hatchback models	Re_L=9.6×10^5 -2.0×106	Identified large-scale unsteady wake modes and rear-pillar vortex effects.
Vino et al. [4]	Ahmed body (30°)	Re_L=4.4×10^5	Observed bluff-body vortex shedding and strong wake mixing.
Lienhart et al. [6]	Ahmed body (25°, 30°)	Re_L≈2.8×10^6	Produced benchmark wake measurements widely used for CFD validation.
Grandemange et al. [8]	Square-back Ahmed body	Re_H=9.2×10^4	Identified slow wake-state switching and faster oscillatory modes.

DOI: 10.54254/2753-8818/2026.DL35585

For seminal experiments, Ahmed et al. [1] still remains. The power of this paper is not just the popularity of the geometry it introduced, but the strong connection it created between rear pressure, wake topology and drag. The body shape was chosen to maintain separation free flow in the forebody and to generate a well-defined wake with topology that was almost entirely controlled by the slant angle of the body base. Therefore, the experiment could be used to directly translate geometry changes to wakestate changes. This separation of roles rendered the Ahmed body extremely valuable for physical interpretation and CFD validation.

The next important step was to transition from time-averaged to dynamically resolved wake measurements. That SAE study performed by Sims-Williams et al. [3] does just that. They demonstrated that the fastback wake includes large scale structures but the dynamics often lack coherence and periodicity in their time accurate pressure measurements and reconstructed three-dimensional flow field. That finding has consequences for a physics paper because it would eliminate a naive model of the wake in which it is dominated by a single clear shedding frequency. Rather, the vehicle wake is a weakly-organized broadband system where several interacting disturbances affect the mean pressure field.

The LDA data set from Lienhart et al. [6] belongs to the other but yet crucial role. Its value is in spatial resolution and statistics details. The measurements at $2.50e1^{\circ}$ and $3.50e1^{\circ}$ slant angles at $4.00e1\ m/s$ provided a basic standard to gauge the performance of the RANS, URANS, DES and LES models. That is a useful benchmark for a physics-oriented manuscript, for it shows which parts of the wake are independent of the method of turbulence closure and which are sensitive. The separated shear layers, the recirculation bubble, and the near-base turbulence anisotropy are the regions that appear to be the most difficult in practice and are at the same time the dominant contributors to drag.

Near-wake measurements by Vino et al. [4] then followed, which were able to provide detail in the regions where a local flow reversal occurred and the flow angles were large, which was where simpler probes had failed. The basic conclusions of their work are directly applicable to the above mechanism chain, namely, that the separated region above the slant is not independent of the base wake region, into which it feeds, but that the frequency measured in the separated region suggests a shedding process that is similar to bluff-body vortex shedding. That's the test bridge of backlight separation and wake-scale drag.

Two 2001 SAE papers, often cited side by side, illuminate complementary aspects of the problem. The first is the unsteady-wake study of SimsWilliams et al. [3]; the second is the drag-reduction-device study of Khalighi et al. [7]. Khalighi and coworkers combined unsteady pressure, hotwire, and PIV measurements with unsteady RANS using the v^2-f model. Their device raised the mean base pressure and reduced drag by more than 20%, not by eliminating the wake, but by narrowing it, deflecting the underbody flow upward, and causing reattachment on the device so that the wake closed more effectively. This is an especially useful case for a physics paper, because it shows that a passive add-on can be interpreted as a purposeful manipulation of separated-shear-layer geometry.

Lastly, Grandemange et al. [2, 8] changed the understanding of the square-back wake by demonstrating that it has a long time bi-stable behaviour. The two asymmetric wake states are found to switch randomly at long time scales and at short time scales the wake exhibits weaker and faster oscillations in their JFM study, which are attributed to the interaction between the top/bottom and lateral shear layers. For CFD, the implication is that a model which is only able to simulate the short-term turbulence fluctuations but does not include the global asymmetric states will not give the overall correct mean pressure distribution. Subsequent numerical studies, in particular by Lucas et

DOI: 10.54254/2753-8818/2026.DL35585

al. [9] indicated that the square-back wake asymmetry is highly sensitive to base geometry and thus confirmed the central role of the rear-end topology in setting the drag.

5. Results and discussion

All of these arguments and experimental results taken together, can be summarized in a compact description of the mechanism of automotive pressure drag. The rearward adverse pressure gradient is the result of the outer inviscid flow. In the boundary layer, that gradient is translated to (4), which through the influence of this sufficiently strong gradient, makes the momentum-integral balance (7) approach its limit $C_f \to 0$. Then the wall shear stress locally becomes zero, the boundary layer separates, and the separated boundary layer turns into an unstable free shear layer.

