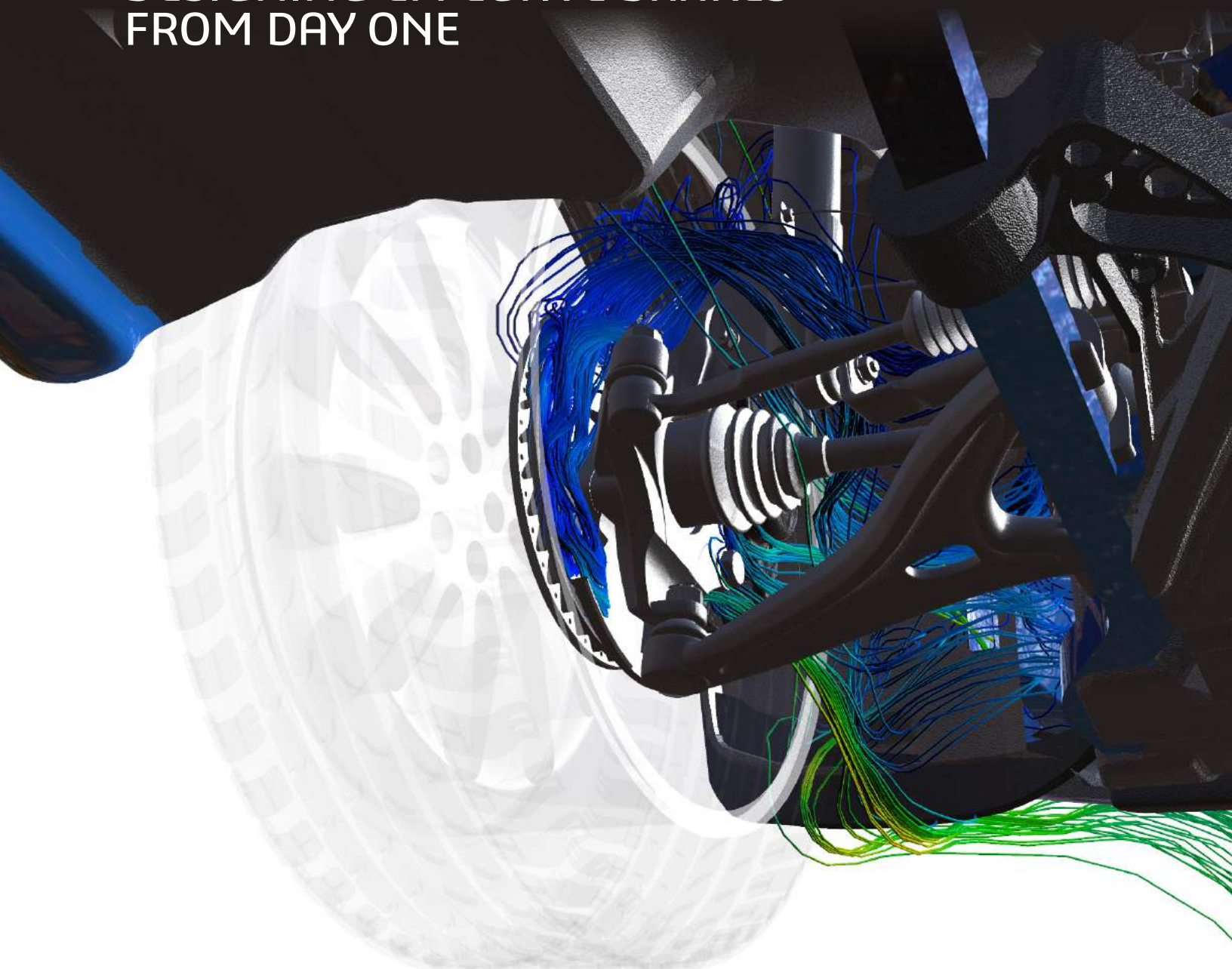




PUT THE BRAKES ON LATE-STAGE FAILURES: DESIGNING EFFECTIVE BRAKES FROM DAY ONE



PUT THE BRAKES ON LATE-STAGE FAILURES:

Designing Effective Brakes from Day One

EXECUTIVE SUMMARY

Brake systems are critical for the safe operation of a vehicle. The braking system is an essential part of a vehicle's design that needs to be verified for dependability, reliability, and performance – especially under extreme conditions. Overheating can cause a decline in brake disc performance or even complete failure: both of which introduce unacceptable risks to drivers, passengers, and others nearby.

Traditionally, prototype vehicle testing evaluates the effectiveness of brake cooling mechanisms. Brake cooling relies on airflow directed from other aspects of a vehicle's geometry: the complex systems of the wheel area and body design including brake cooling ducts. Which means that, by the time a full-vehicle prototype is ready for physical testing, it is often too late in the product life cycle to quickly and cost-effectively make inexpensive design changes that overheating in the braking system would likely necessitate. What's more, results from these testing procedures can be incomplete or unreliable: they may be impacted by the measurement devices themselves, which can under- or over-report. The engineers only get a limited view what is happening so it is difficult to identify the root causes of the thermal issues they may detect.

