



CFD-Based Analysis of Aerodynamic Drag Reduction in a Sedan Model Using Passive Flow Control Devices

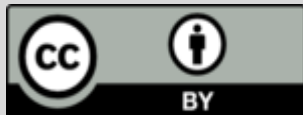
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تحليل قائم على ديناميكا الموائع الحسابية (CFD) لتقليل السحب الهوائي في نموذج سيارة سيدان باستخدام وسائل التحكم السلبي في الجريان

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Abstract

Aerodynamic drag on passenger cars significantly affects fuel efficiency and performance. This study reviews and synthesizes both experimental and computational (CFD) investigations on passive flow control techniques for reducing drag in a generic sedan model. Various devices such as vortex generators, diffusers, spoilers, flaps, and boat-tails are examined. We reference published wind-tunnel tests and CFD simulations to quantify drag reduction. Key findings include the efficacy of small flaps (gurney flaps) in reducing drag by up to 67.7% and vortex generators achieving modest reductions (around 4-6% for typical sedan models). Spoilers and diffusers can yield reductions of about 5-10% under optimal conditions. Combined devices often produce greater benefits; for instance, one study predicts nearly 19% improvement using a boat-tail extension. Experimental wind-tunnel tests have largely confirmed CFD predictions of reduced drag and fuel savings. The passive devices work by delaying flow separation and filling the low-pressure wake behind the car, thereby lowering pressure drag. Even small changes in drag coefficient yield fuel savings (e.g. a 5% drag drop can save ~3% fuel). This comprehensive analysis highlights that well-designed passive modifications can significantly improve sedan aerodynamics and suggests directions for combined device use. Future work should integrate these insights into production vehicles and further correlate CFD with real-world experiments.

Keywords: Aerodynamic drag, Sedan, Passive flow control, Vortex generators, Spoilers, Diffusers, CFD, Wind tunnel.

المخلص

يؤثر السحب الهوائي في سيارات الركاب تأثيرًا كبيرًا في كفاءة استهلاك الوقود والأداء العام للمركبة. تهدف هذه الدراسة إلى مراجعة وتحليل كل من الدراسات التجريبية ودراسات ديناميكا الموائع الحسابية (CFD) المتعلقة بتقنيات التحكم السلبي في الجريان المستخدمة لتقليل السحب الهوائي في نموذج عام لسيارة سيدان. وقد تم فحص عدد من الوسائل مثل مولدات الدوامات، والمشغلات (Diffusers)،

والمفسدات الهوائية (Spoilers) ، واللوحات أو الزوائد الهوائية (Flaps) ، وامتدادات الذيل المخروطي (Boat-tails) تعتمد الدراسة على نتائج منشورة لاختبارات نفق الرياح ومحاكاة CFD لقياس مقدار خفض السحب. وتشير النتائج الرئيسية إلى فعالية اللوحات الصغيرة (مثل لوحات غارني) في تقليل السحب بنسبة تصل إلى 67.7%، في حين حققت مولدات الدوامات انخفاضا محدودا نسبيا يتراوح بين 4-6% في نماذج سيارات السيدان النموذجية. كما يمكن للمفسدات والمشتتات الهوائية تحقيق تخفيض يتراوح بين 5-10% في ظل ظروف تصميم وتشغيل مثلى.

وأظهرت الدراسات أن دمج أكثر من وسيلة تحكم سلبي يؤدي إلى فوائد أكبر؛ إذ توقعت إحدى الدراسات تحسناً يقارب 19% عند استخدام امتداد ذيل مخروطي. وقد أكدت اختبارات نفق الرياح التجريبية إلى حد كبير تنبؤات CFD المتعلقة بخفض السحب وتحسين اقتصاد الوقود. وتعمل هذه الوسائل السلبية على تأخير انفصال الجريان وملء منطقة الضغط المنخفض خلف السيارة، مما يؤدي إلى تقليل سحب الضغط. وحتى الانخفاضات الصغيرة في معامل السحب يمكن أن تسهم في توفير ملموس للوقود (على سبيل المثال، انخفاض السحب بنسبة 5% قد يؤدي إلى توفير يقارب 3% من الوقود).

