Proceedings

ATZ live

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2024 Stuttgart International Symposium on Automotive and Engine Technology

Teil 1

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Proceedings

Ein stetig steigender Fundus an Informationen ist heute notwendig, um die immer komplexer werdende Technik heutiger Kraftfahrzeuge zu verstehen. Funktionen, Arbeitsweise, Komponenten und Systeme entwickeln sich rasant. In immer schnelleren Zyklen verbreitet sich aktuelles Wissen gerade aus Konferenzen, Tagungen und Symposien in die Fachwelt. Den raschen Zugriff auf diese Informationen bietet diese Reihe Proceedings, die sich zur Aufgabe gestellt hat, das zum Verständnis topaktueller Technik rund um das Automobil erforderliche spezielle Wissen in der Systematik aus Konferenzen und Tagungen zusammen zu stellen und als Buch in Springer.com wie auch elektronisch in Springer Link und Springer Professional bereit zu stellen. Die Reihe wendet sich an Fahrzeug- und Motoreningenieure sowie Studierende, die aktuelles Fachwissen im Zusammenhang mit Fragestellungen ihres Arbeitsfeldes suchen. Professoren und Dozenten an Universitäten und Hochschulen mit Schwerpunkt Kraftfahrzeug- und Motorentechnik finden hier die Zusammenstellung von Veranstaltungen, die sie selber nicht besuchen konnten. Gutachtern, Forschern und Entwicklungsingenieuren in der Automobil- und Zulieferindustrie sowie Dienstleistern können die Proceedings wertvolle Antworten auf topaktuelle Fragen geben.

Today, a steadily growing store of information is called for in order to understand the increasingly complex technologies used in modern automobiles. Functions, modes of operation, components and systems are rapidly evolving, while at the same time the latest expertise is disseminated directly from conferences, congresses and symposia to the professional world in ever-faster cycles. This series of proceedings offers rapid access to this information, gathering the specific knowledge needed to keep up with cutting-edge advances in automotive technologies, employing the same systematic approach used at conferences and congresses and presenting it in print (available at Springer.com) and electronic (at Springer Link and Springer Professional) formats. The series addresses the needs of automotive engineers, motor design engineers and students looking for the latest expertise in connection with key questions in their field, while professors and instructors working in the areas of automotive and motor design engineering will also find summaries of industry events they weren't able to attend. The proceedings also offer valuable answers to the topical questions that concern assessors, researchers and developmental engineers in the automotive and supplier industry, as well as service providers.

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Vorwort zum Tagungsband des 2024 Stuttgart International Symposium

Der Bedarf an Mobilität wird mit wachsender Weltbevölkerung auch weiterhin steigen. Dies stellt uns aktuell vor große Herausforderungen angefangen bei der Nachfrage nach individuellen und regional sehr unterschiedlichen Mobilitätslösungen, über Ressourcenknappheit bis hin zu den von den Regierungen, weltweit festgelegten, zu erfüllenden Klimazielen.

Unter dem diesjährigen Leitthema „Global Mobility for Tomorrow“ präsentierten Experten aus Wissenschaft und Wirtschaft auf dem 2024 Stuttgart International Symposium neue, innovative Ansätze in der Fahrzeugentwicklung. Dabei wurde deutlich, dass der Fokus weg vom Produkt allein, hin zu Infrastruktur, Digitalisierung und Energieerzeugung erweitert werden und dass Mobilität zukünftig als Gesamtkette betrachtet werden muss. Globale Mobilität kann nur mit Hilfe von Technologieoffenheit, Vernetzung, Digitalisierung an individuelle Kundenwünsche angepasst und nachhaltig gestaltet werden.

Autonomes Fahren, Elektro- und Hybridantriebe, Nachhaltige Kraftstoffe, Kreislauf- und Lebenszyklusanalyse, Aerodynamik, Thermomanagement, sowie Cyber Security sind nur einige der Fachgebiete, zu denen auf dem Stuttgart International Symposium vom 2. bis 3. Juli 2024 im Haus der Wirtschaft, Stuttgart diskutiert wurde. Die entsprechenden Manuskripte zu ca. 45 Vorträgen und 10 Postern finden Sie nun in dieser Ausgabe.

Preface to the Proceedings of the 2024 Stuttgart International Symposium

The need for mobility will continue to increase as the world's population grows. This currently presents us with major challenges, from the demand for individual and regionally very different mobility solutions, to resource scarcity and the climate targets set by governments worldwide that are to be met.

Under this year's guiding theme of "Global Mobility for Tomorrow", experts from science and industry presented new, innovative approaches to vehicle development at the 2024 Stuttgart International Symposium. It became clear that the focus must be expanded away from the product alone and towards infrastructure, digitalization and energy generation, and that mobility must be viewed as an overall chain in the future. Global mobility can only be adapted to individual customer requirements and designed sustainably with the help of technological openness, networking and digitalization.