Coherent vortical structures appear as this layer rolls up and the entrainment of these vortical structures will dictate the size and location of the recirculation bubble. This is because this bubble corrects the mean base pressure, so it is the only one that contributes to the pressure drag in (12). All of the benchmark studies mentioned above can be understood in the context of this chain – the distinction is around which part of the chain each of these studies addresses best.

The most characteristic regime for the slanted-back Ahmed body is in the vicinity of the critical backlight angle. The geometry allows for partial pressure recovery in the lowdrag state, and weaker suction on the back surfaces. When in the highdrag state, however, the separated structures on the slant and along C-pillars amplify the low pressure area. This strong slant-angle dependence was first identified by Ahmed et al. [1] and Vino et al. [4] and Sims-Williams et al. [3] have demonstrated that the wake is an inherently unsteady phenomenon and is strongly related to these separated structures.

The important thing is not just vortices, it's how vortices are organized. Longitudinal vortices may help if they are able to capture high momentum fluid and promote reattachment, but they may be harmful if they increase the suction without decreasing the wake size.

In the square-back case, analysis of reattachment is no longer a primary concern, but rather, global wake-state dynamics. Grandemange et al. [8] showed that the time-averaged wake is actually symmetric as a result of the flow switching between two asymmetric states on large time scales. Multiple large scale states are therefore statistically occupied to produce the mean base pressure. This slow switching process is overlaid with the faster oscillations with $St \approx 0.17$.

This interpretation also explains why it is basepressure recovery, and not the suppression of all unsteadiness, which is the appropriate design goal. Khalighi et al. [7] was able to obtain significant drag reductions without totally removing the wake, but by altering the structure of the wake to allow it to close more efficiently. They were able to use their device to effectively modify the separated shear layers, and to create a short virtual boat-tail without the need for a long taper.

These observations suggest the following scaling synthesis:

$$C_d \sim -C_{p,b}\frac{A_b}{A_f} + O(C_f\frac{S_w}{A_f}) \tag{14}$$

Since C_f is typically $O\left(10^{-3} - 10^{-2}\right)$, while $-C_{p,\,b}$ is $O\left(10^{-1}\right)$, pressure drag dominates for bluff automotive geometries. Once this is recognized, several empirical observations follow naturally. Rear-end modifications that shrink the recirculation region tend to reduce drag. Configurations near wake transitions are highly sensitive to small geometric changes. Furthermore, CFD models must resolve global wake topology, not just local wall stress.

From a design standpoint, three physical lessons follow. First, rear-end treatments should be evaluated based on their effect on pressure recovery. Second, underbody flow is critical because it

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forms part of the bounding shear layers of the wake. Third, active control methods should target the instability structure of the wake rather than adding momentum indiscriminately, consistent with modern bluff-body flow-control strategies [10]. In this sense, automotive drag reduction is best understood as control of the separated wake through pressure recovery-management.

6. Conclusion

This manuscript argues that aerodynamic drag of road vehicles at high Reynolds number is best understood as a separate wake problem. While the Reynolds number determines that the flow is inertially dominated, it does not by itself determine drag. Instead, the key quantity is the basepressure deficit generated by the global organization of the wake.

That deficit emerges from a well-defined sequence: an adverse pressure gradient drives the wall shear stress toward zero, the boundary layer separates, the detached layer becomes a Kelvin-Helmholtz-active shear layer, vortical structures and recirculation develop, and the resulting base suction dominates the drag.

The Ahmed body is thus the "canonical" reduced model since it captures this physics in a particularly clear manner. Ahmed et al. showed the dominance of rear pressure drag; Lienhart et al. presented high resolution benchmark data; Sims-Williams et al. and Vino et al. shed light on the unsteady structure of the wake, while Khalighi et al. showed practical drag reduction through wake manipulation; and Grandemange et al. revealed the existence of bi-stable global wake modes.

All of these results combined demonstrate that the wake separation is not the key to drag reduction, but the organization and development of the separated wake. Physically, the most important nondimensional parameters are Re, St, and β, along with geometric ratios that influence the topology of the wake. Future models and experiments should be targeted towards associating these parameters to measurable quantities like base pressure, recirculation length and modal dynamics.

Thus, automotive drag is a nonequilibrium wake organization issue. Thus it is necessary to control that organization in an effective design, not simply smooth the body surface.

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