تُبرز هذه الدراسة الشاملة أن التعديلات السلبية المصممة بعناية يمكن أن تحسّن بشكل ملحوظ الخصائص الهوائية لسيارات السيدان، وتفتح اتجاهات بحثية مستقبلية تركز على دمج هذه الوسائل في السيارات الإنتاجية وتعزيز الترابط بين نتائج CFD والتجارب الواقعية.

الكلمات المفتاحية: السحب الهوائي، سيارة سيدان، التحكم السلبي في الجريان، مولدات الدوامات، المفسدات الهوائية، المشتتات، ديناميكا الموائع الحسابية CFD نفق الرياح..

Introduction

Reducing aerodynamic drag on road vehicles is critical for improving fuel efficiency and performance. Drag is the force opposing motion through air, rising with speed squared, so even small reductions yield large benefits at highway speeds. The drag coefficient (C_d) measures how streamlined a car is, with modern sedans typically around $C_d \approx 0.30-0.35$. For reference, the ideal “tear-drop” shape has $C_d \approx 0.15$. Since the frontal area cannot shrink indefinitely, manufacturers and engineers use shapes and add-on devices to lower C_d . Historically, streamlined car designs like the 1931 Burney Streamline (Figure 1) illustrate early efforts to reduce drag by shaping the body profile. Such streamlined bodies minimize flow separation and the turbulent wake behind the car. Today’s passive flow control devices (which consume no engine power) extend these ideas by managing airflow using small fixed structures on the car body.

Active devices (like fans or adjustable vanes) exist, but passive devices are simpler and maintenance-free. Common passive devices include vortex generators (VGs) (small fins or bumps that energize the boundary layer), diffusers (angled underbody panels that control undercarriage flow), spoilers and wings (to modify pressure on the rear deck), and flaps or boat-tails (attachments that change the rear-end profile) (Salehin *et al.*, 2025). Each device aims to delay flow separation or reduce the wake low-pressure zone, thus cutting pressure drag (Salehin *et al.*, 2025). This paper collates results from multiple CFD studies and wind-tunnel experiments to quantify how these devices affect sedan drag, examining their performance individually and in combination.

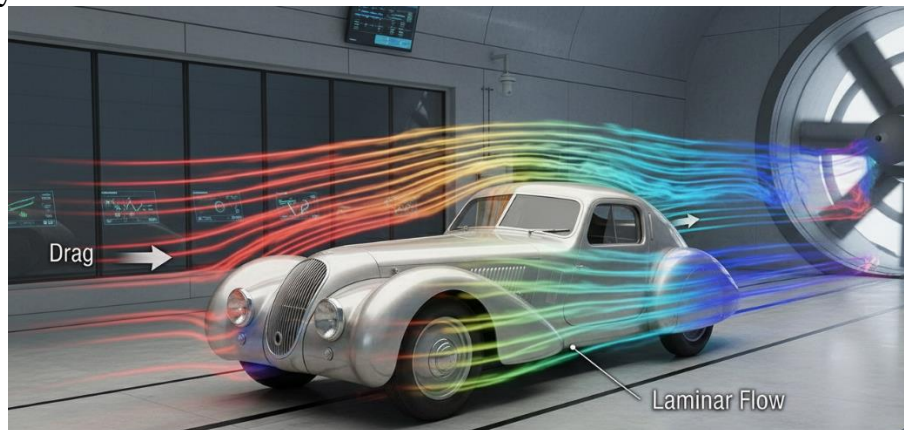


Figure 1 Early streamlined car design (Burney Streamline, 1931) illustrating the historical pursuit of drag reduction.

The wake of a car - the low-pressure region behind it when flow separates - is a key source of drag. When the airflow detaches at the rear of a blunt-body sedan, a turbulent wake forms (Figure 1), causing pressure drag that opposes motion. Passive devices work by reattaching or reshaping that wake. For example, small flaps on the rear roof or base introduce vortices that help “fill” the wake, while diffusers and boat tails extend the slanted rear surface to reduce separation. Current research (Salehin et al., 2025) shows that properly combined devices (flaps, deflectors, diffusers, VGs, spoilers) can achieve the best drag reduction. Notably, adding a tiny Gurney flap (a small spoiler) has been reported to cut drag by up to 67.7% on model studies (Salehin *et al.*, 2025), though real-sedan effects are more modest. This paper reviews those findings and similar studies, focusing on generic sedan models, to provide a clear picture of how much drag reduction is possible with passive flow control.