Autonomous driving, electric and hybrid powertrains, sustainable fuels, circularity and life cycle analysis, aerodynamics, thermal management and cyber security are just some of the specialist areas that were discussed at the Stuttgart International Symposium at the Haus der Wirtschaft in Stuttgart from July 2 to 3, 2024. The corresponding manuscripts of approx. 45 presentations and 10 posters can now be found in this issue.

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Aerodynamics

Macan Goes BEV. Aerodynamics of the First All-Electric Porsche SUV

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Abstract. How does one take the Porsche model that has been the top-seller six times since 2015 and transition it into the e-mobility era? How does one combine its classic Porsche themes – its quintessential design language and track suitability – with modern customer demands like range and consumption? How does one reduce drag by 30% while retaining the identity of the vehicle? Or to frame the question differently: what were the aerodynamic challenges of the new Porsche Macan, the brand's first all-electric SUV with the least drag?

The aerodynamics of the electric Macan were designed using state-of-the-art tools. The basic shape of the vehicle was defined and optimised in a scale model wind tunnel. In a state-of-the-art, full-scale aeroacoustic wind tunnel, further refinements to the vehicle shell and other technical details were made right down to the start of production in collaboration with the designers.

Simultaneous to the measurements in the wind tunnels, the entire aerodynamic development process was supported by detailed flow simulations (CFD).

The aerodynamic improvements and technical measures implemented reduce the drag coefficient by delta $c_D = -0.10$ from the previous value of $c_D = 0.35$ to $c_D = 0.25$. This corresponds to an increase in range of around 85 km in the standardised fuel consumption cycle for Europe (WLTP).

Development of the basic form focused on the roofline, which drops off coupé-like by way of the rear window. The rear section is capped by the active rear spoiler which, in combination with the flaps of the fully closable air intake in the front of the vehicle, makes it possible to have both efficient, range-orientated travel as well as sporty, performance-focused driving.

Other major contributors to reducing drag include the aerodynamically optimised wheels and tyres and the largely closed underbody with its flexible suspension fairings.

Keywords: Retaining classic Porsche themes · Reducing drag by 30 percent

1 Introduction

The first-generation Porsche Macan (see figure 1) has been a success story for the company ever since its world premiere at Petree Hall in Los Angeles on 20 November 2013. Through 2023, a total of 835,235 units of the first generation as well as its facelifts were delivered to customers. During this period, it was the highest-selling Porsche vehicle six

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times over [1]. The classic Porsche disciplines of design identity and track suitability were perfectly harmonised in the brand's first compact SUV as well. The first Macan exemplified both everyday utility and sportiness.

Fig. 1. First-generation Porsche Macan [2]

New customer demands and the desire for e-mobility give rise to new challenges for vehicle manufacturers.

Electric range and consumption as well as fast charging times provide a focal point and motivation in the development of efficiency-enhancing measures for drivers. The technical discipline of aerodynamics plays a major role here. Reductions in the drag coefficient c_D and the vehicle frontal area A_X influence consumption in the standardised driving cycle WLTP (Worldwide harmonized Light vehicles Test Prozedure) by approximately 39% (see Fig. 2). This proportion increases as the vehicle speed increases.

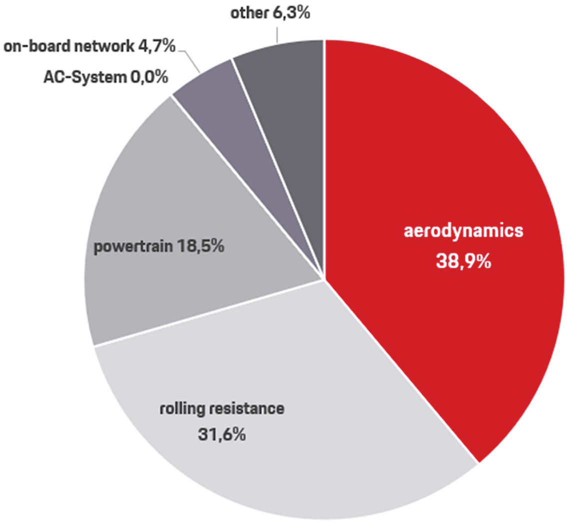

Fig. 2. Energy flow analysis for traction consumption for the new Macan Base 4 in the WLTP cycle [3]

Even an exclusively battery-powered Porsche still demands to be best-in-class in terms of driving performance. This exacting standard means that certain targets, such as achieving axle lift values and the required cooling capacity for the brakes, are not only very important, they are requirements which a typical Porsche vehicle simply must meet.

