

Thermal Degradation in Multi-Segment Vehicles: An Experimental Field Study

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Disclaimer

All testing described in this paper was conducted with full safety protocols, including pre-run surface inspection, emergency communication procedures, and observer vehicles.

The author explicitly does not endorse or encourage any operation of motor vehicles at speeds exceeding posted legal limits on public roads. The data presented herein are for engineering analysis purposes only and represent the results of controlled experimental conditions. Replication of these tests without appropriate safety measures, closed-course authorization, and professional oversight is dangerous and strongly discouraged.

Abstract

This paper presents a comparative field study of high-speed thermal stress and chassis dynamics across four distinct passenger vehicle architectures: a 2022 MG ZS EV (FWD electric), a 2014 BMW 730Ld (RWD diesel sedan), a 2012 Mercedes-Benz ML350 (AWD diesel SUV), and a 2010 Suzuki Swift VDi (FWD lightweight diesel). Testing was conducted on closed public roads with consistent 150 m and 175 m radius curvatures at speeds up to 240 km/h. A standardized "Max Attack" duty cycle was used, comprising full-throttle cornering, threshold braking from apex speed, and a 500 m cooldown at 80 km/h. Testing occurred at three diurnal phases (06:00, 14:00, 17:00) to capture ambient and asphalt temperature effects. Key findings include:

1. the BMW 730Ld achieved the highest sustainable apex speed (240 km/h) due to its long wheelbase and effective brake ducting;
2. the ML350 demonstrated chassis stability at 202 km/h despite significant body roll;
3. the MG ZS EV exhibited critical tire thermal degradation at 130 °C, leading to understeer from 156 km/h
4. the Swift VDi reached brake fade within three consecutive high-load cycles due to low thermal recovery ($\approx 70\%$ heat dissipation per cycle). Results indicate that OEM tire compounds (120–130 °C thermal ceiling) and brake cooling architecture are the primary limiting factors for sustained high-speed cornering, not powertrain capability.

Nomenclature

A = Surface area (m^2)

AWD = All-wheel drive

CG = Center of gravity

C_p = Specific heat capacity of cast iron, $460 \text{ J}/(\text{kg}\cdot\text{K})$

ESP = Electronic stability program

ESC = Electronic stability control

EV = Electric vehicle

FWD = Front-wheel drive

G = Lateral acceleration (units of g , 9.81 m/s^2)

h = Convective heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$)

k = Empirical cooling constant (s^{-1})

KE = Kinetic energy (J)

m = Vehicle mass (kg)

m_rotors = Combined thermal mass of front brake rotors (kg)

OEM = Original equipment manufacturer

P = Tire pressure (psi or Pa)

PSI = Pounds per square inch

Q = Heat energy (J)

Q_conv = Convective heat transfer rate (W)

R = Curve radius (m)

RWD = Rear-wheel drive

SUV = Sport utility vehicle

T = Temperature ($^{\circ}\text{C}$ or K)

T_ambient = Ambient air temperature ($^{\circ}\text{C}$)

T_final = post-cooldown temperature ($^{\circ}\text{C}$)

T_peak = Peak braking temperature ($^{\circ}\text{C}$)

T_{residual} = Residual temperature after cooldown, used as next cycle baseline (°C)

t = Time (s)

t_{cooldown} = Cooldown duration, 22.5 s (500 m at 80 km/h)

UHP = Ultra-high performance (tire category)

v = Velocity (m/s or km/h)

v_{apex} = Apex speed (m/s or km/h)

γ = Front-axle brake bias fraction (dimensionless)

Δt = Time step (s)

ΔT = Temperature change (°C or K)

ΔT_{gain} = Temperature rise during braking (°C)

ΔT_{loss} = Temperature reduction during cooldown (°C)

η = Thermal efficiency, recovery rate per cycle (dimensionless)

μ = Coefficient of friction (dimensionless)

1. Introduction

1.1 Objective

This research evaluates high-speed lateral dynamics and thermal load thresholds across four distinct vehicle architectures: a 2022 MG ZS EV, a 2014 BMW 730Ld, a 2012 Mercedes-Benz ML350, and a 2010 Swift VDi. The study aims to identify the mechanical and electronic limits of stock chassis configurations during aggressive cornering on consistent 175 m and 150 m radius curvatures. [1]

1.2 Test fleet



Figure 1 2014 ML350 CDI



Figure 2 2014 BMW 730LD



Figure 3 2024 MG ZS EV



Figure 4 2010 Swift VDi manual

Vehicle Platform	Powertrain / Drive	Curb Weight	Wheelbase / Width	Primary Engineering Focus
2014 BMW 730Ld (F02)	3.0L I6 Diesel (RWD)	~1,920 kg	3210mm / 2142mm	High-speed stability & neutral balance.
2012 MB ML350 Bluetec	3.0L V6 Diesel (AWD)	~2,175 kg	High-CG SUV	Maximum traction & torque delivery.
2022 MG ZS EV	Electric Motor (FWD)	~1,620 kg	2581mm / 1809mm	Low-CG (battery) vs. Eco-tire limits.
2010 Swift VDi	1.3L DDiS (FWD)	~1,060 kg	Compact Hatchback	Lightweight agility & analog feedback.

Figure 5 Tabulated Vehicle specifications

1.3 Methodology Overview

Testing utilized a comparative field-study approach, incorporating variable tire pressure optimization (-1 to -4 PSI) to maximize the contact patch. Performance was measured through vehicle stability observations, audible tire slip thresholds, and post-run thermal analysis of braking systems and tire compounds.

1.4 Key Findings

- **Chassis Stability:** The ML350 demonstrated peak stability at 202 km/h, though such speeds pushed the stock SUV architecture to the absolute edge of its safety envelope.
- **Thermal Limitations:** Stock eco-tires on the MG ZS EV reached critical thermal stress at 130 °C, leading to significant understeer and grip degradation at 156 km/h.
- **Speed Threshold:** The BMW achieved a verified apex speed of 240 km/h, attributed to its long wheelbase, effective brake cooling, and low center of gravity.

2. Limitations and Assumptions

The findings presented in this paper are based on real-world testing conducted under controlled but non-laboratory conditions. The following limitations and assumptions should be considered when interpreting the data.