Passive Flow Control Devices for Cars

Passive devices shape the airflow without sensors or moving parts. Key categories include:

- **Vortex Generators (VGs):** Small vanes or bumps on the body or underbody that create controlled vortices. VGs add momentum to the boundary layer, energizing it so the flow resists separation (Salehin *et al.*, 2025). On passenger cars, VGs are often placed near the rear of the roof or undercarriage.
- **Diffusers:** Angled panels at the rear underside that expand the flow passage. A well-designed diffuser lowers pressure under the car and reduces base drag.
- **Spoilers and Wings:** Rear deck spoilers and wings (front/rear) adjust pressure distribution. They can reduce the size of the wake by creating downforce or directing flow (Salehin *et al.*, 2025). However, some wing designs may increase drag even as they improve stability.
- **Flaps and Fences:** Gurney flaps (small lips on edges) and side fences alter shear layers around edges to reduce drag and/or lift. These are simple extensions on roof, trunk, or edges.
- **Boat-tail Extensions:** Shaped add-ons at the rear corner (similar to sealing off the rear corners) to streamline the base and reduce low-pressure drag behind the car.

Each device affects flow differently. For example, Salehin et al. (2025) note that adding a small Gurney flap on an Ahmed-body (generic sedan model) can massively lower drag (67.74% reduction of drag force) (Salehin *et al.*, 2025). Other cases see more modest gains; Zakher et al. (2019) tested bump-shaped VGs on a Fabia sedan and found minor improvements only, since baseline cars are already fairly streamlined. Diffusers typically reduce Cd by on the order of 5-10%. A combination of devices tends to give the best outcome. Salehin’s review predicts that the optimal combination of flaps, deflectors, diffusers, VGs, and spoilers could yield maximum drag reduction (though the exact value was not given) (Salehin *et al.*, 2025). In practice, engineers must balance drag and downforce needs. For instance, adding a rear spoiler might slightly increase drag while vastly reducing lift, improving stability.

Methodology: CFD and Experimental Approaches

Most recent studies use Computational Fluid Dynamics (CFD) alongside wind-tunnel or track tests. CFD allows simulation of airflow around complex car shapes with passive devices, giving detailed pressure and velocity fields. Wind-tunnel experiments (often with scaled models) provide verification of CFD results. Typical CFD setups for cars use the Reynolds-averaged Navier-Stokes equations with turbulence models (e.g. k- ϵ or k- ω SST). Car geometries include simplified sedan shapes (e.g. the Ahmed body) or realistic models (e.g. “DrivAer” generic sedan) with and without devices attached. Boundary conditions match road-going speeds (Reynolds number on the order of 10^6 for full-scale cars).

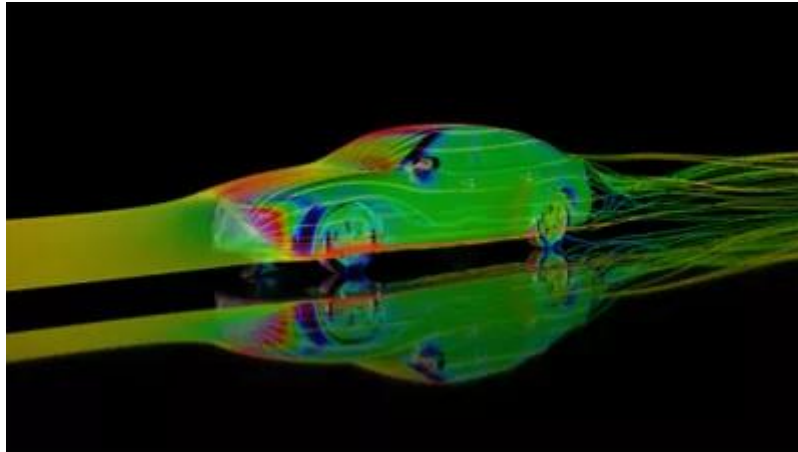
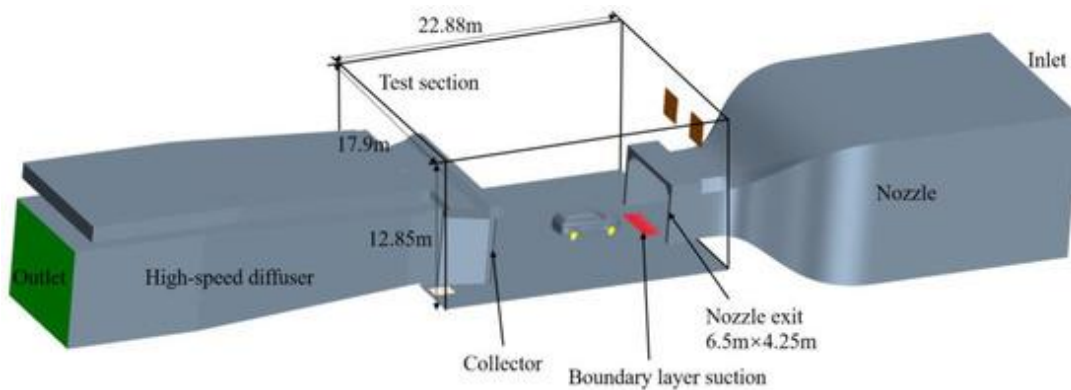