Providing the appropriate battery cooling capacity when stationary during fast charging as well as keeping the side window and exterior mirror free of water soiling while driving are further essential aspects of aerodynamics development at Porsche.

The drag coefficient target value was defined based on the battery capacity, electric power, electrical consumption and target range. The major challenge was to reduce the drag of the all-electric Macan by Δ $c_D = 0.10$ – compared to its predecessor – to $c_D = 0.25$, while retaining the classic Porsche performance characteristics and design identity (Table 1).

Table 1. Technical data, aerodynamics of the Porsche Macan Turbo in the Eco and Perfo vehicle configurations

	Eco	Perfo
c_D [-]	**0.25**	0.28
c_{LF} [-]	0.05	**0.10**
c_{LR} [-]	0.08	**0.02**
A_X [m2]	2.68	2.68

Further technical data

The vehicle was developed on the Premium Platform Electric (PPE41) used jointly with Audi. A 100 kWh lithium-ion performance battery powers the 800-volt architecture already used in the Taycan, which enables charging capacities of up to 270 kW. Two permanent magnet synchronous motors of the latest generation with up to 470 kW of overboost power[1] propel the high-performance and rear-dominated all-wheel drive via a 1-speed gearbox (Table 2).

2 Development tools

Principally, the following tools were used during the aerodynamic development of the new Macan:

- Model wind tunnel with one-third scale vehicle models
- Aerodynamics and aeroacoustics wind tunnel with full-scale models and real vehicles
- Computational Fluid Dynamics (CFD) software

[1] With Launch Control. Details on the measurement procedure for specified values at www.porsche.com/gtr21.

Table 2. Further relevant technical data for the Porsche Macan Base and Turbo [4]

	Base	**Turbo**
Power output [kW]	285	430
Acceleration 0–100 km/h [s]	5.2	3.3
Top speed [km/h]	220	260
Range combined (WLTP) [km]	516–613	518–591
Electric power consumption combined (WLTP) [kWh/100 km]	21.1–17.9	20.7–18.8
Length [mm]	4,784	4,784
Width [mm]	1938	1938
Height [mm]	1622	1621
Wheelbase [mm]	2893	2893
Wheel sizes ["]	20–22	20–22
Tyre widths FA [mm]	235–255	235–255
Tyre widths RA [mm]	285–295	285–295
DIN unladen weight [kg]	2330	2405
Permissible gross weight [kg]	2920	2950
Max. trailer load (braked) [kg]	2000	2000
Max. wading depth air suspension (normal level) [mm]	300	300
Max. ground clearance air suspension (normal level) [mm]	185	184
Open luggage compartment volume (upper edge of rear seats) [L]	540	480

In addition to these methods, continual checks and comparisons of different geometry data sets in 2D were carried out. The ranges for preventing rainwater soiling on the side windows and exterior mirrors were developed in the thermal wind tunnel of the Research Institute for Automotive Engineering and Powertrain Systems (FKFS) on full-scale models and real vehicles. Furthermore, interdisciplinary tests (e.g. vehicle dynamics protection or brake cooling) were carried out on various international test tracks configured for the respective test cases. The test managers and test drivers were supported by the expertise of the aerodynamics engineers.

In the early phase of the project, several one-third scale aerodynamics models were built (see Fig. 3). The outer shell of the non-flow-through models were made entirely of industrial plasticine (also known as “clay”). Rotating wheels were mounted on simplified axle structures. During the model phase of the Macan, two main topics were addressed. Aerodynamics potential analyses provided the designers with the most important information for creating a very good basic aerodynamic shape. Aerodynamics evaluations of the different designs were also conducted in the model wind tunnel.

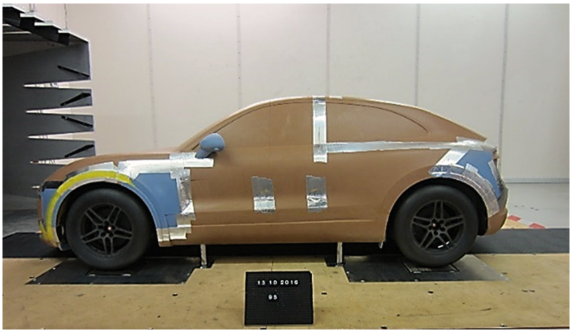

Fig. 3. One-third scale aerodynamics model of the Macan

After the shape was determined, the modular full-scale aerodynamics model was built. In combination with the state-of-the-art aeroacoustics wind tunnel, it is the most precise and therefore most important development tool in aerodynamics. The aerodynamics engineers continued to use it until the project is ready for series production. As with the one-third scale model, the initial design was done in clay. The design of the cooling air path was taken into account from the outset, which included installing prototype heat exchangers with pressure measurement technology for evaluating and optimising the cooling capacity. The model was fully modular and had standard running gear including wheels and brakes. Over the course of development, as the outer skin geometries became more and more concrete, several material changes and modifications took place. The final configuration of the aerodynamics model was equipped with components from series production tools (see Fig. 4). Due to the high level of detail and the variability of the model, non-specialist topics such as component strength and wiper contact pressure were also analysed and optimised in addition to the conventional aerodynamics development. The final stage of a project's wind tunnel measurements involves classification-relevant measurements on various pre-series vehicles (variants).