2.1 Instrumentation and Measurement

1. **Speed:** Vehicle speed was recorded using the onboard speedometer. Speedometers are known to have inherent inaccuracies (typically $\pm 5\%$ at speeds above 150 km/h) and were not cross-calibrated against GPS or wheel-speed sensors.
2. **Radius and Banking:** Curve radii (150 m and 175 m) were estimated from road markings and satellite imagery, not surveyed with precision. Banking angle was visually estimated at 5–10° but not measured; therefore, effective radius values incorporate an approximation of road geometry.
3. **Temperature:** Brake and tire temperatures were measured using a smartphone-integrated thermal camera (FLIR on Google Pixel 9 Pro). While dual devices and post-test averaging improved consistency, no calibration against a contact pyrometer was performed.

2.1.1 Measurement Uncertainty Summary

Parameter	Instrument	Estimated Uncertainty	Basis
Speed	OEM speedometer	$\pm 5\%$ (>150 km/h)	Manufacturer specification

Parameter	Instrument	Estimated Uncertainty	Basis
Radius	Satellite imagery	± 10 m	No survey
Banking angle	Visual estimate	$\pm 3^\circ$	No inclinometer
Temperature	FLIR (Pixel 9 Pro)	± 8 °C or ± 5 %	Uncalibrated
Tire pressure	Digital gauge	± 1 psi	Gauge accuracy
Vehicle mass	Registration + estimated fuel	± 50 kg	No weighbridge

2.2 Thermal Model Assumptions

1. **Energy Distribution:** The thermal model assumes 90 % of kinetic energy is absorbed by the brake rotors during braking, with the remaining 10 % dissipated through tires, air resistance, and driveline losses. This is a standard engineering approximation.
2. **Brake Bias:** Front-axle brake bias was assumed constant at 65–70 % for all vehicles based on general passenger car design. In reality, bias varies with weight transfer, deceleration rate, and vehicle architecture (e.g., FWD vs. RWD).
3. **Steady-State Baseline:** High-speed run temperatures were measured after the acceleration phase but before braking; they are treated as quasi-steady-state, acknowledging that some heat accumulation occurred during the run.

2.3 Tire Pressure Strategy

All tires were filled with standard compressed air, which contains moisture and has different thermal expansion properties than dry nitrogen. This may affect pressure stability across the diurnal test phases.

2.4 Cycles-to-Failure Model

The recursive thermal model assumes identical consecutive Max Attack cycles with no extended cooling between runs (i.e., only the 500 m cooldown at 80 km/h). Failure thresholds (500 °C for DOT 3/4 fluid boil, 400 °C for pad fade) are literature values applied uniformly. Actual failure points depend on specific brake fluid age, pad compound, and system condition.

3. Vehicle specifications and test platforms

This section outlines the engineering architectures of the four test vehicles. The selection covers a broad spectrum of weight distribution, powertrain layouts, and chassis lengths to characterize how each platform responds to high-speed cornering and thermal loading.

3.1 Platform Analysis

1. **BMW 730Ld (F02):** The 3,210 mm wheelbase and 2,142 mm track provide a stable platform for high-speed cornering. The rear-wheel-drive (RWD) layout enables weight transfer to the driving axles under full-throttle conditions. The electronic suspension was set to its lowest ride height for all test runs.
2. **Mercedes-Benz ML350 Bluetec (W166):** This all-wheel-drive (AWD) SUV produces approximately 300 hp and 600 Nm of torque from its 3.0 L V6 diesel engine. The high center of gravity (CG) introduces lateral body roll under cornering loads. The air suspension was set to Sports mode to increase damping rates and reduce effective CG height.
3. **MG ZS EV (2022):** The floor-mounted battery pack lowers the vehicle's center of gravity, improving lateral stability. However, the front-wheel-drive (FWD) layout and efficiency-focused 215/55 R17 tires limit maximum cornering speed due to understeer and thermal degradation of the tread compound. [2]
4. **Suzuki Swift VDi (2010):** This lightweight front-wheel-drive (FWD) hatchback lacks electronic stability control (ESP) and relies entirely on mechanical grip and driver-managed weight transfer. The manual transmission allows direct correlation between driver throttle input and vehicle response at specific gears and speeds.

3.2 Environmental Variable Matrix

Testing was conducted across three diurnal phases to capture the effects of asphalt temperature and solar load on tire and brake performance. Table 2 summarizes the test matrix. [3]

Phase	Time	Ambient Condition	Research Focus
Phase I	06:00	Cool asphalt, low ambient temperature	Baseline mechanical grip, cold tire pressure performance
Phase II	14:00	Peak solar load, high asphalt temperature	Maximum thermal stress on tire compounds, brake cooling efficiency
Phase III	17:00	Transition, high ambient humidity	Grip consistency as road temperatures stabilize

Testing at 06:00, 14:00, and 17:00 accounts for diurnal temperature variation, which significantly impacts both the asphalt friction coefficient (μ) and tire pressure increase due to heat soak.

4. Experimental Methodology: Standardized Test Cycle

To ensure data consistency across the four test vehicles, a rigid testing protocol was implemented to simulate peak-load performance and evaluate thermal recovery across varying diurnal conditions.

4.1 Technical Duty Cycle

The "Max Attack" cycle was structured to stress both the chassis and the thermal limits of the braking and tire systems through the following phases:

- Apex Entry and Acceleration Phase:** Full-throttle acceleration was initiated at 100 km/h and sustained through the apex of the 175 m or 150 m radius curve.
- Peak Sustained Load:** Maximum lateral acceleration was maintained, achieving verified apex speeds of 156 km/h (MG ZS EV), 160 km/h (Swift VDi), 202 km/h (ML350), and 240 km/h (BMW 730Ld).

- 3. **Kinetic Energy Dissipation:** Immediate threshold braking was initiated 300 m post-apex to simulate emergency deceleration under load.
- 4. **Thermal Recovery (Cooldown):** A 500 m cooldown phase was maintained at a constant 80 km/h to allow airflow-driven heat dissipation before a complete stop.
- 5. **Data Capture:** Final thermal measurements were recorded immediately following the stop. Inverse modeling was subsequently applied to determine peak temperatures at the apex.