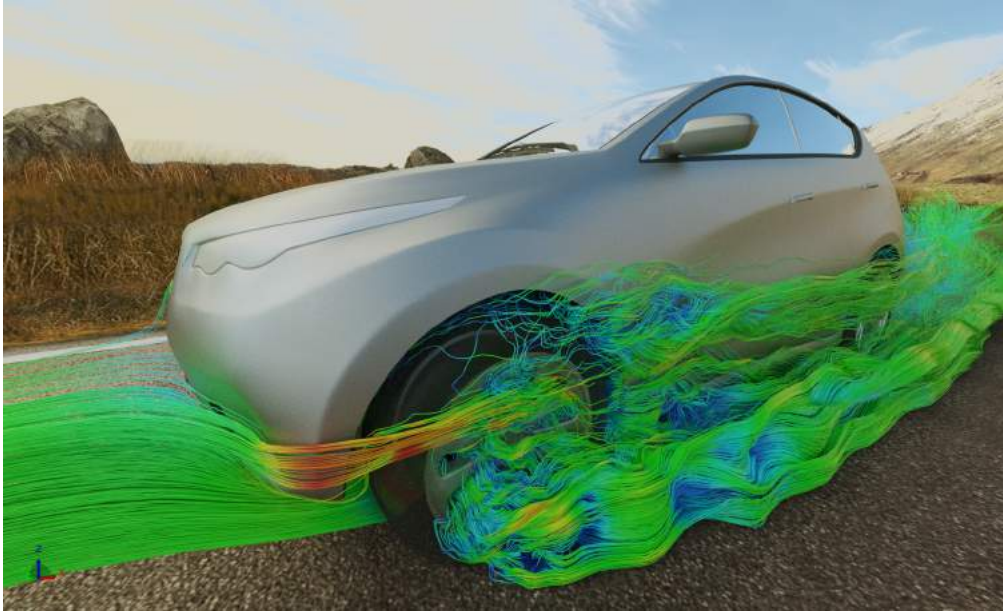
Other pressures on engineering teams introduce a complex, interrelated series of design targets requiring concurrent engineering methods to tackle. Model proliferation in today's market introduces more design variants that need to be verified for their braking system performance. Fuel economy and emissions regulations constrain vehicle design targets like aerodynamic lift, drag, and brake weights and materials—all of which impact brake design and cooling. And prototype testing can't account for many of the real-world operating conditions in which drivers find themselves every day – like long thermal soak, environmental extremes, wind buffeting, dirt and water spray from the road, and even dust from the brakes themselves.

The early, collaborative evaluation of a vehicle's complete digital design – including its brake cooling performance as a key design target – is best performed early on during product development as part of a systems-level approach that concurrently evaluates targets like aerodynamic shape and devices, brake cooling ducts, wheel system design, lift and drag, and more. Digital simulation with the SIMULIA PowerFLOW suite applies a patented, physics-based, and thoroughly validated methodology to evolving 3D geometry to accurately measure the thermal performance of a vehicle's braking system, identify potential issues and their root causes, and target related design improvements before a costly physical prototype is ever produced. It allows for the concurrent evaluation of other, often competing performance targets across a vehicle's systems so engineers can quickly identify trade-offs and justify design decisions critical to improving the brake system's performance. SIMULIA PowerFLOW and PowerTHERM solutions have been extensively validated and successfully applied to many customer use cases, including the six detailed here.

THE IMPORTANCE OF BRAKE COOLING

Durability, performance, and reliability are critical to a vehicle's braking system – which drivers, passengers, and others nearby rely on every day for safety. From everyday driving to extreme conditions, safety is paramount: brakes must perform when





they're needed, no matter what. Which is why understanding the thermal performance of a braking system is so important throughout vehicle design and development. Overheating decreases brake system durability and reliability: leading to issues like high pad wear, which requires the frequent replacement of brake pads; brake fluid boiling, which reduces brake performance; and even brake cracking and resulting operational failure from high thermal stresses.

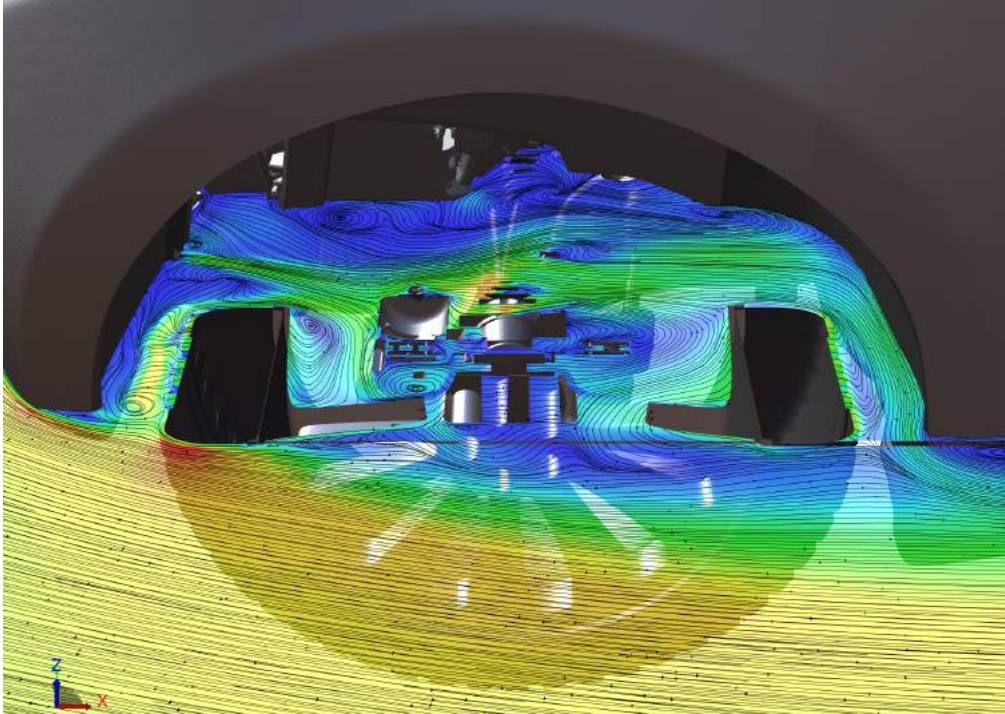
While the thermal stresses on brake discs are well understood at relatively low operating temperatures, higher, more critical temperatures are frequently generated by environmental stresses or extreme driving conditions such as successive braking events. These thermal loads must be more carefully studied and controlled throughout vehicle design, as they adversely affect a braking system's performance to a much greater extent. Continued operation of the brake discs under excessive temperatures like these adverse conditions generate can lead to hot spots and disc thickness variation (DTV) that can result in thermal cracks, judder, brake fade, wear, and reduced braking effectiveness.