Virtual development methods are becoming increasingly influential in vehicle development at Porsche. Flow simulation software (CFD) was used throughout the aerodynamic development process as a parallel supporting tool for the measurements in the wind tunnels. The big advantage of this method compared to experiments is the visualisation of the relevant physical variables (pressure and speed) in the flow field and on the vehicle surface. This makes it possible to carry out targeted, local geometry optimisations. Virtual parameter studies significantly reduced the variety of variants and thus the number of prototype components required for many development topics in preparation for the wind tunnel tests. CFD was used in Macan development both to optimise the vehicle outer skin (see example illustration in Fig. 5) and to design the cooling air path for the provision of cooling capacity for the battery, power units, air conditioning, and brake cooling.

Fig. 4. Evolution of modular aerodynamics model (from left: clay, hard foam, series components)

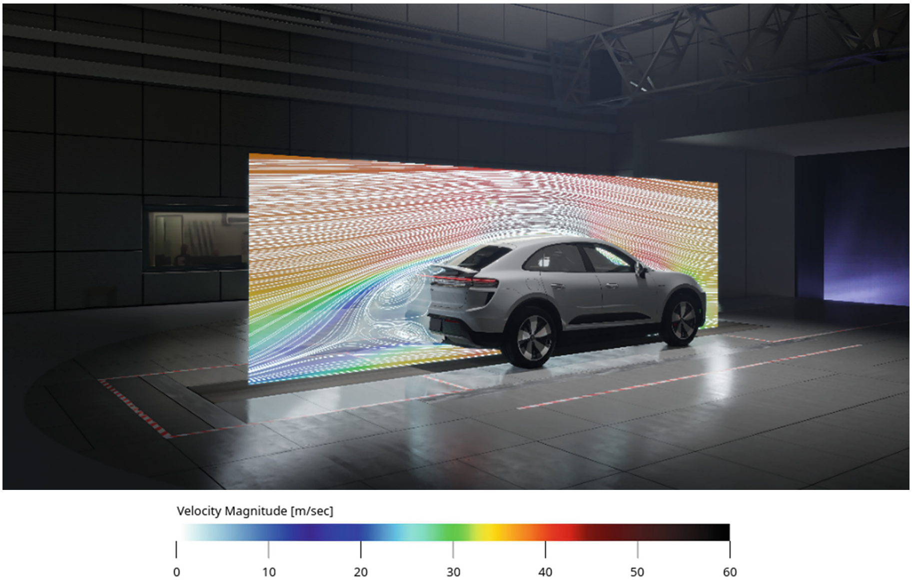

Fig. 5. CFD – flow field at y = 0 mm, coloured with velocity magnitude

Figure 6 shows a typical qualitative distribution of the aerodynamic development ranges depending on the development phase.

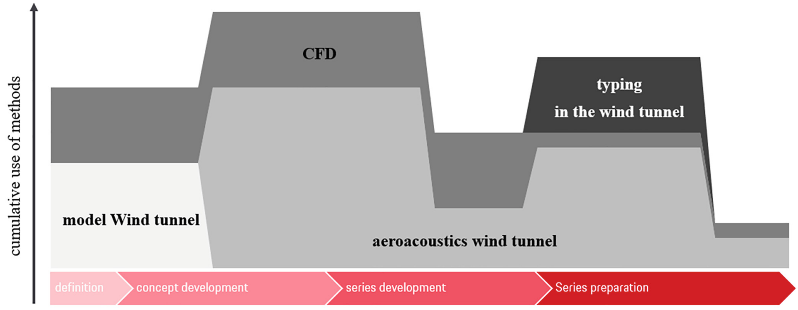

Fig. 6. Method requirements depending on the project phase

3 Aerodynamics Challenges

The transition from combustion engines to electric motors significantly increases the proportion of aerodynamic drag in the overall air resistance. The higher the average speed, the greater the drag due to aerodynamics.

The overall goal of aerodynamics development throughout the project was to reduce the drag by Δ $c_D = 0.1$ compared to its predecessor. The specific target: $c_D = 0.25$.

The overarching aerodynamics concept for achieving this target included four optimisation focus areas: basic shape, wheels, cooling and underbody (see Fig. 7).