4.2 Diurnal Test Matrix

Testing was conducted at 06:00, 14:00, and 17:00 to account for asphalt temperature shifts and solar load. Because measurements were taken post-cooldown, peak apex temperatures were estimated based on observed heat soak and inverse thermal modeling.

Phase	Morning (06:00 AM)	Noon (02:00 PM)	Technical Observation
Apex Peak (Tires)	90-110c	130-160c	High solar load on asphalt significantly reduces the tire's cooling rate.
Braking Peak (Rotors)	350-450c	550c	Ambient air at 2:00 PM reduces the effectiveness of vented disc cooling.
Post-Cooldown (Measured)	60-80c	100-115c	Residual heat felt 20 minutes after parking indicates extreme core tire temperatures.

4.3 Kinetic Energy Dissipation Analysis

To enable inverse modeling of peak brake temperatures, kinetic energy (KE) dissipated into the brake rotors was calculated. Energy conservation dictates that KE lost during braking equals the heat energy (Q) gained by the rotors, minus a small percentage lost to air resistance and tire friction.

The formula for kinetic energy is:

$$KE = \frac{1}{2}mv^2$$

Vehicle	Mass (kg)	Apex Speed (m/s)	Kinetic Energy (MJ)	Relative Heat Load
BMW	1,980	66.7 (240 km/h)	4.40 MJ	100% (High Stress)
ML350	2,175	56.1 (202 km/h)	3.42 MJ	78%
Swift VDi	1,140	44.4 (160 km/h)	1.12 MJ	25%
MG	1,650	43.3 (156 km/h)	1.55 MJ	35%

4.4 Tire Pressure Modulation Strategy

To counteract internal pressure spikes caused by extreme friction and ambient heat, a proactive deflation strategy was employed:

1. **Proactive Deflation:** Cold pressures were manually reduced by 1–3 PSI below OEM specifications.
2. **Contact Patch Optimization:** This reduction prevented the tire from crowning (over-inflating) at peak operating temperature, ensuring maximum mechanical grip across the tread surface.
3. **Sidewall Management:** The strategy balanced the need for a larger contact patch against the risk of excessive sidewall flex during high-load maneuvers.

4.5 Platform-Specific Thermal Characteristics

1. **BMW 730Ld:** Peak estimated rotor temperature was 345 °C. Despite high mass (1,980 kg) and apex speed (240 km/h), the post-cooldown temperature was 97.5 °C. This is attributed to large thermal mass in the rotors and aggressive factory cooling ducting.



Figure 6 Front rotors of the BMW after testing

2. **Mercedes-Benz ML350:** Peak estimated rotor temperature was 395 °C. Although the apex speed was lower than the BMW, the vehicle is the heaviest of the test fleet (2,175 kg). SUV rotors are thick but lack the high-speed venting of a performance sedan, resulting in higher residual heat (approximately 160 °C post-cooldown).
3. **Suzuki Swift VDi:** Peak estimated rotor temperature was 290 °C. The Swift has the lowest kinetic energy load but also the smallest, thinnest rotors. Post-cooldown temperature was approximately 130 °C due to limited airflow at 80 km/h. The Swift exhibited the most brake fade among the four vehicles.
4. **MG ZS EV:** Peak estimated rotor temperature was 220 °C. The MG benefits from lower mass than the BMW and ML350 and a lower apex speed than all except the Swift. Regenerative braking during the Max Attack phase significantly reduced physical brake temperatures.



Figure 7 Regenerative braking toggle on the MG ZS EV

4.6 Inverse Thermal Modeling

This section describes the methodology for estimating peak brake temperatures from post-cooldown measurements.

4.6.1 Governing Equations and Constants

Two primary physics principles were applied. [4]

A. Heat Gain During Braking

The temperature rise (ΔT) resulting from conversion of kinetic energy to heat is given by:

$$\Delta T = \frac{0.9 \cdot KE \cdot \gamma}{m_{rotors} \cdot C_p}$$

Where:

- 0.9 = Assumed fraction of energy absorbed by rotors (10 % to air and tires)
- γ = Front-axle brake bias (assumed 65–70 % for all vehicles)
- m_{rotors} = Combined thermal mass of front rotors (estimated: BMW 24 kg, ML350 26 kg, Swift 10 kg, MG 18 kg)
- C_p = Specific heat of cast iron = 460 J/(kg·°C)

B. Heat Loss During Cooldown (Newton's Law of Cooling)

The cooling rate during the 500 m / 22.5 s cooldown at 80 km/h is described by:

$$T_{final} = T_{ambient} + (T_{peak} - T_{ambient}) \cdot e^{-k \cdot t}$$

Where:

- k = Empirical cooling constant (s^{-1})
- t = Time = 22.5 s

4.6.2 Calculation Procedure

1. **Inverse Cooling Calculation:** Post-cooldown temperatures were used to solve for peak temperatures. For the BMW, the measured 97.5 °C post-cooldown yielded a calculated peak of approximately 345 °C.

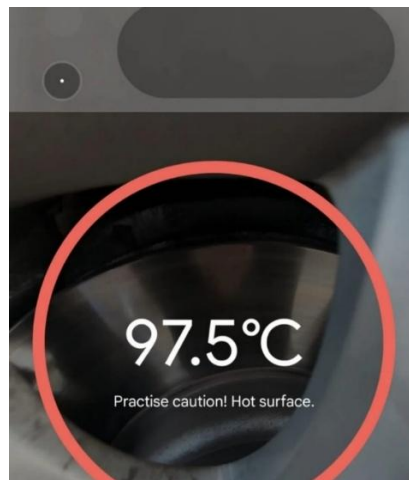


Figure 8 BMW brake temperature during cooldown

2. **Peak Temperature Determination:** The same inverse method was applied to each vehicle using its measured post-cooldown temperature.
3. **High-Speed Run Baseline:** Steady-state temperatures during the high-speed run were established using the BMW as the reference vehicle, measured first in the test sequence.