THE LIMITATIONS OF PHYSICAL TESTS

Since overheating is such a threat to brake performance, the design of brake cooling systems is one of the top concerns during new vehicle development. Tests of brake system performance traditionally require a physical prototype and extensive track or wind tunnel time. In these tests, the brake disc is heated by braking through single or multiple cycles to a high temperature. The subsequent cool-down time is measured. If the maximum temperature level exceeds the allowed range or the cooling rate is not sufficient, aerodynamic changes are the main option to improve the cooling performance.

What's more, brake discs are typically tested on test benches, which are not at all representative of the actual vehicle. This is because the cool-down time for a brake disc – an important metric used to evaluate its reliability and durability – is strongly influenced by airflow onto the brakes. This is difficult to replicate on a test bench because design decisions throughout the wheel system and chassis of the vehicle affect it. As a result, to be faithfully studied, it must be evaluated in context with the complete, production-ready geometry already in place.

But physical testing can be done only late in design, when a prototype exists. And a physical test with known accuracy limitations cannot provide visibility into the invisible forces of airflow and heat that work together to impact brake cooling success. Only simulation can do that.



Accurately Measuring Thermal Extremes

Rigorous, comprehensive physical testing and measurement of brake cooling performance typically requires the use of a vehicle prototype on a track or in a wind tunnel in order to reach the extreme temperatures and driving conditions that would produce extreme stress on brake cooling mechanisms to test their performance. Not only is physical testing costly – relying on expensive testing equipment, costly early-stage prototype builds, and many hours of wind tunnel and track time – it is often unreliable. Unfortunately, this cost is largely spent on prototypes which may not even pass the tests they’re undergoing.

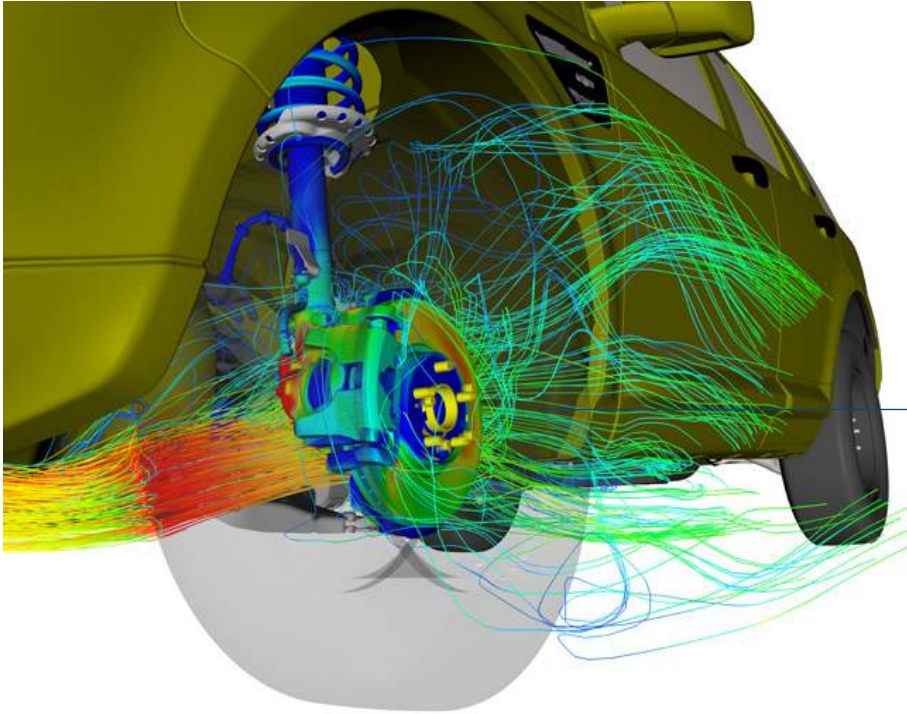
What’s more, the accuracy of those tests can be suspect. The accuracy of temperature measurements during testing depends strongly on wind tunnel or track conditions and disc temperature measurement procedures.

Experimental testing of vehicle braking system offers limited information about temperatures at key locations on rotating brake disc surfaces, and these measurements alone are insufficient to understand the root cause of temperature rise during the test. Other measurement difficulties include large under-prediction or over-prediction of the brake disc temperature due to use of rub on thermocouple. In other words: the sensing mechanism itself can sway the results of the test.

Evaluating the Role of Airflow

The brake system operates in an environment with extremely complex turbulent flow, with interaction between underbody, underhood flows, airflow through brake cooling ducts, and rotating wheels. Visualizing and understanding this complex flow in detail is essential in order to assess any adjustments needed to the geometry of the brake system—but this is virtually impossible to do with any kind of physical testing.

To understand the cause of brake temperature rise, brake designers need access to more information such as air velocities, heat transfer coefficients and heat flux on various brake parts; yet temperature measurements on the brake disc surface may not represent the overall temperature of the disc due to temperature gradients present within brake disc rotors. Furthermore, increases in cooling air flow due to changes in the design of brake disc curved vanes are extremely difficult to measure under vehicle operating conditions. Empirical models of heat transfer cannot be used for predicting temperature at each brake stop, since flow distribution over the brakes is unique for a given vehicle geometry ahead of the brake system, and that distribution is transient in nature. This constraint also influences convective heat transfer through changes in the boundary layer structure.