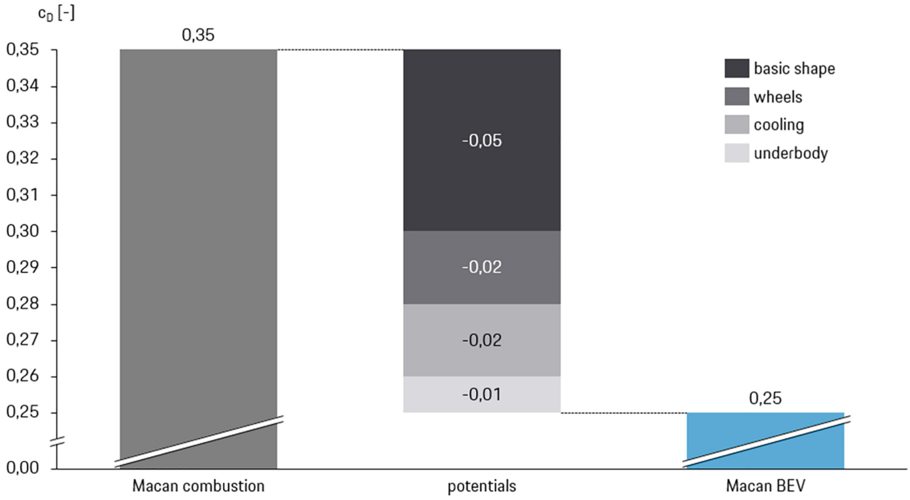

Fig. 7. Aerodynamics concept

3.1 Challenge: Basic Shape

The most efficient measures are basic shape optimisations. They have a permanent effect in the entire speed range, add no additional weight and do not require any additional electrical energy. The challenge is to implement $\Delta\ c_D = -0.05$ in the outer skin of the vehicle while preserving the quintessential design features of the Porsche Design DNA (e.g. strongly flared fenders).

Roofline

Conventional passenger vehicles belong to the aerodynamic category of "blunt bodies". This means that the aerodynamic drag of these vehicles is dominated by pressure drag [5]. The primary area where this drag can be reduced is at the rear of the vehicle. The lower and further back the position of flow separation is in the stream of air over the vehicle, the higher the potential for a low c_D. In other words, the flatter the rear window, the greater the potential (see Fig. 8).

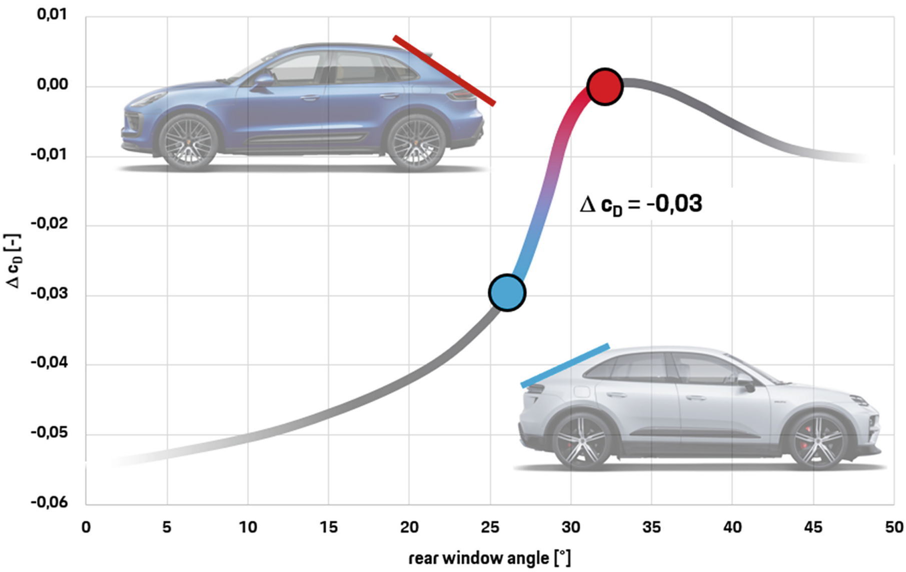

Fig. 8. c_D impact of the rear window angle, comparing the first-generation Macan with the Macan BEV

In terms of the rear windscreen angle, the combustion-powered Macan (approximately 31°) has great aerodynamic potential.

An "aero styling process" was established, with numerous joint optimisation loops in both the model and full-scale wind tunnels and regular coordination rounds with other departments important to this topic (including package and bodywork). The result was a significant change in the shape of the rear of the vehicle. The new Macan has a coupé-style rear with a rear window angle of approximately 26°. The roof frame and the transition from the roof to the rear window are free of components that influence the airflow, so the air can flow freely over the entire vehicle.

An active rear spoiler forms the rear end. This classic Porsche component allows various aerodynamic configurations to be set, depending on the driving conditions (see Sect. 4).

