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Research on Design Optimization and Simulation Methods of Race-Car Performance

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Abstract. Race-car performance at the limit arises from coupled interactions among aerodynamic layout, tyre thermomechanical behaviour, and wheel-torque distribution. Conventional component-by-component design and physical-test-driven development are costly and make multi-physics coupling under extreme track conditions difficult to reproduce. Simulation-based approaches, including computational fluid dynamics, thermodynamic tyre models, and full-vehicle dynamics simulation, provide powerful tools for race-car performance assessment. This paper systematically examines three core subsystems that determine race-car performance and analyses three coupling paths: bidirectional aerodynamics-tyre coupling, tyre-power-distribution constraint coupling, and indirect coupling between aerodynamics and power distribution mediated by the tyres. Parameter adjustments in one subsystem propagate through these coupling chains and alter overall lap-time performance, indicating that decoupled simulation can deviate substantially from real-vehicle responses. The review therefore highlights the need for closed-loop multi-physics co-simulation that integrates aerodynamic computation, thermodynamic tyre modelling, and torque-vectoring control. It also provides a theoretical basis for collaborative multi-parameter optimisation and simulation-oriented race-car design.

Keywords: Race-car, multi-physics co-simulation, aerodynamics-tyre coupling, torque vectoring, performance optimisation

1. Introduction

Racing cars operate near vehicle performance limits, with high speeds, high lateral accelerations, and tyres operating close to the limit of adhesion. Overall performance is determined not by a single component but by interactions among aerodynamic design, tyre behaviour, and wheel-torque distribution [1]. Simulation has therefore become central to modern race-car development because it helps engineers quantify these interactions and coordinate powertrain systems systematically [2].

Simulation tools have advanced substantially in recent years. Traditional testing remains important, but it is expensive and time-consuming. It is increasingly supplemented by digital tools, including computational fluid dynamics (CFD) for aerodynamics, thermomechanical tyre models, multi-degree-of-freedom vehicle-dynamics solvers, and torque-vectoring control algorithms [3]. CFD provides detailed information about the flow field around the body, wings, and diffuser and allows downforce and drag to be compared across configurations. Tyre models that account for

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temperature, load, and slip ratio address a limitation of older empirical formulas, which can become inaccurate under extreme operating conditions. Coupling these models with a full-vehicle dynamics model that incorporates aerodynamic and tyre data enables reconstruction of vehicle responses during hard acceleration, emergency braking, and high-speed cornering. The field is therefore moving from isolated component studies toward integrated frameworks that combine multi-physics co-simulation, multi-parameter optimisation, and control strategies for extreme operating conditions [4].

However, simulation does not eliminate all design challenges. Three issues recur in practice. First, aerodynamic design requires a compromise because additional downforce generally increases drag, and the preferred balance depends on the track. Second, tyre grip varies nonlinearly with tread temperature, load, and slip ratio, while heat accumulation during a run changes tyre behaviour in ways that are difficult to predict. Third, torque-vectoring interacts strongly with the other subsystems, so changes in one parameter can produce coupled effects that may only become evident in simulation or track testing. Traditional testing is costly, slow, and limited to reproducible test conditions. These constraints motivate the shift toward simulation-led design [5].

This review is motivated by three gaps in the existing literature: incomplete understanding of deep subsystem coupling, limited simulation fidelity near performance limits, and difficulties incorporating coupled effects into multi-parameter optimisation. Accordingly, the paper addresses three questions. First, how do aerodynamics, tyre behaviour, and torque distribution influence lap-time performance? Second, how can CFD, tyre modelling, and vehicle dynamics be integrated into a coherent workflow from analysis and parameter adjustment to performance verification? Third, how do subsystem interactions affect overall vehicle performance? Addressing these questions clarifies the practical role of simulation in race-car engineering and provides reference points for design and analysis.

2. Design and control of key performance attributes in racing cars

The dynamic performance of racing cars under extreme conditions depends on the coordinated operation of multiple subsystems. The performance limits of a vehicle under high-speed, high-lateral-acceleration conditions are jointly determined by three factors: aerodynamic design, actual tyre operating conditions, and power-distribution logic. These subsystems do not operate independently: adjustments to the aerodynamic package alter load distribution on the tyres, thereby affecting tyre-road contact; changes in tyre adhesion coefficients and thermal states constrain the torque-output boundaries of the power-distribution controller; and wheel slip and temperature rise caused by power distribution, in turn, modify tyre mechanical properties and indirectly affect the vehicle's aerodynamic balance. Thus, examining any single subsystem in isolation fails to represent the vehicle's operating state accurately under extreme track conditions. This section addresses aerodynamic characteristics, tyre thermomechanical behaviour, and torque-vectoring allocation, explaining the mechanisms of each module while emphasizing their interdependencies. This provides the theoretical basis for subsequent multi-physics coupled simulation and parameter-optimisation analysis.