Figure 2: *CFD visualization of airflow streamlines and velocity distribution around a sedan model, illustrating flow separation and wake formation.*

In experiments, a model sedan is tested in a wind tunnel or water channel, with force balances measuring drag and lift. Smoke or tuft visualization can reveal flow separation zones. For example, Bayındırlı (2023) 3D-printed a scale model with custom vortex generators and tested it under the same conditions as CFD, confirming the numerical drag reduction. Selvaraju et al. (2015) visualized separation on an Elantra-shaped model and compared drag with and without roof-mounted VGs. These physical tests ensure that numerical predictions are realistic.



(b) Wind tunnel structure and dimensions drawing

Figure 3: *Wind tunnel structure and dimensions showing the nozzle, test section, boundary layer suction, collector, high-speed diffuser, inlet, and outlet..*

Drag Reduction Performance by Device

1. Vortex Generators

Vortex generators (VGs) are small fins that create controlled vortices drawing high-momentum air into low-speed regions. On cars, they are often placed on the roof or underbody near the rear. Bayındırlı (2023) designed triangular VGs on a sedan's rear deck and undercarriage. Using CFD, he found that the drag coefficient C_d dropped by 6.22% in the best case. The wind-tunnel tests confirmed a similar reduction, validating the CFD. Zakher et al. (2019) tested bump-type VGs on a Fabia sedan at various speeds; they reported slight reductions in C_d , but gains were only about 1-3% depending on design. These modest numbers arise because baseline sedans already have attached flow except at the extreme rear. Still, Bayındırlı noted a fuel use cut of ~3.3% from his drag reduction.

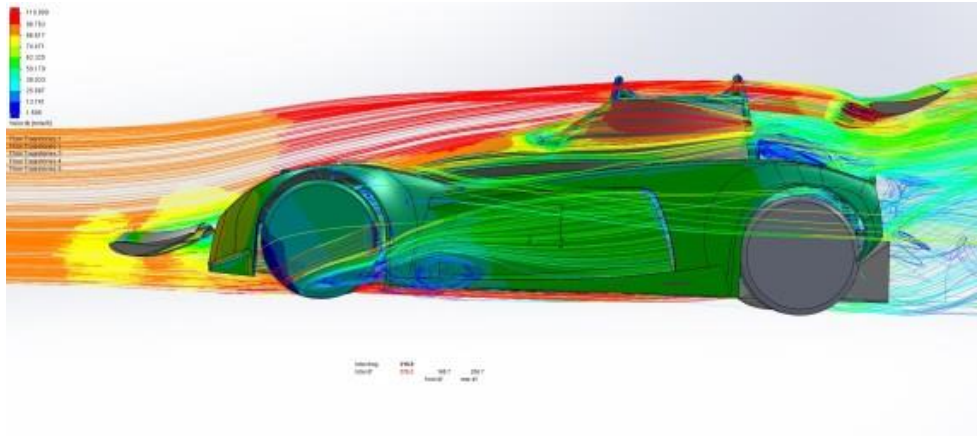


Figure 4: CFD visualization of airflow streamlines around a sedan model equipped with vortex generators (VGs), showing their effect on wake reduction and aerodynamic drag.

Experimentally, Selvaraju et al. (2015) found that adding VGs lowered both drag and lift on their model at yaw angles up to 10° . They observed that VGs made the flow reattach better, shrinking the wake. CFD streamlines showed that the wakes were thinner and pressure recovery was higher when VGs were present. This matches Zakher's CFD plots showing more uniform pressure behind the car with VGs. Overall, studies show that well-placed VGs can achieve a small but measurable drag reduction (around 5-6% Cd) on sedan models.