Airflow through detailed geometry of braking system

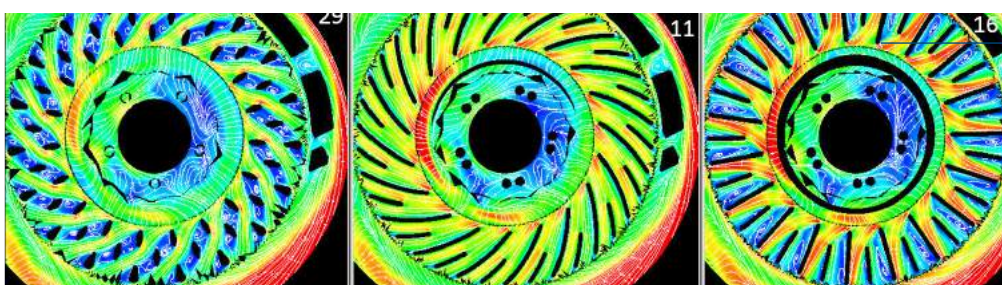
Re-creating real-world operating conditions is largely impossible using physical testing alone. A huge range of environmental conditions that are extremely challenging to re-create during test are experienced every day by drivers – and their brakes must perform reliably during each and every one. Temperature extremes like thermal soak, wind from climate conditions or traffic, dirty and dusty roads, water spray from inclement weather or another vehicle's tires, and even behavior of brake dust can dramatically impact performance, and variations in the conditions are difficult to faithfully re-create during traditional testing.

THE CASE FOR EARLIER EVALUATION

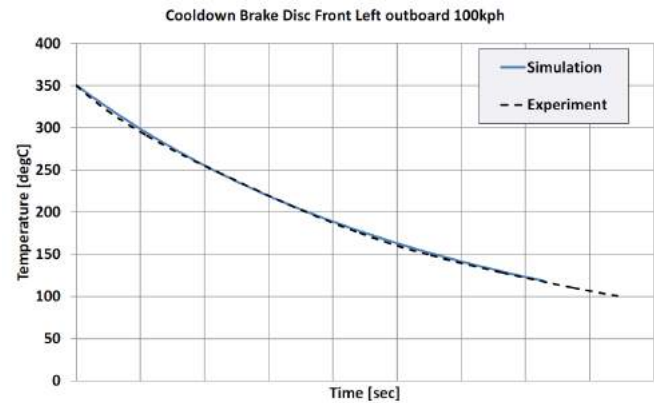
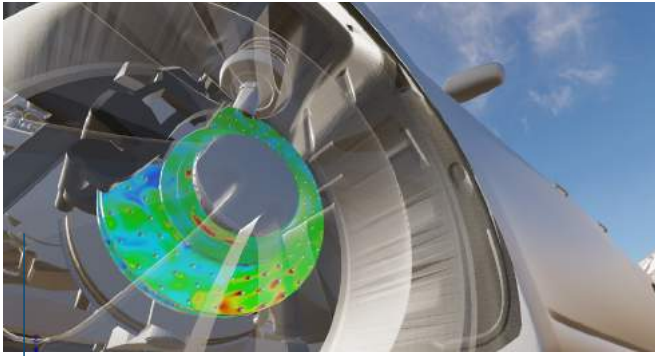
Even when physical testing does uncover issues with the braking system, by this point in vehicle development the design of the hardware that influences brake cooling – which must be close enough to its final design to be produced in prototype form – is also, paradoxically, too mature to accept major design improvements without the introduction of significant additional development time and costs.

Failures discovered at this late stage in product design and development either have to endure these costly delays, or they require fixes that could add parts cost and weight, which can compromise other aspects of a vehicle's performance.

With increasing numbers of vehicle models offered today by OEMs, the need to test and validate the brake cooling systems of every design variant across different models introduces a daunting task to any manufacturer. How brake packages will interact with design decisions that can vary slightly by vehicle model can introduce a huge load on testing – compounding the problem of late-stage failure discovery and timeline or budgetary setbacks.



Visualize and optimize the flow across multiple disc designs.



Brake disc cooldown simulation at constant speed: correlation to experiment enables design optimization²

Reconcile Competing Design Targets

An earlier, systems-level approach to brake cooling design is key. Especially since many vehicle design targets outside of the braking system can impact – or are impacted by – brake cooling design decisions: introducing competing design targets that must be considered concurrently in order to be resolved. With renewed regulatory emphasis worldwide on vehicle emissions, aerodynamic efficiency gains and weight constraints to improve the range of electric vehicles and reduce emissions for traditional and hybrid powertrains are all earning increased focus. Both weight and aerodynamics can be dramatically impacted by the design of brake cooling systems. Vehicle aerodynamics impact brake cooling because much of the cooling airflow directed toward the brakes results from aerodynamic design decisions, including vehicle shape and aerodynamic devices. But brake cooling devices like brake ducts can themselves increase drag and decrease a vehicle's fuel efficiency, creating the need for more efficient brake cooling designs.

Integrate Brake Design and Aerodynamics

A 1% decrease in vehicle drag has as much effect on reducing CO₂ emissions as reducing vehicle weight 7-8 kg, which is why efficient brake cooling systems are so essential. And when you consider that brake rotors are around 21 lbs per wheel for a large sedan, braking systems are a prime target for weight reductions to improve vehicle efficiency. Weight reduction is achieved through reducing the size of the brakes and changing the rotor materials; but the cooling needs of lighter-weight brakes must be thoroughly studied when these changes are made. While lighter weight brakes can improve acoustic and dust issues along with reducing emissions, these systems actually require greater cooling airflow because the heat capacity of the brake is reduced proportionately with its reduction in mass. If these lighter-weight brakes aren't compensated for with increased cooling, their effectiveness, especially for long downhills and performance driving, will be compromised by brake fade. Meanwhile, lighter weight material, such as carbon/silicon carbide ceramic, is more sensitive to surface water contamination. In fact, it is not unheard of for the coefficient of friction to drop by more than 80% when wet¹, which results in a proportional increase in braking distance. Ensuring these lighter weight braking materials stay dry and cool introduces a whole new level of design challenge to engineering teams, since brake cooling is usually increased by reducing the size of the brake dust shield and ducting air towards the brake rotor—yet both of these changes are likely to increase brake wetting.