2.1. Aerodynamic characteristics and aerodynamic design

Race-car aerodynamic development involves a fundamental trade-off between downforce and drag. Increasing downforce improves cornering grip, but the devices that generate it also increase drag and reduce straight-line speed. The preferred balance therefore depends strongly on the circuit. Key

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aerodynamic components include the front wing, bodywork, wheels, underbody, diffuser, and rear wing. In Formula 1, the underbody is particularly important; airflow accelerated through the gap between the floor and the ground can generate more than 45% of total downforce. The diffuser expands the flow and reduces static pressure beneath the vehicle, while rear-wing angle and endplate design contribute to front-to-rear aerodynamic balance [6].

Farroni et al. examined open-wheel aerodynamics with rotating wheels, an effect that is often neglected in simplified simulations. By combining CFD with track telemetry, they showed that wheel rotation alters the flow field by generating vortices that affect the front wing and underbody and shift the overall load distribution. Treating wheels as static obstacles can therefore bias downforce estimates and aerodynamic balance. This work demonstrates that realistic simulations should account for wheel rotation because the associated flow disturbances influence both aerodynamic loads and thermal conditions around the tyres [7].

CFD and wind-tunnel testing serve complementary roles. CFD enables rapid evaluation of many geometry variants and provides detailed maps of pressure, vorticity, and flow separation. Wind-tunnel testing is more expensive and slower, but it provides physical measurements that can identify errors in CFD assumptions, particularly in sensitive regions such as the diffuser throat. Zhao et al., studying Formula SAE (FSAE) cars, also showed that off-axis inflow should be considered: crosswinds can shift the centre of pressure and generate yaw moments that reduce vehicle stability and may create safety concerns [8].

Rear-wing angle is one of the most direct aerodynamic adjustment parameters. Increasing the angle generally raises rear downforce and improves cornering grip, but also increases drag and reduces top speed. Reducing the angle has the opposite effect. Higher angles are therefore more suitable for circuits dominated by corners, whereas lower angles are more appropriate for circuits with long straights. During cornering with sideslip, the effective inflow direction changes relative to the vehicle, altering the wing's effective angle of attack. This can reduce downforce and shift aerodynamic balance in ways not captured by straight-line testing, so off-axis operating conditions should be included in design evaluation.

Aerodynamic components interact rather than contributing independently. The front-wing wake affects flow around the front wheels and underbody; wheel-generated vortices can reach the diffuser; and engine exhaust, depending on its routing, can either support diffuser performance or promote flow separation and reduce downforce. Farroni's TRT-EVO work illustrates this coupling: exhaust heat raises rear-tyre sidewall temperature, which changes tyre mechanical properties. The resulting chain from aerodynamic configuration and exhaust flow to tyre temperature, tyre grip, and vehicle dynamics shows that aerodynamic design can influence the thermal and mechanical behaviour of the tyres and therefore the overall vehicle response.

2.2. Tyre states and power distribution

Tyres are the sole connection between the vehicle and the road, so all driving, braking, and steering forces are transmitted through four contact patches. Tyre grip is not constant; it varies with tread temperature, carcass temperature, vertical load, slip ratio, and wear state. West and Limebeer investigated this behaviour in Formula 1 and found that high-grip compounds operate within relatively narrow temperature windows. For ultrasoft compounds, peak friction occurs when tread temperature is approximately 90-105 °C. Below this range, the rubber remains relatively stiff and produces less grip; above it, overheating can cause blistering and a rapid reduction in grip [9].

West and Limebeer developed a framework linking tyre temperature directly to friction for high-performance racing tyres. Using track data and laboratory tests, they demonstrated a narrow

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operating window and quantified the nonlinear relationship between tread temperature and grip, including performance losses at excessively high or low temperatures. The framework therefore provides a practical basis for tyre-temperature management over a racing stint.

From a thermal perspective, a tyre can be represented by two principal layers: the tread and the carcass. The tread has relatively low thermal mass and heats or cools rapidly because it directly experiences sliding and friction during braking and acceleration. The carcass has greater thermal mass and responds more slowly, acting as a thermal reservoir that can continue transferring heat to the tread after slip-generated heating decreases on a straight. This behaviour produces temperature-lag effects over a lap and slows tread cooling.