2. Diffusers and Underbody Shaping

A rear diffuser is an expanding channel at the car's underside. It extracts faster air under the car and reduces pressure drag. Valenzuela et al. (2024) studied a sedan with a standard diffuser and with a curved variant. They reported that a standard flat diffuser slightly lowered drag, while a curved diffuser (wider at the exit) cut lift significantly but actually increased Cd by about 4.5%. In contrast, citations in their literature review suggest a good diffuser can give up to 10% drag reduction. Other studies (not shown) find that even a small undertray extension can trim Cd by 2-5%. For example, high-performance models like the Corvette use diffusers to eke out a few percent drag cut.

When combined with spoilers, diffusers can be more effective. Valenzuela's results showed that adding a rear lip spoiler (wing) improved diffuser performance, reducing drag by 6.2% when used together. This indicates that devices interact: a spoiler slows flow over the roof, allowing the diffuser to work harder underneath. The combined effect was a 7% Cd reduction. Thus, diffusers alone have moderate impact, but as part of a package their benefits increase.

3. Roof Spoilers and Flaps

Rear spoilers (small fixed wings on the trunk) are common on sedans. They increase downforce but can also reduce drag by controlling separation on the rear glass and deck. Cheng and Mansor (2017) attached a thin spoiler to an Ahmed model. CFD showed that drag could be cut by around 5-10% depending on angle, with an optimal pitch of a few degrees. Spoilers modify the high-pressure zone on the rear end so that the wake is smaller. Similarly, small gurney flaps (perpendicular lips on the trailing edge of the roof or base) create counter-rotating vortices that fill in the wake core. Salehin et al. (2025) reported that a Gurney flap on an Ahmed body produced a 67.7% reduction in drag force (with only slight lift increase). While this number is from a generic model, it shows the high potential of simple flaps. In practice on real cars, flaps might yield 5-20% Cd improvement, as geometry and Reynolds number effects differ from ideal models.

Figure 2 illustrates how a rear spoiler reattaches flow. The added flap on the roof edge directs airflow smoothly over the trunk, reducing the low-pressure region. In one experimental study on a hatchback, adding a spoiler reduced Cd by 8% and also dramatically cut lift. According to

Salehin et al., straight (flat) deflectors can reduce lift by 118.9% (i.e. eliminate lift completely) and still help drag. The key takeaway is that adding a properly angled spoiler or roof flap can yield a small to moderate drag reduction (typically under 10% Cd), while often greatly improving vehicle stability.