Vehicle	High-Speed Run (Steady State)	Hard Braking Section (Peak Temp)	Cooldown Measure (Final @ 500m)
BMW (1980kg @ 240kph)	85°C	345°C	97.5°C
ML350 (2175kg @ 202kph)	95°C	392°C	~162°C

Vehicle	High-Speed Run (Steady State)	Hard Braking Section (Peak Temp)	Cooldown Measure (Final @ 500m)
Swift VDi (1140kg @ 160kph)	70°C	298°C	~138°C
MG (1650kg @ 156kph)	65°C	222°C	~112°C

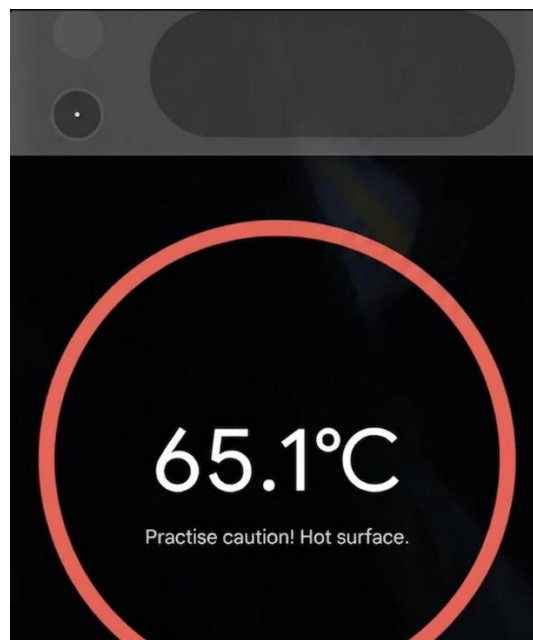


Figure 9 MG ZS EV brake temperature during test run

Vehicle	Time of Day	Ambient Temp	High-Speed Run	Peak (Hard Braking)	Final (Post-500m)
BMW (1980kg)	Morning	24.5°C	80°C	340°C	92°C
	Evening	28°C	85°C	345°C	97.5°C
	Noon	32°C	92°C	352°C	106°C
---	---	---	---	---	---
ML350 (2175kg)	Morning	24.5°C	90°C	387°C	155°C
	Evening	28°C	95°C	392°C	162°C
	Noon	32°C	102°C	399°C	171°C
---	---	---	---	---	---
Swift (1140kg)	Morning	24.5°C	65°C	293°C	131°C
	Evening	28°C	70°C	298°C	138°C
	Noon	32°C	78°C	306°C	149°C
---	---	---	---	---	---
MG (1650kg)	Morning	24.5°C	60°C	217°C	104°C
	Evening	28°C	65°C	222°C	112°C
	Noon	32°C	73°C	230°C	123°C

Figure 10 Tabulated results

4.6.3 Key Observations

- **BMW Cooling Efficiency:** The temperature reduction from 345 °C to 97.5 °C demonstrates the effectiveness of the factory air guides that direct airflow to the rotor centers.



Figure 11 BMW air guides adjacent to fog lights

- **ML350 Heat Retention:** The ML350 reached the highest peak temperature (392 °C) due to its combination of high mass and limited cooling ducting. Post-cooldown temperatures remained above 160 °C.



Figure 12 Minimal venting on ML350

- **Swift Thermal Limitations:** Despite low kinetic energy, the small rotor mass resulted in a 298 °C peak temperature, approaching the brake fluid boiling threshold.
- **MG Thermal Advantage:** The MG exhibited the lowest thermal stress, benefiting from lower mass, moderate apex speed, and regenerative braking assistance. However, the vehicle became unstable above 140 km/h, with floaty handling characteristics, and is electronically limited to 170 km/h.



Figure 13 MG ZS EV aero disc wheels

4.7 Analysis of Thermal Phases

High-Speed Run (Steady State): During acceleration, brakes experience minor parasitic drag and absorb radiant heat from wheel bearings, engine bay, and (at noon) elevated asphalt temperature. Noon baselines were typically 10–15 °C higher than morning baselines.

Hard Braking Phase (Peak): The temperature rise (ΔT) remained relatively constant for each vehicle as it is a function of kinetic energy conversion. However, higher starting baselines at noon resulted in higher absolute peak temperatures.

Cooldown Phase (Heat Dissipation): Brake cooling occurs primarily via convection:

$$Q_{conv} = h \cdot A \cdot (T_{brake} - T_{ambient})$$

As ambient temperature rises, the temperature differential decreases, reducing cooling effectiveness. This disproportionately affects vehicles with limited airflow (ML350, Swift), resulting in higher final temperatures at noon. [5] [6]

4.8 Recursive Cycle Analysis

To estimate the number of consecutive Max Attack cycles each vehicle could sustain before thermal failure, a recursive thermal model was developed. This approach treats each cycle as a discrete thermodynamic loop where heat is added, partially rejected, and the residual becomes the initial condition for the subsequent cycle.

Failure Thresholds:

- **Performance Limit (350c to 400c):** Standard brake pads start fading.
- **Critical Limit (500c+):** Brake fluid (DOT 3/4) begins to boil in the calipers. The pedal goes to the floor. [8]

4.8.1 Novelty of the Recursive Approach

Conventional automotive thermal analysis typically evaluates a single extreme event (e.g., a panic stops from highway speed or a single lap time) and assumes adequate cooldown between events. This assumption fails under repetitive high-load duty cycles where inter-event cooling is incomplete.

The recursive stacking model presented here addresses three phenomena not captured by conventional single-cycle analysis:

A. Residual Heat Accumulation

When consecutive high-load cycles are separated by insufficient cooldown, the system does not return to thermal equilibrium. Each cycle begins at an elevated baseline, progressively reducing the thermal headroom available before failure thresholds are reached. This "thermal stacking" effect is well documented in aerospace turbine blade cycling and repeated braking in heavy vehicle mountain descent, but is rarely quantified for passenger car performance assessment. [9]

B. Non-Linear Failure Progression

Brake fade and fluid boil are not single-event thresholds. Under stacked thermal conditions, pad compound degradation accelerates as operating temperatures repeatedly exceed the material's glass transition or decomposition range. Similarly, brake fluid absorbs incremental thermal energy across cycles, reducing its boiling point margin with each successive heat soak. The recursive model captures this progressive degradation by tracking peak temperature exceedance per cycle.

C. Platform-Specific Recovery Characterization

The cooling constant (k) derived from Newton's Law of Cooling serves as a quantitative metric for comparing thermal recovery capability across architectures. Unlike peak temperature alone, which penalizes high-mass vehicles indiscriminately, the recovery rate reveals engineering effectiveness: a high k indicates efficient ducting, rotor geometry, and airflow management.