The change in the roofline including the implementation of the spoiler has a potential of $\Delta\ c_D = 0.035$. This measure amounts to 70% of the total basic shape potential.

Vehicle layout

In addition to the roofline, the layout of the vehicle is also very important for its aerodynamics. In particular, the shape of the areas in front of the front axle (front end sweep) and behind the rear axle (rear tapering) has a significant impact on aerodynamic drag. Compared to its predecessor, the new Macan is 6 millimeter wider at the front axle and 14 mm wider at the rear axle. Wider body sections at the axles have the effect of increasing the c_D. The aim was to aerodynamically optimise the front end sweep and rear tapering and to compensate for the widened sections (see Fig. 9, left).

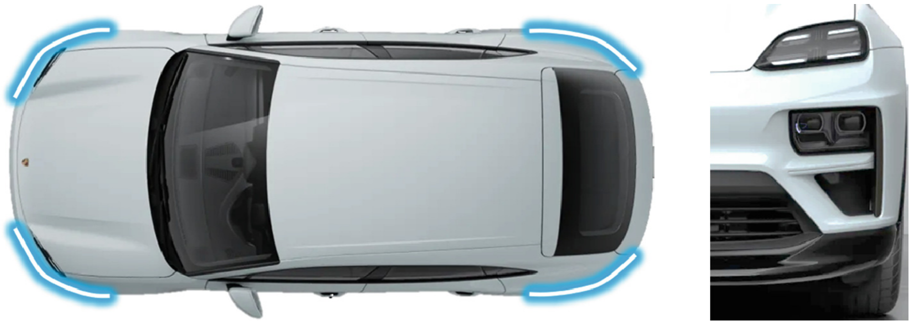

Fig. 9. Left: Vehicle layout optimisation areas, right: lateral front end with two-part headlights [2]

Most variants of the first-generation Macan have lateral radiators and air guides. These package specifications in the Y-dimension chain mean that the front ends are overhanging and cambered. This ensures good airflow in the direction of the wheel arches. The Macan BEV has no heat exchangers/air guides on the sides. The only larger component that dominates the package in this area is part of the two-part headlight (see Fig. 9, right).

A combination of two measures was necessary to ensure the target potential $\Delta\ C_d = -0.01$. An equally strong camber, including an "airblade" at the leading edge, creates good flow around the front end in the direction of the wheels. In addition, a channel for the "air curtain" has been implemented in the luggage space next to and below the headlight. This guides part of the oncoming air flow along the inside of the front end and feeds it back into the airflow around the vehicle almost tangentially past the tyre at the side of the wheel arch. This concept aids flow around the front end and wheel housing (see Fig. 10).

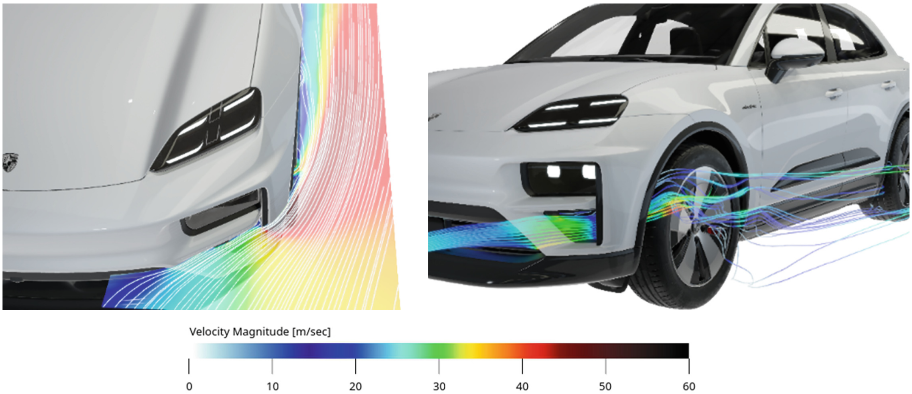

Fig. 10. CFD result – left: Front end bypass, right: air curtain concept

For cars in general, a wider rear end with defined tear-off edges is more favourable in terms of aerodynamic drag than a round, strongly tapered rear end. Defined tear-off edges increase the rear base pressure and avoid the risk of suction peaks.

As in the predecessor Macan, the characteristic Porsche rear layout is more rounded. The body is also 14 mm wider at the rear axle. The goal of aerodynamic optimisation in the area of the rear tapering was $\Delta\ c_D = -0.005$. The target capability was confirmed by the implementation of a tear-off edge (aero-edge) in the upper area of the side of the rear (see Fig. 11).