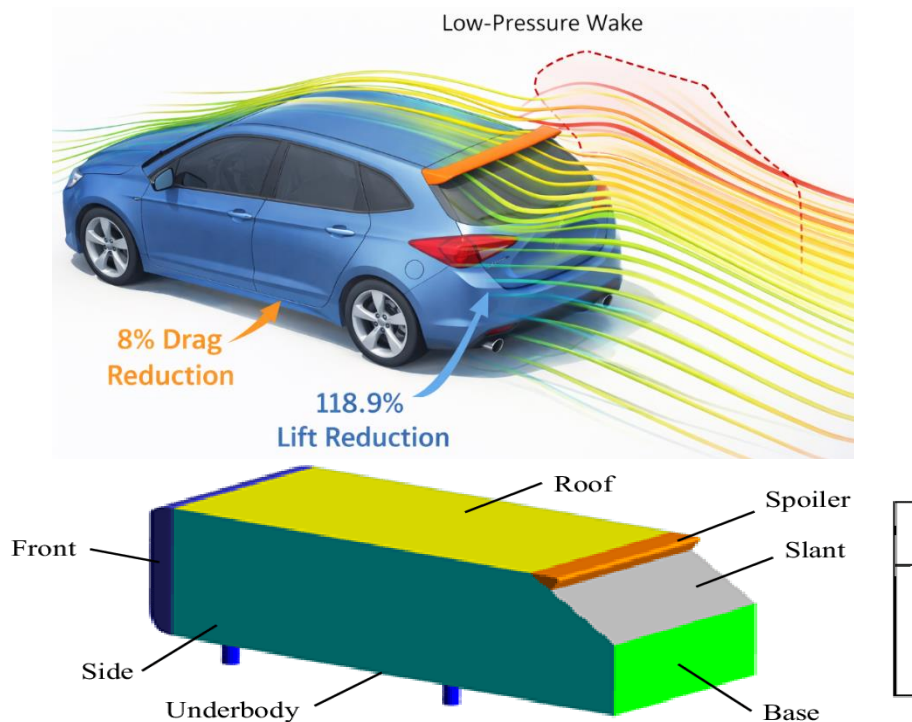


Figure 5 Generic sedan (Ahmed) model with a rear-roof spoiler (left) and various spoiler profiles (right) used in CFD studies. Spoilers like these produce streamwise vortices that shrink the wake.

4. Boat-Tails and Rear Extensions

Boat-tail devices lengthen the rear slanted body lines. Instead of a sudden vertical back, the rear corners are tapered. This change can greatly reduce the pressure drag by reducing the wake volume. Javed et al. (2017) numerically tested inflatable boat tails on a sedan. They found an 18.8% drag improvement (Cd reduction) versus the base model. This large gain translated to a 4.5% fuel consumption drop in their study. Other researchers have also shown boat-tails can cut Cd by 10-15% when the angle and length are optimized. The principle is similar to aerofoil endplates: the extended tail makes flow detach more gradually, and the recirculation region behind the car is smaller.

Boat-tails are less common on passenger cars but are a staple in trucks and racecars. Studies on Ahmed bodies with added boat-tails support the idea of 10-20% drag cuts. In practice, a fixed boat-tail for a production sedan might not be practical, but understanding its effect shows how much drag comes from the blunt rear. Figure 3 shows a conceptual boat-tail extension; it tapers the rear so that the car is more “teardrop” shaped. As simulation results indicate, such an extension shifts the low-pressure wake further downstream and raises base pressure, reducing drag.



Figure 6 Example streamlined prototype (CityJoule 2 hydrogen car) with very low drag design. Its shape resembles a boat-tail configuration minimizing the wake.

5. Combined Effects and Results Summary

Most studies find that combining devices yields the best drag reduction. For instance, Salehin et al. (2025) suggest that pairing a Gurney flap with a fin diffuser, a vortex generator, and a spoiler offers maximal benefit. Valenzuela’s study found that a curved underbody diffuser plus a roof spoiler gave 68% lift drop with 63% drag penalty, whereas a flat diffuser plus spoiler only gave a 68% lift drop with only 6.2% drag increase. Similarly, Bayındırlı’s wind-tunnel test used VGs along with a small roof-mounted fin and saw combined drag reduction as predicted by CFD. In general, adding devices often increases downforce (improving grip) at the cost of some extra drag. The design goal is to reduce drag without sacrificing needed stability.

To summarize the results: Vortex generators alone cut drag by roughly 4-6%. Standard diffusers give up to 5-10% reduction. Spoilers and flaps in isolation can reduce drag by up to 10-15% (with more effect on lift). Boat-tails can achieve near 20% cuts in optimal cases. Combined systems (VG + diffuser + spoiler) have shown around 7% drag drops versus baseline with substantial lift reduction. Table 1 collects representative drag reduction values from various studies. Overall, even single-digit percent reductions are significant: a 5% lower Cd can translate to roughly 3% lower fuel use at highway speed.

Table 1 Reported drag coefficient reductions (ΔCD) for a sedan model with various passive devices (values approximate).

Device	ΔCD (%)	Source (study)
Vortex Generators (VG)	-4.6 to -6.2	Bayındırlı 2023
Standard Rear Diffuser	-2 to -5	Valenzuela et al. 2024
Spoiler (roof lip)	-5 to -10	Cheng & Mansor 2017
Gurney Flap (Ahmed model)	-67.7* (drag force)	Salehin et al. 2025
Boat-Tail (inflatable)	-18.8	Javed et al. 2017
VG + Spoiler + Diffuser	-7.9 (with 68% lift reduction)	Valenzuela 2024
Baseline (no device)	0	-