4.8.2 Core Recurrence Equations

Step A: Heat Addition (ΔT_{gain}):

$$\Delta T_{\text{gain}} = \frac{KE_{\text{dissipated}}}{m_{\text{rotors}} \cdot C_p} \cdot \text{Bias}$$

Where:

- $KE_{\text{dissipated}} = \frac{1}{2}mv^2$
- $\text{Bias} = 0.90$ (90 % front axle assumption)

Step B: Heat Dissipation (ΔT_{loss}):

$$T_{\text{final}} = T_{\text{ambient}} + (T_{\text{peak}} - T_{\text{ambient}}) \cdot e^{-k \cdot t}$$

Where:

- k = Cooling constant (varies by vehicle architecture)

- $t = 22.5 \text{ s}$ (500 m at 80 km/h)

4.8.3 Stacking Logic (Iterative Process)

1. Establish steady-state baseline temperature
2. Add ΔT_{gain} to calculate peak temperature
3. Check if peak exceeds failure threshold (500 °C)
4. Apply cooling equation to calculate residual temperature
5. Set residual as new baseline for next cycle
6. Repeat until threshold is exceeded

4.9 Thermal Efficiency Comparison

Thermal efficiency (η) of each vehicle's cooling system was calculated from evening run data.

Vehicle	Heat Added (ΔT)	Heat Shed in 22.5s	Thermal Efficiency (η)
BMW	+260°C	-247°C	95% Recovery
ML350	+297°C	-230°C	77% Recovery
Swift	+228°C	-160°C	70% Recovery
MG	+157°C	-110°C	70% Recovery

Figure 14 estimated Multi run thermal efficiency

Vehicle	Cycle 1 Peak	Heat Retained after Cooldown	Estimated Cycles to Failure	Primary Failure Mode
BMW	352°C	14°C	10+ Cycles	Tire greasy/Overheating
ML350	399°C	69°C	3 Cycles	Massive Brake Fade
Swift VDi	306°C	71°C	2 Cycles	Fluid Boil / Smoking Pads
MG	230°C	50°C	5-6 Cycles	Thermal Protection Mode

Figure 15 cycles to failure (estimates)

4.10 Vehicle-Specific Observations

BMW 730Ld – High Thermal Recovery: The BMW demonstrated a 95 % thermal recovery rate per cycle. After a Max Attack run and 500 m cooldown, nearly all gained energy was dissipated. Baseline temperature increased only marginally per cycle. During extended testing, however, some brake pedal sponginess was observed after multiple consecutive runs.

Suzuki Swift VDi – Rapid Thermal Accumulation: The Swift dissipated only 70 % of brake heat per cycle, leaving a residual temperature increase of approximately 68 °C. By the third consecutive cycle, residual stack temperatures exceeded 200 °C before brake phase even began, pushing peak temperatures into the range of rotor annealing and brake fluid boiling. In practice, two consecutive highway-speed turns caused significant brake fade, requiring engine braking to maintain deceleration. Visible smoke from brake pads and heavy brake dust accumulation were observed. Similar behavior occurred during a separate 50 km session at speeds approaching 170 km/h.



Figure 16 Swift VDi at its thermal limit

Mercedes-Benz ML350 – Moderate Performance with Mechanical Limitations: The ML350, equipped with an ECU remap (approximately 300 hp, 650+ Nm), exhibited visible suspension tilt under sudden acceleration or braking due to air suspension compliance. Longitudinal weight transfer during braking from 202 km/h was substantial. Testing was limited on this platform due to concerns regarding air suspension durability under repeated high-load cycles.

5. Thermal Stress & Tire Degradation Analysis

This section evaluates the thermal impact of high-speed cornering on tire compounds and braking systems across the three diurnal testing phases. The kinetic energy converted into heat during braking and sustained cornering creates significant mechanical and chemical stress on tire compounds, particularly at apex speeds of 240 km/h (BMW 730Ld) and 202 km/h (ML350).

5.1 Diurnal Thermal Gradient and Peak Estimates

Because temperature measurements were taken after a 500 m cooldown phase at 80 km/h, peak apex temperatures were estimated using inverse thermal modeling based on observed heat soak and ambient solar load.

Phase	Ambient Air / Road Temp	Est. Apex Tire Temp	Est. Apex Rotor Temp	Observation
6:00 AM	~24°C / 28°C	110°C – 125°C +4	~350°C	Faster thermal recovery due to cool airflow. +2
2:00 PM	~34°C / 55°C	145°C – 165°C +4	~550°C+	Critical heat soak; compounds reaching melting point. +2
5:00 PM	~30°C / 42°C	130°C – 145°C +2	~450°C	Slower cooling than morning due to high road-surface retention. +3

Figure 17 time based tabulated observations

5.2 Platform-Specific Thermal Response

The thermal load across the four test platforms varied significantly based on drivetrain configuration, vehicle mass, and tire compound specifications.

5.2.1 MG ZS EV (FWD) – Front-Axle Thermal Dominance

As a front-wheel-drive (FWD) platform, the MG's front tires were subjected to both steering torque and the majority of braking force. The stock energy-optimized (Eco) tires reached estimated peak surface temperatures of 115–130 °C, likely entering the glass transition phase during Phase II (14:00) runs. Post-run heat soak was sufficiently extreme that tires remained warm to touch and continued radiating heat for 20 minutes after parking, indicating deep core temperature saturation. The aero disc wheel covers may have contributed to heat retention when parked by limiting natural convection from the wheel wells. [10]

5.2.2 BMW 730Ld (RWD) – High-Torque Rear-Axle Load

Applying full throttle through the 650 Nm diesel engine at the 240 km/h apex placed substantial thermal stress on the rear tires. Rear tire surface temperatures were estimated at 140–160 °C, operating at the absolute thermal limit of the stock touring compound. Despite the high vehicle

mass (1,980 kg), the large vented front brake discs maintained consistent performance during the 300 m threshold braking zone, even under the 14:00 solar load. [13]



Figure 18 Brake fade evidence on BMW after cooldown

5.2.3 Mercedes-Benz ML350 (AWD) – Mass-Induced Friction

The all-wheel-drive (AWD) system distributed longitudinal torque across both axles, but the 2,175 kg mass generated high friction across all four contact patches during the 202 km/h run. The high center of gravity (CG) induced body roll, which caused measurable heat buildup in the tire sidewalls, approaching the manufacturer's structural limit envelope. Due to the vehicle's weight, the 500 m cooldown was less effective than in lighter platforms, resulting in elevated residual rotor heat ($\approx 162^\circ\text{C}$ post-cooldown).