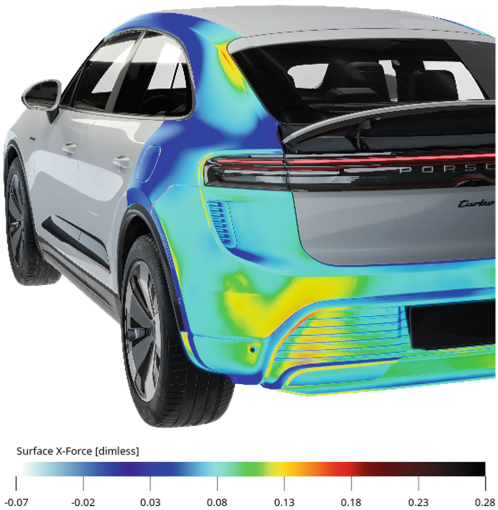

Fig. 11. CFD result – Macan BEV rear section, coloured to show resulting air forces against the direction of travel

Figure 11 clearly shows that, behind the tear-off edge, there are lower forces moving against the direction of travel than in the lower, relatively round area.

3.2 Challenge: Wheels

A comparison between the standard wheels of the ICE and battery-electric Macan (see Table 3) illustrates the challenge of reducing the wheel programme by delta $c_D = -0.02$ compared to predecessor.

Table 3. Size comparison for standard wheels of the different Macan generations

	Macan I PA	New Macan
Wheel size	**18"**	**20"**
Tyre width FA [mm]	235	235
Tyre width RA [mm]	255	285

The new standard wheels are 2 inch larger and 30 mm wider on the rear axle. In order to turn these fundamental aerodynamic disadvantages into advantages, alterations must be made to the rims and tyres [6].

In addition to the three standard wheels (Base, S and Turbo), three 21-inch and four 22-inch wheel designs are available as equipment variants.

Rims

The aim of rim optimisation is to optimise all standard rims plus at least one additional rim in both the 21 and 22-inch sizes. This ensures that there is an efficient wheel in every wheel size. Figure 12 shows a diagram of the measures for implementing aerodynamically optimised rims.

Fig. 12. Aerodynamic rim optimisation

To lower the C_d value, the rims were designed with large and flat spokes. Furthermore, there was a closed ring extending radially inwards from the rim flange (outlined in red in Fig. 12) to prevent the very sensitive interaction of the air with the rapidly rotating outer spoke areas. Some of the measures were combined, but on most rims, they were implemented individually.

Tyres

The greatest aerodynamic potential is in the tyre sidewall area. From an aerodynamics standpoint, very pronounced and tapered rim protection edges should be avoided. In addition, the rim/tyre overlap should be minimal. In the new Macan, the distinctive rim protection edges were softened/replaced by larger radii. The rim/tyre overlap was handled either by adapting the tyres or widening the rim flange on a case by case basis.

The result of wheel optimisation is a significant reduction in the.c_D spectrum over the entire wheel range ($\Delta\ c_D = -0.015$). The standard wheel range covers the entire spectrum between performance (track suitability) and efficiency (travelling) (see Fig. 13).

Fig. 13. Efficiency-performance spectrum of the wheel range

3.3 Challenge: Cooling

The cooling requirements for an all-electric vehicle are significantly lower than for a car with a combustion engine. The total air intake cross-section required for engine and brake cooling in the new Macan is approximately 50 percent less than for its predecessor. The air guides for the cooling air of both systems are located in the central air intake. Cooling air flaps regulate the air mass flow as required (see Fig 14).

Power unit cooling

The centrally arranged cooling module (platform component PPE41) consists of two heat exchangers arranged one behind the other (NT cooler in front of condenser) with a mono fan behind.

Due to the fully closable air intake and the low cooling requirements typical of BEVs, there is virtually no front end flow-through in most driving conditions. Thus, there are no negative effects on drag. In driving situations with opened flaps (e.g. at $v \geq 160$ km/h

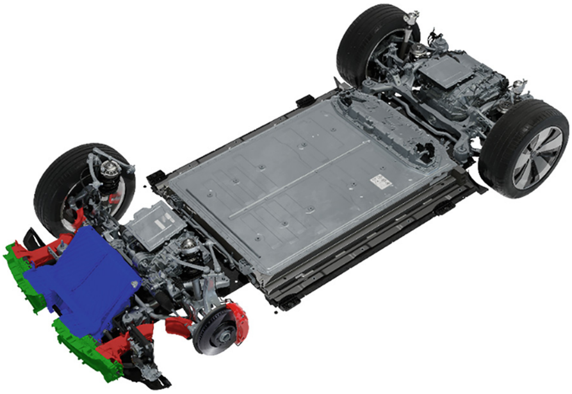

Fig. 14. Package of different cooling air paths: power unit cooling (blue), brake cooling (red)

or at high ambient temperatures), the c_D increase or the efficiency effects should nevertheless be as low as possible. As a result, the cooling air path, which also largely consists of platform components of the PPE41, has been aerodynamically optimised in cooperation with Audi. Both a supply air duct coming from the front end and an exhaust air duct connected to the underbody panelling are mounted on the aforementioned cooling module. The cooling air is channelled from the air inlet in the front end through the cooling module in a sort of capsule and then directed tangentially into the underbody flow (see Fig. 15).