EFFECTIVE BRAKE COOLING DESIGN

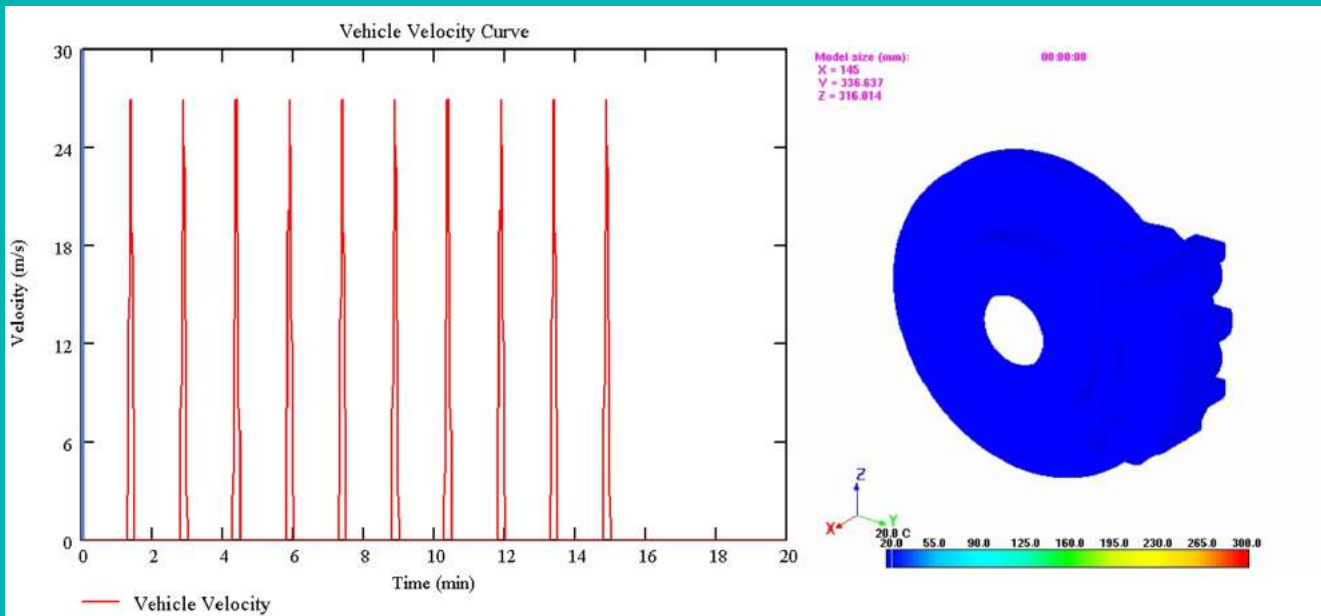
The ideal solution for brake cooling design is to evaluate brake system performance early in the product lifecycle – before a prototype is even built – by applying physics-based simulation technology to the 3D CAD data already under development across product engineering teams. It must offer high-fidelity physics to accurately represent the thermal transients under which brakes operate, including real-world conditions like thermal soak, temperature extremes resulting from climate, and grueling cycles of heavy acceleration and braking – known as drive cycles – in order to faithfully re-create even the most rigorous of test and real-world experiences vehicles can undergo. And, it must be capable of applying to the simulation all of the various weather and road conditions real-world braking systems experience everyday—from dirt, water, and ice to even the brake dust particles themselves—ensuring that brakes will perform no matter the weather.

CASE STUDY 1: SIMULATING EXTREME CONDITIONS

In a duty cycle simulation of approximately 20 minutes for an automotive disk brake system – consisting of twenty five consecutive stop brakes followed by a cooling-down process – the results compared well with experimental data obtained in open road experiments. The simulations of the air flow structure and thermal behavior around a passenger car (mid-size sport utility vehicle) were performed with fully resolved

geometry details at varying vehicle and airflow velocities. Conduction, radiation, and convection effects were taken into account by an automated coupling simulation between the flow and thermal solvers.²

²S. Jelic, S. Meyland, W. Jansen, and A. Alajbegovic. "A coupled approach to brake duty cycle simulation." Low Carbon Vehicles, MIRA International Vehicle Aerodynamics Conference, 8; 171-182.



An Early, Integrated Approach to Systems

To meet multiple, sometimes competing, targets for vehicle performance – including aerodynamic lift and drag, brake weight, and brake cooling requirements, among many others – evaluating the complete 3D geometry as it evolves concurrently allows engineers to see the effects of their design choices across all of these targets simultaneously, which is especially important as they seek a final design that maximizes brake performance without sacrificing other critical dimensions like vehicle weight and fuel economy.

Considering the system design as a whole while changes are being made across many shape, component design, and materials characteristics that can impact brake performance is critical because better choices for brake durability, reliability, and ultimately vehicle safety may necessitate changes in other, related systems. An early, detailed, highly visual representation of these critical interactions – supported by high-fidelity physics that enables the visualization and measurement of temperature, airflow, and thermal transients – can help multiple engineering teams compare the differences between design choices and justify the changes needed across so many interrelated vehicle systems. The cooling air that brakes rely on to keep them performing optimally is characterized by a complex, unsteady flow that interacts with the finely-detailed 3D geometry of the braking system's design and is further impacted by other characteristics like exterior design, air ducts, and even wheel and rim selections. A digital methodology based on the 3D geometry of the vehicle as it evolves throughout design and development lets thermal engineers simulate and analyze the impact of each of these design choices, and their complex interactions, on brake cooling, performance, and safety.