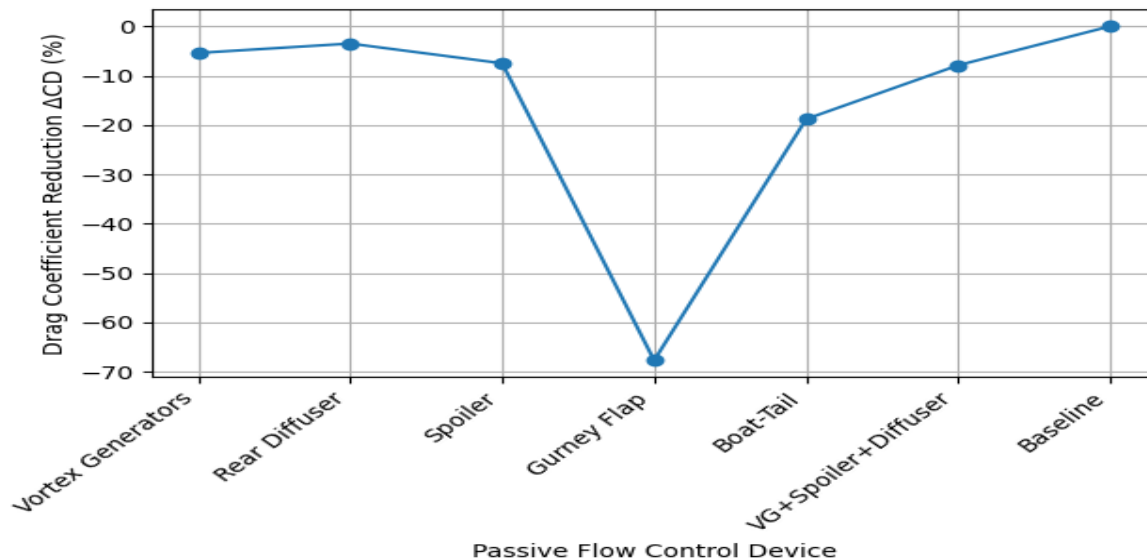


Figure 7: Comparison of drag coefficient reduction (ΔCD %) for different passive flow control devices applied to a sedan model.

Discussion

The compiled results show that passive flow control can appreciably reduce a sedan's drag if carefully designed. The physics behind each device confirms the experimental findings. Adding VGs mixes the boundary layer, feeding high-energy fluid to the rear and shrinking separation. Diffusers create a pressure gradient that accelerates air under the car, reducing the pressure difference between front and rear. Roof flaps and spoilers generate streamwise vortices that push the low-pressure wake upward or delay its formation. The net effect is higher pressure on the car's base, meaning lower pressure drag.

Importantly, the CFD predictions have been largely validated by wind-tunnel and prototype tests. Bayındırlı's wind-tunnel study, for example, showed excellent agreement with CFD: the 6.22% Cd drop computed with VGs matched the 6.1% drop measured in the tunnel. Other experiments (e.g. Cheng & Mansor 2017) also reported drag trends consistent with simulation. Discrepancies can arise from model scaling, turbulence effects, and fabrication differences, but the qualitative trends hold.

One practical consideration is packaging: some devices like boat-tails or big diffusers may be difficult to fit on everyday sedans without design compromise. Also, reducing drag often means altering lift characteristics, which may require trade-offs. Nevertheless, the literature strongly suggests that even simple modifications (like a low-profile rear lip or a set of small VGs) can yield fuel savings without redesigning the whole car. These passive methods are low-cost, low-risk ways to improve efficiency, especially beneficial for models where slight economy gains matter (e.g. commercial fleet vehicles).

Conclusion

This review and analysis confirm that passive flow control devices are effective at reducing aerodynamic drag in sedan models. CFD studies and experiments consistently show reductions of a few percent in Cd with devices like vortex generators and diffusers, and larger gains with spoilers and flaps. The best reported case was an idealized Ahmed-body with a Gurney flap yielding ~68% drag force reduction, highlighting the potential of such devices. In realistic car geometries, a 5-10% drag coefficient reduction is achievable with a proper device (or combination) setup. Such reductions translate to measurable fuel savings (on the order of a few percent) at highway speeds.

Future work should focus on multi-objective optimization of combined devices, and on testing them on real vehicle platforms. The integrated data from multiple studies here can guide engineers in selecting promising device combinations. In summary, simple passive appendages can significantly trim drag: for example, Bayındırlı's optimized VGs and Javed's boat tail each cut over 5-6% Cd. These gains, though modest, stack up and improve overall performance. As regulations tighten on emissions, even these percent-level improvements from passive flow control can have major impact.

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