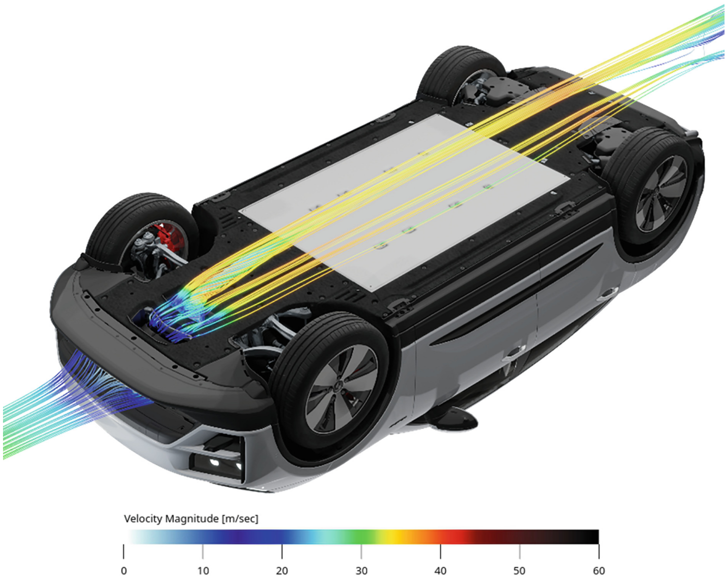

Fig. 15. Cooling air path

The drag generated by the cooling air is only $\Delta\ c_{D,C} = 0.015$.

Brake cooling

A Porsche must be Suitable for circuits regardless of vehicle segment and powertrain type. The brake discs must be supplied with the corresponding cooling capacity. The task of the Aerodynamics unit is to develop a concept together with the Chassis, Body and Package units to ensure the specified brake cooling time. The target concept was designed completely virtually and confirmed repeatedly on the test track.

In the new Macan, the permanently open brake air duct was moved from the underbody into the front end, behind the cooling air flaps (similar to in the Taycan) in the lateral air inlet areas. The brake cooling air flows through the duct into the wheel arch and from there is guided by the brake air spoiler attached to the chassis in the direction of the brake bell (see Fig. 16).

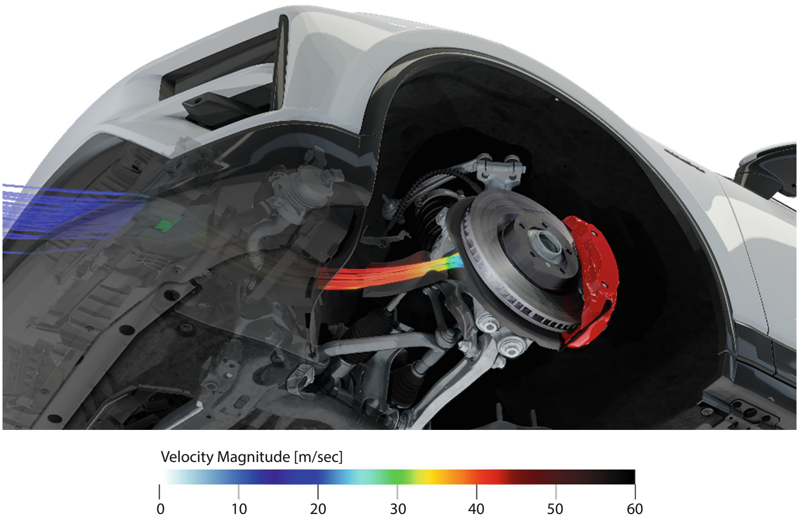

Fig. 16. Brake cooling illustration

This concept provides cooling capacity in line with requirements, much like the power unit cooling. The aerodynamic effect is $\Delta\ c_{D,BC} = +0.003$.

3.4 Challenge: Underbody

All-electric vehicles do not have any particularly hot components (exhaust system, muffler or gearbox) in the underbody area. There is no need to leave large areas of the underbody open for cooling reasons. Because the battery, including the protective panelling, is located between the axles, a large area in the centre of the vehicle is already closed. The challenge was to cover all other adjacent areas of the underbody (front and rear axle panelling, side areas toward the door sill and chassis parts) as extensively and smoothly as possible. The transitions between the panels are almost tangential and free of interfering edges or recesses (see Fig. 17).