Using complete 3D geometry, simulations can faithfully evaluate thermal effects on brake discs, pads, and even fluid heat-up and potential vaporization throughout complex conditions like thermal soak, continuous braking and acceleration (drive / duty cycles), and even environmental conditions including wind, dirt, tire spray, and brake dust. Different geometry and even material choices can be tested digitally before the costly process of prototyping, to evaluate different brake weights and to ensure that every model variant in a manufacturer's product portfolio – including shape and device variations as well as optional rim and tire combinations and their impact during rotation on cooling airflow to brakes – can be verified to ensure they don't negatively impact brake performance and safety.

The Benefits of Thermal Simulation

Brake disks get very hot very quickly, and their temperature is a function of the complex interaction between conduction, radiation, and convective cooling to the surrounding air. Any simulation must be able to accurately predict this interaction in an easy to use way. Furthermore, the all-important cooldown is, by definition, a transient problem occurring on a longer timescale than most fluid simulation tools can handle.

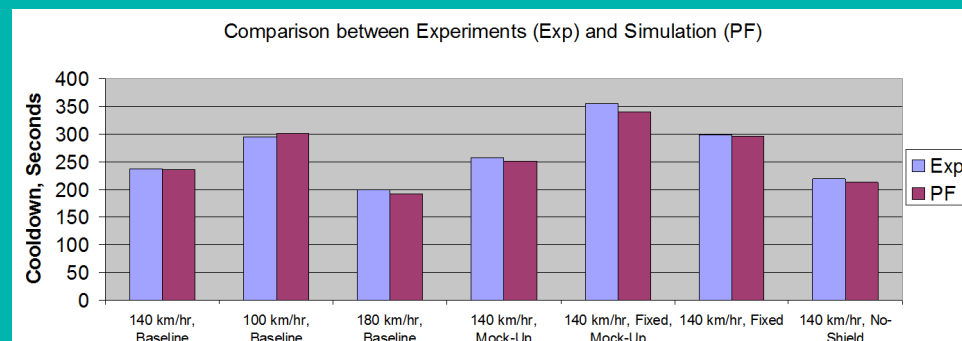
SIMULIA's PowerFLOW and PowerTHERM solutions accurately predict thermal brake performance under extreme testing conditions by leveraging 3D CAD geometry during the early design phase. PowerFLOW's unique, inherently transient Lattice Boltzmann-based physics enables simulations that accurately predict real-world transient conditions on even the most complex rotating

CASE STUDY 2: ACCURATELY PREDICTING COOL-DOWN TIME

An important metric in the vehicle brake design process, the cool-down time for a brake disc strongly influences the durability and reliability of brakes. However, the brake cool-down time is a function of many vehicle and chassis factors, making it time-consuming and expensive to evaluate and optimize in hardware testing. In this study, an alternative approach to hardware testing for evaluating brake design cool-down time was evaluated by implementing a CFD (Computational Fluid Dynamics) simulation-based methodology in SIMULIA PowerFLOW and PowerTHERM. Simulation cases were compared with test data and good agreement was observed between test data and simulation results over a wide range of design parameters. The study demonstrated that coupled PowerFLOW and PowerTHERM can accurately predict, for a production vehicle, brake disc cool-

down time over a wide range of design parameters. Cool-down times calculated from simulations matched test data to within an average of 2.5%. The cool-down curves showed good agreement as well. In terms of accelerating the design process, it was determined that turnaround time is fast enough to impact the design process, while incorporating all component details packaged in a real vehicle and evaluated under open-road conditions to faithfully and accurately provide real-world performance data and inform better design decisions early on during vehicle development.³

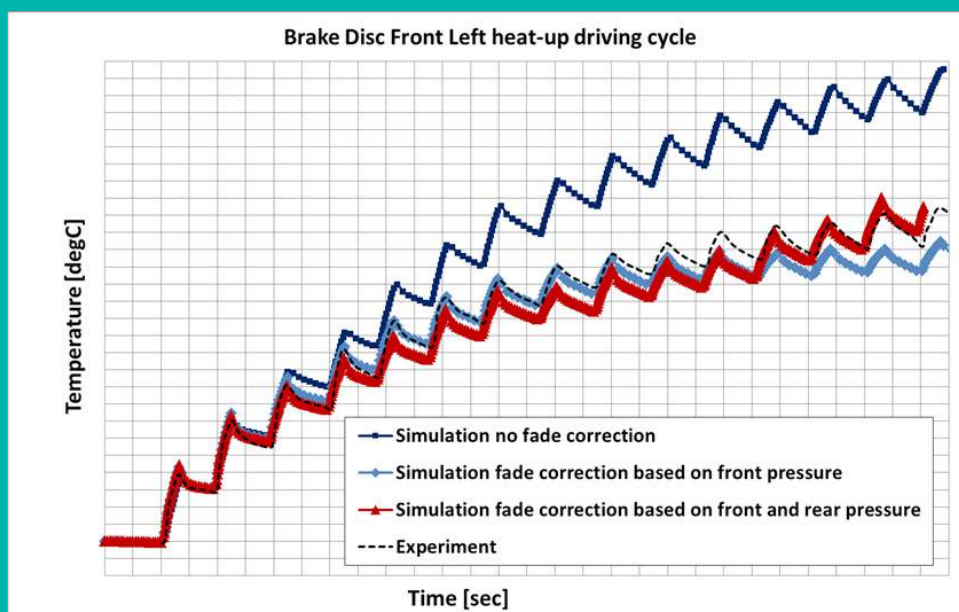
³D. Mukutmoni, S. Jelic, J. Han, and M. Haffey. "Role of Accurate Numerical Simulation of Brake Cooldown in Brake Design Process," SAE Int. J. Passeng. Cars - Mech. Syst. 5(4):2012