Farroni et al. extended this representation through the TRT and TRT-EVO models by adding a sidewall module to the conventional tread-and-carcass structure. The sidewall absorbs heat from the exhaust, and this heat migrates toward the contact patch non-uniformly. Camber angle, tyre pressure, and exhaust thermal loading all affect the temperature distribution across the tread. The model distinguishes the heating and cooling behaviour of individual tread ribs, providing a more detailed representation of contact-patch thermal behaviour [7].

TRT-EVO extends conventional lumped-parameter tyre models by representing the sidewall and simulating multiple combinations of camber, pressure, and exhaust thermal load. The results show that contact-patch temperature is spatially non-uniform and that different tread regions heat and cool at different rates. This level of detail is important for simulating tyre behaviour under aggressive driving and illustrates that tyre temperature is influenced by aerodynamics, power distribution, and suspension geometry. Tyre thermal simulation therefore lies at the intersection of several vehicle subsystems.

Tyre wear introduces an additional source of irreversible performance degradation. Two common racing-tyre wear modes are graining and blistering. At low temperatures, large slip angles can tear the rubber surface and cause graining; at high temperatures, subsurface overheating can cause the tread surface to blister. Both mechanisms reduce available grip. As laps accumulate, wear changes vehicle dynamics and handling balance even under similar driver inputs. Thermal management therefore aims to keep tread temperature within its effective operating window while limiting abnormal wear and maintaining tyre performance over the required stint.

Ruiz Diez et al. investigated front-rear torque-vectoring strategies for multi-motor race cars. Their simulation study exploited the rapid torque response of electric motors and showed that shifting drive torque between the front and rear axles can generate additional yaw moment and alter steering behaviour. The study also emphasized that torque commands must remain within the tyre friction ellipse, which places physical limits on controller outputs. This work provides a clear representation of torque-vectoring control and the constraints imposed by tyre adhesion [10].

Because tyre force capacity is limited, torque vectoring can be used to approach the vehicle's performance envelope more effectively. The controller actively distributes drive and brake torque among the wheels to generate yaw moment, modify turn-in response, and use the available grip at each tyre. In multi-motor architectures, electric motors can shift torque rapidly between the front and rear axles without relying on conventional mechanical differentials. During cornering, modifying the front-to-rear drive ratio can reduce understeer or delay oversteer. However, the controller must remain within the friction ellipse; excessive wheel torque produces wheelspin, reduces usable grip, and can increase lap time.

Tyre thermal management and torque distribution are strongly coupled and jointly determine the available adhesion limits. Torque commands directly modify wheel slip ratios, and increased slip raises frictional heat generation, which changes tread and carcass temperatures. As tyre temperature

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changes, the peak longitudinal and lateral friction coefficients also change, thereby updating the safe torque limits of the controller. If a control strategy maintains high slip on selected wheels, those tyres may heat more rapidly, leave the optimal temperature window, experience accelerated wear, lose grip, and degrade lap-time performance.

Using the publicly available Stanford Revs race-car database, Kegelman et al. proposed tyre-condition analysis based on real driver trajectory data. By analysing large volumes of track data from professional racing drivers, they compared tyre load and slip histories under different driving inputs and showed that driver behaviour directly modifies tyre thermal-load distributions. The results indicate that tyre operating conditions depend not only on vehicle hardware but also on driving strategy, which should therefore be represented when defining simulation input conditions [11].

Analysis of professional-driver trajectories in the Stanford Revs database showed that different steering and throttle strategies can produce distinct tyre-load and slip histories even when comparable lap times are achieved. For example, a late-apex, slow-in-fast-out line changes the timing of braking and throttle application and therefore the spatial and temporal distribution of tyre heating. These results indicate that driver inputs and torque-vectoring strategies jointly influence tyre behaviour, while tyre grip limits constrain both driver actions and controller outputs.

Tyres therefore impose hard constraints on any power-distribution strategy. A controller should not optimise steering response alone; it should also account for thermal load and wear and avoid prolonged high-slip states. In race-car simulation, thermodynamic tyre models can be integrated into the vehicle-dynamics framework so that tyre temperature and wear states are updated concurrently with torque-vectoring calculations. This enables evaluation of both immediate dynamic performance and longer-term effects on tyre condition.