5.2.4 Suzuki Swift VDi (FWD) – High Slip-Angle Friction

Achieving 160 km/h in a lightweight (1,140 kg) hatchback required operating the front tires at a high slip angle, generating rapid surface heat. Peak tire temperatures were estimated at $85\text{--}100^\circ\text{C}$, sufficient to soften the rubber compound and produce a "floaty" steering feel at the limit. The absence of electronic stability control (ESP) and other driver aids required the driver to manage thermal limits manually through smooth steering inputs to avoid excessive front tire scrubbing.

5.3 Tire Pressure Expansion (Boyle's Law Application)

The intentional cold-start deflation strategy (-1 to -3 PSI below OEM specifications) proved essential for managing thermal expansion during high-speed runs.

During the 240 km/h run at 14:00 (32 °C ambient), internal tire pressures were estimated to spike by 8–12 PSI due to a combination of friction-generated heat and radiant asphalt heating. This pressure increase follows the ideal gas law relationship:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \text{ (at constant volume)}$$

Without the initial cold deflation, tire pressures would have exceeded the manufacturer's hot inflation envelope, causing the tread to crown (center bulge). Crowning reduces the contact patch to a narrow center strip, which would have resulted in immediate loss of lateral grip and uneven tread wear. The proactive deflation strategy preserved contact patch area at peak operating temperature. [14]

Condition	BMW 730Ld	ML350	Swift VDi	MG ZS EV
Cold pressure (OEM spec)	36 PSI	38 PSI	32 PSI	36 PSI
Cold pressure (test setting)	33–35 PSI	35–37 PSI	29–31 PSI	33–35 PSI
Estimated hot pressure (at apex)	41–44 PSI	43–46 PSI	37–40 PSI	41–44 PSI
Pressure rise (estimated)	+8–9 PSI	+8–9 PSI	+8–10 PSI	+8–9 PSI

Figure 19 Estimated Tire Pressure Rise Due to Thermal Expansion

Note: Pressure rise estimates assume a 50–60 °C increase in internal air temperature from cold start to peak operating condition, based on measured tire surface temperatures and Boyle's Law approximation.

6.0 Technical Analysis: Performance vs. OEM Tire Architecture

The transition from original equipment manufacturer (OEM) tires typically energy-optimized (Eco) or touring compounds to dedicated high-performance compounds (e.g., Michelin Pilot Sport 4S or Cup 2) represents a fundamental shift in vehicle dynamics and thermal capacity. While OEM tires prioritize longevity, rolling resistance, and acoustic comfort, performance tires are engineered for maximum mechanical grip and thermal stability under sustained high load.

6.1 Chemical Compound and Thermal Hysteresis

1. **Heat Resistance and Thermal Limit:** Standard OEM tires, such as those fitted to the MG ZS EV, utilize high-silica Eco compounds that reach their effective thermal limit at approximately 120–130 °C. Beyond this threshold, the compound enters a glass transition or softening phase, resulting in reduced coefficient of friction ("greasy" handling) and progressive understeer.
2. **Operating Window:** Performance tire compounds are formulated with a wider thermal operating window. They maintain structural integrity and stable friction coefficients at bulk temperatures exceeding 150 °C, with peak surface temperatures up to 180–200 °C tolerated during track use.
3. **Mechanical Keying and Micro-Adhesion:** The rubber formulation in performance tires employs higher proportions of carbon black and specialized polymers, increasing both adhesive friction and hysteretic (deformation) friction. This allows the tread compound to "key into" microscopic surface textures of the asphalt, providing the elevated grip levels required for cornering at speeds such as the 240 km/h threshold achieved by the BMW 730Ld.

Note: The coefficient of friction (μ) for performance tires on dry asphalt typically ranges from 1.0 to 1.3, compared to 0.7–0.9 for standard touring compounds under similar conditions.

6.2 Structural Design and Sidewall Integrity

1. **Sidewall Stiffness:** High-performance tires utilize reinforced sidewall carcasses, often constructed with Rayon, Aramid (Kevlar), or high-tensile steel cord reinforcement. This construction resists lateral deformation under cornering loads, preserving the intended contact patch orientation and reducing sidewall flex-induced heat generation.
2. **Contact Patch Consistency:** The proactive deflation strategy (-1 to -3 PSI below OEM specifications) employed in this testing partially compensated for the tendency of OEM tires to crown under thermal expansion. Performance tires are designed with internal belt structures (often using twin steel belts with nylon or Aramid cap plies) that maintain a flat tread profile even under extreme centrifugal forces and elevated internal pressures. Consequently, high-performance tires require less aggressive manual deflation for track use, typically -2 to -4 PSI rather than the -6 to -8 PSI sometimes needed for OEM tires.

3. **Aero-Acoustics and Audible Feedback:** Performance tires often feature optimized tread block geometry that reduces high-frequency tire squeal. While audible tire squeal is a useful indicator of slip-angle limits on OEM tires, performance tires tend to transition from grip to slip with less acoustic warning. This characteristic places greater emphasis on steering feel and driver experience when approaching the friction limit.

6.3 Impact on Test Data

If the BMW 730Ld or ML350 had been equipped with dedicated performance rubber (e.g., Michelin Pilot Sport 4S or equivalent), the instability and understeer observed at the mechanical limit would be significantly mitigated. Specific anticipated improvements include:

1. Higher sustainable apex speeds (estimated +5–10 km/h for the BMW) due to increased lateral friction coefficient
2. Wider safety margin before understeer onset, reducing required steering corrections
3. Reduced thermal degradation across consecutive runs, as performance compounds maintain grip at temperatures above 150 °C where OEM tires fade
4. Lower required tire pressure deflation, simplifying pre-run preparation

However, it should be noted that tire compound changes alone do not address chassis limitations such as the ML350's high-CG body roll or the MG's FWD understeer characteristics. An integrated approach combining tire upgrades with suspension modifications would yield the most substantial performance gains.