³ Comparison between Experiments (Exp) and Simulation (PF). Average difference: 2.5%

geometry. PowerTHERM is a fully-coupled, highly accurate, transient, conduction and radiation solver. The combination of PowerFLOW and PowerTHERM provides a complete thermal analysis, including all three heat transfer modes – radiation, conduction, and convection; complex transient flows, including accurate unsteady turbulent wall model for heat transfer prediction; and complex geometry, like the finely detailed geometry around the brakes, tires, and other nearby vehicle shapes and devices that can dramatically impact the unsteady flow field around the brakes during vehicle operation.

SIMULIA PowerFLOW solutions enable the accurate prediction and visualization of temperatures, airflow, and temperature fields for braking systems. It faithfully represents vehicle aerodynamics – which is critical to understanding cooling flow paths impacting the braking system – and offers time-accurate unsteady flow simulation, realistically rotating rim and disc capabilities along with truly rotating treaded tires, and even particulate matter representing dirt, water, ice, and brake dust – all of which are critical to a high-fidelity simulation of vehicle operation under real-world conditions.



CASE STUDY 3: ELIMINATING OVER-PREDICTION

Bentley and The PowerFLOW team co-presented a simulation method for brake duty cycles with brake fade correction. Thermal loading of brake discs is well understood at relatively low operating temperatures, and therefore modeling of disc thermal performance at low temperatures is also relatively well understood. However, at more critical temperatures, the thermal load can adversely affect the braking performance, leading to brake fade. The simulation leveraged advanced thermal modeling together with dedicated vehicle testing to establish boundary conditions at higher braking temperatures.

The specific thermal performance of each brake was tested at elevated temperature.

This thermal performance data was then used to refine the thermal simulation model. To validate the model, a 15 stop fade cycle test was run. The model takes into account the solid conduction calculation through the disc, convective flow field analysis and the brake system thermal performance characteristic as previously described. The results of the simulation were compared with the vehicle test results, showing that simulation methods predict brake disc temperatures using a brake fade correction method for a fifteen stop duty cycle. Without the brake fade correction, the predicted temperatures would overpredict.⁴

⁴ K. Bhambare, M. Haffey, and S. Jelic. "Brake Duty Cycle Simulation for Thermal Design of Vehicle Braking System," SAE Technical Paper 2013-36-0015, 2013.

Visual interpretation of thermal conditions and flow fields – via color gradients against 3D geometry, photo-realistic renders, or even time-lapse animations – lets engineers quickly identify potential problems before they are built into physical prototypes, pinpoint and correct root causes, and realize potential design changes and improvements recommended by the analysis results to eliminate problems early, while vehicle geometry is still under development. Rapid turnaround time for model setup, simulation, visualization, and design modification lets engineers quickly make design changes to the baseline and evaluate the improvements in brake performance digitally.

CASE STUDY 4: SIMULATING TRUCK DRUM BRAKE COOLING

Trucks can carry a heavy load, and, when applying the brakes – for example, during a mountain downhill route or an abrupt stop – brake temperatures can rise significantly. Elevated temperatures in the drum brake region can reduce braking efficiency, or can even cause the brake system to fail, catch fire, or suffer damage.

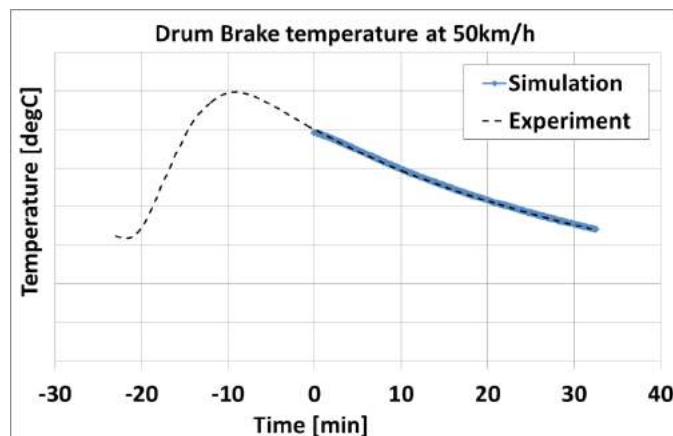
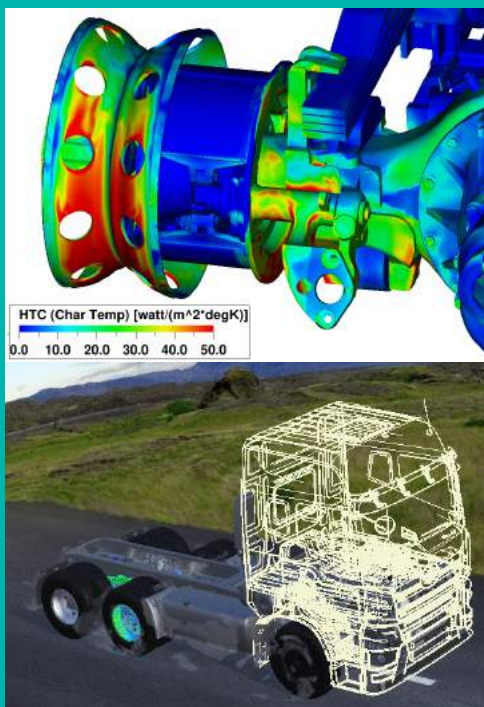
The design of truck drum brakes therefore needs to be able to transfer heat out of the system by convection, conduction, and/or radiation. All three heat transfer modes play an important role, since the drum brakes of trucks are not much exposed to external airflow, which differs significantly from the disc brakes of passenger cars. This complex heat transfer problem is not easy to understand. Numerical methods provide insight by visualization of the different heat transfer modes.