3. Analysis of coupling mechanisms among race-car subsystems

On-track race-car dynamics result from interactions among aerodynamics, tyre thermodynamics, and torque-vectoring control rather than from a simple sum of subsystem responses. Changes in one module can propagate through coupling paths and ultimately alter lap time. Ignoring these interactions and simulating subsystems independently can therefore produce responses that differ substantially from the real vehicle. This section examines three coupling paths - aerodynamics-tyre, tyre-power distribution, and aerodynamics-power distribution - to clarify how physical quantities transfer among subsystems and influence overall performance. This analysis provides a basis for multi-physics co-simulation and parameter-iteration studies.

3.1. Coupling between aerodynamics and tyre systems

The geometry of a race car's aero package changes the centre of pressure and shifts vertical loads between the four wheels. More downforce means larger tyre contact loads, and within reason, that improves lateral and longitudinal grip. But load changes also alter the pressure distribution inside the contact patch, which affects how much frictional heat the tread generates and how the temperature field evolves. At the same time, as tyres warm up, the rubber changes its mechanical behaviour, carcass deformation shifts, and the ride height moves—sometimes by enough to change the flow under the floor, which feeds back into downforce and drag.

Farroni et al. developed an aerodynamics-tyre coupling analysis framework for high-speed race cars by combining CFD flow solutions with thermodynamic tyre models. The framework captured coupled evolution caused by rotating-wheel flow disturbances and exhaust heating and confirmed

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that aerodynamic loads and tyre thermal states interact bidirectionally. This differs from approaches that simulate aerodynamics and tyres independently and shows that co-simulation should exchange state information in both directions rather than rely on static, one-way inputs [7].

The exposed wheel regions show this coupling particularly clearly. Vortices shed by rotating wheels reduce the effective flow area beneath the floor and can decrease downforce. At the same time, hot exhaust jets transfer heat to tyre sidewalls and change the temperature gradient through the tyre structure. Rising tyre temperature can alter internal pressure, radial stiffness, and ride height, which then modifies aerodynamic balance. During cornering with sideslip, crosswinds can also redistribute aerodynamic loads laterally, producing unequal left-right tyre heating and gradual balance drift over a stint [8].

3.2. Coupling between tyre thermodynamics and power distribution

Tyres form the physical link between the power-distribution controller and the road. All drive and brake torque is transmitted through the contact patches, and the applied torque determines wheel slip ratio. Slip generates frictional heat that changes tread and carcass temperatures. As tyre temperature and wear evolve, friction-ellipse boundaries shift, thereby updating the safe upper and lower torque limits available to the controller.

West and Limebeer experimentally investigated relationships among slip ratio, heat generation, and friction coefficient for high-performance racing tyres. Using track data, they quantified how slip level affects heat-generation power and showed that changes in slip can rapidly alter operating temperature and therefore available grip. These results demonstrate that power-control outputs and tyre thermal states are coupled and that torque limits should adapt to the tyre's real-time thermal state rather than remain fixed [9].

If a controller applies large differential torques for extended periods to sharpen steering response, wheel slip remains elevated and frictional heating increases. The tyres may then leave their optimal temperature range. Overheating can cause blistering and reduce peak grip, while unchanged torque demand can further increase slip. This positive feedback can accelerate thermal degradation and reduce vehicle performance.

Ruiz Diez et al. investigated torque-vectoring control for multi-motor race cars and proposed constraint frameworks that explicitly account for the tyre friction ellipse. Their simulations showed that controllers with fixed amplitude limits that ignore tyre thermal evolution can lose performance and may become unstable over longer runs. The study therefore indicates that control algorithms should use tyre-state feedback to adapt torque limits dynamically [10].

Parra et al. investigated model-predictive torque-vectoring control for electric race cars and noted that many optimal-distribution architectures consider geometric friction-ellipse constraints but neglect tyre heat accumulation caused by slip. Under prolonged extreme operation, this can shift the effective constraint boundaries. Simulations showed that thermal constraints can reduce overheating while preserving steering agility and limiting excessive differential-torque output [12]. This work demonstrates that tyre thermal states should participate directly in control optimisation rather than be treated only as post-processing outputs.

Kissai et al. conducted co-simulation research on race-car torque-vectoring distribution and tyre thermo-mechanical coupling. Using an Amesim-Simulink platform, they compared three control schemes: fixed amplitude limits, amplitude limits based only on vertical load, and adaptive amplitude limits incorporating thermo-mechanical coupling. Under repeated extreme cornering, the first two schemes produced sustained one-sided tyre overheating and progressive loss of peak lateral acceleration. In contrast, the adaptive scheme balanced slip-induced heat generation between left

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and right wheels, delayed tyre-performance degradation, and produced more stable lap-time performance [13]. This result provides a benchmark for tyre-thermodynamics-power-distribution coupling in multi-physics co-simulation.