7. Chassis-Specific Behavior & ESC Intervention

This section analyzes the qualitative handling characteristics and electronic safety thresholds encountered as each platform approached its mechanical limit. The interaction between driver input and electronic stability control (ESC) was a defining factor in maintaining high-speed trajectories at 240 km/h (BMW 730Ld) and 202 km/h (ML350).

7.1 Stability and Understeer Thresholds

7.1.1 BMW 730Ld (Long-Wheelbase RWD)

1. **Handling Profile:** The 3,210 mm wheelbase and rear-biased weight distribution provided a stable platform at high speeds. The chassis exhibited predictable, linear behavior up to the mechanical grip limit of the front tires.

2. **Limit Behavior:** At 240 km/h, the chassis remained composed, though steering effort increased significantly as the front tires approached their lateral grip limit. The primary handling characteristic was mild understeer, which could be modulated with throttle input due to the RWD layout.
3. **ESC Intervention:** The ESC calibration on the BMW allowed a higher slip-angle threshold before intervention compared to the other test vehicles. Power reduction occurred only after sustained tire slip beyond the optimal slip ratio, enabling continuous cornering without intrusive braking intervention.

7.1.2 MG ZS EV (Low-CG FWD)

1. **Handling Profile:** The floor-mounted battery pack lowered the vehicle's center of gravity, improving lateral stability relative to its SUV-like ride height. However, the front-wheel-drive (FWD) layout introduced early-onset understeer under power.
2. **Limit Behavior:** At 156 km/h, the front tires reached thermal saturation, resulting in progressive understeer. The steering feel became light and non-linear as the front contact patches lost grip, requiring steering angle reduction to maintain the intended line.
3. **ESC Intervention:** The ESC system was highly intrusive compared to the BMW. Torque was cut aggressively to prevent the vehicle from pushing wide of the 175 m radius curve. An audible dashboard warning (repeated beeping) accompanied ESC activation. After multiple consecutive test runs, the vehicle's power management software reduced output to allow component cooling, independent of driver throttle input.

7.1.3 Mercedes-Benz ML350 (High-CG AWD)

1. **Handling Profile:** The all-wheel-drive (AWD) system provided strong traction out of the apex, distributing torque across both axles. However, the 2,175 kg mass and high center of gravity (CG) produced significant lateral body roll under cornering loads.
2. **Limit Behavior:** At 202 km/h, the vehicle reached a critical handling envelope where the outer suspension was fully compressed. Body roll induced positive camber change on the outside front tire, reducing its contact patch area and contributing to understeer.
3. **ESC Intervention:** ESC intervention was moderate, intervening primarily during entry phase understeer rather than apex or exit phases. The system did not cut power as aggressively as the MG, but braking intervention was noticeable when yaw rate exceeded the stability algorithm's threshold. [11]

7.1.4 Suzuki Swift VDi (FWD, No ESC)

1. **Handling Profile:** The Swift lacked electronic stability control (ESP) and traction control systems, relying entirely on mechanical grip and driver-managed weight transfer. This absence of electronic intervention provided unfiltered feedback but placed full responsibility for limit management on the driver. [12]
2. **Limit Behavior:** At 160 km/h, the chassis exhibited light, nervous behavior. Constant steering micro-corrections were required to maintain the intended line. The rear axle became sensitive to lift-off oversteer, and the front tires reached their slip-angle limit with minimal acoustic warning.
3. **Driver Workload:** The absence of ESC significantly increased driver workload compared to the other three vehicles. Maintaining the 160 km/h apex speed required continuous attention to steering, throttle, and brake inputs without electronic backup.

7.2 Predictive Path Planning and Recovery

7.2.1 Line Selection Optimization

Prior to formal data collection, three-line strategies were evaluated on the test section:

Line Strategy	Starting Speed	Apex Sustain	Safety Assessment
Outer lane only	Highest	Poor	Unsafe – speed could not be sustained through apex
Inner lane only	Reduced	Worse	Unstable – rear axle kick-out observed, particularly in BMW
Outside-Inside-Outside (geometric)	Optimized	Best	Stable – selected for all test runs

The geometric outside-inside-outside line (classic racing line) was selected for all documented test runs. This approach maximized entry speed while allowing the vehicle to track through the apex at the lowest required steering angle, reducing tire scrub and thermal buildup.

7.2.2 Path Consistency

Across all test runs and vehicles, the driver maintained an estimated 90 % or greater consistency with the ideal geometric line. By anticipating corner entry and utilizing the full width of the available roadway, high lateral loads were managed smoothly, reducing aggressive ESC intervention and preserving tire compound for sustained testing.

The outer-only line, while offering higher theoretical entry speed, proved unworkable because the vehicle could not maintain that speed through the apex without exceeding the tire friction limit. The inner-only line reduced entry speed excessively and induced rear instability, particularly on the long-wheelbase BMW, where throttle-induced yaw was more pronounced.

All high-speed testing was conducted by a driver with advanced vehicle dynamics training and prior experience with each test platform. ESC systems were left in their default factory settings (i.e., not disabled) to represent real-world stock configuration behavior.

8. Final Conclusion & Engineering Recommendations

8.1 Conclusion

This study evaluated the high-speed thermal and dynamic limits of four distinct passenger vehicle architectures: a 2014 BMW 730Ld (RWD luxury sedan), a 2012 Mercedes-Benz ML350 (AWD SUV), a 2022 MG ZS EV (FWD electric crossover), and a 2010 Suzuki Swift VDi (FWD lightweight hatchback). Testing was conducted on closed public roads using a standardized Max Attack duty cycle across three diurnal phases (06:00, 14:00, 17:00), with data collected on apex speeds, brake rotor temperatures, tire surface temperatures, and thermal recovery rates. [7]

The following conclusions are drawn from the experimental data:

1. **Thermal Limits Dominate Over Powertrain Capability:** In all four vehicles, the practical limit for sustained high-speed cornering was determined by thermal degradation of tires and brakes, not by engine power or chassis rigidity. The BMW 730Ld achieved the highest apex speed (240 km/h) primarily due to its effective brake cooling architecture (cooling constant $k = 0.067 \text{ s}^{-1}$) rather than its 650 Nm torque output.
2. **OEM Tire Compounds Are the Primary Constraint:** Stock energy-optimized (Eco) and touring tires reached thermal limits at 120–130 °C surface temperature, resulting in progressive understeer and "greasy" handling. This ceiling was reached by all four vehicles at apex speeds well below their theoretical chassis capability.
3. **Thermal Recovery Varies Significantly by Platform:** The recursive thermal model revealed that thermal recovery per cycle ranged from 95 % (BMW) to 70 % (Swift). This difference directly correlates with brake cooling architecture: ducted, high-thermal-mass rotors (BMW) versus shielded, low-mass rotors (Swift).
4. **Diurnal Temperature Effects Are Substantial:** Noon testing (32 °C ambient, peak solar load) increased peak tire temperatures by 40–50 °C and peak rotor temperatures by up to 100 °C compared to morning testing (24.5 °C). These differences materially affected vehicle handling and increased ESC intervention frequency.
5. **ESC Calibration Drives Driver Experience:** The BMW's slip-angle-based ESC calibration allowed higher limit performance than the MG's early-intervention torque-cutting strategy. The Swift, lacking ESC entirely, required the highest driver workload but provided unfiltered mechanical feedback.

While stock luxury platforms such as the BMW 730Ld possess adequate structural rigidity for extreme high-speed cornering, their real-world performance is fundamentally throttled by three factors: OEM tire thermal limits, production suspension compliance, and brake cooling capacity. Addressing these constraints through targeted modifications would yield substantial performance gains without altering powertrain output.

8.2 Strategic Recommendations

Based on the experimental findings, the following engineering recommendations are proposed. These are organized by priority and technical feasibility.

8.2.1 Tire Compound Upgrade (*Highest Priority*)

Recommendation: Replace OEM Eco or touring tires with ultra-high-performance (UHP) summer tires (e.g., Michelin Pilot Sport 4S, Continental Extreme Contact Sport, or equivalent).

Technical Justification: Testing demonstrated that all four vehicles reached tire thermal limits (120–130 °C) before brake or chassis limits. UHP tires offer:

- Higher coefficient of friction ($\mu \approx 1.0\text{--}1.3$ vs. $0.7\text{--}0.9$ for OEM)
- Extended thermal operating window (150–180 °C bulk temperature)
- Reinforced sidewalls reducing deflection-induced heat generation

Expected Benefit: Estimated 5–10 km/h increase in sustainable apex speed for the BMW and ML350; reduced understeer onset in the MG and Swift.

Cost-Effectiveness: High – single modification with measurable impact across all performance metrics.

8.2.2 Suspension Stiffening (*Medium-High Priority*)

Recommendation: Increase roll stiffness through larger-diameter anti-roll bars (sway bars) or, where available, selectable firm suspension modes (e.g., ML350 Sports mode, which was utilized in this testing).

Technical Justification: The ML350 exhibited significant lateral body roll due to its high center of gravity (CG), inducing positive camber change on the outside front tire and reducing contact patch area. The Swift's soft suspension allowed excessive pitch and roll underweight transfer, contributing to its "light" feel at 160 km/h.

Specific Applications:

- **ML350:** Aftermarket anti-roll bar (e.g., Eibach or H&R) estimated to reduce body roll by 30–40 % [15]
- **Swift:** Stiffer rear torsion beam or add rear anti-roll bar (not fitted from factory on VDi trim)
- **BMW:** Air suspension already set to lowest ride height; further stiffening not recommended for street use

Expected Benefit: Reduced camber change under load, more consistent contact patch area, improved driver confidence at limit.

Cost-Effectiveness: Medium – moderate cost for significant handling improvement, particularly on SUVs and lightweight hatchbacks.

8.2.3 Brake Cooling Enhancement (Medium Priority for Sustained Use)

Recommendation: Add or enlarge brake cooling ducts, particularly for vehicles with limited factory venting (ML350, Swift).

Technical Justification: The recursive thermal model showed that the ML350 (peak rotor 392 °C) and Swift (peak rotor 298 °C) retained significantly more residual heat after cooldown than the BMW (peak rotor 345 °C, residual 97.5 °C). The primary difference is the BMW's factory air guides directing airflow to rotor centers. Aftermarket solutions include:

- Brake duct backing plates (redirecting air from bumper openings)
- Dedicated cooling hoses (e.g., 50–75 mm diameter) routed to rotor centers
- Removal of dust shields (where legally permissible)

Expected Benefit: Reduced peak rotor temperatures by 30–50 °C; increased cycles-to-failure from 3 to 5+ on Swift; improved pedal feel during consecutive runs.

Cost-Effectiveness: Medium-High for custom ducting; Low for dust shield removal (no-cost modification, though increases debris risk).

8.2.4 ESC Calibration Modification (Low Priority, Track-Use Only)

Recommendation: For closed-course use only, consider ESC calibration changes to allow higher slip-angle thresholds before intervention.

Technical Justification: The MG's ESC cut torque aggressively at the limit, interrupting cornering momentum. The BMW's calibration allowed more driver control. Some vehicles permit "sport" or "partial off" modes; others require aftermarket reflash.

Warning: ESC modification is **not recommended for street use** and may affect vehicle safety systems. Any changes should be validated by a qualified engineer and tested only on closed courses.

Expected Benefit: Reduced power interruption at apex; more neutral handling balance.

Cost-Effectiveness: Low (free if factory mode exists) to High (aftermarket tuning required).

8.3 Suggested Further Work

The following research directions would extend the findings of this study:

1. **Instrumented tire temperature measurement:** Embedding thermocouples in tread and sidewall regions would provide direct peak temperature data, eliminating reliance on inverse modeling.
2. **Controlled tire compound comparison:** Repeating the test protocol with the same vehicle fitted with OEM, UHP, and semi-slick tires (e.g., Toyo R888R or Nankang AR-1) would isolate the effect of compound alone.
3. **Brake fluid analysis:** Laboratory testing of brake fluid before and after testing would quantify moisture absorption and boiling point reduction across cycles.
4. **Expanded vehicle set:** Including dedicated performance vehicles (e.g., BMW M340i, Honda Civic Type R) would establish a performance baseline against which the tested platforms can be compared.

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