The numerical methods used in this case simulate the transient heat transfer of a truck drum brake system cooldown at constant driving speed. PowerFLOW's 3D CFD Lattice Boltzmann-based solver calculated the convection by

leveraging a two-way coupling between a radiation and a conduction calculation.

The simulation included realistic rotation of the wheels and used 3D solid elements for the conduction. Simulation results were compared with experimental test results, which were performed in the Tongji thermal wind tunnel in Shanghai. Due to the sufficiently large nozzle exit area, this wind tunnel can provide realistic experimental data for trucks. Results obtained from the simulation compare faithfully to the experimental data. As shown in the figures below, the simulation method predicted brake disc temperature cooldown. Simulation worked well with HTC midpoint approach under low convection driving conditions.⁵

⁵ S. Sun, G. Liao, Q. Fu, K. Lu et al. "A Coupled Approach to Truck Drum Brake Cooling," SAE Technical Paper 2015-01-2901, 2015



CASE STUDY 5: SIMULATING BRAKE DUST DEPOSITION

To study how the cloud of heated particles ejected from brake disk and pads upon application of the brakes – commonly known as brake dust – can be swept up into the flow around the wheels and deposited on surfaces to impact vehicle performance, JLR and The PowerFLOW team embarked on a simulation of this phenomenon on a CFD model of the Jaguar S Type.

There are few other ways to realistically obtain data from wheel soiling due to brake dust. Widely different environmental conditions and brake usage patterns make it hard to generalize results in-use. And test track experiments similarly can't isolate brake dust from other debris. Key capabilities for this simulation included the ability to simultaneously investigate brake cooling, wheel system drag, and brake dust deposition, while accounting for the realistic effects of wheel rotation, flow, and particles. The study investigated three different approaches to accounting for wheel-rotation: applying a rotational velocity boundary condition (VBC), moving reference frame (MRF) or a sliding (rotating) mesh (RM). It also examined two simulation techniques for modelling the propagation of the brake-dust through the flow field: time-averaged Lagrangian particle tracking (ALPT) and transient Lagrangian particle tracking (TLPT). In comparison to a simplified laboratory experiment, it was demonstrated that the combination of rotating (wheel) mesh and transient Lagrangian particle tracking (RM/TLP) is shown to produce a wheel-soiling pattern that most closely



resembles the experimental data. This methodology was applied to a whole-car aerodynamic CFD model, integrated within the vehicle aerodynamics / thermal management toolset along with insights into the brake-dust soiling mechanism – the release of brake-dust particles from the brake's surface. Conclusions related how flow structures generated by a wheel in isolation differed from those seen with the wheel installed in a wheel arch. The flow structures apparently responsible for the dust transport were determined to be generated by the rotation of the spoke, which makes it likely that wheels with bluff spoke designs may be more vulnerable to soiling while more aerodynamically profiled spokes may reduce susceptibility to soiling.⁶

⁶A. Gaylard, D. Lynch, J. Amodeo, R. Amunugama. "The Simulation of Brake Dust Deposition." 8th MIRA International Conference on Vehicle Aerodynamics.

CONCLUSION

When safety is at stake, clearly understanding and addressing all of the forces that can dramatically impact brake cooling—like thermal conditions, aerodynamic forces, and rotational geometry—cannot rely solely on physical prototype testing, which lacks the completeness, accuracy, visibility, and actionable insight early in the design stage that digital simulation can offer. By applying real-world conditions to 3D design data using accurate, physics-based thermal and aerodynamic simulation, SIMULIA PowerFLOW solutions provide a responsive, integrated, and early design-stage view into brake system performance, ensuring that brake cooling designs meet their targets for reliability, safety, and timely delivery.

CASE STUDY 6: IMPROVING BRAKE DESIGN FOR A GT3 RACE CAR

The constant acceleration and deceleration of racetrack driving generates excessive heat, which must be absorbed by the brakes. To avoid the safety risks of lost braking effectiveness due to overheating, brakes must be designed with convective cooling to assist the radiation and conduction cooling that naturally occur in the brakes, but without increasing drag or disc weight.

Brake cooling on the track differs significantly from duty cycle testing, in that duty cycles apply the exact same braking and acceleration pattern for the same time period with every cycle. But on the track, vehicle velocity changes continuously as acceleration and deceleration change. Simulation during early design lets engineers visualize the complex airflow in and around the brake disc, helps them modify the design to optimize cooling airflow, and can lead to lower brake system temperatures that let the driver push the limits even further during racing. This approach helps to ensure that drag is not

added through inefficient design changes, while offering insight into actual operating temperatures that could lead to further improvements - like opportunities to further reduce brake disc weight if cooling is proven to be very effective.

This study of a GT3 type vehicle compared simulation results to experimental results on a race track. The test was continued until brake disc temperatures reached a steady-state condition (temperature did not increase any more after each lap). By leveraging real rotating geometry and the complex 3D model, conditions were simulated in SIMULIA's PowerFLOW and PowerTHERM solutions. Close correlation was found between experimental and simulation data. Plus, the early, design-stage simulation let engineers find a design improvement to lower the outboard oil temperature and improve cooling of the outboard side of the caliper.⁷

⁷ W. Hunt, A. Price, S. Jelic, V. Staelens, M. Saif Ul-Hasnain. "A coupled simulation approach to race track brake cooling for a GT3 race car." 10th FKFS-Conference. Sept 29-30, 2015. Stuttgart.

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