3.3. Indirect coupling between aerodynamics and power distribution

There is no direct physical interaction between aerodynamic and power-distribution systems; their coupling is mediated by the tyres. Aerodynamic loads change the vertical force on each wheel and therefore the torque that can be transmitted before grip is lost, setting upper bounds for the torque-vectoring controller. Differential slip generated by torque distribution changes tyre temperature, which influences tyre stiffness, deformation, and ride height. Changes in ride height then modify aerodynamic performance. The resulting feedback loop is therefore aerodynamics to torque limits to tyre state to ride height to aerodynamics.

Kegelman et al. examined this interaction using track data from professional racing drivers and analysed how aerodynamic balance changed under different torque outputs and driving conditions. Their data indicate that power-distribution strategy can influence aerodynamic performance indirectly through tyre thermal deformation. This provides real-vehicle support for representing torque distribution, tyre state, and aerodynamic response within an integrated simulation framework.

Möller et al. examined this indirect coupling using a combined finite-element and CFD approach for open-wheel race cars. Differential slip between left and right tyres produces asymmetric heat generation, which changes tyre temperature and radial stiffness unequally. The resulting asymmetric tyre deformation changes ride height and modifies the flow field beneath the floor and around the front wheels, shifting the front-to-rear downforce ratio. Their analysis therefore identifies the coupling chain from torque distribution to asymmetric tyre temperature, tyre deformation, and aerodynamic-balance drift, and provides a physical basis for modelling this pathway [14].

These indirect coupling effects accumulate over successive laps. Two vehicles with identical aerodynamic hardware but different torque-vectoring calibrations can therefore exhibit different rates of performance degradation. This demonstrates that aerodynamic design and control strategy cannot be evaluated independently when tyre thermal evolution is significant. Aerodynamics, tyre thermodynamics, and torque-vectoring control should instead be represented within the same closed-loop simulation to capture their joint evolution over time.

4. Conclusion

This paper examines interactions among three core race-car subsystems: aerodynamics, tyre thermodynamics, and torque-vectoring power distribution. Particular attention is given to three coupling paths: aerodynamics-tyre, tyre-power distribution, and aerodynamics-power distribution. The review shows that these subsystems interact through multiple physical channels and jointly influence lap-time performance. Race-car limit performance is therefore not a simple superposition of component performance. Closed-loop interactions arise among aerodynamic load redistribution, tyre thermo-mechanical evolution, and motor differential-torque output. Adjusting a parameter in one subsystem can propagate through the coupling network and alter other subsystems, so decoupled simulation may deviate substantially from real-vehicle behaviour.

Aerodynamic and tyre systems form a bidirectional coupling loop. Aerodynamic devices redistribute vertical wheel loads and influence contact-patch pressure and heat-generation rates. Changes in tyre temperature alter radial stiffness and chassis ride height, which can disturb underfloor flow and shift downforce and aerodynamic balance. Rotating-wheel vortices and exhaust-

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gas heating can amplify these interactions. Simulations that assume stationary wheels and fixed tyre states may therefore fail to reproduce extreme cornering and multi-lap operation. Two-way data exchange between aerodynamic and thermodynamic tyre models is required.

Strong constraint coupling also exists between tyre thermodynamics and torque-vectoring power distribution. Differential torque changes wheel slip ratio, while slip-induced frictional dissipation changes tyre temperature. The resulting thermal state updates friction-ellipse boundaries and therefore the torque limits available to the controller. Fixed torque limits that ignore heat accumulation can accelerate overheating, wear, and dynamic-performance degradation over long runs. A robust control architecture should therefore incorporate tyre temperature and wear into the optimisation constraints so that torque limits adapt to the current tyre state while preserving steering response.

Aerodynamics and power distribution are coupled indirectly through the tyres. Even with unchanged aerodynamic hardware, altering torque split can change aerodynamic balance: differential slip changes tyre temperature, temperature changes tyre deformation, deformation changes ride height, and ride-height changes alter aerodynamic balance. Because these effects accumulate over multiple laps, power-distribution calibration influences not only traction and yaw response but also aerodynamic behaviour. Aerodynamic design and control-algorithm evaluation should therefore be treated as coupled problems.

Overall, the evidence argues against optimising each subsystem in isolation. A multi-physics co-simulation framework should integrate aerodynamics, thermodynamic tyre models, and torque-vectoring control in a closed loop. Such integration is necessary to reproduce the coupled evolution of vehicle states over a run and to support collaborative parameter optimisation that better reflects on-track behaviour.

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